KANSAS GEOLOGICAL SURVEY
OPEN-FILE REPORT 88-39

HYDROGEOLOGY AND WATER CHEMISTRY OF THE GREAT PLAINS (DAKOTA, KIOWA, AND CHEYENNE) AND CEDAR HILLS AQUIFERS IN CENTRAL KANSAS
End of Contract Report

Submitted to the
Kansas Corporation Commission

by

P.A. Macfarlane
M.A. Townsend
D.O. Whittemore
J. Doveton
M. Staton

Kansas Geological Survey
1930 Constant Avenue
University of Kansas
Lawrence, KS 66047-3726

HYDROGEOLOGY AND WATER CHEMISTRY OF THE GREAT PLAINS (DAKOTA, KIOWA, AND CHEYENNE) AND CEDAR HILLS AQUIFERS IN CENTRAL KANSAS

END OF CONTRACT REPORT

Submitted to the

Kansas Corporation Commission

by

P.A. Macfarlane, M.A. Townsend, D.O. Whittemore,
J. Doveton and M. Staton

Kansas Geological Survey
University of Kansas
Lawrence, Kansas

December, 1988

Kansas Geological Survey
Open-file Report 88-39

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Shallow underground disposal of oil-field brines in the Cedar Hills has prompted concern related to induced upward migration of the brines into freshwater zones of the Great Plains aquifer in central Kansas. Within this area, 460 wells are actively being used to dispose of oil-field brines into the Cedar Hills aquifer at an average rate of 550 bbls. per day per well. In order to evaluate the potential for upward migration of these brines, the Kansas Geological Survey conducted a subregional hydrogeologic investigation of the Great Plains and Cedar Hills aquifers to assess the geologic and hydrologic factors affecting containment of the disposed and naturally-occurring brines. Sandstones, shales and mudstones of the Dakota Formation, Kiowa Formation, and Cheyenne Sandstone comprise the framework of the Great Plains aquifer. Sandstone, siltstone, and shale of the Cedar Hills Formation comprise the framework of the Cedar Hills aquifer. In the eastern half of the area, the Cedar Hills aquifer directly underlies the Great Plains aquifer, but in the western part relatively impermeable Jurassic and Permian strata separate these two aquifer systems. Ground-water flow in the Great Plains aquifer is generally from the deeper part of the Western Kansas basin and southern outcrop areas towards the Smoky Hill and Saline Rivers.

Ground-water flow in the Cedar Hills aquifer is subparallel to the flow in the Great Plains aquifer where they are in contact. Elsewhere in the western part of the area the configuration of the Cedar Hills potentiometric surface has been affected by fluid injection. Total dissolved solids concentrations of ground waters in the Cedar Hills and lower Great Plains aquifers are generally greater than 20,000 mg/l and decrease vertically upward into the upper part of the Great Plains aquifer. Throughout the central Kansas area, the hydrologic data from the monitoring sites indicates vertically upward movement of fluids from the Cedar Hills and into the Great Plains aquifer. This is supported by the similarity of general water chemistry, Br/Cl versus Cl mixing curves, and the stable isotope data between aquifers. Hydrologic testing suggest that upward movement of brines may be facilitated locally by fractures. These results indicate that shallow underground disposal of oil-field brines should be discontinued in the area of interconnection between the Cedar Hills and Great Plains aquifers.

1.0 INTRODUCTION

1.1 Purpose of This Report

The Great Plains aquifer system is a vast, largely untapped resource that underlies much of western Kansas. The framework of this aquifer system consists of the Dakota Formation, The Kiowa Formation and Cheyenne Sandstone. Little is known of the hydrogeology and water quality of this aquifer system in Kansas, especially the relationship of the Great Plains aquifer system to other interconnecting aquifers. Recently, the Kansas Corporation Commission has become concerned that disposal of oil-field brines into the Cedar Hills Sandstone may be inducing upward migration of saline waters and disposed oil-field brines into usable shallow aquifers containing fresh and usable waters. This injection horizon occurs just below the Great Plains aquifer system in much of the area.

To address these concerns, the Kansas Geological Survey initiated a study of the Great Plains and Cedar Hills aquifer systems in an eight county area of central Kansas. This investigation was conducted to determine the hydrogeology and water quality of these aquifers and to identify areas of upward migration of naturally occurring and oil-field brines from the Cedar Hills Sandstone into the shallower freshwater aquifers. In order to accomplish these objectives:

(1) the results of previous geologic and hydrogeologic investigations of the Great Plains and Cedar Hills aquifers were collected and analyzed to obtain stratigraphic, hydrogeologic and hydrochemical information;

(2) maps were prepared to show the top configuration and thickness of geologic units in the study area based on the examination of geophysical well logs, well cuttings and outcrops;

(3) several multiple completion monitoring wells were constructed to obtain water chemistry and hydrologic information vertically across the Great Plains and Cedar Hills aquifers; and

(4) water level data and water samples were collected from wells, springs, and surface waters to define the present-day water flow and determine the origin of chemical constituents of waters in the Great Plains and Cedar Hills aquifers in the study area.

This report is a summary of the results of that investigation and presents some preliminary conclusions concerning the hydrogeology and water chemistry of these very complex aquifers in the eight county area. The conclusions drawn from this investigation should be considered preliminary. Several unanswered questions remain to be explored. These are listed under Future Research Needs (11.0). It is important to note that many of these questions are fundamental to our understanding of the movement of waters in these rocks and bear significantly on questions of water quality and interconnection between the Cedar Hills and Great Plains aquifers.

1.2 Geographic Extent of the Study Area

The study area is located in the Smoky Hills and the High Plains physiographic provinces in central Kansas and covers all or parts of Russell, Ellis, Barton, Rush, Rooks, Osborne, Graham, and Trego counties (Figure 1). Included within the study area are portions of the Smoky Hill, Saline, Solomon, Wet Walnut, and Arkansas River drainage basins. The largest population centers in the study area are Hays and Russell located in Ellis and Russell counties, respectively.

1.3 Acknowledgements

The authors wish to express their appreciation to the following agencies and individuals who helped to make this report possible. Our appreciation is given to the Kansas Corporation Commission, especially the District 6 office in Hays, and the Interagency Dakota Technical Committee who provided us with guidance and data. Appreciation is also given to Bill Bryson and Don Butcher who helped us over rough spots in the work and provided much-needed moral support. Within KGS many individuals contributed their expertise and talent to the collection of data in the field and laboratory, and the assembly of this document. The authors wish to acknowledge Larry Hathaway, Karmie Galle, and Bud Waugh of the Analytical Services Section, Joe Anderson of Exploration Services, Renate Hensiek of Graphic Arts and Anna Corcoran of the Geohydrology Section. Finally, a debt of gratitude is owed our administration who helped smooth some of the bureaucratic wrinkles that developed between agencies and kept the project afloat.

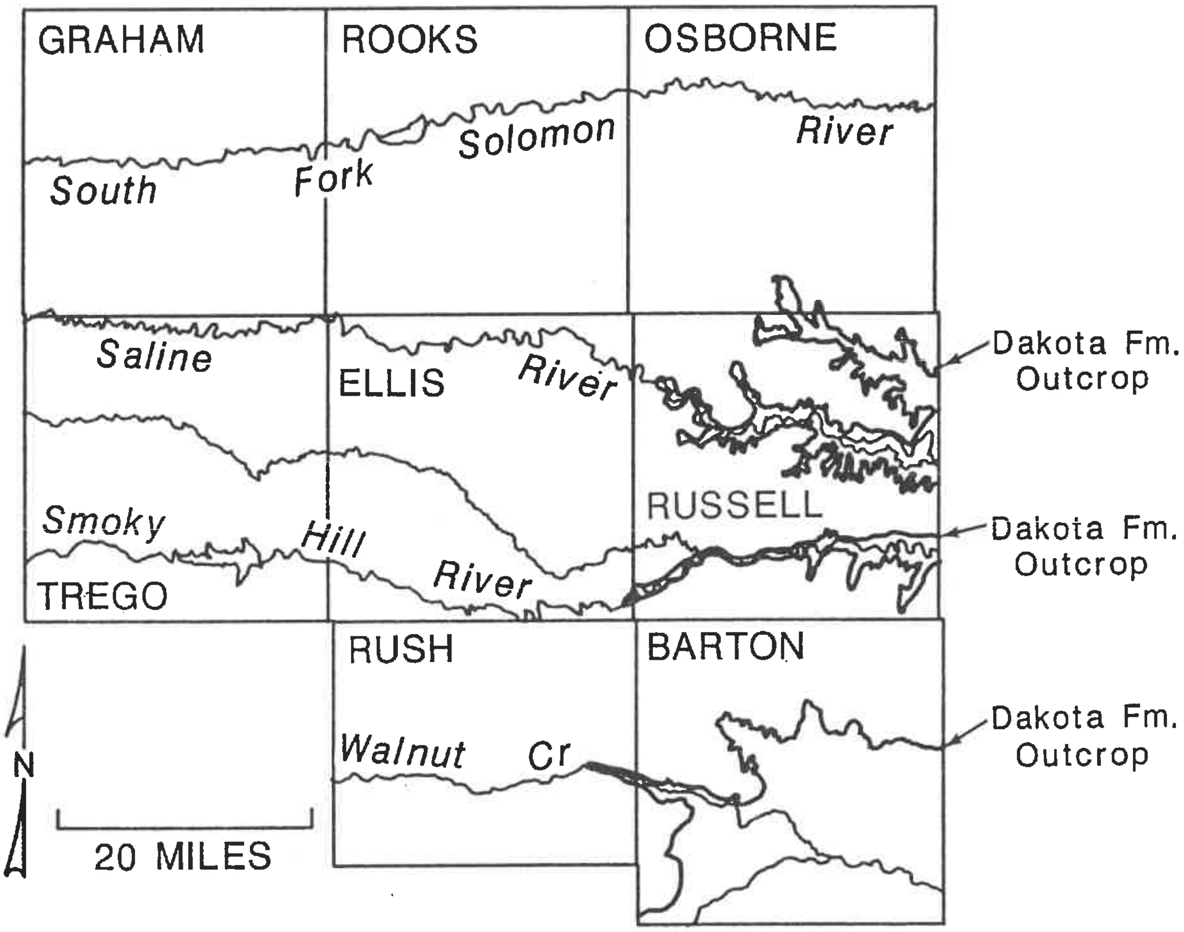


Figure 1. Location and extent of the study area.

2.0 SUMMARY OF PREVIOUS RESEARCH ON THE GREAT PLAINS AND CEDAR HILLS AQUIFERS IN THE STUDY AREA

2.1 Geologic Investigations Focusing on Stratigraphy and Depositional Environments

Studies focusing on the stratigraphy and depositional environments of the Lower Cretaceous Series have been conducted along the outcrop and in the subsurface of Kansas, Nebraska, and Colorado since the late 1800's. Only the most recent of these investigations will be mentioned here in this short review. Excellent summaries of the nomenclatural history of the Lower Cretaceous in Kansas are given by Latta (1946), Merriam (1963), and Franks (1966).

Since the Dakota Group was defined by Meek and Hayden (1861) the name has been applied somewhat indiscriminantly to various sedimentary sequences composed of Lower Cretaceous sandstones and shales that may not all be time equivalent. Most of these early works have largely dealt with rocks exposed at the surface. The Cheyenne and Kiowa have been recognized as formations since they were defined by Cragin in 1889 and 1894, respectively (Latta, 1946). The Dakota has been officially recognized as a formation by the Kansas Geological Survey since 1942 when the term was restricted to cover the sequence between the base of the Graneros Shale and the top of the Kiowa Formation. Plummer and Romary (1942) subdivided the Dakota Formation into two members, the Janssen Clay member above and the Terra Cotta Clay member below, based on field work along the outcrop in central Kansas.

With the discovery of oil and the need to dispose of the produced brines, interest shifted to the subsurface. A reconnaissance investigation by Frye and Brazil (1943) was conducted to determine the hydrogeology of the unconsolidated and bedrock aquifers in Ellis and Russell counties. They mapped what they believed to be the easternmost extent of the Cheyenne Sandstone in western Russell County. Later, Swineford and Williams (1945) conducted a geologic and hydrologic investigation of the Lower Cretaceous in the same area at the request of the State Board of Health. Concern was expressed that insufficient geologic criteria were being used to approve the shallow disposal of oil-field brines in the Cheyenne Sandstone. Swineford and Williams examined drill cuttings and the light and dark fractions of insoluble residues in an attempt to differentiate the Cheyenne Sandstone from adjacent formations. They found that differences in grain size and roundness of the sandstone grains and the composition of the insoluble residue suite could be used to locate formational boundaries. Moreover, they revised the earlier work of Frye and Brazil by concluding that the Cheyenne Sandstone extends farther east of western Russell County than the earlier investigation had indicated.

Much later, Merriam (1957) renamed the Dakota Formation the Omadi in an attempt to correlate the Kansas Lower Cretaceous rock section with the same section as defined farther north in Nebraska. He defined three members which are, from oldest to youngest, the Cruise, the Huntsman, and the Gurley. In this scheme, the Dakota was elevated to group status including, from oldest to youngest, the Cheyenne, the Kiowa, and the Omadi Formations. These formational names were applied to the subsurface by Merriam (1957; 1963) and used to show the stratigraphic relationships between the various Mesozoic-age rock units in the subsurface of western Kansas. This terminology has not been adopted by the Kansas Geological Survey.

Our present understanding of the stratigraphy and depositional environments in the Lower Cretaceous comes from fieldwork that was done along the central and southern Kansas outcrop in the decades of the 1960's, and 1970's. Franks (1966) mapped the Dakota and Kiowa Formations along the outcrop. Field mapping shows the contact between the Dakota and Kiowa Formations to be locally disconformable. In some cases, sharp contacts abruptly separate clay rocks of the Dakota

Formation from sandstones and clay rocks in the Kiowa and, in other instances, basal sandstones in the Dakota rest on interbedded sandstones and clay rocks in the Kiowa. Franks has interpreted the upper portion of the Kiowa to be part of a regressive sequence of interbedded shales and sandstones. The upward increase in grain size and increase in kaolinite in the Kiowa marks the onset of regressive conditions. At the base of the Dakota, the occurrence of conglomeratic sandstones and red-mottled clay rocks signifies the development of alluvial depositional systems. Previously, Twenhofel (1920, 1924) and Tester (1931) had concluded that the two formations were laterally and vertically conformable and gradational. This conclusion was based on the occurrence of Kiowa sandstones containing leaf fossils similar to those found in the Dakota strata. The concept of the intertonguing of the two units led to the development of a large scale deltaic model of sedimentation involving the two formations.

Using the results of Scott (1970), Franks (1975, 1980) proposed a transgressive-regressive model of sedimentation to account for the distribution of lithofacies seen in the Cheyenne, Kiowa, and Dakota sequence of formations in Kansas. The Cheyenne Sandstone and Kiowa Formation record a northeastward transgression of the sea across Kansas.

Sedimentation was governed by the type and rate of sediment supplied to the interior seaway and the rate of subsidence during early Kiowa time. These rocks were deposited in and near the eastern margins of the Early Cretaceous epicontinental sea that spread over the southern Western Interior.

Franks' (1975, 1980) interpretation of the geologic framework shows a progressive overlapping of older Lower Cretaceous stratigraphic units on the Cretaceous-Permian boundary from southwest to northeast across the Kansas outcrop. Accordingly, the Cheyenne Sandstone is present only in southern Kansas and does not extend in the subsurface very far northward of the outcrop. This contradicts the earlier work of Frye and Brazil (1943) and Swineford and Williams (1945) in the Ellis-Russell County area and Merriam (1957). These authors show that the Cheyenne Sandstone is present in much of the subsurface of western Kansas. However, Franks (1975, 1979 and 1980) believes that the lower part of the Kiowa Formation, the so-called "Longford member," resembles and has been confused with the Cheyenne Sandstone. These rock units are not time equivalent even though they are similar in aspect (Scott, 1970). Farther north the Kiowa Formation rests directly on the Cretaceous-Permian boundary. Near the Nebraska-Kansas border, in the north central part of the state, the Kiowa is not present and the Dakota rests directly on the Lower Permian.

Farther up the stratigraphic column in the upper part of the Dakota Formation, clay rocks of the Janssen member contain lenticular channel sandstones of the Rocktown Channel sandstone in north-central Kansas (Rubey and Bass, 1925). These rocks are interpreted as having been deposited in a deltaic complex under the influence of a transgressing Graneros sea (Hattin, 1965; Franks, 1965, 1975; Siemers, 1971, 1976). The Rocktown Channel sandstone body has been divided by Siemers into two major subfacies, grading within approximately 30 miles from a highly sinuous distributary channel sandstone into estuarine and delta-front sandstones. A lower cross-bedded sandstone subfacies is 54 to 66 feet thick and 900 to 1800 feet wide and is more less confined to a sinuous, elongated v-shaped trough whereas the upper flat-bedded subfacies forms a tabular-shaped unit. These rocks reflect an increasingly marine character in the style of sedimentation in the upper part of the Dakota westward of the outcrop as the Dakota intertongues with the Graneros Shale in northwest Kansas (Hattin and Siemers, 1987).

2.2 Review of Previous Hydrogeologic Investigations of the Great Plains and Cedar Hills Aquifers in the Study Area

Hydrogeologic investigations of the Great Plains aquifer have concentrated on locating potential surface and ground-water supplies for municipal, domestic and stock uses and on the effects of oil-industry activities on water quality. These include Frye and Brazil (1943), Swineford and Williams (1945), Leonard and Berry (1961), and county reports by Latta (1950), Hodson (1965), and McNellis (1973).

One of the earliest of these studies was conducted by Frye and Brazil (1943) in the oil-field areas of Ellis and Russell Counties. Their objective was to evaluate the resource potential of surface and ground waters and to assess the effects of oil-field activities on water quality. During the course of the study, several test holes were drilled into the Dakota and Kiowa Formations and the Cheyenne Sandstone in Russell and Ellis County. As the drilling of each test hole progressed, water samples and hydraulic head measurements were taken. The unpublished data from the test-hole drilling program shows that the vertical direction of ground-water flow is upward from the deeper aquifers in the Lower Cretaceous to shallow aquifers. The authors note that the chemical quality of ground waters in the Dakota is highly variable laterally and vertically. A water sample collected from a deeper zone in the Lower Cretaceous in one of the test holes was analyzed and contained 22,900 mg/l chloride. However, a water sample taken from a nearby well in the Dakota contained a chloride concentration of only 23 mg/l. Additionally, water level measurements were taken in wells obtaining water from the Dakota and a map was prepared to show the potentiometric surface of the upper part of the Dakota in T14-15S between R12-15W. The map clearly shows that ground waters from the upper part of the Dakota discharge to the Smoky Hill River in Russell County. As a part of their investigation, Frye and Brazil looked into the brine-disposal practices of the oil industry in Russell and Ellis Counties. They found that oil-field brines were being disposed in evaporation pits, shallow disposal wells drilled into the sandstones of Lower Cretaceous age (including the lower part of the Dakota Formation), and deep disposal wells drilled into porous rocks of Pennsylvanian age or older. They concluded that disposal of oil-field brines could be done safely in the Cheyenne Sandstone since sandstones in the Cheyenne constituted a stratigraphic trap. In contrast, sandstones in the Dakota were found not to be suitable because brines injected into the lower portions of the Dakota Formation would migrate upwards into the fresh water zones through interconnecting sandstone lenses.

Somewhat later, Swineford and Williams (1945) investigated the vertical variation of water quality in the Lower Cretaceous and Lower Permian in western Russell County, where Frye and Brazil (1943) had conducted their earlier investigation. During the drilling of test holes through the Lower Cretaceous and Lower Permian rocks, they collected water samples in order to determine the vertical variation of water quality in each borehole. They found a progressive increase in total dissolved solids (TDS) and chloride content with depth. Ground waters in the upper part of the Dakota were found to contain less than 9000 ppm TDS. In contrast, the TDS content of ground waters from the lower part of the Dakota Formation ranged from 9,000 to 61,000 mg/l. In the lower units the concentration of TDS in ground waters from the Kiowa and Cheyenne ranged from 33,000 to 62,000 mg/l and from 31,000 to 71,000 mg/l in the Permian red beds (Cedar Hills Sandstone). Figure 2 shows schematically the variation of TDS with depth considering all of the samples collected.

Most importantly, the authors were able to delineate hydrochemical zones in these aquifer units based on an interpretation of the water chemistry. They found that all of the water samples from the upper half and some from the lower half of the Dakota were distinctly different in

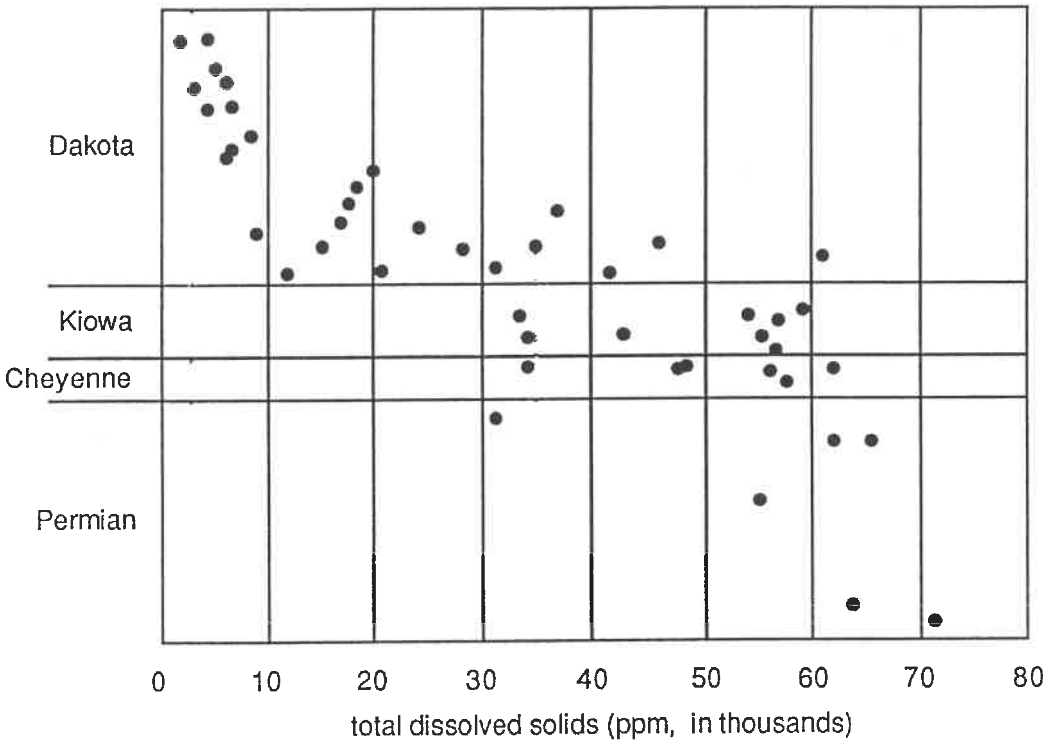


Figure 2. Composite water quality profile of the Lower Cretaceous and Permian bedrock aquifers in Russell County, generalized from test drilling. Adapted from Swineford and Williams (1945).

constituent composition from those samples that came from the Kiowa, Cheyenne, and Cedar Hills. The authors interpret this variation in water chemistry to be the result of the mixing of sodium chloride brines from the lower units with formation waters in the lower half of the Dakota Formation. This is discussed further in section 6.2.3.

Noting the differences in water chemistry of the Lower Dakota between the oil-field areas and those areas on the edge of or away from the oil fields, Swineford and Williams also concluded that ground waters from the lower part of the Dakota have been affected by disposal of oil-field brines. They speculated that this could have occurred as a direct result of induced migration upwards from lower injection horizons in the Cheyenne and Cedar Hills Sandstones caused by the "pressuring up" of injection horizons or through unplugged or improperly plugged boreholes in the oil-field areas.

Later work by Latta (1948), Jordan et al. (1964), and Hargadine et al. (1979) found that mineralized waters from the Dakota Formation eventually discharge into the alluvial aquifers and surface waters of the Smoky Hill, Saline, and Solomon Rivers in north-central Kansas.

Concern for the protection of ground waters in the Dakota from contamination by oil-related activities and the lack of information about water quality in the Lower Cretaceous rocks (Great Plains aquifer system) has prompted several reconnaissance-level surveys using log analysis techniques to derive the salinity of ground water in northwest Kansas. Early work by the Kansas Geological Survey produced relative salinity maps of the upper and lower sandstones in the Cheyenne Sandstone (Anonymous, 1960). Relative salinity of the waters was calculated from a combination of SP, and long and short normal resistivity logs. The relative salinity was calculated because water samples from the Cheyenne Sandstone were not available to calibrate the calculated results. The results of this reconnaissance-level effort show considerable variability in ground-water salinity laterally and vertically in northwest Kansas. However, the author could not attribute the cause of this variation. Much later, Malone (circa 1984-85) produced a similar map showing the salinity of ground waters in the Dakota of northwest Kansas for Murfin Drilling Company, Wichita, Kansas. The map shows relatively fresh waters in the Dakota for Logan, Graham, Sheridan and parts of Decatur, Trego, and Norton counties. Waters in the Dakota are relatively saline in Cheyenne, Rawlins, Sherman, Thomas, and Wallace counties.

Several county and subregional reconnaissance studies that have dealt in part with the Great Plains aquifer system in the study area have also been completed. These include reports on southeastern Trego, southern Ellis, and northern Rush counties in the Smoky Hill valley (Leonard and Berry, 1961), Rush County (McNellis, 1973), and Trego County (Hodson, 1965). Within these areas the authors report widespread use of aquifers in the Dakota Formation for domestic and stock uses where other supplies are not available.

Perhaps the most important regional study of the Great Plains aquifer system has been conducted recently under the U.S. Geological Survey's CM RASA Program (Helgeson et al. in review). Using existing data, their study puts the hydrogeology and water quality of the Great Plains aquifer system in a regional perspective that covers parts of Kansas, Nebraska, Wyoming, Colorado, New Mexico, and Oklahoma. In an evaluation of the Lower Cretaceous bedrock aquifer system, they note that variation in the water chemistry of the Great Plains aquifer appears to be related largely to the degree that the aquifer has been flushed of formation waters. Calcium-bicarbonate and mixed cation-mixed anion type waters are found near the outcrop areas. Sodium-chloride type waters are contained in the aquifer either where these rocks are more deeply buried and have not been flushed by recharge waters, or where they are being recharged by saline waters from the underlying Permian.

3.0 METHODS OF STUDY

3.1 Geologic Framework of the Study Area

The initial stages of the investigation were devoted to characterizing the subsurface geology of the study area. This phase of the project involved reviewing the data from previous studies of the Lower Cretaceous, and Lower and Upper Permian age units where these units outcrop in central and southern Kansas. Considerable time was spent collecting geophysical well logs in the study area and interviewing the Staff at the District 6 Office, Kansas Corporation Commission, in Hays.

The geophysical logs on file at the District 6 Office along with geophysical and sample logs collected from KGS and USGS were used to develop a geologic data base. Formation tops were picked by correlation with logs of nearby drill holes used by Swineford and Williams (1945) in western Russell County. In areas away from established points of correlation, samples of drill cuttings from the KGS Wichita Well Sample Library were used to guide correlation of well logs.

Maps were prepared from this geologic database to show the configuration of the top of the Dakota Formation and the Cedar Hills Sandstone and the thickness of the Kiowa Formation-Cheyenne Sandstone, the Cedar Hills Sandstone, and the interval between the top of the Cedar Hills and the base of the Lower Cretaceous. The map showing the thickness of the rocks between the top of the Cedar Hills Sandstone and the base of the Lower Cretaceous was prepared to show where the Cedar Hills Sandstone is separated from the Cheyenne Sandstone. This pertains to the upward migration of salt water into the Lower Cretaceous from the Cedar Hills Sandstone.

3.2 Hydrologic and Water Quality Investigations

Later during the project, the emphasis shifted to the construction and installation of several multiple-completion monitoring wells in the study area. Well sites near Hill City in Graham County, and Gorham in Russell County, were selected due to the availability of about-to-be abandoned boreholes. One additional well site was located in Ellis County, north of the city of Hays (Hays North).

At the Hays North location, a borehole was drilled and cased in order to construct a multiple-completion monitoring well. The borehole at Hays North was drilled by Rosencrantz-Bemis Drilling Company, Great Bend, in February, 1987. During the drilling, samples of the drill cuttings were collected and logged by KGS personnel. At the completion of drilling operations, the hole was geophyscially logged by Schlumberger, Great Bend, Kansas.

The wells at Hill City and Gorham were cased with 5-1/2 in. OD steel pipe and at the Hays North site with 8-5/8 in. OD steel pipe. Two piezometers were constructed and positioned in the Hill City borehole (upper and lower Dakota); three at Gorham (upper Dakota, Cheyenne, and Cedar Hills); and four at Hays North (upper and lower Dakota, Cheyenne, and Cedar Hills). At the completion of construction, the piezometers were developed either by hand bailing or using an air compressor to remove the water contained in the piezometer. Since then, the piezometers have been used to monitor water levels and collect water samples for chemical analysis.

Additional monitoring of fluid levels was also carried out at an unused Cedar Hills disposal well, the Kramer "D" #1 SWD, located in SE, SE, SE sec. 7, T14S, R19W, Ellis County during January, 1987. Static fluid levels were recorded hourly using a pressure transducer connected to an SE-1000A Hydrologic Monitor. Simultaneously, atmospheric pressure changes were being monitored in Hays at the District 6 Office, KCC. Due to a malfunction in the pressure transducer, only 300 hours of the approximately 400 hours of monitoring provided usable water-level data.

This static monitoring has provided valuable information on the properties of the Cedar Hills aquifer in that part of Ellis County.

Additional data on shallow disposal practices also became available through KGS participation in the activities of the Cedar Hills Subcommittee of the Oil and Gas Advisory Council. This subcommittee was charged with assessing the suitability of continued use of shallow disposal of oil-field brines into the Permian-age Cedar Hills, Salt Plain, and Whitehorse Formations in south-central and southern Kansas, including Rush and Barton Counties. As a result of our work with the committee, we collected additional information on shallow disposal well operations and the hydrogeology of the Cedar Hills aquifer in south-central Kansas.

During the course of the investigation two areal surveys of wells in the Great Plains aquifer were conducted to collect water level data and water samples for chemical analysis by the KGS Analytical Services Section. Static (non-pumping) water levels were measured in domestic, stock, and municipal water wells during November, 1987, and January, 1988. The static water levels were converted to static water-level elevations and used to construct a map of the configuration of the potentiometric surface of the upper part of the Great Plains aquifer system (upper part of the Dakota). Additional data from previous studies were used to "fill in" and provide detail in areas where no data were gathered during our survey. Water samples were collected from domestic, stock, municipal, and oil-field water supply wells in the study area. At the time of collection, measurements were made of the temperature (degrees Centigrade), the specific conductance, and the pH of the water. The specific conductance and the pH measurements were later verified in the laboratory prior to analysis.

Two water samples, one acidified and one non-acidified, were collected from each sample site. The non-acidified 500 ml. sample was analyzed for the following constituents: Ca, Mg, Na, K, Sr, CO_3, HCO_3, SO_4, and Cl. The smaller 150 ml. acidified sample was analyzed for Fe, Mn, Ba, B, F and NO_3. The chemical analysis of these samples was performed by the Analytical Services Section, KGS. Concentrations of Br and I were determined in the non-acidified samples by D. Whittemore.

Samples for oxygen, deuterium, and sulfur isotopes were collected in 1 liter nalgene bottles. Extra bottles of sample were collected for sulfur analysis if the specific conductivity was less than approximately 3000 µmhos/cm. Samples were kept cold until sent for analysis by Geochron

Laboratories. One duplicate sample was sent with each set of samples for comparison purposes.

Oil-field brines were collected from wells that pumped from a single formation and did not have anti-flocculent chemical feeds connected to the system. Samples were collected in an 18 litre nalgene container with a spigot for decanting off the water portion of the sample. The sample sat for 15 to 30 minutes to facilitate preliminary separation of the oil/water mixture. Several gallons of water were collected and stored in coolers until return to the laboratory. The samples were filtered several times with coarse filter paper to remove excess oil, then a millipore filtration system was used to remove any remaining sediment from the sample before analyses were done.

The resulting data on the various constituent concentrations were plotted on maps along with data from USGS WATSTORE and the KCC to show the distribution of chloride and TDS. The Ca, Mg, Na, K, HCO_3, SO_4, Cl, and NO_3 concentrations were used to prepare Piper diagrams showing geochemical trends in water chemistry in the Great Plains aquifer. The source of salinity in the ground waters was determined using the mixing curve methods developed by Whittemore (1984, 1988). The isotope geochemistry of the ground waters was used to further determine the origin of constituents and waters in the aquifer system.

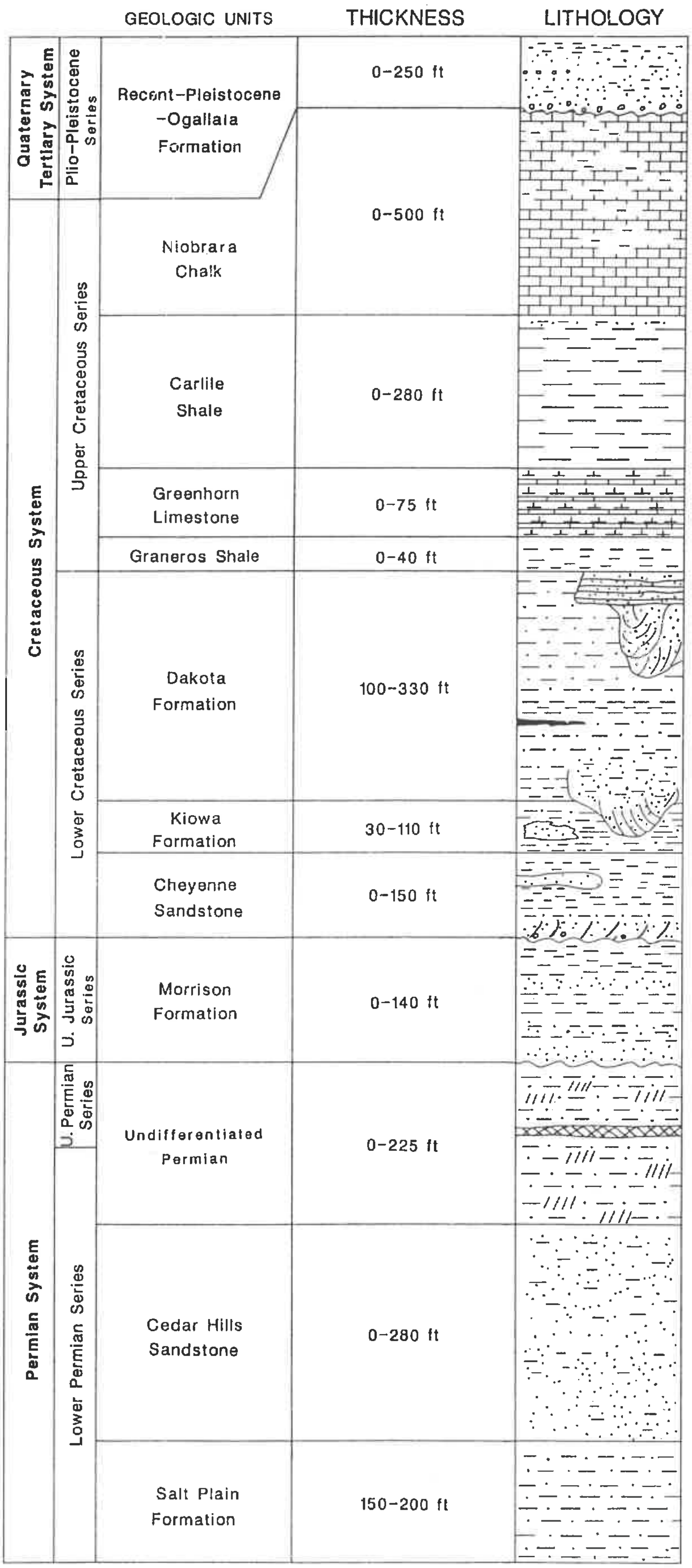
4.0 GEOLOGIC SETTING

4.1 Stratigraphy

4.1.1 Lithologic Description, Thickness, and Extent of the Formations

Described below are the geologic units that occur at the surface or in the shallow subsurface of the study area above the Harper Formation (Lower Permian). Figure 3 shows the time-stratigraphic and rock-stratigraphic classification of these rocks adapted from Zeller (1968) with the expected range in thickness and lithologies represented in graphic form. Maps showing the top and thickness of the Dakota Formation, thickness of strata belonging to the Kiowa Formation and Cheyenne Sandstone, extent and thickness of strata from the base of the Cretaceous to the top of the Lower Permian Cedar Hills Sandstone, and the extent and thickness of Cedar Hills Sandstone are included in this report as Figures 4-7, 14 and 15.

Recent-Pleistocene-Ogallala Formation: Sedimentary deposits of Recent and Pleistocene age consist of unconsolidated gravels, sands, silts, and clays. These materials make up the alluvium and older terrace deposits found in the stream valleys of the study area. Terrace deposits



		GEOLOGIC UNITS	THICKNESS	LITHOLOGY
Quaternary Tertiary System	Plio-Pleistocene Series	Recent-Pleistocene -Ogallala Formation	0-250 ft	
Cretaceous System	Upper Cretaceous Series	Niobrara Chalk	0-500 ft	
		Carlile Shale	0-280 ft	
		Greenhorn Limestone	0-75 ft	
		Graneros Shale	0-40 ft	
	Lower Cretaceous Series	Dakota Formation	100-330 ft	
		Kiowa Formation	30-110 ft	
		Cheyenne Sandstone	0-150 ft	
Jurassic System	U. Jurassic Series	Morrison Formation	0-140 ft	
Permian System	U. Permian Series Lower Permian Series	Undifferentiated Permian	0-225 ft	
		Cedar Hills Sandstone	0-280 ft	
		Salt Plain Formation	150-200 ft	

Figure 3. Stratigraphic column of the near-surface rock units in the study area.

composed of Pleistocene-age materials are well-developed in the Smoky Hill, Saline, and Solomon River valleys (Frye and Leonard, 1952). Loess mantles many of the stream divides in the study area. Much of the land surface of Graham, northern Trego, and northern Ellis Counties is mantled by the eroded remnants of the Ogallala Formation. In western Graham County the Ogallala is as much 250 feet thick. At the Hays North monitoring site, which is located on an upland, approximately 35 feet of residual Ogallala Formation is present.

Niobrara Chalk: This formation crops out in a northwesterly trending belt and underlies the northwest one-half of the study area. The Niobrara Chalk consists of an upper member, the Smoky Hill Chalk, and a lower member, the Fort Hays Limestone. Interbedded shale, thin seams of bentonite, shaley chalk, and chalk comprise the Smoky Hill Chalk Member. The thickness of this member ranges up to a maximum of 440 feet in Graham County. The Fort Hays Limestone Member consists of massive chalk beds separated by thin beds of chalky shale. The thickness of the Fort Hays, where it has not been eroded, is fairly uniform and ranges from 55 to 65 feet.

Carlile Shale: The Carlile Shale consists of the Codell Sandstone Member, the Blue Hill Shale Member, and the Fairport Chalk Members. This formation is exposed throughout much of the study area in eroded slopes, stream valleys, and canyons cut through the Fort Hays Limestone Member and east of the Fort Hays escarpment. Where the unit has not been partially eroded, the thickness of Carlile Shale ranges from 260 to 280 feet. The Codell Sandstone consists of heavily bioturbated and reworked sandy siltstone and very fine-grained calcareous sandstone. Along the outcrop, the Codell is locally not present. However, gamma-ray logs of the interval show that the Codell is usually well-developed in the subsurface. The top of the Codell is separated from the overlying Niobrara Chalk by a non-depositional or erosional surface of little local relief. The base of the Codell is gradational with the underlying Blue Hill Shale Member. Thickness of the Codell ranges up to five feet within the study area. The Blue Hill Shale Member consists of dark gray shale, silty near the top, with numerous zones of calcareous concretions. The Blue Hill Shale Member grades downward into the Fairport Chalk Member. The Fairport consists of beds of chalky to marly shale interbedded with chalky limestone and marlstone in the middle and upper parts of the section and chalky limestone in the lower part. This unit grades downward into the underlying Greenhorn Limestone.

Greenhorn Limestone: This formation is composed of thin-bedded chalky limestone and calcareous shale. The Greenhorn Limestone is present at the surface in much of the southeastern part of the study area and has been subdivided into the Pfeifer Shale, Jetmore Chalk, Hartland Shale, and Lincoln Limestone Members. The thickness of the Greenhorn Formation in the subsurface is generally 70 to 75 feet. The contact separating the Greenhorn Limestone from the Graneros Shale is one of non-deposition and local erosion (Hattin, 1978).

Graneros Shale: The Graneros Shale consists mostly of fissile, non-calcareous, gray to dark gray shale. Thin beds of cross-laminated, fossiliferous, well-sorted sandstone are locally developed. Thin seams of bentonite are quite common throughout this formation. A particularly well-developed bentonite bed is found near the top of the Graneros and has been named the "X" bentonite by Hattin (1965). The thickness of this bentonite layer ranges up to approximately one foot locally. The "X" bentonite is present along much of the Graneros outcrop in central and southern Kansas and has been used as a stratigraphic marker by Siemers (1971, 1976).

Dakota Formation: The Dakota Formation consists of floodplain deposits of interbedded siltstone, claystone, thin-bedded sandstone and lignites; lenticular, (fluvial or distributary) channel sandstones; and delta front sandstones (Franks, 1975; Siemers, 1971). Plummer and Romary (1942) have divided the Dakota Formation into two members, the Jansen Clay Member (upper) and the Terra Cotta Clay Member (lower). The Janssen is dominated by gray to dark gray, kaolinitic clay rocks, interbedded lignite and sandstone. The Terra Cotta Clay Member is composed of kaolinitic clay rocks that are light gray to light greenish gray. In the subsurface of Kansas these members of the Dakota Formation have not been recognized (Franks, 1975). Both members contain well-developed lenticular channel sandstone bodies. Well-developed channel sandstones--the Rocktown Channel Sandstone (Rubey and Bass,1925)--and associated tabular, flat-bedded, delta front sandstones can be found near the top of the Dakota Formation in Russell County (Siemers, 1971, 1976). The Dakota Formation is present at the surface in much of Russell and Barton counties and portions of eastern Rush, southeastern Ellis, and southern Osborne counties and the formation is present in the subsurface west of the outcrop belt. Where uneroded, the thickness of this formation ranges from 200 to 310 feet across the study area (Figure 4). The Dakota appears to be thinnest in Russell and eastern Barton counties and thickest in the northern half of Trego and the southern half of Graham counties.

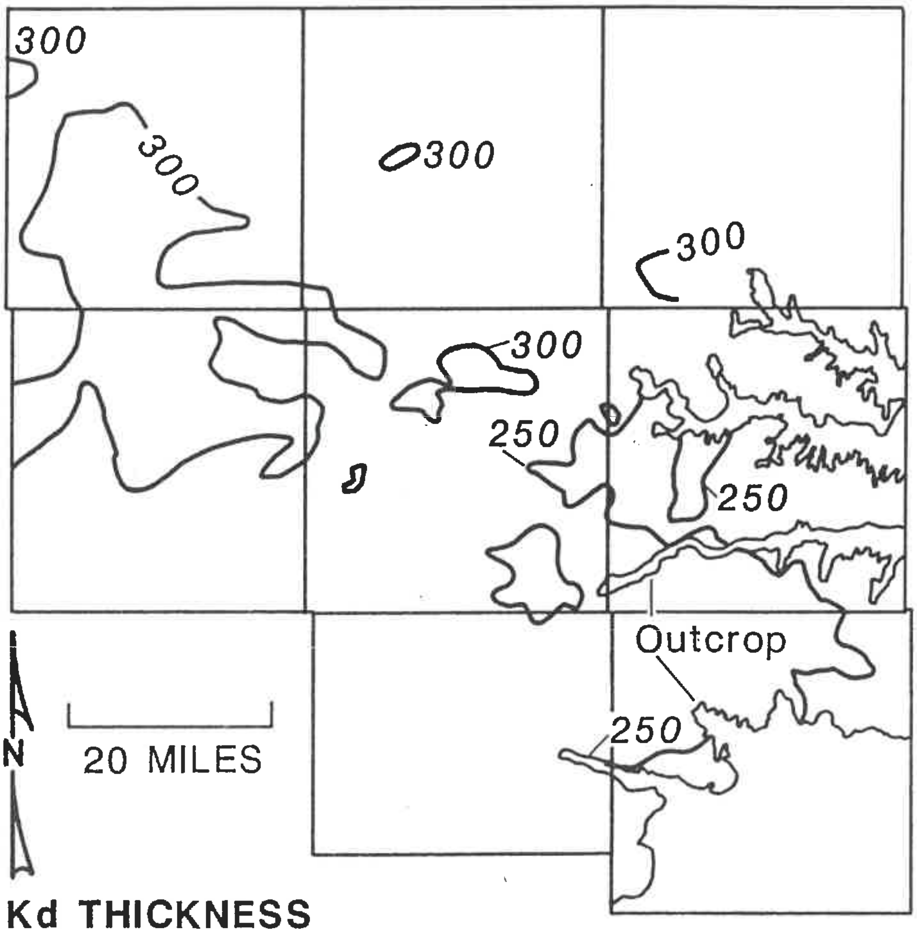


Figure 4. Thickness of the Dakota Formation in the study area.

The Dakota appears to rapidly thicken from less than 225 feet to more than 275 feet in eastern Ellis County. Over most of the study area, the thickness of the Dakota Formation ranges from 275 to 300 feet.

Kiowa Formation and Cheyenne Sandstone: The Kiowa Formation consists of largely of gray, clay shales and siltstones containing illite and smectite clays interbedded with thin, sheet-like and thick, lenticular sandstones (Franks, 1965, 1975). Most of the sandstone is very fine grained, well sorted, well rounded, and quartzose, and contains abundant flakes of muscovite. Farther east where the Kiowa is at the surface, Franks (1975) reports that the grain size of the clastics that comprise the thick lenticular sands ranges from medium to conglomeratic. Charcoal and beds of fossiliferous limestone are common in this unit. The Cheyenne Sandstone consists of brownish gray to light gray or white shales and siltstones interbedded with fine-grained sandstones and fine to coarse-grained conglomeratic sandstones. Typically, sandstones lower in the section, near the top of the Permian contain frosted, well-rounded, fine to medium-grained sand derived from the underlying Permian. Similarly, well-rounded, frosted grains are also found in the Kiowa where the unit directly overlies the Permian. The clays that make up the shales and siltstones tend to be kaolinitic and smectitic (Franks, 1975).

The Kiowa Formation and the Cheyenne Sandstone have been grouped together for the purposes of this report for two reasons. Firstly, Franks (1975, 1980) and Scott (1970) believe that the Cheyenne Sandstone has been miscorrelated with the lower part of the Kiowa Formation in the subsurface. They note that the lower part of the Kiowa, the "Longford member" of Franks (1965), is composed of many of the same lithologies that occur in the Cheyenne. However, these units are not time equivalent. The difficulty of distinguishing between the Kiowa and Cheyenne is also noted by Swineford and Williams (1945). They found that in Russell County a distinction between units could be made based only on the presence of micaceous, glauconitic sandstones and siltstones, marine shell fragments, or the presence of red ironstone and impure hematite. Secondly, an examination of well logs and cuttings suggests that these rocks appear to have the same porous media properties. As a result, the Kiowa Formation and the Cheyenne Sandstone probably behave hydrologically as a single unit (a hydrostratigraphic unit) in the study area. Thickness of the combined Kiowa Formation and Cheyenne Sandstone ranges from less than 100 to more than 250 feet (Figure 5).

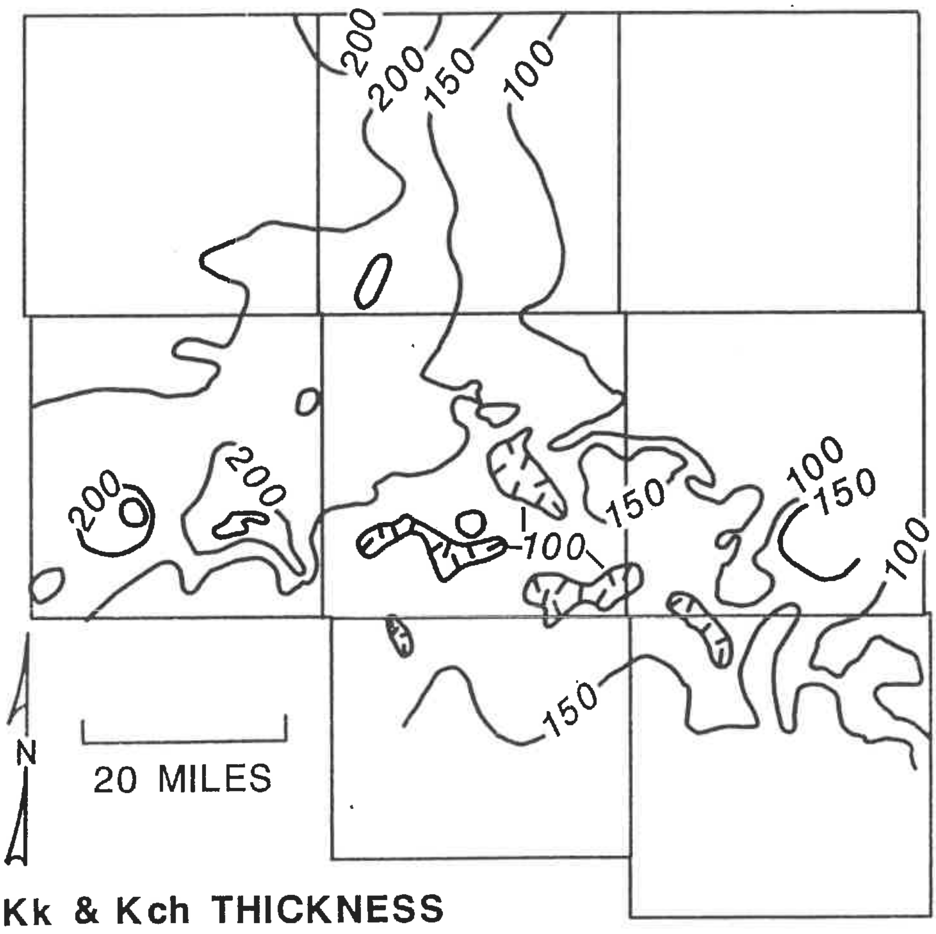


Figure 5. Thickness of strata belonging to the Kiowa Formation and Cheyenne Sandstone in the study area.

Morrison Formation: The Morrison Formation consists of interbedded shales, siltstones, and sandstones, and, near the base of the formation, some lenticular channel sandstones. The lenticular sandstones range up to fifty feet in thickness in southeastern Trego County and are of fluvial origin (Merriam, 1963). The interbedded shales and siltstones appear to contain relatively high concentrations of radioactive elements based on the gamma ray logging response. The Morrison is thought to be present in the subsurface of most of Graham, western and southern Trego, and northwest Rush Counties. Eastward of this area the Morrison has been removed by pre-Cretaceous erosion. The Morrison is separated from the underlying Permian formations by a regional unconformity.

Undifferentiated Permian: The Undifferentiated Permian is composed of strata belonging to the Whitehorse and Blaine Formations, and the Flower-pot Shale. In the study area, the Whitehorse and the Flower-pot consist of red to brown evaporitic shales and siltstones and minor sandstones. The Blaine Formation consists entirely of anhydritic gypsum or anhydrite in the study area (Merriam, 1963). Where present, the thickness of the Blaine is approximately 10 to 15 feet and shows a pronounced response on gamma ray-neutron logs. The thickness of strata belonging to the Morrison Formation and the undifferentiated Permian ranges from featheredge at the eastern extent to more than 350 feet in southwest Trego County (Figure 6). The undifferentiated Permian is truncated by pre-Cretaceous erosion eastward of R19W.

Cedar Hills Sandstone: The Cedar Hills Sandstone consists of red sandstone and interbedded sandy siltstone and shale (Swineford, 1955). The sandstones are composed largely of well-rounded, frosted, fine to medium-grained quartzose sands with feldspar as the most important minor constituent. Grains of sand are frequently iron-stained with hematite. Individual beds of shale in the Cedar Hills are 15 to 30 feet thick and can be traced for 10 to 20 miles in the subsurface. Thickness of the Cedar Hills ranges from featheredge at its eastern extent to more than 275 feet in northwestern Trego County (Figure 7). Eastward of R19W, younger Permian and Jurassic rocks have been truncated by pre-Cretaceous erosion and the Cedar Hills underlies the Lower Cretaceous in much of Ellis and western Russell counties.

Salt Plain Formation: The Salt Plain Formation is composed largely of red silty shale. Minor sandstone and sandy siltstone are locally developed just below the base of the Cedar Hills Sandstone.

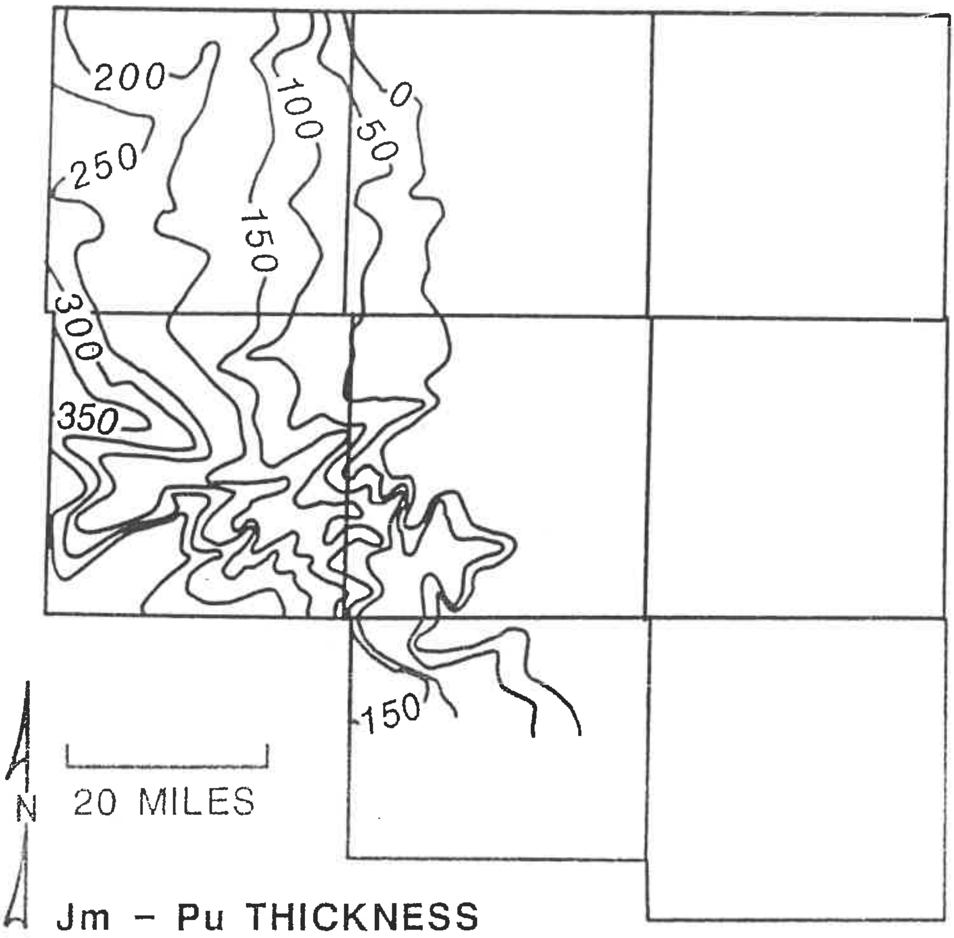


Figure 6. Thickness of strata between the top of the Cedar Hills Sandstone and the base of the Cheyenne in the study area.

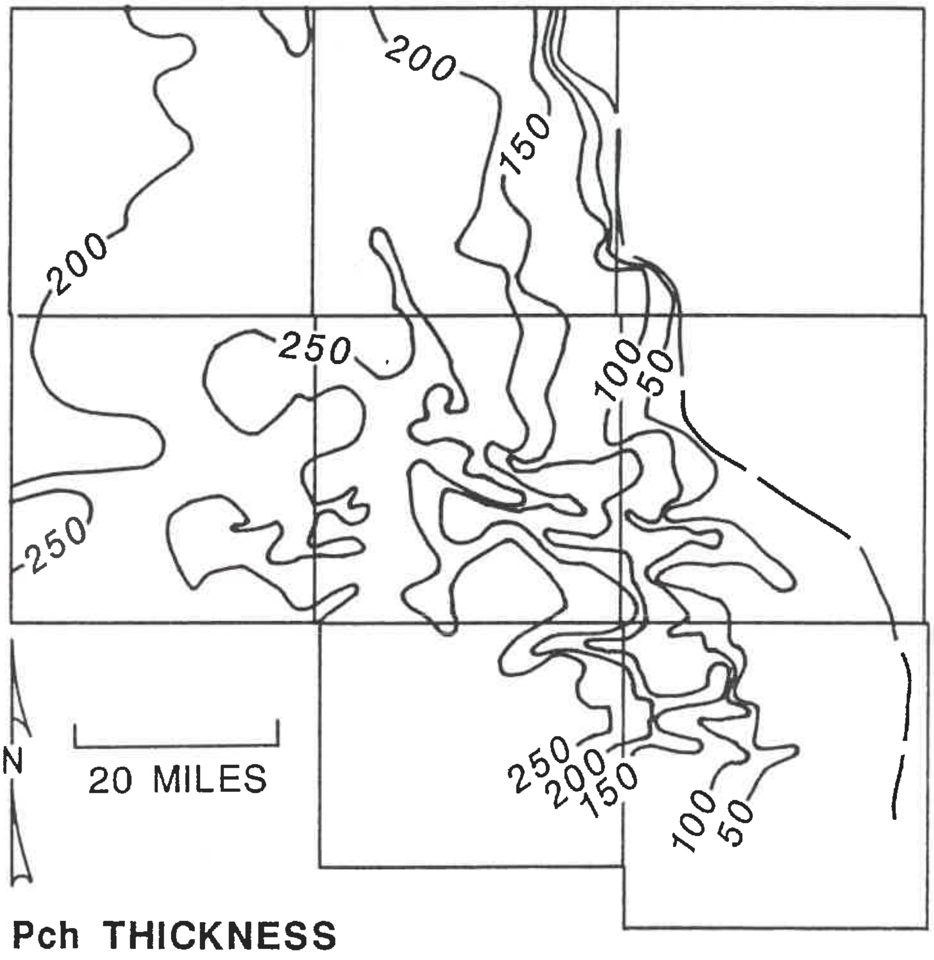


Figure 7. Thickness of the Cedar Hills Sandstone in the study area.

4.1.2 Log Analysis and Petrophysical Properties of the Cretaceous-Permian Sequence in the #1 Braun, Ellis County, (Hays North Monitoring Site)

Wireline logging program: A borehole geophysical logging program was selected to provide information for the location of stratigraphic tops, compositional analysis of lithologies, estimation of effective porosities and inferred permeabilities, and interpretation of depositional environments at all scales. The following logs were run in KGS Braun #1:

Total gamma ray (API units);
Spectral gamma ray (potassium %, uranium ppm, thorium ppm);
Hole diameter caliper (inches);
Cable tension (lb);
Formation density (gm/cc);
Photoelectric absorption index (barns/electron);
Compensated neutron porosity (limestone equivalent porosity units);
Spontaneous potential (millivolts);
Spherically focused resistivity (ohm-meters);
Medium induction resistivity (ohm-meters);
Deep induction resistivity (ohm-meters);

The lithodensity-neutron and spectral gamma ray logs for the well are shown as Figures 8 and 9.

Stratigraphic tops of section formations: Interpretation of the character of the log curves was coordinated with the lithologic information from drill cuttings to establish the following stratigraphic tops listed in Table 1.

Table 1. Formation tops in the #1 Braun well, NW, NW, NW Sec. 30, T12S, R18W.

FORMATION/MEMBER	DEPTH TO THE TOP	ELEVATION
NIOBRARA		
Fort Hays Limestone	35	2105
CARLILE SHALE	88	2052
Blue Hill Shale	90	2050
Fairport Chalk	284	1856
GREENHORN LIMESTONE	360	1780
GRANEROS SHALE	435	1705
DAKOTA FORMATION	488	1652
KIOWA FORMATION	78	1356
CHEYENNE SANDSTONE	828	1312
CEDAR HILLS SANDSTONE	897	1243
TOTAL DEPTH	1197	943

Summary of petrographic information from published studies: Since one of the primary objectives of the log analysis in this well was to make a detailed compositional analysis, a review was made of published petrographic data from these formations. These data function

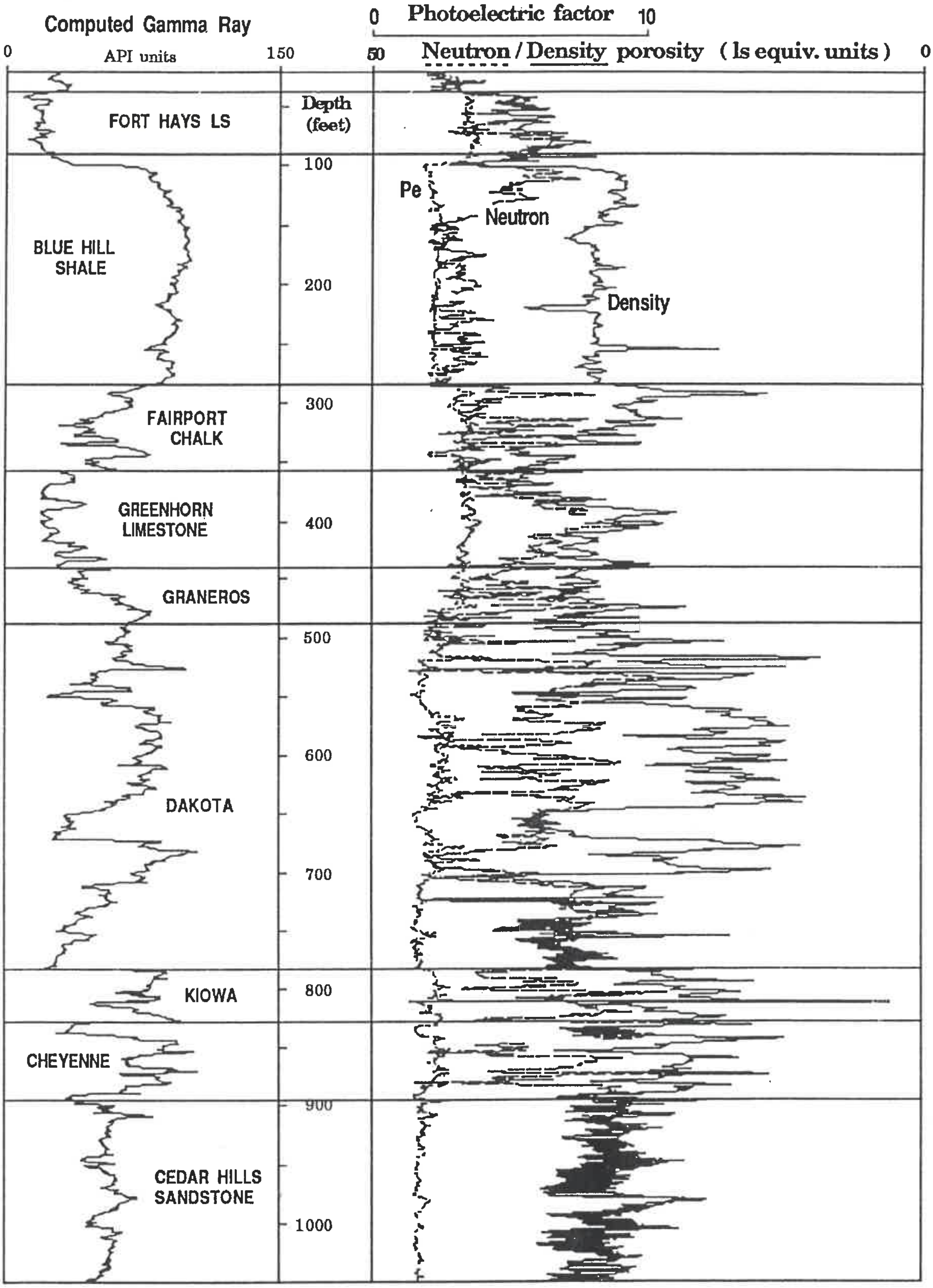


Figure 8. Gamma ray-lithodensity-neutron logs from KGS #1 Braun, NE,NE,NE Sec. 30, T12S, R18W.

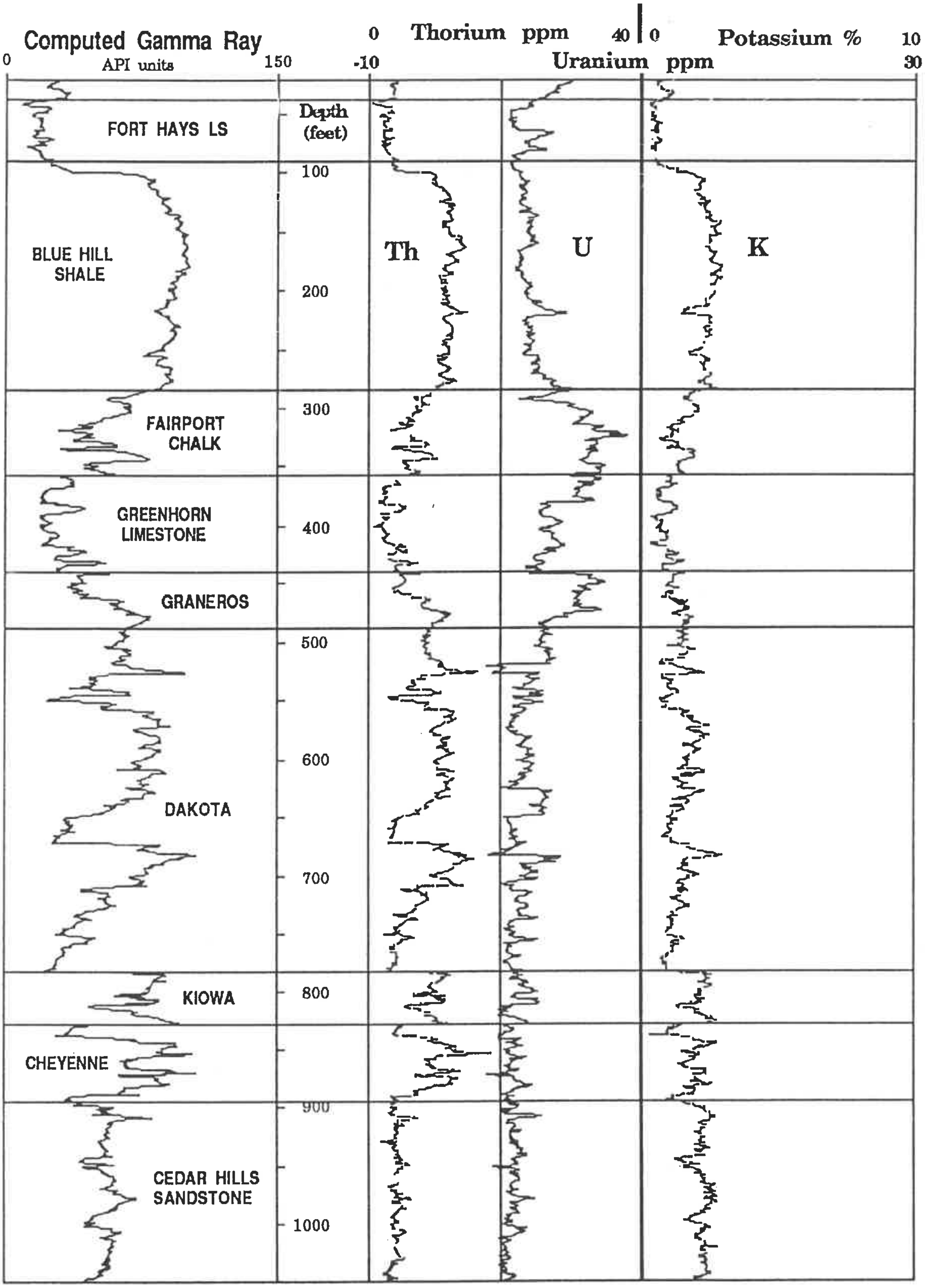


Figure 9. Spectral gamma ray (thorium, uranium, potassium) from KGS #1 Braun, NE,NE,NE Sec 30, T12S, R18W.

as a broad source of "ground truth" which identify the mineral components to be determined from the logs and their relative volumetric importance.

The Cedar Hills Sandstone outcrops in Barber County where it consists of red and white feldspathic sandstones, siltstone and silty shale (Zeller, 1968). Holdoway (1978) made a detailed examination of core from a test well in Wichita County and described the composition of the Cedar Hills Sandstone as ranging from quartz arenite to lithic subarkose. The sandstone samples contained quartz grains which were commonly coated with hematite, between 5 and 10 percent fresh feldspars which often showed microcline twinning, small amounts of rock fragments derived from felsic intrusives, opaque minerals, and traces of authigenic clays. The sandstones were unusual in that they were frequently halite cemented. Although Holdoway (1978) made no analyses of clay minerals in the Cedar Hills, James (1972) reported chlorite vermiculite and illite from the insoluble residues of the immediately overlying the Flower-pot Shale.

Merriam et al. (1959) made the most detailed compositional analysis of the Lower Cretaceous formations and Graneros Shale in their study of a lengthy core from Cheyenne County. They found that the matrix of the sandstones was dominantly quartz with traces of feldspar, chert, schist fragments, and detrital tourmaline. The shales of the Lower Cretaceous were mostly a mixture of illite and kaolinite with subsidiary amounts of chlorite, smectite, and mixed-layer clays. Smectite became a major component in the overlying Graneros Shale.

Spectral gamma ray log analysis: Natural gamma radiation in rocks is almost entirely attributable to potassium-40 and the radioactive isotopes of the uranium and thorium families. A conventional gamma ray log records a pooled summation of counts from all radioactive sources. In the design of the spectral tool, "windows" are set to count gamma radiation within specific energy ranges. These measurements are then processed by computer to allocate the total count between the three prime radioactive sources. The gamma ray spectral log is recorded as parallel curves of thorium and uranium which are both scaled in parts per million, together with potassium (see Figure 9). Potassium is logged as a proportion, but is normally converted to percent in log analysis calculations.

The potassium-thorium crossplot is now widely used as an aid in the recognition of clay-mineral associations and the discrimination of micas and feldspars. A crossplot of digitized log data (sampled at the standard rate of two readings per foot) from the Cedar Hills Sandstone, Lower

Cretaceous formations, and Graneros Shale is shown in Figure 10 and uses the chartbook crossplot scale conventions (Schlumberger, 1986). The lines which radiate from the origin have gradients matched with values of Th/K ratios and have proved useful in the broad distinction of radioactive minerals marked on the plot.

The cluster of points from the Cedar Hills Sandstone is clearly separated from Cretaceous zones and is readily interpreted as a quartz-feldspar-illite system. This aspect conforms very well with the petrography of this unit, described earlier. The Lower Cretaceous zones plot as a broader and more diffuse cloud, as would be expected for a mixed sequence of sandstones, siltstones, and shales. However, the cloud coincides with the kaolinite-smectite-illite range of Th/K ratios which, once again, shows excellent agreement with known petrography. Crossplot data from the Graneros Shale overlaps the Lower Cretaceous points. However, there is distinctive bias towards higher Th/K ratios, which probably reflects the increased importance of smectite as a significant component.

In addition to the thorium-potassium ratio, the thorium-uranium ratio has useful diagnostic properties. In a pioneer paper, Adams and Weaver (1958) concluded that the Th/U ratio was often strongly linked

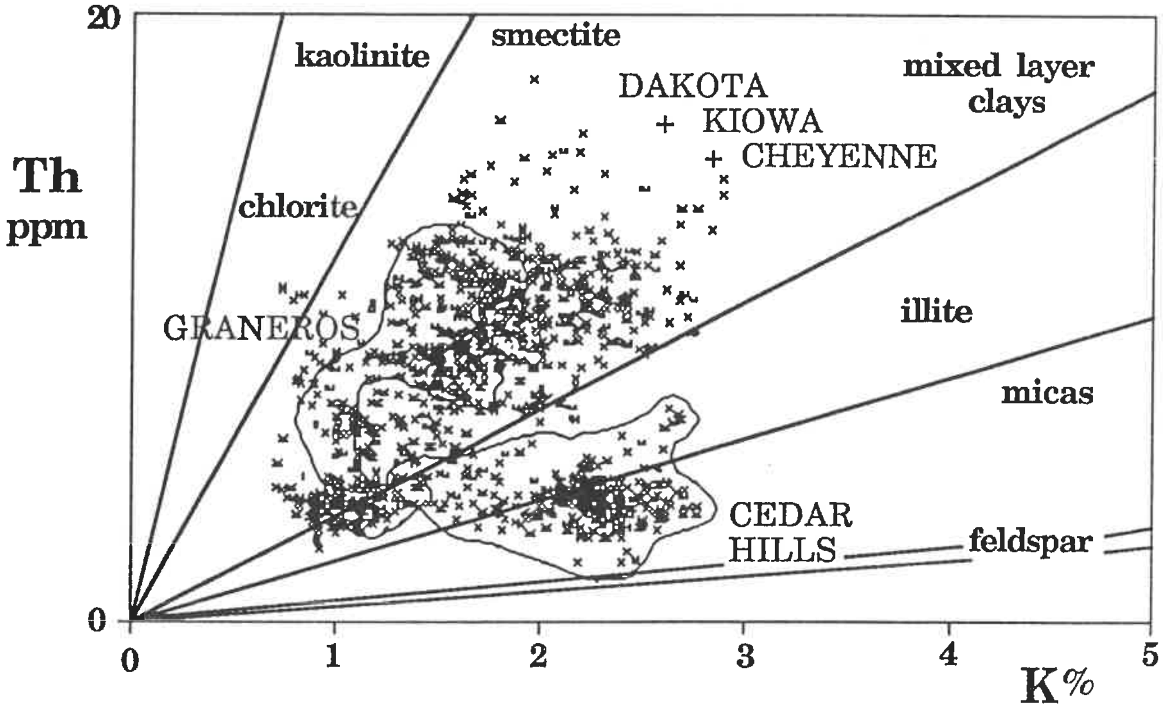


Figure 10. Thorium-potassium crossplot of Cedar Hills Sandstone, Lower Cretaceous Series, and Graneros Shale, KGS #1 Braun.

with depositional environment, based on their laboratory analysis of many samples of differing lithologies. They suggested that when the ratio was computed to be less than two (i.e., uranium-rich), the depositional environment had promoted uranium fixation under probable reducing conditions and was most commonly marine. By contrast, ratio values of greater than seven (uranium-poor), implied uranium mobilization through weathering and/or leaching, and therefore indicated an oxidizing, possibly terrestrial environment. Zelt (1985) made gamma ray spectral measurements of Upper Cretaceous outcrops in Colorado, Utah, and New Mexico and showed relationships between the Th/U ratio and transgression-regression cycles as well as inferred distance from shoreline. He found that anomalous ratio values could be correlated regionally between outcrops and on spectral logs from the subsurface and suggested that they were related to major changes in oxygenation and/or salinity in the Western Interior Seaway.

The Th/K and Th/U ratios were plotted as logs in the Braun #1 well together with the gamma ray trace and a graphic lithology log from the description of drill cuttings (Figure 11). The simultaneous consideration of these data throughout the sequence reveals striking and readily interpretable patterns. The long term trend in the Th/K ratio log shows a

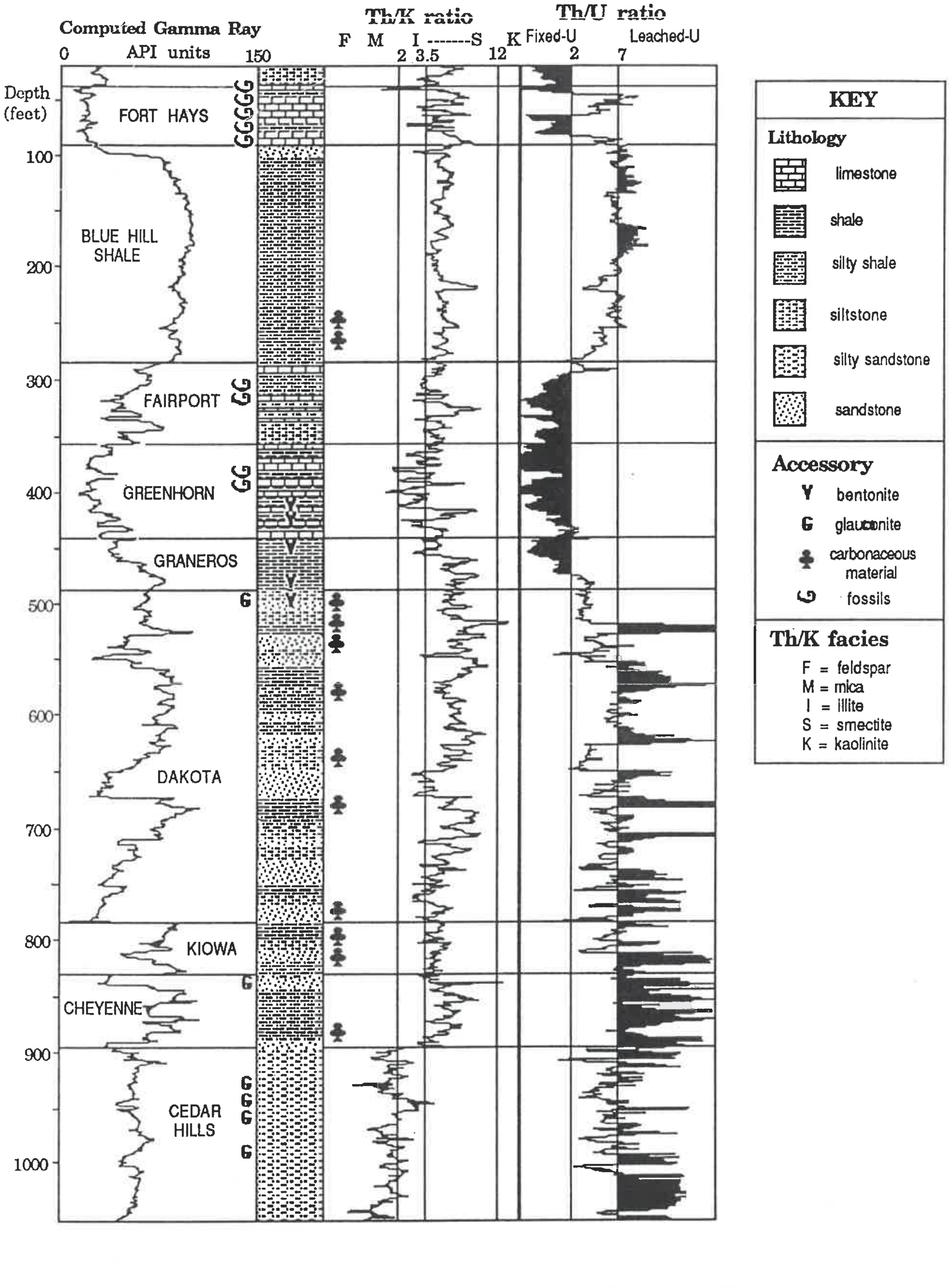


Figure 11. Gamma ray, cuttings, lithlog, Th/K, and Th/U from KGS #1 Braun.

progressive enrichment of potassium with depth, and probably reflects compactional changes which cause a gradational transition from smectite through mixed-layer clays to illite. An abrupt shift occurs at the Cretaceous-Permian contact and clearly highlights the major basal Cretaceous unconformity. The illite-feldspar signature of the Cedar Hills Sandstone changes to a Lower Cretaceous trace which oscillates between illitic and kaolinitic clay mineral facies, possibly linked with marine and deltaic fresh-water environments, respectively. Fluctuations in the Upper Cretaceous units appear to pick up changes in illite, smectite and mixed layer clays as products of predominantly marine environments, and these are the clay mineral components reported in x-ray diffraction analyses of insoluble residues (Arthur et al., 1985). The high amplitude variations in the Graneros Shale and Greenhorn Limestone may reflect the occurrence of bentonites (observed in the drill cuttings) interbedded with normal illitic marine shales. These bentonites represent altered ash deposits generated by explosive events from volcanoes in the Idaho Montana and New Mexico-Arizona regions (Kauffman, 1985).

The Th/U ratio log was indexed with the diagnostic values of 2 and 7 suggested by Adams and Weaver (1958) to aid depositional environment interpretation through its use as an oxidation potential indicator. The ratio indicates an oxidizing environment for much of the Cedar Hills Sandstone, which corresponds to its postulated origin as eolian sands (Holdoway, 1978). The occurrence of glauconite in drill cuttings from the upper part of the formation is a strong indicator of marine origin and is matched by a decline in the ratio to a neutral range. This section may reflect deposition in shallow bodies of water linked with an ephemeral sea, as suggested by Holdoway (ibid) for the Flower-pot Shale.

The Cheyenne Sandstone was deposited on an irregularly eroded surface which formed a series of northward-trending valleys in Kansas (Merriam, 1963). The Th/U ratio log exhibits a high frequency character in the Cheyenne, but is consistently higher than seven in value and so is compatible with an oxidizing terrestrial environment of alluvial sediments.

The lower part of the overlying Kiowa Formation marks a transgressive phase and is generally considered to be represented by a marine environment in Kansas (Merriam, ibid). The average Th/U ratio in the Kiowa is lower than in the Cheyenne, but shows only a weak trend to the intermediate range. This feature is a pale shadow of the strong signals in the spectral ratio of Upper Cretaceous transgressions in this well. However, the subdued character is in concordance with a paleogeographic map of peak transgression in the Kiowa (Vuke, 1981), which shows the wellsite close to shoreline. Higher up in the Kiowa, regressive conditions prevailed during deposition (Franks, 1980).

Stacked repetitions of high and medium Th/U ratios characterize the Dakota Formation. These probably reflect high lateral variability in clastic facies and interplay between mostly brackish and fresh-water regimes of distributary channels, bays, and marginal marine deposits, which would be expected to typify a delta complex.

The relatively smooth, long-term cyclic pattern of the Th/U ratio in the marine sequence of the Upper Cretaceous is in stark contrast to the high frequency character of the ratio in the deltaic deposits below and is an excellent indicator of a broad transgression/regression couplet on an open marine shelf. In fact, the broad sine-wave feature conforms precisely with the outcrop interpretation of the Greenhorn Cycle as a classic example of a symmetric, third-order tectonoeustatic cycle (Glenister and Kauffman, 1985). Hattin (1985) was able to correlate demonstrably time-parallel beds in the Greenhorn from outcrops in Kansas to locations in Colorado and New Mexico. He concluded that the exceedingly widespread deposition of relatively thin units implied a regionally flat, gently sloping sea-floor. The model would account for the strong simple transgression-regression signal in the ratio log from the top of the Dakota to the base of the Niobrara. The transgressive phase of the cycle started in the uppermost part of the Dakota Formation, continued through the Graneros Shale, and reached maximum development in the Greenhorn Limestone. The regressive hemicyclothem was initiated at the top of the Greenhorn and continued through the Fairport Chalk and Blue Hills Shale, to terminate in the Codell Sandstone.

There is an abrupt break in the Th/U ratio log at the boundary between the Codell Sandstone and the overlying Fort Hays Limestone. This contact is thought to represent a long period of non-deposition followed by a major transgression (Hattin and Siemers, 1987). The ratio log clearly shows this transgression, but also indicates a distinctive regressive event at the top of the Fort Hays. This anomaly closely coincides with a similar peak on a Th/U log from a Colorado well observed by Zelt (1985), who attributed it to a regional warm water pulse or low salinity event suggested from oxygen isotope studies in the carbonate phase. The Smoky Hills Chalk at the top of the borehole succession is marked by a log ratio feature that indicates renewed transgression.

Lithodensity-neutron log analysis: The spectral gamma ray log analysis indicates generalized clay mineral associations. However, the similarity of potassium and thorium levels of some clay minerals and the multi-clay character of most shales causes ambiguities of interpretation. Consequently, additional diagnostic information from other logs is useful, particularly for detailed work on clay mineral identification and facies recognition within the Lower Cretaceous units.

The recent introduction of the photoelectric factor as a supplementary curve to the conventional neutron and density logs has substantially improved the log recognition of mineralogy. The display of lithodensity-neutron logging data on a RHOMAA-UMAA crossplot is the most direct means to ascertain rock compositions from this log combination (McCall and Gardner, 1982). RHOMAA is the hypothetical density of the rock matrix computed as the projection of the rock's bulk density which eliminates the effect of the fluids in the pore space. UMAA is the theoretical volumetric photoelectric absorption index of the matrix, calculated from the photoelectric factor using similar considerations.

A RHOMAA-UMAA crossplot of digitized data from the Lower Cretaceous formations is shown in Figure 12. This plot is indexed with the approximate locations of clay minerals which, in reality, show ranges of variability as a consequence of differing compositions and morphologies. The cloud of points shows a distinctive wedge pattern

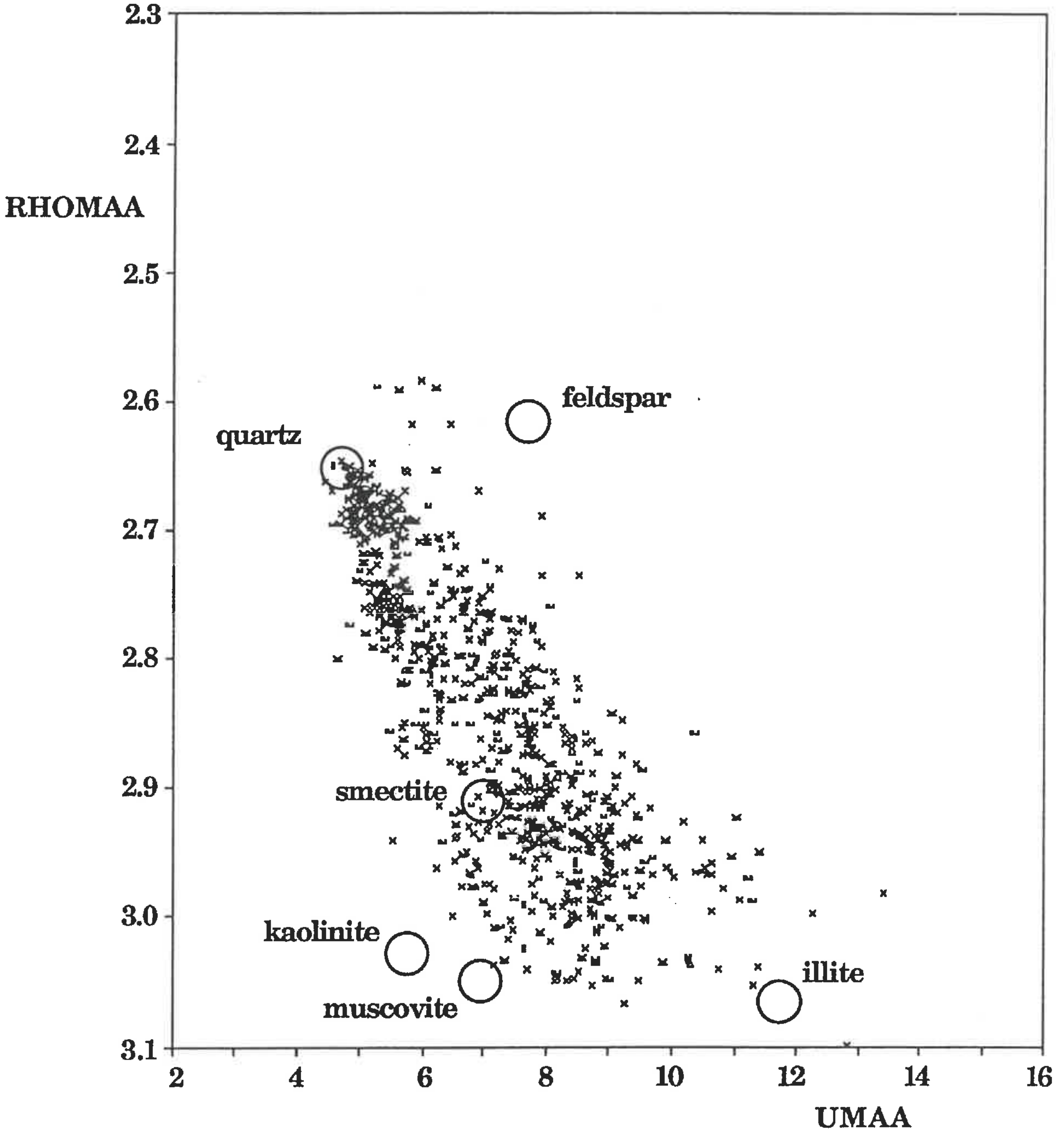


Figure 12. RHOMAA-UMAA crossplot of Lower Cretaceous (Cheyenne, Kiowa, Dakota) in KGS #1 Braun.

whose upper vertex is sited at the coordinates of quartz. The wedge ranges between "low-Z clays" (kaolinite, smectite, and muscovite) and "high-Z clays" (illite and chlorite) and can reasonably be represented by a composition triangle. Any zone point may then be recast as proportions of the three end members. The RHOMAA-UMAA data for the Lower Cretaceous were transformed to proportional logs of these three components by a matrix algebra computer algorithm described by Doveton (1986). The result is shown in Figure 13, together with thorium-potassium and thorium-uranium ratio logs. Comparison of the three sets of curves will be the basis for detailed analysis of the entire Lower Cretaceous. This will extend beyond mineral characterization to the subdivision of clastic facies and depositional environments. The analysis should provide important information for use in lateral correlation and clues to the likely shapes and trends of individual sandstone bodies, which will be useful in three-dimensional modelling.

4.2 Geologic Structure

The structural dip of the top of the Dakota Formation is to the north at approximately 7 feet per mile in most of the study area (Figure 14). In western Trego and Graham counties the dip is to the north-northwest at

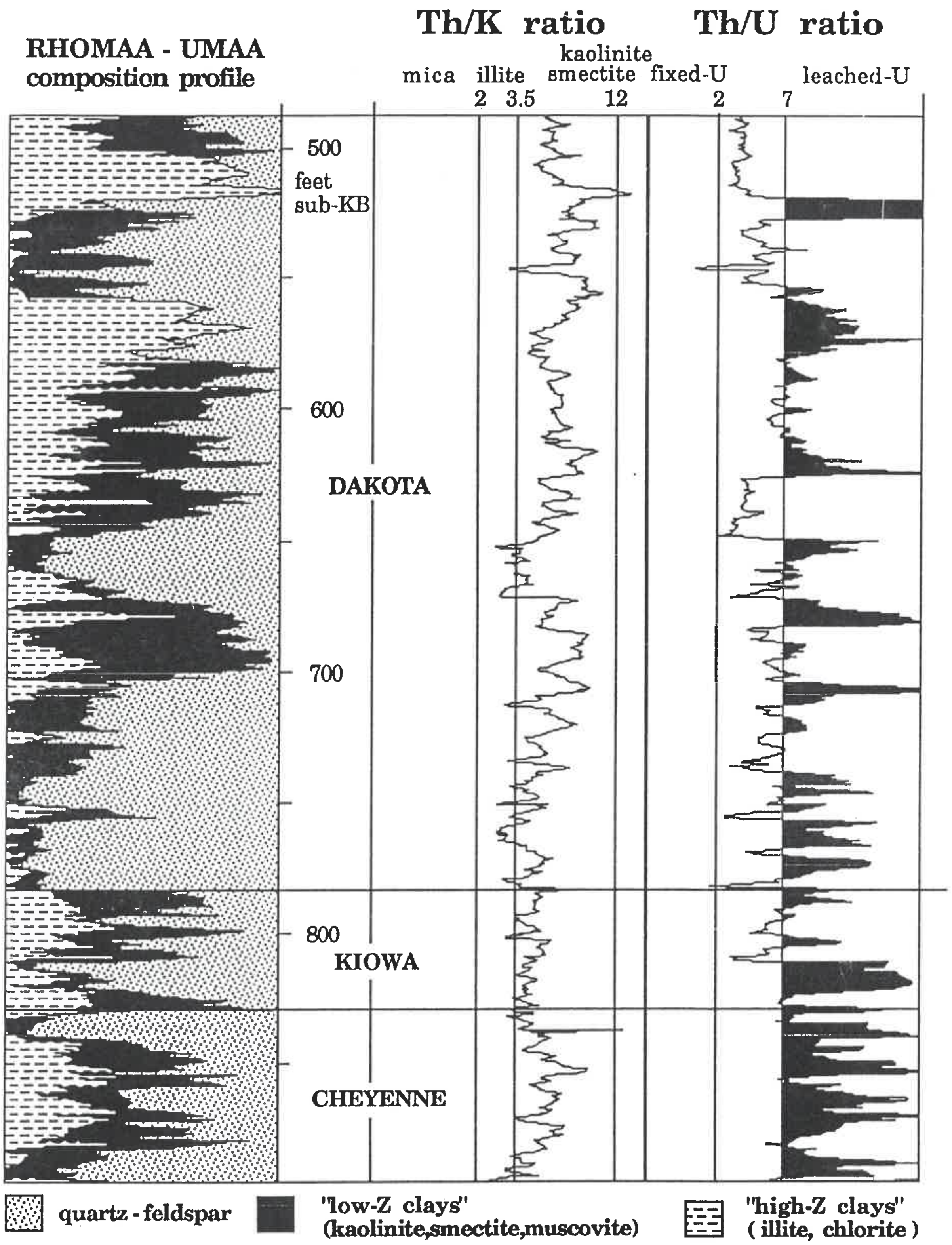


Figure 13. Composition profile of Lower Cretaceous formations based on RHOMAA-UMAA plot parameters, together with GR spectral ratios in KGS #1 Braun.

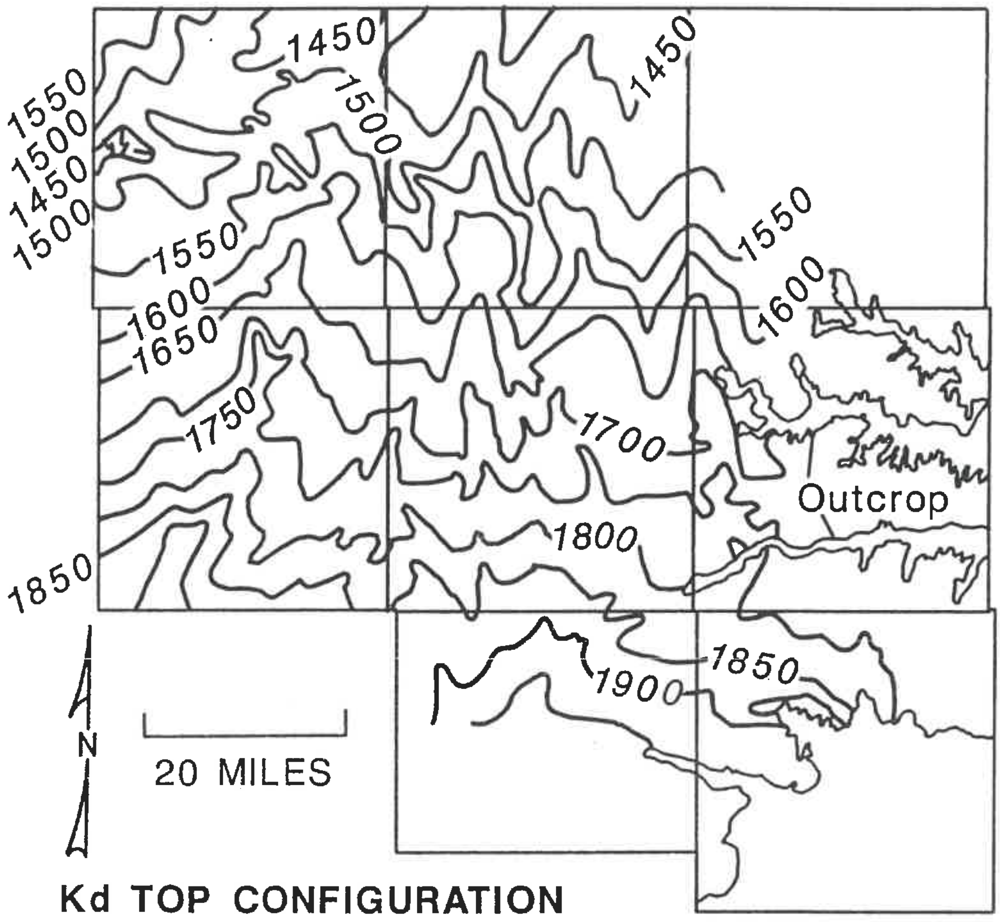


Figure 14. Configuration of the top of the Dakota Formation in the study area.

approximately the same degree of tilt. Similarly, the dip on the eroded surface of the Cedar Hills top is northerly in the central and eastern portions of the study area (Figure 15). The Cedar Hills top dips to the northwest at 16 feet per mile in the northwest and extreme western parts of the study area where the Cedar Hills is covered by younger Permian rocks.

These changes of dip in the near surface rocks reflect the boundary between the Central Kansas uplift and the Cambridge arch in the eastern and central portions of the study area and the Western Kansas basin in the western part. The Central Kansas uplift is a large uplifted and eroded structural feature covering most of the study area. Its development was largely completed by the end of the Pennsylvanian (Merriam, 1963). However, the Western Kansas basin is a feature that developed during the Mesozoic and was tilted to the northwest with the development of the Denver basin in eastern Colorado and southwestern Nebraska (Merriam, ibid).

Many minor structures are present in the surface rocks and are reflected in the configuration of the top of the Dakota Formation. The Fairport-Natoma anticline is a north-south feature located along the Ellis-Russell County line. The east-west oriented Pfeifer anticline is

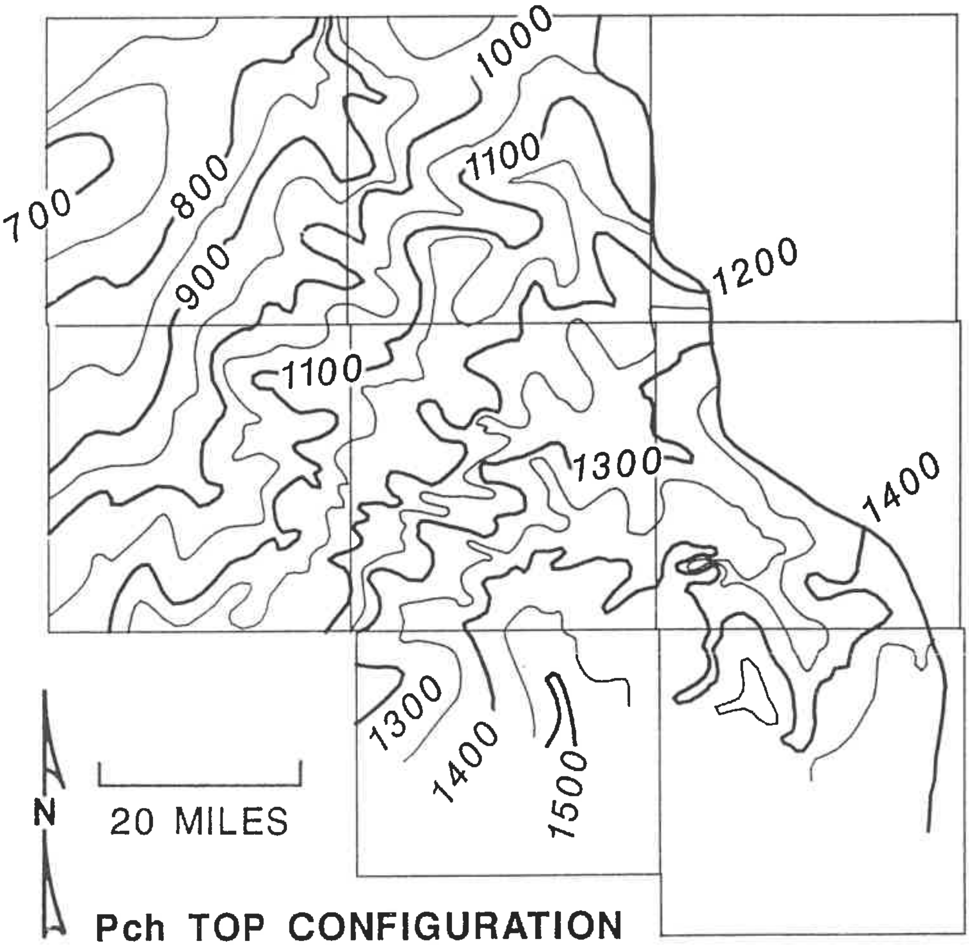


Figure 15. Configuration of the top of the Cedar Hills Sandstone in the study area.

located near the southern end of the Fairport-Natoma anticline. Both features are located on the crest of the Central Kansas uplift and appear in the deeper Paleozoic and Precambrian rocks as complex, elongate, fault-bounded uplifts. Another structural feature that shows up particularly well in the near-surface rocks is the north-south trending Stockton anticline located in Rooks and Ellis counties in R19W. Many smaller named and un-named structures are also present in the study area, such as the Wakeeney anticline in T11S, R23W, Trego County. An extensive un-named structural low is also present in T8S, R24-25W. This structure is also present on Merriam's (1963) top configuration maps of the Carlile Shale, Dakota Formation, and Stone Corral Formation.

Faults are present at the surface in association with the Niobrara Formation throughout the western part of the study area. In an early reconnaissance of the geology of Ellis County, Bass (1926) mapped 76 occurrences of surface faulting in the Smoky Hill Chalk Member in T12S, R20W. Later work by Merriam (1963) shows that these faults are probably not related to regional structure.

Occurrences of faulting or jointing of the exposed bedrock can be seen or implied from the analysis remote sensing images of the land surface. Shown in Figure 16 is a preliminary map showing the occurrence of remote

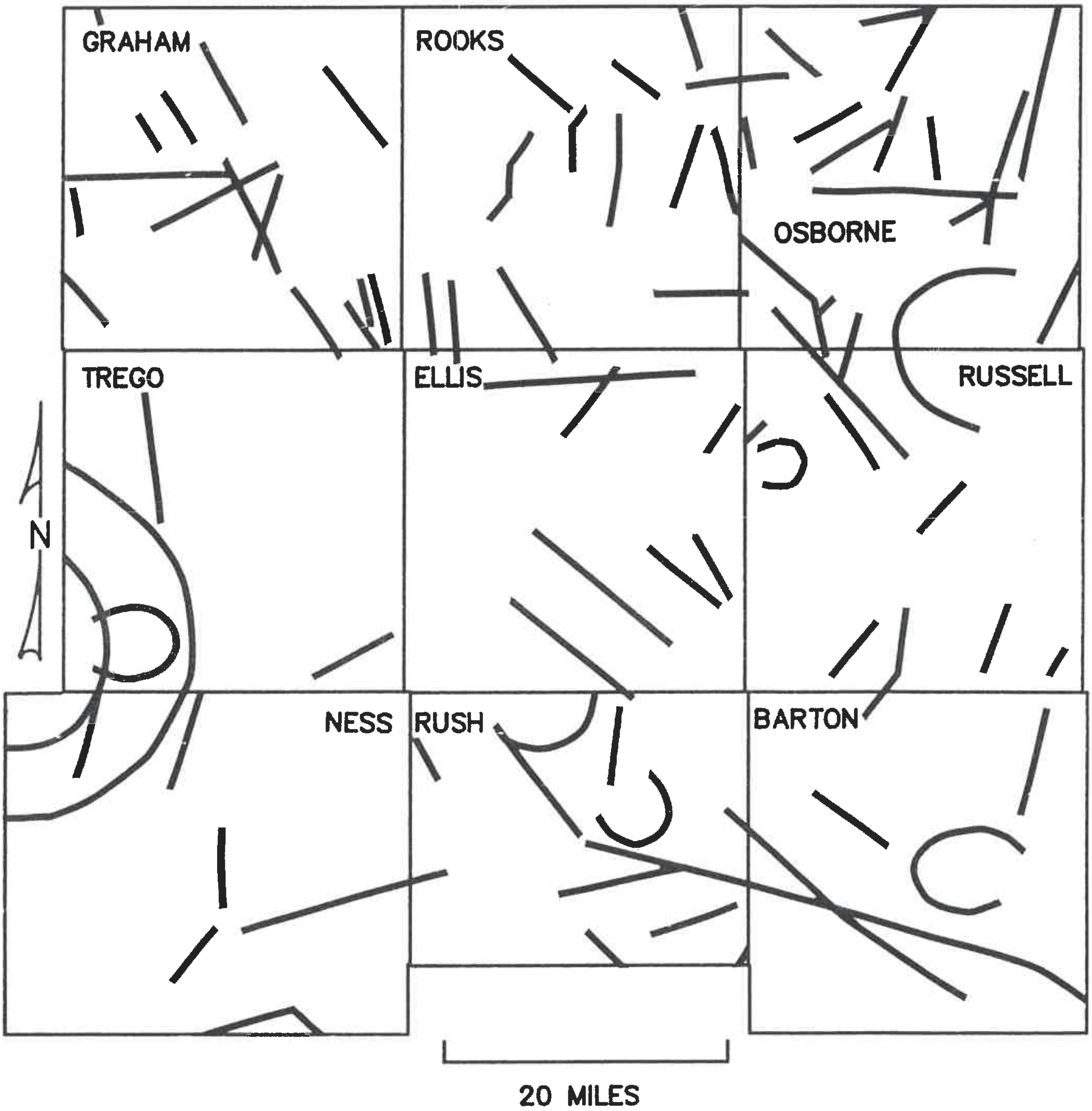


Figure 16. Remote-sensing lineaments in the study area. Adapted from unpublished work by McCauley (1985).

sensing lineaments in the study area and the adjacent Ness County (McCauley, 1985). This map shows that the jointing of the near-surface rocks follows the NW-SE trend of the Central Kansas uplift in the study area and the predominant trend of the Precambrian bedrock surface (Cole, 1976). A weaker NE-SW lineament trend is present in western Graham County that but is much more pronounced farther west in Sheridan and Thomas counties. This trend is parallel to the strike of the Precambrian bedrock surface in the Western Kansas basin and approximately perpendicular to the trend of the Central Kansas uplift. None of the lineaments found at the surface coincide with known faults in the Precambrian.

5.0 REGIONAL GROUND-WATER FLOW SYSTEMS

5.1 Definition of Regionally Significant Aquifer Systems

Four regionally significant aquifers are present within the study area. The shallow water-table aquifers consist of unconsolidated alluvial materials associated with the Smoky Hill, Saline, and Solomon river valleys. Elements of the High Plains aquifer are also present and consist of the Ogallala Formation and associated Pleistocene deposits found in the upland areas of Graham, northern Trego, Rooks, Ellis, and Russell counties. Below these near-surface unconfined aquifers are the Great Plains aquifer system consisting of the Dakota Formation, the Kiowa Formation, and the Cheyenne Sandstone (Helgeson et al., in review); and the Cedar Hills aquifer consisting of the Cedar Hills Sandstone.

For the purposes of this report the Great Plains aquifer system has been subdivided into two parts: an upper part, consisting of the Dakota Formation and a lower part, consisting of the Kiowa Formation and Cheyenne Sandstone. This subdivision has been made based on perceived differences between the Dakota Formation and the Kiowa Formation-Cheyenne Sandstone. In general, the Dakota Formation consists of thick lenticular channel sandstones enclosed in an alluvially deposited sequence of interbedded claystones, siltstones, and sandstones. These channel sandstones occur commonly in the upper part and near the base of the Dakota Formation. In contrast, the Kiowa Formation and Cheyenne Sandstone consist largely of interbedded shales, siltstones, and thin-bedded sandstones. Thicker lenticular sandstones do occur in these formations particularly near the base of the Cheyenne but they are infrequent and generally not widespread. We believe that these lithologic and architectural differences are reflected in the bulk porous media properties of the Dakota Formation and the underlying Lower Cretaceous formations. As a result, an upper and a lower hydrostratigraphic unit can be distinguished in the Great Plains aquifer.

Over most of the study area the Great Plains aquifer system is confined by overlying Upper Cretaceous rocks referred to by Helgeson et al. (in review) as the Great Plains Confining System. The Upper Cretaceous rocks that comprise the Great Plains Confining System are the Graneros Shale, the Greenhorn Limestone, the Carlile Shale, and the Niobrara Chalk. Not discussed in this report is the Codell Sandstone aquifer, which locally produces sufficient water to supply domestic and stock needs in the study area. The Codell Sandstone aquifer occurs at the top of the Carlile Shale.

Separating the Great Plains aquifer system from the underlying Cedar Hills aquifer are younger Permian and Jurassic rocks in Graham and Trego counties that appear to act as confining layers for the Cedar Hills aquifer. The formations that comprise the confining layer are the Flower-pot Shale, the Blaine Formation, the Whitehorse Formation, and the Morrison Formation.

Ground water is transmitted through pores within the rocks and through fractures in these aquifer systems in response and in the opposite direction of the hydraulic gradient according to Darcy's Law (Freeze and Cherry, 1979). The direction of water flow is from a point of greater to lesser hydraulic head. Temperature differences are assumed to influence the flow of ground water across the region only slightly.

The lateral direction of ground-water flow is determined by constructing a potentiometric surface map of the aquifer in the region of interest. The configuration of the potentiometric surface is determined by contouring a map of measured static water levels in wells that penetrate the aquifer. The direction of ground-water flow is perpendicular to the orientation of the contours in the down gradient direction if the anisotropy of the aquifer is negligible. In terms of regional systems, ground-water flow is from points of recharge to points of discharge (Freeze and Cherry, 1979).

The vertical component of the hydraulic gradient is determined by measuring the hydraulic heads at two vertically separated observation points within the ground-water system. As before, the component direction of flow is from a point of greater to lesser hydraulic head.

5.2 Ground-Water Flow in the Great Plains Aquifer System

Figure 17 shows the potentiometric surface of the upper part of the Great Plains aquifer system (upper part of the Dakota Formation) in the study area. Two distinct flow paths can be delineated based on the configuration of the potentiometric surface: (1) a west to east flow component bringing deeper ground waters in the Great Plains aquifer system from the Western Kansas Basin as part of the larger regional flow system, and (2) a southwest to northeast flow component that appears to be part of a subregional or local flow system that parallels the outcrop of the rocks that comprise the Great Plains aquifer system. These two flows converge in the study area along the southern half of T15S.

A similar pattern can also be seen for the lower part of Great Plains aquifer system (Cheyenne) shown in Figure 18. The contours for this map

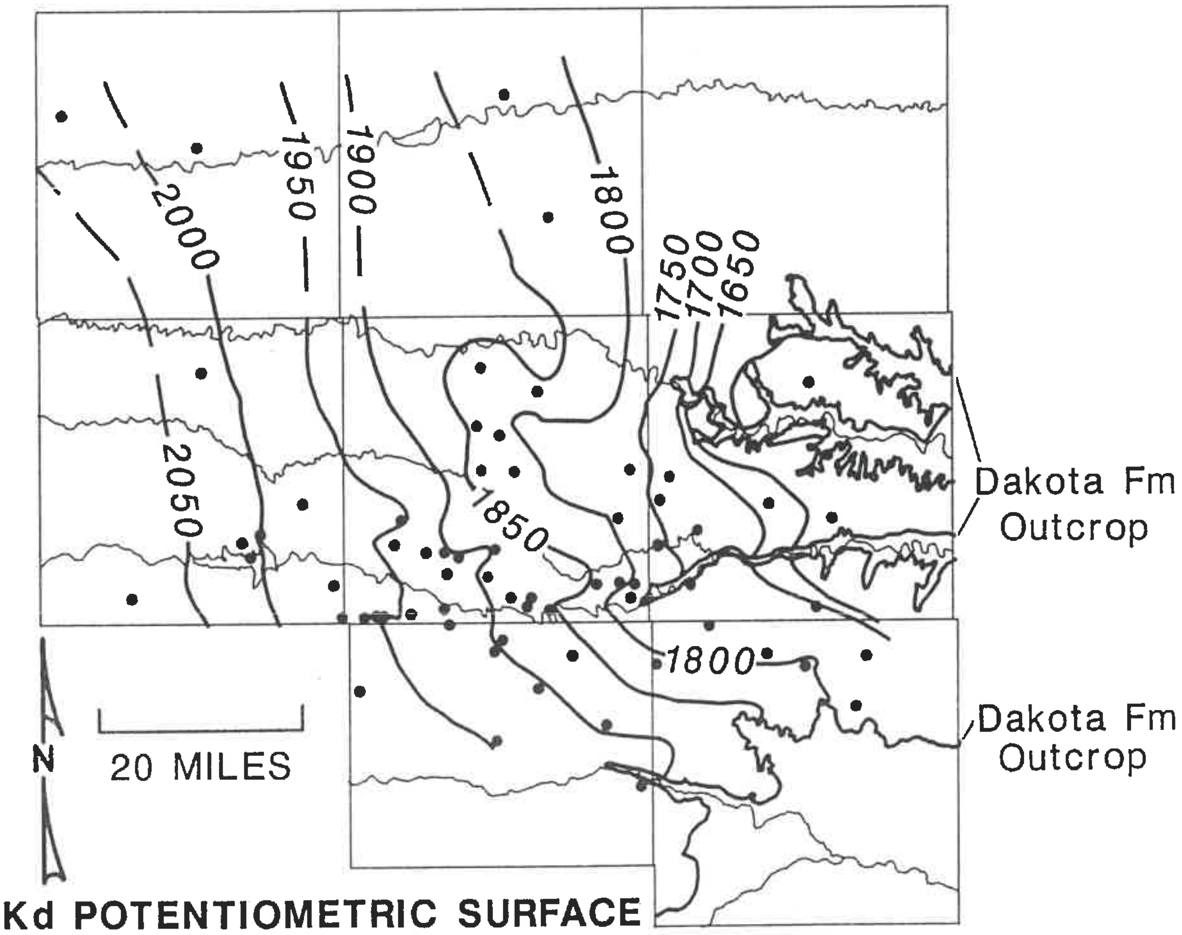


Figure 17. Potentiometric surface of the upper portion Great Plains aquifer.

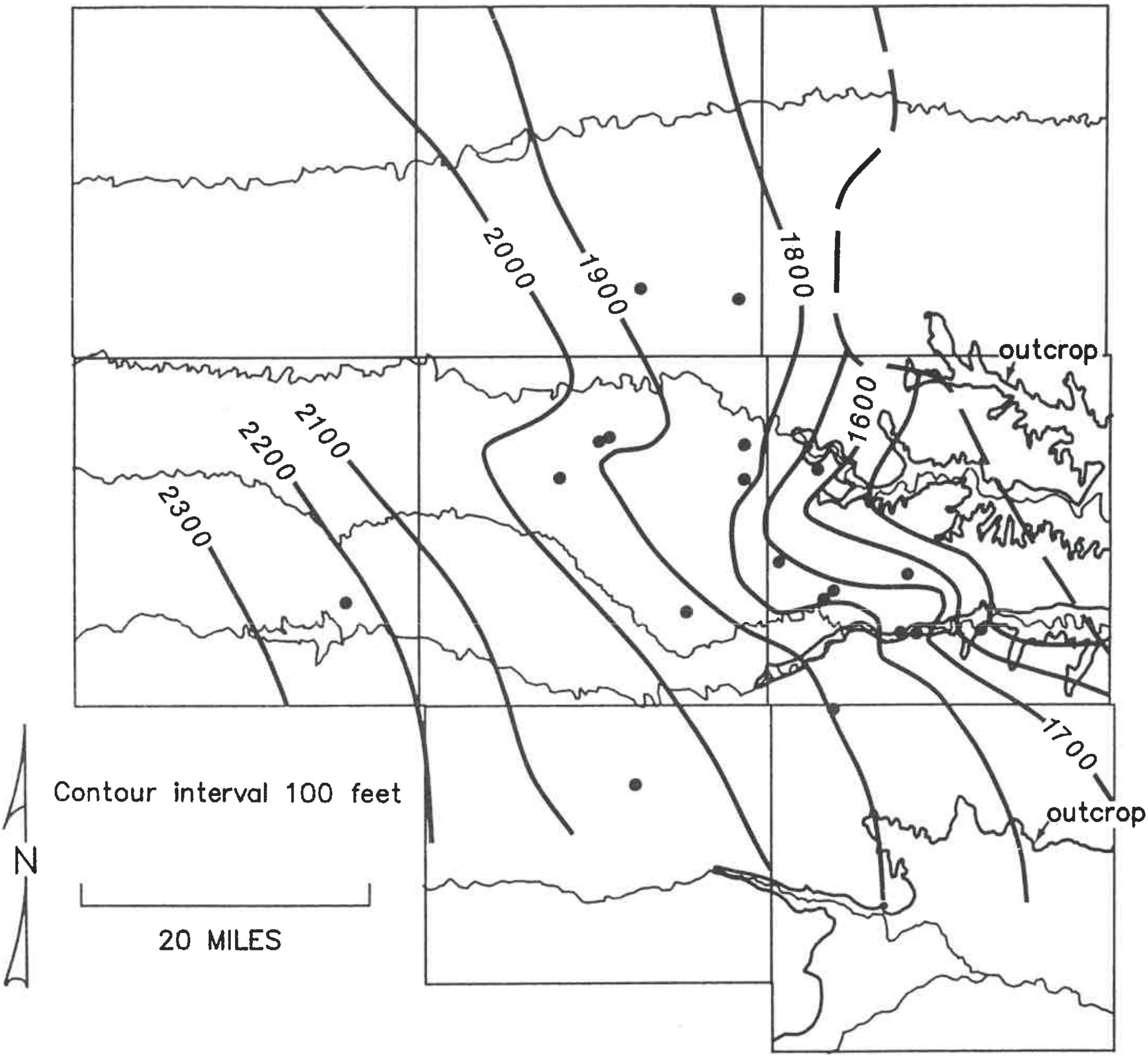


Figure 18. Potentiometric surface of the lower portion Great Plains aquifer.

are generalized due to lack of data. Some of the data points used to construct this map are from studies completed in the 1970's (Bryson, 1970's).

Within the study area, the potentiometric surface of the lower part of the Great Plains aquifer is higher in elevation than the potentiometric surface of the upper part over most of the study area. Hydraulic head differences between the upper and lower portions of the Great Plains aquifer are as much as 100 feet locally. More typically, these differences are on the order of 50 feet over the area. This indicates an upward flow component from deeper to shallower zones within the Great Plains aquifer system over virtually the entire study area with the exception of the Gorham area in western Russell County. At the Gorham monitoring site, the hydraulic head difference between the upper and lower portions of the aquifer is approximately 25 feet. In this area the movement of ground water is from the upper part of the aquifer to the lower part.

Recharge to the Great Plains aquifer system comes from precipitation falling on the northeast-trending outcrop belt, underflow from the Western Kansas basin, interaction with the Cedar Hills aquifer, and as leakage through the Great Plains Confining System from near-surface aquifers. Helgeson et al. (in review) estimated that the long-term average recharge rate to the Great Plains aquifer is on the order of 10 ft^3/sec. in the central Kansas outcrop areas of the Dakota and Kiowa Formations. These authors could not quantify leakage through the overlying Great Plains Confining System or recharge from the underlying Cedar Hills aquifer in central Kansas directly due to lack of sufficient data. However, from a regional steady-state ground water flow model of the Great Plains aquifer, they estimated that leakage from overlying units to the aquifer is 296 ft^3/sec. The Cedar Hills aquifer is vertically adjacent and in hydraulic connection with the Great Plains aquifer east of R19W in the study area. Underflow into the study area is estimated to be on the order of 36 ft^3/sec. along the western and southern boundaries of the area assuming an average horizontal hydraulic conductivity of 10 ft/day for the Great Plains aquifer.

Discharge from the Great Plains aquifer is to streams and wells in the study area and to areas adjacent to the study area as underflow. The total pumpage from municipal, domestic, and stock use is estimated to be 0.14 ft^3/sec. (100 acre-ft/year). The average discharge rate to streams has been estimated by Helgeson et al. (in review) to be between 46 and 60 ft^3/sec. for streams in central Kansas. Assuming a horizontal hydraulic conductivity of 10 ft/day, discharge to the Saline and Smoky Hill Rivers from the Great Plains aquifer in Russell County is estimated to be 0.3 ft^3/sec. per mile of river valley (19 ft^3/sec for both river valleys). No estimates of underflow to areas adjacent to the study area have been made.

The effects of pumping on the potentiometric surface of the upper part of the Great Plains aquifer system can seen in southern Ellis County near the Smoky Hill River and in the area north of Hays in Ellis County. In both areas many domestic and stock wells withdraw water from this part of the Great Plains aquifer.

5.3 Ground-Water Flow in the Cedar Hills Aquifer

The ground-water flow system in the Cedar Hills aquifer can be subdivided areally into two parts based on the configuration of the potentiometric surface. Figure 19 shows the potentiometric surface of the Cedar Hills aquifer in the study area. Data used to prepare this map came from surveys run during the 1970's by the Kansas Department of Health and Environment and were supplied by Bill Bryson, KCC. Additional data were developed from measurements made during the course of this study.

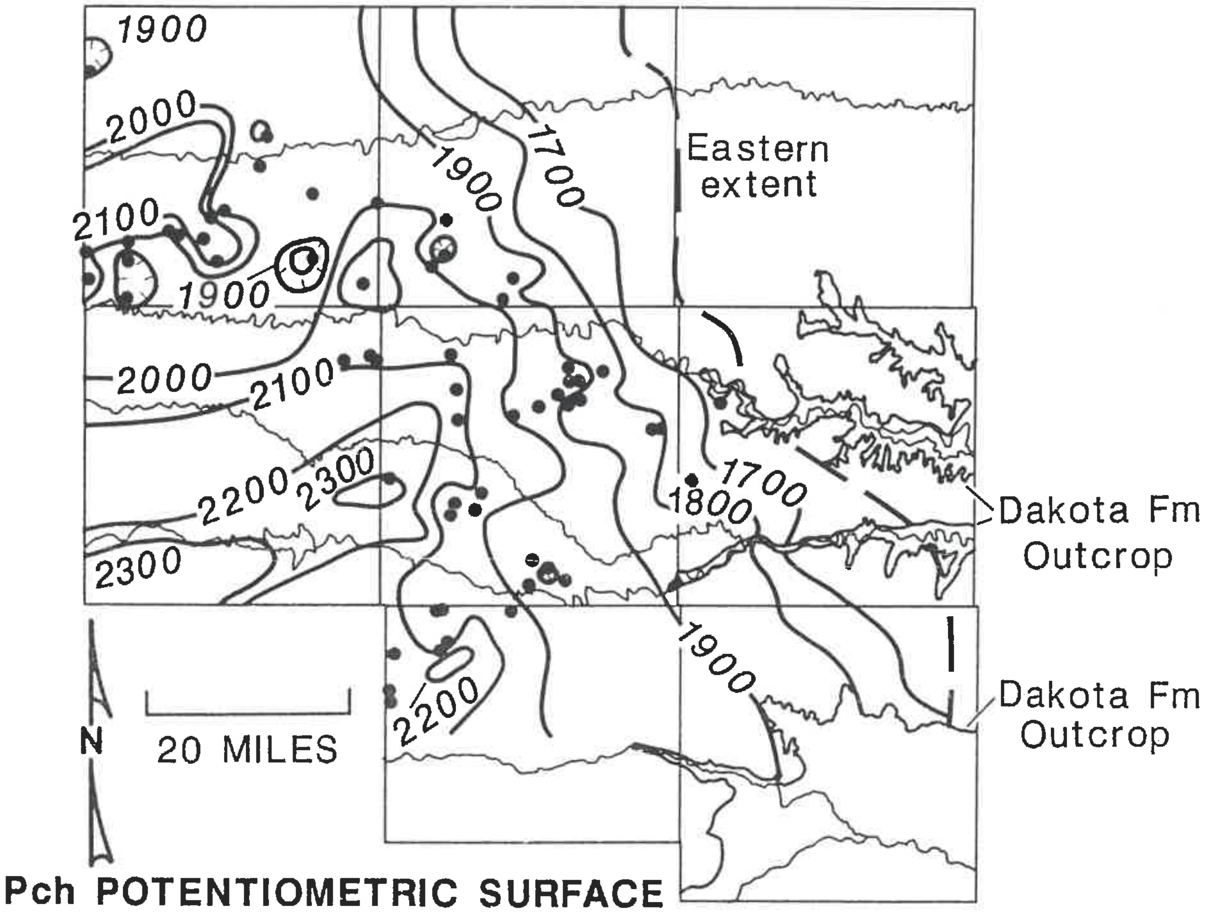


Figure 19. Potentiometric surface of the Cedar Hills aquifer.

Pre-Cretaceous erosion has removed younger Permian-aged strata east of a north-northwest trending line that extends through western Ellis, Rooks, and Rush counties. Eastward of this line, the Cedar Hills underlies and is believed to be hydraulically interconnected with the Great Plains aquifer. Interconnection between the two aquifer systems is suggested by fundamental changes in the configuration of the potentiometric surface eastward of this line (Figure 19). The direction of ground-water flow in the lower part of the Great Plains aquifer is distinctly subparallel with the eastward flow direction indicated for the Cedar Hills aquifer in this area.

Westward of the Cedar Hills subcrop, the potentiometric surface has been affected by the injection of oil-field brines and shows the effects of fluid pressure build-up in southern Trego, northwestern Rush, and western Graham counties. These areas of pressure build-up have resulted from coalescing areas of higher fluid pressure in the aquifer where injection is taking place and appear as a series of isolated highs in the potentiometric surface (Figure 19).

The potentiometric surface of the Cedar Hills aquifer is generally higher than the potentiometric surfaces in the upper and lower Great Plains aquifer over most of the study area. Hydraulic head differences on the order of 50 feet or more are common. However, only limited data on the these aquifers are available in Rooks and eastern Graham counties.

Recharge to the Cedar Hills aquifer is from two sources: underflow from areas southwest of the study area and injection of oil-field brines through disposal wells. Underflow to the Cedar Hills aquifer has not been estimated from due to the irregularity of the potentiometric surface. Recharge to the Cedar Hills aquifer from injection wells is estimated to have been approximately 6.9 ft^3/sec. (5035 acre-feet per year) during the 1975-1983 period. Figure 20 shows the distribution of disposal wells in Russell, Ellis, Trego, Graham, Rooks, Osborne and Barton counties.

Discharge from the Cedar Hills is believed to be to the overlying lower portions of the Great Plains aquifer east of R19W in the study area. Discharge from the Cedar Hills aquifer has not been estimated due to lack of information on the vertical component of hydraulic conductivity in the Great Plains and the Cedar Hills aquifers.

Static fluid level and injection pressure data gathered by the KCC suggest, at least theoretically, that hydraulic fracturing of the Cedar Hills aquifer may be taking place during injection at some of the disposal sites. Shown in Figure 21 are the results of a survey of shallow injection wells in Rush County conducted by KCC to determine the variation of fluid

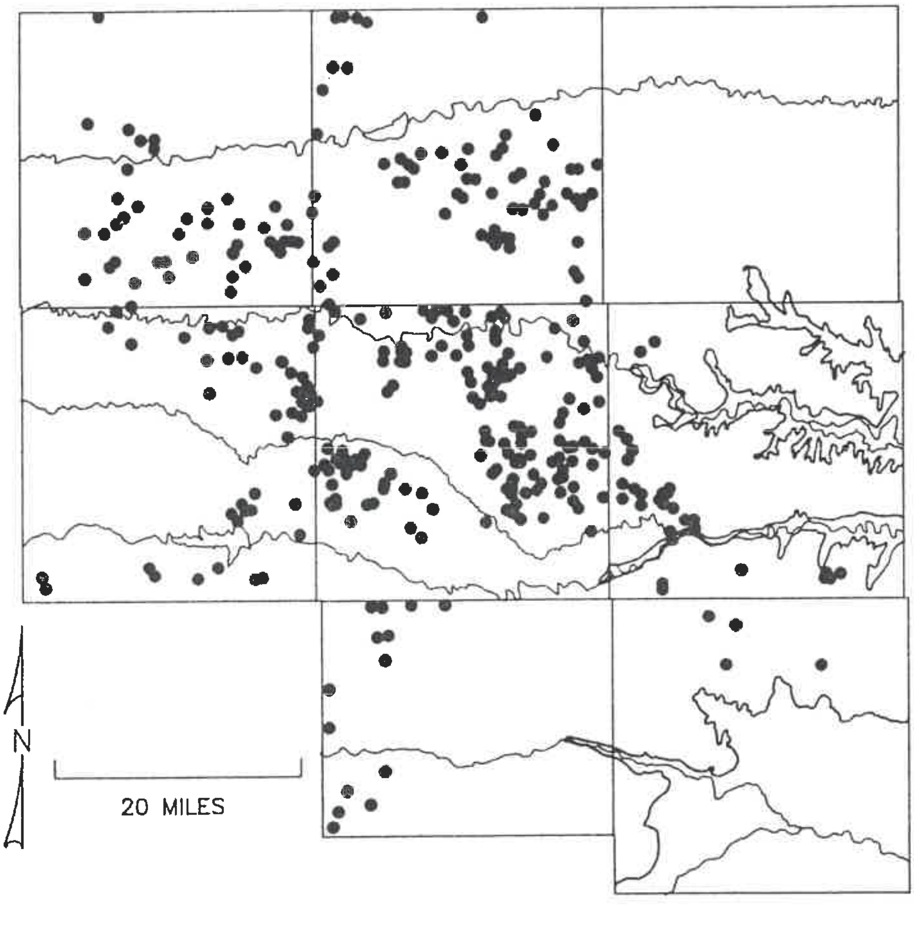


Figure 20. Distribution of shallow oil-field brine disposal wells in the study area.

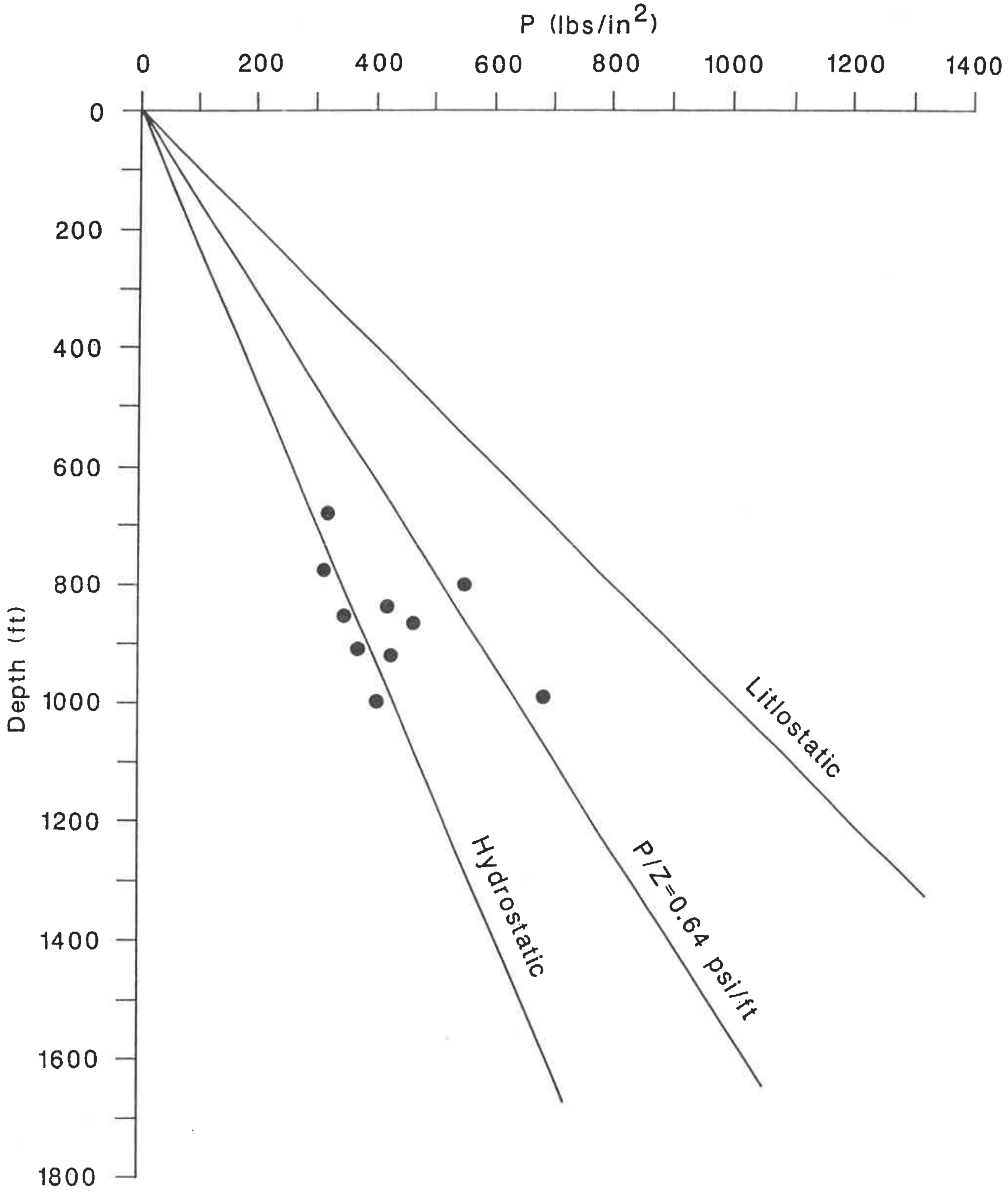


Figure 21. Injection fluid pressures versus depth below land surface for some Cedar Hills disposal wells western Rush County.

pressure in the vicinity of the well during injection. This was done by measuring static fluid levels and monitoring fluid pressures, during and after injection. Plotted on the figure are two lines showing the increase hydrostatic fluid pressure and lithostatic pressure with depth. Also shown is a third line showing an increase in fluid pressure with depth of 0.64 psi/ft. Hubbert and Willis (1972) have shown that theoretically the minimum injection pressure-depth ratio required to initiate hydraulic fracturing (normal faulting in tectonically relaxed areas) in a well is approximately 0.64 psi/ft of depth for a homogeneous and isotropic porous media. This assumes an effective overburden pressure of 1.00 psi/ft which is typical for most sedimentary rocks. The total injection pressure is calculated as the sum of the fluid pressure in the formation and the applied injection pressure at the surface assuming no losses due to friction and fluid compression. Figure 21 shows that two of the injection wells surveyed have clearly exceeded the theoretical minimum injection pressure required for hydraulic fracturing. This theoretical minimum injection pressure/depth ratio may be low for flat-lying, lenticular formations if the rocks already contain fractures and other discontinuities (Lorenz et al., 1986).

6.0 REGIONAL GROUND-WATER GEOCHEMISTRY

6.1 Types of Chemical Data Collected and Examined

Chemical data were collected for Barton, Russell, Ellis, Rush, Rooks, Trego, Graham, part of Ellsworth counties. A general survey of ground-water chemistry was made using sixty samples collected in June, 1987, from domestic, stock, and municipal wells. Selection of the sampling points was based on data from the USGS WATSTORE file, KGS reports for the various counties, and the water-well record file at the KGS. The wells were selected on the basis of depth, location in the county, and availability of information on the screened interval. Some of the wells could not be located in the field and alternative sampling sites were used where available. Some of the samples had high nitrate concentrations indicating either recharge from the surface through the well bore or else a gravel pack in the well from the zone of interest to the surface. Sample data from these wells were not used for the general evaluation of water chemistry. Chemical determinations were also made for samples from the three monitoring sites in the Upper and Lower Dakota Formations, Cheyenne Sandstone, and Cedar Hills Sandstone.

Oil-field brines were collected from wells producing oil from the Arbuckle and Kansas City Groups. These wells were chosen either to evaluate possible sources of saltwater near Cheyenne Bottoms, or were used as examples of brines that are currently being disposed in the Cedar Hills Sandstone. Other oil-field brine data with accurate chemical determinations were selected from the files of D. Whittemore for Russell County. Procedures for sample collection and types of constituent determinations made in the current study are given in the section on methods of study (3.0).

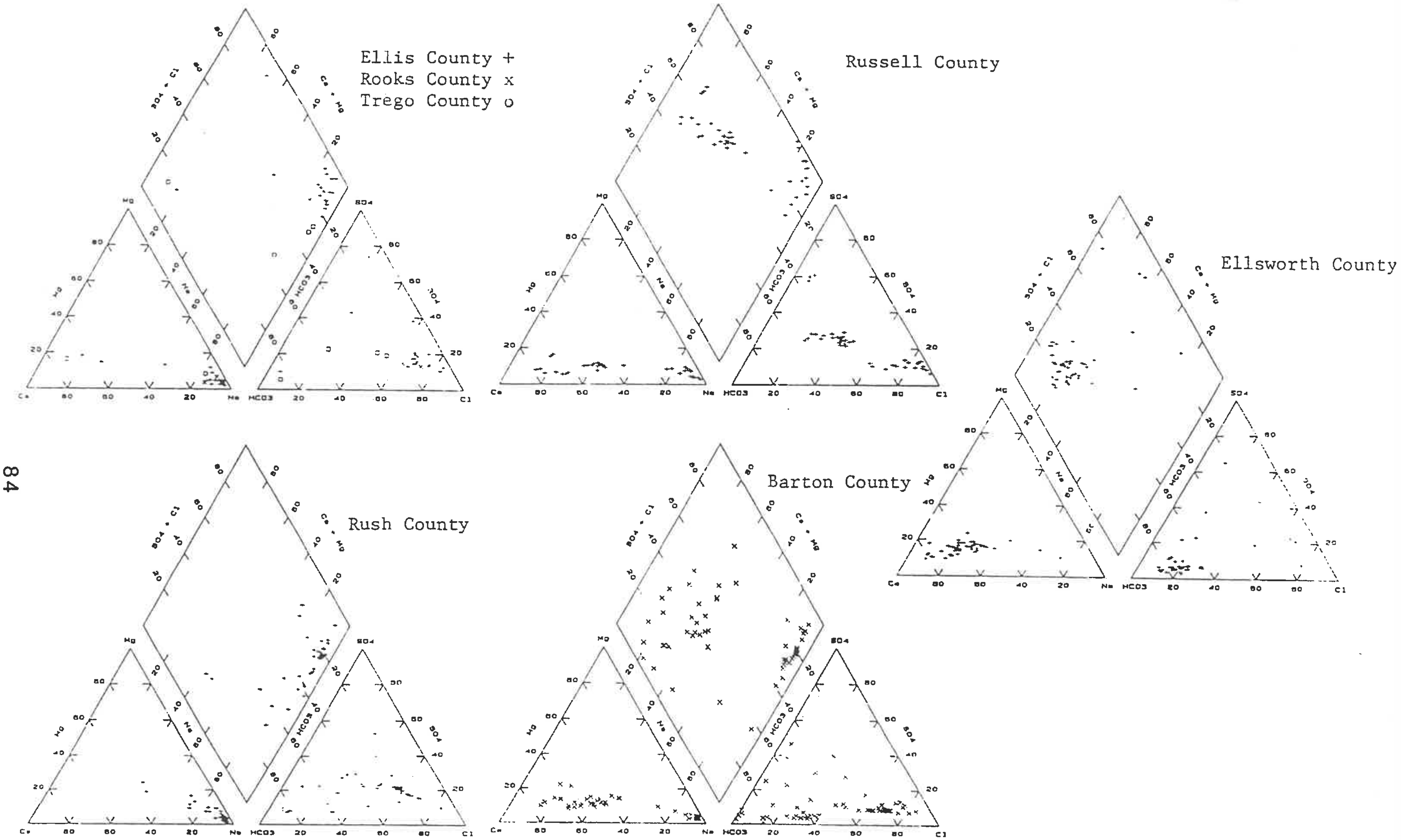
In addition to chemical analyses made by the KGS, data for the Dakota Formation (Great Plains aquifer) were selected from the USGS WATSTORE data file for the counties in the study area. The data were evaluated using the computer model WATEQF for aqueous chemical equilibria written by Plummer et al. (1976) to determine whether the cation-anion balance was correct to within ±5%. Data meeting this criteria were used in further evaluations of water chemistry. A summary of analyses used in the study are presented in Appendices A and B.

6.2 Chemical Characteristics of Ground Waters

6.2.1 Chemical Types of Ground Waters

Trilinear diagrams (Piper, 1944) were drawn for the USGS and KGS data sets to evaluate the occurrence of different chemical types of waters from water-supply wells in the study area (Figure 22). These diagrams were plotted on a county by county basis or groups of counties depending upon the quantity of data available in the area. The depths reported for the wells were compared to formation tops picked from geophysical logs of nearby boreholes where available.

The trilinear diagrams indicate a trend from calcium-bicarbonate type water in Ellsworth County and parts of Barton County, the eastern part of the study area, toward a calcium-bicarbonate-sulfate water in Russell County, to sodium-bicarbonate and sodium-chloride waters in parts of Russell, Barton, Ellis, Rooks, Rush, and Trego counties. A trilinear diagram for the samples collected by the KGS indicates similar trends (Figure 23 and Table 2). At this writing it is uncertain if these transitions are related to well depth. A generalized graph of all of the well depths versus total-dissolved-solids concentrations does not indicate a prominant trend (Figure 24). It is possible that depth versus



Ellis County +
Rooks County x
Trego County o

Russell County

Ellsworth County

Rush County

Barton County

Figure22. Distribution of Water Chemistry by County (USGS WATSTORE Data Set).

Figure 23. Trilinear Diagram of Water Samples Collected by KGS in June, 1987. (See Table 1 for Symbols).

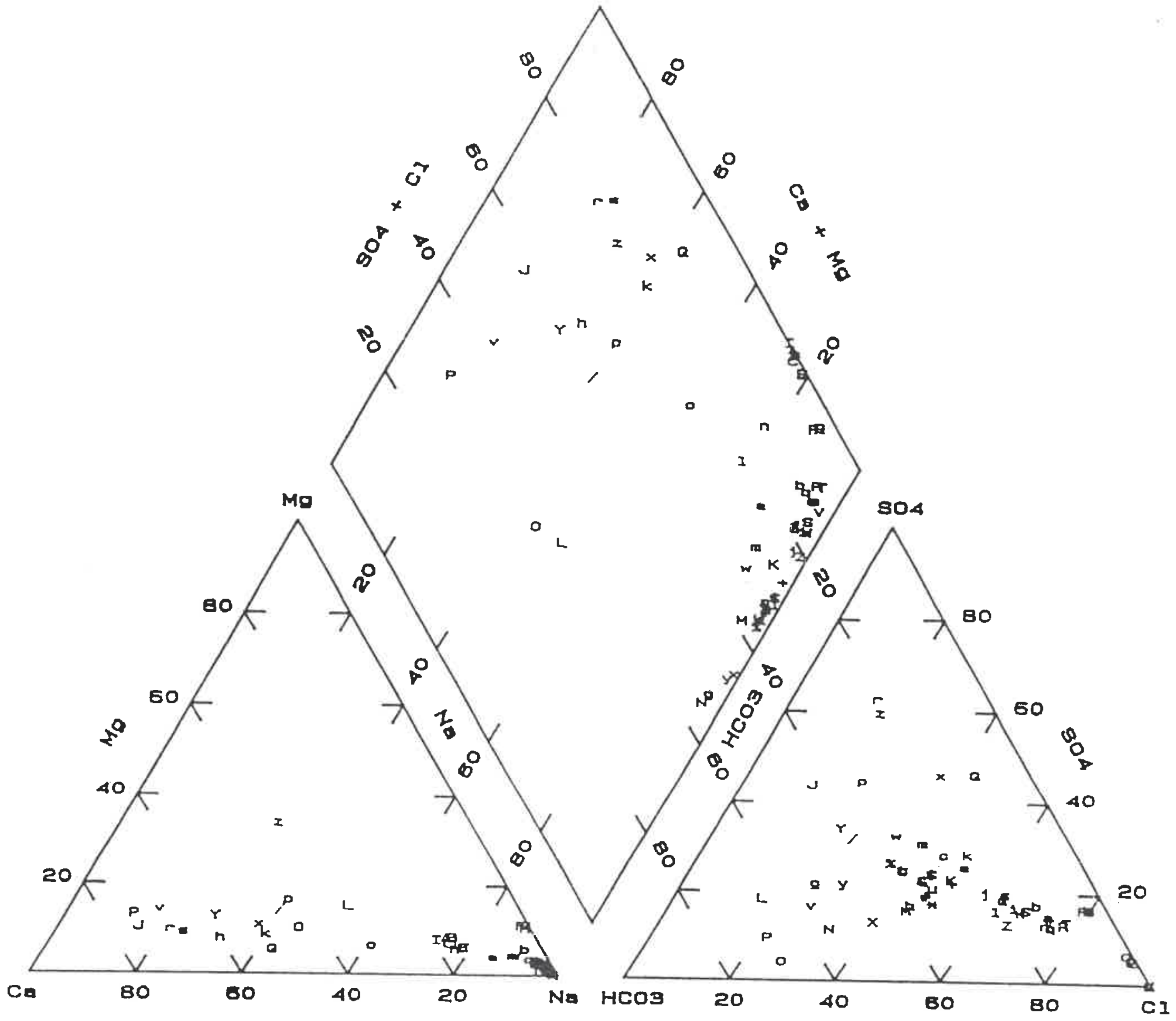


Figure 24. Total Dissolved Solids (TDS) Versus Depth for All Data
(See Appendices A & B)

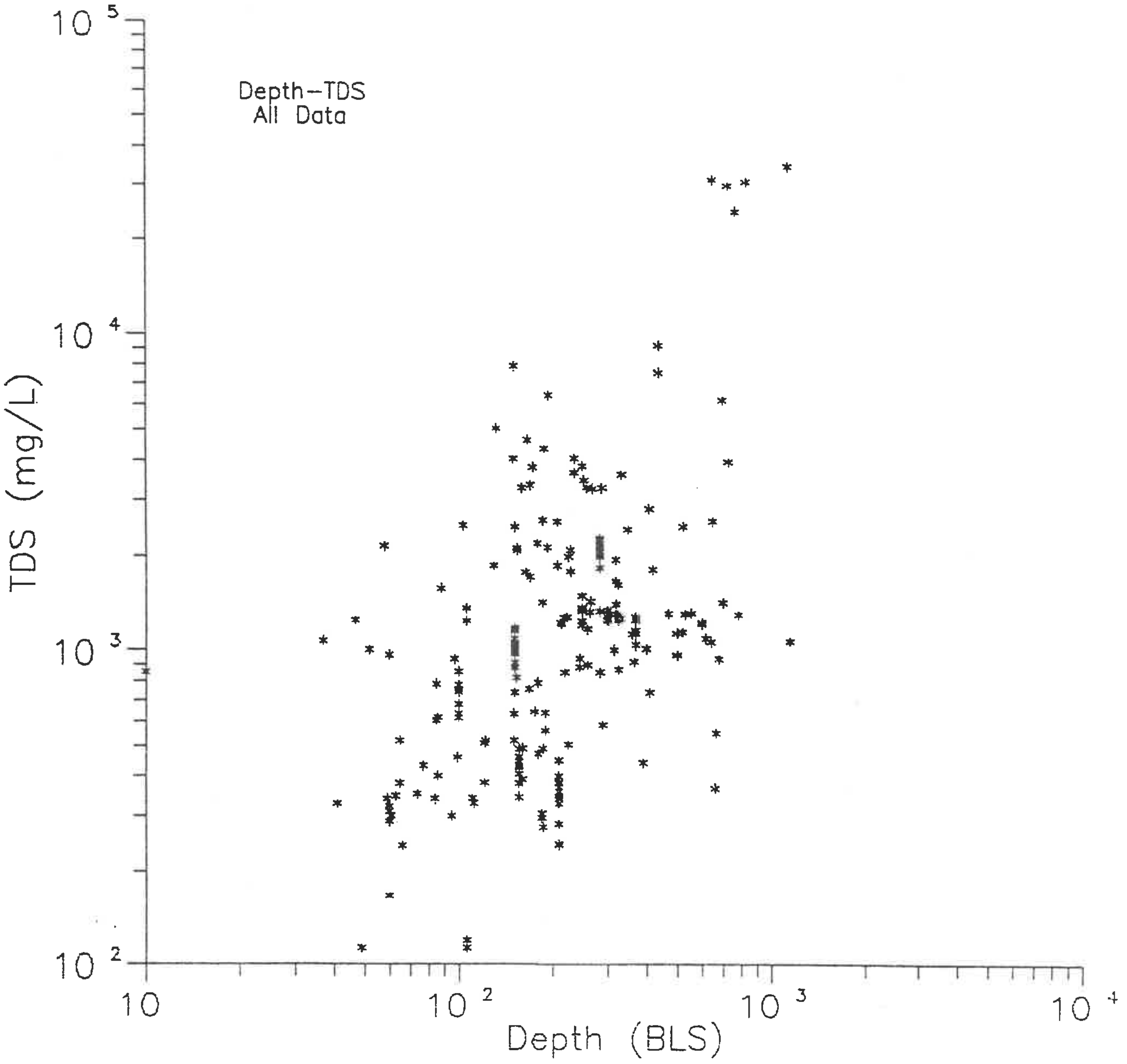


Table 2. Cation and Anion Percentages, Chemical Type of Water, and Identification of Symbols Used in the Trilinear Diagram for Ground Waters from Cretaceous and Permian Rocks in the Study Area (Figure 22). The percentages were calculated using milliequivalent/L values computed from the data in Appendix B (meq/L = mg/L x valance ÷ formula weight).

Ca % of meq/L	Mg % of meq/L	Na+K % of meq/L	CO_3 + HCO_3 % of meq/L	SO_4 % of meq/L	Cl+NO_3 % of meq/L	Character on diagram	KGS lab number	Site	Water type
1.57	11.41	87.01	4.79	16.60	78.59	A	87298	Braun-Cheyenne	Na-Cl
0.62	11.46	87.91	3.40	16.61	79.97	B	87299	Braun-Cedar H.	Na-Cl
0.86	11.05	88.07	3.57	17.01	79.40	C	87300	Braun-L. Dakota	Na-Cl
2.36	10.86	86.78	5.40	16.17	78.43	D	87842	Braun-U. Dakota	Na-Cl
1.90	10.31	87.80	5.01	15.45	79.54	E	880003	Braun-U. Dakota	Na-Cl
74.16	10.60	15.22	42.76	43.82	13.40	F	87302	Braun-spring	Ca-SO_4, HCO_3
35.85	8.23	55.92	15.89	19.40	64.71	G	87843	Hill City-U.D.	Na, Ca-Cl
12.62	8.69	78.68	0.90	8.41	90.60	H	880002	Gorham-Cedar H.	Na-Cl
9.27	6.94	83.79	0.98	9.58	89.45	I	880000	Gorham-Cheyenne	Na-Cl
1.14	1.38	97.48	8.67	13.14	78.18	J	880001	Gorham-U. Dakota	Na-Cl
2.75	3.02	94.21	26.75	22.86	50.38	K	87483	BT 5	Na-Cl
32.21	15.67	52.10	64.73	18.58	16.68	L	87484	BT 8	Na-HCO_3
2.86	2.75	94.38	38.69	16.05	45.24	M	87485	BT 12	Na-Cl, HCO_3
2.69	1.50	95.79	55.23	11.78	32.97	N	87486	BT 15	Na-HCO_3, Cl
43.88	10.79	45.31	68.03	4.36	27.59	O	87487	BT 43	Na, Ca-HCO_3
73.56	13.47	12.96	68.17	9.67	22.14	P	87488	BT 84	Ca-HCO_3
51.17	5.91	42.91	10.87	46.44	42.68	Q	87489	EL 11b	Ca, Na-SO_4, Cl
2.81	3.44	93.74	9.98	13.34	76.67	R	87490	EL 13	Na-Cl
1.73	2.23	96.03	15.73	16.47	67.79	S	87491	EL 20	Na-Cl
2.26	2.79	94.93	9.38	13.90	76.71	T	87492	EL 37	Na-Cl
1.42	1.40	97.17	35.19	24.66	40.13	U	87493	EL 39	Na-Cl, HCO_3
1.13	1.87	96.98	12.62	13.74	73.63	V	87494	EL 41	Na-Cl
1.11	1.81	97.06	16.97	15.85	67.16	W	87495	EL 42	Na-Cl
0.67	0.43	98.88	46.25	13.70	40.04	X	87496	GH 1	Na-HCO_3, Cl
58.35	13.23	28.41	42.29	34.11	23.58	Y	87497	GH 2	Ca-HCO_3, SO_4
0.78	0.72	98.48	20.92	13.33	65.73	Z	87498	RO 6	Na-Cl

Table 2 con't.

Ca % of meq/L	Mg % of meq/L	Na+K % of meq/L	CO_3 + HCO_3 % of meq/L	SO_4 % of meq/L	Cl+NO_3 % of meq/L	Character on diagram	KGS lab number	Site	Water type
1.99	2.81	95.19	12.38	14.92	72.69	a	87499	RO 11	Na-Cl
3.48	5.95	90.55	13.18	17.65	69.16	b	87500	RO 12	Na-Cl
2.08	3.36	94.55	12.95	12.64	74.40	c	87501	RO 60	Na-Cl
3.04	2.72	94.23	19.03	18.77	62.19	d	87502	RH 3	Na-Cl

total-dissolved-solids contents by county may correlate better with the variation of water types found throughout these counties. This aspect will be evaluated at a later time.

6.2.2 Distribution of Water Types

The chemical data on the samples collected by KGS shows that there are two major divisions of water types: sodium-chloride and mixed-type waters (Figure 25; Table 2). The mixed types include sodium-bicarbonate to calcium-sodium-sulfate-chloride waters and all combinations in between. The mixed type waters are represented by one symbol in Figure 25 as there is not enough information at present to fully explain the origin of these types of waters. Their presence suggests that one or more of the following processes may have been important in the origin of water types: (1) cation-exchange processes between the clay/shales in and around the sandstone lenses and the ground water in the system; (2) cross-formational flow across shale membranes; (3) dilution of formation waters by recharge from the surface; or (4) mixing of the ground waters with deeper brines moving upward into the system.

Figure 25 indicates that a corridor of sodium-chloride water exists through Rush, Ellis, Rooks, and parts of Russell counties. The occurrence

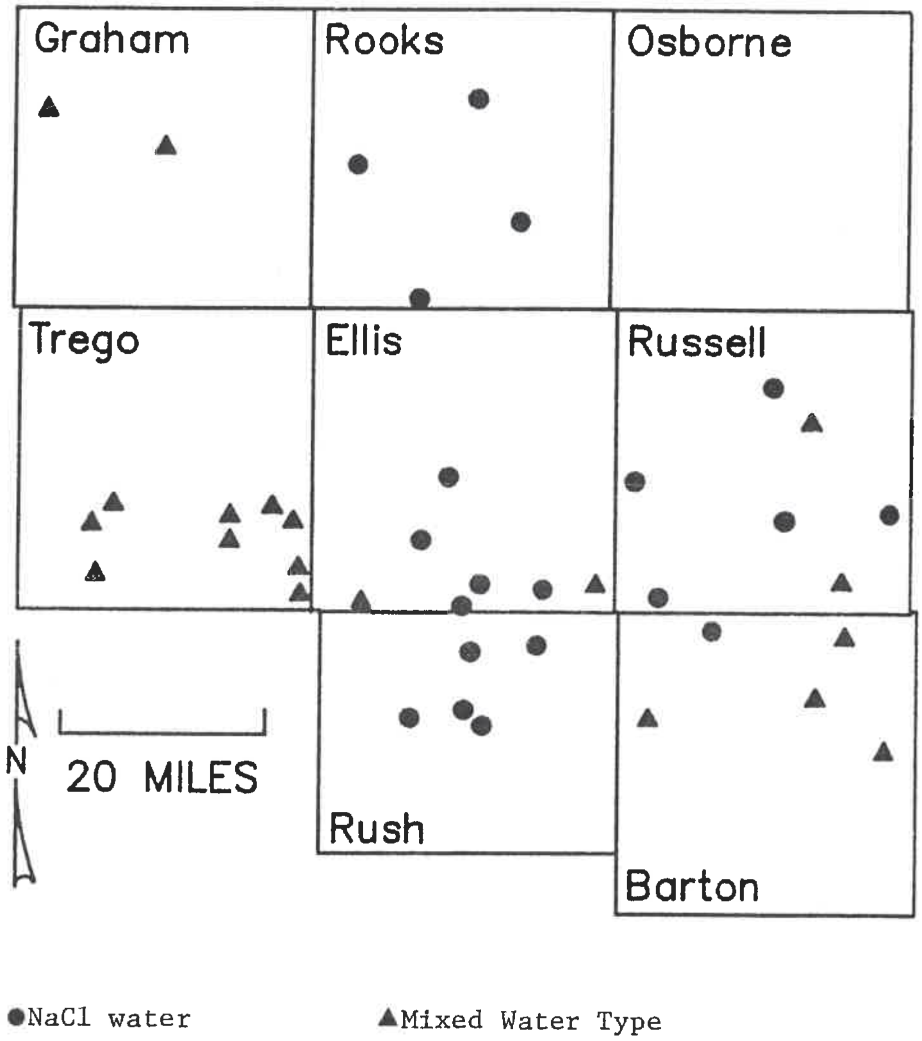


Figure 25. Distribution of water types from KGS sampling June, 1987 (see Table 2)

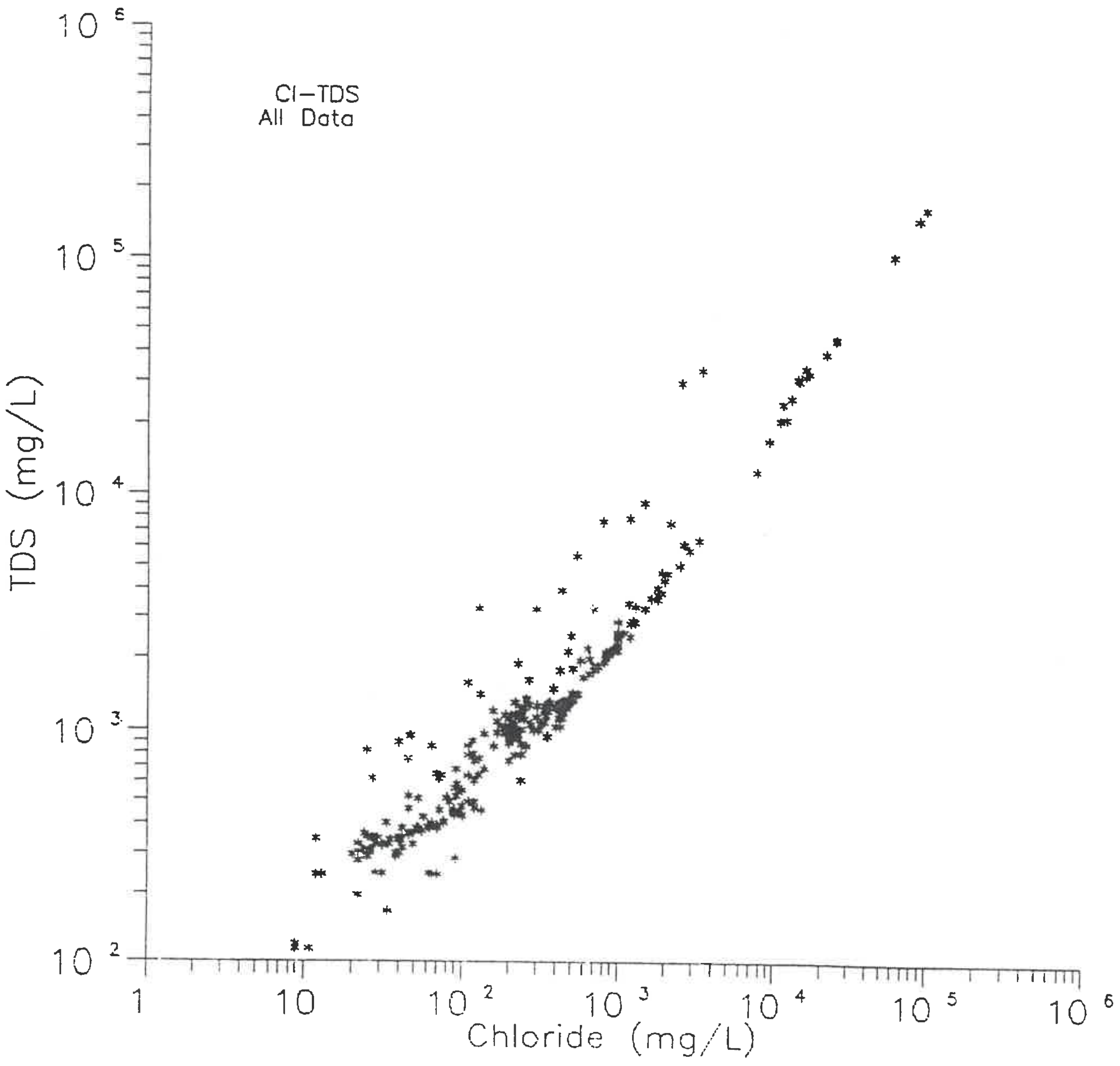


Figure 26. Total Dissolved Solids (TDS) Versus Chloride Concentration for All Wells

of sodium-chloride waters appears related to the Stockton and Fairport Natoma Anticlines in central Ellis and Rooks counties and in western Russell county. The oil-field brine samples (Table 3) plot near the sodium and chloride ends of the trilinear diagram (Figure 23).

6.2.3 Relationship between Total Dissolved Solids and Chloride Concentrations

A strong linear relationship exists between TDS and chloride concentrations (Figure 26). The scatter of points to the left of the line is probably related to waters with appreciable sulfate and/or bicarbonate concentrations relative to the chloride concentration. The waters represented as points to the left of the trend may be related to the mixed cation/anion type waters shown in Figures 23 and 25. Further information on flow dynamics in the system is needed in order to determine the origins of these waters.

Swineford and Williams (1945) characterized the waters in south-central to southwest Russell county. The percentage distribution of the major cation and anion equivalent concentrations in their water samples are given in Table 4 for comparison with the waters collected by the KGS in 1987. In general, the Dakota and lower formations contain sodium-

Table 3. Cation and Anion Percentages and Chemical Type of Water for Oil-Field Brines from the Study Area.

Ca % of meq/L	Mg % of meq/L	Na+K % of meq/L	CO3+ HCO3 % of meq/L	SO4 % of meq/L	Cl+NO3 % of meq/L	KGS lab number	Site	Water Type
17.23	8.76	73.99	0.03	0.00	99.96	87293	Fourway	Na-Cl
15.88	8.53	75.57	0.14	0.02	99.82	87294	Phillips	Na-Cl
17.38	7.33	75.27	1.44	6.60	91.95	87295	Allen	Na-Cl
15.14	6.29	78.56	0.88	5.64	93.46	87296	Nixon Irwin 1	Na-Cl
14.84	6.26	78.88	0.74	5.32	93.93	87297	Nixon Irwin C	Na-Cl
19.27	8.17	72.54	0.03	0.00	99.96	87301	Dreiling Leiker	Na-Cl

chloride waters with relatively low magnesium, calcium, bicarbonate, and sulfate concentrations. A few of the lower Dakota waters have low calcium, magnesium, and proportionately higher bicarbonate contents that are due to base-exchange and concomitant adjustment of carbonate equilibria. Swineford and Williams stressed the extreme difference between waters in the Upper Dakota and some of the waters in the Lower Dakota and those in the Kiowa, Cheyenne and Cedar Hills. The major chemical characteristics of the waters they examined are not much different from the water quality of the samples recently collected. They also stated that oil-field brines have probably affected the overall water chemistry of parts of the Dakota. The following results and discussion more conclusively address the effects of natural mechanisms and oil-brine disposal on water chemistry.

6.3 Origin of Dissolved Constituents

6.3.1 Determinations Based on Constituent Relationships

Most of the fresh ground waters (total-dissolved solids contents less than 1000 mg/l) in the Great Plains aquifer within the study area have calcium/magnesium molar ratios appreciably greater than unity and

Table 4. Cation and Anion Percentages and Formation for Data from Russell County (Swineford and Williams, 1945, Table 4).

Ca % of meq/L	Mg % of meq/L	Na + K % of meq/L	HCO3 % of meq/L	SO4 % of meq/L	Cl % of meq/L	Formation	Depth	Location
2.01	11.33	86.64	0.92	14.54	84.53	Permian	710-732	13S 15W 35BD
2.12	3.99	93.88	8.50	11.20	80.29	U. Dakota	225-233	13S 14W 32BC
2.43	3.93	93.63	8.58	11.08	80.32	L. Dakota	303	" " "
3.26	5.15	91.21	4.99	10.78	84.21	L. Dakota	412-420	" " "
3.31	0.17	88.51	2.70	12.21	85.08	Permian	625	" " "
5.00	6.47	88.52	1.54	7.54	67.10	L. Dakota	377	13S 14W 33BA
2.75	9.86	87.38	1.39	13.33	85.27	Permian	560-570	" " "
2.64	5.54	91.81	4.1	12.97	82.92	L. Dakota	295-310	14S 14W 10AB
3.01	7.19	89.79	2.79	13.15	84.05	Cheyenne	422-430	" " "
4.58	5.70	89.70	4.47	7.82	87.70	L. Dakota	270-280	14S 14W 14DC
4.19	7.37	88.42	3.01	11.19	85.78	L. Dakota	355-370	" " "
3.98	7.68	88.33	2.86	10.89	86.29	Cheyenne	423-443	" " "
2.83	12.20	84.96	0.29	14.70	85.00	Permian	680-692	" " "
2.61	6.12	91.25	3.62	9.46	86.91	L. Dakota	270-275	14S 14W 10CD
3.30	5.59	91.09	3.50	8.61	87.98	L. Dakota	355-370	" " "
3.22	8.43	88.34	1.97	11.75	86.26	Cheyenne	448-465	" " "
1.89	3.35	94.75	13.16	11.47	74.69	U. Dakota	240-245	13S 13W 31BC
2.05	3.88	94.05	9.90	11.62	78.46	L. Dakota	355-368	" " "
3.67	6.33	89.98	3.39	11.45	85.15	L. Dakota	380-410	" " "
24.76	9.54	65.68	18.20	12.03	69.75	U. Dakota	110-125	14S 14W 25AB
3.77	7.09	89.13	3.33	11.59	85.07	L. Dakota	255-260	" " "
3.64	7.19	89.15	1.43	9.98	88.58	Cheyenne	370-380	" " "
3.55	8.47	88.02	1.03	11.51	87.45	Permian	420-433	" " "
3.27	3.16	93.55	15.38	13.08	71.53	U. Dakota	120-130	14S 14W 30AB
4.31	4.13	91.54	11.21	11.57	77.20	U. Dakota	186-190	" " "
3.75	7.38	88.86	2.92	10.92	86.14	L. Dakota	275-300	" " "
3.58	6.57	89.98	4.03	11.57	84.39	L. Dakota	320-335	" " "
8.51	7.02	84.46	10.62	7.93	81.43	L. Dakota	235-250	14S 14W 21DC
3.13	6.05	90.81	3.65	11.48	84.85	L. Dakota	265-290	" " "
6.10	7.77	86.11	2.98	11.93	85.07	L. Dakota	320-350	" " "
3.31	7.39	89.29	1.55	10.73	87.71	Cheyenne	440-475	" " "

Table 4. Cation and Anion Percentages and Formation for Data from Russell County (Swineford and Williams, 1945, Table 4).

Ca %of meq/L	Mg % of meq/L	Na + K % of meq/L	HCO_3 % of meq/L	SO_4 % of meq/L	Cl % of meq/L	Formation	Depth	Location
2.09	2.29	95.61	18.54	7.58	73.86	U. Dakota	160-170	14S 14W 27AC
5.14	6.74	88.10	6.91	12.23	80.85	U. Dakota	215-225	" " "
3.24	7.24	89.50	1.32	10.48	88.18	L. Dakota	345-360	" " "
6.39	5.53	88.00	7.56	13.80	78.6	U. Dakota	200-220	13S 15W 33BC
3.57	7.14	89.27	5.64	12.19	82.15	L. Dakota	300-375	" " "
3.32	8.17	88.50	3.80	12.13	84.05	Cheyenne	495	" " "
3.54	7.79	88.60	4.38	12.35	83.20	Permian	545-550	" " "

Sodium + Potassium (Na + K) values not analytically measured. Values are calculated.

sulfate concentrations comprising a substantial percentage of the anions (Table 2). Dissolution of limestone containing various amounts of gypsum is the predominant source of the major constituents in these waters.

The origin of the water is probably surface recharge in the local or subregional vicinity that flows from the surface through Cretaceous rocks to the location of the well. Some of the fresh ground waters are derived from shallow wells, while others are from wells a few to several hundred feet in depth. Many of the fresh waters also have nitrate concentrations exceeding 10 mg/l (as nitrate) in comparison with the low nitrate contents of most of the ground waters in the Great Plains aquifer. The nitrate is an indicator of surface contamination, supporting the mechanism of a local surface source of water.

Several of the slightly brackish (1000-3000 mg/l total-dissolved solids) ground waters also contain relatively high concentrations of nitrate. These waters could be a mixture of shallow ground waters from surface recharge mixed with deeper, saline water. Many of the wells are open over large intervals that include several different water-bearing zones, thus, the water pumped from such wells can be derived from different sources.

The relative concentrations of the major cationic constituents --i.e., calcium, magnesium, and sodium-- in ground waters in the Great Plains aquifer are derived not only from mixing of varying amounts of local or regional recharge with saline ground water, but also are affected by ion exchange. Many of the ground waters collected in this study have a Na/(Ca + Mg) equivalent ratio greater than 10 in comparison with the oil brines which have a Na/(Ca + Mg) of 2-4. The high ratios can be explained by the movement of fresher water into the aquifer and exchange of calcium and magnesium for sodium on clays in the Great Plains aquifer. Most of the ground water containing high nitrate concentrations have Na/(Ca + Mg) equivalent ratios less than 0.8, further indicating that these waters are derived from surface recharge through carbonate rocks and have not been appreciably affected by ion exchange in the Great Plains aquifer. Other waters with both high nitrate contents and high Na/(Ca + Mg) equivalent ratios are probably a mixture of waters from different formations due to the construction of the wells.

In order for the exchange process that increases the Na/(Ca + Mg) to occur, the clays must have previously been in contact with waters of higher Na/(Ca + Mg), i.e., more saline waters with a Na/(Ca + Mg) equivalent ratio appreciably greater than unity. The origin of the clays or the saline water cannot be determined on the basis of the major constituents alone. The distribution of boron concentrations in the fresh to moderately saline waters collected in this study suggest that some of the exchanging clays causing chemical alteration of the water chemistry had a marine origin. Boron concentrations in the fresh to moderately saline (less than 10,000 mg/L total-dissolved solids) waters are positively correlated with the Na/(Ca + Mg) ratios (Figure 27). Marine clays contain substantially more boron than continental clays, both in structural and adsorbed positions (Fairbridge, 1972). As fresher waters flowed through the marine clays, both major cation and boron exchange could occur. Concomitant processes with the cation exchange have

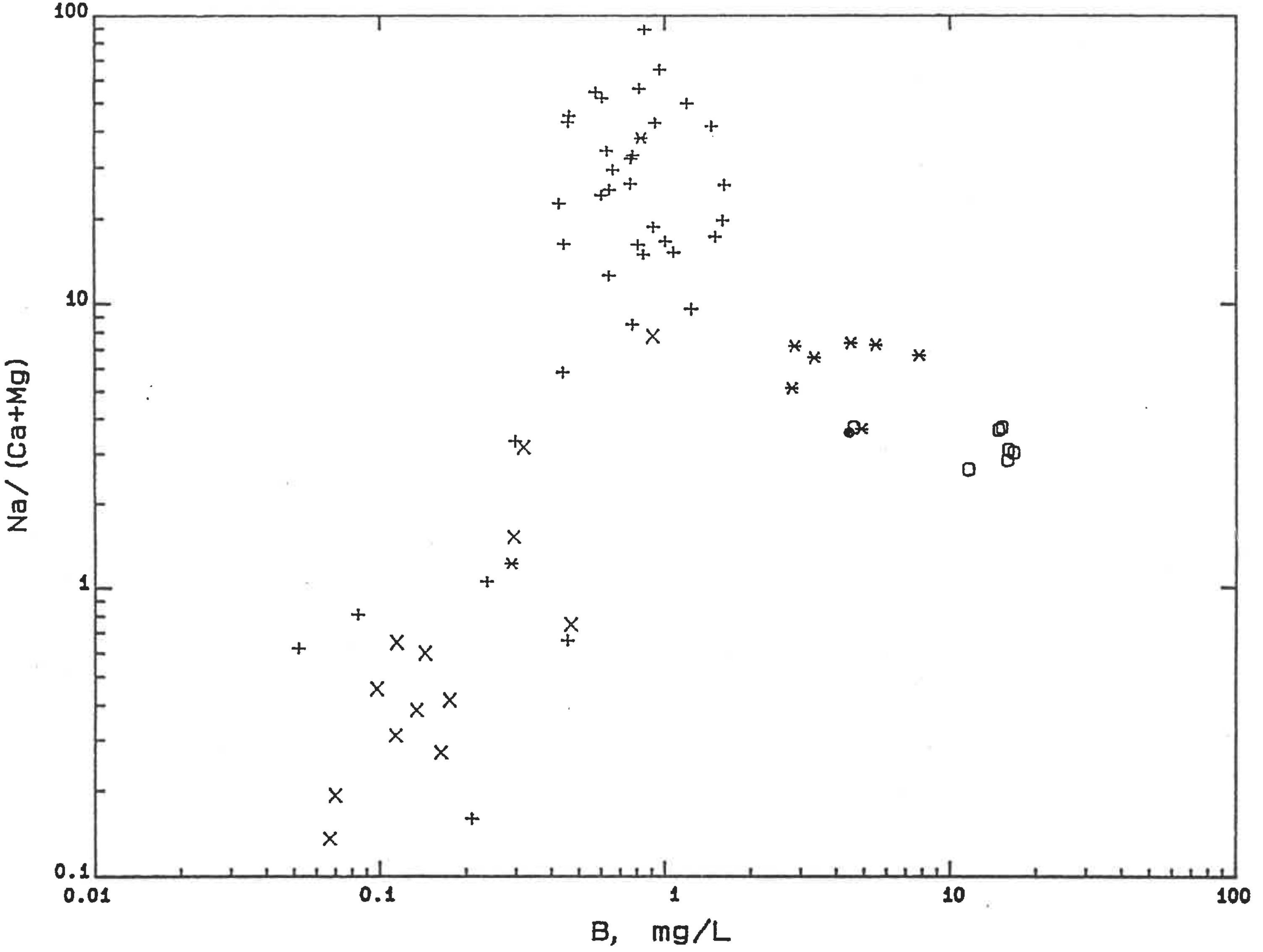


Figure 27. Equivalent ratio of Na/(Ca+Mg) versus boron concentration for KGS data. Well waters with nitrate concentrations <10 mg/L (+) and >10 mg/L (X); multiple-completion monitoring wells (*); oil-field brines (O); seawater (●).

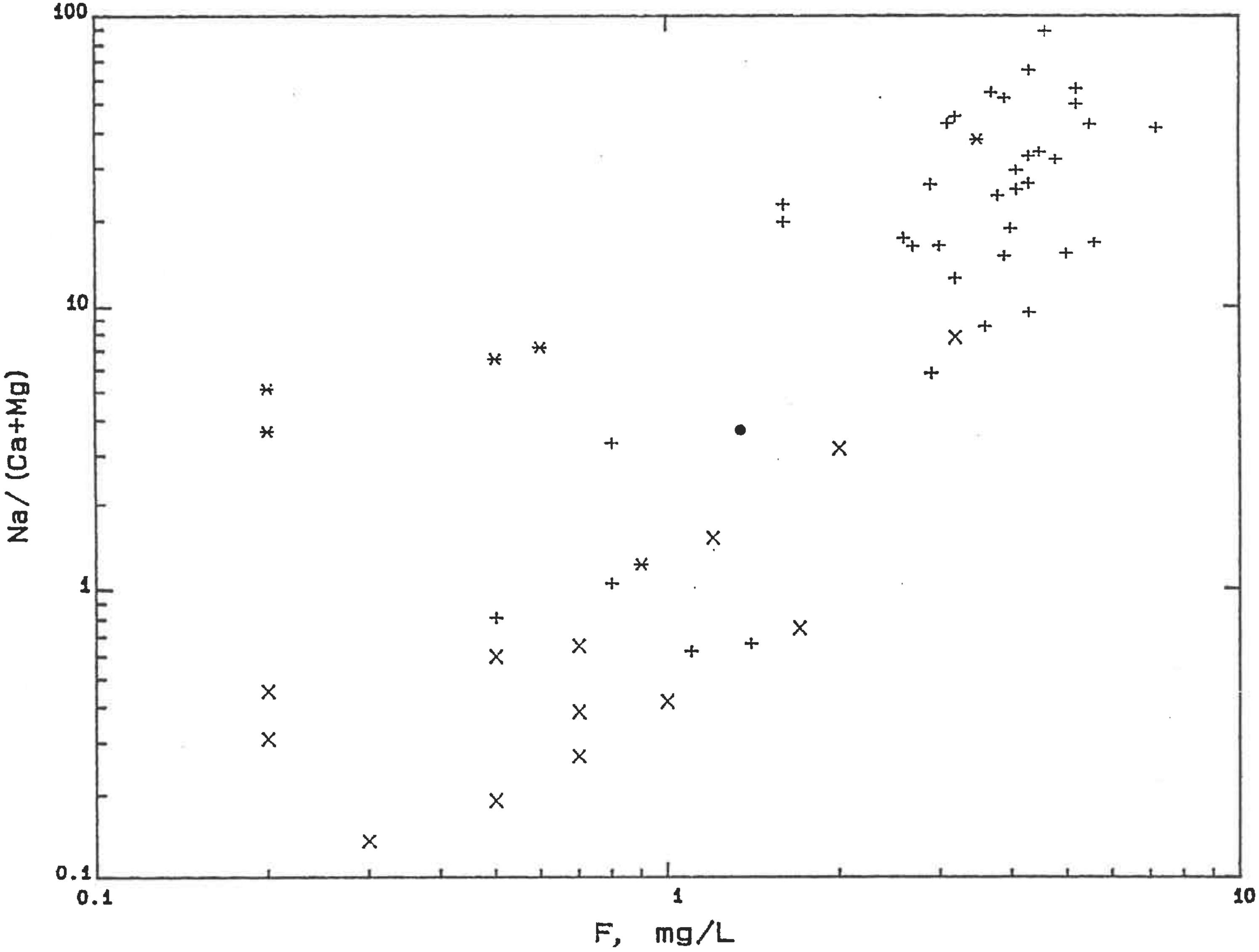


Figure 28. Equivalent ratio of Na/(Ca+Mg) versus fluoride concentration for KGS data. Well waters with nitrate concentrations <10 mg/L (+) and >10 mg/L (X); multiple-completion monitoring wells (*); oil-field brines (O); seawater (•).

further affected the water chemistry within the Great Plains aquifer. As calcium and magnesium decreased during the exchange, the waters became under-saturated with respect to calcite. Calcite could then dissolve resulting in increases in calcium and bicarbonate concentrations. The dissolved calcium would then be readsorbed on the clays, while most of the bicarbonate would stay in solution. Many of the ground waters in the Great Plains aquifer have relatively high bicarbonate concentrations (greater than 500 mg/l). However, calcite contents in the sediments of the Great Plains aquifer are small. Therefore, many of the waters affected by exchange during flow through clays are still undersaturated with respect to calcite, thereby limiting the increase in the bicarbonate contents.

The decrease in the calcium concentrations caused by ion exchange have also caused increases in the fluoride contents of ground waters in the Great Plains aquifer as shown by a positive correlation between Na/(Ca + Mg) ratios and fluoride concentrations (Figure 28). Chemical equilibrium calculations indicate that the mineral fluorite is the probable control on the fluoride content of high fluoride (greater than 1 mg/l) waters. As the calcium content of waters flowing through clays in the aquifer decreased during exchange, fluorite dissolved to bring the water back into equilibrium with the mineral. Many of the fluoride concentrations in the usable waters are greater than the drinking water standard.

6.3.2 Identification of Salinity Sources Using Mixing Curves

The origin of the present salinity of waters in the Great Plains aquifer was determined from mixing curves on plots of Br/Cl, I/Cl, and B/Cl versus chloride concentration based on the method of Whittemore (1984, 1988). Points for ground waters collected during this study fit within boundaries for the mixing of fresh waters with saltwaters containing Br/Cl and I/Cl weight ratios appreciably below those for oil-field brines from the study area (Figures 29 and 30). Weight ratios of B/Cl for oil-field brines range from the same as to only slightly higher than the B/Cl of the expected saltwater source for the mixing zone enclosing points for the aquifer waters (Figure 31).

Although the B/Cl and I/Cl ratios for seawater fall within the expected range for the salinity source for the Great Plains aquifer waters, connate water similar to the composition of seawater cannot be the major source of salinity because the Br/Cl ratio for seawater is much higher than for the expected saltwater source. Points for waters sampled from the

Haberer No. 1 well in Russell County (NW, SW, NW sec. 23, T12S, R15W) drilled by the U.S. Geological Survey are also plotted on Figures 29 and 30, and labeled HD for water from the Dakota Formation and HC for water from the Cheyenne Sandstone and Cedar Hills Sandstone. The Haberer well samples plot near the center of the saltwater end of the mixing zones for Br/Cl and I/Cl drawn for the samples collected from the present study. The range in the Br/Cl, I/Cl, and B/Cl ratios for the expected saltwater source are all somewhat higher than the ratios for halite-solution brines from the Cedar Hills Sandstone and Salt Plain Formation in eastern Stafford County (Whittemore et al., 1987). The ranges of Br/Cl and B/Cl ratios for the saltwaters from the Permian rocks in Stafford County are 1-2 x 10^4 and 9-24 x 10^5. The Br/Cl in the Permian saltwaters in Stafford County is about the same as for that in halite-solution brines from the Hutchinson Salt Member of the Wellington Formation, while the B/Cl is higher than the 2.5-7 x 10^5 range for the Wellington (Whittemore, et al., 1981). Although only a few iodine determinations are available for saltwaters from the Permian bedrock in Stafford County, the values for I/Cl appear to be in the same range as for halite-solution brines from the Wellington Formation, 1.4-3 x 10^6.

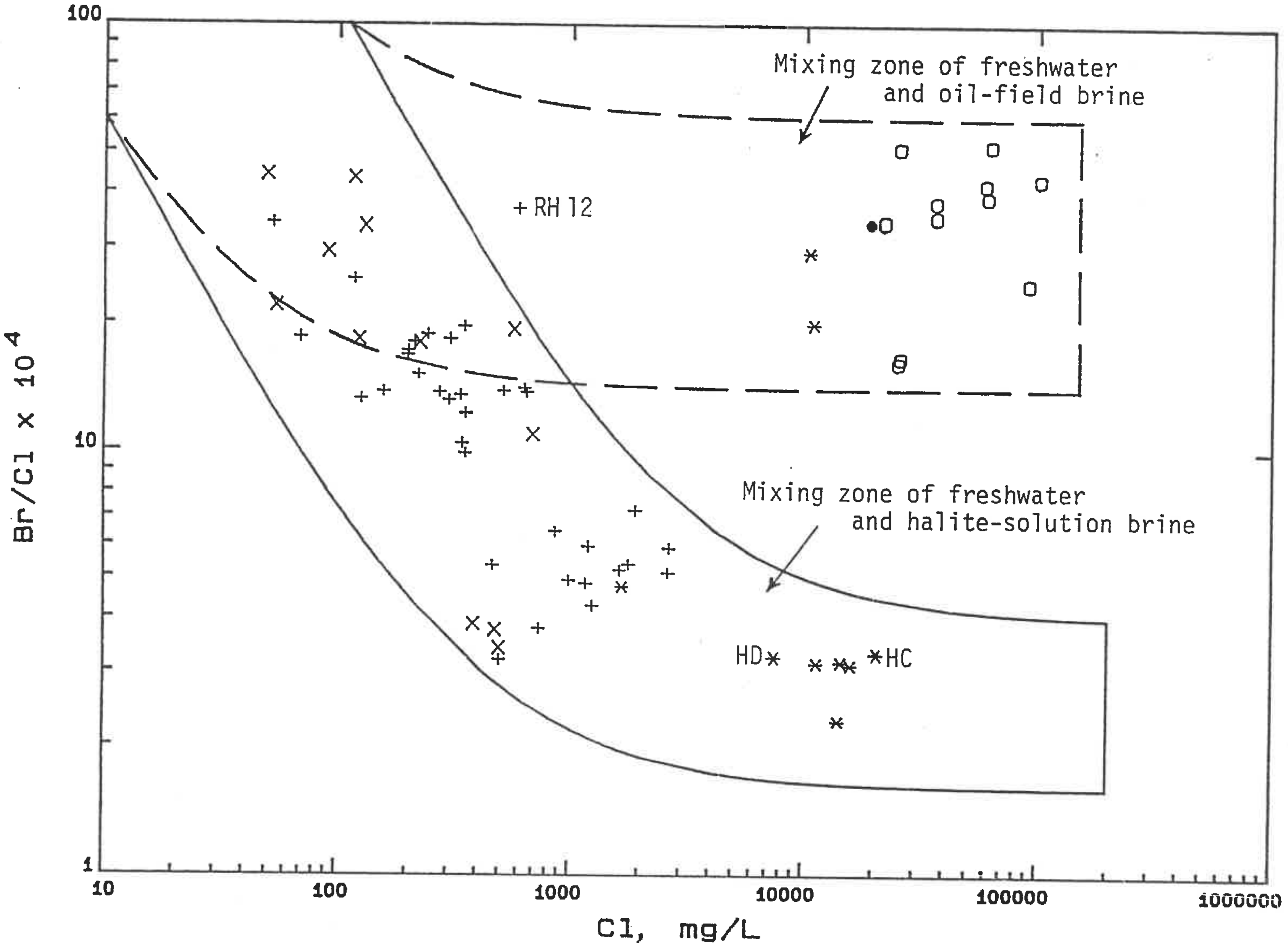


Figure 29. Weight ratio of Br/Cl x 10^4 versus chloride concentration for KGS data. Well waters with nitrate concentrations <10 mg/L (+) and >10 mg/L (X); multiple-completion monitoring wells (*); oil-field brines (O); seawater (•).

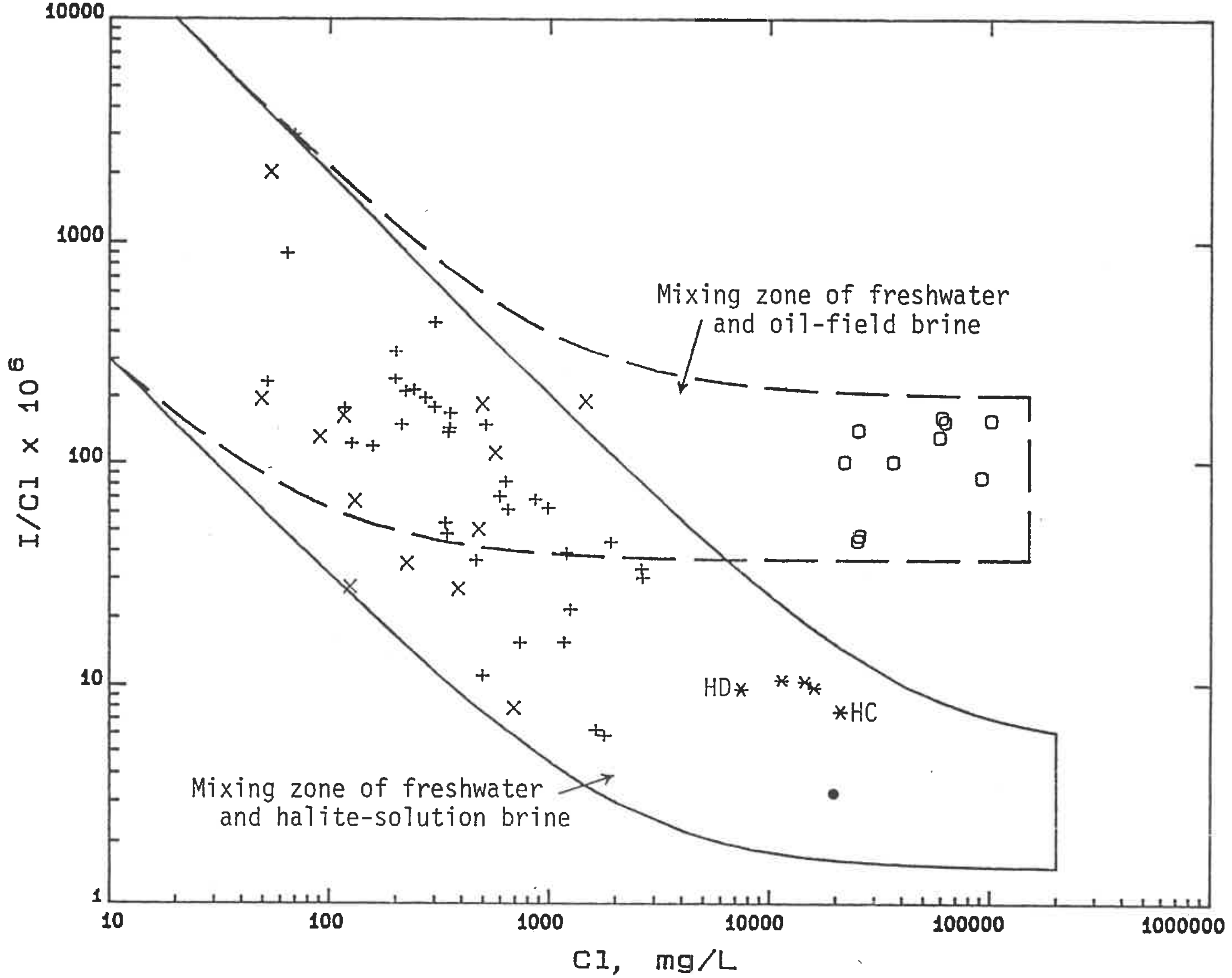


Figure 30. Weight ratio of I/Cl x 10^6 versus chloride concentration for KGS data. Well waters with nitrate concentrations <10 mg/L (+) and >10 mg/L (X); multiple-completion monitoring wells (*); oil-field brines (O); seawater (●).

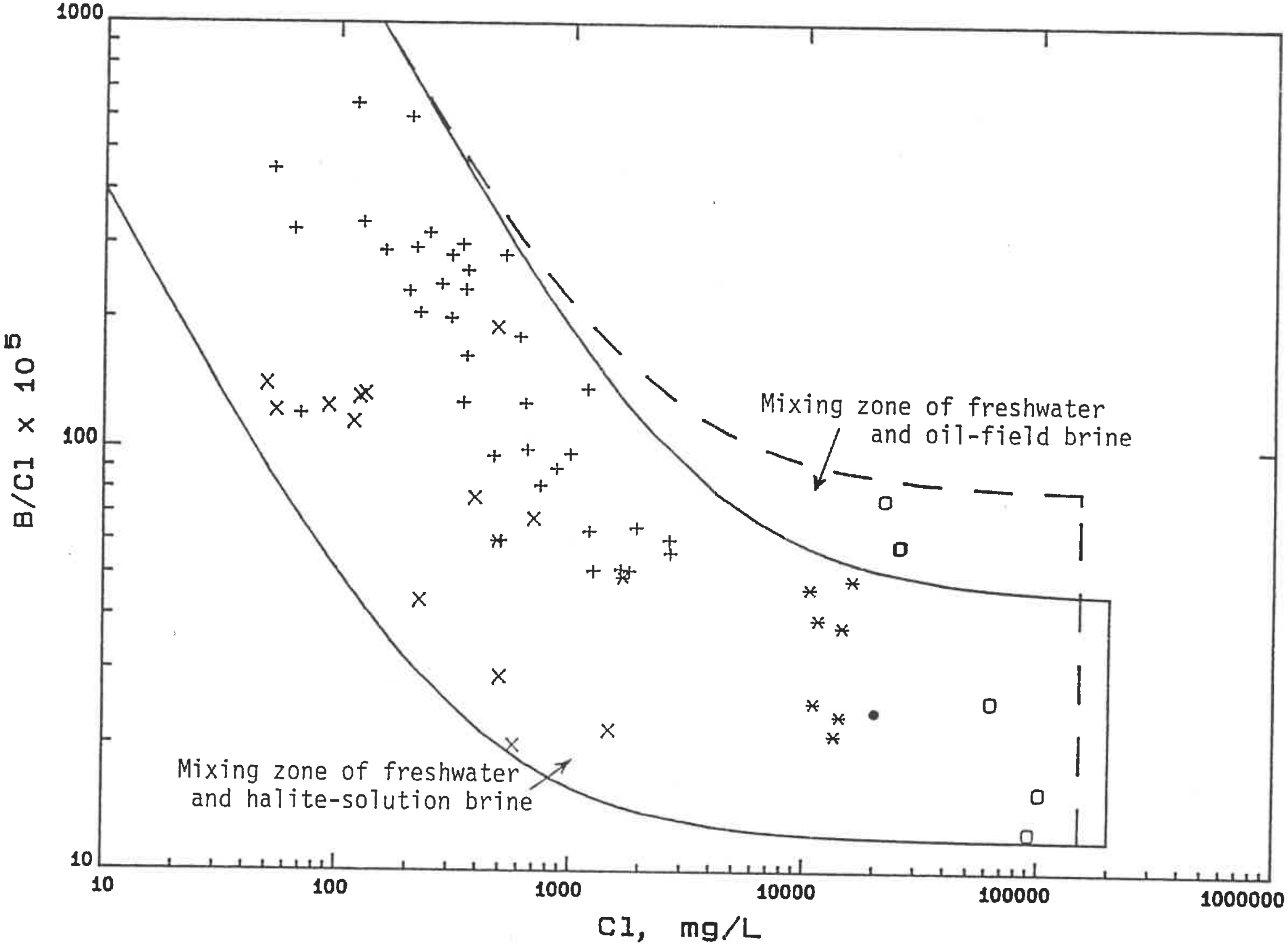


Figure 31. Weight ratio of B/Cl x 10^5 versus chloride concentration for KGS data. Well waters with nitrate concentrations <10 mg/L (+) and >10 mg/L (X); multiple-completion monitoring wells (*); oil-field brines (O); seawater (●).

The major salinity source for ground waters from the Great Plains aquifer sampled during the current study thus appears to be halite-solution derived from underlying Permian rocks. The higher ratios of Br/Cl for saltwaters in the Permian rocks of Stafford County and in the Wellington Formation farther to the east might reflect small amounts of waters similar in chemistry to seawater remaining in the mixture after the intrusion of the Permian saltwaters. The slightly higher I/Cl and B/Cl for the expected salinity source for the Great Plains aquifer could be the result of chemical changes occurring during the flow of water through clays. Boron concentrations could have increased during ion exchange as described above, and small amounts of iodine could have been leached from higher contents of organic matter that are often associated with clays, particularly marine clays.

Only one well-water sample collected from the Cretaceous rocks during the areal survey of water quality may have been affected by a saltwater source with a Br/Cl similar to oil-field brine. The sample site (RH 12) is in northern Rush County. If the water is a mixture of ground water having a chemistry that would place it below the mixing curve boundary for freshwater and halite-solution brine in Figure 29, with oil-field brine in the middle of the Br/Cl range for oil brine in this figure, the chloride contribution from the oil brine would need to be at least 200 mg/l. No oil fields appear on the Kansas Geological Survey map of oil and gas in Kansas in the area of this well, however. Additional investigation of this site is needed to explain the anomalous chemistry of the ground water.

The other two points for waters collected in this study that fall within the freshwater and oil-brine mixing zone are for the Gorham monitoring site. The results of the identification are discussed under the section on the monitoring sites.

6.3.3 Isotope Studies

The use of isotopes in hydrologic studies is based on the premise that the relative mass abundance of light to heavy isotopes is large and that the occurrence of some natural process modifies the relative abundance of an element's isotopes in a system (Turan, 1982). Measurement of absolute isotope abundance is difficult; therefore, relative isotopic ratios are measured. The common method is to compare the abundance of the natural isotope with a standard. For example, $^{18}O/^{16}O$ of a sample is compared to the $^{18}O/^{16}O$ of SMOW (Standard Mean Ocean Water as established by the

International Atomic Energy Agency). The relative abundance of is represented by the formula:

$$\delta^{18}O = (R_{sample}/R_{standard} - 1) \times 1000$$

where $R = {}^{18}O/{}^{16}O$. The symbol δ (delta) designates relative difference in concentration with units of permil (0/00). A value of $\delta^{18}O = -10$ 0/00 means that the sample contains 10 parts per thousand less ^{18}O than the standard. Isotope values with a negative sign are considered isotopically depleted with respect to a standard; those samples with a plus sign are considered isotopically heavier with respect to a standard. The variation of sign for isotopes is useful in interpreting the type of environment the water has come from or migrated into or the type of water/rock interaction that has occurred along the flow path.

Each isotope such as deuterium (^{2}H or D), and sulfur-34 (^{34}S) is defined similarly. The only difference is the standard to which each is compared. Oxygen-18 and deuterium are compared to SMOW. Sulfur-34 is compared to the Canyon Diablo meteorite (Nielson,1979).

Fractionation by chemical and physical reactions is the process by which isotopes are separated and concentrated. Physical fractionation processes include rates of diffusion, evaporation, condensation, freezing, or melting. A phase change such as the condensation of rain separates isotopes by physical fractionation (Faure, 1979; Turan, 1982). Chemical fractionation occurs due to the different bond energies of light and heavy isotopes. Heavier isotopes concentrate in chemical compounds with the strongest chemical bonds. The strength of the chemical bonds is a function of vibrational frequency and relative velocity of the molecules. Lighter molecules have higher vibrational frequencies and therefore the bonds between molecules are easier to break. The heavier isotopes have lower vibrational frequencies (i.e. stronger bonding tendencies) and therefore concentrate in resulting products (Bigeleison, 1965; Turan, 1982).

Twenty-six samples were collected for determination of ^{18}O, D, and ^{34}S. The isotope values and designation letters are listed in Table 5. These isotopes were chosen for study because of their usefulness in determining the mixing of waters, cross-formational flow, and invasion of salt water into other formations.

Table 5. Formations Sampled for Oxygen, Deuterium, and Sulfur Isotopes

Rock Unit	County Code	Location			$\delta^{18}O$ (permil)	δD (permil)	$\delta^{34}S$ (permil)	Isotope Label
Barton County								
KC-Lan	009	18S	13W	22D	-1.2	-12	11.7	R
Arb	009	18S	13W	23B	-5.7	-49	25.4	S
Arb	009	18S	13W	22-#5	-11.3	-84	20.7	T
U.Dakota	009	19S	13W	12DBD	-7.6	-56	-4.5	P
U.Dakota	009	19S	13W	12BBD	-8.0	-58	-2.6	Q
Ellis County								
Arb	051	14S	19W	17BS/2	-9.1	-69	15.5	W
Arb	051	14S	19W	17BN/2	-9.2	-75	16.8	X
U. Dakota	051	12S	19W	30A	-8.9	-65	*	E
L.Dakota	051	12S	18W	30A	-8.4	-57	11.7	F
Cheyenne	051	12S	18W	30A	-8.0	-57	11.8	G
Cedar Hills	051	12S	18W	30A	-8.7	-62	12.1	H
Arb	051	13S	18W	23	-0.9	-10	13.4	Y
Spring	051	12S	18W	30A	-7.1	-50	-8.4	Z
Graham County								
U.Dakota	065	08S	23W	25	-11.4	-78	13.8	B
L. Dakota	065	08S	23W	25	-11.4	-84	6.6	C
L. Dakota	065	07S	25W	21DCD	-12.1	-89	*	D
GMD5								
Salt Plain	155	24S	10W	06DCCC	-6.7	-45	11.3	AA
Cedar Hills	185	25S	12W	11AAAD	-8.9	-68	11.5	BB
Cedar Hills	185	23S	13W	36DCCC	-6.3	-44	8.1	CC
Russell County								
U.Dakota	167	13S	15W	32BCB	-10.7	-80	4.8	I
U. Dakota	167	13S	15W	32BCB	-11.1	-82	*	J
Cheyenne	167	13S	15W	32BCB	-10.0	-73	3.6	K
Cedar Hills	167	13S	15W	32BCB	-11.0	-82	12.9	L
U. Dakota	167	12S	15W	14	-11.2	-80	6.9	M
L. Dakota	167	12S	15W	14	-11.0	-74	7.3	N
Lansing-KC	167	13S	15W	32B	-11.1	-82	*	O

* Interference in sample.

6.3.3.1 Oxygen and Deuterium Isotopes

Variation in isotopic composition is due to a variety of causes such as evaporation processes, mixing of waters of different origins, cross-formational flow processes, or recharge from meteoric water. ^{18}O and D values are frequently plotted together and interpreted in comparison to the meteoric water line as developed by Craig (1961). The line defined by the equation: $\delta D = 8 (\delta ^{18}O) + 10$ is based on precipitation data collected on a world-wide basis. This line is shown in Figure 32 as a reference for the data collected in this study. The D and ^{18}O content in precipitation from any locality will plot on this line. The D and ^{18}O values for precipitation from Manhattan, KS, ($\delta D = -53$, $\delta ^{18}O = -7.5$, Chadhuri, personal communication, 1988) are shown in Figure 32 for reference.

The data collected in this study shows a parallel best fit line to the meteoric line. This indicates that the source of the water at the tested sites was primarily from meteoric water although the age of that water may have been Pleistocene or older. Oxygen-18 and deuterium are not used for age dating.

A wide variety of sources of waters were collected for this study in order to determine if any mixing scenarios were occurring between the brines that might be disposed of in the Cedar Hills formation and the

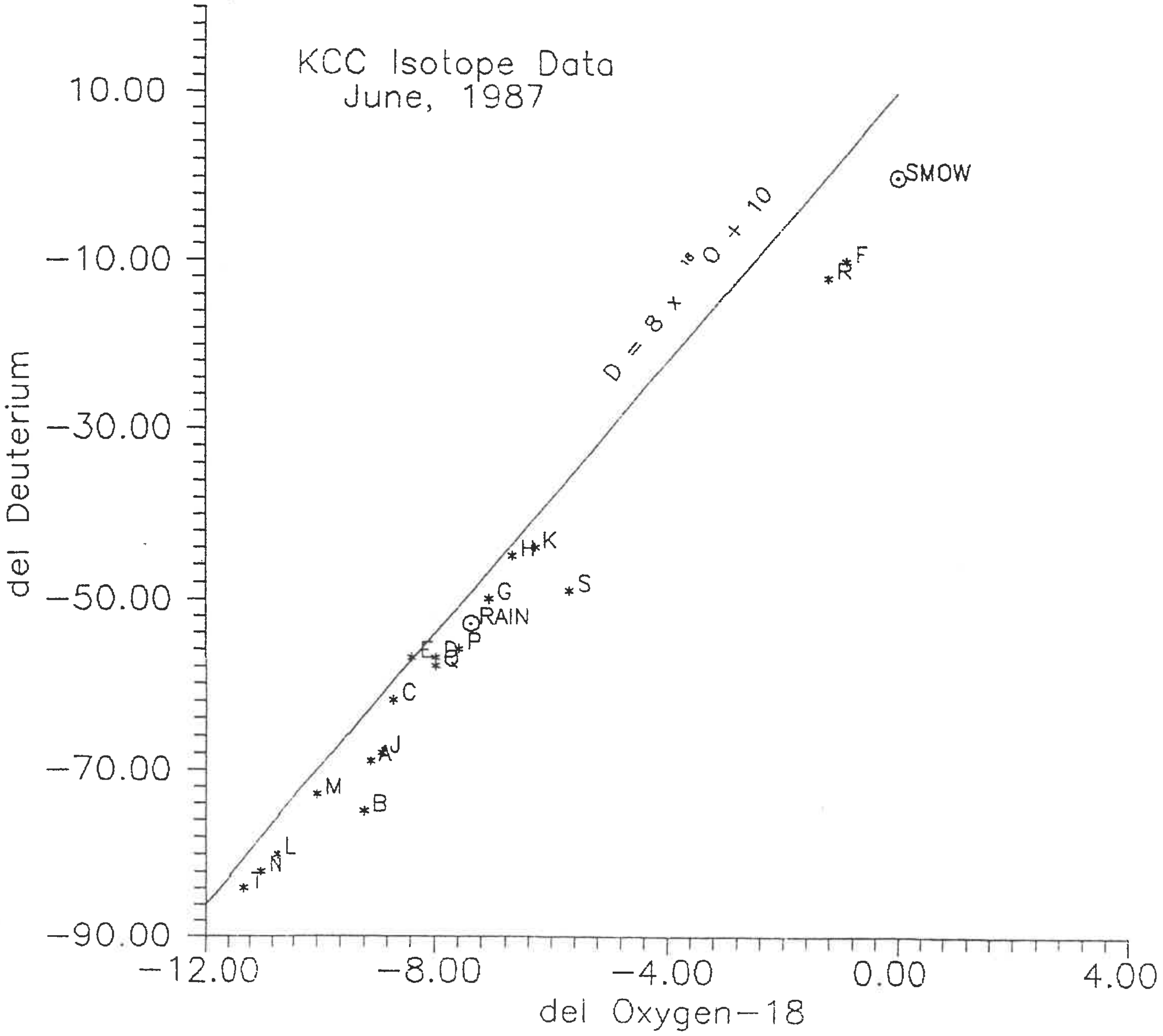


Figure 32. ^{18}O and Deuterium Composition of Groundwaters and Oil-Field Brines from Study Area (See Table 4 for Labels)

overlying formations. The scatter on the $\delta\,^{18}O$ - δ D diagram (Figure 32) suggests that mixing is not occurring between water types but is occurring vertically at some test sites. The ^{18}O and D isotopes indicate that the waters from the Hays North site (C, D, E) are similar to each other. Samples L, M, and N from the Gorham site are also similar to each other. These isotopes also emphasize the difference in water chemistry between these two sites. For the Gorham monitoring site, vertical variations in the overall water chemistry, together with the relative changes in ^{18}O and D, suggest that the lower part of the Great Plains aquifer is being recharged by the upper Great Plains and the Cedar Hills aquifers (Figures 17 and 36). At the Hays North well site, the difference between the isotope values for the Dakota, Cheyenne, and Cedar Hills aquifers and various brine samples supports the Br/Cl data that the source of salt water is from halite solution rather than from oil-field brine sources. These topics are discussed further in section 7.0.

6.3.3.2 Sulfur Isotopes

$\delta^{34}S$ versus sulfate concentrations for the samples collected are shown in Figure 33. The letters representing the various samples are listed in Table 4. The parallel lines in the figure represent the limits of values for

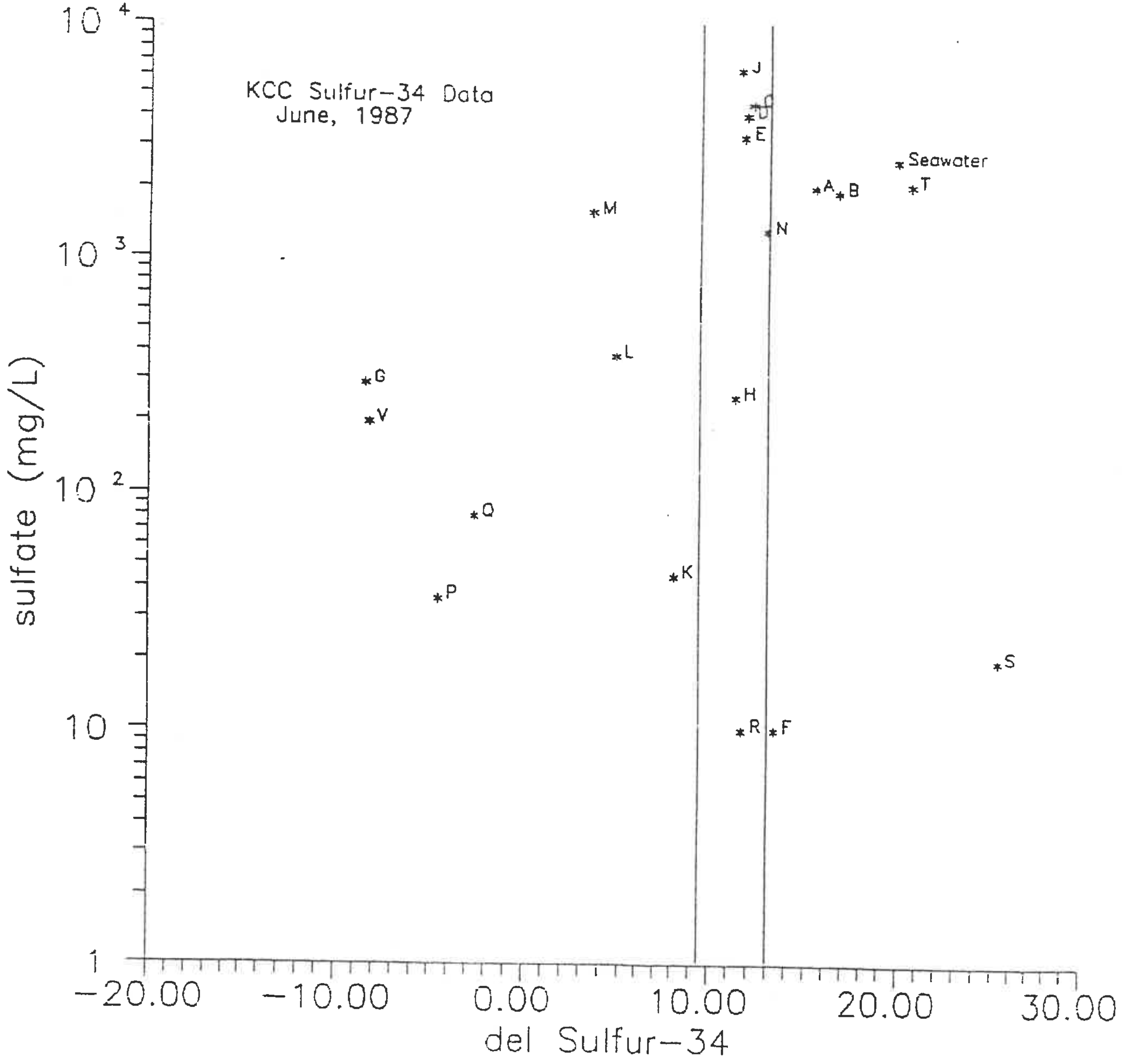


Figure 33. ^{34}S Versus Sulfate Concentration of Groundwaters and Oil-Field Brines from Study Area (See Table 4 for Labels)

Permian evaporites from around the world as listed by Thode and Monster (1961). The range of $\delta^{34}S$ in Permian rocks is from +9.3 to +13.0. The samples collected at the Hays North site in Ellis county (points C,D,E) all fall within the range of Permian evaporites. The Permian water samples from GMD5 in Stafford and Reno counties (H,J,K) also fall within the range of Permian evaporites. The samples from the Gorham multiple-completion monitoring well in Russell county (L,M,N) vary somewhat. Point N is water from the Cedar Hills Sandstone and falls within the Permian value range. Points L and M are samples from the Upper Dakota aquifer, and the Cheyenne Sandstone respectively. Both of these values are in the +3.0 to +5.0 range. These values and those to the left of the Permian evaporite limits suggest the possibility of oxidation processes.

Disseminated sulfide minerals or organic sulfur may be the source of the lower concentration of ^{34}S in the various ground waters. Kinetic fractionation during sulfide oxidation by bacteria results in sulfate that is depleted in ^{34}S (Pearson and Rightmire, 1980). In surface waters there is a tendency for sulfate derived from evaporite sources to be enriched in ^{34}S while sulfate derived from the oxidation of organic sulfur or sulfide minerals will be depleted in ^{34}S. Ground waters may be reducing enough that sulfide is the dominant ionic species. Fractionation between coexisting sulfate and sulfide in reducing environments in ground waters may result in values below the evaporite limit frequently seen in surface waters ($\delta^{34}S$ = +10 or greater) (Pearson and Rightmire, 1980; Thode and Monster, 1965). Several of the waters collected for this study contained noticeable H_2S smell both during collection and analysis. The occurrence of lignites and organic layers in the Great Plains aquifer suggests the presence of disseminated sulfide minerals such as pyrite in the sediments. The minerals may be a source of sulfide that could be oxidized by oxygen-rich ground water or sulfide-oxidizing bacteria resulting in an overall decrease of the ^{34}S content. We will be resampling the Upper Dakota well at the Hays North site, the Hill City site, and possibly at the Gorham site to determine if there was any problem due to time lag between sample collection and sample analysis that would result in the observed values.

7.0 HYDROGEOLOGIC SETTING AT THE MONITORING SITES

7.1 Construction of the Multiple-Completion Monitoring Wells

The multiple-completion monitoring wells constructed during this investigation consist of two or more standpipe piezometers placed at various levels within a single steel-cased borehole. Each standpipe piezometer was positioned adjacent to an interval where the steel casing had been perforated. These intervals were carefully chosen from an examination of geophysical logs of the hole. Targeted zones for monitoring were chosen based on the likelihood of encountering porous and permeable zones. Each standpipe piezometer was constructed of Schedule 80, flush-joint, PVC pipe. For most of the piezometers, a ten-ft. section of well screen was attached at the bottom of the pipe string. The perforated interval of the borehole was then gravel-packed with a coarse-grained arkosic gravel. Zones above and below the gravel pack zone were back-filled with a coarse to fine-grained sand using a tremie pipe. Above the gravel pack and fill material zone, a plug of cement was carefully tremied into the hole to hydraulically isolate the lower monitored zone from the upper part of the borehole. This process was repeated with the construction and placement of each piezometer until the hole was filled to the surface.

During the process, proper materials selection, careful placement of the gravel-pack, fill materials, and cement ensured that hydrologic isolation between observation points in the borehole was maintained.

Described below are hydrogeologic site conditions around each of the three multiple-completion monitoring wells at Gorham, Hays North, and Hill City.

7.2 The Gorham Monitoring Site

7.2.1 Local Geologic Setting

The Gorham monitoring site is located in western Russell County along the crest of the north-plunging Fairport-Natoma Anticline. Figure 34 is a map showing the configuration of the top of the Dakota in the vicinity of the monitoring site. The map shows that in vicinity of the monitoring site the near-surface rocks are essentially flat lying. East and west of the site the rocks in the near surface dip away from the crest of the Fairport-Natoma anticline at 30 to 40 feet per mile. Unconsolidated surficial deposits of Pleistocene age mantle the site area and are underlain by the Upper Cretaceous Greenhorn Limestone. Dakota Formation outcrops are approximately five miles north and south of this monitoring site.

GORHAM MONITORING SITE

Kd top configuration

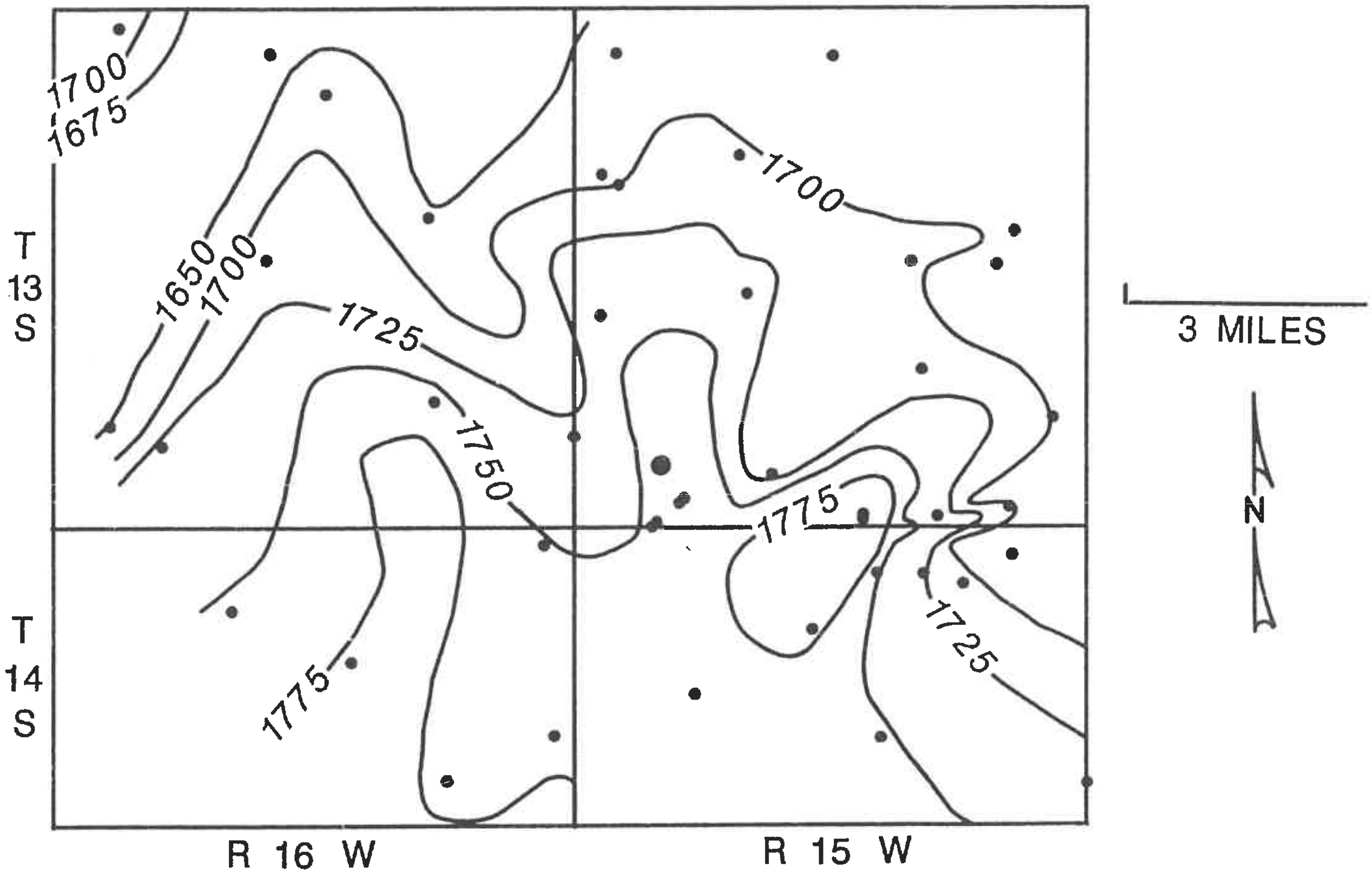


Figure 34. Configuration of the top of the Dakota Formation in the vicinity of the Gorham multiple-completion monitoring well.

7.2.2 Arrangement of the Piezometers

The multiple-completion well at the site consists of three 1.5-in. OD standpipe piezometers placed in a borehole cased with 5.5-in. OD steel casing. Three ten-foot sections were perforated for the monitoring well in the following intervals (measured in feet below the top of the steel casing): 200-210, 470-480, and 575-585. A ten-foot section of screen is located at the bottom of each piezometer to allow monitoring of the upper part and lower parts of the Great Plains aquifer (upper Dakota Formation and Cheyenne Sandstone, respectively), and the Cedar Hills aquifer. The construction is shown schematically in Figure 35. Construction of the monitoring site began on March 9 and was completed by March 20, 1987.

7.2.3 Hydrologic Conditions

Shallow ground waters occur near the base of the Pleistocene loess in residual gravels and weathered bedrock. West of the monitoring site, these gravels contain sufficient ground water to supply the town of Gorham. The thickness of the unconsolidated materials at the site is approximately 22 ft. Figure 36 shows the hydrographs (record of water levels) for the piezometers at the monitoring site from mid-July, 1987, to mid-January, 1988. Overall, the hydraulic head in the upper part of the Great Plains

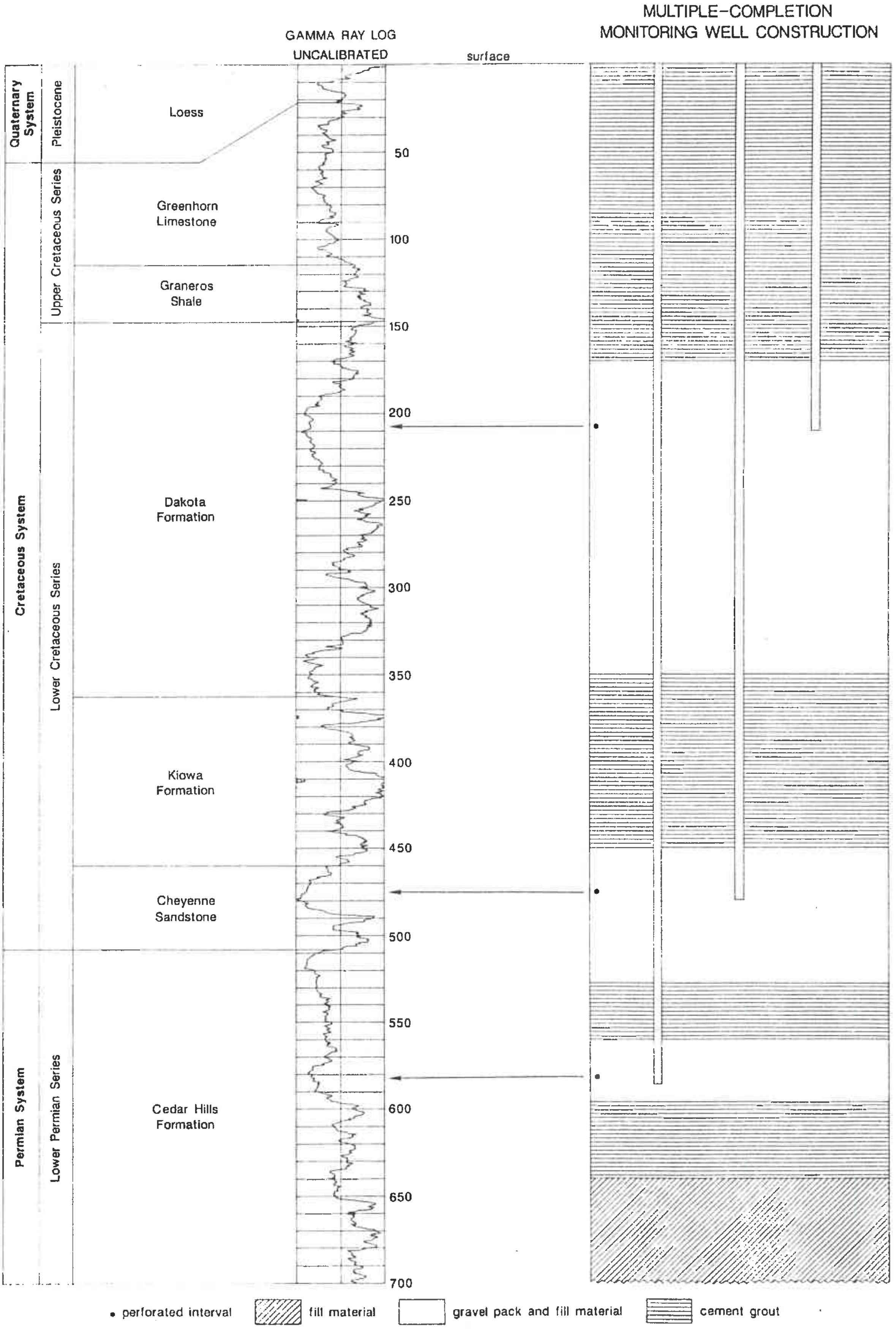


Figure 35. Construction and location of monitored zones, Gorham multiple-completion monitoring well-site.

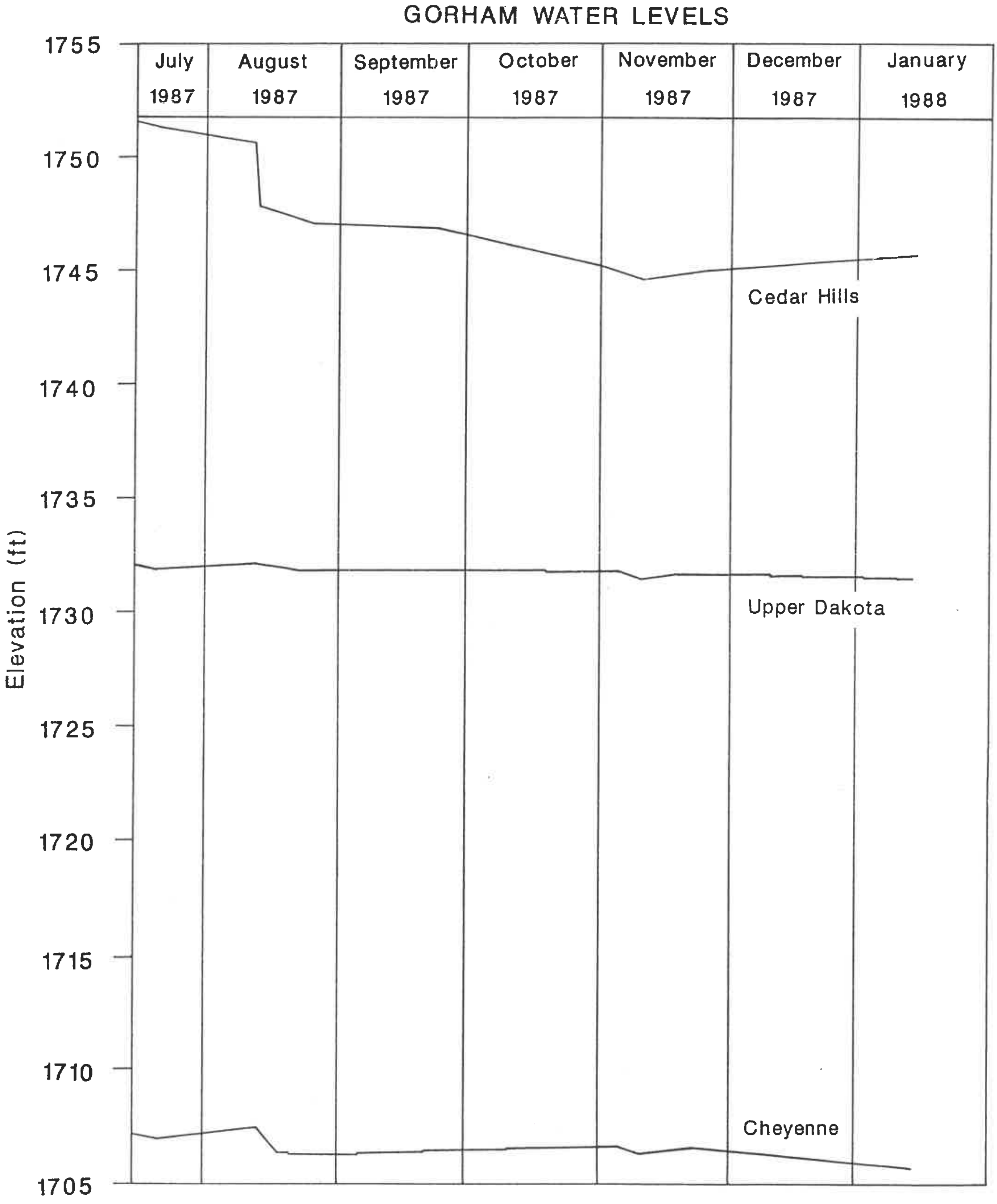


Figure 36. Hydrographs of the piezometers, Gorham multiple-completion monitoring well.

aquifer (upper Dakota) is higher than in the lower part (Cheyenne). However, the hydraulic head in the Cedar Hills aquifer is considerably higher than hydraulic head in the Great Plains aquifer. This suggests that the intermediate portions of the Great Plains aquifer (lower part of the Dakota Formation) may be receiving recharge from shallower and deeper zones and that a water-quality transition between fresh and saline waters may be present in this portion of the aquifer. This is discussed further in section 7.2.4.

Some perspective on the nature of the flow system in the Great Plains and Cedar Hills aquifers can be gained by examining the rate of increase of fluid pressure with depth at the Gorham monitoring site. Figure 37 shows a plot of these fluid pressures at the corresponding depth of measurement below land surface. For locations intermediate between regional recharge and discharge areas, the rate of increase of fluid pressure with depth should approximate the rate of increase of hydrostatic pressure (Toth, 1979). In recharge and discharge areas, the rate of fluid pressure increase with depth will be less than or greater than the rate of hydrostatic pressure increase, respectively. At the Gorham site, relatively low fluid pressures in the upper and lower portions of the Great Plains and Cedar Hills aquifers indicate subpressuring of these aquifers.

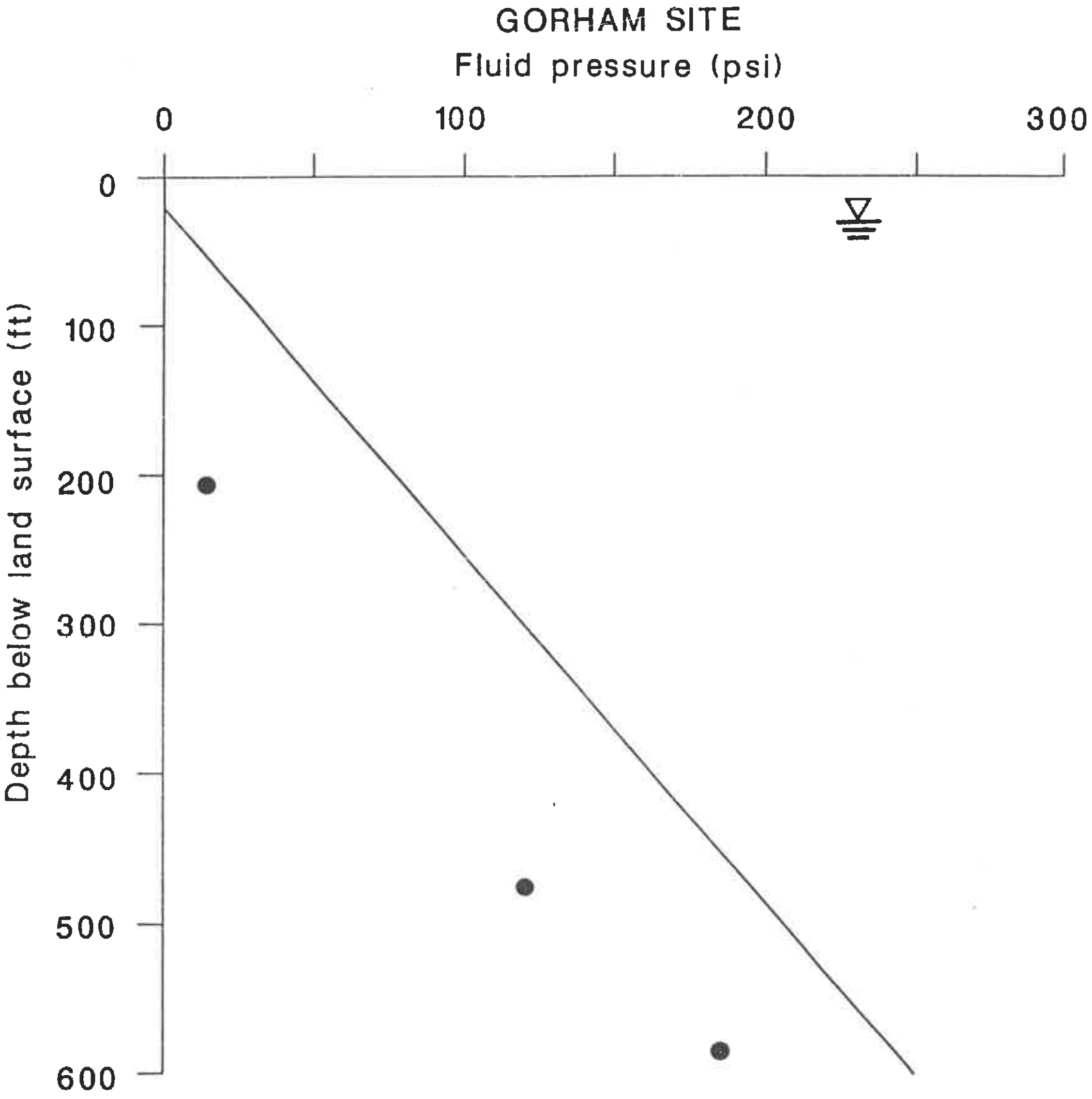


Figure 37. Profile of fluid pressure versus depth, Gorham multiple-completion monitoring well.

These low fluid pressures suggest that the Great Plains and Cedar Hills aquifers are relatively isolated from the near surface hydrologic system. A fairly typical example of an underpressured aquifer system is the Great Plains aquifer in the Denver Basin. Russell (1972) reports fluid pressure-depth ratios of 0.23 and 0.261 psi/ft for sandstones belonging to the Dakota Formation in the Denver Basin in Colorado and Nebraska, respectively. Fluid pressure-depth ratios at the Gorham site increase from 0.08 psi/ft. for the upper part of the Great Plains aquifer to 0.32 psi/ft. for the Cedar Hills aquifer. The hydrostatic pressure increase with depth is 0.43 psi/ft. This situation is problematic since the Dakota Formation outcrop is less than five miles away from the monitoring site and is believed to be a discharge zone for the Great Plains aquifer (Figures 17 and 18). Viewed in this light, the apparent underpressuring may be caused by relatively greater isolation of these aquifers from recharge sources than points of discharge even though the aquifer is only 200 feet below land surface.

7.2.4 Ground-Water Geochemistry

Waters collected from all three zones of the well are of sodium-chloride type. Calcium and magnesium concentrations in the sample from the Upper Dakota aquifer are very low in comparison with the dissolved sodium content. The values suggest that cation exchange has affected the water chemistry. However, the field pH of the sample was higher (9.15) than that expected (near 7) for the aquifer. The high pH could indicate leaching of cement in the well. The pH could have decreased calcium and magnesium concentrations by precipitating calcium carbonate containing some magnesium. The bicarbonate concentrations are also somewhat lower than expected if cation exchange with concomitant carbonate solution had occurred. Future well development should provide water samples with lower pH that will allow more conclusive examination of cation exchange and carbonate equilibria relationships for the Upper Dakota. However, the high pH should not appreciably affect the relationships of the anionic and neutral species and the sodium concentration in the sample. Thus, the relatively high Na/Cl ratio suggests that cation exchange may have been important in the origin of the present water chemistry.

The Cheyenne and Cedar Hills waters contain relatively high calcium and magnesium concentrations, low to moderate bicarbonate contents, and Na/Cl ratios below 0.62, indicating that cation exchange does not appear to have had a substantial effect on the present water chemistry. The ratios of major constituents in the waters from the two aquifers are similar to those for oil-field brines in the local area surrounding the site (Kansas Geological Survey, 1973). Swineford and Williams (1945) also determined that the introduction of oil-field brines had affected the chemistry of some of the waters in the Dakota Formation in Russell County.

Conclusive evidence based on Br/Cl ratios and mixing curves indicates that appreciable amounts of oil-field brines disposed into the Cedar Hills Sandstone and possibly the Cheyenne Sandstone can be detected in the aquifers away from the injection sites. The points for both the Cedar Hills and Cheyenne water samples plot within the mixing zone of freshwaters and oil brines on Figure 29, while the point for the sample from the Upper Dakota aquifer plots in the middle of the mixing zone between freshwater and halite-solution brine. Thus, the oil-field brine does not appear to have migrated to the Upper Dakota strata at this site.

Saline seepage from the Great Plains aquifer into Salt Creek several miles to the northeast of the monitoring site has earlier been identified as being predominatly derived from a halite-brine source (Whittemore and Pollock, 1979). The salinity identification for the seepage and the Upper

Dakota water at the Gorham site indicate that uncontaminated saline water in the Great Plains aquifer in west-central Russell County has a different chemistry from that found in the Cedar Hills and Cheyenne samples at the monitoring site.

The Br/Cl and Na/Cl ratios for the water from the Cedar Hills strata are higher and lower, respectively, than those for the Cheyenne Sandstone. The first interpretation is that more oil brine is mixed with the original ground water in the Cedar Hills aquifer than in the Cheyenne aquifer. An explanation could be that oil brine injected into the Cedar Hills Sandstone has migrated upward into the Cheyenne strata. Mixing curves of Br/Cl versus chloride concentration drawn from a probable oil-brine endpoint through the points for the present waters from the two aquifers to the middle of the freshwater and halite-brine mixing zone could be used to estimate the chloride content of the original, uncontaminated water in the aquifers. If a single type of oil-field brine with a chloride concentration higher than that present in the two aquifer waters is used as an endpoint, the extrapolation would give a chloride content of original water in the Cedar Hills aquifer substantially less than that in the Cheyenne aquifer. This would be an unexpected result. Alternatively, if the chloride contents of uncontaminated waters in the two aquifers were nearly the same or higher in the Cedar Hills than in the Cheyenne Sandstone, the oil brine sources would have been different. Either different oil brines could have been injected into the Cedar Hills at the beginning than the latter period of the disposal history, or different oil brines were injected into both the Cedar Hills and Cheyenne strata.

The location of the oil-brine samples on both the oxygen-deuterium and sulfur isotope graphs (Figures 32 and 33) indicates that brines similar to these are not the source of contamination of the ground waters sampled at the monitoring site. Isotope fingerprinting of petroleum brines suggests that samples from the same field or pool withdrawing oil from the same geologic horizon will be similar, whereas samples from different geologic horizons or different fields but from the same horizon may vary significantly (Thode and Monster, 1965). The samples collected in this study were from different fields although from the same geologic units. The lack of stable isotope and ^{34}S correlation between the brines and water at the Gorham site is most likely due to not having samples from the production wells that produced the brine that was disposed in the Gorham area. Brines will be sampled at production wells that historically have supplied saltwaters to nearby Cedar Hills disposal wells.

7.3 The Hill City Monitoring Site

7.3.1 Local Geologic Setting

The Hill City monitoring site is located in central Graham County west of the Central Kansas uplift in the Western Kansas basin. Thin deposits of loess mantle the upland areas near the site. The near surface bedrock is the Smoky Hill Chalk Member of the Niobrara Chalk. Figures 38 and 39 show the configuration of the top of the Carlile Shale and the Dakota Formation, respectively, in the vicinity of the monitoring site. The near surface rocks dip to the northwest at 10 to 15 feet per mile in the well site vicinity. Additionally, an aligned series of structural lows on the top configuration maps is coincident with a remote sensing lineament. This suggests that the site may be located near a fracture system that has some surface expression. A similar, aligned series of structural lows in the bedrock occurs in northwest Graham County (Merriam, 1963). These structural lows are reflected at least to the top of the Stone Corral.

7.3.2 Arrangement of the Piezometers

The multiple-completion monitoring well at the site consists of a 1.5-in. OD and a 2-in. OD piezometer in a 5.5-in. OD steel-cased borehole. The

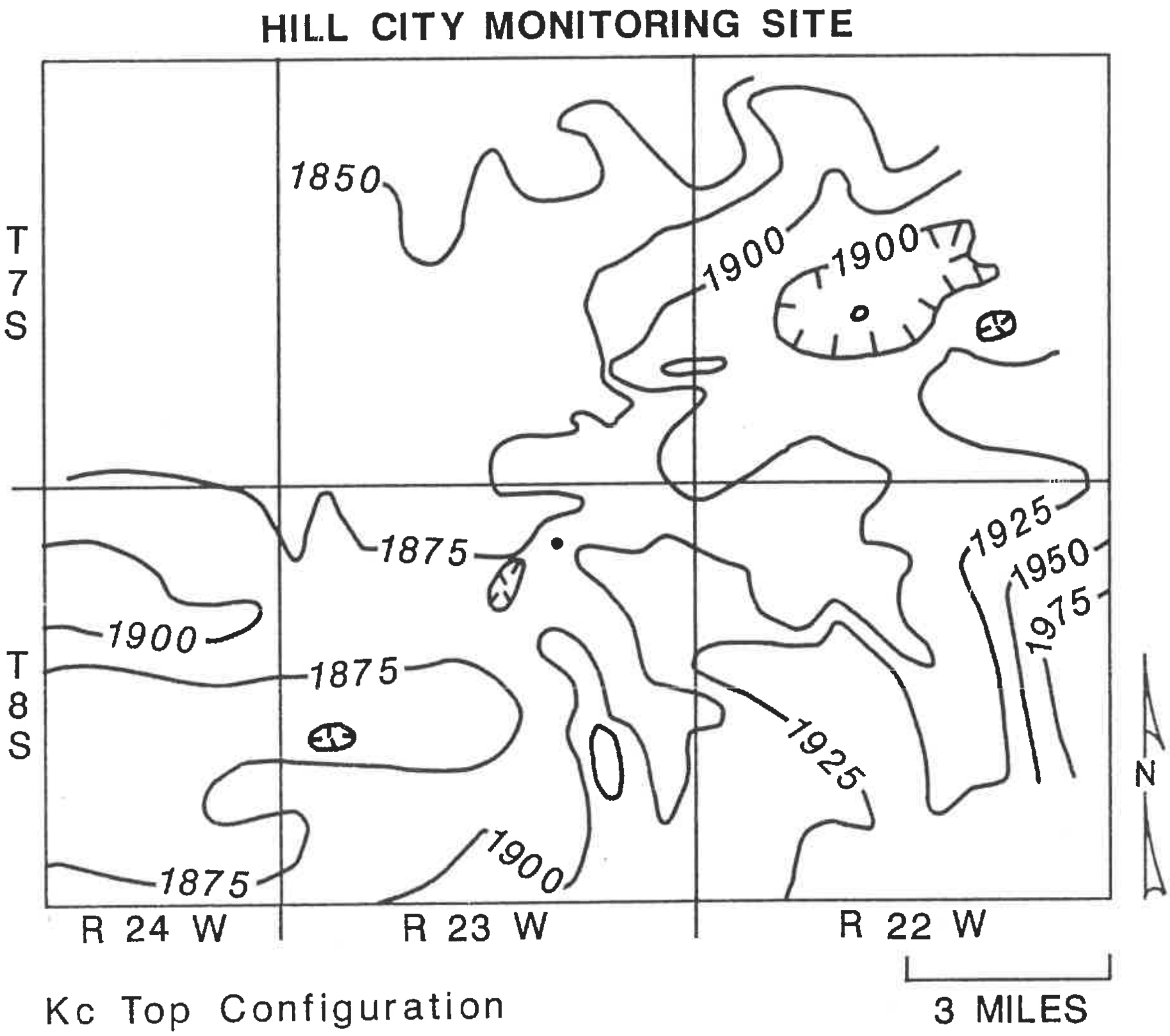


Figure 38. Configuration of the top of the Carlile Shale in the vicinity of the Hill City multiple-completion monitoring well.

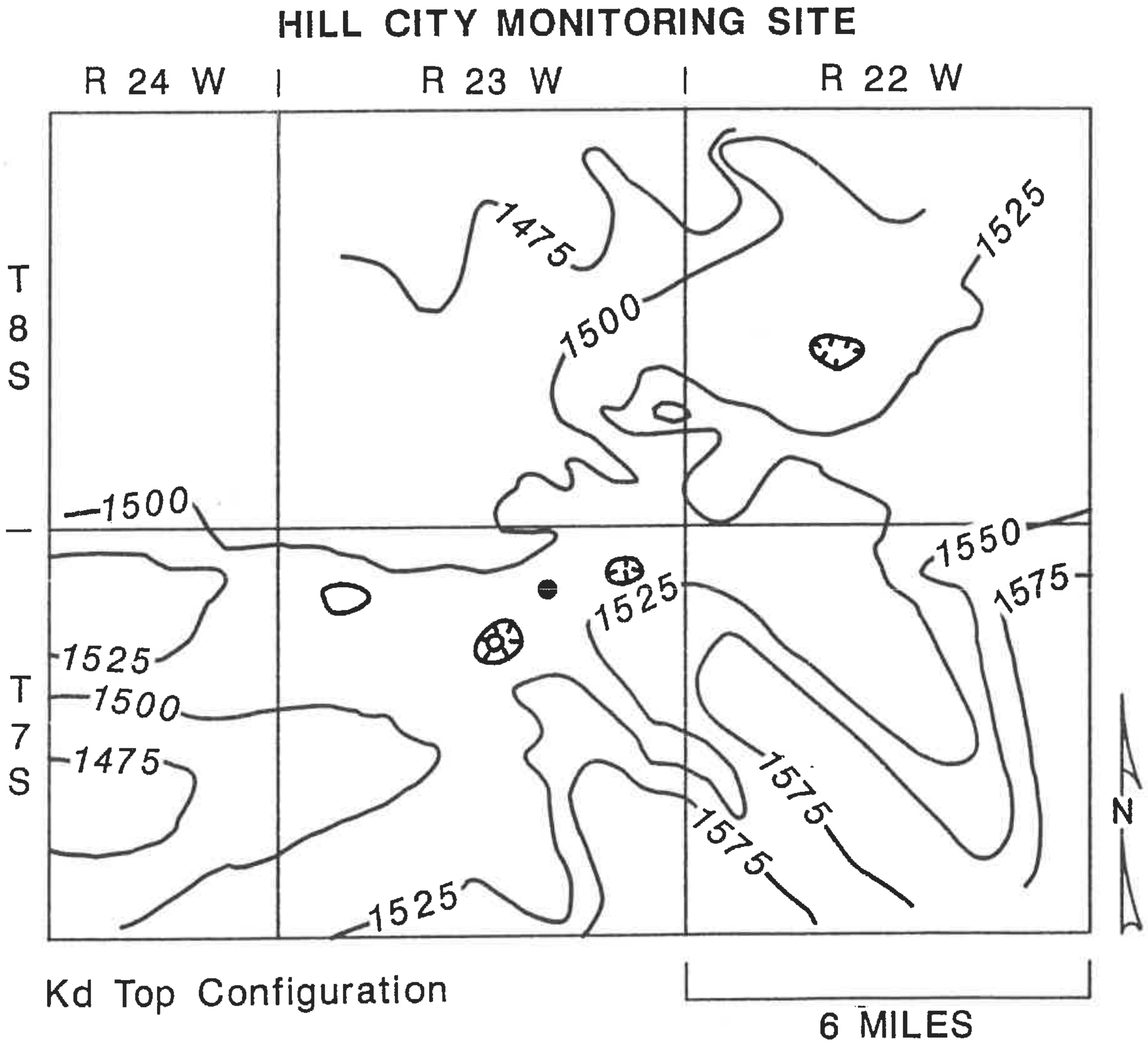


Figure 39. Configuration of top of the Dakota Formation in the vicinity of the Hill City multiple-completion monitoring well.

piezometers monitor two intervals in the upper part of the Great Plains aquifer (Dakota Formation): 773-797 feet and 1063-1075 feet below the top of the casing. The 1.5-in OD piezometer is used to monitor the lower zone and has ten feet of well screen at the bottom of the piezometer. The 2.0-in. OD piezometer is used to monitor hydrologic conditions in the upper zone and has 25 feet of well screen at the bottom of the piezometer. The construction of the multiple-completion monitoring well is shown schematically in Figure 40. Construction at the Hill City site began on August 22 and was completed by August 26, 1987.

7.3.3 Hydrologic Conditions

At the Hill City monitoring site the hydraulic head of the lower part of the Dakota Formation (upper part of the Great Plains aquifer) is approximately 20 feet higher than the hydraulic head in the upper part of the Dakota Formation. Figure 41 shows the hydrographs of the two piezometers at the Hill City site for the period of monitoring from the later part of August through November, 1987. The large decline in water level in the upper piezometer near the end of September was caused by pumpage from the upper piezometer. Measurements were taken before and immediately after pumping, and then again near the end of October. This piezometer was

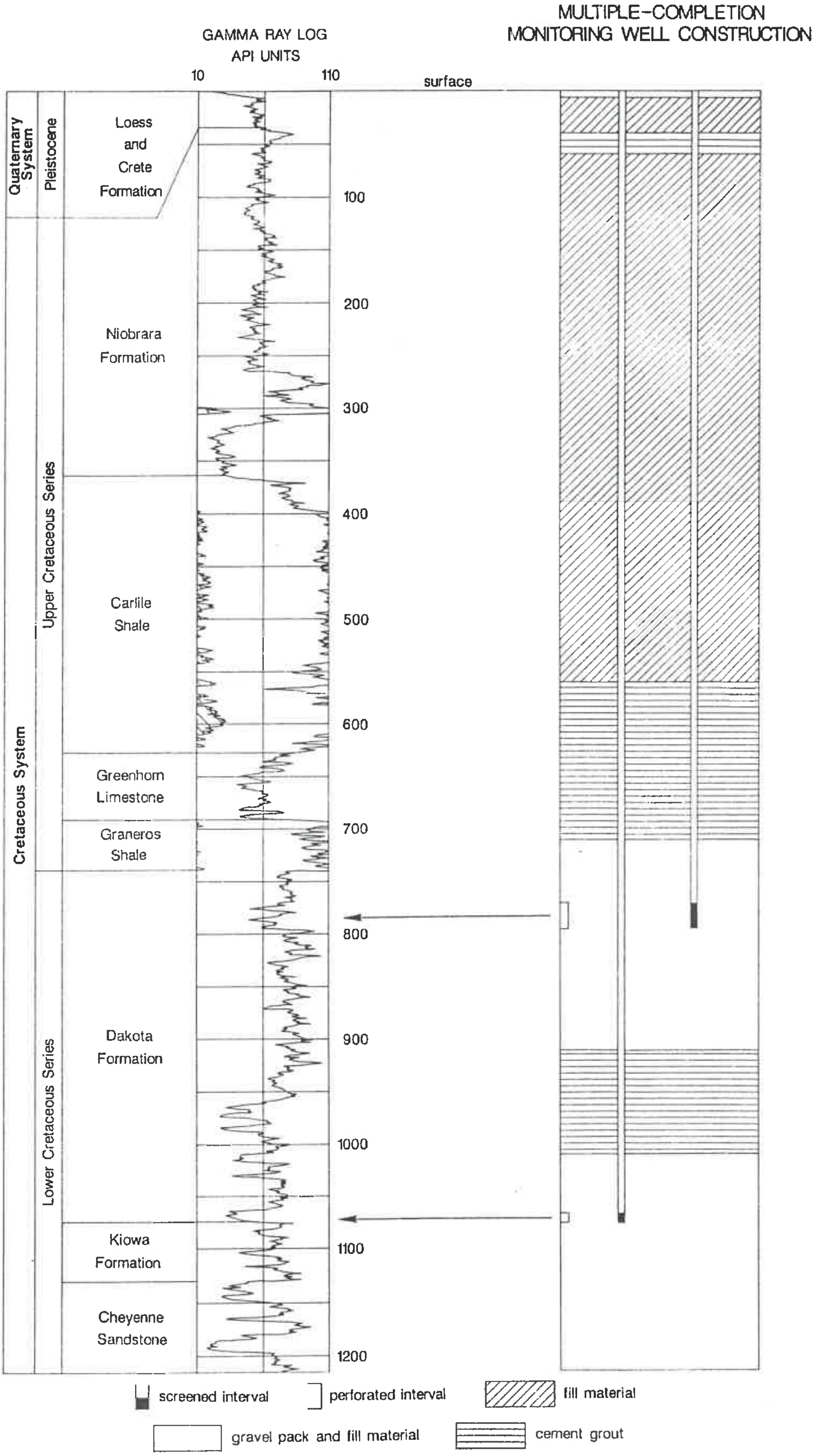


Figure 40. Construction and location of monitored zones, Hill City multiple-completion monitoring well.

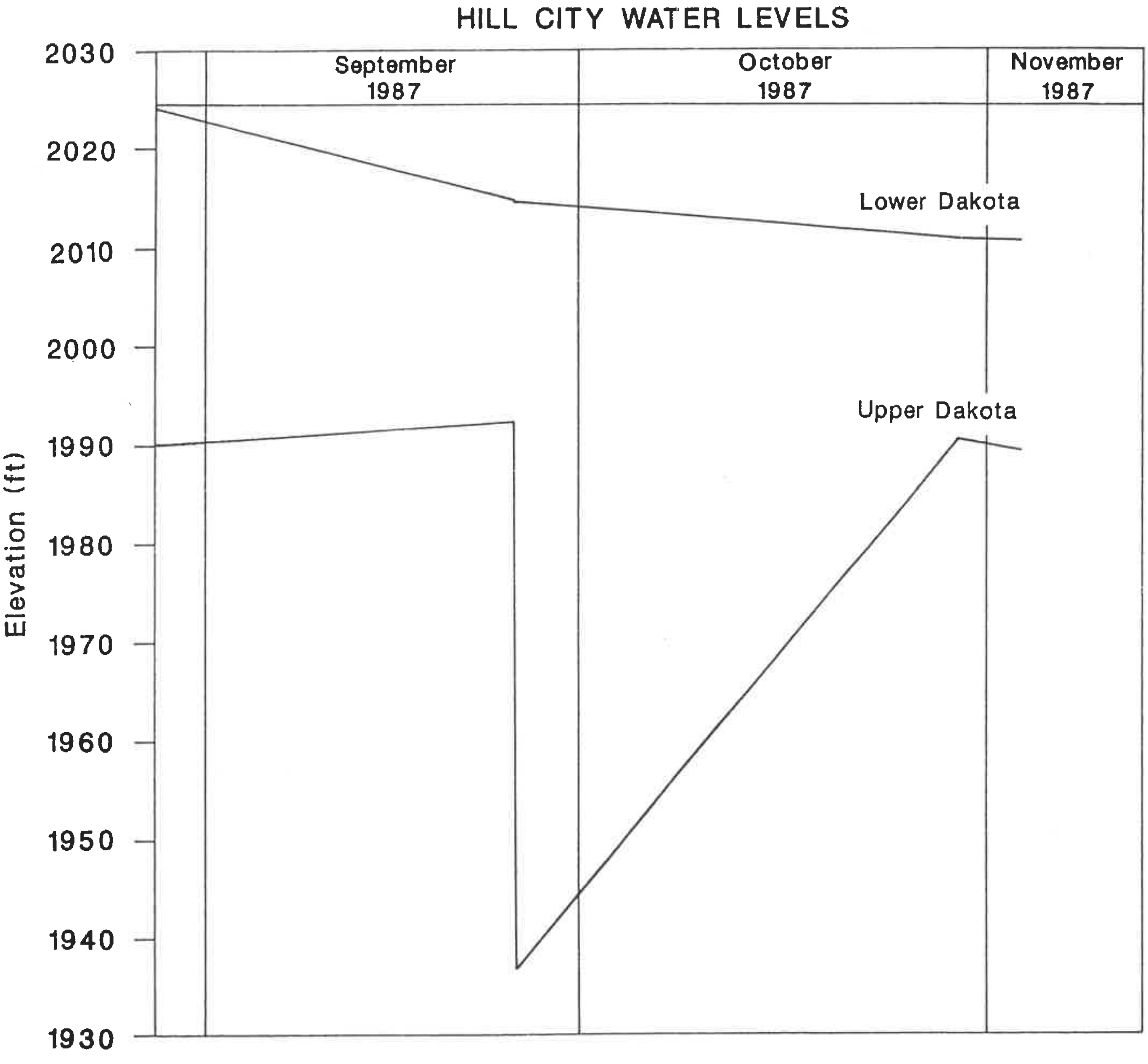


Figure 41. Hydrographs of the piezometers, Hill City multiple-completion monitoring well.

pumped for approximately two hours small hand bailer to remove 20 gallons of water. Note that the approximately 55 feet of decline in the upper piezometer has caused a very slight (0.3 ft.) decline of water level in the lower piezometer. These piezometers are separated vertically by approximately 266 feet of interbedded mudstones, claystones, and thin-bedded sandstones.

Like the Gorham site, the upper part of the Great Plains aquifer (Dakota Formation) is also under subhydrostatic pressure conditions. Figure 42 is a plot of the fluid pressures in the upper part of the Great Plains aquifer measured in the piezometers at the Hill City site. Included in the diagram is the estimated fluid pressure in the Cedar Hills aquifer beneath the monitoring site based on reported fluid levels. The fluid pressure-depth ratios increase with depth and range from 0.31 to 0.37 psi/ft.

These results are difficult to interpret considering the limited water-quality information available as of this writing. The chloride concentration of the water sample taken from this piezometer is 485 mg/l. During June, 1987, a water sample was obtained from an oil-field water supply well tapping the lower part of the Great Plains aquifer (lower Dakota, Kiowa, and Cheyenne). The chloride concentration of the water sample was 304 mg/l. The static water level in this well is approximately

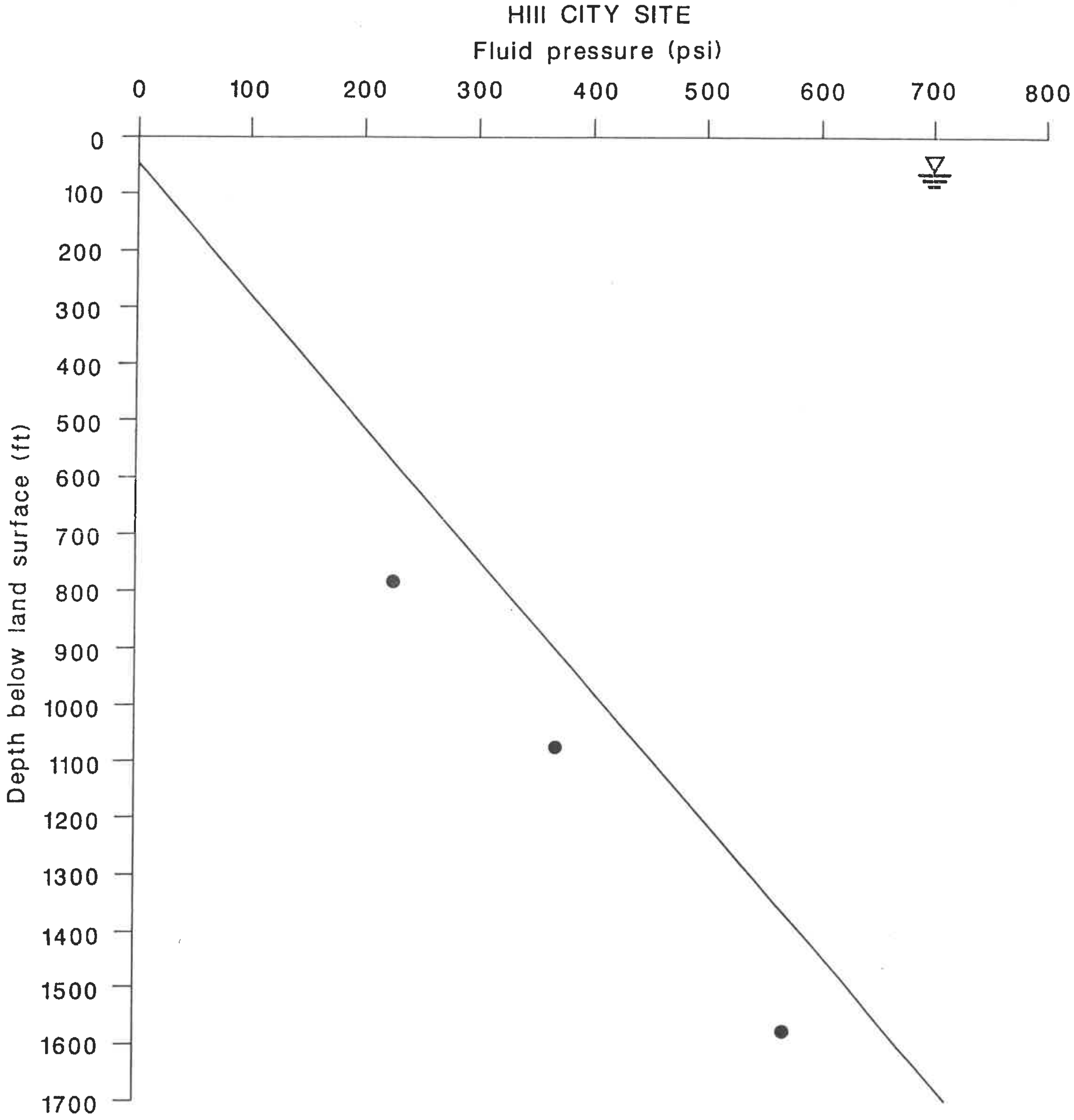


Figure 42. Profile of fluid pressure versus depth, Hill City multiple-completion monitoring well.

385 feet lower than the water table elevation in the overlying High Plains aquifer. The fluid pressure-depth ratio for this well which is constructed with a long screened interval is 0.27 psi/ft.

It is readily apparent from the fluid pressures and water levels that the Great Plains aquifer is not well connected to the near surface hydrologic system in Graham County. However, near-surface geologic structures suggest that fractures may provide pathways for water moving down from the High Plains aquifer into the Great Plains aquifer. Furthermore, the chloride concentration of ground waters in this part of the Great Plains aquifer are unexpectedly low for a deep, confined aquifer system. If these pathways are present, then the fluid pressures in the Great Plains aquifer should not be subhydrostatic. This suggests the possibility that these freshwaters may be very old.

7.3.4 Ground-Water Geochemistry

A representative water sample has only been collected from the upper piezometer in the Upper Dakota aquifer. The chemical type of the water is sodium-calcium-chloride. Dissolved constituents concentrations indicate that cation exchange and associated carbonate solution have not been important in the origin of the water chemistry. Constituent ratios and location on plots of constituent relationships such as Figures 27, 28, and 31 show that the water is similar to other waters that have not been appreciably affected by cation exchange that were collected from the Great Plains aquifer system to the east as a part of this study. An interference in the sample precluded an accurate determination of the bromide concentration. Additional treatment of the sample is planned to attempt to remove the interference.

7.4 The Hays North Monitoring Site

7.4.1 Local Geologic Setting

The Hays North monitoring site is located in northern Ellis County on the east flank of the Stockton Anticline, near the axis of a northwest-plunging syncline (Figure 43). The near surface rocks in the vicinity of the well site dip to the southwest at approximately 50 to 70 feet per mile. Northward extension of a remotely-sensed lineament along the trend coincides with the steeply dipping east flank of the plunging syncline and linear segments of the North Fork, Big Creek stream channel. At the surface the unconsolidated Ogallala Formation mantles the upland area around the well

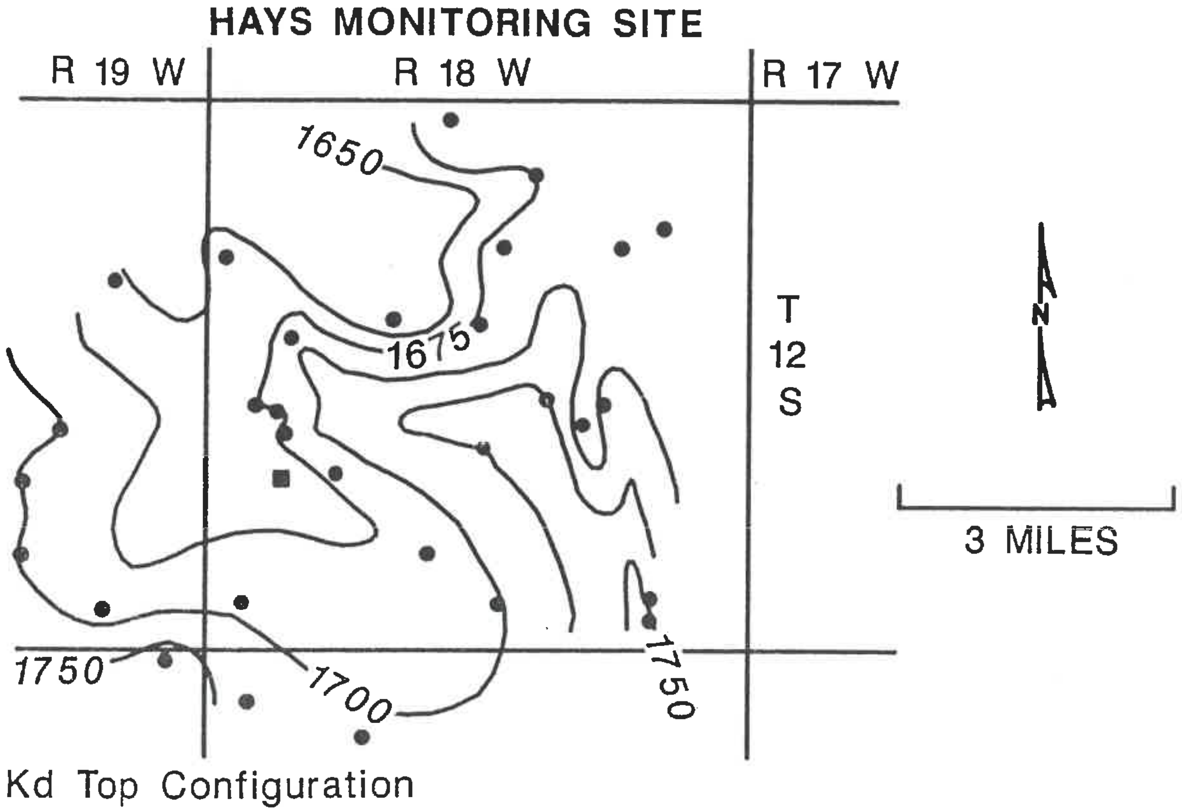


Figure 43. Configuration of the top of the Dakota Formation in the vicinity of the Hays North multiple-completion monitoring well.

site. The bedrock below the Ogallala is the Fort Hays Member of the Niobrara Chalk.

7.4.2 Arrangement of the Piezometers

Four piezometers have been placed inside the steel-cased borehole at the Hays North site. Figure 44 is a schematic of the well construction at the site. Piezometers were placed in the hole to monitor hydrologic conditions in the Great Plains aquifer at three intervals (upper and lower Dakota, and the Cheyenne) and in the Cedar Hills aquifer: 650-660, 766-776, 830-840, and 1130-40 feet below the top of the casing. For each piezometer the upper 400 feet of pipe is 2-in. OD and the lower segment down to total depth is 1.5-in OD.

7.4.3 Hydrologic Conditions

At the Hays North site, a shallow water-table aquifer is present in the Ogallala. Depth to water at the site is approximately 5 feet and nearby streams appear to be spring fed by the Ogallala in the upland areas. Saturated thickness at the site is estimated to be on the order of 30 feet. The Codell Sandstone aquifer is present and is used for water supply by many of the farmsteads near the site. The elevation of the Codell

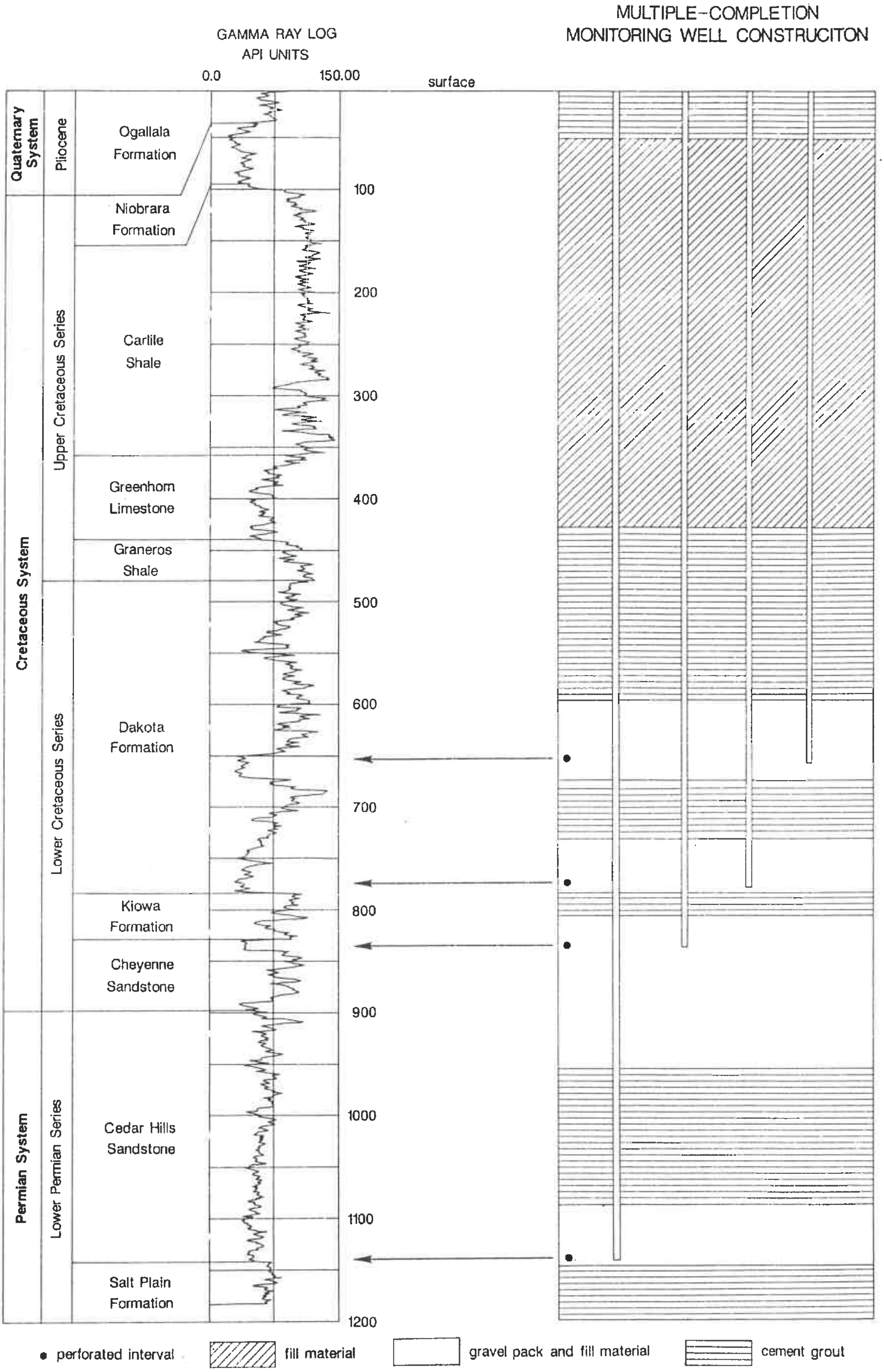


Figure 44. Construction and location of monitored zones, Hays North multiple-completion monitoring well.

potentiometric surface, computed from the static water-level in a well less than one mile south of the site was 2143 feet above mean sea level on November 3, 1987.

At the Hays North site, the vertical direction of ground-water flow is upward within the Cedar Hills and Great Plains aquifers. The hydrographs of the piezometers at the site show that water levels in the Cedar Hills aquifer are approximately 125 feet higher than water levels in the upper part of the Great Plains aquifer (Figure 45). Fluctuations of water level in the upper Dakota are mostly the result of pumpage in the upper Dakota piezometer. Note that pumpage in this piezometer has an effect on water levels in the lower Dakota piezometer suggesting interconnection. The decline and long-term rise of water levels in the upper and lower Dakota piezometers appear to be the result of pumpage from nearby domestic and stock wells using the Dakota (upper part of the Great Plains aquifer) for water supply. The low water levels in July suggest that the rate of withdrawal of water was much higher during the summer than later in the year. The increased rate of withdrawal may also have affected water levels in the Cheyenne during July since these water levels show a similar trend.

Neither shallow disposal of oil-field brines nor the increased withdrawal of water from the upper part of the Great Plains aquifer appear

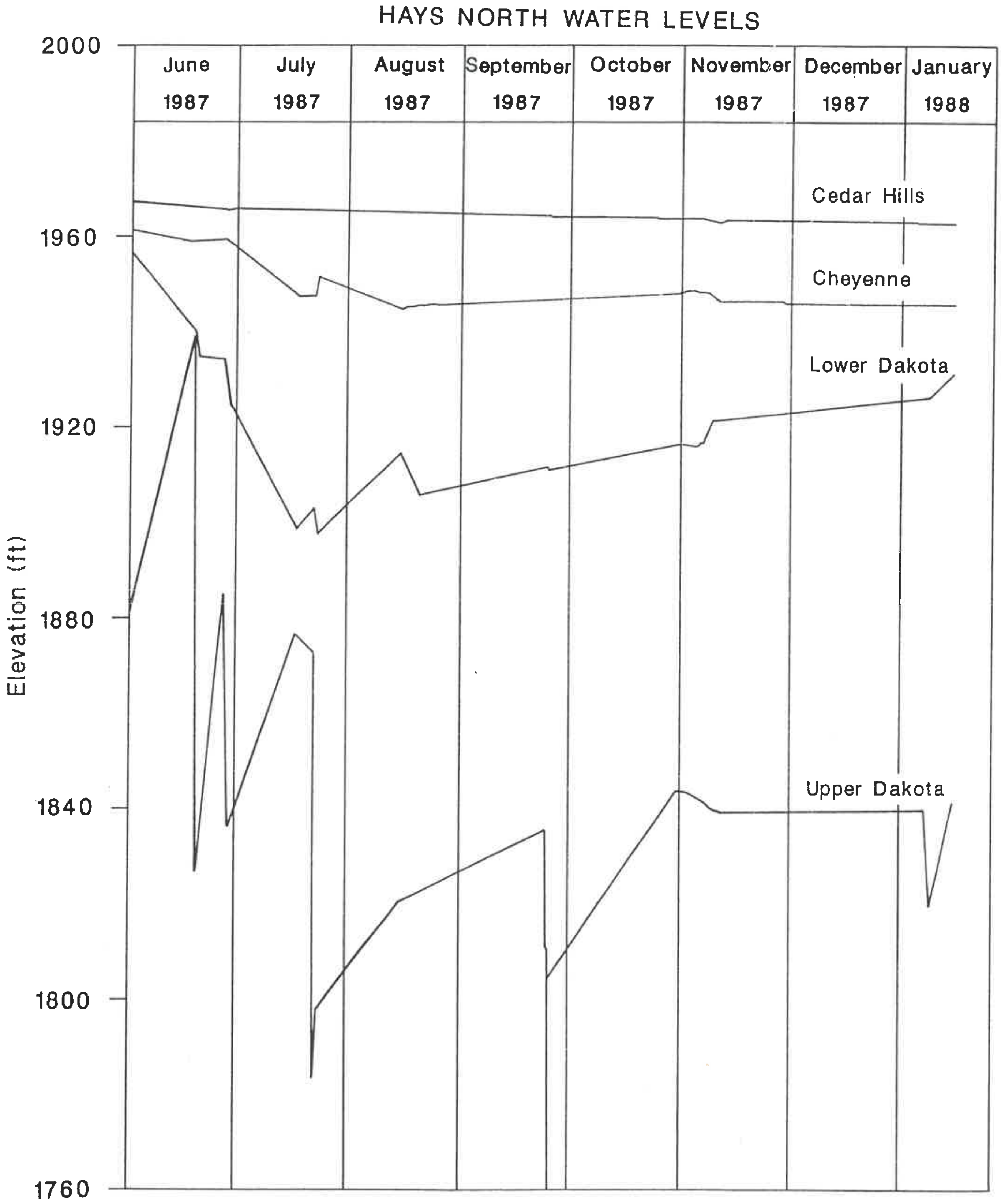


Figure 45. Hydrographs of the piezometers, Hays North multiple-completion monitoring well.

to have affected the water levels in the Cedar Hills during the more than seven months of monitoring. However, pumpage of the Cedar Hills appears to significantly affect water levels in the Cheyenne. Figure 46 shows the decline of water levels in the Cheyenne piezometer as the Cedar Hills piezometer was pumped using an air compressor during well development. Steady water-level declines were recorded in the Cheyenne until the air compressor was turned off at which time water levels in the Cheyenne recovered. During the approximately 280 minutes of pumping the total water-level decline in the Cheyenne piezometer was approximately 24 feet. The total drawdown in the Cedar Hills piezometer from pumping is estimated to have been approximately 100 feet based on water-level measurements made during recovery in the pumped piezometer. This preliminary data and the longer-term water-level fluctuations of the piezometers suggests that the Cedar Hills and Great Plains aquifers are hydraulically-interconnected and behave as a single system at the Hays North site.

A comparison of water levels in the Cedar Hills and Great Plains aquifers with water levels in the Ogallala and Codell Sandstone indicates that the deeper, confined aquifers are relatively isolated from the near-surface hydrologic environment. The potentiometric surface of the Cedar Hills

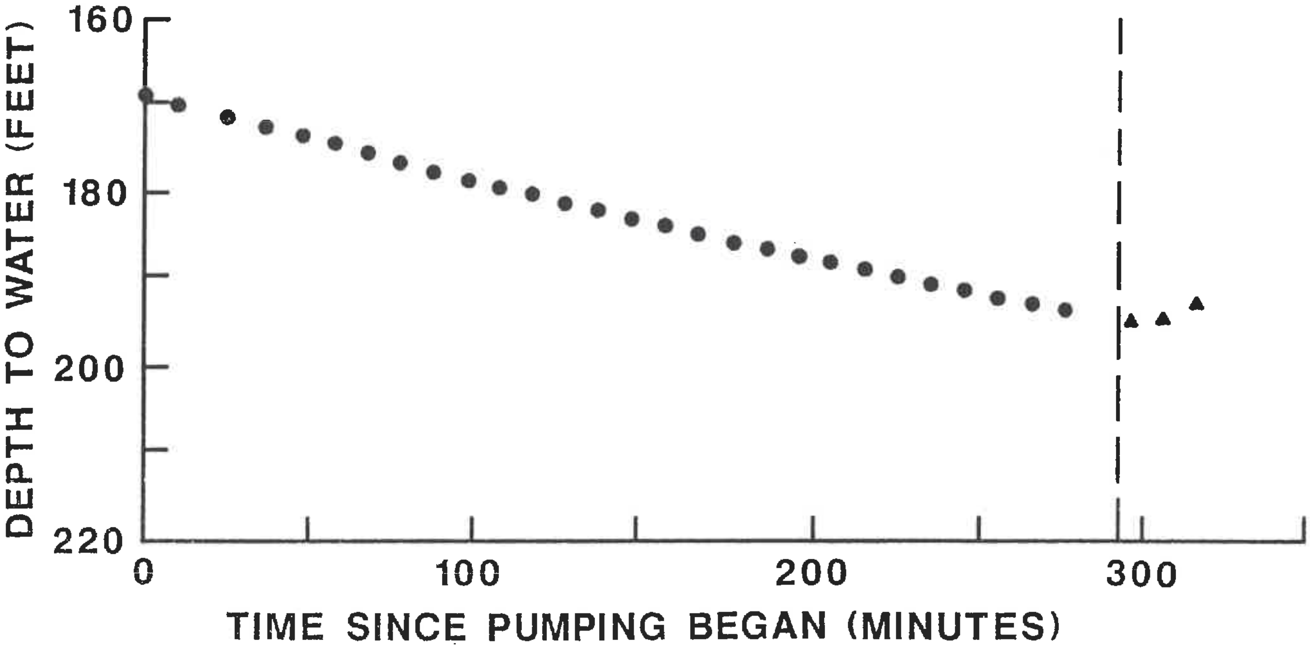


Figure 46. Response of the water level in the Cheyenne piezometer to pumpage in the Cedar Hills piezometer, Hays North multiple-completion monitoring well.

aquifer, although with the highest hydraulic head, is approximately 75 feet lower (or 45 feet lower, using a fresh-water equivalent hydraulic head value) than the potentiometric surface of the Codell Sandstone.

7.4.4 Ground-Water Geochemistry

The waters sampled from the four zones at the monitoring site vary little in their major and minor constituent chemistry, except for somewhat higher concentrations of calcium, strontium, and bicarbonate relative to chloride in the water from the upper Dakota aquifer in comparison to those in the other three zones. The range in the ratios of Br/Cl, B/Cl, and I/Cl for the samples are within the analytical error. The location of points for the waters on Br/Cl and I/Cl versus chloride concentration mixing curves (Figures 29 and 30) indicate that the major source of salinity is halite-solution brine. The Br/Cl, I/Cl, and B/Cl ratios are all somewhat higher than those for saline waters with a halite-brine salinity source in Permian rocks in the Great Bend Prairie to the south and the Smoky Hill River valley to the east. Thus, as discussed previously under the section on regional ground-water geochemistry, the waters may represent diluted mixtures of halite brines mixed with remnants of altered connate waters. The location of the points for the monitoring site waters on a plot of Na/(Ca + Mg) versus boron concentration (Figure 27) shows that the waters do not follow the predominant trend of the fresher ground waters in the Great Plains aquifer, but lie nearer the point for seawater.

The similarity in the constituent relationships supports the hydrologic conclusion that the Cedar Hills and Great Plains aquifers behave as an interconnected system at this location. The sulfur-34, oxygen-18, and deuterium isotopes further support the idea of vertical mixing between the formations (see section on isotopes). The total dissolved solids and most of the dissolved constituent concentrations decrease from the Cedar Hills aquifer upwards into the lower Dakota Formation. Water sampled from the upper Dakota Formation contains somewhat higher dissolved contents that are between the values for waters from the Cheyenne and lower Dakota strata. The increase in total dissolved solids may be due to lower permeability and thus an increase in the amount of time for recharge water to reach the upper Dakota Formation and cause dilution. The lower Dakota appears to be more permeable and may permit a greater flow of fresher recharge water into the system, thereby causing greater dilution of the water in that zone.

8.0 WATER USE FROM THE GREAT PLAINS AQUIFER AND SHALLOW DISPOSAL OF OIL-FIELD BRINES

8.1 Water Use from the Great Plains Aquifer

The Great Plains aquifer is used for municipal, domestic, and stock use throughout the study area. The principal aquifer tapped by these water supplies is the Dakota Formation (upper part of the Great Plains aquifer), where the dissolved solids and concentrations of other dissolved constituents are small enough to allow use of ground water from this unit. The area of most intensive use covers southern Ellis, Russell, and Trego counties, and northern Rush and Barton counties. Water from the Great Plains aquifer is used for municipal supply at LaCrosse (as a supplemental source), Liebenthal, McCracken (rural water district), and Loretta in northern Rush County and Claflin in Barton County; and for industrial use by Cities Service Gas Company at Otis. The total amount of water withdrawn for municipal supply from the Great Plains aquifer is approximately 50 acre-ft annually. During the course of the study, three oil-field water supply wells were located in Rooks and Graham counties that withdraw water from the Great Plains aquifer for use in secondary recovery operations.

8.2 Shallow Disposal of Oil-Field Brines

Shallow disposal of oil-field brines through injection wells has been practiced by the oil industry since the 1930's (Jewett and Butcher, 1957). Injection horizons in the lower part of the Dakota Formation in part of Russell County, the Cheyenne Sandstone and Cedar Hills Sandstone have been used since that time. During the early 1940's, the State Board of Health allowed disposal of oil-field brines into the lower part of the Dakota for a brief time (Bill Bryson, personal communication, 1987).

At present the Cedar Hills Sandstone is the only injection horizon being approved for shallow disposal by the KCC. Approximately 460 Cedar Hills disposal wells are in operation in the study area and are field-checked periodically for injection pressures by the KCC (as of September 1987; Figure 20). During the period 1975-1983, the average rate of disposal was approximately 93,757,000 bbls (5035 acre-ft) per year in the study area or approximately 550 bbls per day per disposal well.

Disposal in the Cedar Hills Sandstone is generally done under "gravity flow" conditions (no additional injection pressures applied to the brines to induce movement into the formation). However, in northwestern Rush County and other locations where the static fluid levels in the Cedar Hills are above land surface, additional fluid pressures are required to move the brines from the well bore into the formation. Applied pressures measured at the well heads in this area range from less than 10 to more than 200 psig. In contrast, disposal of oil-field brines into the Cheyenne Sandstone was routinely done under conditions of applied pressure in order to cause the formation to accept the disposed brines. Applied pressures ranged up to 250 psig measured at the well head during injection. New injection wells have not been permitted to dispose into the Cheyenne since the early 1970's.

9.0 THE POTENTIAL FOR UPWARD MIGRATION OF SALINE WATERS INTO SHALLOWER FRESHWATER ZONES OF THE GREAT PLAINS AQUIFER AND NEAR-SURFACE

9.1 Criteria for Evaluation

Determination of the potential for upward movement of ground waters below the water table can be shown most effectively using information gathered about the ground-water environment along vertically separated measurement points (Freeze and Cherry, 1979; Javandel, 1983). In this regard, it is sufficient to show hydraulic head differences between points in the ground-water system. Evidence of movement can also be developed from an analysis of the water chemistry along the vertical direction to show mass transport or from the calculation of the vertical component of ground-water velocity using the material properties of the rocks.

Ideally, many of these determinations should be made over the study area. However, in this investigation, only three such determinations have been made from the multiple-completion monitoring wells and the results are being generalized to cover an extensive area. Fortunately, the locations of the monitoring sites have been reasonably well distributed and representative of the hydrogeology of the Great Plains and Cedar Hills aquifers in the study area. This has allowed for some degree of predictability about the hydrologic system.

9.2 Geographic Areas of Potential Upward Movement of Saline Waters into Shallow Freshwater Aquifers

Aquifers in the Cheyenne and Cedar Hills Sandstones are the primary sources of salt water in the shallow subsurface of the study area. Fresh water is not known to occur in the Cedar Hills aquifer in the study area. As a result the Cedar Hills aquifer is being used as a disposal zone for oil-field brines. In several areas of Russell and Ellis counties, the Cheyenne was also used as a disposal zone for oil-field brines. However, the occurrence of fresh water in the Cheyenne, Kiowa, and lower Dakota (middle and lower portions of the Great Plains aquifer) in a well in western Graham County suggests that the Cheyenne has been locally flushed of salt water at least by fresher recharge waters. This well is located in an area of relatively low ground-water that were salinities mapped using SP resistivity methods. At the Hill City monitoring site, the vertical direction of ground-water flow appears to be upwards from the lower to the upper part of the Dakota Formation (upper part of the Great Plains aquifer). In this part of the study area, more than 350 feet of younger Permian and Jurassic sedimentary rocks separate the Cedar Hills aquifer from the Great Plains aquifer.

Farther east, these younger Permian and Jurassic rocks are not present and the Cedar Hills and Great Plains aquifers are interconnecting aquifer systems (Figure 6). In this part of the study area, significant hydraulic head differences between the Cedar Hills and overlying Great Plains aquifers indicate that saline ground waters from the lower aquifer have the potential for moving upward into shallower zones of the Great Plains aquifer. An analysis of the ground-water geochemistry data shows that waters in the Dakota aquifer east of the Cedar Hills aquifer subcrop are sodium chloride-type waters and generally contain higher chloride levels than those west of the subcrop. This indicates that upward movement between the Cedar Hills and Great Plains aquifers is occurring in the area where the lower aquifer subcrops beneath the Great Plains aquifer. The coincidence of zones of sodium-chloride waters in the upper part of the Great Plains aquifer with geologic structures suggests that some of this salt water may be migrating upward through fractures rather than through interconnecting lenses of sandstone. However, insufficient data are available to determine the flow rates.

These findings indicate that the Cedar Hills aquifer may not be suitable for the continued use as a disposal zone for oil-field brines in the subcrop area. The most important consideration in the disposal of wastes using shallow injection is containment in the injection horizon in order to prevent contamination of fresh and usable surface and ground-water supplies (Warner and Lehr, 1980). Based on the preliminary findings from this study continued use of the Cedar Hills as a disposal horizon will increase the discharge of naturally occurring saltwaters present in the Cedar Hills as the fluid pressure in the injection zone increases. A comparison of Cedar Hills injection well fluid-level data collected by the Kansas Department of Health and Environment in the 1970's with data collected in this study for the same area indicates that some fluid levels may have risen as much as 100 feet since the time of the original survey. Hydrologic testing of the Cedar Hills aquifer should be conducted to determine the effect of injection on the disposal zone and the overlying Great Plains aquifer during injection, especially in those areas where high injection pressures are used to inject the oil-field brines into the disposal horizon.

10.0 PRELIMINARY CONCLUSIONS

The preliminary conclusions of this hydrogeologic and water quality investigation consist of descriptions of the ground-water flow system and water chemistry of the Great Plains and Cedar Hills aquifers in the study area. These aquifers are widely used in the study area: the Great Plains aquifer for water supply and the Cedar Hills aquifer for the shallow disposal of oil-field brines.

The framework of the Great Plains aquifer consists of the Dakota Formation, Kiowa Shale, and Cheyenne Sandstone. Preliminary analysis of a diverse set of geophysical logs from a borehole drilled in northern Ellis County indicates that geophysical logs can be used to determine paleoenvironments and clay mineralogy in these rocks, and, consequently, stratigraphic boundaries between units. This aquifer system has been subdivided further into upper and lower portions based on the sedimentary architecture of the rock units themselves, that is, the distribution and nature of the lithofacies represented in these rocks. The upper portion of this aquifer system consists of thick, lenticular, alluvially deposited, channel and tabular, flat-bedded, delta-front sandstones, and interbedded mudstones, claystones, and thinly bedded sandstones of the Dakota

Formation. The lower portion of the Great Plains aquifer consists of strata belonging to the Kiowa Formation and Cheyenne Sandstone. These units consist largely of non-marine to shallow marine or marginal marine, lenticular sandstones and interbedded clay shales, siltstones, and thinly bedded sandstones. Lenticular, alluvially deposited sandstones occur sporadically near the base of the Lower Cretaceous. Shallow marine, off-shore bar and distributary sandstones are developed in the Kiowa Formation, primarily east of the study area.

The ground-water flow system in the Great Plains aquifer consists of two components. A component of flow originating in the Western Kansas basin moves west to east across the study area. Another northeastward-moving component of flow moves parallel to the Dakota outcrop and enters the study area from the southwest into Rush and Barton counties. These flow systems converge in the study area along T15S.

The Cedar Hills aquifer consists of the Lower Permian Cedar Hills Sandstone. The thickness of the Cedar Hills aquifer ranges from featheredge in western Russell County to over 275 feet in Rush and Trego counties where it has not been truncated by pre-Lower Cretaceous erosion. It is estimated that on the average, 5035 acre-feet of oil-field brines were injected annually into the Cedar Hills aquifer through 460 shallow disposal wells in the study area from 1975-1983.

The Cedar Hills aquifer ground-water flow system can be subdivided into two portions based on the configuration of the potentiometric surface. West of R19W fluid pressures have been affected by injection of oil-field brines under confined conditions and, as a result, the potentiometric surface is a series of isolated highs and lows. East of R19W, the aquifer is hydraulically interconnected with the Great Plains aquifer and the configuration of the Cedar Hills potentiometric surface is subparallel with the potentiometric surface for the lower part of the Great Plains aquifer.

Hydraulic head data from the monitoring sites and areal surveys of water levels show that the vertical component of ground-water flow is directed upward from the lower part of the Great Plains aquifer to the upper part. East of R19W, the Great Plains aquifer is hydraulically interconnected with the Cedar Hills aquifer, and saline waters from the Cedar Hills aquifer are moving upward into the Great Plains aquifer. This upward movement has affected the water chemistry of the lower part of the Great Plains aquifer. Upward movement of these waters may be facilitated by fractures associated with minor structural features on the Central Kansas uplift. West of the subcrop, water levels are lower in the Cedar Hills aquifer than in the lower part of the Great Plains aquifer except where injection has increased fluid pressures in the Cedar Hills aquifer. Little site specific data are available to determine the more precisely the relationship between the Cedar Hills and Great Plains aquifers west of R19W.

Fluid pressures in the Cedar Hills and Great Plains aquifers are subhydrostatic across the study area. This suggests that these aquifers are relatively well confined and isolated from the near surface hydrologic system. However, the occurrence of relatively fresh waters in the deeper part of the system is problematic if this system is relatively isolated. These fresh waters may be very old or possibly may have come from the Ogallala through fractures in the overlying rocks.

Contamination of the Cedar Hills and Cheyenne aquifers by oil-field brines has been identified at the Gorham monitoring site. The brine contamination has not affected the quality ground water in the overlying aquifer of the upper Dakota at this location. These preliminary conclusions have important implications for the use of the Great Plains aquifer as a water supply and the Cedar Hills aquifer for the disposal of oil-field brines. Upward movement of saline waters from the Cedar Hills into the Great Plains aquifer in the area where they are interconnected, may be accelerated by the continued use of this aquifer for the disposal of oil-field brines. West of the Cedar Hills subcrop, high injection pressures may cause hydraulic fracturing of the media and as a result allow the upward movement of salt water into shallower zones, including the Great Plains aquifer.

11.0 FUTURE RESEARCH NEEDS

Future research is needed to develop a more detailed understanding of the hydrogeology and water chemistry of these aquifers in order to resolve some of the scientific questions raised by this investigation. Listed below are some key areas where more work is needed.

(1) Stratigraphic Framework. A review of the literature shows that a usable stratigraphic framework correlated with surface exposures of the Lower Cretaceous rocks in central Kansas does not exist. Work completed during the course of this investigation suggests that by using a diverse combination of lithodensity and natural gamma-ray logs, it is possible to perform a paleoenvironmental analysis of the lithofacies and establish a consistent rock-stratigraphic framework. This information is important in order to predict the distribution of major sandstone-bearing zones in the subsurface and to facilitate regulation of oil-industry activities by physically establishing the requirements for surface casing. In order to accomplish this goal, a combination of geologic and log-analysis techniques will need to be applied.

The next phase of analysis of the logs from the KGS #1 Braun will be focused on porosity estimations and permeability predictions within the

Lower Cretaceous formations and Cedar Hills Sandstone, as well as neutron log studies of the bound-water and compactional character of the shale units. In these investigations, research work will be closely coordinated with hydrologic studies, so that results may be integrated effectively into ground-water models.

(2) Description of the Flow System. In order to develop a more quantitative description of the flow system in the Great Plains and Cedar Hills aquifers, water level information, materials properties, and additional water chemistry data need to be developed. This includes hydrologic testing of the monitoring sites to determine the horizontal and vertical hydraulic conductivities and storage properties, use of additional environmental isotopes to determine the ages and geochemical evolution of ground waters in the system, and more recent surveys of water levels and water quality in the Cedar Hills aquifer. Estimates of the materials properties will be useful for developing mathematical simulations of the ground-water flow system. This information can be used to determine rates of interchange between the Cedar Hills and Great Plains aquifers and to test hypotheses. An estimate of the age of ground waters in the Great Plains aquifer will be useful for assessing the potential of recharge to the aquifer from the surface. Much of the Cedar Hills data used in this report was developed in the 1970's from information supplied by well operators. As a result, it is difficult to assess the quality of this early survey data.

(3) Mechanics of Injection. Monitoring of the oil-field brine injection wells needs to be carried out in the subcrop area and at a site west of the subcrop in order to determine the effects of injection on the disposal horizon and overlying aquifers in both areas. In order to do this, carefully-controlled testing and precise observations of the quantities of fluids injected and fluid pressures in the overlying aquifers must be carried out at specific sites. This would probably entail the installation and monitoring of a multiple-completion monitoring well over time to observe the increase of fluid pressures in the Cedar Hills from injection and the effects in the overlying aquifers near the brine disposal well.

REFERENCES CITED

Adams, J.A.S., and Weaver, C.E., 1958, Thorium to uranium ratios as indications of sedimentary processes: example of concept of geochemical facies: AAPG Bull., v. 42, no. 2, p. 387-430.

Anonymous, 1960, Salinity determination of ground water by electric log analysis in the Lower Cretaceous (Cheyenne) of northwestern Kansas: Kansas Geological Survey, Open-File Report 60-6, 26 p.

Arthur, M.A., Dean, W.E., Pollastro, Claypool, G.E., and Scholle, P.A., 1985, Comparitive geochemical and mineralogical studies of two cyclic and transgressive pelagic limestone units, Cretaceous Western Interior Basin, U.S.: SEPM Field Trip Guidebook No. 4, p. 16-27.

Bass, N.W., 1926, Geologic investigations in western Kansas: Kansas Geological Survey, Bulletin 11, p. 1-96.

Bigeleisen, J., 1965, Chemistry of isotopes: Science, v. 147, no. 3657, p. 463-471.

Bryson, W., 1970, Fluid level elevations in the Cedar Hills sandstone: Unpublished map.

Bryson, W., 1987, personal communications.

Chadhuri, S., 1988, personal communication.

Cole, V.B., 1976, Configuration of the top of Precambrian rocks in Kansas: Kansas Geological Survey, Map M-7, 1:500,000.

Craig, H., 1961, Isotopic variations in meteoric waters, Science, v. 133, no. 3465, p. 1702-1703.

Dansgaard, W., 1964, Stable isotopes in precipitation: Tellus, v. 26, no. 4, p. 436-468.

Doveton, J.H., 1986, Log analysis of subsurface geology - concepts and computer methods: New York, John Wiley Interscience, 273 p.

Fairbridge, R.W. (ed.), 1972, The Encyclopedia of Geochemistry and Environmental Sciences, Van Nostrand and Reinhold, New York, p. 88-92.

Faure, G., 1977, Principles of Isotope Geology, New York, John Wiley & Sons, 450 p.

Franks, P.C., 1966, Sedimentary petrology and stratigraphy of the Kiowa and Dakota Formations, north-central Kansas: PhD Thesis, University of Kansas, Lawrence, Kansas, 252 p.

______________, 1975, The transgressive-regressive sequence of the Cretaceous Cheyenne, Kiowa, and Dakota formations of Kansas. In: Caldwell W.G.E. (ed), The Cretaceous System in the Western Interior of North America: Geological Association of Canada, Special Paper 13, p. 469-521.

______________, 1979, Record of an early marine transgression- Longford member, Kiowa Formation: Kansas Geological Survey, Bulletin 219, 55 p.

______________, 1980, Models of marine transgression-example from Lower Cretaceous fluvial and paralic deposits, north-central Kansas: Geology, vol. 8, p. 55-61.

Freeze, R.A. and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, New Jersey, Prentice Hall, 604 p.

Frye, J.C., and Brazil, J.J., 1943, Ground water in the oil-field areas of Ellis and Russell Counties, Kansas: Kansas Geological Survey, Bulletin 50, 104 p.

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

Glenister, L.M., and Kauffman, E.G., 1985, High resolution stratigraphy and depositional history of the Greenhorn regressive hemicyclothem, Rock Canyon Anticline, Pueblo, Colorado, SEPM Field Trip Guidebook No. 4, p. 170-183.

Grundhl, T., 1980, A stable-isotopic view of the Cambro-Ordovician aquifer system in northern Illinois: MS thesis, unpublished, Northern Illinois University, DeKalb, 88 p.

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

Hattin, D.E., 1985, Distribution and significance of widespread, time-parallel pelagic limestone beds in Greenhorn Limestone (Upper Cretaceous) of the Central Great Plains and southern Rocky Mountains: SEPM Field Trip Guidebook No. 4, p. 28-37.

Hattin, D.E., 1965, Stratigraphy of the Graneros Shale (Upper Cretaceous) in central Kansas: Kansas Geological Survey, Bulletin 178, 83 p.

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

Helgeson, J.O., Leonard, R.B., and Wolf, R.J., in review, 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: US Geological Survey, Professional Paper 1414-E.

Hodson, W.G., 1965, Geology and ground-water resources of Trego County, Kansas: Kansas Geological Survey, Bulletin 174, 80 p.

Holdoway, K., 1978, Deposition of evaporites and red beds of the Nippewalla Group, Permian, western Kansas: Kansas Geological Survey, Bulletin 215, 43 p.

Hubbert, M.K., and Willis, D.G., 1972, Mechanics of hydraulic fracturing: in Cook, T.D. (ed), Underground Waste Management and Environmental Implications, American Association of Petroleum Geologists, Memoir 18, p. 239-257.

James, G.W., 1972, Mineralogy and distribution of water-insoluble residues from AEC Test Hole 5 in Bayne, C.K., and Brinkley, D., eds., Geology, hydrology thickness and quality of salt at three alternative sites for disposal of radioactive waste in Kansas: University of Kansas, Center for Research, Inc., p. 50-57.

Javandel, I., 1983, Field determination of the hydrologic properties and parameters that control the vertical component of groundwater movement: Lawrence Berkeley and Laboratory, LBL-15050, 116 p.

Jewett, J.M., and Butcher, D., 1957, Disposal of oil-field brines in Kansas: Kansas Geological Survey, Open-File Report 57-2, 22 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: US Geological Survey, Water-Supply Paper 1651, 90 p.

Kansas Geological Survey, 1973, Kansas brine: Kansas Geological Survey computer data file.

Kauffman, E.G., 1985, Cretaceous evolution of the Western Interior Basin of the United States: SEPM Field Trip Guidebook No. 4, p. iv-xiii.

Latta, B.F., 1946, Cretaceous stratigraphy of the Belvidere area, Kiowa County, Kansas: Kansas Geological Survey, Bulletin 64, pt. 6, p. 217-260.

__________ , 1948, Ground-water supplies at Hays, Victoria, Walker, Gorham, and Russell, Kansas with special reference to future needs: Kansas Geological Survey, Bulletin 76, pt. 6, p. 121-196.

__________ , 1950, Geology and ground-water resources of Barton and Stafford Counties, Kansas: Kansas Geological Survey, Bulletin 88, 228 p.

Leonard, A.R., and Berry, D.W., 1961, Geology and ground-water resources of southern Ellis County and parts of Trego and Rush Counties, Kansas: Kansas Geological Survey, Bulletin 149, 156 p.

Lorenz, J.C., Branagan, P., Warpinski, N.R., and Sattler, A.R., 1986, Fracture characteristics and reservoir behavior of stress-sensitive fracture systems in flat-lying lenticular formations: Society of Petroleum Engineers, Paper No. 15244, 8 p.

Malone, P., circa 1984, Map showing salinity of Dakota rocks as calculated by spontaneous potential: Unpublished map prepared for Murfin Drilling Company, Wichita, Kansas.

McCall, D.C., and Gardner, J.S., 1982, Lithodensity log applications in the Michigan and Illinois basins: Transactions of the Society of Professional Well Log Analysts, Paper C, 21 p.

McCauley, J., 1985, Landsat lineaments of western Kansas: an unpublished map, 1:500,000, Kansas Geological Survey, Lawrence, Kansas.

McNellis, J.M., 1973, Geology and ground-water resources of Rush County, central Kansas: Kansas Geological Survey, Bulletin 207, 45 p.

Merriam, D. F., 1957, Subsurface correlation and stratigraphic relation of rocks of Mesozoic age in Kansas: Kansas Geological Survey, Oil and Gas Investigations 14, 25 p.

______________, Atkinson, W.R., Franks, P.C., Plummer, N., and Preston, F.W., 1959, Description of a Dakota (Cretaceous) core from Cheyenne County, Kansas: Kansas Geological Survey Bulletin 134, Pt. 1, p. 5-104.

______________, 1963, The geologic history of Kansas: Kansas Geological Survey, Bulletin 162, 317 p.

Nielson, H., 1979, Sulfur Isotopes in, Jager, E., and Hunziker, J.C. (eds.), Lectures in Isotope Geology: New York, Springer-Verlag, p. 283-312.

Pearson, F.J. Jr., and Rightmire, C.T., 1980, Sulfur and oxygen isotopes in aqueous sulfur compounds, in, Fritz, P., and Fontes, J.Ch (eds.), Handbook of Environmental Isotope Geochemistry, New York, Elsevier Scientific Publishing Co., p. 227-258.

Piper, A.M., 1944, A graphic procedure in the geochemical interpretation of water analyses: Am. Geophys. Union Trans., v. 25, p. 914-923.

Plummer, L.N., Jones, B.F., and Truedall, A.H., 1978, WATEQF: a Fortran IV version of WATEQ, a computer program for calculating chemical equilibrium of natural waters. User's guide: USGS Water-Resources Investigations 76-13, 61 p.

Plummer, N. and Romary, J.F., 1942, Stratigraphy of the pre-Greenhorn Cretaceous beds of Kansas: Kansas Geological Survey, Kansas Geological Survey, Bulletin 41, pt. 9, p. 313-348.

Rubey, W.W., and Bass, N.W., 1925, The geology of Russell County, Kansas: Kansas Geological Survey, Bulletin 10, pt 1, p. 1-86.

Russell, W.I., 1972, Pressure-depth relations in Appalachian region: American Association of Petroleum Geologists, Bulletin, 56(3), p. 528-536.

Schlumberger, 1986, Log Interpretation Charts, 122 pp.

Scott, R.W., 1970, Stratigraphy and sedimentary environments of Lower Cretaceous rocks, southern Western Interior: AAPG, Bulletin 54, p. 1225-1244.

Siemers, C.T., 1971, Stratigraphy, paleoecology, and environmental analysis of the upper part of the Dakota Formation (Cretaceous), central Kansas: Unpub. PhD, Indiana University, Bloomington, 287 p.

____________, 1976, Sedimentology of the Rocktown Channel sandstone, upper part of the Dakota Formation (Cretaceous) central Kansas: Journal of Sedimentary Petrology, v. 20, no. 1, p. 97-123.

Swineford, A. and Williams, H.L., 1945, The Cheyenne Sandstone and adjacent formations of a part of Russell County, Kansas: Kansas Geological Survey, Bulletin 60, pt. 4, p. 101-168.

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

Tester, A.C., 1931, The Dakota Stage of the type locality: Iowa Geological Survey, 35, p. 195-332.

Thode, H.G., and Monster, J., 1965, Sulfur-isotope geochemistry of petroleum, evaporites, and ancient seas: in, Young, A., and Galley, J.E. (eds.), Fluids in Subsurface Environments, AAPG Memoir #4, Oklahoma, Tulsa, AAPG, p. 367-377.

Toth, J., 1979, Patterns of dynamic pressure increment of formation-fluid flow in large drainage basins, exemplified by the Red Earth region, Alberta, Canada: Canadian Petroleum Geology Bulletin, v. 27, p. 63-86.

Turan, L., 1982, Isotopes in ground-water investigations: Ground Water, v. 20, no. 6, p. 740-745.

Twenhofel, W.H., 1920, The Commanchean and Dakota strata of Kansas: American Journal of Science, v. 49, p. 281-297.

______________, 1924, Geology and invertebrate paleontology of the Commanchean and "Dakota" formations of Kansas: Kansas Geological Survey, Bulletin 9, 135 p.

Vuke, S., 1981, Depositional environments of the Early Cretaceous seaway, northwestern United States: Northwestern Geology, v. 10, p. 1-112.

Warner, D.L., and Lehr, J.H., 1980, Subsurface wastewater injection- the technology of injecting wastewater into deep wells for disposal: Premier Press, Berkely, Calif., 512 p.

Whittemore, D.O., 1984, Geochemical identification of salinity sources. In: French, R.H. (ed.), Salinity in Water Courses and Reservoirs, Proceedings of the International Conference on State-of-the-Art Control of Salinity, Ann Arbor Science, Butterworth Publishers, Stoneham, Mass., p. 505-514.

__________________, Basel, C.L., Galle, O.K., and Waugh, T.C., 1981, Geochemical identification of saltwater sources in the Smoky Hill River Valley, McPherson, Saline, and Dickinson counties, Kansas: Kansas Geological Survey Open-File Report 81-6, 78 p.

__________________, 1988, Bromide as a tracer in ground-water studies: Geochemistry and analytical determination: Proceedings of Ground Water Geochemistry Conference, Denver, Colorado, National Water Well Association, Dublin, Ohio, p. 339-360.

__________________, and Pollock, L.M., 1979, Determination of salinity sources in water resources of Kansas by minor alkali and halide chemistry: Kansas Water Resources Research Institute, Contribution no. 208, Manhattan, Kansas, 28 p.

__________________, McClain, T., Cobb, P.M., and Davis, R., 1987, Geochemistry of ground waters in the saline intrusion area of Groundwater Management District No. 5, south-central Kansas: draft of Kansas Geological Survey report in preparation.

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

Zelt, F.B., 1985, Paleoceanographic events and lithologic/geochemical facies of the Greenhorn marine cycle (Upper Cretaceous) examined using natural gamma-ray spectrometry: SEPM Field Trip Guidebook No. 4, p. 49-59.

Appendix A. Dissolved Constituent Concentrations for Samples from USGS WATSTORE Data Files

County Code	Location	Sampling Date	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	HCO3 mg/L	SO4 mg/L	Cl mg/L	NO3 mg/L	TDS mg/L (calc)	Depth BLS ft
165	19S 17W 27ADD	07-07-78	38	13	60	7.0	290	22	22	0.44	305	185
165	19S 18W 27CCB	05-16-60	20	13	140	0.0	300	28	90	1.7	440	390
165	19S 20W 26BAA	05-13-60	7	8	270	0.0	320	170	120	3.6	735	410
165	19S 19W 24CCB	05-16-60	19	9	190	0.0	280	130	93	2.7	581	290
9	19S 12W 15DDD	10-24-42	110	11	28	0.0	300	13	77	13.0	400	86
165	19S 20W 17DDC	05-13-60	7	7	420	0.0	440	210	250	4.4	1115	360
9	19S 13W 11CBB	10-24-42	200	32	160	0.0	260	110	250	360.0	1240	47
9	19S 12W 05DDC	05-19-81	66	9	40	2.0	0	11	34	4.0	166	60
165	19S 20W 04BBB	10-11-60	10	5	310	0.0	330	200	160	0.80	848	284
165	18S 18W 31DDA	10-11-60	10	3	240	0.0	350	95	110	1.8	632	150
165	18S 17W 34BCA	10-11-60	18	10	220	0.0	410	120	70	1.9	641	175
165	18S 20W 36ABB	10-11-60	13	5	450	0.0	360	230	340	1.0	1216	214
165	18S 16W 28CDC	05-17-60	10	15	270	0.0	550	140	46	1.3	753	168
165	18S 18W 26DDA	10-12-60	29	10	150	0.0	330	52	84	0.40	488	187
9	19S 15W 30ACA	05-20-81	140	17	130	7.0	0	69	240	0.0	603	85
165	18S 17W 18CCC	10-07-60	21	10	460	0.0	340	140	470	0.40	1269	224
9	18S 14W 07CCC	09-06-44	76	10	26	0.0	260	31	26	4.3	301	61
9	18S 12W 12BCC	10-12-44	96	8	22	0.0	330	2	28	9.7	328	41
165	18S 18W 09AAB	10-12-60	14	6	480	0.0	300	230	440	1.8	1319	265
9	18S 15W 01BCC	10-16-44	8	6	320	0.0	360	76	260	1.8	849	220
9	18S 11W 04ADA	08-27-45	86	12	100	0.0	320	22	110	2.4	490	160
9	18S 15W 01BCA	08-23-67	19	11	480	15.0	390	94	520	0.40	1331	250
9	18S 15W 01BCB	06-16-61	18	10	440	0.0	380	89	450	1.2	1195	250
9	18S 11W 03BBC	01-26-61	79	10	60	0.0	310	18	100	2.6	431	77
9	18S 11W 04AAD	08-09-65	75	10	68	4.4	310	18	77	0.90	406	156
9	17S 12W 31DCC	10-15-44	150	28	160	0.0	460	240	140	19.0	963	60
9	17S 13W 31DD	10-15-44	86	34	710	0.0	360	130	1000	3.5	2141	58
9	17S 14W 33DDA	09-07-44	120	28	61	0.0	360	200	27	2.0	615	86
165	17S 18W 33ACD	03-12-65	14	3	450	13.0	280	210	410	0.30	1238	300
53	17S 07W 35ADA	12-29-64	78	8	24	3.0	260	19	38	2.4	300	0

Appendix A. Continued

County Code	Location	Sampling Date	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	HCO3 mg/L	SO4 mg/L	Cl mg/L	NO3 mg/L	TDS mg/L (calc)	Depth BLS ft
165	17S 18W 34BBD	07-06-64	13	7	470	13.0	290	220	430	0.10	1296	302
165	17S 20W 36ABB	10-12-60	9	3	320	0.0	270	160	240	1.3	866	325
53	17S 08W 25CCC	05-08-61	73	12	28	0.0	260	18	39	1.8	300	95
165	17S 19W 27DDC	05-16-60	100	46	550	0.0	430	450	580	0.40	1938	320
165	17S 17W 28DCD	05-12-60	18	22	640	0.0	320	240	700	4.9	1782	230
71	17S 42W 36BBB	12-17-48	18	9	380	0.0	450	210	220	0.0	1058	1140
9	17S 12W 27CCB	10-15-44	180	24	74	0.0	410	310	25	1.5	816	153
165	17S 20W 30CCB	07-17-80	32	25	400	9.1	300	400	270	1.3	1285	325
53	17S 10W 27AAC	11-16-61	73	15	40	0.0	310	16	41	1.5	339	84
165	17S 18W 28AAD	05-12-60	38	29	1300	0.0	250	290	1800	7.1	3587	335
9	17S 13W 28BB	09-07-44	150	37	210	0.0	370	370	190	20.0	1159	260
165	17S 18W 20DAA	10-12-60	10	5	500	0.0	270	190	500	1.9	1340	300
165	17S 16W 20AAA	10-13-60	7	1	390	0.0	440	88	290	2.1	995	315
53	17S 09W 16DDB	06-06-66	93	16	57	4.0	330	27	89	1.8	450	0
53	17S 09W 16DAB	07-11-85	88	14	48	2.8	0	30	62	0.0	245	210
53	17S 09W 13ABB	11-16-61	72	19	33	0.0	330	20	22	0.40	329	112
9	17S 13W 10DDD	10-16-44	140	15	33	0.0	410	21	46	62.0	519	65
9	17S 14W 11CCD	09-07-44	57	14	93	0.0	350	31	100	3.1	470	180
53	17S 07W 10CCA	11-20-61	69	14	53	0.0	240	74	42	8.9	379	65
53	17S 10W 10DBD	09-30-64	88	10	34	2.7	350	12	27	4.4	350	0
53	17S 10W 10CAB	04-16-53	83	16	50	0.0	360	40	33	0.90	400	0
53	17S 10W 10ACA	04-26-67	93	12	31	3.7	360	16	24	5.3	362	0
9	17S 12W 02CBC	10-15-44	66	16	110	0.0	350	100	46	6.6	517	150
53	17S 08W 04ADD	11-18-61	70	15	35	9.0	310	18	40	0.40	340	59
9	17S 15W 02ADD	09-07-44	62	58	2300	0.0	490	430	3300	8.8	6400	196
9	16S 11W 36DC	10-15-44	77	11	0	0.0	320	10	22	1.4	278	187
165	16S 16W 32CCB	05-12-60	19	13	510	0.0	330	210	510	3.4	1428	266
9	16S 13W 33DAA	09-07-44	21	15	630	0.0	570	390	430	4.3	1771	164
53	16S 10W 26CCC	11-21-61	96	11	22	0.0	320	15	40	0.0	341	111
165	16S 18W 27CDD	05-12-60	19	11	680	0.0	360	270	700	3.8	1861	209

Appendix A. Continued

County Code	Location	Sampling Date	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	HCO3 mg/L	SO4 mg/L	Cl mg/L	NO3 mg/L	TDS mg/L (calc)	Depth BLS ft
9	16S 14W 26BBB	09-07-44	70	49	1600	0.0	580	520	2100	6.2	4630	167
9	16S 13W 20DDA	04-16-68	22	15	830	16.0	460	160	980	0.0	2249	285
165	16S 17W 22AAA	10-06-60	13	10	510	0.0	270	190	540	1.6	1397	320
165	16S 17W 16DCD	07-12-85	12	7	380	5.5	0	200	430	0.0	1035	370
165	16S 19W 17BAB	05-13-60	8	16	360	0.0	400	180	240	2.9	1004	400
9	16S 11W 11CC	10-16-44	29	32	1200	0.0	410	280	1500	18.0	3261	260
9	16S 12W 12 CBC	10-15-44	6	4	220	0.0	380	48	91	2.8	558	190
9	16S 15W 11DA	09-07-44	37	15	490	0.0	360	120	560	20.0	1419	187
165	16S 18W 10CB0	10-29-49	21	12	790	0.0	340	270	890	0.80	2151	0
9	16S 13W 12ADD	10-15-44	19	13	730	0.0	550	280	660	9.7	1982	227
9	16S 14W 09BC	10-15-44	45	35	1600	0.0	470	420	2000	8.8	4340	190
9	16S 13W 08AAA	10-15-44	36	35	1400	0.0	430	230	1900	7.1	3820	252
9	16S 15W 06DD	10-15-44	24	19	950	0.0	380	270	1100	10.0	2560	209
165	16S 18W 06DAC	05-13-60	14	19	760	0.0	310	260	880	2.8	2088	230
53	16S 08W 04DAA	11-18-61	130	43	180	8.5	340	160	310	0.0	999	52
165	16S 20W 05BBD	05-13-60	8	10	480	0.0	430	220	360	3.8	1294	530
167	15S 14W 31CC0	11-26-41	31	16	700	0.0	440	140	820	0.0	1923	0
53	15S 10W 36CCB	11-16-61	140	55	710	0.0	370	170	1200	0.0	2457	152
53	15S 08W 34CAA	11-20-61	49	10	48	0.0	210	54	25	0.0	289	60
53	15S 06W 35AAA	11-20-61	26	4	11	0.0	90	10	11	6.2	112	49
51	15S 18W 33BAA	07-28-80	18	10	760	10.0	360	250	850	1.3	2076	154
195	15S 22W 35ABA	09-29-60	68	9	13	0.0	250	13	12	2.9	241	66
195	15S 21W 25DDD	06-14-60	10	12	480	0.0	420	220	370	0.0		555
51	15S 19W 27DAA	03-21-47	85	15	28	0.0	340	32	12	4.0	343	156
51	15S 17W 14DDD	03-24-47	87	35	1100	0.0	460	560	1300	8.0	3316	171
195	15 S 24W 15CCC	09-09-59	9	8	400	0.0	310	170	340	0.40	1080	618
51	15S 16W 14ABB	03-24-47	120	14	0	0.0	310	110	0	40.0	436	204
51	15S 16W 18BBB	03-24-47	92	25	860	0.0	360	410	1000	20.0	2584	188
167	15S 14W 07ABD	05-06-42	22	21	1400	0.0	460	310	1800	4.2	3783	174
51	15S 16W 09AA	03-24-47	56	50	1800	0.0	190	520	2500	3.5	5023	133

Appendix A. Continued

County Code	Location	Sampling Date	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	HCO3 mg/L	SO4 mg/L	Cl mg/L	NO3 mg/L	TDS mg/L (calc)	Depth BLS ft
51	15S 18W 09BBB	10-31-49	560	89	340	0.0	280	1800	300	4.1	3231	270
51	15S 19W 04ADB	10-28-49	77	25	210	0.0	300	310	130	0.0		290
167	15S 12W 02BAA	08-01-80	200	30	57	8.0	280	450	47	9.7	939	245
51	15S 17W 05BAA	03-24-47	43	26	1500	0.0	380	460	1800	5.0	4021	150
167	14S 12W 34DAA	05-04-42	43	20	1000	0.0	410	210	1000	7.1	2482	104
53	14S 09W 34ADB	11-18-61	100	8	18	0.0	310	21	29	17.0	346	63
53	14S 07W 26DCC	04-12-79	200	39	160	2.0	130	210	260	420.	1355	106
51	14S 19W 29DDC	10-28-49	17	10	850	0.0	540	270	1000	3.9	2416	350
53	14S 08W 28CBD	11-20-61	110	8	14	0.0	300	37	25	10.0	351	74
53	14S 06W 26ADC	11-21-61	38	14	110	0.0	220	140	46	1.5	458	99
167	14S 15W 20DA0	03-02-42	94	52	2100	0.0	420	450	2900	13.0	5816	0
167	14S 15W 13DD0	05-06-42	730	300	5300	0.0	420	1200	9300	19.0	17056	0
167	14S 15W 14DD0	04-10-42	0	260	3800	0.0	300	510	7800	8.8	12526	0
53	14S 10W 09DDC	11-16-61	390	56	39	0.0	360	800	110	0.0	1572	88
167	14S 11W 07CAB	07-18-80	190	9	88	5.0	440	200	110	36.0	854	100
167	14S 12W 06CA0	05-05-43	100	37	1000	0.0	370	190	1000	0.0	2509	0
167	14S 13W 06BB0	11-12-41	250	2	1000	0.0	760	220	1000	0.90	2846	0
167	13S 14W 30BC0	05-21-42	39	42	2000	0.0	500	550	2600		5487	0
167	13S 14W 19D00	09-20-41	620	630	11000	0.0	1330	3500	17000		33405	0
51	12S 17W 31CC	01-15-42	38	36	1400	0.0	430	440	1800		3925	730
195	12S 21W 24CDC	10-12-59	16	10	180	0.0	310	100	61		545	665
51	12S 16W 14BC	03-17-42	150	170	3000	0.0	640	1500	4000		9140	440
167	11S 12W 07DDC	08-22-50	160	28	290	0.0	410	260	330		1345	0
167	11S 12W 07DDB	07-18-85	190	26	180	4.8	0	230	280		911	151
167	11S 12W 07DDB	08-07-84	180	29	250	6.3	0	320	280		1065	37
163	07S 17W 19BBD	04-08-69	59	65	2800	35.0	1120	810	3300		7620	0
163	07S 19W 17ADD	04-08-69	72	15	610	12.0	430	230	660		1885	0
163	06S 18W 33DAD	04-08-69	100	110	2700	32.0	1060	1200	3200		7863	151
195	15S 22W 24CDC	09-29-60	68	9	13	0.0	250	13	12	0.50	242	66
195	15S 21W 25DDD	06-14-60	10	12	480	0.0	420	220	370	5.2	1304	555
195	15S 24W 15CCC	09-09-59	9	8	400	0.0	310	170	340	3.2	1083	618

Appendix B. Site Information, Chemical Properties, and Dissolved Constituent Concentrations for Samples Collected by the Kansas Geological Survey.

County Code	Location	Location description	Depth BLS ft	Formation	Sample date	Specific conductance umho/cm	pH, field	pH, lab	Total dissolved solids (calc) mg/L
				Spring					
51	12S 14W 03DA	Braun Spring	0		05-21-87	1230	7.25	8.2	852
				Water-supply wells					
9	16S 14W 03DA	R. Bradshaw	180		06-16-87	3600	7.25	8.0	2185
9	17S 12W 17AAA	L. Frenzl	225		06-16-87	860	6.65	7.6	503
9	17S 15W 28DCC	J. Hickey	220		06-19-87	2400	7.70	8.2	1265
9	16S 12W 12CBC	N. Weber	190		06-15-87	1120	7.10	8.0	634
9	18S 11W 03BAD	City of Claflin	160		06-16-87	720	6.90	7.9	389
9	16S 14W 09BCB	E. Nuss	ND		06-16-87	820	6.95	8.0	3630
51	15S 16W 14BAB	R. Von Lintel	160		06-17-87	4530	6.70	7.6	3251
51	15S 17W 23AB	Leiker	237		06-18-87	6310	7.45	8.0	3630
51	15S 18W 33ABB	L. Werth	130		06-17-87	3370	7.65	8.2	1855
51	15S 18W 23BABB	Stremel	238		06-17-87	6840	7.35	8.0	4034
51	15S 20W 35CAA	J. Klaus	365		06-17-87	1520	8.15	8.4	917
51	14S 19W 36DAD	D. Befort	410		06-17-87	4860	7.75	8.2	2794
51	13S 18W 22CCB	M. McLaren	400	Alluvium/Dakota	06-18-87	3900	7.55	8.2	2224
65	07S 25W 21DCD	Cities Service	ND		06-17-87	2400	8.35	8.6	1268
65	07S 25W 21DCD	Cities Service	ND		07-05-88	2060	8.40	8.5	1210
65	08S 22W 34CCD	C. Hocker	260	Codell	06-15-87	1420	6.85	7.6	895
163	08S 20W 14DAD	Windmill	650		06-18-87	4470	8.20	8.4	2559
163	09S 17W 09DDD	T. Thompson	700		06-18-87	10200	8.40	8.1	6162
163	10S 19W 35BBD	Murfin Drilling	ND		06-17-87	8000	6.50	8.1	4685
163	07S 18W 11CCC	K. Bigge	ND		06-17-87	10200	7.70	8.2	6132
165	16S 17W 15DDD	St. Marys Church	320		06-16-87	2650	7.55	8.0	1302
165	17S 18W 33ACD	City of LaCrosse	369		06-17-87	2000	7.25	8.0	1147

County Code	Location	Location description	Depth BLS ft	Formation	Sample date	Specific conductance umho/cm	pH, field	pH, lab	Total dissolved solids (calc) mg/L
165	17S 19W 27DDC	DeWald	320		06-16-87	2980	7.75	8.2	1657
165	17S 16W 20	C. Rothe	180		06-16-87	1360	7.60	8.4	786
165	16S 18W 21DBB	E. Herman	20	Greenhorn LS	06-16-87	1700	6.70	7.8	988
165	16S 18W 16CDB	City of Liebenthal	170		06-17-87	3080	7.80	8.3	1708
167	12S 13W 03BBD	Zweifel	255		06-15-87	5750	7.00	8.0	3437
167	12S 12W 31BDC	Jim Romine	144		06-15-87	820	7.45	7.8	450
167	14S 13W 12DAD	Bunker Hill	285		06-15-87	2700	6.85	7.8	1325
167	15S 12W 14ADD	Koetkeymer	194		06-16-87	3400	7.55	8.2	2119
167	15S 14W 26BAAA	H. Bender	221		06-17-87	6200	7.20	8.0	3716
167	14S 11W 10ADD	V. Doubrava	250		06-16-87	2850	6.95	7.9	1490
167	14S 11W 10DCA	V. Doubrava	215		06-16-87	1850	6.75	7.7	1204
167	15S 15W 27BCD	B. Dumler	ND		06-16-87	4980	7.40	8.1	2877
167	13S 14W 03CBD	G. Machin	20	Alluvium	06-17-87	2000	7.00	7.8	1478
167	13S 14W 32CCD	E. Mai	25	Alluvium	06-18-87	3370	6.85	7.8	2169
195	14S 24W 19DDA	C. Kline	500		06-16-87	1650	7.35	8.4	963
195	15S 21W 25DDD	North	330		06-16-87	2400	7.55	8.2	1257
195	15S 22W 35ABA	Brason	660		06-16-87	640	7.05	8.2	365
195	15S 24W 15CCC	A. Montgomery	600		06-16-87	2050	7.10	8.3	1215
195	14S 21W 04DAD	Kuppartz	525		06-17-87	3520	6.75	7.8	2464
195	14S 22W 21BCB	Schoenthaller	500		06-17-87	2900	8.45	9.0	1122
195	14S 22W 20AAA	Schoenthaller	700		06-17-87	2000	6.95	8.0	1409
195	14S 22W 35AAA	Cedar Bluff C.S. Camp	470		06-17-87	2250	-	8.4	1298
195	14S 21W 05ABA	A.A. Fles	521		06-17-87	1960	6.90	8.4	1132
195	14S 24W 19CCA	Wiedamann	680		06-16-87	1600	-	8.4	934
195	15S 24W 16DDD	Montgomery	640		06-16-87	1850	7.50	8.4	1054
195	15S 21W 12CCC	Branner	420		06-18-87	3090	6.80	8.5	1800
195	14S 21W 10CBB	Augustine	600		06-16-87	2100	7.30	8.4	1200
195	14S 22W 22BAC	Rolling	630		06-17-87	1100	6.95	8.2	676

County Code	Location	Location description	Depth BLS ft	Formation	Sample date	Specific conductance umho/cm	pH, field	pH, lab	Total dissolved solids (calc) mg/L
				Multiple-completion wells (monitoring sites)					
65	08S 23W 02DCB	Hill City, U. Dakota	785	Upper Dakota	07-05-88	2850	8.25	9.1	1737
65	08S 23W 02DCB	Hill City, L. Dakota	1140	Lower Dakota	07-05-88	30400	7.50	8.2	20000
51	12S 18W 30AA	Hays North site (Braun)	1185	Cedar Hills	05-13-87	49100	7.60	7.8	34140
51	12S 18W 30AA	Hays North site (Braun)	835	Cheyenne	05-15-87	43700	7.45	8.2	30410
51	12S 18W 30AA	Hays North site (Braun)	772	Lower Dakota	05-21-87	35700	7.50	8.2	24360
51	12S 18W 30AA	Hays North site (Braun)	655	Upper Dakota	09-24-87	43200	6.75	7.5	30740
51	12S 18W 30AA	Hays North site	655	Upper Dakota	01-07-88	41400	-	7.6	28730
51	12S 15W 14	Marsh, Russell Co.		Upper Dakota	07-05-88	22000	7.05	7.8	13350
51	12S 15W 14	Marsh, Russell Co.		Lower Dakota	07-05-88	23,200	8.10	8.2	14460
167	13S 15W 32BCB	Gorham site	585	Cedar hills	11-23-87	30800	7.20	7.5	19390
167	13S 15W 32BCB	Gorham site	480	Cheyenne	11-23-87	32300	7.50	7.4	20640
167	13S 15W 32BCB	Gorham site	210	Upper Dakota	11-23-87	6500	9.15	9.0	3756
167	13S 15W 32BCB	Gorham site	210	Upper Dakota	07-05-88	7300	8.40	9.4	
				Oil-field brines					
9	18S 13W 22D	Fourway	ND	Kansas City	05-14-87	176000	-	6.4	164700
9	18S 13W 23B	Philips	ND	Arbuckle	05-14-87	132000	-	7.0	103200
9	18S 18W 22B	Allen NW, site 2, well 5	ND	Arbuckle	05-14-87	56900	-	7.6	39370
51	14S 19W 17BN/2	Nixon Irwin #1, N well	ND	Arbuckle	05-21-87	64700	-	7.5	44780
51	14S 19W 17BS/2	Nixon Irwin C#1,	ND	Arbuckle	05-21-87	66000	-	7.4	45590
51	13S 18W 23	Dreiling Leiker #1	ND	Arbuckle	05-21-87	163000	-	6.7	149300
51	13S 15W 32B	Weigel	ND	Arbuckle	07-05-88	61,600	-	7.7	41170

Location	Location description	SiO2 mg/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	CO3 mg/L	HCO3 mg/L	SO4 mg/L	Cl mg/L	NO3 mg/L
				Spring							
12S 18W 30A	Braun spring	29	219	19	46	9.5		357	288	65	
				Water-supply wells							
16S 14W 03DA	Bradshaw		21	14	817	12		584	393	639	<5
17S 12W 17AAA	Frenzl		61	18	109	7.1		354	80	53	<5
17S 15W 28DCC	Hickey		13	7.6	487	8.6		499	163	339	<5
16S 12W 12CBC	Weber		6.2	2.1	250	4.2		369	62	128	<5
18S 11W 03BAD	City of Claflin		67	10	77	4.0		297	15	70	<5
16S 14W 09BCB	Nuss		135	15	25	3.9		358	40	55	22
15S 16W 14BAB	Von Lintel		542	38	516	9.1		339	1140	695	137
15S 17W 23AB	Leiker		35	26	1330	16		370	389	1650	<5
15S 18W 33ABB	Werth		11	8.6	695	9.1		296	244	741	<5
15S 18W 23BABB	Stremel		32	24	1530	17		379	442	1800	<5
15S 20W 35CAA	Klaus		4.5	2.7	350	5.5	2.2	320	179	215	<5
14S 19W 36DAD	Befort		11	11	1070	9.3		357	306	1210	<5
13S 18W 22CCB	McLaren		8.7	8.6	864	8.6		378	278	869	<5
07S 25W 21DCD	Cities Service		3.1	1.2	516	3.8	12	580	141	304	<5
07S 25W 21DCD	Cities Service	14	2.4	1.1	484	4.0	10	576	151	265	<5
08S 22W 34CCD	Hocker		189	26	102	6.1		389	247	118	14
08S 20W 14DAD	Windmill		7.0	3.9	1000	7.2	3.6	539	274	997	
09S 17W 09DDD	Thompson		42	36	2290	20		777	737	2650	<5
10S 19W 35BBD	Murfin Drilling		56	58	1660	13		630	664	1920	<5
07S 18W 11CCC	Bigge		45	44	2330	16		803	617	2680	<5
16S 17W 15DDD	Church, Loretta		14	7.6	493	8.2		246	191	467	<5
17S 18W 15DDD	City of LaCrosse		41	10	383	8.9		264	229	345	<5
17S 19W 27DDC	DeWald		17	11	612	12		312	248	600	<5
17S 16W 20	Rothe		4.9	3.1	303	5.2	1.4	431	137	119	<5
16S 18W 21DBB	Herman		209	18	124	5.1		383	140	227	75
16S 18W 16CDB	City of Liebenthal		11	6.9	646	8.5		306	231	653	<5
12S 13W 03BBD	Zweifel		12	19	1300	9.8		757	542	1180	<5
12S 12W 31BDC	Romine		81	9.0	68	8.6		96	102	134	<5

Location	Location description	SiO2 mg/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	CO3 mg/L	HCO3 mg/L	SO4 mg/L	Cl mg/L	NO3 mg/L
14S 13W 12DAD	Bunker Hill		74	19	400	5.0		299	178	501	<5
15S 12W 14ADD	Koetkeymer		47	19	696	75		583	497	481	16
15S 14W 26BAAA	Bender		215	44	1040	156		505	374	1480	156
14S 11W 10ADD	Doubrava		166	21	347	23		386	330	388	24
14S 11W 10DCA	Doubrava		180	42	188	9.64		403	426	159	<5
15S 15W 27BCD	Dumler		40	21	1070	14		379	284	1260	<5
13S 14W 03CBD	Machin		339	30	120	4.0		301	692	125	17
13S 14W 32CCD	Mai		493	43	201	9.8		386	326	573	331
14S 24W 19DDA	Kline		4.5	1.9	374	4.8	2.4	331	188	224	<5
15S 21W 25DDD	North		4.0	2.2	490	6.0		398	207	351	<5
15S 22W 35ABA	Brason		94	12	25	3.6		221	52	50	19
15S 24W 15CCC	Montgomery		26	11	429	7.4		390	304	244	<5
14S 21W 04DAD	Kuppartz		428	57	358	6.8		419	882	501	23
14S 22W 21BCB	Schoenthaller		4.2	2.2	445	6.3	31	484	192	202	<5
14S 22W 20AAA	Schoenthaller		175	99	161	8.7		310	650	132	26
14S 22W 35AAA	Cedar Bluff Camp		6.1	2.7	514	5.6	4.1	424	198	358	<5
14S 21W 05ABA	Fles		4.4	1.8	439	4.8	2.9	333	212	303	<5
14S 24W 19CCA	Wiedamann		4.2	1.7	361	4.5	3.1	337	192	201	<5
15S 24W 16DDD	Montgomery		6.8	3.2	405	6.3	4.1	335	187	276	<5
15S 21W 12CCC	Branner		8.6	3.9	714	8.1	7.4	584	250	519	<5
14S 21W 10CBB	Augustine		4.2	2.0	468	5.5	3.1	315	207	355	<5
14S 22W 22BAC	Rolling		108	21	106	3.9		285	173	92	31
		Multiple-completion wells (monitoring sites)									
08S 23W 02DCB	Hill City, U. Dakota	22	3.3	0.9	708	32	83	762	244	343	<5
08S 23W 02DCB	Hill City, L. Dakota	14	280	136	7380	113		168	2190	9790	<5
12S 18W 30AA	Hays, Cedar Hills	27	182	801	11500	76		1690	4610	16100	
12S 18W 30AA	Hays, Cheyenne	20	64	713	10300	65		1070	4110	14600	
12S 18W 30AA	Hays, L. Dakota	20	72	557	8340	86		892	3340	11500	
12S 18W 30AA	Hays, U. Dakota	31	252	705	10600	80		1690	3980	14250	0.3
12S 18W 30AA	Hays, U. Dakota	34	188	620	9940	81		1470	3570	13560	<10
12S 15W 14	Marsh, Russell Co.	14	168	273	4700	28		1184	1960	5610	<5
12S 15W 14	Marsh, Russell Co.	14	182	291	5030	33		1277	2020	6250	<5

Location	Location description	SiO2 mg/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	CO3 mg/L	HCO3 mg/L	SO4 mg/L	Cl mg/L	NO3 mg/L
13S 15W 32BCB	Gorham, Cedar Hills	76	845	353	5980	105		180	1330	10570	<10
13S 15W 32BCB	Gorham, Cheyenne	28	661	300	6790	108		207	1600	11020	<5
13S 15W 32BCB	Gorham, U. Dakota	9.3	15	11	1440	52	2.9	316	384	1686	<5
13S 15W 32BCB	Gorham, U. Dakota	8.5	8.2	7.6	1520	61	101	254	384	1746	<5
				Oil-field brines							
18S 13W 22D	Fourway	48	9820	3030	48200	276		62	<10	102000	862
18S 13W 23B	Philips	42	5800	1890	31500	252		159	20	62800	478
18S 18W 22B	Allen NW, site 2-#5	29	2360	604	11600	206		594	2140	22000	47
14S 19W 17BN/2	Nixon Irwin #1-N	36	2350	592	13800	310		414	2070	25300	61
14S 19W 17BS/2	Nixon Irwin C#1-S	38	2360	604	14200	313		350	1980	25800	64
13S 18W 23	Dreiling Leiker #1	24	10100	2600	43400	359		49	<10	92100	470
13S 15W 32	Weigel	24	2420	822	12600	204		496	2050	22700	<5

Location	Location description	Sr mg/L	F mg/L	NH4 mg/L	Total Fe mg/L	Total Mn mg/L	Ba mg/L	B mg/L	Br mg/L	I mg/L
				Spring						
12S 18W 30A	Braun Spring	0.9			0.16	0.03	0.44	0.21	<0.05	0. 058
				Water-supply wells						
16S 14W 03DA	Bradshaw	0.5	2.7		1.7	0.04	0.020	0.81	0.90	0. 052
17S 12W 17AAA	Frenzl	0.8	0.8		20.8	0.14	0.040	0.24	0.18	0. 0123
17S 15W 28DCC	Hickey	0.4	5.6		0.20	0.06	0.034	1.01	0.46	0.0181
16S 12W 12CBC	Weber	0.1	1.6		0.26	0.005	0.026	0.43	0.17	0.0156
18S 11W 03BAD	City of Claflin	0.4	0.5		0.12	<0.004	0.21	0.084	0.13	0.21
16S 14W 09BCB	Nuss	0.7	0.3		0.0	<0.004	0.27	0.067	0.12	0.111
15S 16W 14BAB	Von Lintel	6.0	1.7		0.12	0.038	0.025	0.47	0.76	0.0054
15S 17W 23AB	Leiker	1.2	3.9		0.29	0.031	0.025	0.85	0.86	0.0101

Location	Location description	Sr mg/L	F mg/L	NH4 mg/L	Fe mg/L	Mn mg/L	Ba mg/L	B mg/L	Br mg/L	I mg/L
15S 18W 33ABB	Werth	0.3	3.8		0.42	0.017	0.018	0.60	0.28	0.0113
15S 18W 23BABB	Stremel	1.0	4.0		0.56	0.017	0.009	0.92	0.97	0.0104
15S 20W 35CAA	Klaus	0.1	4.5		0.58	0.007	0.014	0.63	0.39	0.032
14S 19W 36DAD	Befort	0.2	4.8		0.35	0.007	0.013	0.77	0.72	0.047
13S 18W 22CCB	McLaren	0.2	4.3		0.06	0.005	0.020	0.78	0.56	0.059
07S 25W 21DCD	Cities Service	0.3	4.6		5.2	0.047	0.021	0.85	0.56	0.133
07S 25W 21DCD	Cities Service	0.2	4.6	0.7	0.18	0.018	0.026	1.01	0.45	0.143
08S 22W 34CCD	Hocker	1.1	0.7		0.35	<0.004	0.16	0.135	0.51	0.0192
08S 20W 14DAD	Windmill	0.3	4.3		<0.02	0.010	0.016	0.96	0.49	0.062
09S 17W 09DDD	Thompson	2.3	1.6		2.3	0.029	0.018	1.60	1.36	0.087
10S 19W 35BBD	Murfin Drilling	1.8	4.3		4.1	0.075	0.013	1.24	1.39	0.084
07S 18W 11CCC	Bigge	2.5	2.6		2.4	0.023	0.021	1.51	1.58	0.080
16S 17W 15DDD	Church, Loretta	0.3	3.0		0.19	0.005	0.014	0.45	0.25	0.0168
17S 18W 33ACD	City of LaCrosse	0.4	2.9		0.45	0.011	0.023	0.44	0.36	0.0164
17S 19W 27DDC	DeWald	0.4	5.0		2.3	0.034	0.020	1.08	2.20	0.042
17S 16W 20	Rothe	0.2	4.3		0.07	0.004	0.023	0.76	0.30	0.021
16S 18W 21DBB	Herman	1.4	0.2		<0.02	<0.004	0.12	0.098	0.41	0.0079
16S 18W 16CDB	City of Liebenthal	0.2	4.1		0.15	0.006	0.016	0.64	0.90	0.040
12S 13W 03BBD	Zweifel	0.3	2.9		0.26	0.029	0.014	1.62	0.57	0.0180
12S 12W 31BDC	Romine	0.4	1.1		0.08	<0.004	0.064	0.052	0.04	0.0057
14S 13W 12DAD	Bunker Hill	0.6	0.8		2.6	0.242	0.025	0.30	0.16	0.0055
15S 12W 14ADD	Koetkeymer	1.1	3.2		2.5	0.057	0.026	0.91	0.18	0.024
14S 11W 10ADD	Doubrava	1.1	1.2		0.08	0.249	0.019	0.30	0.15	0.0103
14S 11W 10DCA	Doubrava	1.2	1.4		4.4	0.502	0.026	0.46	0.22	0.0188
15S 15W 27BCD	Dumler	0.9	3.2		3.8	0.105	0.021	0.64	0.54	0.027
13S 14W 03CBD	Machin	2.9	0.7		0.05	<0.004	0.019	0.164	0.23	0.0034
13S 14W 32CCD	Mai	2.1	0.2		0.12	0.008	0.071	0.114	1.11	0.063
14S 24W 10DDA	Kline	0.1	3.1		0.77	0.005	0.016	0.46	0.34	0.047
15S 21W 25DDD	North	0.1	5.2		0.31	0.021	0.016	0.82	0.69	0.048
15S 22W 35ABA	Brason	0.6	0.51		1.2	<0.004	0.36	0.07	0.22	0.0097
15S 24W 15CCC	Montgomery	0.9	3.6		0.10	0.008	0.071	0.114	1.11	0.063
14S 21W 04DAD	Kuppartz	2.7	0.5		0.12	0.095	0.026	0.144	0.17	0.092
14S 22W 21BCB	Schoenthaller	0.3	5.2		0.51	0.017	0.015	1.20	0.35	0.065

Location	Location description	Sr mg/L	F mg/L	NH4 mg/L	Fe mg/L	Mn mg/L	Ba mg/L	B mg/L	Br mg/L	I mg/L
14S22W20AAA	Schoenthaller	4.8	1.00		0.10	<0.004	0.015	0.176	0.44	0.0088
14S 22W 35AAA	Cedar Bluff Camp	0.1	5.5		0.03	<0.004	0.020	0.93	0.44	0.060
14S 21W 05ABA	Fles	0.2	3.9		0.11	<0.004	0.024	0.60	0.40	0.054
14S 24W 10CCA	Wiedamann	0.1	3.2		0.43	0.012	0.020	0.46	0.34	0.048
15S 24W 16DDD	Montgomery	0.1	4.1		0.76	0.016	0.022	0.66	0.38	0.054
15S 21W 12CCC	Branner	0.2	7.2		0.11	<0.004	0.021	1.46	0.72	0.077
14S 21W 10CBB	Augustine	0.1	3.7		0.03	<0.004	0.020	0.58	0.35	0.051
14S 22W 22BAC	Rolling	1.0	0.7		0.02	<0.004	0.069	0.115	0.27	0.0120
Multiple-completion wells (monitoring sites)										
08S 23W 02DCB	Hill City, U. Dakota	0.2	7.9	1.4	0.34	0.02	0.024	2.44	0.51	0.120
08S 23W 02DCB	Hill City, L. Dakota	7.5	1.4	7.5	0.33	0.38	0.20	1.69		0.100
12S 18W 30AA	Hays, Cedar Hills	3.1			2.6	<0.2	<0.2	7.8	5.0	0.155
12S 18W 30AA	Hays, Cheyenne	0.8			41.4	4.3	<0.2	5.5	4.6	0.150
12S 18W 30AA	Hays, L. Dakota	1.0			37.8	1.6	<0.16	4.5	3.6	0.120
12S 18W 30AA	Hays, U. Dakota	5.7	0.5	2.3	62.2	3.6	0.094	3.35	4.5	0.110
12S 18W 30AA	Hays, U. Dakota	5.3			27.6	1.8	0.086	2.86	4.5	0.080
12S 15W 14	Marsh, Russell Co.	3.3	2.9	1.8		0.30		3.09	2.15	0.086
12S 15W 14	Marsh, Russell Co.	3.5	2.7	1.5		0.42		2.28	2.4	0.090
13S 15W 32BCB	Gorham, Cedar Hills	25			1.5	0.42	0.15	4.89	31	0.82
13S 15W 32BCB	Gorham, Cheyenne	17			0.55	0.49	0.12	2.80	22.5	0.60
13S 15W 32BCB	Gorham, U. Dakota	0.5			3.9	0.53	0.067	0.83	0.69	0.054
13S 15W 32BCB	Gorham, U. Dakota	0.5	3.5	1.8	1.30	0.25	0.13	1.24	0.72	0.059
Oil-field brines										
18S 13W 22D	Fourway							15.9	440	15.8
18S 13W 23B	Philips							16.0	325	9.6
18S 18W 22B	Allen NW, site 2-#5							16.7	75	2.20
14S 19W 17BN/2	Nixon Irwin #1-N							14.8	41	1.12
14S 19W 17BS/2	Nixon Irwin C#1-S							15.2	43	1.20
13S 18W 23	Dreiling Leiker #1							11.6	227	7.8
13S 15W 32	Weigel	74	1.6	12		0.25	0.41	12.9	83	2.14