

**KANSAS GEOLOGICAL SURVEY**  
**OPEN-FILE REPORT 89-30**

The Impact of the Regional Ground-water Flow System  
on Water Quality in the Dakota and Overlying  
Aquifers and Surface Waters in Central Kansas

by

P. Allen Macfarlane

*Disclaimer*

The Kansas Geological Survey does not guarantee this document to be free from errors or inaccuracies and disclaims any responsibility or liability for interpretations based on data used in the production of this document or decisions based thereon. This report is intended to make results of research available at the earliest possible data, but is not intended to constitute final or formal publications.

**KANSAS GEOLOGICAL SURVEY**  
1930 Constant Avenue  
University of Kansas  
Lawrence, KS 66047

**THE IMPACT OF THE REGIONAL GROUND-WATER FLOW SYSTEM ON WATER  
QUALITY IN THE DAKOTA AND OVERLYING AQUIFERS AND SURFACE  
WATERS IN CENTRAL KANSAS**

**By**

**P. Allen Macfarlane  
Kansas Geological Survey  
Lawrence, Kansas**

Portions of this paper were presented at  
the 1989 Geological Society of America Annual Meeting,  
St. Louis, MO.

**Kansas Geological Survey  
Open-File Report 89-30**

# THE IMPACT OF THE REGIONAL GROUND-WATER FLOW SYSTEM ON WATER QUALITY IN THE DAKOTA AND OVERLYING AQUIFERS AND SURFACE WATERS IN CENTRAL KANSAS

## Abstract

*In central Kansas, the ground-water chemistry of the Dakota and overlying aquifers and surface waters is affected by upward-moving saline waters from underlying aquifers in the Permian. Fluid pressure vs. depth profiles from the surface down to the Arbuckle (Deep Carbonate) aquifer generally show that the Dakota and underlying aquifers are subnormally pressured. However, higher than expected pore pressure gradients can be found beneath the Cretaceous-Permian boundary in the subsurface. Salt marshes, springs, flowing wells that produce saltwater, and salt-affected reaches of streams are common in this area.*

*A cross-sectional view of the ground-water flow system illustrates the hydrologic phenomena described above and suggests that these features are directly related to the topography and the hydrostratigraphy. In central Kansas, the Dakota aquifer acts as a drain for the upper part of the Permian aquitard and Cedar Hills aquifer and saline waters tend to move upwards into the Dakota aquifer and laterally toward stream-aquifer systems. The present configuration of the regional ground-water flow system is complex and is hypothesized to consist of both modern and relict components. The modern component of the system is responsive to changes in the water-table configuration that have been brought about by episodes of uplift, erosion, and deposition during the late Mesozoic (latest Cretaceous Period) and Cenozoic Eras. The relict component consists of the deeper part of the flow system below the top of the Cretaceous or Permian bedrock surface. This part of the system is in a transient state and has responded much more slowly to changes in the configuration of the water table due to the less permeable nature of the strata that comprise the aquifer and aquitard units in consolidated strata relative to the deposits that constitute the water-table aquifer framework.*

## Introduction

The Dakota aquifer is presently an important source of water for public water supply, irrigation and other agricultural purposes, and industry in much of western and central Kansas. The Dakota aquifer consists of Cretaceous interbedded sandstones and mudstones (siltstones and shales) of nonmarine and marine origin. The importance of this aquifer system as a source of water will likely increase in the future where the supply of water from the overlying High Plains and alluvial aquifers is insufficient to meet the needs of the local population.

Water quality is one of several limiting factors that bear on the present and future use of the Dakota aquifer for water supply in central and western Kansas. Saline waters from aquifers in the underlying Permian and from the lower part of the Dakota aquifer significantly impact the chemical quality of ground waters not only in the upper part of the Dakota aquifer but also in overlying aquifers and surface waters in much of central Kansas. Salt-affected reaches of streams, salt marshes and springs in river valleys, and flowing wells that produce saltwater are a common occurrence in this region (Hay, 1890, 1891; Jordan et al., 1964; Whittemore, 1978; Hargadine et al., 1979; and Cobb, 1980).

Many of the streams that drain this area discharge waters higher in total dissolved solids, chloride, and sulfate concentrations under low-flow conditions than in other parts of the state. Where upward migration of saline waters into shallower aquifers and surface waters has occurred, these sources of water are not suitable for most uses under low-streamflow conditions. Many of the affected river systems supply water to the more heavily populated regions of eastern Kansas.

These occurrences of natural saltwater in shallow aquifers and surface waters are directly related to the flow of ground-water in large regional systems (Toth, 1972, 1984). Discharge areas of these systems are characterized by increases in hydraulic head and dissolved solids concentration with depth below the water table. The increase of hydraulic head with depth causes cross-formational flows of more saline ground waters between aquifers and upward movement toward the surface. As a result, flowing wells that produce saline water and other natural salt-related features are common. Similar occurrences of natural upward

migration of saltwater involving the Dakota aquifer and other related aquifers in similar hydrogeologic settings have been documented in several areas of the Midcontinent (see e.g. Benz et al., 1961). These conditions suggest that: (1) central Kansas is included in the natural discharge area of the Permian aquifers that underlie much of western Kansas, and (2) the Dakota is acting as a drain conducting saltwater from the Permian to the land surface.

Development of a clear understanding of how the regional ground-water flow system causes this upward movement of saline waters in central Kansas is necessary prior to setting surface and ground-water management policies for these saltwater intrusion areas, including the Dakota and overlying shallow aquifers. The purpose of this paper is twofold: (1) to document the flow patterns in the regional ground-water flow system in central Kansas and demonstrate its effect on surface and ground-water quality, and (2) to propose mechanisms that explain the observed ground-water flow patterns and the resulting variations in water-quality in central Kansas.

The primary focus of the paper is on the interactions between aquifers in the plane of a vertical cross-section that extends from the Kansas-Colorado border in southwest Kansas to the Saline River valley in central Kansas, oriented along the flow paths of the major aquifer systems discussed in this paper (Figure 1). Hydraulic head data for the cross-section came from several sources: (1) kriged estimates of hydraulic head in the Dakota aquifer made for this research using SURFACE III, a geostatistical mapping package (Sampson, 1988); (2) Stullken and Pabst (1982) for the High Plains aquifer of southwestern Kansas; (3) estimates of predevelopment hydraulic head made from a map of the Cedar Hills Sandstone potentiometric surface compiled from various sources; and (4) field measurements made by Kume and Spinazola (1985). It is believed that the relationships between aquifer systems expressed in this cross-section reasonably reflect the relationships between aquifers in other parts of Kansas.

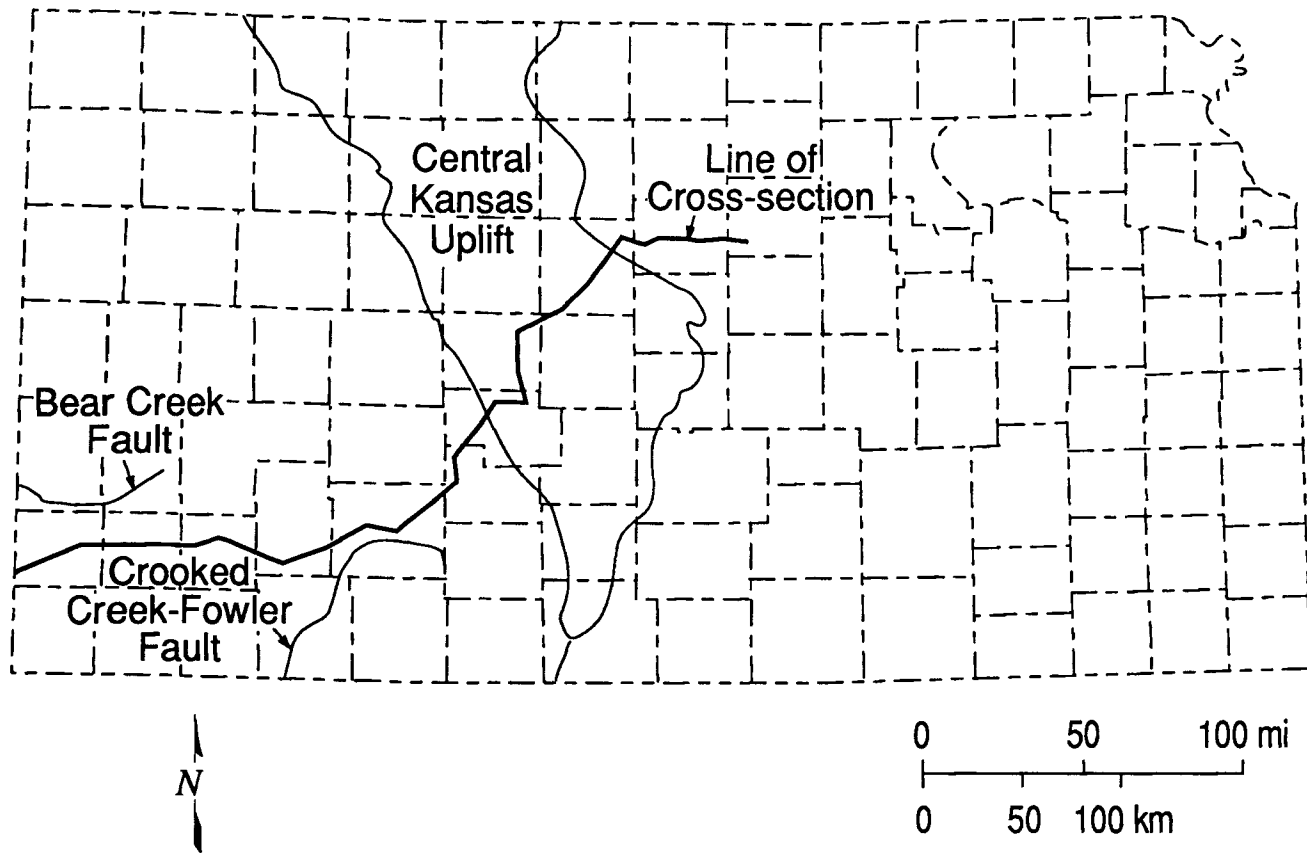


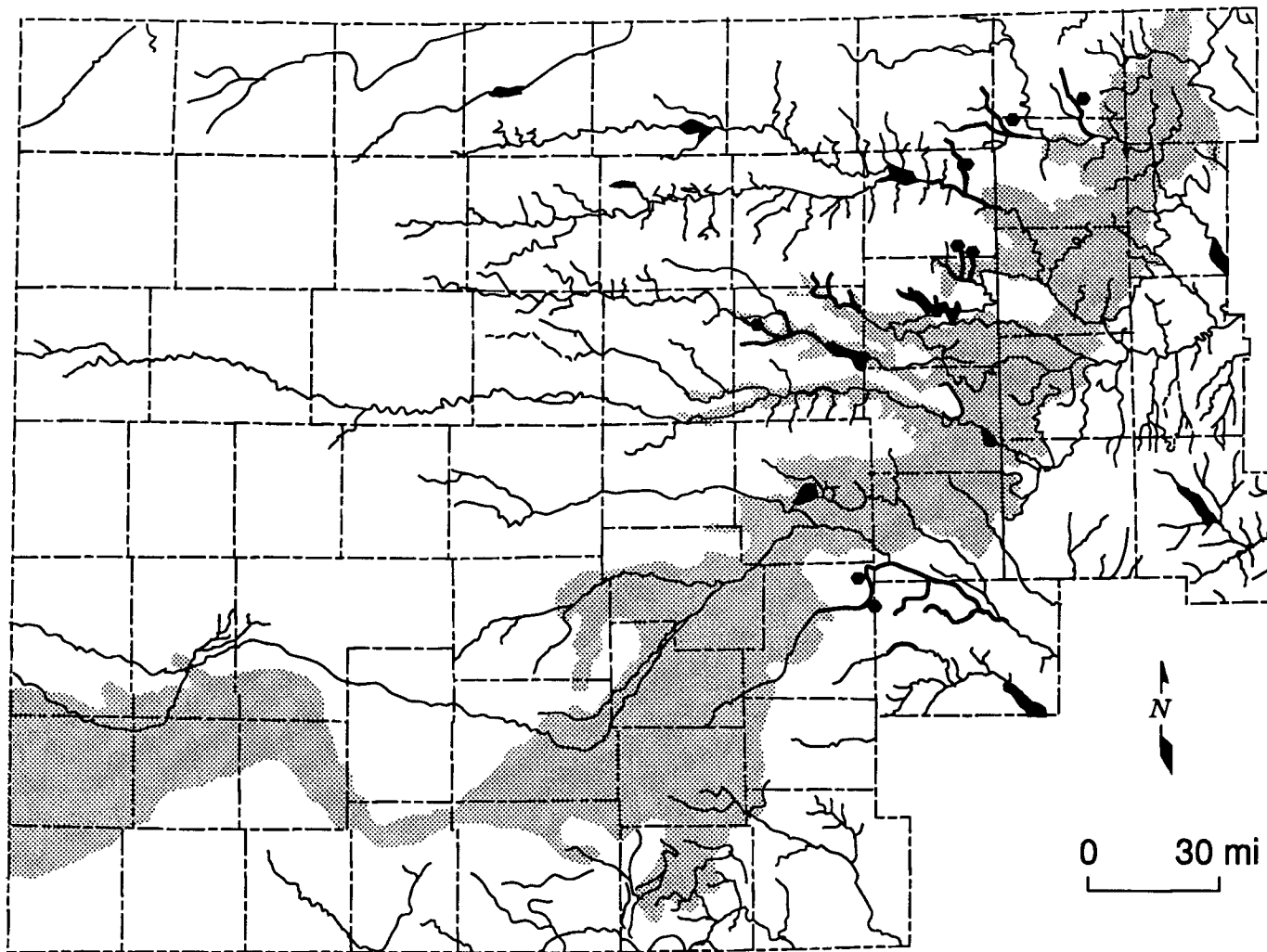
Figure 1. Location of the SW-NE vertical cross-section in Kansas.

## Physical Setting

*Regional Geomorphology.* The study area is included in the Great Plains physiographic province (Fenneman, 1946). The topography varies from relatively undissected High Plains in the west to well-dissected landscapes in the east drained by eastward-flowing entrenched and underfit streams. Northeast-southwest trending escarpments formed by the Greenhorn Limestone and Fort Hays Member of the Niobrara Chalk are prominent features of the central Kansas landscape but are buried beneath Cenozoic unconsolidated deposits in southwest Kansas. Land surface elevations range from approximately 4000 feet above mean sea level along the Kansas-Colorado border just north of the southwest end of the cross-section to less than 1400 feet in the Smoky Hill River valley in central Kansas a few miles eastward of the cross-section. A maximum relief of approximately 250 feet is developed in the area adjacent to the Saline River in northern Russell County near the eastern end of the cross-section. The slope of the land surface is to the east at approximately 6 feet per mile.

Salt marshes and springs are common in the river valley areas in many parts of central Kansas (Figure 2). In the Saline, Solomon, and Republican River valleys these hydrologic features occur near the top of the Dakota Formation. Salt-affected reaches of streams are also common in this area where the valleys are underlain by Lower Cretaceous and

The regional dip of the top of the Dakota Formation is to the north-northeast at 7 to 8 feet per mile in the study area except where local structure has modified the prevailing regional dip direction and magnitude. The Bear Creek, Crooked Creek-Fowler faults and many closed structural lows in the bedrock surface beneath Cenozoic deposits have resulted from the dissolution of salt in the Permian red beds (Merriam, 1963) of western and central Kansas (Figure 1). Some solution collapse features associated with oil industry activity that have resulted from improperly plugged or unplugged boreholes are also present in several areas of central Kansas (Walters, 1977). Figure 3 shows the significant regional structures in western and central Kansas and surrounding areas.



Salt infected rivers  Salt marsh 

Figure 2. Distribution of salt marshes. Springs and salt-affected reaches of streams in the vicinity of the Dakota aquifer.

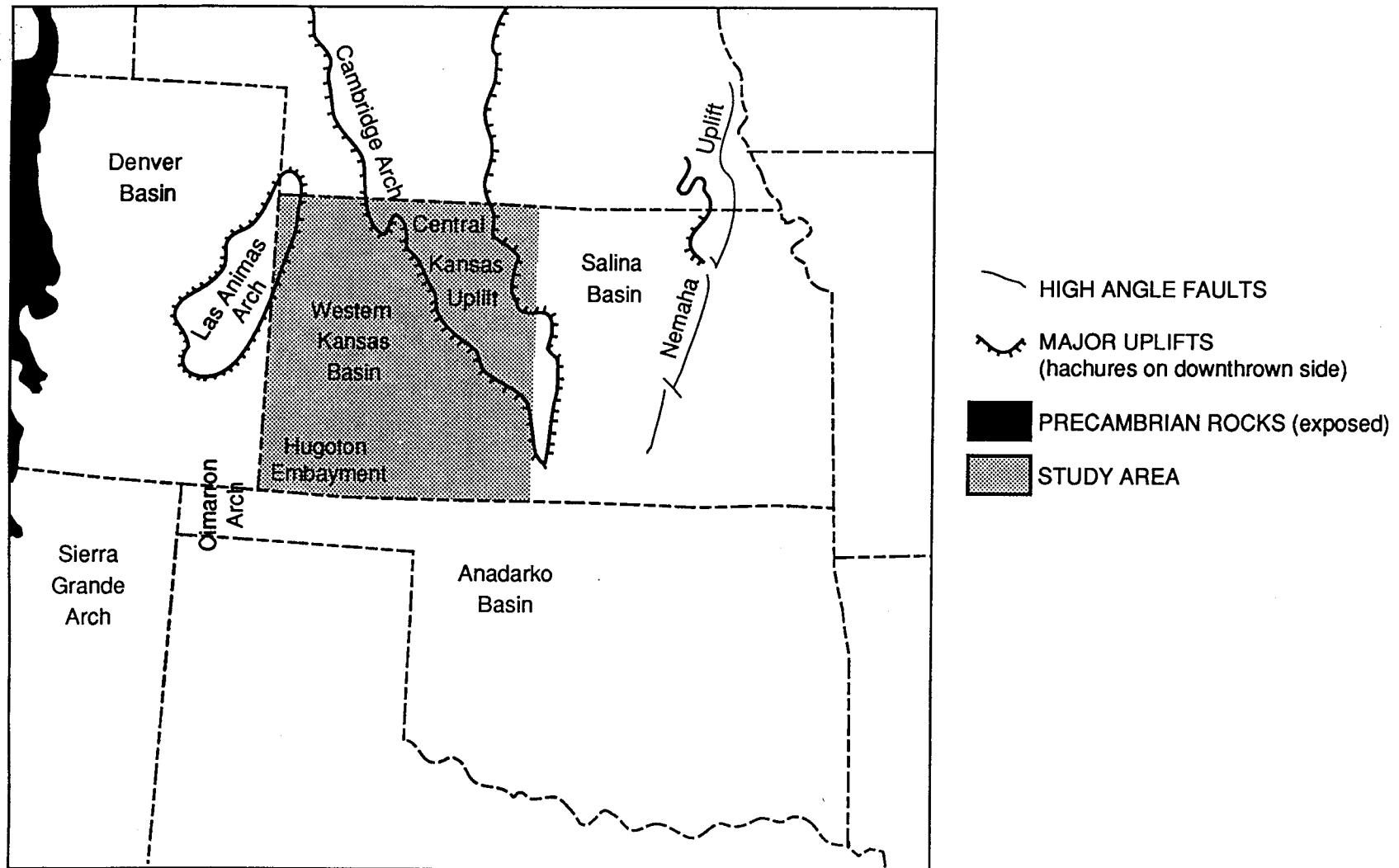


Figure 3. Regional geologic structures in the vicinity of western and central Kansas.

*Regional Geologic Framework.* The geologic units represented in the shallow subsurface of the study area consist of Permian, Jurassic, and Cretaceous strata and unconsolidated Cenozoic deposits (Table 1) (Zeller, 1968). Below these near-surface units older Permian and Pennsylvanian interbedded shales, halite, and carbonates, Mississippian, Ordovician and early Cambrian carbonates are also present above the Precambrian surface (Merriam, 1963). The strata that comprise these older stratigraphic units form several regionally-significant aquifer systems, such as the Arbuckle (Deep Carbonate) which is composed of thick sequences of Ordovician and Cambrian cherty dolomite, dolomitic shale and sandstone, and sandstone.

Along the line of cross-section in the shallower part of the subsurface Permian strata belong to the Upper and Lower Permian Series. The lithologies represented consist of: (1) red bed-evaporite sequences deposited in a nonmarine-marine environment under hot, arid conditions and (2) sandstones of the Cedar Hills Sandstone subareally deposited by eolian processes and subsequently salt-cemented by evaporation of shallow ground waters (Swineford, 1955; Holdoway, 1978). Pre-Cretaceous subareal exposure of the Cedar Hills Sandstone has probably removed much of the salt cement from the Cedar Hills Sandstone in central and western Kansas. The formation is locally salt-cemented in the Permian Syracuse basin (western part of the Cretaceous Western Kansas basin) and in parts of south-central Kansas. Beds of anhydrite, are present at the top of the Cedar Hills Sandstone nearer the Denver basin in northern and extreme western Kansas near the Colorado border. The red-bed evaporite sequence consists of interbedded shales, siltstones, and fine-grained sandstones, and evaporites, and bedded evaporites consisting of halite and anhydrite.

Jurassic strata belonging to the Morrison Formation rest unconformably on the Permian in the northwest half of western Kansas. In southwest Kansas, near the Kansas-Colorado border, the Morrison consists of interbedded fine-grained sandstones and mudstones of fluvial and lacustrine origin.

Cretaceous strata rest unconformably on the Jurassic and Permian units and belong to the Upper and Lower Cretaceous Series. In southwest and central Kansas and southeastern Colorado transgressive and regressive shales and siltstones and interbedded chalky shales and thin limestones

	STRATIGRAPHIC UNIT	THICKNESS	HYDROSTRATIGRAPHIC UNIT
Quaternary and Tertiary Systems	Alluvium/Ogallala Fm.	0 - 600 ft.	Water-Table Aquifer
	Montana and Colorado Groups	0 - 1400 ft.	Upper Cretaceous Aquitard
Cretaceous System	Dakota Fm.	0 - 700 ft.	Dakota
	Kiowa Fm. "Shale" Mbr.		Kiowa "Shale" Aquitard
	Longford Mbr.		Aquifer
	Cheyenne Ss.		
Jurassic System	Morrison Fm.	0 - 4600 ft.	
	Upper Permian Series		
Permian System	Lower Permian Series	Cedar Hills Ss	0 - 250 ft.
		Hutchinson Salt Mbr.	0 - 700 ft.
Penn. System	Upper, Middle, and Lower Pennsylvanian Series		
Miss., ?Devonian, Ordovician, and Cambrian Systems	Upper and Lower Mississippian, Upper, Middle, Lower Ordovician, and Upper Cambrian Series	0 - 1400 ft.	
		0 - 150 ft.	
	Precambrian		Precambrian Aquiclude

Table 1. Regional stratigraphy and hydrostratigraphy of western and central Kansas

associated with the Greenhorn cycle of deposition are represented in Upper Cretaceous strata (Hattin and Siemers, 1987). Fluvial to paralic to shallow offshore sequences of interbedded sandstone and mudstone and shale in the Dakota Formation, Kiowa Formation, and Cheyenne Sandstone are represented in the Lower Cretaceous Series (Hamilton and Cross, 1989). Sediments in the upper part of the Dakota Formation are time equivalent to sediments in the Graneros Shale that were being deposited off-shore in the developing interior seaway to the west (Hattin and Siemers, 1987). Figure 4 shows the stratigraphic relationships between the formations represented in the Lower Cretaceous Series and Graneros Shale (Upper Cretaceous Series) in Kansas.

Above the Cretaceous and Permian bedrock surface the study area is mantled by variable thicknesses of unconsolidated Quaternary and Miocene-Pliocene deposits (Ogallala Formation). These consist of unconsolidated fluvial, lacustrine, and eolian sediments derived from episodic erosion of the Rocky Mountains in eastern Colorado during the latter part of the Tertiary and the High Plains and Rocky Mountains during the late Pliocene and Quaternary (Frye and Leonard, 1952; Frye et al., 1956; and Gustavson and Winkler, 1988). These deposits fill paleovalleys cut into older unconsolidated deposits and bedrock by eastward-flowing streams during the early part of the Tertiary.

### Hydrostratigraphic Units

Six hydrostratigraphic units were defined in the cross-section based on actual hydraulic conductivity data from the literature or from generalized ranges of values for the lithologies represented in the subsurface (Freeze and Cherry, 1979). In all, three aquifer and three aquitard hydrostratigraphic units are defined in the shallow subsurface along the line of cross-section (Table 1). The distribution of these aquifer and aquitard units in the cross-section is shown in Figure 10.

The Permian aquitard consists of Upper and Lower Permian Series red bed-evaporite sequences and salt-cemented sandstones of the Cedar Hills Sandstone. Fractures are assumed to be the primary pathway of fluid

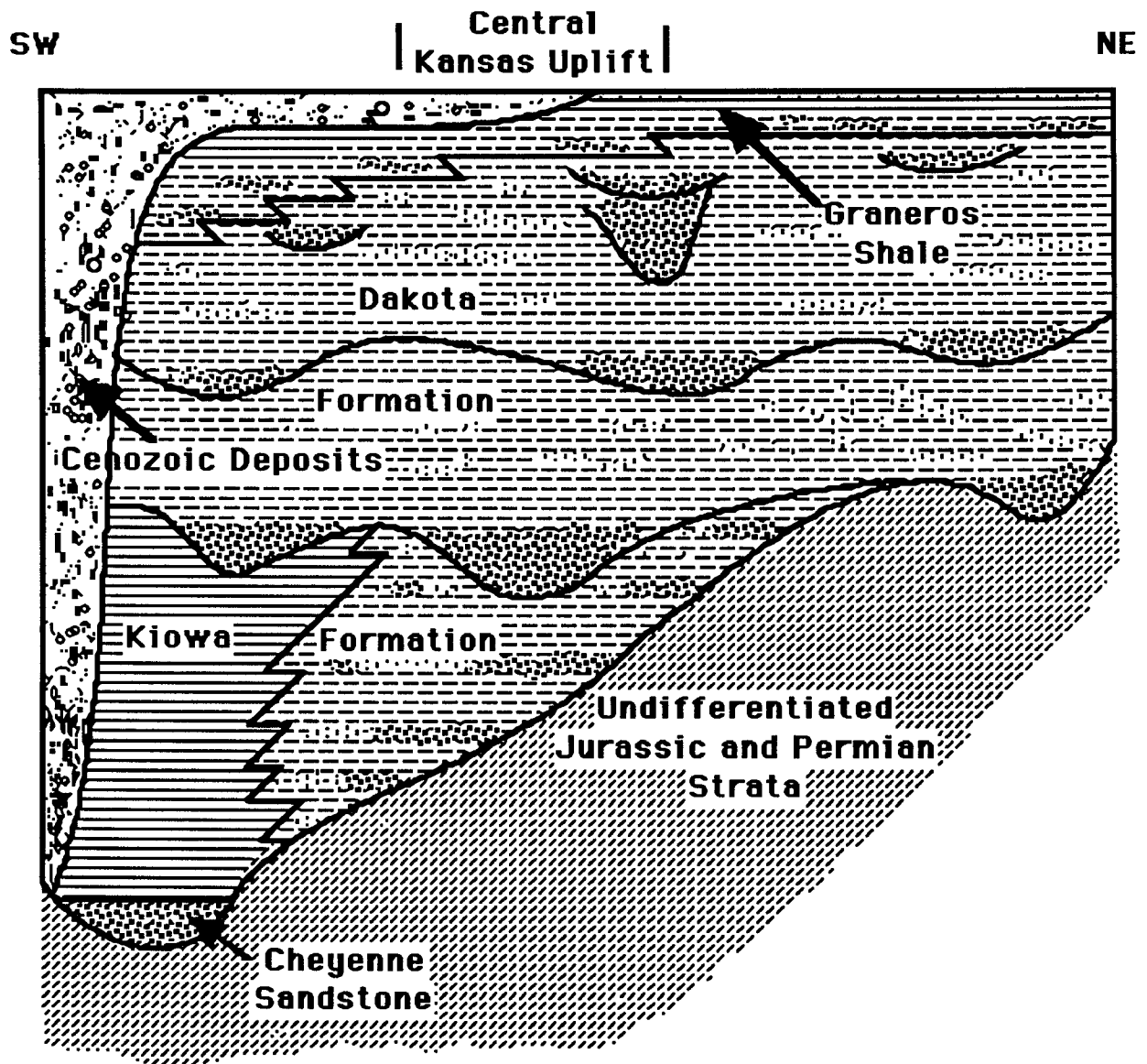


Figure 4. Southwest to northeast schematic cross-section of the Lower Cretaceous strata along the outcrop-subcrop belt in Kansas. Modified from Franks, 1979.

movement through this aquitard. In the Palo Duro basin of Texas, Kreitler et al. (1985) report a regionalized hydraulic conductivity of  $10^{-6}$  ft/day for the evaporite aquitard, a hydrostratigraphic unit consisting of similar lithologies to the Permian aquitard defined in this study. They concluded that flow through fractures is much more significant than porous-media flow through the aquitard in the Palo Duro basin.

Within the Permian aquitard the saltwater-bearing Cedar Hills Sandstone aquifer is composed of sandstones not presently salt-cemented. ground-water flow is from structurally higher areas in southwest Kansas, Oklahoma, and southeastern Colorado toward discharge areas where the aquifer is hydraulically connected to the Dakota aquifer in central Kansas. Regional simulation of the steady-state flow system covering a large part of the central Midcontinent indicates that the rate of discharge from the Permian is on the order of  $0.1 \text{ ft}^3/\text{sec}$  in central Kansas. In this area the Cedar Hills aquifer is in contact with the overlying Dakota aquifer (Helgeson et al., in press). The regionalized hydraulic conductivity value for the Cedar Hills aquifer is assumed to be on the same order of magnitude as that of the Dakota aquifer within the cross-section.

Overlying the Permian aquitard and Cedar Hills aquifer is the Dakota aquifer which consists of upper and lower portions, separated by a discontinuous aquitard, the "Kiowa Shale" Member of the Kiowa Formation. The hydraulic conductivity of the "Kiowa Shale" aquitard is assumed to be  $10^{-6}$  ft/day which is similar to that of the Skull Creek Shale in South Dakota. Interbedded fluvial, paralic, and offshore sandstones and mudstones in the Dakota Formation, Longford Member of the Kiowa Formation, and the Cheyenne Sandstone comprise the Dakota aquifer framework. Figure 5 is a plot of hydraulic conductivity from pumping tests vs. depth to the midpoint of the water-producing zone of the pumping well in the Dakota aquifer. All of the data come from pump tests of the aquifer in central and southwest Kansas. The data are further classified by lithofacies represented in the water-producing zone. Ignoring the differences in lithofacies of the pump-tested interval, the hydraulic conductivity is negatively correlated with depth which confirms the findings of Belitz and Bredehoeft (1988) in the Denver basin. They attributed the negative correlation to decreased porosity from the weight of the overburden and diagenetic effects resulting from deep burial in the

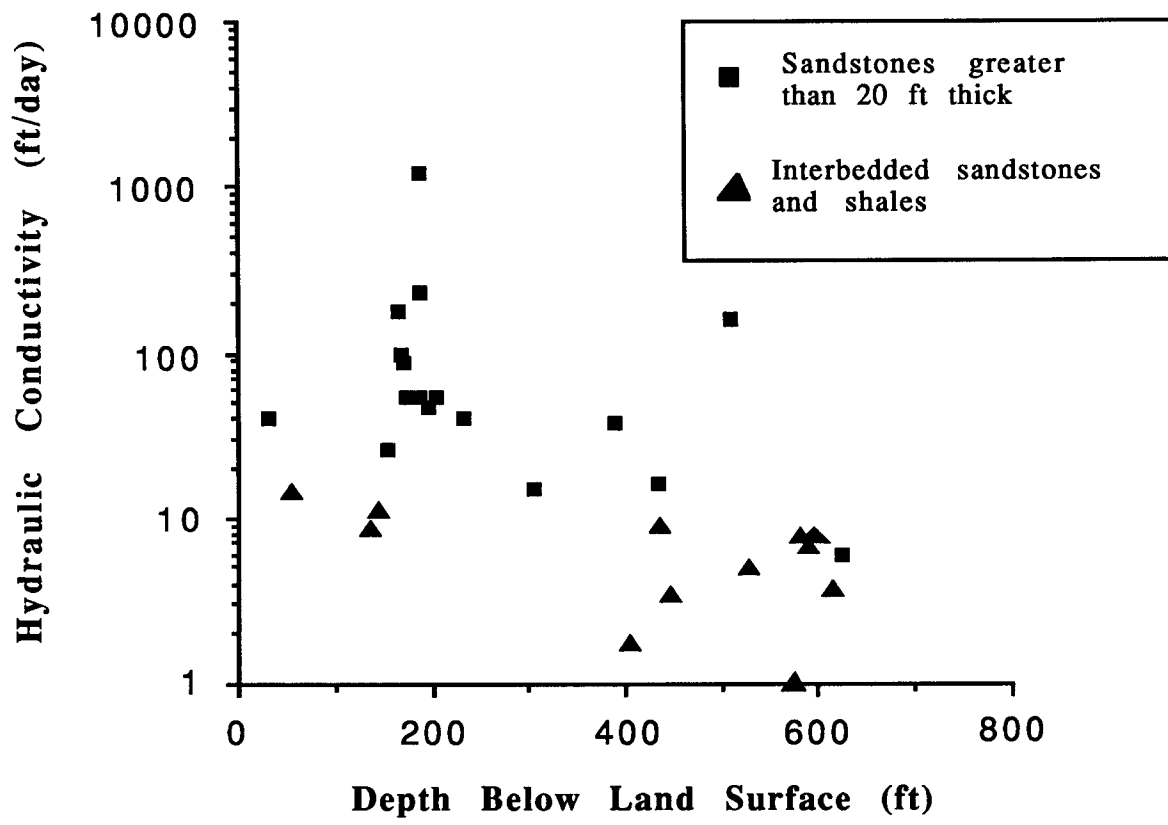


Figure 5. Hydraulic conductivity vs. depth data from pump tests of the Dakota aquifer in Kansas arranged according to lithofacies classification.

basin. However, it is apparent from the figure that the lithology of the aquifer is a more significant parameter affecting hydraulic conductivity than the depth to the tested zone in central and southwest Kansas. Furthermore, the distribution of hydraulic conductivity may also be a function of spatial location since the thicker, more permeable sandstones are more likely to be associated with nonmarine sedimentation eastward of the Cretaceous interior seaway. This is supported by the available data which indicates that the hydraulic conductivity of the Dakota aquifer increases from less than 10 ft/day in southwestern Kansas to more than 50 ft/day in the central part of the state.

In central and widely separated areas of southwestern Kansas the strata that comprise the Dakota aquifer crop out at the surface and the aquifer is unconfined. Elsewhere, in southwestern Kansas the aquifer subcrops beneath Cenozoic deposits and is hydraulically connected to the water table. Where covered by the Upper Cretaceous aquitard, confined flow conditions govern the movement of water. However, in parts of central Kansas adjacent to the outcrop the potentiometric surface of the Dakota aquifer is below the top of the Dakota aquifer (Macfarlane et al., 1988).

Figure 6 is the assumed pre-development potentiometric surface map of the Dakota aquifer in central and western Kansas. Two primary ground-water flow paths can be defined from the potentiometric surface map. Ground waters move along these flow paths from recharge areas in southwest Kansas-southeast Colorado to discharge areas in the central part of Kansas. One flow path parallels the outcrop and subcrop areas of the aquifer and is influenced by local sources of recharge and discharge. The other flow path is northeastward through the confined portion of the Dakota aquifer and eastward into north-central Kansas discharge areas. The Dakota aquifer is primarily recharged by precipitation falling on the outcrop and the overlying water-table aquifer in southwest Kansas and by the underlying Cedar Hills aquifer where they are hydraulically connected in the central part of the state. Belitz and Bredehoeft (1988) estimate that the Dakota aquifer receives only 9.0 ft<sup>3</sup>/sec. through the Upper Cretaceous aquitard in all of the Denver basin and areas to the east and whereas the aquifer receives 29.2 ft<sup>3</sup>/sec in outcrop/subcrop areas in southwestern Kansas and southeastern Colorado. Discharge from the Dakota aquifer to

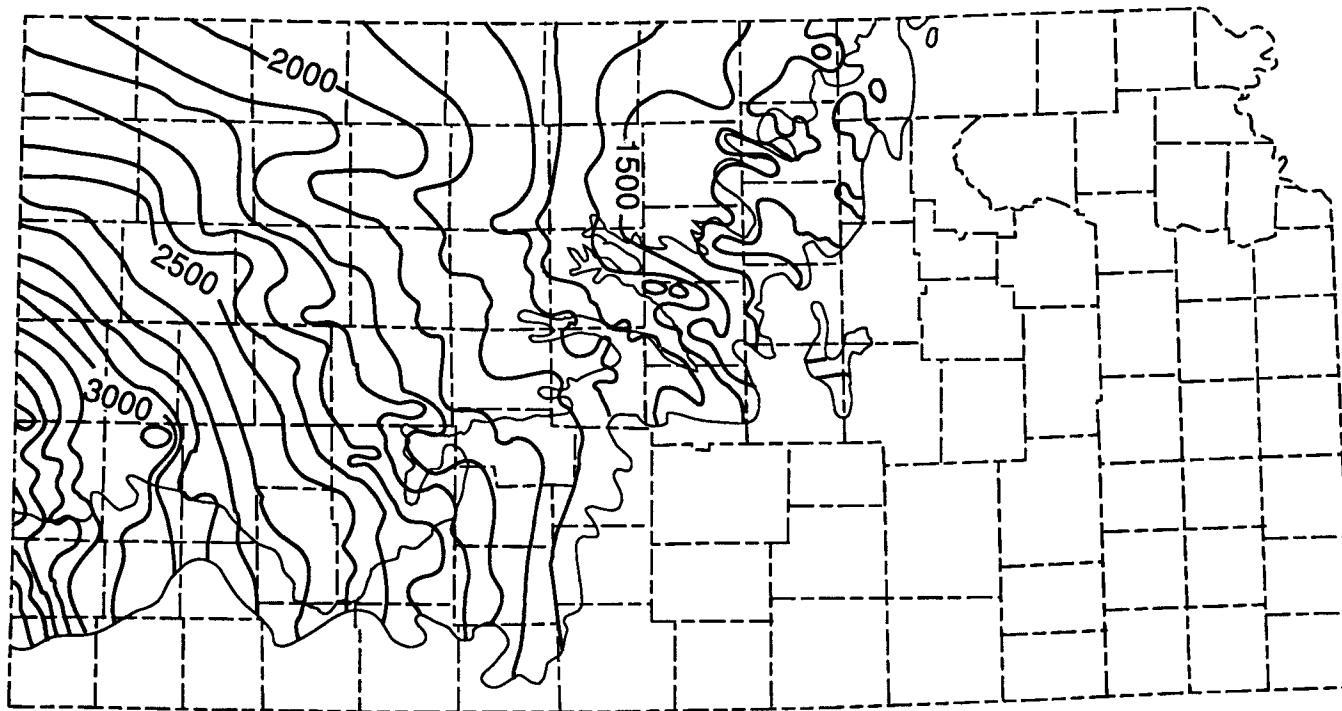


Figure 6. Potentiometric surface of the Dakota aquifer in Kansas.

overlying aquifers and surface waters is estimated to be 30.4 ft<sup>3</sup>/sec in southwestern and central Kansas and southeastern Colorado.

Over much of western and central Kansas Upper Cretaceous shales and interbedded chalky shales and thin-bedded limestones form the Upper Cretaceous aquitard above the Dakota aquifer. Fluids move through the Upper Cretaceous aquitard very slowly probably through fractures. Belitz and Bredehoeft (1988) have shown that Upper Cretaceous strata in the Denver basin and the adjacent High Plains severely limit the amount of recharge received by the Dakota aquifer. From their steady-state simulation of the regional flow system, they concluded that the hydraulic conductivity of the strata comprising the Upper Cretaceous aquitard is on the order of 10<sup>-6</sup> ft/day.

At the surface the water-table aquifer consists of the High Plains aquifer in southwest Kansas and the alluvial valley aquifers. Ground-water flow in the High Plains aquifer is generally from west to east toward discharge areas in the river valleys of central Kansas. The pre-development saturated thickness of the water-table aquifer ranges up to 400 feet in the southwest part of the state. Recharge to the water table under steady-state conditions in southwest Kansas is estimated to range up to 0.25 inches per year in areas of sandy soils and the regionalized

### Patterns of Surface and Ground-Water Quality in Southwest and Central Kansas

Ground-water quality in the unconsolidated Cenozoic deposits reflects the combined effects of freshwater recharge, rock/water interactions, and the upward discharge of saline waters from the Permian and Lower Cretaceous aquifers. In southwestern Kansas, Ca-HCO<sub>3</sub> type waters with total dissolved solids (TDS) concentrations ranging up to 675 mg/l predominate where the water table is receiving significant recharge from precipitation (Hathaway and Magnuson, 1985). To the north of the cross-section TDS concentrations greater than 675 mg/l and Ca-SO<sub>4</sub> and Ca-HCO<sub>3</sub>-SO<sub>4</sub> type ground waters underlie playa areas. To the south along the Kansas-Oklahoma border, Krothe and Oliver (1982) found that the TDS concentration of ground waters in the water-table aquifer is controlled by

the nature of the underlying bedrock. In areas underlain by Mesozoic-age rocks the TDS concentration of ground waters in the overlying water-table aquifer was lower than in those areas underlain by Permian bedrock. In the alluvial aquifers of the Pawnee River and Walnut Creek valleys Ca to mixed cation and HCO<sub>3</sub> to mixed anion type waters predominate. TDS concentrations of these ground waters range upwards from 275 mg/l to more than 675 mg/l (Hathaway and Magnuson, 1985). This water chemistry probably reflects the presence of marcasite in the Blue Hill Shale that underlies these aquifers and recharge from precipitation as infiltration and ground/surface water interactions. The chemical quality of the surface waters in the Smoky Hill and Saline Rivers in central Kansas is directly related to stream discharge and the the influx of Na-Cl type waters from the Dakota aquifer (Jordan et al., 1964; Whittemore, 1978; and Hargadine et al., 1979). The dissolved solids concentration of surface waters in the Saline River at low flow ranges up to more than 4000 mg/l. At higher discharge rates lower TDS concentrations and Ca-HCO<sub>3</sub>, Na-HCO<sub>3</sub>, or Na-Cl type surface waters are discharged by the Saline and Smoky Hill River systems.

Water quality within the Dakota aquifer is highly variable along the cross-section reflecting the effects of recharge from overlying and underlying aquifers, rock/water interactions, and mixing of water types within the aquifer. Ca,Mg-HCO<sub>3</sub>, Na-HCO<sub>3</sub>, and mixed cation-mixed anion type waters predominate in the primary recharge areas where the Dakota is hydraulically connected to the overlying water-table aquifer in southwest Kansas. In the outcrop areas of central Kansas where local ground-water flow systems provide recharge to the upper part of the aquifer Ca-HCO<sub>3</sub> type waters predominate. Na-Cl and Na-mixed anion type waters predominate where the aquifer is being recharged by the Permian in the vicinity of the Central Kansas uplift. Na-HCO<sub>3</sub> type waters are present largely as a result of cation exchange involving clay minerals. Figure 7 shows the distribution of chloride concentrations in the Dakota aquifer in Kansas (Helgeson et al., in press). Chloride concentrations below 100 mg/l are common in southwest Kansas where the Dakota aquifer subcrops beneath the overlying water-table aquifer. To the northeast in the vicinity of the Central Kansas uplift, chloride concentrations increase irregularly to levels exceeding 1000 mg/l. This trend continues into the



0 - 100 mg/L  101 - 1000 mg/L  1001 - 5000 mg/L  > 5000 mg/L 

Figure 7. Distribution of chloride concentration in ground waters from the Dakota aquifer modified from Helgeson et al. (in press).

outcrop belt where the chloride concentrations begin to decrease down to 100 mg/l due to recharge.

Ground waters in the Cedar Hills Sandstone aquifer are Na-Cl type waters with dissolved solids concentrations on the order of 20,000 mg/l (Macfarlane and others, 1988). The salinity source for these waters is the dissolution of halite either from the salt-cemented portions of the Cedar Hills Sandstone or other Permian strata.

### Pore Pressure vs. Depth Profiles in the Dakota Aquifer and Underlying Permian

Within a ground-water flow system pore pressures below the water table (zone of saturation) should increase hydrostatically with depth (approximately 0.433 psi/ft for a freshwater aquifer). Under these conditions water levels in piezometers will rise approximately to the level of the water table. Exceptions to this occur in recharge areas where the rate of increase should be slightly less than and in discharge areas where the rate of increase should be slightly more than the rate of hydrostatic increase. Rates of fluid pressure increase that are "significantly" less than hydrostatic are considered subnormally pressured.

Figure 8 is a plot of fluid pressure vs. depth profiles for the Dakota aquifer and underlying Permian from data collected at a number of sites in Kansas. Individual profiles are plotted in the figure rather than the fluid pressure-depth data points in order to emphasize the differences between sites of measurement and to avoid problems of misinterpretation due to topographic effects and sparse data (Orr and Kreitler, 1985).

Most of the profiles plot entirely below and are parallel to the line representing the rate of hydrostatic pressure increase with depth. The plotted profiles show that the Dakota aquifer and underlying Permian are subnormally pressured in northwest and in much of central Kansas. Most of the profiles through the Dakota aquifer interval are nearly parallel to the rate of hydrostatic pressure increase suggesting little or no tendency for vertical movement within the aquifer. However, some of the fluid pressure gradients are higher than hydrostatic in the upper part of the Permian and lower part of the Dakota aquifer in central Kansas. Pore pressure-depth data from drill-stem tests of aquifer units below the Cedar

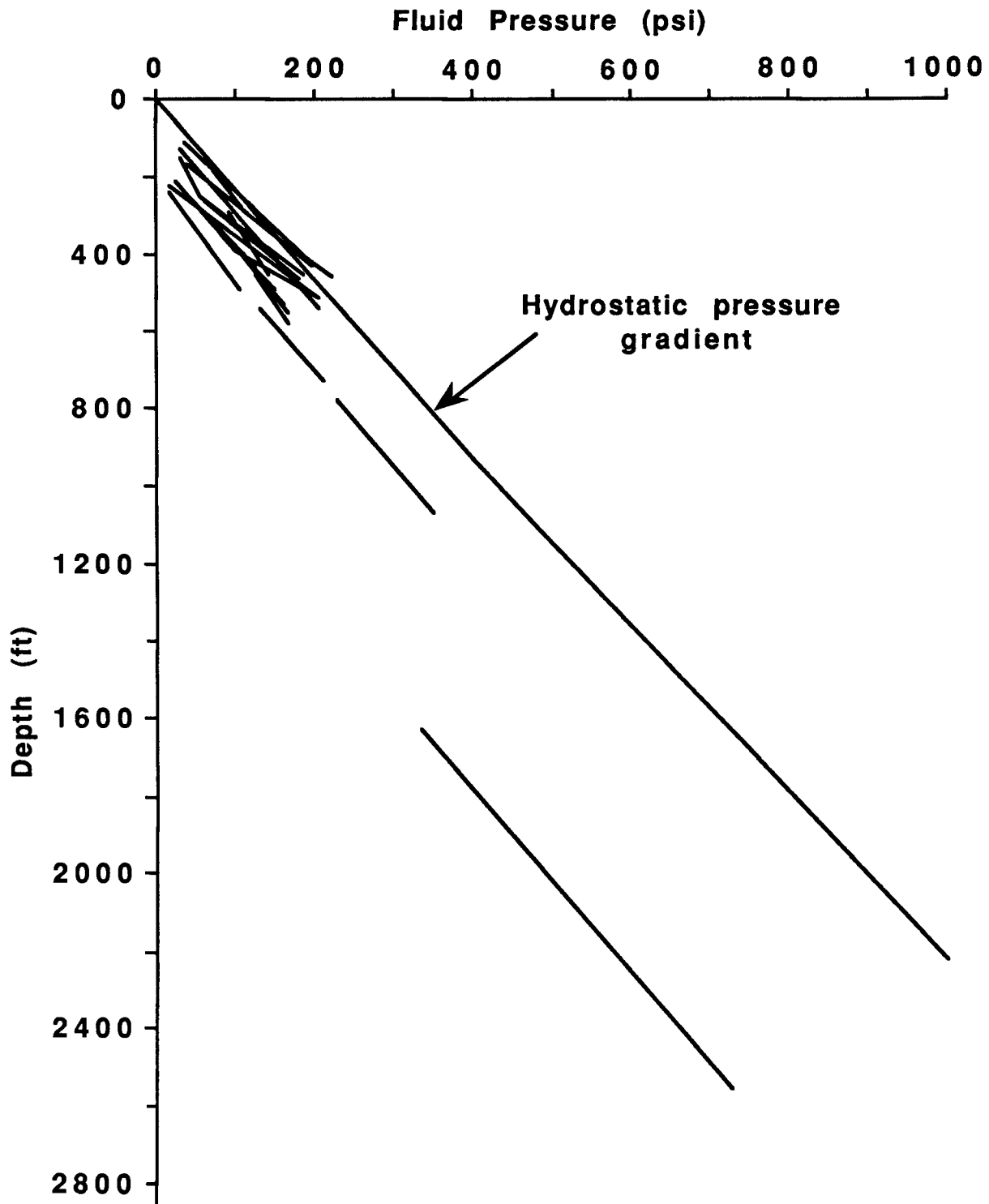


Figure 8. Fluid pressure vs. depth profiles for the Dakota aquifer and underlying Permian aquitard in Kansas.

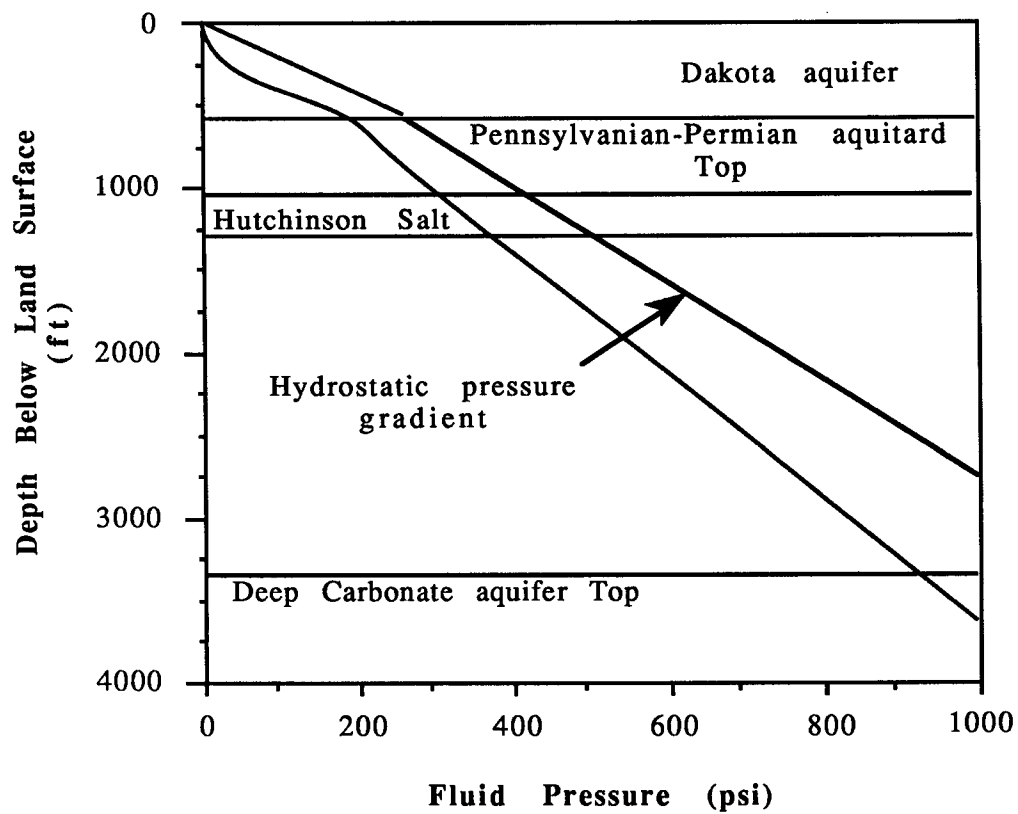


Figure 9. Fluid pressure vs. depth profile for a site in western Russell, County, Kansas.

Hills Sandstone aquifer down to the top of the Precambrian show increasing degrees of subnormal pressuring with depth throughout western and central Kansas. Figure 9 shows a typical fluid pressure vs. depth profile from the surface down to the Arbuckle aquifer in central Kansas. Fluid pressures are considerably less than hydrostatic below the top of the Permian aquitard. Equivalent fresh-water hydraulic heads in the Arbuckle are as much as 2000 feet below the water table in southwestern Kansas and 500 feet below the water table in central Kansas.

### Regional Ground-Water Flow Patterns in Southwest and Central Kansas

Studies of regional ground-water flow systems have shown that the ground-water flow patterns observed in a rigid rock framework are a function of relief and the length of the flow path from recharge to discharge areas (Freeze and Cherry, 1979). This is a direct consequence of the hydraulically continuous nature of the rock framework considered over geologically-significant periods of time (so-called steady-state conditions). Consequently, in an idealized ground-water basin under steady-state conditions, topographic relief modified by variations in rock permeability are responsible for the differentiation of local, subregional, and regional-scale flow systems.

Figure 10 shows the contoured distribution of hydraulic head in the shallow subsurface of southwestern and central Kansas along the cross section. In order to construct this cross section the following assumptions were made: (1) where there is no recognized unconfined aquifer at the surface in the cross section, the water table is assumed to be a reflection of and, at a regional scale, to be coincident with the land surface; and (2) each hydrostratigraphic unit is assumed to be homogeneous and isotropic, even though it is acknowledged that the hydraulic conductivity tensor is affected by the characteristics of the bedding and distribution of specific lithofacies within the aquifer and aquitard units. The second assumption arises due to the lack of data on the vertical components of the hydraulic conductivity tensor in the plane of the cross section for the various hydrostratigraphic units. Also from the second assumption, the direction of water movement through the cross section is perpendicular to the

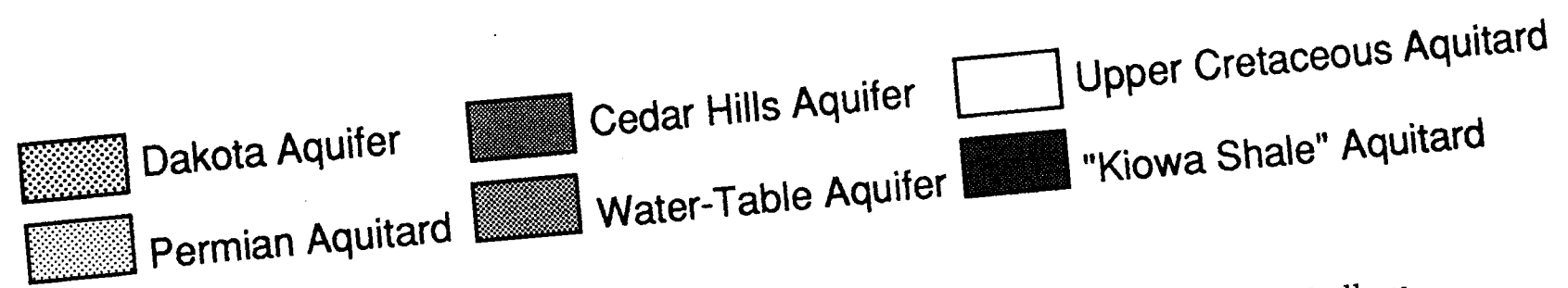
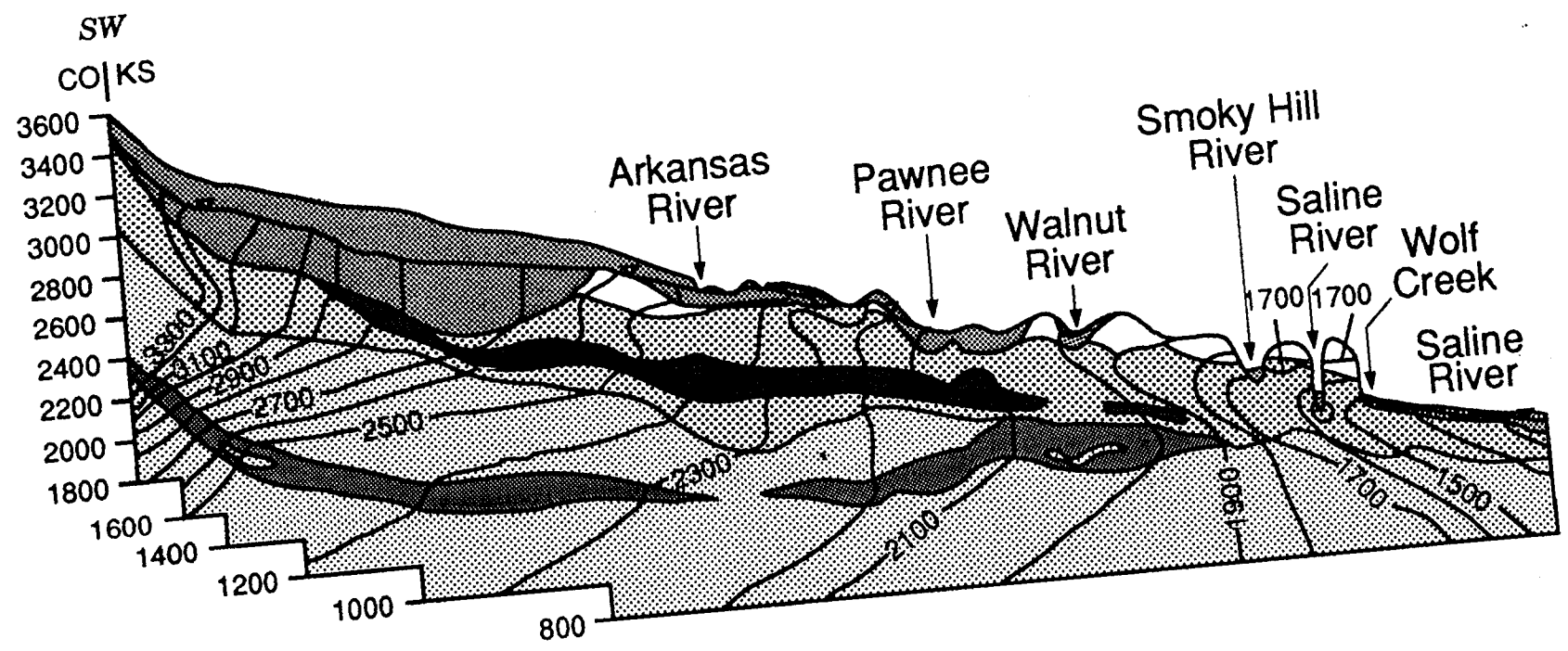


Figure 10. Hydrostratigraphic units and ground-water flow patterns in the shallow subsurface in southwestern and central Kansas

equipotential lines and opposite in direction to the hydraulic head gradient (isotropic condition within individual aquifer and aquitard hydrostratigraphic units). Flow rates between aquifers, discharge to surface waters, recharge to aquifers, and leakage rates are only generally known from steady-state simulation of ground-water flow in geographically extensive areas (for example see Belitz and Bredehoeft, 1988 and Helgeson et al., in press). For the most part the hydraulic conductivity data base derived from field investigations is sparse and does not include data from the aquitard units. As a result, the hydraulic conductivity data base is largely derived from simulation or the literature.

Ground-water flow within the plane of the cross section is from recharge areas in southwestern Kansas and southeastern Colorado eastward and northeastward toward discharge areas in central Kansas. Southwest of the Pawnee River valley the Dakota aquifer receives freshwater recharge from the overlying water-table aquifer where the Upper Cretaceous aquitard is not present. The ground-water flow direction is generally parallel to bedding in the upper and lower portions of the aquifer. Hydraulic heads are slightly less in the lower portion of the Dakota aquifer than in the upper portion indicating downward movement through the "Kiowa Shale" aquitard. In this part of the cross section the Dakota aquifer appears to act as a conduit transporting ground waters away from the water-table aquifer in southwestern Kansas.

Below the Dakota aquifer, steep hydraulic head gradients are present in the Permian red bed-evaporite aquitard southwest of the Arkansas River indicating downward flow of water from the upper Permian to aquifers farther down in the Permian-Pennsylvanian. This steep gradient is associated with a closed potentiometric low in the Pennsylvanian in the Anadarko basin (Larson, 1971). Belitz and Bredehoeft (1988) attributed this potentiometric low to the osmotic movement of water downward into the Pennsylvanian in response to chemical concentration gradients in the upper part of the Pennsylvanian-Permian aquitard.

Near the Pawnee River valley in central Kansas the vertical component of flow is upward from the upper part of the Permian into the lower Dakota aquifer. However, the local-scale flow system around the Pawnee River extends only to shallow depth beneath the valley. Below the upper part of the Permian at the bottom of the cross section the flow

through the Permian red bed-evaporite sequence is downward toward the Mississippian and the Arbuckle aquifers. As a result a "ground-water divide" is present just below the Permian/Cretaceous unconformity within the cross section and separates vertically upward and downward components of the flow system in the Permian aquitard and Cedar Hills aquifer. Thus, it appears from the flow pattern and the pore pressure *vs.* depth profiles that the Cedar Hills aquifer and overlying Permian aquitard are slightly overpressured with respect to overlying and underlying hydrostratigraphic units. This "ground-water divide" continues to near the end of the cross section in the Saline River valley.

Farther along the cross section between the Pawnee River and Walnut Creek and extending into the outcrop areas, the Dakota aquifer seems to act as a drain for the upper part of the Permian red bed-evaporite aquitard and the Cedar Hills Sandstone aquifer near the outcrop. Coincidentally, the Dakota aquifer becomes confined by the Upper Cretaceous aquitard and recharge from the overlying water-table and precipitation is restricted. Upward migration of ground waters from the Cedar Hills and Permian red bed-evaporite aquitard is facilitated by pinch-out of the "Kiowa Shale" aquitard and disappearance of the Permian aquitard above the Cedar Hills Sandstone aquifer. Saltwater moves upward from the Cedar Hills aquifer and lower portion of the Dakota aquifer into upper portions of the Dakota aquifer. As a result, this produces a mixed cation-mixed anion type water with elevated dissolved solids concentration and at several localities precipitation of calcite in sandstones of the lower part of the Dakota Formation. Eventually these waters become part of the local-scale flow system in the vicinity of the Saline River and are discharged laterally from the Dakota aquifer into nearby stream/aquifer systems.

Westward of the Dakota aquifer outcrop belt lateral drainage of water from the aquifer to streams and upward movement of saline waters from the Cedar Hills aquifers and Permian aquitard are probably much more significant than recharge through the Upper Cretaceous confining layer. Recharge is probably limited to those areas where the overlying aquitard is fractured. At one location within five miles of the outcrop belt, Macfarlane et al. (1988) found that the hydraulic head in the uppermost part of the Dakota aquifer was lower than the top of the aquifer indicating

unconfined conditions and negative pore pressures at the top of the aquifer. This is consistent with the Belitz and Bredehoeft (1988) conceptual model of flow in the Dakota aquifer for the Denver basin and adjacent areas to the east.

### The Effects of Cenozoic Basin Development on the Regional Flow System (a Hypothesis)

The evolution of sedimentary basins, involving uplift, deposition, and erosion causes major changes in basin hydrodynamics and the hydrochemistry of basinal fluids. Transient flow conditions induced by geologic processes acting over finite periods of geologic time produce changes in the flow system at a rate that depends on the diffusivity of the rock framework and the arrangement and thickness of aquifer and aquitard units in the basin (Toth and Millar, 1983; and England and Freeze, 1988). The duration and magnitude of these changes is directly related to modifications in the flow-system boundary conditions caused by the geologic processes acting on the basin. These changes in the boundary conditions relate principally to modifications in the configuration of the water table over time. Regional uplift or subsidence and erosional and depositional processes can cause transient adjustments of hydraulic heads by elevating or lowering the surface topography, causing changes in the the elevation head, and propagating changes in the pore pressure distribution downward below the zone of saturation (Bradley, 1975). Thus, an overprinting of a more recent pattern of ground-water movement on a relict flow system may occur as a result of tectonic movements or changes in the topography in the basin. Toth has shown that the time of adjustment may be geologically significant, on the order of millions of years, if aquitards of substantial thickness are present in the subsurface.

Several examples of this behavior have been identified in the Midcontinent region. Pollastro and Scholle (1986) and Rice (1984) attributed pore pressures higher than hydrostatic in shallow Niobrara gas fields along the eastern edge of the Denver basin to removal of overburden during the Tertiary and Quaternary. Senger et al. (1987) and Dutton and Simpkins (1989) were able to explain subnormal pressures in the deepest

part of the Palo Duro basin in the Texas panhandle and the isotropic geochemistry of shallow ground waters, respectively, by examining the Cenozoic erosional and tectonic history of the region.

The presence of the "ground-water divide" in the cross section and anomalously high pore pressure gradients below the Permian-Cretaceous boundary are unexpected. Furthermore, the occurrence of subnormal fluid pressures in the consolidated rock aquifers indicates that the flow systems in these aquifers are not in equilibrium with the overlying water table. These phenomena, and possibly including Larson's (1971) closed potentiometric low in the Pennsylvanian, may be attributed to a time lag in the response of the regional ground-water flow system to tectonic and erosional events that have taken place in the High Plains region during the latter part of the Mesozoic and Cenozoic Eras.

The geologic record of the High Plains in Kansas is not continuous throughout the latest Cretaceous and Cenozoic and must be inferred from what is known about the early part of this time period in eastern Colorado and Nebraska (Kirkham and Ladwig, 1980; Stout et al., 1971). However, the geologic events that occurred in Kansas during the Miocene-Pliocene and Quaternary are reasonably well known (Smith, 1940; Frye, 1945; Frye and Leonard, 1952; Merriam and Frye, 1954; Merriam, 1963; and Frye, 1970). Table 2 is a summary of the geologic processes active in central Kansas and Rocky Mountain foreland adjacent to the mountain front in Colorado.

Episodes of erosion and deposition and tectonic movements have caused major changes in the water-table configuration in central and western Kansas since latest Cretaceous time. During the early and middle part of the Tertiary, the area underwent several periods of uplift and cycles of erosion and deposition so that prior to the Miocene only a thin cover of Upper Cretaceous strata remained in central Kansas. Stream erosion removed considerable thicknesses of Cretaceous strata below the Pierre Shale from Kansas, including an estimated 1400 feet of strata from central Kansas, assuming deposition during Pierre time in this part of the state. Also, the High Plains region in Kansas was tilted slightly to the northwest prior to the Miocene (Merriam, 1963). This would have increased the elevation of the water table and consequently hydraulic heads in the water-table aquifer in the southern part of the regional

GEOLOGIC TIME	DOMINANT GEOLOGIC PROCESSES IN		
	ROCKY MTN. FORELAND	CENTRAL KANSAS	
LATE CRETACEOUS	LARAMIDE OROGENY	RETREAT OF THE INLAND SEA; ESTABLISHMENT OF DRAINAGE; DEPOSITION	ESTABLISHMENT OF DRAINAGE PATTERNS; EROSION OF THE CRETACEOUS SURFACE
PALEOCENE		CONTINUED AGGRADATION	?
EOCENE		UPLIFT OF THE FRONT RANGE; AGGRADATION	?
OLIGOCENE		CONTINUED AGGRADATION	?
MIOCENE/ PLIOCENE		RENEWED UPLIFT OF ROCKY MTNS; EASTWARD TILTING	NW TILTING; AGGRADATION
QUATERNARY		EASTWARD TILTING; EROSION	EROSION EARLY AND LATER DEPOSITION BY STREAMS
RECENT		EROSION BY STREAMS	EROSION BY STREAMS

Table 2. Summary of depositional, erosional, and tectonic events in the High Plains region of eastern Colorado and central Kansas.

ground-water flow system relative to the northern portion. Erosion stripped off the Upper Cretaceous strata in southwest and southeastern Colorado uncovering the Dakota aquifer and the underlying Permian red bed-evaporite aquitard. Eastward of the central Kansas area, the Dakota aquifer outcropped beneath the westward-retreating Fort Hays and Greenhorn escarpments. The recharge area for the Dakota aquifer was probably the southeast Colorado-southwest Kansas area during this time and the flow path would have extended from this area to discharge areas eastward of central Kansas. Meanwhile, pore pressures near the discharge end of the Dakota aquifer probably declined due to lack of recharge through the overlying Upper Cretaceous aquitard. As a result hydraulic head differences between the underlying Cedar Hills aquifer increased and ground waters from the Permian would have begun to move upward into the Dakota and overlying surface waters. Pore pressures may have slowly begun to adjust to the removal of overlying sediments, northwestward tilting of the region, and the new water-table configuration. Downward propagation of transient changes in pore pressure probably continued to lag behind adjustments in the water-table configuration at the end of pre-Ogallala time as the land surface was eroded. Prior to the deposition of the Ogallala Formation, the dissected Greenhorn escarpment probably had retreated into the central Kansas area to its approximate geographic location.

With the deposition of the Ogallala in the Miocene-Pliocene, the westward retreat of the Fort Hays and Greenhorn escarpments was halted. Water-saturated sediments deposited in southwestern Kansas and southeastern Colorado probably provided a more consistent source of recharge to the Dakota aquifer than precipitation on the outcrop surface. A maximum of 100 feet of Miocene-Pliocene sediments was deposited in the central Kansas area (Merriam, 1963). With the deposition of the overlying unconsolidated sediments, the Dakota aquifer was flushed of connate waters in the shallow subsurface by recharge from the water-table aquifer. Hydraulic heads in the Dakota aquifer would have increased in subcrop areas in response to deposition of water-saturated Ogallala sediments. Increased hydraulic heads in the discharge area might have slowed or eventually shut-off the upward movement of saltwater from the Permian toward shallow aquifers and surface waters.

Later in the Pliocene and into the Quaternary, eastward tilting of the High Plains rejuvenated streams in central and western Kansas and caused erosion of the Ogallala Formation, dissection of the Greenhorn escarpment in central Kansas, and entrenchment of streams. Frye (1945) estimates that approximately 150 feet of Cretaceous strata and Ogallala Formation were removed from the Saline River valley in central Kansas during this time. Eastward tilting would have increased the elevation of the water table in western Kansas and eastern Colorado causing the Dakota and underlying aquifers to be more subnormally pressured. Removal of the water-saturated sediments above the Dakota aquifer in discharge areas would have lowered hydraulic heads in the outcropping Dakota aquifer of central Kansas and established a new water-table configuration. Meanwhile pore pressures in the underlying Permian strata may still have been adjusting to the pre-Ogallala water-table configuration in central Kansas and pore pressures in the deeper part of the flow system may have been adjusting to the pre-Miocene removal of Cretaceous sediments from central Kansas. At the present time, pore pressures in the Permian and older strata of central Kansas are probably adjusting to changes in the water-table configuration brought about by this latest (late Pliocene-Quaternary) cycle of erosion and still may be adjusting to the effects of late Cretaceous-early Tertiary erosion and tilting and Miocene-Pliocene deposition.

As a result of these erosional and depositional episodes, the present-day regional ground-water flow system is composed of modern and relict components in the cross-section from southwest to central Kansas. The modern portion of the system flows through the water-table aquifer and local flow systems where the Dakota aquifer strata crop out in central Kansas. The relict part of the system flows through the consolidated rock hydrostratigraphic units which have hydraulic conductivities much lower than the water-table aquifer. In the upper part of this more sluggish component of the regional flow system, the Dakota aquifer may be sufficiently permeable to dampen or short-circuit the downward propagation of pore-pressure transients into the Permian and deeper strata due to the close proximity of this aquifer to the water table. As a result the equilibration of pore pressures in the regional flow system may occur at very slow rates below the Dakota aquifer. Equally important, the

lateral drainage of ground water from the Dakota aquifer toward discharge areas allows subnormal pressures in this aquifer to continue and thus ensures the continued existence of the "ground-water divide" near the Dakota aquifer discharge area.

### Conclusions

The regional flow system in central and western Kansas can be subdivided into primary components that are not in equilibrium with each other: a shallow flow system in the unconsolidated Cenozoic deposits that is adjusted to the configuration of the modern water table and a deeper flow system in the consolidated strata only partially adjusted to the modern water table. The Dakota and the deeper carbonate aquifers function as drains for the Permian and Pennsylvanian strata in much of central Kansas. Where the Dakota aquifer is hydraulically connected to the overlying High Plains aquifer the predominant direction of flow is downward from the water table into the Permian and Pennsylvanian. Water movement in the Dakota aquifer is primarily along the bedding with a minor downward component. Northeast of this area near the Central Kansas uplift the Dakota is overlain by the Upper Cretaceous aquitard and recharge to the aquifer is limited. However the aquifer is recharged by upward movement of saltwater from the Permian in this area. The chemical quality of ground waters in the Dakota aquifer changes due to mixing of ambient ground waters in the upper part of the aquifer with higher dissolved solids concentration Na-Cl type waters from below. In the Dakota aquifer outcrop areas, saline waters are discharged by the aquifer to nearby surface waters.

The disequilibrium between the shallow and deeper flow systems can be explained as a delayed response in time to changes in the water-table configuration caused by Cenozoic episodes of deposition, erosion, and tilting in the western and central Kansas areas. The present distribution of hydraulic head in the cross-section is a composite of modern and relict ground-water flow systems due to the slow propagation of pore pressure changes in the deeper flow system. This has resulted from the low hydraulic conductivity ranges of the aquifer and aquitard units. More importantly, the presence of the more transmissive Dakota aquifer in the near-surface may allow this aquifer to act as a partial barrier dampening

Further research needs to be done to explore the effects of past geologic processes on the regional ground-water flow system in western Kansas.

#### REFERENCES CITED

- Belitz, K., and Bredehoeft, J.D., 1988, Hydrodynamics of the Denver basin: explanation of subnormal fluid pressures: American Association of Petroleum Geologists Bulletin, 72(11), pp. 1334-1359.
- Benz, L.C., Mickelson, R.H., Sandoval, F.M., and Carlson, C.W., 1961, Ground-water investigations in a saline area of the Red River valley, North Dakota: Journal of Geophysical Research, 66(8), pp. 2435-2443.
- Bradley, J.S., 1975, Abnormal formation pressure: American Association of Petroleum Geologists Bulletin, 59(6), pp. 957-973.
- Cobb, P.C., 1980, The distribution and mechanisms of salt water intrusion in the fresh water aquifer and in Rattlesnake Creek, Stafford County, Kansas: Unpub. MS, University of Kansas, Lawrence, 176 p.
- Dutton, A.R., and Simpkins, W.W., 1989, Isotopic evidence for paleohydrologic evolution of ground-water flow paths, southern Great Plains, United States: Geology, 17, pp. 653-656.
- England, L.A., and Freeze, R.A., 1988, Finite-element simulation of long-term transient regional ground-water flow: Ground Water, 26(3), pp. 298-308.
- Fenneman, N.M. 1946, Physical subdivisions of the United States [map]: U.S. Geological Survey, 1:7,000,000, 1 sheet.
- Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Prentice Hall Inc., Englewood Cliffs, New Jersey, 604 p.
- Franks, P.C., 1979, Record of Early Cretaceous marine transgression - Longford Member, Kiowa Formation: Kansas Geological Survey Bulletin 219, 55 p.

Frye, J.C., 1945, Valley erosion since Pliocene "Algal Limestone" deposition in central Kansas: Kansas Geological Survey Bulletin 60, part 3, pp. 85-100.

\_\_\_\_\_, 1970, The Ogallala Formation - a review: Proceedings of the Ogallala Aquifer Symposium, Texas Tech University, Lubbock, Texas, 242 p.

\_\_\_\_\_, and Leonard, A.B., 1952, Pleistocene geology of Kansas: Kansas Geological Survey Bulletin 99, 230 p.

\_\_\_\_\_, \_\_\_\_\_, and Swineford, A., 1956, Stratigraphy of the Ogallala Formation (Neogene) of northern Kansas: Kansas Geological Survey Bulletin 118, 92 p.

Gustavson, T.C., and Winkler, D.A., 1988, Depositional facies of the Miocene-Pliocene Ogallala Formation, northwestern Texas and eastern New Mexico: *Geology*, 16, pp. 203-206.

Hargadine, G.D., Balsters, R.G., and Luehring, J., 1979, Mineral intrusion in Kansas surface waters: Kansas Water Resources Board, 211 p.

Hamilton, V.J., and Cross, T.A., 1989, Sequence stratigraphy of lower Cretaceous strata in Kansas(abstract): Geological Society of America, Abstracts with Programs, 21(6), p. A337.

Hatheway, L.R., and Magnuson, L.M., 1985, Atlas of chemical quality data for irrigation waters of western Kansas: Kansas Geological Survey Chemical Quality Series 11, 5 sheets.

Hattin, D.E., and Siemers, C.T., 1987, Guidebook Upper Cretaceous stratigraphy and depositional environments of western Kansas (with modifications): Kansas Geological Survey Guidebook Series 3, 55 p.

Hay, R., 1890, Notes on some Kansas salt marshes: Transactions of the Twenty-Second Meeting of the Kansas Academy of Science, 1889, volume 12, part 1, pp. 97-100.

\_\_\_\_\_, 1891, Geology of Kansas salt: Seventh Biennial Report of the Kansas Board of Agriculture, pp. 83-92.

- Helgeson, J.O., Leonard, R.B., and Wolf, R.J., in press, Aquifer systems underlying Kansas, Nebraska, and parts of Arkansas, Colorado, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming--hydrology of the Great Plains aquifer system in Nebraska, Colorado, Kansas, and adjacent areas: U.S. Geological Survey Professional Paper 1414-E, 161 p.
- Holdoway, K., 1978, Deposition of evaporites and red beds of the Nippewalla Group, Permian, western Kansas: Kansas Geological Survey, Bulletin 215, 43 p.
- Jordan, P.R., Jones, B.F., and Petri, L.R., 1964, Chemical quality of surface waters and sedimentation in the Saline River basin, Kansas: U.S. Geological Survey Water Supply Paper 1651, 90 p.
- Kirkham, R.M., and Ladwig, L.R., 1980, Energy resources of the Denver and Cheyenne basins, Colorado: Colorado Geological Survey Environmental Geology 12, 258 p.
- Kreitler, C.W., Fisher, R.S., Senger, R.K., Hovorka, S.D., and Dutton, A.R., 1985, Hydrology of an evaporite aquitard: Proceedings of the 17th International Congress of International Association of Hydrogeologists on the Hydrogeology of Rocks of Low Permeability, Tuscon, Arizona, 17(1), pp. 150-168.
- Krothe, N.C., and Oliver, J.W., 1982, Sulfur isotopic composition and water chemistry from the High Plains aquifer, Oklahoma panhandle and southwestern Kansas: U.S. Geological Survey Water Resources Investigations 82-12, 28 p.
- Kume, J., and Spinazola, J.M., 1985, Geohydrology of sandstone aquifers in southwestern Kansas: Kansas Geological Survey Irrigation Series 8, 49 p.
- Larson, T.G., 1971, Hydrodynamic interpretation of the Mid-Continent, in I.H. Cram, ed, Future petroleum provinces of the United States - their geology and potential: American Association of Petroleum Geologists Memoir 15, pp. 1043-1046.
- Macfarlane, P.A., Whittemore, D.O., Townsend, M.A., Doveton, J. and Staton, M., 1988, Hydrogeology and water chemistry of the Great Plains (Dakota, Kiowa, and Cheyenne) and Cedar Hills aquifers in central

Kansas - end of contract report: Kansas Geological Survey Open-File Report 88-39.

Merriam, D.F., 1963, The geologic history of Kansas: Kansas Geological Survey Bulletin 162, 317 p.

\_\_\_\_\_, and Frye, J.C., 1954, Additional studies of the Cenozoic of western Kansas: Kansas Geological Survey Bulletin 109, part 4, pp. 49-64.

Orr, E.D., and Kreitler, C.W., 1985, Interpretation of pressure-depth data from confined underpressured aquifers exemplified by the Deep-Basin Brine aquifer, Palo Duro basin, Texas: Water Resources Research, 21(4), pp. 533-544.

Pollastro, R.M., and Scholle, P.A., 1986, Exploration and development of hydrocarbons from low-permeability chalks - an example from the upper Cretaceous Niobrara Formation, Rocky Mountain Region: *in* Spencer C.W., and Mast, R.F., (eds), Geology of Tight Gas Reservoirs, American Association of Petroleum Geologists Studies in Geology #24, pp. 129-141.

Rice, D.D., 1984, Occurrence of indigenous biogenic gas in organic-rich, immature chalks of Late Cretaceous age, eastern Denver basin: *in* Palacas, J.G., (ed), Petroleum Geochemistry and Source Rock Potential of Carbonate Rocks, American Association of Petroleum Geologists Studies in Geology #16, pp. 135-150.

Senger, R.K., Kreitler, C.W., and Fogg, G.E., 1987, Regional underpressuring in Deep Basin aquifers, Palo Duro basin, Texas - 2. the effect of Cenozoic basin development: Water Resources Research, 23(8), pp. 1494-1504.

Smith, H.T.U., 1940, Geologic studies in southwestern Kansas: Kansas Geological Survey Bulletin 34, 212 p.

Stout, T.M., DeGraw, H.M., Tanner, L.G., Stanley, K.O., Wayne, W.J., and Swinehart, J.B., 1971, Guidebook to the late Pliocene and early Pleistocene of Nebraska: Conservation and Survey Division, Nebraska Geological Survey, 109 p.

Stullken, L.E, and Pabst, M.E., 1982, Altitude and configuration of the water table in the High Plains aquifer of Kansas, pre-1950 [map] : U.S. Geological Survey Open-File Report 82-117, 1 sheet.

\_\_\_\_\_, Watts, K.R., and Lindgren, R.J., 1985, Geohydrology of the High Plains aquifer, western Kansas: U.S. Geological Survey Water-Resources Investigations Report 85-4198, 86 p.

Toth, J., 1972, Properties and manifestations of regional ground water movement: Proceedings of the 24th International Geological Congress, Montreal, Section 11, pp. 153-163.

\_\_\_\_\_, 1984, The role of regional gravity flow in the chemical and thermal evolution of ground water: Proceedings of the First Canadian/American Conference on Hydrogeology - Practical Applications of Ground Water Geochemistry, Banff, Alberta, Canada, National Water Well Association, Dublin, Ohio, pp. 3-39.

\_\_\_\_\_, and Millar, R.F., 1983, Possible effects of erosional changes of the topographic relief on pore pressures at depth: Water Resources Research, 19(6), pp. 1585-1597.

Sampson, R.J., SURFACE III: Interactive Concepts Incorporated, 277 p.

Swineford, A., 1955, Petrography of upper Permian rocks in south-central Kansas: Kansas Geological Survey Bulletin 111, 179 p.

Walters, R.F., 1977, Land subsidence in central Kansas related to salt dissolution: Kansas Geological Survey Bulletin 214, 82 p.

Whittemore, D.O., 1978, Factors controlling variations in river quality in Kansas: Kansas Water Resources Research Institute Contribution 197, 46 p.

Zeller, D.E. (ed), 1968, The stratigraphic succession in Kansas: Kansas Geological Survey Bulletin 189, 81 p.