Chapter 9

Potentiometric Surfaces for Seven Stratigraphic Units and an Explanation for Underpressure in the Greater Anadarko Basin, Oklahoma, Texas, Kansas, and Colorado

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By Philip H. Nelson and Nicholas J. Gianoutsos

Chapter 9 of 13

Petroleum Systems and Assessment of Undiscovered Oil and Gas in the Anadarko Basin Province, Colorado, Kansas, Oklahoma, and Texas—USGS Province 58

Compiled by Debra K. Higley

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Suggested citation:
Nelson, P.H., and Gianoutsos, N.J., 2014, Potentiometric surfaces for seven stratigraphic units and an explanation for underpressure in the Greater Anadarko Basin, Oklahoma, Texas, Kansas, and Colorado, chap. 9, *in* Higley, D.K., comp., Petroleum systems and assessment of undiscovered oil and gas in the Anadarko Basin Province, Colorado, Kansas, Oklahoma, and Texas—USGS Province 58: U.S. Geological Survey Digital Data Series DDS–69–EE, 24 p., *http://dx.doi.org/10.3133/ds69EE*.

ISSN 2327-638X (online)

Contents

Plates

Figures

Tables

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
barrel (bbl), (petroleum, 1 barrel=42 gal)	0.1590	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Pressure	
atmosphere, standard (atm)	101.3	kilopascal (kPa)
bar	100	kilopascal (kPa)
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)

Potentiometric Surface Maps for Seven Stratigraphic Units and an Explanation for Underpressure in the Greater Anadarko Basin, Oklahoma, Texas, Kansas, and Colorado

By Philip H. Nelson and Nicholas J. Gianoutsos

Abstract

The controls on subsurface pressure across the northern part of the Anadarko Basin are examined with the aid of potentiometric maps constructed for seven stratigraphic units ranging in age from Cambrian to Early Permian. Pressure data from drillstem tests are converted to hydraulic head, a step that is complicated by variations in brine density within the basin, as shown by maps of salinity for each of the seven stratigraphic units considered in this study. Seven potentiometric maps were constructed using a series of filtering and mapping steps to drape a surface over the highest values of hydraulic head. The maps show that, for rocks of Desmoinesian, Missourian, Virgilian, and Lower Permian age, hydraulic head values approach surface elevation values along the Nemaha uplift in central Oklahoma where Lower Permian and Pennsylvanian strata are exposed. From the Nemaha uplift westward to southwestern Kansas and the panhandle areas of Oklahoma and Texas, hydraulic head increases by several hundred feet in each rock unit, whereas surface elevation increases by thousands of feet. The underpressuring of the aquifer-supported oil and gas fields, which increases from east to west, is a consequence of the westward-increasing vertical separation between surface elevation and hydraulic potential. Recharge to the deep confined rock units is limited. The thick cap of Permian evaporites and shales restricts recharge to the underlying strata, preventing reestablishment of a normal hydrostatic gradient. Recharge from the west is restricted because of onlap of Pennsylvanian and older strata onto the eastern flank of the Sierra Grande arch. Present-day underpressuring of oil and gas reservoirs on the northwest flank of the basin is the result of uplift and exposure of Lower Permian and Pennsylvanian strata along the Nemaha uplift and restricted recharge to the basin.

Introduction

This study explores the cause of widespread underpressure in the western and northern parts of the greater Anadarko Basin, an area that extends from the southeast corner of Colorado eastward to central Kansas and Oklahoma and includes the Oklahoma Panhandle and a portion of the Texas Panhandle (fig. 1). The structure of the Anadarko Basin is defined by the elevation contours of the Woodford Shale (fig. 1); a line drawn through the deepest part of the Woodford Shale serves to locate the deep basin in subsequent figures. Further discussion of the geology of the Anadarko Basin is given by Higley (chapters 5 and 7 of this report). Underpressure exists in rock units that are Paleozoic in age (fig. 2); rock units younger than Permian form unconfined aquifers above the deeper confined rock units where both underpressure and overpressured conditions exist. Chapter 8 of this report (Nelson and Gianoutsos), which also covers the study area of figure 1, examines the extent of overpressure which presently is confined to the deep basin but is hypothesized to have had a greater areal extent in the geologic past. The terms overpressure and underpressure refer to preproduction fluid pressures that are respectively greater than and less than hydrostatic pressure. The two studies on formation fluid pressure were undertaken in conjunction with the work reported by Higley (chapter 7 of this report) and Gaswirth and Higley (chapter 5 of this report) on the assessment of oil and gas in the Anadarko Basin.

The existence of underpressured oil and gas reservoirs in parts of the Anadarko Basin has been reported by a number of authors. Breeze (1970) documented the transition in the Morrow Formation in northwestern Oklahoma from overpressure in the deep basin to underpressure on the flank of the basin; his area of study is outlined in figure 1. Blubaugh (1999a, 1999b) mapped the widespread extent of underpressuring in the Hunton Group of Silurian and Devonian age. In the course of documenting the overpressured megacompartments in the deep Anadarko Basin, Al-Shaieb and others (1994) noted the existence of underpressured areas but did not investigate their cause; their study area is outlined in figure 1 and their data set is discussed in a companion report (Nelson and Gianoutsos, chapter 8 of this report). Original reservoir pressure in the extensive Permian age Panhandle-Hugoton gas field (fig. 1) was 435 pounds per square inch (psi) at a depth range of 2,500 to 3,000 feet for a pressure-depth ratio of less than 0.18 pounds per square inch per foot (psi/ft), as described by Pippin (1970) and Sorenson (2005). In 14 fields of 6 counties

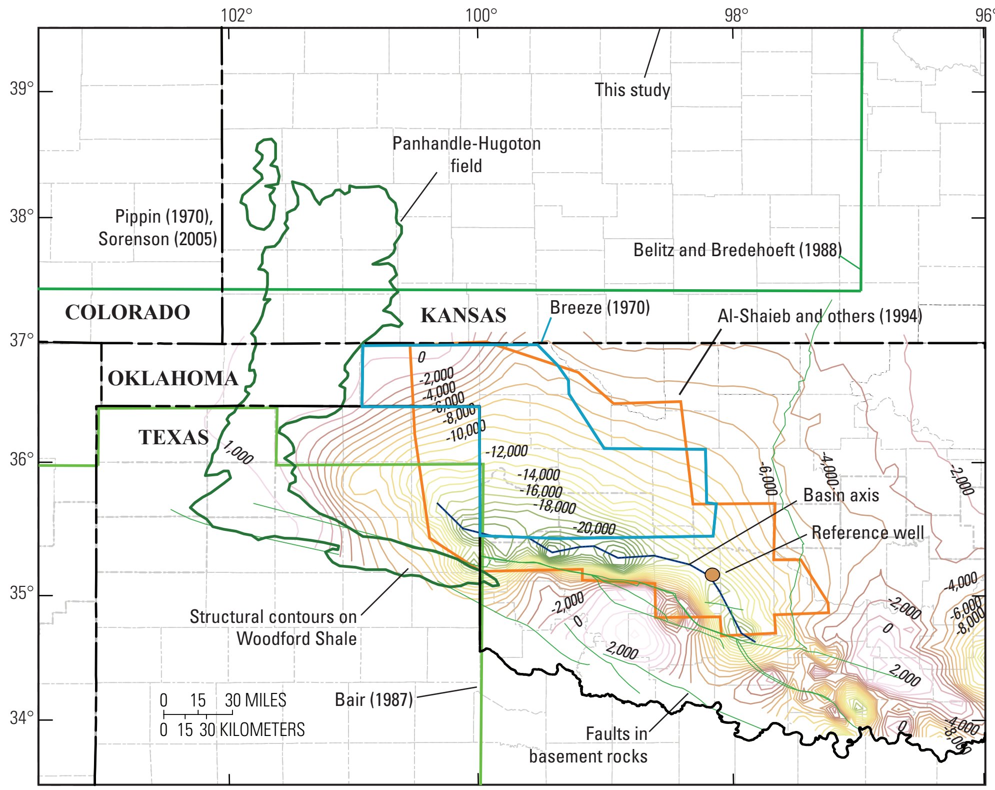


Figure 1. Map showing areas of this and previous studies of overpressure and underpressure. Contours for the top of the Woodford Shale show the structure of the Anadarko Basin; basin axis appears in subsequent figures as a reference line. Reference well is the Ferris 1-28 well. The study area for this chapter extends from latitude 33.5° to 39.5° N. and longitude 96° to 103.5° W.

of the eastern part of the Texas Panhandle, the pressure-depth ratio ranges from 0.21 to 0.40 psi/ft with a median value of 0.29 psi/ft (Taylor and others, 1977)—rocks in these 14 fields range from Ordovician to Late Pennsylvanian in age, representing 6 of the 7 stratigraphic units considered in this report. Thus, many authors have either noted the presence of underpressure or have reported pore pressure values significantly less than a nominal hydrostatic pressure-depth ratio of 0.465 psi/ft. From the broad geographic and stratigraphic ranges reported, it is clear that underpressuring in the Anadarko Basin is a widespread phenomenon.

In addition to the aforementioned studies, pressure and depth to the top of reservoir are available for many reservoirs in the Anadarko Basin (NRG Associates, 2009). The ratios of those two values are posted on a map for reservoirs of Desmoinesian age (fig. 3). For purposes of discussion, pressure-depth ratios between 0.43 and 0.50 psi/ft can be considered to be normally pressured. Only 10 values fall within the normal pressure range and these are scattered throughout much of the mapped area. A few values exceed 0.50 psi/ft; 3 of these are along or immediately north of the basin axis where overpressuring is known to exist. The rest of the pressure-depth ratios are less than 0.43 psi/ft, showing that underpressuring is widespread throughout much of the area. The lowest values, which are less than 0.30 psi/ft, are mostly clustered in the Texas and Oklahoma Panhandles. The map (fig. 3) substantiates that much of the area is underpressured, most notably the northern and northwestern flanks of the basin. It is also apparent that pressure-depth ratios for reservoirs do not follow any trends in relation to geographic position. The same can be said of pressure data from individual wells, a condition which has provided a challenge in determining potentiometric levels in this study.

Three studies concerned with the distribution of subsurface pressure were helpful to us in developing our hypotheses on the nature of underpressure in the Anadarko Basin. Sorenson (2005) explained the underpressuring of the Hugoton-Panhandle gas field in terms of aquifer communication with outcrop in eastern Kansas. This report builds on Sorenson's findings by examining the potentiometric distribution of the entire stratigraphic section throughout the basin, finding that the tie to outcrop lies along the Nemaha uplift in central Oklahoma. A hydrodynamic study of the Palo Duro Basin (Bair, 1987) used water level and drillstem measurements extending beyond the limits of the basin itself; the northern

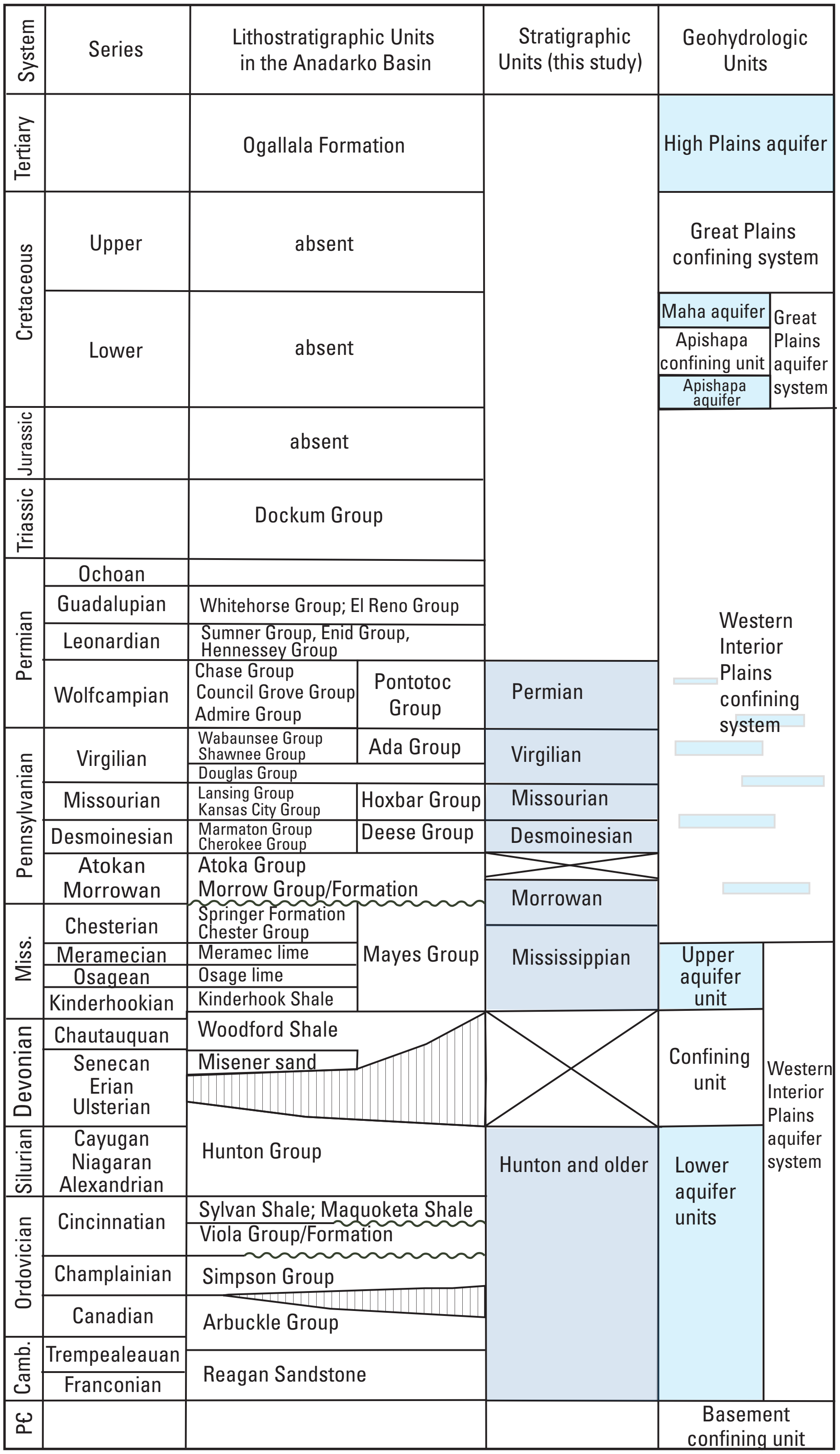


Figure 2. Stratigraphic chart of the Anadarko Basin, with stratigraphic units (purple shading) as defined in this study to examine pressure data. The lithostratigraphic units are modified from Higley (chapter 3 of this report). Geohydrologic units were defined by Jorgensen and others (1996) for a regional study; light blue shading indicates the presence of rock units with well defined patterns of hydraulic head that can be considered to be aquifers. Cretaceous rocks are not present in the study area of figure 1 but are present in the regional study area of Jorgensen and others (1996). Wavy lines represent unconformities. Areas with vertical lines represent periods of non-deposition. PC, Precambrian; Camb., Cambrian; Miss., Mississippian.

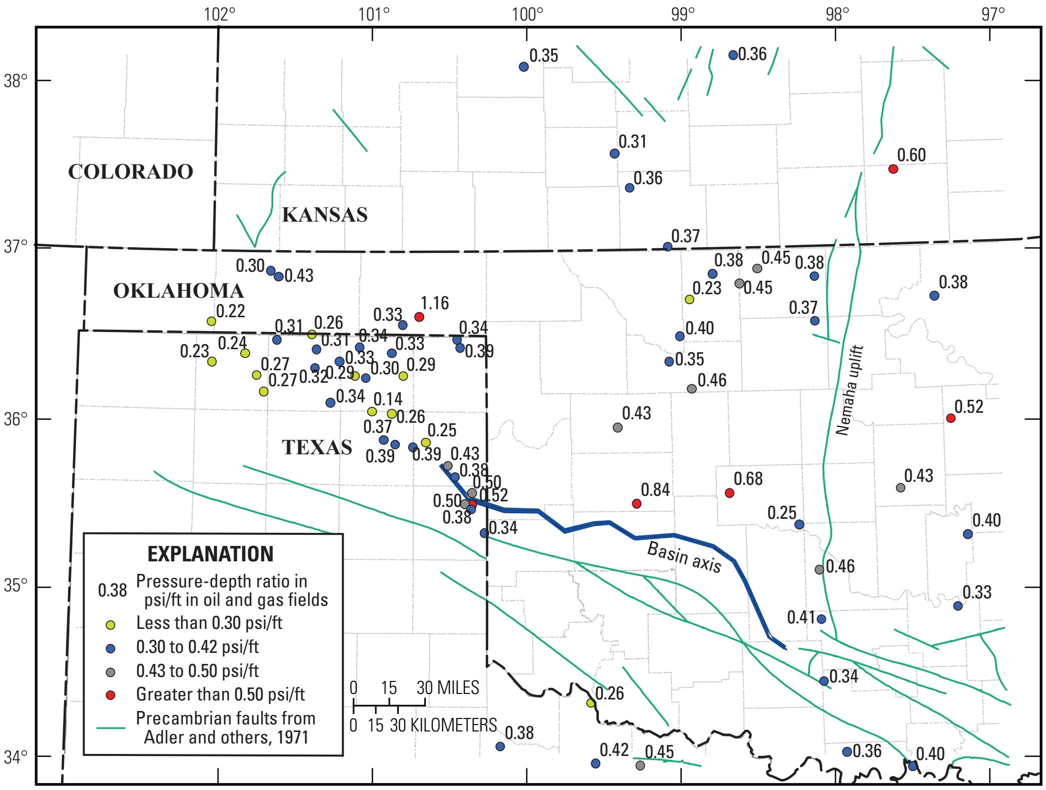


Figure 3. Map of Anadarko Basin showing pressure-depth ratios for reservoirs of Desmoinesian age, based on data from NRG Associates (2009). psi/ft, pounds per square inch per foot.

and eastern boundaries of Bair's study are shown in figure 1. The strata in the deepest of three hydrostratigraphic flow units, which includes Cambrian to Wolfcampian rocks, are underpressured. The underpressured condition is partly attributed to the "greater depth from the ground surface to potentiometric levels in the deep-basin strata beneath the High Plains compared to the Rolling Plains" and that "the regional flow pattern is controlled by the elevation and location of outcrops serving as regional recharge and discharge areas" (Bair, 1987, p. 169). Belitz and Bredehoeft (1988) examined the cause of underpressure in the Denver Basin and developed a hydrologic flow model extending from eastern Colorado into southern South Dakota, Nebraska, and Kansas; the southwestern corner of their study area is indicated in figure 1. The general cause of an underpressured or subnormal condition was stated by Belitz and Bredehoeft (1988, p. 1356):

> "Generally, subnormal fluid pressures might be found in any subaerial, topographically tilted, structural basin capped by a thick sequence of low-permeability rocks (i.e., shale or evaporites). The tilt can provide the topographic driving force for the fluid flow. The low-permeability cap can provide insulation from the elevation head of the water table, and the structure can provide the mechanism for reducing permeability in the basin deep that allows for better hydrologic connection to low-elevation outcrops than to high-elevation outcrops."

As indicated by the findings of Bair (1987), Belitz and Bredehoeft (1988), and Sorenson (2005), surface topography and outcrop elevation are critical considerations in diagnosing an underpressured condition. Surface elevation is greater than 4,400 ft above sea level in the northwestern part of the study area, and declines to less than 800 ft in the southeastern part (fig. 4). Contours of surface elevation trend north-south in most of the study area, with westward swings where river valleys are present. As a consequence of the general north-south elevation contours, outcrops in central Oklahoma and Kansas also trend north-south, as shown by outcrops of Lower Permian Garber Sandstone and Virgilian formations, and the base of the Permian Wellington Formation (fig 4). These north-south

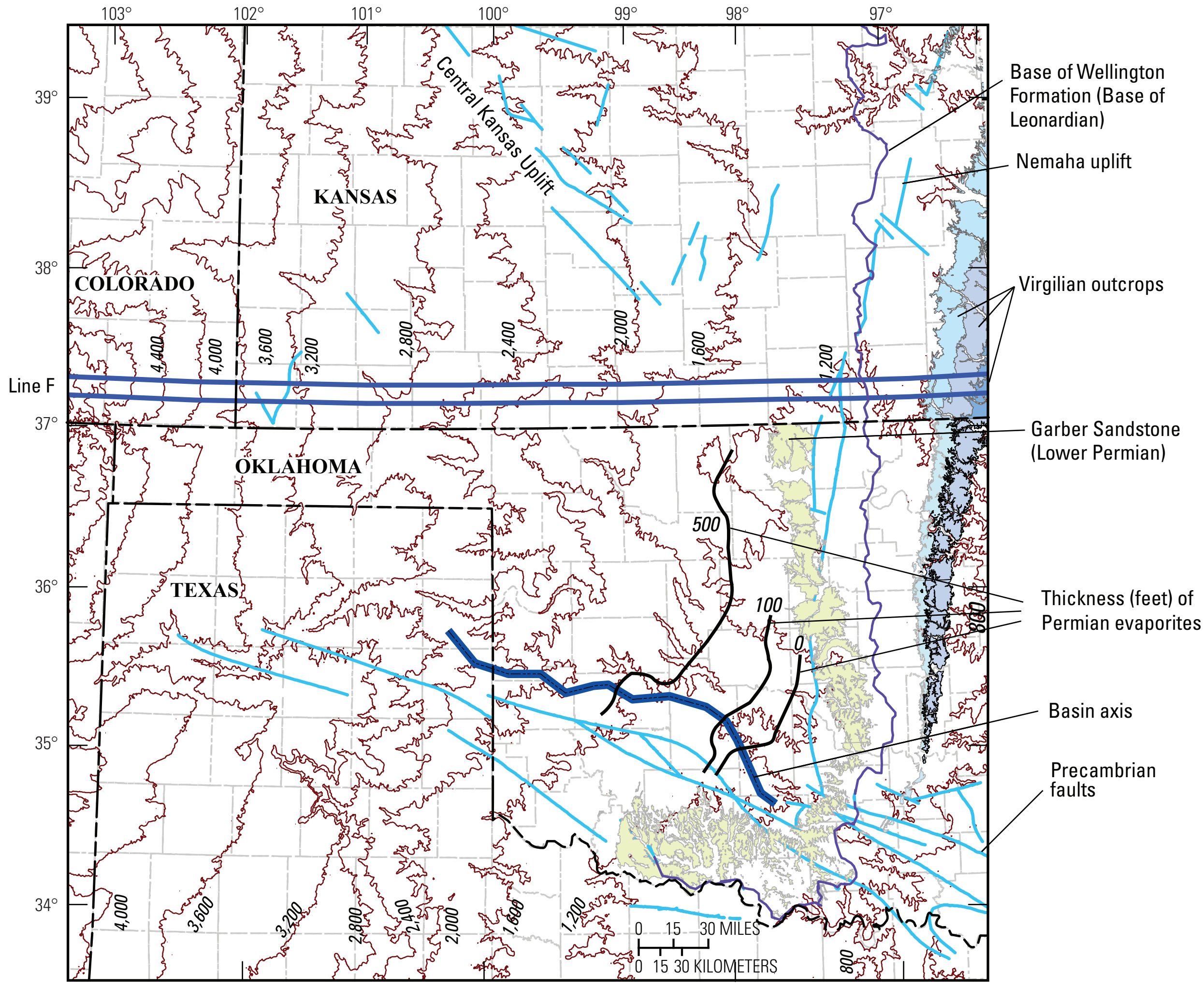


Figure 4. Map of greater Anadarko Basin showing surface elevation contours in 400-foot intervals, basin axis, Precambrian faults, and outcrops of selected formations. Precambrian faults from Adler and others (1971). Thickness of Permian evaporites from Gianoutsos and others (chapter 10 of this report). Outcrops of Garber Sandstone and three Virgilian formations, and base of Wellington Formation in Kansas and Oklahoma from Stoesser and others (2005). East-west oriented Line F shows location of drillstem test data shown in figure 10.

trending outcrops of Early Permian and Late Pennsylvanian age, in close proximity to the Nemaha uplift, play an important role in our interpretation of the hydrologic regime of the basin.

The burial history chart (fig. 5) reveals rapid deposition and burial during Late Mississippian and Pennsylvanian time. During times of rapid burial, overpressure developed in rocks of the Morrowan, Atokan, Desmoinesian, Missourian, and to a lesser degree in the Virgilian Series, all or in part of Pennsylvanian age, as indicated schematically by the red highlighting in figure 5; overpressure development is the subject of a companion report (Nelson and Gianoutsos, chapter 8 of this report). Uplift and erosion occurred in recent geologic time as indicated by the linear decrease in depth for all rock units from 45 to 0 Ma. As uplift and erosion took place, hydrologic conditions were altered, causing the development of underpressure, as symbolized by the vertical blue bar at the right hand side of figure 5. The areal and stratigraphic distribution of underpressure, as expressed in potentiometric and derivative maps, is the subject of this chapter of the report. The burial history chart demonstrates that the creation of overpressure and underpressure are widely separated in geologic time.

Mudstones and evaporites of Permian age form a low permeability cap (fig. 5) that covers most of the study area. The cross section of figure 6 shows that a sequence of mudstones and evaporites is 1,800-ft thick at the Texas-Oklahoma border. Anhydrites and gypsum of the Blaine Formation (fig. 6) extend into Oklahoma where they are mapped in outcrop (Fay, 1964). Based on mud log data from oil and

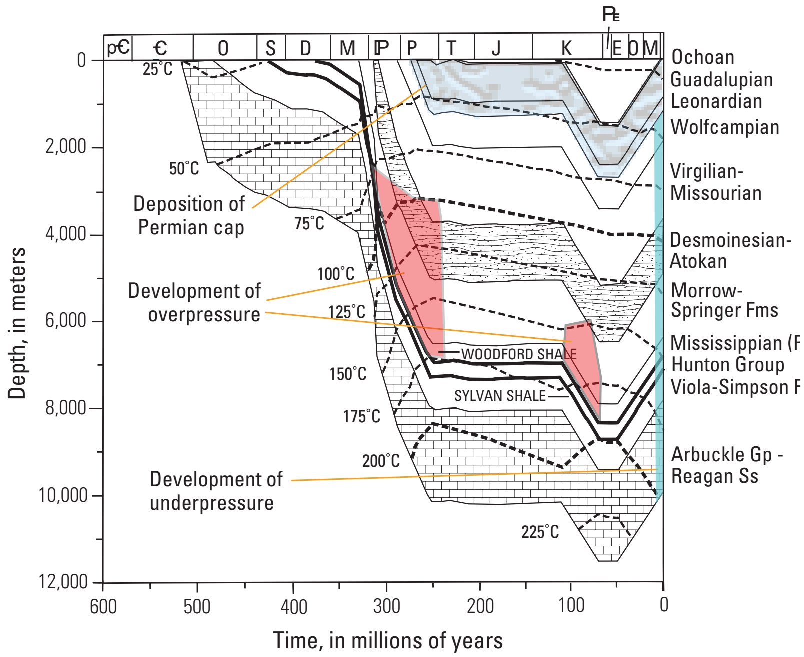


Figure 5. Burial history for the Ferris 1-28 well, from Carter and others (1998). Overpressure developed during rapid burial during Pennsylvanian time with a possible secondary development around 100 Ma. Underpressure development is believed to be recent, commensurate with exposure of strata in central Oklahoma. The Permian cap provides a low permeability seal over the area. pC, Precambrian; Є, Cambrian; O, Ordovician; S, Silurian; D, Devonian; M, Mississippian; P, Pennsylvanian; P, Permian, T, Triassic, J, Jurassic; K, Cretaceous; P_E, Paleocene; E, Eocene; O, Oligocene, M, Miocene; Fms, Formations; Gp, Group; Ss, Sandstone, °C, degrees Celsius.

gas wells, evaporites are nearly ubiquitous in Upper Permian strata throughout the Anadarko Basin (Gianoutsos and others, chapter 10 of this report), thinning to zero thickness immediately west of the Nemaha uplift (fig. 4). The eastward extent of Leonardian strata is demarcated by the base of the Wellington Formation of the Enid Group in the vicinity of the Nemaha uplift (fig. 4). Although no direct measurements of permeability were conducted for this study, the permeability of evaporites below 1,500 ft of burial is reduced to levels so low that the beds are considered impermeable to groundwater flow, based on geological evidence and laboratory measurements (Ingebritsen and others, 2008, p. 340–342). Thus an impermeable cap of Permian age separates shallow aquifers from deeper strata that are Pennsylvanian and older.

These four geologic elements—basin structure, surface topography, uplift and erosion, and an impermeable cap (figs. 1, 4, 5, and 6)—compose the essential elements resulting in the present-day hydrologic regime. The main contribution of this report is documentation of the potentiometric surfaces at the basin scale for seven stratigraphic units—Hunton Group-and-older, Mississippian, Morrowan, Desmoinesian, Missourian, Virgilian, and Permian. Inspection of the potentiometric surfaces, and of a second set of surfaces showing the separation between each potentiometric surface and surface elevation, provide an explanation for the underpressured conditions that exist in the northern and northwestern portions of the greater Anadarko Basin.

The present study lies in the southwestern part of a regional examination of major hydrologic units in the central Midwest, an area encompassing all of Kansas and Nebraska and parts of adjoining states (Jorgensen and others, 1993). The relation between the aquifers and confining units of the regional study and the stratigraphic units of this chapter of the report can be examined in figure 2. Of the units defined in the regional study, the Western Interior Plains aquifer and confining systems are most relevant to the present study. The lower and upper aquifer units of the Western Interior Plains aquifer are nearly identical to the Hunton-and-older and Mississippian

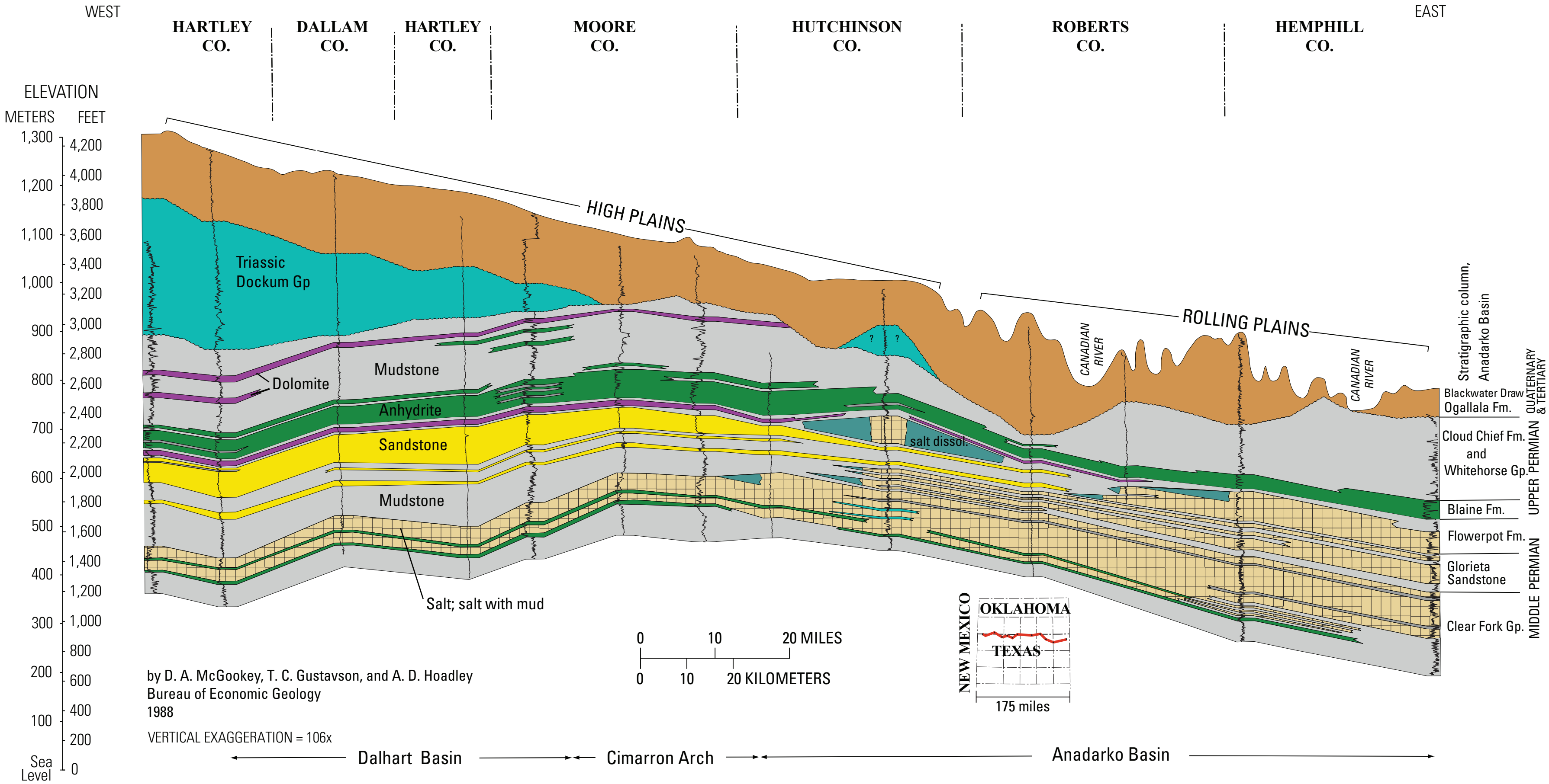


Figure 6. Structural cross section showing Permian and younger rocks in the Texas Panhandle (see inset for location). Mudstone, anhydrite, and salt form impermeable layers in Permian rocks. An interpreted salt dissolution feature is near the center of the section. From McGookey and others (1988). Co., County; Quat., Quaternary; Tert., Tertiary; Fm., Formation; Gp., Group.

stratigraphic units of the present study. The Western Interior Plains confining system includes permeable sandstone and limestone beds within thick shale units. Because the sandstone and limestone beds do not extend across the entire area of the confining system, they are not considered a regional hydraulic system (Jorgensen and others, 1993, p. B50). However, as demonstrated in this paper, maps of hydraulic head values for the Morrowan, Desmoinesian, Missourian, Virgilian, and Permian stratigraphic units suggest good hydraulic continuity over our study area. Corresponding lithostratigraphic units for the Cretaceous age Great Plains aquifer and confining systems are not shown in figure 2, because Cretaceous age rocks are only marginally present in our study area and were not considered as part of this study. The High Plains aquifer, which consists of the Ogallala Formation and unconsolidated deposits, will receive only brief consideration in this chapter of the report.

To develop potentiometric surfaces, we used pressure measurements in oil and gas wells that were obtained from drillstem tests over a time period of more than 50 years. Two steps are required to construct a potentiometric surface from pressure data. The first step, the conversion of a pressure measurement to hydraulic head, seemingly a straightforward computation, is complicated by the presence of gas and by variations in the density of water, the latter primarily because of salinity variations; these complications are discussed in the following sections, "Conversion of pressure to hydraulic head" and "Effect of density variations on the computation of hydraulic head." The second step, the conversion of individual hydraulic head values to form a potentiometric surface, requires examination of a large number of values distributed unevenly within the study area. For several reasons, only a fraction of these values are valid and can be used to define a potentiometric surface. The useful fraction is determined on a set of 13 west-east swaths on which the data are inspected and filtered, and from which a potentiometric level is defined as a continuous curve along the length of the swath. The potentiometric levels from the swaths are then combined using mapping algorithms to construct a potentiometric surface. These procedures are described in detail in the section "Potentiometric surfaces."

Conversion of Pressure to Hydraulic Head

In oil and gas exploration, formation pressure *P* is routinely measured and plotted as a primary parameter of interest. As an example, pressure data from the Oklahoma Panhandle are plotted as a function of the elevation of the test interval (fig. 7). A solid blue line represents a hydrostatic gradient of 0.465 psi/ft and an intercept of 2,542 ft on the vertical axis, which is the average surface elevation for this dataset. Virtually all the pressure data fall to the left of the hydrostatic line, indicating a state of underpressure. Four dashed lines, each with a gradient of 0.465 psi/ft, intercept the elevation axis at 0, 500, 1,000, and 1,500 ft. Each intercept represents the value of hydraulic head *H* for a point lying on its respective line. For example, a point lying on the upper dashed line has a value of *H* equal to 1,500 ft.

In hydrological work, hydraulic head *H* (also referred to as potentiometric elevation) is a primary parameter of interest. In order to map potentiometric surfaces within a stratigraphic unit, we need to convert measurements of *P* to *H*. The relation between the two, which is discussed in textbooks (for example, Fetter, 1988; Toth, 2009), is straightforward if three assumptions can be made regarding the fluids in the formation. First, it is assumed that flow velocity is negligible, so that kinetic energy is unimportant compared to potential energy. Second, it is assumed that fluid density does not vary much within the area under study. This second assumption is violated because the density of water varies with pressure, temperature, and salinity; the resulting limitations on the conversion of *P* to *H* and the resulting potentiometric surfaces are discussed in the section "Effect of density variations in the computation of hydraulic head." Third, if gas instead of water is the continuous phase, then the simple relation that follows cannot be applied, as discussed by Nelson and Condon (2008). Consequently, we chose not to compute *H* in the deep overpressured basin, because we suspect that gas is the continuous phase in parts of the deep basin.

Hydraulic head, *H*, is the sum of two components,

$$H = Z + P/\rho g \qquad (1a)$$

where

Z is the elevation of the perforated interval, *P* is the formation pressure, ρ is the density of water, and *g* is the acceleration of gravity. In oilfield units *Z* is in feet, *P* is in psi, ρg is in psi/ft, and consequently *H* is in feet. Equation 1a can be rearranged,

$$Z = H - P/\rho g \qquad (1b)$$

which is the equation for the lines plotted in figure 7, with *Z* the variable on the vertical axis, *H* the intercept on the vertical axis, *P* the variable on the horizontal axis, and $1/\rho g$ the slope of the line. For any pressure measurement *P* at an elevation *Z*, the equivalent *H* can be determined graphically (fig. 7) or computationally using equation 1a. It should be mentioned that a pressure-depth plot is not compatible with equation 1b. Compatibility with equation 1b requires that pressure be plotted as a function of elevation, as it is in figure 7.

Following the convention of other investigators in the Anadarko Basin, we set $\rho g = (\rho g)_o = 0.465$ psi/ft, which corresponds to a brine density of 1.07 g/cm^3. As already mentioned, density varies as a function of salinity, temperature and pressure, so adoption of a fixed value of 0.465 psi/ft introduces errors that are discussed in the section "Effect of density variations in the computation of hydraulic head." The reference

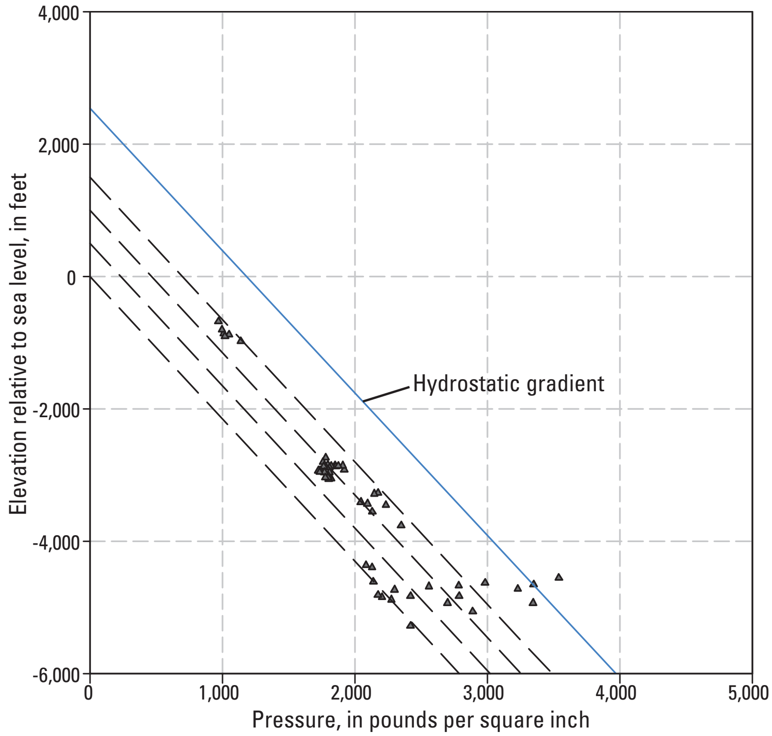


Figure 7. Graph showing pressure in relation to elevation from wells in a small area in the Oklahoma Panhandle. The average surface elevation of 2,542 feet is represented by the y-intercept of the hydrostatic gradient. The dashed lines are reference lines for the pressure data, most of which correspond to underpressured conditions.

elevation for Z is taken to be sea level, which means that H is determined relative to sea level. Elevations above sea level are positive and elevations below sea level are negative.

As an example, consider the case where the pressure P determined from a drillstem test is 700 psi, the mean perforated depth D for the drillstem test is 2,000 ft, and the Kelly Bushing elevation (KBE), is 3,500 ft (Well *A* in fig. 8). (Depth in a well is measured from the Kelly bushing on the drill rig rather than from ground surface; consequently KBE must be used to determine the elevation of a point in the well corresponding to a particular depth.)

The mean elevation for the drillstem test is

$$Z = -(D - KBE) = -(2{,}000 - 3{,}500) = 1{,}500 \text{ ft.}$$

The hydraulic head is

$$H = Z + P/(\rho g)_o = 1{,}500 + 700/0.465 = 3{,}000 \text{ ft.}$$

And the pressure/depth ratio for this example is

$$P/D = 700/2{,}000 = 0.35 \text{ psi/ft.}$$

Hydraulic head is computed for each stratigraphic unit and displayed as a function of latitude or longitude. Pressures from drillstem tests, depths of measurement, and KBEs were taken from IHS Energy (2009). The pressure value is the largest of either the initial shut-in value or the final shut-in value of a drillstem test. A very low pressure will result in a hydraulic head not much greater than Z, the measurement elevation, and is considered invalid. A potentiometric surface is determined by mapping and contouring the high values of hydraulic head of each stratigraphic unit.

The pressure-depth ratio can be expressed in terms of H, Z, and D by rearranging equation 1a and dividing by D,

$$P/D = 0.465*(H - Z)/D \qquad (2a)$$

which shows that the pressure-depth ratio is proportional to $(H - Z)/D$. In figure 8, $(H - Z)/D = (3{,}000–1{,}500)/2{,}000 = 0.75$ ft in Well A and $(H - Z)/D = [1{,}000-(-2{,}000)]/4{,}000 = 0.75$ in Well B, showing that the P/D ratio is 0.75 that of normal in both wells, and is equal to $0.75 \times 0.465 = 0.35$ psi/ft. Equation 2a has a simple geometrical interpretation: if the cross formed by the vertical brown line (length D) and the horizontal blue

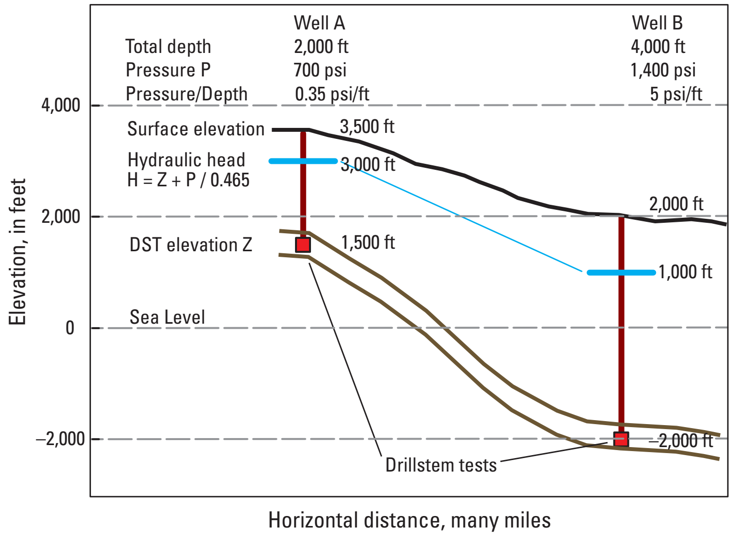


Figure 8. Example demonstrating the calculation of hydraulic head and pressure-depth ratio for two wells testing the same formation. The pressure-depth ratio is the same in the two wells, but the hydraulic head is much greater in Well A than in Well B. ft, foot; psi, pounds per square inch; psi/ft, pounds per square inch per foot.

line (elevation H) retains the same proportion from one well to the next, then the pressure-depth ratio is constant.

Equation 2a can also be written in terms of the vertical separation between the surface elevation KBE and H,

$$P/D = 0.465*\{1 - (KBE - H)/D\} \qquad (2b)$$

The main products of the present work are maps of hydraulic head H, referred to as potentiometric surfaces, and of $H - KBE$, the separation between H and the Earth's surface. The separation $H - KBE$ is used as an indicator of underpressure rather than the ratio P/D.

Effect of Density Variations in the Computation of Hydraulic Head

The conversion of pressure P to hydraulic head H in equation 1a requires a choice of density ρg. We used a value $(\rho g)_o = 0.465$ psi/ft, a value that corresponds to a sodium chloride brine with a specific gravity of 1.074 and a salinity of approximately 101,700 parts per million (ppm) at standard conditions of pressure and temperature. Because density varies with salinity, pressure, and temperature, the effect of this assumption on H at different locations in the basin requires evaluation.

Relation Between Salinity and Density for Sodium Chloride Solutions

Salinity is measured by weighing a salt solution, then weighing the solids that remain after evaporating the solution. Salinity is referred to as "total dissolved solids" (TDS) and expressed as weight percent or as ppm. For example, 1,000 grams (g) of solution containing 30 g of solids would have TDS = (30/1,000)*100 = 3 weight percent or $(30/1{,}000)*10^6$ = 30,000 ppm. The TDS of sea water is around 35,000 ppm.

The volume of brine is not a simple function of solute weight and water weight. Consequently, the density of brine (weight divided by volume) cannot be computed simply from TDS, it must be measured. Measurements for sodium chloride brine are tabulated in terms of specific gravity (SG) as a function of TDS (Wolf and others, 1973). (The specific gravity of brine is equivalent to the weight of brine divided by the weight of an equivalent volume of distilled water. Specific gravity is a dimensionless quantity.) The density of brine in field units such as pounds per gallon (ppg), or pounds per square inch per foot (psi/ft) are related to SG by

$$SG = \rho g \text{ (ppg)} / 8.33 = \rho g \text{ (psi/ft)} / 0.433 \qquad (3)$$

where 8.33 ppg is the density of water in pounds per gallon and 0.433 psi/ft is the density of water in psi/ft. In the petroleum industry, the unit of psi/ft is referred to as pressure gradient. However, psi/ft is also a unit of density, being the weight in pounds of water contained in 12 cubic inches (one square inch in area by one foot in height). The relations among density, specific gravity, and salinity for sodium chloride solutions are given in table 1.

The density of water increases with an increase in pressure and decreases with an increase in temperature. Because both pressure and temperature increase with increasing depth, the two effects tend to cancel over restricted ranges of pressure and temperature. For example, the volume factor for water is 1.00±0.01 for a temperature of 100 °F and pressures of 1,000, 2,000, and 3,000 psi, and also for a temperature of 150 °F and pressures of 3,000, 4,000, and 5,000 psi (table 2). However, at 200 °F, a pressure greater than 5,000 psi is required to maintain a volume factor of 1.00±0.01. Temperatures of 200 °F and greater are attained in the deep basin, but not on the flanks of the basin that are the focus of this study. Thus, most of the variation in density will be because of salinity variations, which are examined next.

Salinity of Subsurface Waters

In the Anadarko Basin, the salinity of produced waters takes a wide range of values, from less than 10,000 ppm to greater than 300,000 ppm (fig. 9, pl. 1). The 8 salinity increments of approximately 30,000 ppm chosen for the maps of plate 1 correspond to equal increments of 0.01 psi/ft for density, as shown in table 1. High salinity values are shown in the brightly colored symbols and low salinities are in dull colors. Unfortunately, the salinity data are not distributed evenly across the basin, but are clustered along and east of the Nemaha uplift in Oklahoma and within the Central Kansas uplift (pl. 1). Data within the deep Anadarko Basin are few in number, with the exception of data for the Morrow Formation (pl. 1*C*). Some observations are:

1. The highest values, greater than 220,300 ppm, lie along the south-north trending Nemaha uplift in the following units: Hunton-and-older, Mississippian (limited data), Desmoinesian, Missourian, and Virgilian. Salinities

Table 1. Increments of density used for salinity maps of plate 1, in units of pounds per square inch per foot. Specific gravity (dimensionless) is equivalent to density. Equivalent total dissolved solids (parts per million, ppm) for sodium chloride solutions taken from Wolf and others, 1973. $\Delta\rho/\rho$ (dimensionless) is the fractional change in density from the base value of 0.465 psi/ft.

[psi/ft, pounds per square inch per foot; TDS, total dissolved solids]

Density (psi/ft)	0.433	0.445	0.455	0.465	0.475	0.485	0.495	0.505
Spec. gravity	1	1.028	1.051	1.074	1.097	1.120	1.143	1.166
TDS (ppm)	0	35,754	70,552	101,737	132,349	162,377	191,723	220,284
$\Delta\rho/\rho$	–0.0688	–0.0430	–0.0215	0.0000	0.0215	0.0430	0.0645	0.0860

Table 2. Specific volume of water as a function of pressure and temperature, from Amyx and others (1960).

Pressure (pounds per square inch)	Temperature (°F)			
	100	150	200	250
1000	1.0025	1.0153	1.0335	1.0560
2000	0.9995	1.0125	1.0304	1.0523
3000	0.9966	1.0095	1.0271	1.0487
4000	0.9938	1.0067	1.0240	1.0452
5000	0.9910	1.0039	1.0210	1.0418

decrease eastward from the Nemaha uplift in all five of these units, showing similar salinity trends in all units for which data are available for the Nemaha uplift.

2. Along the central Kansas uplift, in rocks of Missourian, Virgilian, and Permian age, TDS is greater than 220,300 ppm at the southeast end of the uplift and decreases to the northwest, although values at the northwest end of the uplift generally remain greater than 100,000 ppm. In rocks that are Hunton and older in age, the highest values are 132,000 ppm at the southeast end of the central Kansas uplift, and decrease to the northwest where many values are less than 36,000 ppm. Thus, along the Central Kansas uplift, waters in rocks that are Hunton and older in age are considerably less saline than rocks of Missourian, Virgilian, and Permian age.

3. Waters in rocks of Morrowan age are less than 36,000 ppm in the deep basin and onto the shelfal area of the northeastern Texas Panhandle and the eastern Oklahoma Panhandle (pl. 1*C*). Values are erratic north and west of the limit of the 36,000 ppm values. Spatial variations in the chemistry of Morrowan waters are discussed in chapter 8 of this report on present-day overpressure and paleopressure indicators (Nelson and Gianoutsos, chapter 8 of this report).

4. In areas other than the Nemaha uplift and the Central Kansas uplift, and with the exception of the Morrowan unit, the salinity data are few in number and reveal no obvious trends.

Problem of Variable Brine Density in Computing Hydraulic Head

Variable brine density constitutes an important theoretical problem in basin-scale groundwater flow modeling (Bachu, 1995; Bachu and Michael, 2002). In dealing with aquifers of limited spatial extent, it is reasonable to assume constant brine density when computing hydraulic head in accordance with equation 1a,

$$H = Z + P/\rho g \qquad \text{(1a)}$$

However, for the deep confined basin-scale aquifers that are considered in this chapter of this report, the brine density ρg varies throughout the basin because of variations in salinity, pressure, and temperature. As explained by Bachu (1995), because of the variations in density ρg, the driving force on a unit quantity of brine cannot be written simply as the gradient of a potential, *H*. However, the horizontal component of flow in aquifers of finite dip can be represented in the following formulation of Darcy's law (Bachu and Michael, 2002, equation 5),

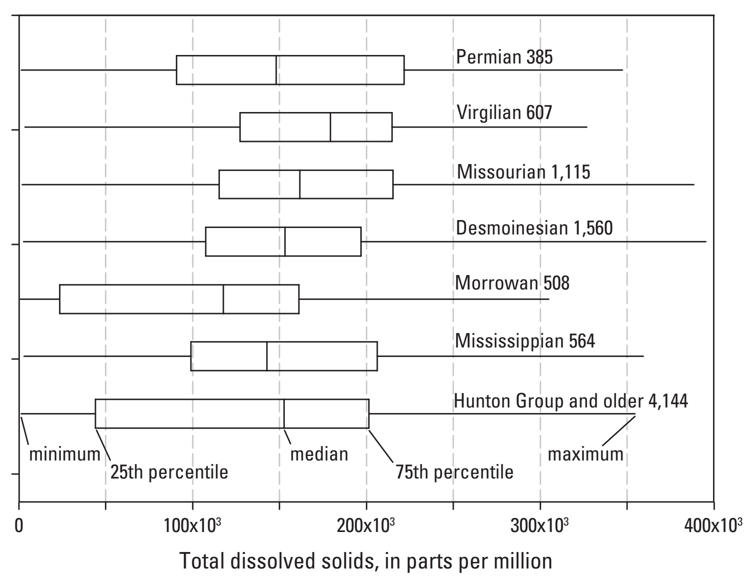


Figure 9. Box-and-whiskers plot of salinity in seven stratigraphic units with number of samples in each group. Each whisker and each box represents 25 percent of the data. Salinity data taken from a compilation by Breit (2002), which is based on waters produced from oil and gas wells.

$$q = -\frac{k\rho_o g}{\mu}\left(\nabla H_o + \frac{\Delta\rho}{\rho_o}\nabla E\right) \tag{4}$$

where

k is permeability, μ is viscosity, H_o is defined in equation 1a with ρ set equal to ρ_o, $\Delta\rho = \rho - \rho_o$, and E is the elevation of the surface representing the aquifer. This formulation shows that the flow vector $\boldsymbol{q}$ is the vector sum of ∇H_o, which is directed along the maximum hydraulic gradient, and ∇E, which is directed along the maximum slope of the aquifer surface. The term ∇H_o is the force due to the combined gradients of pressure and measurement elevation and is directed perpendicular to the contours of H_o. The term $(\Delta\rho/\rho)\nabla E$ is the buoyancy force because of variations in brine density and is directed downslope if $\rho > \rho_o$, and $\Delta\rho$ is therefore positive, or upslope if $\rho < \rho_o$. In areas where the leading term, is unchanging, the direction of flow vector $\boldsymbol{q}$ is given by the vector sum of the two terms in equation 4.

The buoyancy term $(\Delta\rho/\rho)E$ in equation 4 is insignificant in areas where (1) density (ρg) is equal to ($\rho_o g$) or nearly so, and (or) (2) lateral changes in the elevation of the aquifer are small. In these two situations, the flow vector direction depends only on the gradient of hydraulic head. On the other hand, the ∇H_o term can be less than the ∇E term in equation 4 wherever the hydraulic head H_o has little lateral variation but density and aquifer elevation are changing. As a consequence of salinity and elevation changes, the flow vector $\boldsymbol{q}$ will undergo local variations in direction that cannot be derived from inspection of the potentiometric surface. This fact must be kept in mind when inspecting the potentiometric surfaces discussed in the subsection "Maps showing potentiometric surfaces and overpressured areas."

Numerical hydrologic models are a means of accounting for variations in density and permeability. As an example, along the Nemaha uplift and central Kansas uplift where salinity variations are greatest, a numerical model that accounts for variable density produced flow vectors that differ significantly from flow vectors produced by a constant-density model (Signor and others, 1996, p. C59–C75). However, at this point our purpose in constructing potentiometric maps and cross sections is to understand the nature of underpressuring in the Anadarko Basin and not to model groundwater flow. Equation 4 is not used to compute flow vectors but serves to explain the limitations of the potentiometric surfaces that are a product of this report.

The preceding discussion of density variations leads to two conclusions regarding the computation of hydraulic head in the Anadarko Basin. First, we cannot expect that local flow vectors can be accurately derived from the potentiometric surfaces. Second, the effect of salinity variations are likely to be greatest in those areas where salinity gradients are manifest, particularly along the Nemaha uplift and along the southern edge of the Central Kansas uplift.

Computation of Hydraulic Head along West-East and South-North Swaths

The computation of hydraulic head along a west-east profile is illustrated in figure 10, which shows drillstem tests within a swath that is six miles wide in the north-south direction. Each data point in parts *A*, *B*, and *C* of figure 10 represents either data (surface elevation, elevation of drillstem tests, pressure) or a computed parameter (hydraulic head, pressure-depth ratio) from rocks of Missourian age. The surface elevations reveal the eastward drop from 4,200 ft in the west to 1,000 ft at the east end of the swath. The concave-upward pattern of the test elevations, which lie above sea level at the west and east ends of the swath, results from the intersection of the west-east line and the northward-shallowing basin geometry. The upper edge of the pressure data forms a convex-upward pattern, which when summed with the test elevations in accordance with equation 1a, forms the upper edge of the hydraulic head pattern (fig. 10*A*) that is labeled "interpreted level of hydraulic head." Although the elevations and pressure measurements vary by thousands of feet, their values are complementary and tend to cancel when summed, leaving an interpreted level of hydraulic head that changes by less than 500 ft from west to east.

Pressures falling below the convex-upward bound in figure 10*B* did not sample the original formation pressure and result in hydraulic head values that fall below the upper edge in figure 10*A*. Thus, only a fraction of the pressure measurements convert to interpretable values of hydraulic head which are indicated by the horizontal lines at the upper edge of the red dash symbols. A few values of hydraulic head *H* that are higher than the interpreted level of hydraulic head, such as those from longitude 101° to 102° W., could be because of small isolated compartments of high pressure or possibly because of pressure maintenance operations. The elevation of the Ogallala water table is considerably higher than the interpreted level of hydraulic head for the Missourian rocks (fig. 10*A*). The impermeable cap of Permian rocks (fig. 5) separates the shallow Ogallala aquifer from the deeper and older hydrological systems represented by Missourian rocks in figure 10.

Dividing a pressure measurement by the depth of the measurement results in the pressure-depth ratio plotted in figure 10*C*. As was the case for hydraulic head, only the upper edge of the data swarm represents the true pressure-depth ratio at that location, because most of the pressure measurements were less than true formation pressure. The upper edge of the swarm of pressure-depth values reaches a maximum at long 98° W., where it is somewhat less than the value of

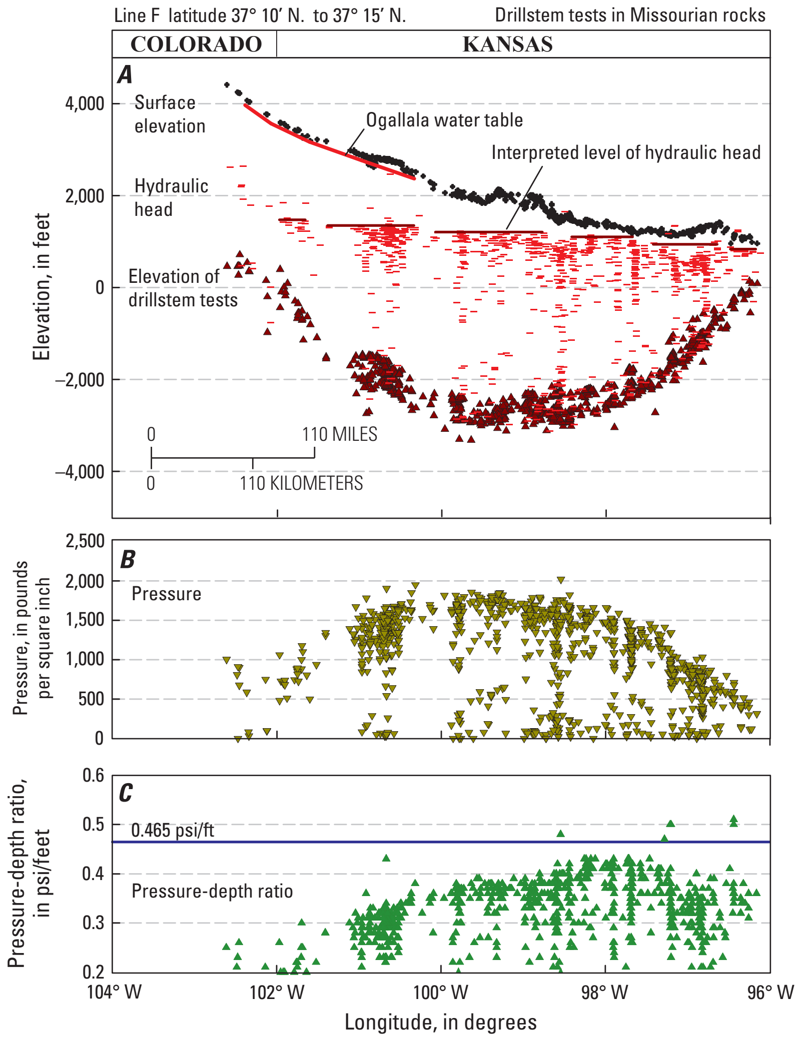


Figure 10. Data from drillstem tests in Missourian rocks from west-east swath Line F close to and parallel with the Kansas-Oklahoma border (location in figure 4). *A*, Surface elevation (black plus symbols), elevation of drillstem tests (triangular symbols), and computed hydraulic head (red dash symbols); *B*, pressure measurements; *C*, computed pressure-depth ratio indicating underpressure where less than 0.465 pounds per square inch per foot (psi/ft).

0.465 psi/ft that was assumed for the conversion of pressure to hydraulic head (equation 1a). West of that point, the pressure-depth ratio declines to less than 0.3 psi/ft, illustrating a westward increase in the degree of underpressure. As seen in figure 10*A*, the progressive westward increase in the degree of underpressure coincides with increasing separation between the surface elevation and the interpreted level of hydraulic head. In the following discussion, we will use the separation between surface elevation and the upper edge of hydraulic head as an indicator of underpressure, rather than the pressure-depth ratio.

The format of figure 10*A* is repeated in plate 2, which contains four south-north cross sections arranged in four columns. Seven stratigraphic units are displayed for each south-north cross section; the stratigraphic units form the seven rows of plate 2. The geometry of the surface elevations and the drillstem test elevations on plate 2 have a different "look" than those of figure 10. On each cross section of plate 2, the surface elevation is relatively unvarying from south to north; however, the west-to-east drop in surface elevation is apparent on the progression from lines H, where surface elevation is around 3,000 ft, to line N, where surface elevation is around 1,000 ft. The drillstem test elevations, which display a U-shaped geometry on the west-east line in figure 10, show the asymmetry of the Anadarko Basin on the south-north lines of plate 2. For example, the Desmoinesian test elevations on line J drop by 6,000 ft from north to south. The major structure bounding the southern part of the basin is revealed by the upturn in test elevations at latitude 35° 30' N. on the Desmoinesian and the Hunton-and-older sections of line J.

As previously discussed in connection with figure 10, only the uppermost values of hydraulic head are valid. The separation between those uppermost values and the surface elevation, which tracks the degree of apparent underpressuring, can be inspected as a function of longitude and stratigraphic unit. The separation feature is highlighted by yellow shading in the explanation on plate 2. Separation is greatest on the westernmost cross sections of Swath H and appears on all seven horizons, although data are sparse on the section for Hunton-and-older rocks. Separation appears to be greater in the deeper (Mississippian and Hunton-and-older) horizons than in the shallower (Permian and Virgilian) horizons. Separation diminishes from west to east in all of the seven stratigraphic units. For example, in rocks of Desmoinesian age at latitude 38° N., the separation of 1,600 ft on line H diminishes to 1,300 ft on line J, to 900 ft on line L, and to 500 ft on line N. The separation increases from south to north on line N as the surface elevation increases from south to north. A similar south-to-north increase in separation cannot be seen on lines H, J, or L because surface elevation is nearly constant along these three lines. In summary, the separation between the surface elevation and the upper edge of hydraulic head values (pl. 2) is fairly constant from south to north but diminishes from west to east.

Potentiometric Surfaces

A potentiometric surface is compiled by contouring the measurements of hydraulic head *H* over the study area. The resulting surface represents the level to which water would rise in tightly cased wells that are in hydraulic connection with a confined aquifer. In this study, we compile potentiometric surfaces for each of the seven stratigraphic units.

Procedure

The problem of map representation of hydraulic head is analogous to fitting a rubber sheet downward onto a sea of data, in which only the sea surface is of interest. Points falling below the sea surface should not be represented. The problem is compounded by local spikes of unwanted high values that extend upwards from the sea surface. Ideally, the spikes should pass through the rubber sheet, leaving them extending upwards and unrepresented. To handle this problem, we used software designed to deal with potential field (gravity and magnetics) data. The data were divided into 13 west-east swaths (pl. 3), each displaying hydraulic head on the vertical axis and longitude on the x-axis. Individual values of hydraulic head were either used in the filtering process (red points on lines 1-13 in pl. 3) or were deactivated if not used in the filtering process (green points in pl. 3).

Each swath was filtered independently of the others to establish 13 independent fits. A rolling statistic curve called ROLL was calculated by taking the maximum of 11 points, 5 to the left and 5 to the right of each hydraulic head value. The purpose of ROLL was to select points on the uppermost values of hydraulic head (values judged to be erroneously high were deactivated before the application of ROLL). The output of ROLL, shown as a green line in pl. 3, was input to a low-pass filter called LOWROLL. The 81-point low-pass filter utilized 40 points to the left and 40 points to the right of each output point. The smoothed output of the low-pass filter is shown as a series of blue dots in each swath of plate 3.

Special problems that were encountered included areas of sparse data, areas of data with high scatter, and end effects. As already mentioned, each line for each stratigraphic unit was cleaned manually by removing points significantly below the tops of the values and removing high points that were considered outliers in the data set. In some cases, spaces were added in the database to manipulate the LOWROLL points to better follow the tops of the hydraulic head data. For example, if 40 blank spaces were added to the left of a point, the ROLL and LOWROLL would then only be calculated by the values to the right of that point. This process was used when the user clearly determined where the top of the hydraulic head values were but the output of LOWROLL was displayed in a slightly different location. Problems of this type were dealt with on a case-by-case basis as adjustments were made to improve the fit of the “rubber sheet” to the top of the surface on each swath.

The potentiometric surface for each stratigraphic unit was based upon the outputs of the low-pass filter for all of the swaths in a given stratigraphic unit. A grid was calculated using a minimum curvature algorithm with spacings of 0.1 and 0.01 (pl. 3). The 0.01-potentiometric surface, which clearly shows the relation between individual points on a swath and the resulting contour interval, was used for quality control and editing of the 0.1-surface, which with additional notation is presented in plate 4. In this way, potentiometric surfaces were constructed from computations of hydraulic head for each of the seven stratigraphic units.

In order to represent the height of the potentiometric surface with respect to the land surface, a second set of maps was constructed by computing the difference between the filtered (LOWROLL) values and the Kelly Bushing of each well. These data were then treated in a manner similar to that followed for the potentiometric surfaces to create maps of the separation be the Earth’s surface and the potentiometric surface (pl. 5).

Maps Showing Potentiometric Surfaces and Overpressured Areas

For each stratigraphic unit (Permian, Virgilian, Missourian, Desmoinesian, Morrowan, Mississippian, and Hunton-and-older), the potentiometric surface, in feet above sea level, is shown as a colored contour map (pl. 4). The Morrowan and Desmoinesian maps include an outline of their respective overpressured areas (red areas in parts *C* and *D* of pl. 4), drawn to include pressure-depth ratios greater than 0.5 psi/ft, based on inspection of the data set from Al-Shaieb and others (1994) and the drillstem-test-derived map of potentiometric surface. Potentiometric contours are also interrupted in the Hunton-and-older, Missourian, and Virgilian units (gray areas in parts *A, E,* and *F* of pl. 4), where the data in the central basin were insufficient to define a potentiometric surface. The overpressured areas in the deep basin are not considered further here, but are discussed in a companion paper by Nelson and Gianoutsos (chapter 8 of this report). Most importantly, the seven maps of plate 4 show that the overpressured zone in the deep basin has left an imprint in all rock units, except possibly those of Permian age.

As further introduction to plate 4, consider the potentiometric surface for Permian rocks (pl. 4*G*), which has widely separated contours between 1,250 and 1,500 ft (light green area), demonstrating a low hydraulic gradient over more than one-half of the mapped area. The low hydraulic gradient is also shown in the west-east and south-north swaths of figure 10 and plate 2. In the western portion of the map (pl. 4*G*), contours are tightly grouped and the surface rises from 1,500 to 3,250 ft. The pattern of a broad area of low hydraulic gradient flanked on the west by a narrow area of high hydraulic gradient is common to all potentiometric surfaces except the Morrowan (pl. 4). The change in hydraulic gradient from high in the west to low in the east can be explained by changes in permeability or hydraulic conductivity. According to Darcy’s law, an inverse relation exists between hydraulic gradient and hydraulic conductivity. One-dimensional flow can be expressed as $Q = -K(dH/dX)$, where Q is the flow rate, K is hydraulic conductivity, and dH/dX is the hydraulic gradient expressed as the change in hydraulic head H over a distance X. This concept is illustrated in a model (fig. 11), in which flow is constrained to a pipe. Hydraulic conductivity K is low in the short, western segment of the pipe and high in the longer eastern segment. The tight clustering of increments of head H in the western segment, which is comparable to the contours in plate 4*A*, was computed for the ratios of length and hydraulic conductivity indicated in the diagram: the length X_E and hydraulic conductivity K_E of the eastern segment are 4 and 30 times greater, respectively, than X_W and K_W of the western segment. Thus, areas with a low hydraulic gradient (wide spacing between contours in pl. 4) are likely to be areas with high K relative to areas with a low hydraulic gradient (tightly spaced contours).

Because the pressure-depth ratio can be computed from the separation between potentiometric and land surfaces (eq. 2b), it follows that the separation between potentiometric surface and land surface is an indicator of whether pressure in a given stratigraphic unit is underpressured or normally pressured. The separation is mapped for the seven stratigraphic units (pl. 5) by subtracting the land surface represented in figure 4 from each of the potentiometric surfaces in parts *A-G* of plate 4. The zero contour, separating pink from gray-blue areas, is the locus of intersection of the two surfaces.

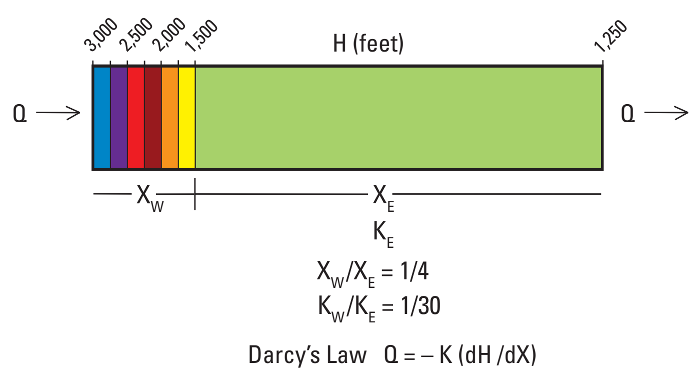


Figure 11. Hydraulic head H computed for one-dimensional flow Q in a medium of low hydraulic conductivity in the west, K_W, and high conductivity in the east, K_E, with $K_W/K_E = 1/30$. The length of the low-conductivity section, X_W, is 1/4 the length of the high-conductivity section, X_E. Values of H range from 1,250 to 3,000 feet, with colors between 250-foot contours of H selected to match the colors in plate 4. Concept for one-dimensional model taken from Belitz and Bredehoeft (1988).

Where the separation is positive (pink areas), groundwater has the potential to flow to the surface through tightly cased wells completed in the aquifer or through naturally occurring conduits in overlying geologic units. Under unconfined conditions, groundwater will discharge to springs and streams where the water table intersects land surface. The areas with wide spacing between contours that are present in plate 4 are not present in plate 5 because the land surface varies more than the potentiometric surfaces, especially in the western part of the study area. As a result, the land surface topography dominates the maps of plate 5, resulting in the north-south banding over a large portion of the maps.

Hunton-and-older Stratigraphic Units

The potentiometric surface drops from around 1,500 ft in the western and southwestern portions of the study area to less than 500 ft in the eastern part of the study area (pl. 4*A*). The potentiometric surface ranges between 750 and 1,000 ft over much of central Kansas, including the Central Kansas uplift, showing a remarkably low gradient over an area that is more than 200 miles from west to east and more than 150 miles from south to north. The dense drilling pattern in Kansas is largely due to oil and gas production from the Arbuckle Group on the Central Kansas uplift. (The Cambrian-Ordovician Arbuckle Group may compose a separate hydrological system as the connection to the surface may lie along its surface exposures in central Missouri [L. Watney, Kansas Geological Survey, written commun., June 2011)] Groundwater, which flows from high head to low head, generally flows north-northeast across the northern flank of the Anadarko Basin, where the contour shading grades from yellow or light green to light blue in southern Kansas and northern Oklahoma. The 750-foot contour lies immediately east of and parallel to the Nemaha uplift.

The separation between land surface and the potentiometric surface drops steadily from west to east (pl. 5*A*). Because the potentiometric surface is nearly flat (pl. 4*A*), the separation between land surface and potentiometric surface is dominated by land surface topography. The 0±300 contour areas occupy a large area of roughly 150 by 150 miles in the southeastern part of the map where the Nemaha and the Arbuckle fault systems intersect. Locally, the separation exceeds +300 ft, suggesting artesian flow conditions for wells completed in the Hunton-and-older stratigraphic unit. The Arbuckle-Simpson aquifer comprises the Simpson, Arbuckle, and Timbered Hills Groups (Christenson and others, 2011) and crops out in the southeast part of the map (pl. 5*A*) in a location that is consistent with the potentiometric surface.

Mississippian Stratigraphic Unit

This potentiometric surface (pl. 4B) is similar to the one for Hunton-and-older rocks (pl. 4A), with a broad low gradient area of values ranging from 750 to 1,000 ft in Kansas, and a southeast-northwest trending 1,000-ft contour separating areas of higher hydraulic head in Oklahoma and Texas from lower values in Kansas. A west-east trend of values exceeding 1,750 ft in western Oklahoma and the northeast corner of the Texas Panhandle occupies an area that is overpressured in Desmoinesian and Morrowan rocks (figs. 4C and 4D); however this area is not overpressured in Mississippian rocks, although scattered measurement of high hydraulic head made it difficult to define a reliable potentiometric surface. The 750-ft south-north contour lies east of the Nemaha uplift. As with the Hunton-and-older stratigraphic unit, groundwater flows generally north-northeastward from the northern flank of the basin, from northern Oklahoma into southern Kansas. A potentiometric surface for Mississippian rocks was not examined by Al Shaieb and others (1994), so no comparisons can be made.

The separation between land surface and the potentiometric surface for Mississippian rocks (pl. 5*B*) is similar to that for Hunton-and-older rocks (pl. 5*A*), as expected because the potentiometric surfaces are similar.

Morrowan Stratigraphic Unit

A northwest-southeast trending truncation edge bounds the Morrowan and Springer rock units (pl. 4C), which consequently occupy a smaller fraction of the study area than other rock units. The potentiometric surface rises from somewhat greater than 750 ft at the truncation edge in Kansas to values greater than 2,000 ft in a four-county area of southwestern Kansas, southeastern Colorado, and the Oklahoma Panhandle. A west-east belt of values exceeding 1,750 ft lies immediately north of the overpressured area.

Establishment and maintenance of a low (750–1,500 ft) potentiometric surface is presumed to be through hydraulic connectivity with either overlying Desmoinesian or underlying Mississippian strata, or both, because the Morrowan rocks do not extend far enough eastward to directly establish a discharge to surface. However, immediately north of the overpressured area, where the northeast corner of the Texas Panhandle meets the southeast corner of the Oklahoma Panhandle, lies an area of high hydraulic head (pl. 4*C*), as mentioned above, which creates a corresponding area where the potentiometric surface approaches the land surface (pl. 5*C*). This area may be a relic of a once-overpressured part of the system, (see fig. 14 and relevant discussion in Nelson and Gianoutsos, chapter 8 of this report) as it lies well to the west of the zero contour on other difference maps.

Desmoinesian Stratigraphic Unit

The potentiometric surface drops from values in excess of 2,500 ft in southeastern Colorado to values ranging from 500 to 1,500 ft in a broad low-gradient area in the eastern half of the mapped area (pl. 4*D*). A low-potential area approximately 30 by 50 miles in central Kansas includes values less than 500 ft. The southern edge of the overpressured area lies immediately south of the basin axis. Two salients projecting northward from the main overpressured area are mapped with both the data from this study (bright contours underlying the shaded overpressure) and the data set from Al-Shaieb and others (1994). A halo of hydraulic head values in the 1,000- to 1,500-ft range surrounds the overpressured area. The overpressured area shown in plate 4*D* is larger than that of the overpressured Red Fork Sandstone area shown by Al-Shaieb and others (1994), because the Desmoinesian pressure map includes formations and units of Desmoinesian age in addition to the Red Fork Sandstone.

The potentiometric surface approaches land surface (-300 ft line in pl. 5*D*) along a line trending northeast in the eastern part of the mapped area. The -300 ft contour approaches and parallels the Nemaha uplift in northern Oklahoma and southern Kansas, suggesting that the Nemaha uplift is the discharge area for rocks of Desmoinesian age. The eastern edge of the overpressured area lies about 20 miles from the Nemaha uplift in the southeastern part of the Anadarko Basin. This relatively short distance from edge of overpressure to discharge point reflects the effectiveness of the pressure seal.

Missourian Stratigraphic Unit

The potentiometric surface ranges from 1,000 to 1,250 ft along the Nemaha uplift and increases steadily westward to the western Kansas border where values exceed 1,750 ft (pl. 4E). As noted on the map, an area in north-central Kansas is well defined by the data, but sporadic measurements of higher head exist within the area. The potentiometric surface cannot be defined in a large southern area that encompasses the deep basin due to scatter in hydraulic head; numerous values of hydraulic head greater than 2,000 ft exist. Pressure-depth ratios of 0.5 psi/ft and greater suggest that this area is slightly overpressured, with pressure-depth ratios generally 0.5 to 0.6 in the informal lower Missourian sandstones—Medrano, Marchand, and Cleveland. This interpretation of overpressure in the lowermost Missourian sandstones differs from that of Al-Shaieb and others (1994), who categorized the Missourian unit as normally pressured.

As is the case with other maps of the separation between the potentiometric and land surfaces, the contour spacing and orientation of the Missourian stratigraphic unit (pl. 5*E*) is dominated by the land surface. The -300-ft contour lies 70 miles west of and parallel to the Nemaha uplift. The map indicates that an area east of the Nemaha uplift and another area south of the Arbuckle fault zone have potentials high enough for artesian flow (separation values greater than 0 ft).

Virgilian Stratigraphic Unit

The potentiometric surface increases from 1,000 to 1,250 ft along the Nemaha uplift to more than 1,500 ft in the northwestern part of the study area (pl. 4*F*). Between these two areas lies a broad low-gradient area with head values ranging from 1,500 to 1,250 ft. This low west-to-east decrease in the potential surface is interrupted in two areas. Values range up to 2,250 ft within the Central Kansas uplift, where the potentiometric surface is clearly defined despite a small fraction of measurements with higher hydraulic head. Higher head values are also located in the deep Anadarko Basin, but in this area there were insufficient data to determine the potentiometric surface.

The potentiometric surface approaches land surface (-300 ft line in pl. 5*F*) along a line that is 70 miles west of and parallel to the Nemaha uplift. The broad discharge area for Virgilian strata extends from the -300 ft line to the eastern edge of the study area. West of the -300 line, the separation increases steadily to the western edge of the study area.

With the exception of the deep basin, the maps of potentiometric surface and separation between potentiometric and land surfaces are rather similar for Missourian and Virgilian rocks (compare pls. 4*E* and 4*F*, and pls. 5*E* and 5*F*). The similarity suggests that Missourian and Virgilian units are closely coupled and may act as one hydrologic system. The two systems were considered as one system by Al-Shaieb and others (1994).

Permian Stratigraphic Unit

The potentiometric surface increases from 750 ft along the Arbuckle fault trend to 1,250 ft along the Nemaha uplift and remains between 1,250 and 1,500 ft over an area that is roughly one-half of the study area (pl. 4*G*). In the westernmost counties of Kansas, an area which includes the western edge of the Hugoton gas field, values climb rapidly, exceeding 3,000 ft at the western edge of the study area. The hydraulic gradient in western Kansas, Oklahoma, and Texas is the highest of any of the maps (pl. 4*A* to 4*F*). The computed hydraulic head values that were used to define the map of plate 4*G* are the most consistent of the seven mapped units, in that the surface is well defined on all 13 swaths with very few points above the surface and no areas, other than gaps shown as blank areas, where the surface could not be defined.

The map of the separation between the potentiometric surface and land surface for Permian rocks (pl. 5*G*) is similar to the maps for the Desmoinesian, Missourian, and Virgilian units (pls. 5*D*, 5*E*, 5*F*), the main difference being that, in the Permian stratigraphic unit, the separation is less in the westernmost part of Kansas and Oklahoma, due to the greater height of the Permian potentiometric surface in this area. The discharge area, represented by the 0±300 contours, straddles the Nemaha uplift area and includes the high transmissibility Central Oklahoma aquifer (pl. 5*G*) where the water table lies just below surface elevation. The Central Oklahoma aquifer comprises the Garber Sandstone and Wellington Formation (fig. 4), as well as the Chase, Council Grove, and Admire Groups, all of Lower Permian age (Parkhurst and others, 1996).

Discussion

The main feature of the potentiometric surfaces is the broad low-gradient area in central Kansas and northern Oklahoma, manifested as hydraulic head elevations between 1,250 and 1,500 ft in Permian, Virgilian, and Missourian units and as elevations between 750 and 1,000 ft in Desmoinesian, Mississippian, and Hunton-and-older units (pl. 4). The main feature in the maps showing separation between the Earth's surface and the potentiometric surfaces (pl. 5) is the north-south stripes formed as a result of subtracting the eastward-declining topography (fig. 4) from the broad low-gradient areas (pl. 4). Separation maps for Permian, Virgilian, Missourian, and Desmoinesian units show separation changing from -2,400 ft in the west to 0±300 ft in the vicinity of the Nemaha uplift.

The position of the 0±300 ft contour for Permian, Virgilian, Missourian, and Desmoinesian units is explained by the location of outcrops along and immediately east of the Nemaha uplift (fig. 12). The southern part of the Nemaha uplift also appears to be the control or partial control for the Mississippian and Hunton-and-older rock units. Along the Nemaha uplift, through exposure of strata to the surface or just below the surface and through connections with permeable faults, water pressure in the aquifers has equilibrated with atmospheric pressure causing the potentiometric elevation to be generally equal to surface elevation. The exact locations of equilibration are unknown and the areas where equilibration takes place is likely to be only a fraction of the area encompassed by the 0±300 ft contours. Shales and evaporites of Permian age provide hydraulic isolation of deep strata from the surface so that the area around the Nemaha uplift is the dominant pressure equilibration point for these four units.

The separation maps reflect the degree of apparent underpressuring expected to exist in oil and gas wells in Permian and Pennsylvanian strata. To estimate the degree of underpressure at a desired location and depth, the separation $KBE – H$, which is expressed in feet, can be read from the appropriate map in plate 5 and converted to a pressure-depth ratio in psi/ft using equation 2b. For example, consider a location on the Texas-Oklahoma border at the northeasternmost corner of the Texas Panhandle, where the separation contour on the Desmoinesian map (pl. 5*D*) is H - KBE = -900 ft, or KBE - H = +900 ft . For a Desmoinesian interval at a depth of 6,700 ft, the pressure/depth ratio from equation 2b is 0.465*(1-900/6700) = 0.403, which is slightly underpressured. Note that underpressure cannot be read directly from the separation maps because equation 2b requires that the depth be specified independently.

A comparison between the Virgilian separation map of plate 5F and the pressure-depth ratio for a number of oil and gas reservoirs is shown in figure 13. The separation map was derived from well-based pressure measurements, not from reservoir-based pressure measurements, so the comparison of figure 13 is something of a check although not an independent check. The pressure-depth ratios are slightly subnormal (0.42 psi/ft) where the separation is close to 300 ft, are less than 0.30 psi/ft where the separation is greater than 1,500 ft, and decrease to values of 0.15 psi/ft where the separation is more than 1,800 ft. Between the eastern and western extremes, the pressure-depth ratio decreases more or less steadily as separation increases. Bearing in mind that the pressure-depth ratio is related to, but not directly proportional to separation, the general agreement between the trends in the pressure-depth ratios and the separation map gives confidence that underpressuring in oil and gas reservoirs and a low-gradient potentiometric surface are one and the same phenomenon.

A scenario for the origin of the Panhandle oil and gas field in Texas was presented by Sorenson (2005), in a pressure-depth plot and a series of five maps showing paleogeology from Late Permian to Quaternary. (Our only modification to Sorenson's scenario, which is summarized in this paragraph, is that aquifer pressure is equilibrated along the Nemaha uplift, in place of his proposed equilibration point in northeastern Kansas.) The Panhandle oil and gas field formed in Late Permian time and remained in place until early Tertiary when some spillage of gas northward into the Kansas Hugoton field may have begun. Aquifer pressure dropped in late Tertiary time as downcutting exposed Permian rocks. As aquifer pressure dropped, the Panhandle gas expanded, augmented by gas coming out of solution in oil. Reservoir pressure fell to its present-day value of 435 psi at a depth range of 2,500–3,000 ft, for a pressure-depth ratio of less than 0.18 psi/ft (Sorenson, 2005). In support of this scenario, the outline of the Hugoton field coincides with a maximum separation between surface elevation and potentiometric surface, as shown in figure 14. The maximum in separation corresponds to the western edge of the broad, low-gradient area where potentiometric elevation ranges between 1,250 and 1,500 ft (pl. 4*G*), demonstrating that the location of the Hugoton gas field is bounded on the west by a sharp increase in potentiometric elevation.

Having established the discharge zone to be in the general vicinity of the Nemaha uplift, the question arises: where is the zone of recharge? Recharge is expected to take place where strata crop out at a high-elevation terminus of a groundwater system, in this case along the Rocky Mountain uplift in southeastern Colorado and northeastern New Mexico. However, during Pennsylvanian time the Sierra Grande arch in northeastern New Mexico was a positive feature. Pennsylvanian and pre-Pennsylvanian strata of the Anadarko Basin terminate on the eastern flank of the Sierra Grande arch, disrupting hydrological continuity with the Raton Basin and the Rocky Mountain uplift. Hydrological continuity to the west is limited to Lower Permian (Wolfcampian) continental deposits that drape the Sierra Grande arch in southeastern Colorado and a narrow west-east strip in New Mexico immediately south of the New Mexico–Colorado border (Wilson, 1977; Robson and Banta, 1987, Roberts and others, 1976).

Recharge is limited by what can best be described as a choke caused by onlap of Pennsylvanian and older strata on the Sierra Grande arch (fig. 12). Flow from west of the arch is restricted to permeable beds in Lower Permian (Wolfcampian and Leonardian) strata that are approximately 1,000 ft thick on top of the arch, as shown at longitude 104° W. of figure 12.

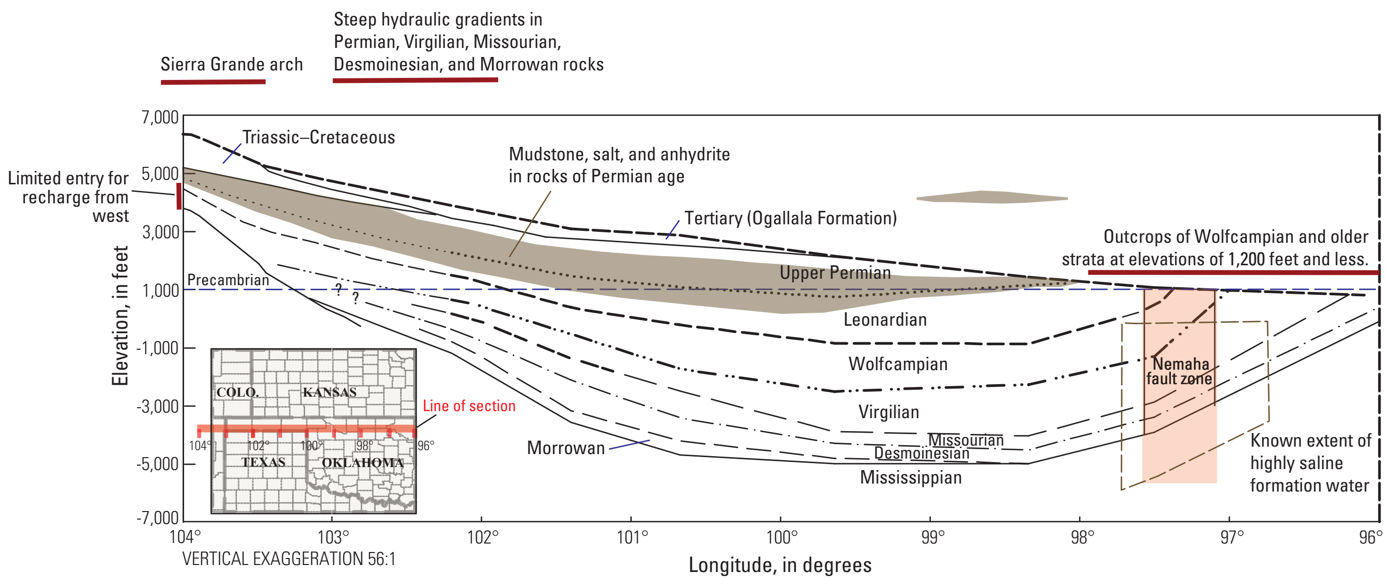


Figure 12. West-east structural cross section showing features influencing the creation and maintenance of underpressure. Permian and Pennsylvanian strata crop out along and east of the Nemaha uplift. Brown shading indicates the impermeable evaporite-bearing strata of Permian age. Pinchout and thinning of strata on the Sierra Grande arch provide limited entry for recharge. East of longitude 102° W. the cross section is based largely on well data. West of long 102° W. the cross section is based on information from Roberts and others (1976), Weeks and Gutentag (1981), and McGookey and others (1988).

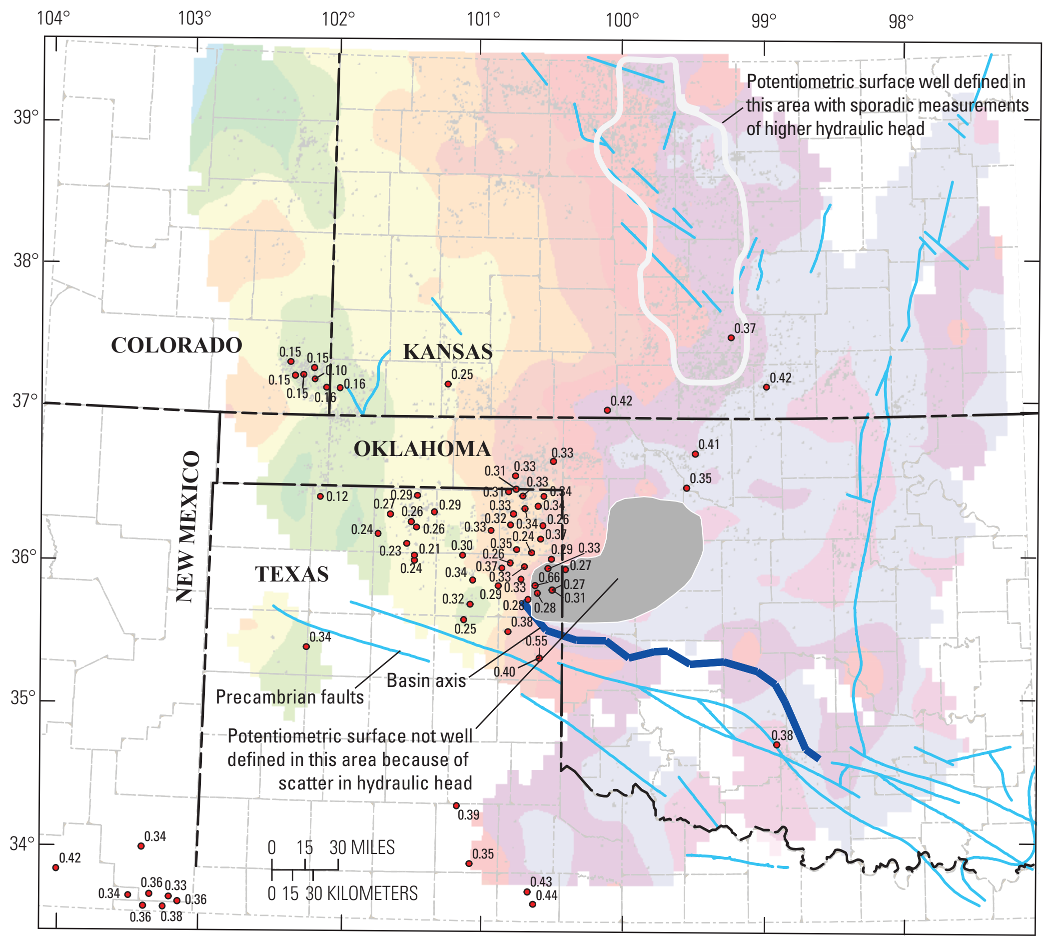
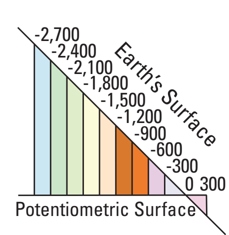


Figure 13. Comparison between a separation map from plate 5F and degree of underpressuring for the Virgilian unit. Contours on the separation map give the Virgilian potentiometric surface minus the surface elevation. Dots give the location of individual oil and gas fields for which pressure-depth ratios were computed from data provided by NRG Associates (2009).



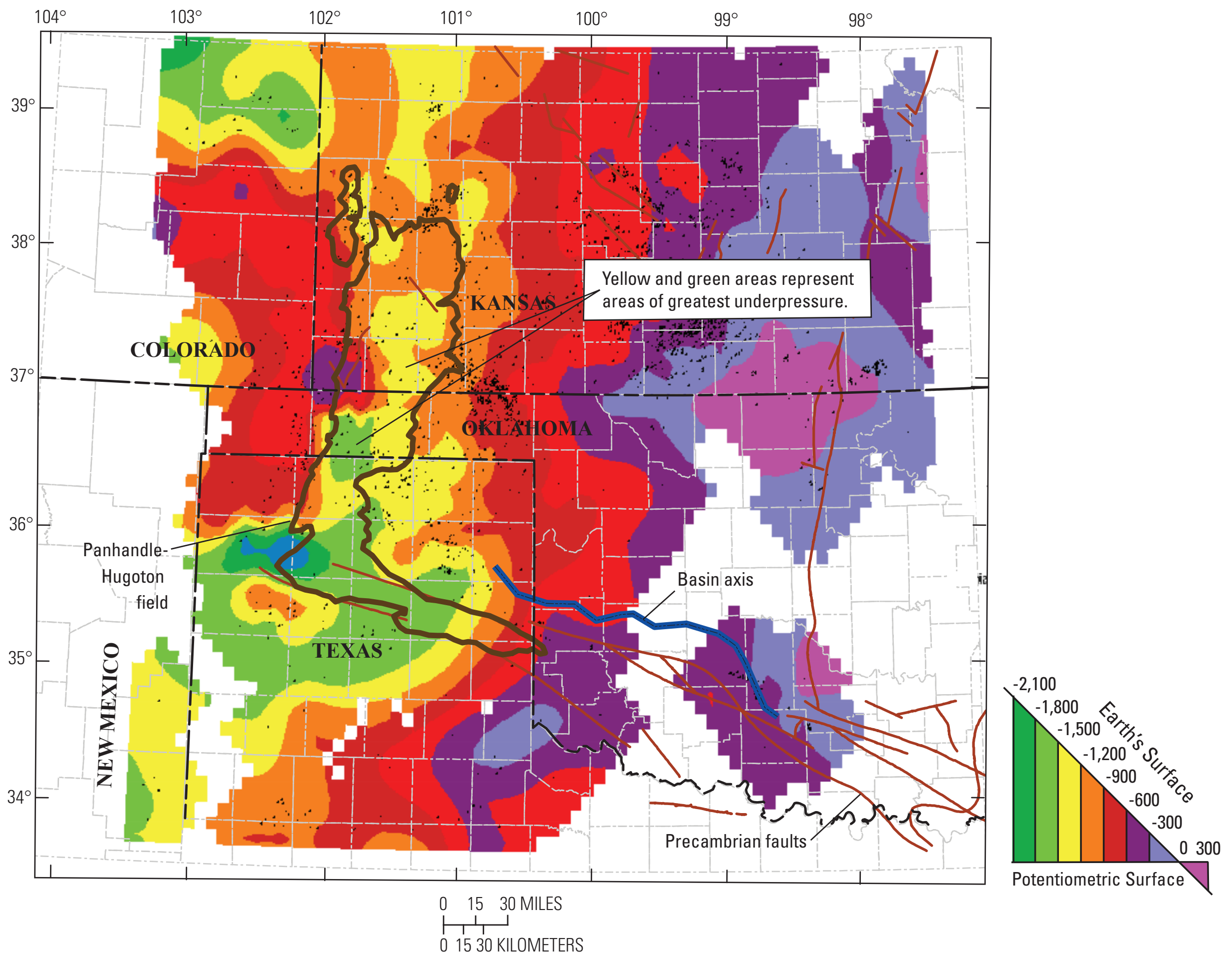


Figure 14. Map with contours showing separation between the potentiometric surface in Permian rocks and land surface elevation, in feet. For example, the yellow areas show where the potentiometric surface lies -1,500 to -1,800 ft below surface elevation. The underpressured Hugoton-Panhandle gas field lies in a trough of maximum separation between the potentiometric surface and surface elevation.

East of the arch, groundwater flow must spread downward from Lower Permian strata into the eastward-thickening Pennsylvanian strata. Flow must also spread laterally, as the arch is not covered everywhere by rocks of Wolfcampian age (fig. 6 of Roberts and others, 1976). Consequently, the north-south cross-sectional area open to flow over the arch is much smaller than the north-south cross-sectional area to be filled by eastward-migrating waters. In addition, discharge to the east may be inhibited by dense, high salinity waters in all seven stratigraphic units along the Nemaha uplift (pl. 1 and fig. 12). It is likely that these highly saline waters result from the dissolution of salt in Upper Permian strata. Buoyancy (negative buoyancy in this case) forces tend to cause the denser waters to descend westward and downward, counter to the overall west-to-east hydraulic gradients indicated in the potentiometric surfaces of plate 4. These two effects—limited recharge from the west and density-induced counter-flow from the east—combine to set up a relatively stagnant groundwater system in the deep confined aquifers of the Anadarko Basin. The presence of overpressured strata in the deep basin (Nelson and Gianoutsos, chapter 8 of this report) further restricts groundwater circulation in deep confined aquifers. A supporting insight is provided by Gallardo and Blackwell (1999, p. 357) who studied the thermal regime of the basin: "We found no evidence for significant fluid flow in this basin at the present time … the temperature structure can be explained adequately by normal conductive heat flow when the thermal conductivity of the rocks is taken into account in the modeling."

Our interpretation of a stagnant low-gradient groundwater system with limited hydraulic continuity to the west is counter to a scenario of a regional groundwater sysem recharged from the west and flowing from west to east in continuous strata that were tilted upward during Laramide uplift (Jorgensen, 1989).

Summary

Conversion of pressure from drillstem tests to hydraulic head, seemingly straightforward in a water-dominated system, is complicated by variations in salinity across the basin. Errors are not easily assessed because salinity is poorly documented in much of the basin. Nevertheless, the seven potentiometric surfaces and the seven derivative surfaces showing separation between land surface and potentiometric surface portray the state of hydraulic potential and the nature of underpressuring over the greater Anadarko Basin.

On the basis of their respective potentiometric and separation surfaces, the seven stratigraphic units fall into three groups.

1. In the units designated as Hunton-and-older and Mississippian, a large fraction of the potentiometric surface lies 750 to 1,000 ft above sea level (pl. 4*A, B*). The separation maps indicate that the discharge area lies in the southeast part of the study area (pl. 5*A*, *B*).

2. Northwest of the overpressured deep Anadarko Basin, the potentiometric and separation surfaces of the truncated Morrow age rocks are similar to the Mississippian surfaces. Hence, it appears that the Morrowan groundwater system is coupled to the groundwater system in Mississippian strata in this area.

3. The potentiometric surfaces of the four uppermost units—Desmoinesian, Missourian, Virgilian, and Permian—share a general north-south to northeast-southwest trend in the contour patterns. The Nemaha uplift lies within the -300 to +300 ft contours of the separation surfaces in all four units (pl. 5*D-F*), indicating that the discharge areas lie in the vicinity of the Nemaha uplift.

Outside the overpressured area in the deep basin, hydraulic potentials of Lower Permian and older strata are controlled by outcrops at elevations of 1,200 ft and less. Land surface rises to the west, so separation between land surface and potentiometric surface increases westward, and consequently, so does the degree of underpressuring. Underpressured reservoirs, including that of the Hugoton field, are the result of exposure of strata to atmospheric pressure in the vicinity of and east of the Nemaha uplift.

Four lines of evidence point to a low-flow to no-flow hydrologic system in the confined strata of the Anadarko Basin. Recharge of groundwater into Pennsylvanian and older strata on the northern flank of the Anadarko Basin is greatly limited by the presence of the low-permeability Permian cap. Recharge is further constricted by the pinchout of strata on the Sierra Grande uplift to the west (fig. 12). Highly saline formation water in strata along the Nemaha uplift imposes a fluid density barrier to west-to-east flow. And finally, overpressured strata in the deep basin further restrict fluid movement.

Our hypothesis of a markedly low-flow system warrants further investigation, possibly with detailed hydrological modeling. Features of the system awaiting elucidation are (1) the steep hydraulic gradient between longitude 102° W. and 103° W., (2) better mapping of salinity variations and the effect of high salinity waters along the Nemaha uplift, and (3) the details of pressure equilibration along the Nemaha uplift for the different stratigraphic units.

There are two practical ramifications of this work. First, the geologically recent drop in pressure brought on by the exposure of discharge zones along the Nemaha uplift has altered the original pressure distribution in the Anadarko Basin. The expansion of the Hugoton gas field is but one outcome. Other, smaller oil and gas fields have doubtless undergone gas expansion as a result of the pressure drop. The effects of this late-stage modification remain to be worked out for the distribution of oil and gas, particularly for gas. Second, the hydraulic potential of the deep confined strata is important when considering the injection and sequestration of carbon dioxide, if and when that takes place. A low-flow hydrologic regime, capped by impermeable strata, makes an attractive setting for carbon dioxide sequestration because the time durations for return flow to the surface are likely to be quite long.

Acknowledgments

We benefitted from discussions with many people who visited our poster on this topic at annual meetings of the Geological Society of America and the American Association of Petroleum Geologists. We also benefitted from reviews by Noel Osborne, Sarah Hawkins, and Tom Judkins of the U.S. Geological Survey. Water salinity maps were originally compiled by Jessica Mager and Marvin Abbott of the U.S. Geological Survey. Rick Saltus of the U.S. Geological Survey introduced us to the Oasis Montaj software package and suggested the general filtering approach.

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