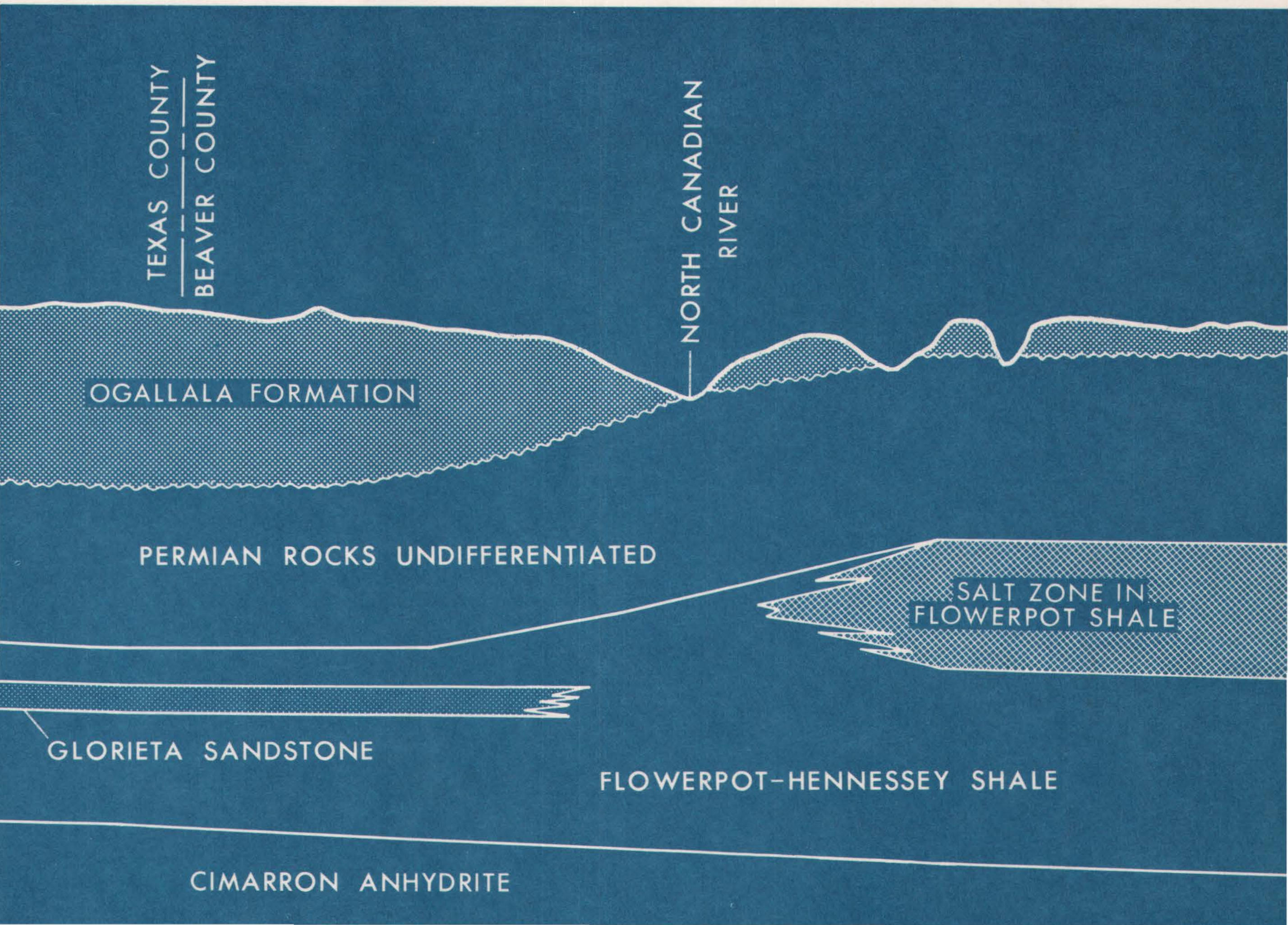
Hydrogeologic Information on the Glorieta Sandstone and the Ogallala Formation in the Oklahoma Panhandle and Adjoining Areas as Related to Underground Waste Disposal

GEOLOGICAL SURVEY CIRCULAR 630



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By James H. Irwin and Robert B. Morton

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Abstract

The Oklahoma Panhandle and adjacent areas in Texas, Kansas, Colorado, and New Mexico have prospered because of the development of supplies of fresh water and of oil and gas. The Ogallala and, in places, Cretaceous rocks produce fresh water for irrigation, public supply, and domestic and stock use through approximately 9,000 irrigation and public-supply wells and a large but undetermined number of other wells. Disposal of oil-field brine and other wastes into the Glorieta Sandstone is of concern to many local residents because of the possibility of pollution of the overlying fresh-water aquifers, particularly the Ogallala Formation. Permits for 147 disposal wells into the Glorieta have been issued in this area.

This report summarizes the data on geology, hydrology, and water development currently available to the U.S. Geological Survey. Geologic information indicates that, in the report area, the Glorieta Sandstone lies at depths ranging from about 500 to 1,600 feet below the base of the Ogallala Formation. The rocks between those two formations are of relatively impermeable types, but solution and removal of salt has resulted in collapse of the rocks in some places. Collapse and fracturing of the rocks could result in increased vertical permeability. This might result in movement of brine under hydrostatic head from the Glorieta Sandstone into overlying fresh-water aquifers, in places where an upward hydraulic gradient exists or is created by an increase in pressure within the Glorieta. Abandoned or inadequately sealed boreholes also are possible conduits for such fluids.

The mixing of water in the fresh-water aquifers with brines injected into the Glorieta is not known to have occurred anywhere in the report area, but the information available is not adequate to show positively whether or not this may have occurred locally. Much additional information on the stratigraphy and hydrology—particularly, data on the potentiometric surface of water in the Glorieta—needs to be collected and analyzed before conclusions can be drawn regarding the possibility of vertical movement of oil-field brines from the Glorieta to fresh-water aquifers above.

INTRODUCTION

The development of the natural resources of southwestern Kansas, the Oklahoma and Texas Panhandles, and the adjacent areas of Colorado and New Mexico during the past few decades has brought a rich and thriving economy to the area. Oil and gas development brought vitality and wealth. The development of large quantities of water suitable to irrigate the semiarid land and to serve its population has led to a booming agricultural and cattle-ranch economy.

But, as so often is the case, progress through this development and beneficial use of natural resources has generated problems—principally, potential depletion of the resources and possible adverse effects of wastes. Thus, among all who develop the land and its resources there is a common concern to protect, where necessary, as well as to develop. In the area of this report the practice of disposal of certain wastes by injection into the earth has been cited as a possible threat to overlying fresh ground-water supply. The anxiety of those who depend on this water has demonstrated the need for more geologic and hydrologic data pertinent to the problem.

Of immediate concern to many is the question of whether or not injection of oil-field brines into the Glorieta Sandstone will pollute the fresh water of the Ogallala Formation and other fresh-water aquifers that lie several hundred feet above the Glorieta Sandstone. The purpose of this report is to summarize the geologic and hydrologic data concerning the relation of the Glorieta Sandstone to the Ogallala Formation that are currently available to the U.S. Geological Survey.

The scope of the report is limited because no detailed study of the geology and hydrology of the Glorieta Sandstone (or its equivalent strata known by other names) in the report area has been made. The U.S. Geological Survey, in cooperation with various State agencies in Kansas, Oklahoma, Texas, Colorado, and New Mexico, has conducted studies of the fresh-water aquifers, principally the Ogallala Formation, in most of the report area. Most of these studies have been published and are listed in the selected references.

This report, therefore, is based on data from published reports of the U.S. Geological Survey and State agencies; data from the files of the district offices of the Water Resources Division of the U.S. Geological Survey in the five States; and information obtained from records of the Oklahoma Corporation Commission, the Oklahoma Geological Survey, the Oklahoma Water Resources Board, the Texas Railroad Commission, the Kansas State Board of Health, and

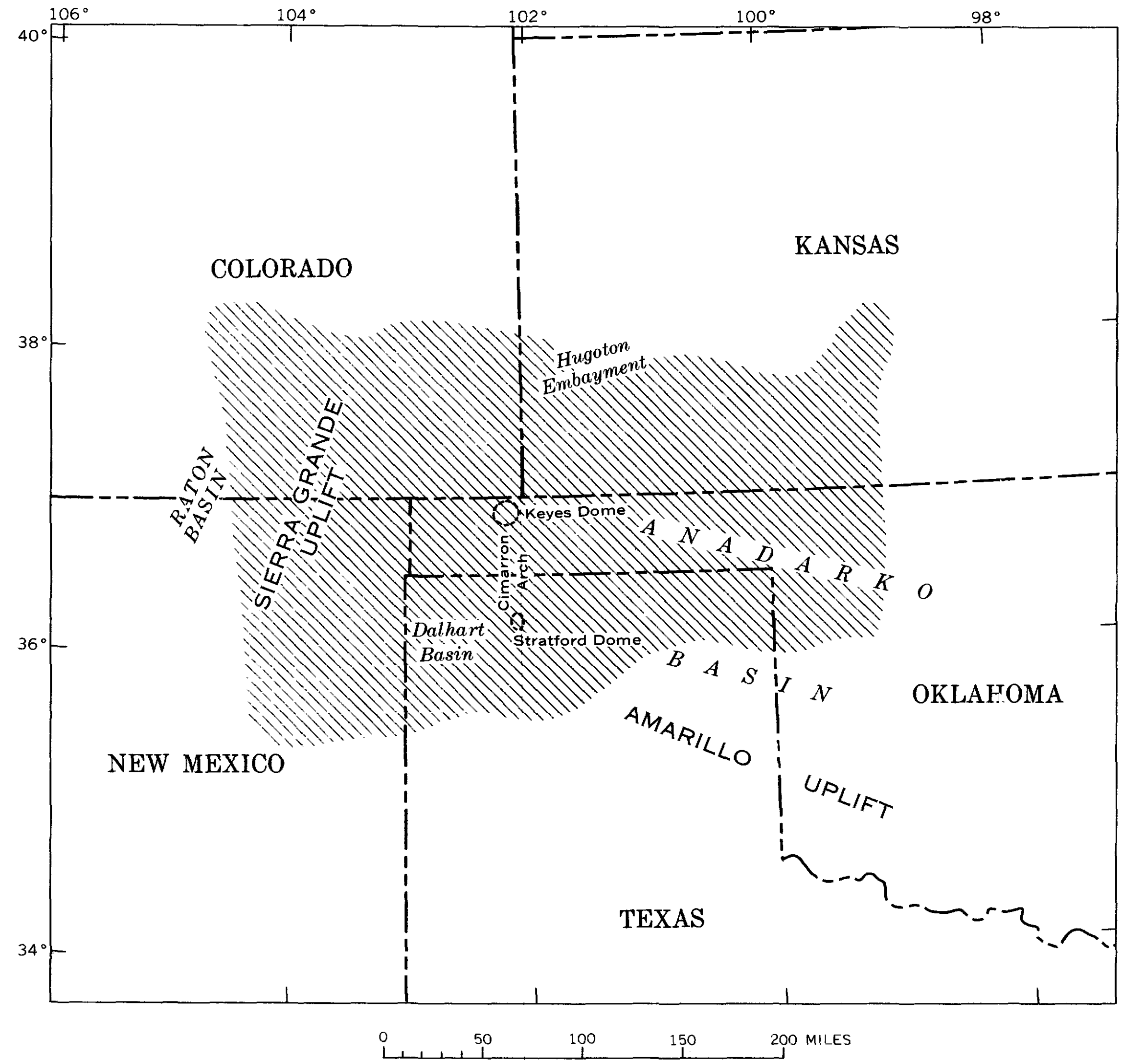

FIGURE 1.—Location of report area (shaded) and relative positions of some of the principal tectonic features.

numerous oil companies that operate in the area. Acknowledgment is due these State agencies and oil companies, the Texas County Irrigation Association, the North Plains Irrigation District, Dumas, Tex., and many others for their help in compiling these data. Special recognition is due Peter R. Stevens, Austin, Tex., and Roy H. Bingham, Donald L. Hart, Jr., and Richard P. Orth, Oklahoma City, Okla., for their invaluable assistance in compiling data and preparing this report.

The report limits were selected to include the area where the Ogallala Formation and related deposits occur as a continuous aquifer in the five-State area and are shown in figure 1. The area is approximately 47,000 square miles. The northern boundary is the Arkansas River in Colorado and Kansas; the southern boundary is approximately the Canadian River in New Mexico, Texas, and Oklahoma. The western boundary is approximately long 104° W. in Colorado and New Mexico, and the eastern boundary is approximately long 99° W. in Kansas and Oklahoma.

REGIONAL GEOLOGIC SETTING

STRUCTURE

As shown on figure 1, the major positive structural features of the report area are the Amarillo and Sierra Grande uplifts, and the major negative structural features are the Anadarko and Raton basins. The Hugoton embayment is a northwestern extension of the Anadarko basin, and to a lesser degree the Dalhart basin probably is a western lobe of the Anadarko. The Keyes dome, Cimarron arch, and Stratford dome are alined roughly parallel to the Sierra Grande uplift and, as a group, may be part of a positive structural axis related but subordinate to the Sierra Grande. The Keyes-Stratford dome alinement forms an interrupted structural divide of low relief near the western extremity of the Anadarko basin. Most of the report area, therefore, is within the northwestern limits of the Anadarko basin. The Anadarko basin is asymmetrical; its principal axis has a southeastward trend and lies only a short distance northeast of, and parallel to, the Amarillo uplift. The axis extends from the Texas and Oklahoma Panhandles southeastward toward south-central Oklahoma. Over most of the report area, the rocks described occur at relatively shallow depths and are relatively undisturbed; consequently, the prevailing dip at shallow depth is to the southeast at an average rate of 1° or less.

SUBSURFACE ROCKS

During studies being conducted by the U.S. Geological Survey in cooperation with the Oklahoma Water Resources Board in the Oklahoma Panhandle, a series of geologic sections were prepared showing the relation of the Ogallala Formation to the underlying rocks. Two of the sections were extended to include the area of this report. Locations of these sections are shown on plate 1. Section *A–A′* (pl. 2) is about 168 miles long and extends from Colfax County, N. Mex., to Beaver County, Okla. Section *B–B′* (pl. 2) reaches from approximately the Arkansas River in Hamilton County, Kans., to about the Canadian River in Potter County, Tex., a straight-line distance of approximately 250 miles.

Geologic section *C–C′* (pl. 3) was prepared independently by David L. Vosburg for the Oklahoma Geological Survey and was kindly made available by the author and the State Survey for use in this report. Section *C–C′* is from unpublished data and is subject to revision. It extends a straight-line distance of about 110 miles across Texas and Cimarron Counties, Okla. The stratigraphic nomenclature used on the geologic section does not necessarily follow that formally adopted by the U.S. Geological Survey. The location of section *C–C′* is shown on plate 3.

The geologic sections were prepared mostly by electric-log correlations and were verified in many instances by a study of sample logs of well cuttings. The correlations generally are straightforward; consequently, the sections are a valid representation of the regional geology. Examples of typical electric logs with correlations are shown in figure 2.

The correlation chart (fig. 3) shows equivalent or approximately equivalent rock units in the report area.

The following geologic observations have general application but are most appropriate

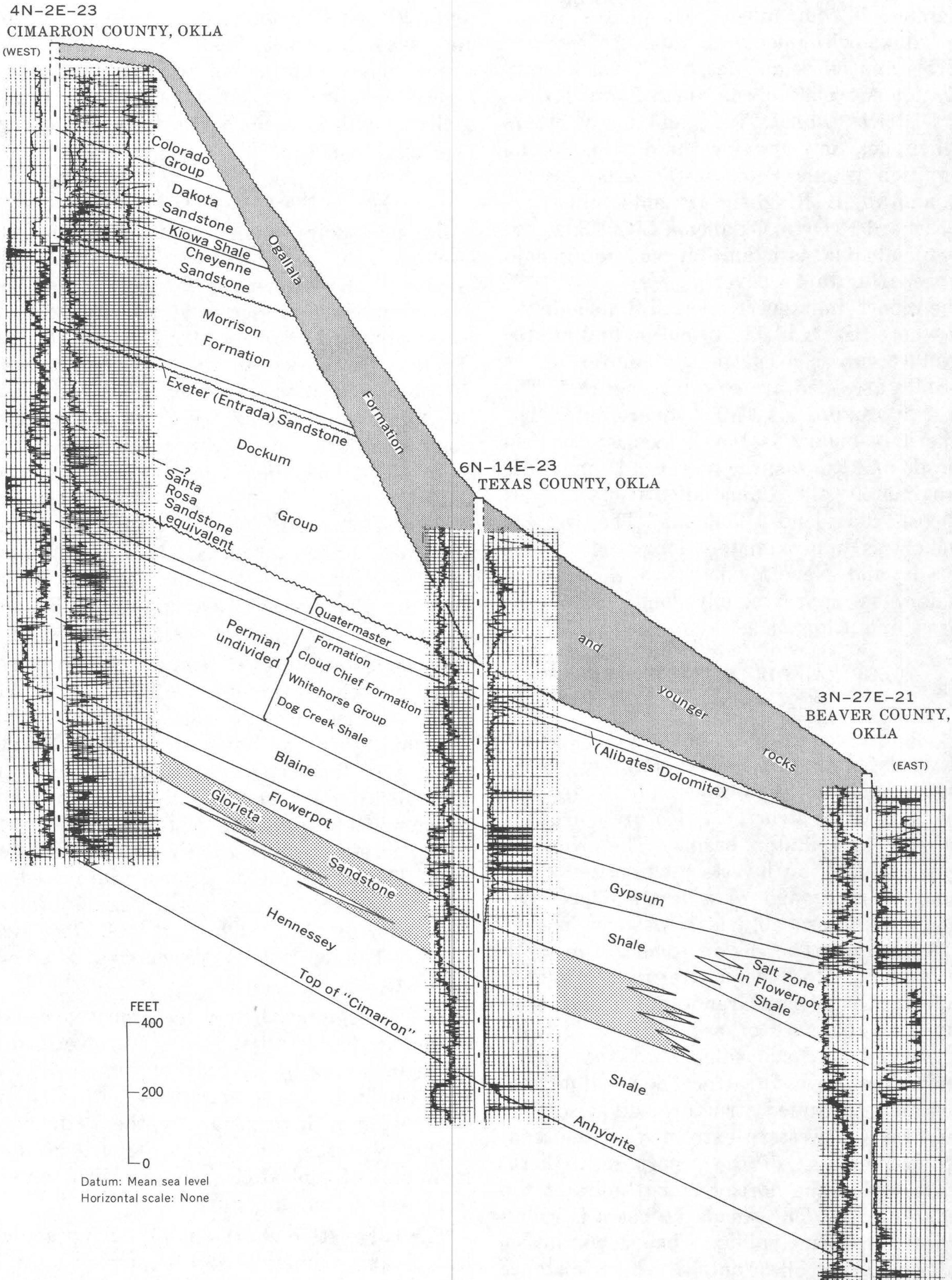

FIGURE 2.—Representative electric logs of wells showing geologic correlations in the Oklahoma Panhandle.

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AGE	NORTHEASTERN NEW MEXICO		TEXAS PANHANDLE		OKLAHOMA PANHANDLE		KANSAS	
TERTIARY & QUATERNARY		OGALLALA FORMATION AND YOUNGER ROCKS		OGALLALA FORMATION AND YOUNGER ROCKS		OGALLALA FORMATION AND YOUNGER ROCKS		OGALLALA FORMATION AND YOUNGER ROCKS
CRETACEOUS		PIERRE SHALE		ABSENT		ABSENT		PIERRE SHALE
CRETACEOUS		NIOBRARA FORMATION — ABSENT		ABSENT		ABSENT		NIOBRARA FORMATION
CRETACEOUS		CARLILE SHALE		ABSENT		ABSENT		CARLILE SHALE
CRETACEOUS		GREENHORN LIMESTONE		ABSENT	COLORADO GROUP	GREENHORN LIMESTONE		GREENHORN LIMESTONE
CRETACEOUS		GRANEROS SHALE		ABSENT	COLORADO GROUP	GRANEROS SHALE		GRANEROS SHALE
CRETACEOUS		DAKOTA SANDSTONE		ABSENT		DAKOTA SANDSTONE		DAKOTA SANDSTONE
CRETACEOUS		ABSENT / KIOWA SHALE MEMBER (PURGATOIRE FORMATION)		ABSENT		PURGATOIRE FORMATION: KIOWA SHALE MEMBER		KIOWA SHALE
CRETACEOUS		ABSENT / CHEYENNE SANDSTONE MEMBER (PURGATOIRE FORMATION)		ABSENT		PURGATOIRE FORMATION: CHEYENNE SANDSTONE MEMBER		CHEYENNE SANDSTONE
JURASSIC		MORRISON FORMATION		MORRISON FORMATION		MORRISON FORMATION		ABSENT
JURASSIC		EXETER (ENTRADA) SANDSTONE		EXETER (ENTRADA) SANDSTONE		EXETER (ENTRADA) SANDSTONE		ABSENT
TRIASSIC	DOCKUM GROUP	CHINLE FORMATION	DOCKUM GROUP		DOCKUM GROUP		DOCKUM GROUP	
TRIASSIC	DOCKUM GROUP	SANTA ROSA SANDSTONE	DOCKUM GROUP	SANTA ROSA SANDSTONE ?	DOCKUM GROUP	SANTA ROSA SANDSTONE ?	DOCKUM GROUP	
TRIASSIC	DOCKUM GROUP	TECOVAS FORMATION	DOCKUM GROUP		DOCKUM GROUP		DOCKUM GROUP	
PERMIAN		ABSENT / QUARTERMASTER FORMATION		QUARTERMASTER FORMATION: ELK CITY MEMBER		QUARTERMASTER FORMATION: ELK CITY MEMBER		BIG BASIN (TALOGA) FORMATION
PERMIAN		ABSENT / QUARTERMASTER FORMATION		QUARTERMASTER FORMATION: DOXEY MEMBER		QUARTERMASTER FORMATION: DOXEY MEMBER		BIG BASIN (TALOGA) FORMATION
PERMIAN		ABSENT / QUARTERMASTER FORMATION		QUARTERMASTER FORMATION: ALIBATES DOLOMITE LENTIL		QUARTERMASTER FORMATION: ALIBATES DOLOMITE LENTIL		BIG BASIN (TALOGA) FORMATION
PERMIAN	ARTESIA GROUP	ABSENT		CLOUD CHIEF FORMATION		CLOUD CHIEF FORMATION		DAY CREEK DOLOMITE
PERMIAN	ARTESIA GROUP	ABSENT	WHITEHORSE GROUP	RUSH SPRINGS SANDSTONE	WHITEHORSE GROUP	RUSH SPRINGS SANDSTONE		WHITEHORSE GROUP
PERMIAN	ARTESIA GROUP	?	WHITEHORSE GROUP	MARLOW FORMATION	WHITEHORSE GROUP	MARLOW FORMATION		WHITEHORSE GROUP
PERMIAN		SAN ANDRES LIMESTONE	EL RENO GROUP	DOG CREEK SHALE	EL RENO GROUP	DOG CREEK SHALE	NIPPEWALLA GROUP	DOG CREEK SHALE
PERMIAN		SAN ANDRES LIMESTONE	EL RENO GROUP	BLAINE GYPSUM	EL RENO GROUP	BLAINE GYPSUM	NIPPEWALLA GROUP	BLAINE GYPSUM
PERMIAN		SAN ANDRES LIMESTONE	EL RENO GROUP	FLOWERPOT SHALE / FLOWERPOT SALT	EL RENO GROUP	FLOWERPOT SHALE / FLOWERPOT SALT	NIPPEWALLA GROUP	FLOWERPOT SHALE / FLOWERPOT SALT
PERMIAN		GLORIETA SANDSTONE		GLORIETA SANDSTONE		GLORIETA SANDSTONE		CEDAR HILLS SANDSTONE
PERMIAN		YESO FORMATION	CLEAR FORK GROUP	(hachured)		HENNESSEY SHALE / UPPER "CIMARRON" SALT		SALT PLAINS FORMATION
PERMIAN		YESO FORMATION	CLEAR FORK GROUP	(hachured)		HENNESSEY SHALE / UPPER "CIMARRON" SALT		HARPER SILTSTONE
PERMIAN		YESO FORMATION / SANGRE DE CRISTO FORMATION	CLEAR FORK GROUP	"CIMARRON" ANHYDRITE		HENNESSEY SHALE / "CIMARRON" ANHYDRITE		STONE CORRAL FORMATION
PERMIAN		YESO FORMATION / SANGRE DE CRISTO FORMATION	CLEAR FORK GROUP	TUBB SAND		HENNESSEY SHALE / LOWER "CIMARRON" SALT	SUMNER GROUP	NINNESCAH SHALE
PERMIAN		YESO FORMATION / SANGRE DE CRISTO FORMATION	CLEAR FORK GROUP	RED CAVE		HENNESSEY SHALE / LOWER "CIMARRON" SALT	SUMNER GROUP	NINNESCAH SHALE
PERMIAN		SANGRE DE CRISTO FORMATION	WICHITA GROUP	"PANHANDLE LIME"		WELLINGTON FORMATION	SUMNER GROUP	WELLINGTON FORMATION
PERMIAN		SANGRE DE CRISTO FORMATION		HERINGTON LIMESTONE	CHASE GROUP		CHASE GROUP	

FIGURE 3.—Correlation chart showing geologic nomenclature. The stratigraphic nomenclature and correlations used were determined from several sources and may not necessarily follow usage of the U.S. Geological Survey.

to the Oklahoma Panhandle which is centrally located in the subject area. Thicknesses reported are determined from the geologic sections or from published reports.

Rocks of Permian Age

The undifferentiated Permian rocks shown below the Hennessey Shale, with the exception of the New Mexico section, consist mostly of the upper few hundred feet of the Chase Group and the Wellington Formation. The Wellington Formation consists typically of a lower salt-anhydrite unit, a mottled maroon-green shale unit, and an upper anhydrite unit and has a thickness of about 600 feet in the Oklahoma Panhandle.

The Hennessey Shale is a mixture of red and green shale with local stringers of anhydrite, gypsum, or dolomite and is approximately 300 feet thick. The equivalent rock interval in the Texas Panhandle is the Clear Fork Group and in northeastern New Mexico it is the Yeso Formation (fig. 3).

The "Cimarron" anhydrite, the equivalent of the Stone Corral Formation of Kansas (Lee and Merriam, 1954, p. 3), is shown on sections *A–A′* and *C–C′*. The "Cimarron" consists of varying amounts of interbedded white anhydrite, finely crystalline buff-colored dolomite, and salt. Commonly, the "Cimarron" is 50 feet thick in the Oklahoma Panhandle, but locally it may be more than 100 feet, mostly because of a greater thickness of bedded salt. Elevations of the top of the "Cimarron" anhydrite are the most reliable data for determining structural dip.

The Glorieta Sandstone is the shallowest Permian sandstone of significant thickness and continuity in the report area and is equivalent to the Cedar Hills Sandstone of Kansas (fig. 3). The Glorieta is discussed in more detail later in the report.

The Flowerpot Shale overlies the Glorieta Sandstone in most of the area, but it may be absent locally. The Flowerpot Shale is varicolored and gypsiferous; the usual thickness is 30 to 35 feet but it increases locally to 125 feet.

The salt zone in the Flowerpot Shale occurs mostly in the extreme eastern part of the area as shown on section *A–A′* (pl. 2); however, section *C–C′* (pl. 3) shows local remnants of the salt zone as far west as Cimarron County, Okla. The salt zone generally consists of salt-bearing shale near the base that grades upward into relatively pure salt near the top. Locally, the salt zone is nearly 500 feet thick, but more commonly it is about 350 feet.

The Blaine Gypsum in the subsurface commonly consists of six or seven distinct white gypsum or anhydrite beds separated by lesser amounts of red shale, dolomite, and salt. The Blaine ranges in thickness from slightly less than 100 feet to approximately 350 feet but generally is about 100 to 130 feet thick. The thicker sections are the result of the deposition of additional anhydrite and salt at the top of the Blaine. On well logs the thick section appears as a single lithologic unit, but the upper part may be an evaporite facies of the overlying Dog Creek Shale (Jordan and Vosburg, 1963, p. 42).

The undifferentiated Permian rocks above the Blaine Gypsum include, where present, the Dog Creek Shale, Whitehorse Group, Cloud Chief Formation, and Quartermaster Formation. The undifferentiated Permian rocks range in thickness from approximately 200 to 600 feet and consist mostly of red shale and red to pink fine-grained sandstone or siltstone; varicolored shale, gypsum or anhydrite, dolomite, and salt are present in lesser amounts.

The top of the Permian section is placed at the top of a red shale zone, generally 70 to 80 feet thick, overlying the Alibates Dolomite Lentil of the Quartermaster Formation. The red shale interval shows a strong gamma-ray reading, and the Alibates is an excellent marker in samples and on most electric logs.

In north-central Colfax County, N. Mex., the Permian section above the Glorieta apparently has thinned considerably and is represented by the San Andres Limestone (fig. 3).

Rocks of Triassic Age

In the Oklahoma Panhandle and adjacent areas, rocks of Triassic age are represented by the Dockum Group (Cummins, 1890, p. 189). The Dockum Group has an approximate maximum thickness of 650 feet and for the convenience of this discussion is divided into lower and upper units.

The lower unit of the Dockum is mostly pink to red sandstone. The grains are of medium size and are subrounded. Polished loose sand grains ranging from fine to coarse are reported, and in places the sandstone is slightly micaceous and shaly. The aggregate thickness of sandstone in the lower unit ranges from approximately 50 to more than 200 feet and averages about 100 feet. The remaining part of the lower unit of the Dockum consists of thin layers of varicolored shale and siltstone interbedded with sandstone. The upper unit of the Dockum is principally red and green shale and lesser amounts of thinly bedded, mostly fine-grained pink to red shaly sandstone.

Rocks of Jurassic Age

The Exeter Sandstone (Entrada Sandstone in Colorado, New Mexico, and Kansas) is the basal member of the Jurassic in the report area. Generally, the Exeter (Entrada) is a soft white to pink sandstone. The grains are medium sized, subrounded to rounded, and well sorted. In the Oklahoma Panhandle the sandstone ranges in thickness from zero at the subcrop limit to about 35 feet and, because of its thinness, is difficult to identify in the subsurface.

The Morrison Formation overlies the Exeter Sandstone and from its subcrop limit reaches a thickness of about 325 feet in the Oklahoma Panhandle and 550 feet in Union County, N. Mex. It consists principally of pale green and red shale and siltstone interbedded with lesser amounts of thin reddish shaly sandstone. Locally, it contains thin limestone and anhydrite.

Rocks of Cretaceous Age

The basal units of the Cretaceous System are referred to as the Cheyenne Sandstone and Kiowa Shale in Kansas, Oklahoma, Colorado, and New Mexico. In the latter three States these rocks are considered to be members of the Purgatoire Formation. The Kansas nomenclature, in which the Cheyenne and Kiowa are of formational rank, is used in this report. The Cheyenne Sandstone ranges in thickness from 0 to approximately 125 feet in the Oklahoma Panhandle. In southeastern Colorado the Cheyenne is 0 to 250 feet thick. Typically, the Cheyenne is a white to brown sandstone. Grains are medium to coarse and are rounded to subrounded. Isolated erosional remnants of Cretaceous rocks, probably the Cheyenne Sandstone, occur in the Oklahoma Panhandle.

The Kiowa Shale, which overlies the Cheyenne Sandstone, ranges in thickness from 0 to 65 feet in the Oklahoma Panhandle and commonly is about 30 feet thick. The Kiowa consists of dark-gray to black shale, is locally fossiliferous and calcareous, and in places may contain thin beds of dense gray limestone. The Kiowa commonly grades upward into a sandy shale or sandstone phase.

The Dakota Sandstone conformably overlies the Kiowa Shale. In most places the upper surface of the Dakota is an erosional surface; its thickness ranges from zero to more than 200 feet. In well samples, the Dakota is a light-gray to brown sandstone. Grains are fine to medium sized and subangular to rounded.

In the Oklahoma Panhandle, the Colorado Group consists of the Graneros Shale and the Greenhorn Limestone and ranges in thickness from 0 to approximately 175 feet. The lower unit, the Graneros Shale, is predominantly a gray to black shale interbedded with thin layers of gray fossiliferous limestone; in places it is sandy. The upper unit, the Greenhorn Limestone, is a gray crystalline, fossiliferous limestone interbedded with almost equal amounts of gray shale.

The Cretaceous rocks in southwestern Kansas are undivided and range in thickness from 0 to about 300 feet. The Cretaceous rocks are considerably thicker in the Raton basin of New Mexico. Almost 3,000 feet of Cretaceous sedimentary rocks are shown in the westernmost well in section *A–A′* (pl. 2). In northeastern New Mexico the rock interval mapped as Dakota Sandstone includes the Cheyenne Sandstone and Kiowa Shale of adjoining areas.

SURFACE ROCKS

The surface rocks in southwestern Kansas, in most of Baca and southern Prowers Counties in the southeastern corner of Colorado, and in the Oklahoma and Texas Panhandles generally are Tertiary and Quaternary clastic deposits. The Tertiary and Quaternary rocks, including the Ogallala Formation, are discussed in detail later in the report. Older sedimentary rocks ranging in age from Permian to Cretaceous crop out locally along larger streams where erosion has removed the younger rocks. Most of the sedimentary rocks in Otero, Bent, northern Prowers, eastern Las Animas, and parts of western Baca Counties, Colo., are of Cretaceous age. Rocks ranging in age from Permian to Jurassic crop out locally along the major streams. In southeastern Las Animas County, Quaternary lava flows have formed a topographic feature called Mesa de Maya. The surface rocks of Union and Colfax Counties, N. Mex., range in age from Precambrian to Quaternary. Cretaceous and Tertiary sedimentary rocks predominate in Colfax County; lesser amounts of intrusive and extrusive igneous rocks, ranging from Cretaceous to Quaternary in age, are present. The surface rocks of Union County are about evenly divided between consolidated sedimentary rocks of Jurassic to Cretaeous age, clastic deposits of Tertiary age, and lava flows of Tertiary and Quaternary age.

RELATION OF THE GLORIETA SANDSTONE TO THE OGALLALA FORMATION

GLORIETA SANDSTONE

The type locality of the Glorieta Sandstone is on Glorieta Mesa along the Pecos River in Santa Fe and San Miguel Counties, N. Mex., approximately 20 miles southeast of Santa Fe and southwest of the study area. The Glorieta Sandstone of this report occupies a position in the stratigraphic sequence similar to that of the type locality, and the following description of its physical characteristics in the subsurface resembles that of typical Glorieta Sandstone. Well samples show that it is usually a white to pink fine- to medium-grained slightly gypsiferous unconsolidated sand; the sand grains are rounded and polished. Owners of wells completed in the Glorieta report that entrance of sand into the well with the water is a common and serious problem.

The Glorieta commonly is 200 feet thick in Texas County, Okla., and in adjoining parts of the Texas Panhandle and probably averages more than 100 feet where present in the report area. The Glorieta is slightly lenticular, however, and apparently is absent locally 6 miles southeast of Boise City in Cimarron County, Okla.

In most places the Glorieta is about 1,000 to 1,200 feet below land surface; however, beginning in eastern Cimarron County, Okla., the depth to the Glorieta increases westward and probably exceeds 4,000 feet in the Raton basin of New Mexico.

The regional stratigraphic relations of the Glorieta Sandstone in the subsurface are not clearly understood. The geologic sections show that the Glorieta undergoes a facies change into an evaporite sequence to the north and east. The Glorieta thins considerably over the Amarillo uplift to the south. To the west, the Glorieta crops out in the north-central part of New Mexico. The outcrop of Glorieta closest to the report area is in Mora County, N. Mex., about 45 miles southwest of the westernmost well on section *A–A′* (pl. 2). The Glorieta is correlated with the Cedar Hills Sandstone in Kansas and western Oklahoma. It is considered a member of the San Andres Limestone to the south of the report area in Texas. Facies-change relations in the deeper parts of the basins in western Oklahoma and Texas need further study. The approximate extent of the Glorieta is shown on plate 1.

OGALLALA FORMATION AND YOUNGER SEDIMENTARY ROCKS

In Kansas, Colorado, and parts of the Oklahoma Panhandle, the Ogallala Formation is overlain by younger sedimentary rocks that are, in part, derived from erosion of the Ogallala and are not readily distinguishable from the Ogallala. Local residents commonly refer to all unconsolidated surface rocks as the Ogallala, although deposits younger than the Ogallala may be present. In the text of this report, the term Ogallala includes the Ogallala Formation of Tertiary age and, where present, younger sedimentary rocks of Tertiary and Pleistocene age.

The Ogallala consists of interbedded sand, siltstone, clay, lenses of gravel, thin limestone, and caliche. The proportions of the different rock types composing the Ogallala change rapidly from place to place, but sand generally predominates. Rocks of the Ogallala generally are light tan, buff, or almost white, but locally may show pastel shades of almost any color. The Ogallala Formation was deposited on the eroded land surface that existed in Pliocene time. The Ogallala ranges in thickness from zero to more than 700 feet, and, as shown by the geologic sections, the base of the formation is in contact with rocks ranging in age from Permian through Cretaceous. Originally, the Ogallala Formation blanketed more of the High Plains region than it does today, but its original thickness and extent have been modified by erosion. Plate 1 shows the present extent of the Ogallala in the report area.

The younger deposits sometimes included in the Ogallala are primarily loess, dune sand, and alluvium. The loess and dune sand may have appreciable lateral extent. Loess deposits cover most of southwestern Kansas. Overlying the loess in southwestern Kansas is an estimated 1,500 square miles of dune sand. In the Oklahoma Panhandle an estimated 600 square miles of younger sediments, mostly dune sand, loess, and high terrace deposits, are present. Narrow alluvial deposits are associated with some of the larger streams in the report area, especially along the Arkansas, Cimarron, and North Canadian Rivers and their principal tributaries.

CHARACTER OF THE STRATA BETWEEN THE GLORIETA SANDSTONE AND THE OGALLALA FORMATION

The thickness of the interval between the base of the Ogallala and the top of the Glorieta Sandstone ranges roughly from 800 to 1,000 feet in Kansas, 600 to 700 feet in the western part of the Texas Panhandle, and 500 to 1,600 feet, or more, in the Oklahoma Panhandle. The thickest interval in Oklahoma is in western Cimarron County; however, in most of the Oklahoma Panhandle the Ogallala-Glorieta interval is 500 to 1,100 feet thick. The rocks in this interval, discussed previously in more detail by formation and group, include anhydrite and gypsum, shale, siltstone, sandstone, lesser amounts of dolomite, and in some places bedded salt. Water-soluble rocks such as salt and gypsum occur in different amounts throughout the rocks of Permian age in this interval. One of the most significant water-soluble rock intervals is the salt zone in the Flowerpot Shale. Evidence shown on geologic sections *A–A′* (pl. 2) and *C–C′* (pl. 3) indicates that this salt zone originally was more extensive. As mentioned previously, the main salt body is now to the east, whereas thinner residual salt deposits occur locally to the west. The thick accumulation of Ogallala and younger rocks in the eastern half of Texas County (section *A–A′*) occupies a depression on the Permian surface believed to have been caused mostly by solution and removal of salt from the Flowerpot by migrating ground water prior to or during deposition of the Ogallala. Removal by solution of a large volume of salt from a body of rocks reduces their load strength and results in collapse of the overlying rocks. Rock failure under these conditions may occur slowly over a prolonged period through gradual settling, or it may occur rapidly by sudden collapse of the overlying rocks into solution cavities. Recent sudden movement has occurred in Beaver County, Okla., and in Hamilton County, Kans., where the land surface subsided several feet over a period of a few months.

The amount and nature of the distortion of the collapsed rock is not known, but it is necessary to assume that fracturing of the rock may have occurred. According to the strength and rigidity of the rocks (their "competence"), the fractures may or may not have "healed" after the subsidence ceased and hundreds of feet of younger rocks were added.

In all known localities, the salt zone of the Flowerpot Shale appears to terminate abruptly in a solution boundary. Interpreted locations of such solution boundaries are shown on geologic section *C–C′* (pl. 3).

HYDROLOGY

OGALLALA FORMATION AND YOUNGER ROCKS

The Ogallala Formation is the principal aquifer in the area. The areal extent of the Ogallala is shown on plate 1, and in most of this area wells in the Ogallala yield adequate quantities of water suitable for irrigation, public supply, and other uses.

The depth to water in wells in the Ogallala ranges widely, from less than 50 feet in a few places to a maximum of about 400 feet locally in Ochiltree County, Tex. The depth to water in most of the report area is between 150 and 250 feet. Information on the depth to water in most of the area is available in published and open-file reports listed in the selected references of this report.

The saturated thickness (interval between the water table and the base of the aquifer) of the Ogallala ranges from zero to more than 600 feet in southeastern Stevens County, Kans., and northeastern Texas County, Okla. Assuming equal porosity, the amount of water in storage is greatest where the saturated thickness is at a maximum. Existing data indicate that a vast amount of ground water, roughly estimated as in excess of 370,000,000 acre-feet, is theoretically available from the Ogallala in the report area. This volume of water does not represent the amount that could be pumped economically because, as water levels decline and well yields decrease, extracting the lower 30 to 50 feet of available water might be impractical. Well yields from the Ogallala depend primarily upon saturated thickness, coarseness of the water-bearing sands, and type of well construction. Yields range from a few gallons per minute for windmills to more than 2,000 gpm (gallons per minute) for some irrigation wells. Yields of irrigation wells commonly are 500 gpm or more; specific capacities (yield per foot of drawdown) range from about 6 gpm to 100 gpm and average about 20 gpm.

OTHER AQUIFERS

The Dakota Sandstone and the Cheyenne Sandstone, both of Cretaceous age, produce water for irrigation, public supply, and domestic and stock use in southeastern Colorado, southwestern Kansas, western Cimarron County, Okla., Union County, N. Mex., and northwestern Dallam County, Tex. In many parts of this area, these Cretaceous sandstones furnish part of the supply for many multiple-screen wells that obtain water also from the overlying Ogallala. In Baca County, Colo., an estimated 75 percent of the irrigation wells obtain all or part of their water from the Cheyenne Sandstone and 15 percent obtain all or part of their water from the Dakota Sandstone (U.S. Geological Survey, 1967, p. 16, 21).

Yields from the Cheyenne range widely because of the lithology of the unit. Where the sandstone is fine grained and moderately well cemented, yields are generally small (10 to 20 gpm or less), but in localities in Colorado where the sandstone is friable and poorly cemented, yields of up to 3,000 gpm have been reported. The average measured yield in Baca and southern Prowers Counties, Colo., is 500 gpm (Richards and others, 196?, p. 5), and in Grant and Stanton Counties, Kans., yields up to 500 gpm are possible where the Cheyenne is predominantly sandstone (Fader and others, 1964, p. 18). Wells tapping the Dakota Sandstone alone usually yield less than 100 gpm, although yields as large as 500 gpm have been measured in southeastern Colorado.

The Santa Rosa Sandstone of the Dockum Group of Triassic age is an aquifer in New Mexico and in parts of the Texas Panhandle and is a potential aquifer in some other parts of the report area. The Dockum Group is a source of irrigation water in southeastern Baca County, Colo. (Richards and others, 1968, p. 5), where maximum well yields of as much as 2,500 gpm are reported. Well depths necessary to reach the base of the Dockum in the Oklahoma Panhandle range from a few hundred feet in Texas County to 1,200 feet in western Cimarron County. Water from this unit is under artesian pressure and may flow from wells on low ground.

The rocks of Permian age generally are not used as a source of water in the report area. Shallow Permian rocks in Beaver County, Okla., may be a source of water for stock and domestic use in those localities where water from other aquifers is unavailable. This water contains high concentrations of dissolved minerals, and well yields are small. Water in these rocks is under artesian pressure and may flow from some wells.

QUALITY OF WATER

OGALLALA FORMATION

Water in the Ogallala Formation is of relatively uniform quality throughout the report area. The water generally is of the calcium magnesium bicarbonate type and contains between 200 and 500 ppm (parts per million) of dissolved solids. Hardness of water ranges between 150 and 300 ppm as calcium carbonate, and the chloride content ranges between 5 and 50 ppm. Selected analyses of water in the Ogallala are shown in table 1. Bar graphs on plate 4 show the chloride and dissolved-solids content of the water. This plate also shows the contrast between the dissolved-solids and chloride content of water in the Ogallala and water in the Glorieta Sandstone.

The chemical quality of water in the Ogallala is acceptable for most local uses and generally is rated good for irrigation. Although hard, the water is used for municipal supply throughout the area without treatment other than chlorination. Locally, fluoride concentrations are higher than desirable.

OTHER AQUIFERS

Water in the Cheyenne Sandstone generally is of good quality and is suitable for irrigation and other uses. In most places it is of the calcium bicarbonate type. Locally, the sulfate content is high and exceeds the bicarbonate content. In southeastern Colorado the dissolved-solids concentrations range from 210 to 1,900 ppm (Richards and others, 1968, p. 5).

The quality of water in the Dakota Sandstone is variable. In some areas the water is undesirable for domestic use because of an excessive amount of dissolved solids, iron, and fluoride. Water from the Dakota in some localities is known to have a high sodium content, which may adversely affect the soil structure and drainage characteristics of fine-grained soils. However, because much of the water from the Dakota that is used for irrigation is pumped from multiple-screen wells and is thereby mixed with water of better quality, the sodium hazard is reduced.

Water produced from wells in rocks of Triassic and Jurassic age ranges widely in chemical quality; in many areas the water contains more than 1,000 ppm dissolved solids, has high sodium and chloride contents, and may be undesirable for most uses.

ROCKS OF PERMIAN AGE

Although the base of fresh water in the report area has not been mapped in detail, a few chemical analyses of water samples and interpretation of electric logs of many oil and gas tests in the Oklahoma Panhandle indicate that water of poor quality generally may be expected in rocks of Permian age and also in younger rocks at depths greater than 1,200 feet below land surface. Water-soluble minerals, mainly salt and gypsum, are responsible for the poor water quality in rocks of Permian age. Water in the Permian rocks is generally of the sodium chloride or calcium sulfate type, but locally may be a mixture of both types. Leaching of evaporites from outcrops of Permian rocks results in a marked increase in the concentration of dissolved solids in the surface waters of Beaver County, Okla. Thus, in most of the report area, water in the Permian and older rocks contains dissolved solids in excess of 1,000 ppm and is unsuitable for most uses without treatment or dilution.

Water samples from the Glorieta Sandstone have not been analyzed chemically by the U.S. Geological Survey. However, records of analyses of 20 water samples from the Glorieta Sandstone in Kansas, Oklahoma, and Texas provided by several oil operators in the area are compiled in table 1. Information on collection methods was not available for most of the samples. The chloride concentrations in the 20 samples range from about 1,500 to 184,000 ppm; however, in about half of them the chloride concentrations range between 20,000 and 32,000 ppm. Dissolved-solids concentrations range from 9,200 to 314,000 ppm. The chloride and dissolved-solids contents of water from the Glorieta Sandstone are shown on plate 4 by bar graphs, along with similar graphs for the Ogallala. These analyses indicate that water in the Glorieta Sandstone in the report area is highly mineralized and, therefore, is not a source of water chemically suitable for ordinary use without extensive and costly treatment. Also brines and other waste products have been disposed into the Glorieta for a number of years and locally may have degraded the quality of the water still further.

RESOURCE DEVELOPMENT

WATER RESOURCES

The report area is predominatly an agricultural and ranching region, and although the precipitation is relatively low (14 to 22 inches per year) nature has provided the area with a tremendous underground water supply in the Ogallala Formation. This ground-water reservoir supplies most of the water used for municipal, irrigation, domestic, and stock purposes. Development of this resource for irrigation farming has brought rapid growth and prosperity to the area.

Development of irrigation farming began on a limited basis in the 1930's in the northern High Plains of the Texas Panhandle, in the 1940's in southwestern Kansas and southeastern Colorado, and a little later in the Oklahoma Panhandle. Drought conditions in the early 1950's led to an accelerated development of wells in the report area. The number of irrigation wells in the Texas part of the area increased from 150 wells in 1952 to 1,206 wells in 1959 (Alexander, 1961). In Grant and Stanton Counties and adjacent areas in Kansas, less than 10 irrigation wells were in use in 1940; in 1965 this area had more than 700 irrigation wells. Rapid development of wells in the Oklahoma Panhandle has occurred in the 1960's; Cimarron County, Okla., had 26 irrigation wells in 1952, 92 in 1957, 149 in 1963, and 433 in 1966. Although a number of irrigation wells produce from the Cretaceous sandstone alone (Cheyenne and Dakota Sandstones), they are not shown on the map (pl. 4). In Baca and Prowers Counties, Colo., there are 26 irrigation wells in the Dakota Sandstone and 182 irrigation wells in the Cheyenne Sandstone. In Union county, N. Mex., about 10 irrigation wells produce from the Cretaceous rocks. Currently about 9,000 irrigation and public supply wells in the report area yield water from the Ogallala Formation and rocks of Cretaceous age.

OIL AND GAS RESOURCES

The report area is one of the most important regions of oil and gas development in the United States. The major fields are in the western part of the Anadarko basin and include the Hugoton gas field in Kansas, Oklahoma, and Texas; part of the Panhandle oil and gas field in Texas; the Greenwood gas field in Morton County, Kans., Baca County, Colo., and Texas County, Okla.; the Keyes gas field in Cimarron County, Okla.; the Hansford County gas field in Texas; the Laverne-Mocane oil and gas field in Beaver and Harper Counties, Okla.; and the Camrick oil and gas field in Beaver and Texas Counties, Okla. Numerous smaller fields add significantly to the oil and gas production of the area.

The Hugoton field and the adjacent Panhandle field contain one of the world's largest known gas reserves. Discovered in 1918, it is now being drained by more than 10,000 wells producing from rocks of Permian and Pennsylvanian age. The Hugoton-Panhandle field has produced a total of 24.5 trillion cubic feet of gas and has an estimated remaining reserve of about 28 trillion cubic feet (Mason, 1968).

DISPOSAL WELLS

With the development of the oil industry, came the problem of disposal of oil-field brines and other wastes. Disposal of such waste generally is to surface disposal pits or by subsurface injection. Because of the possible pollution of ground water by the infiltration of oil-field brines from the shallow pits, and pollution of surface runoff by breakouts from the pits, the practice of disposal of waste into subsurface formations through injection wells has increased throughout the area. Many disposal wells inject into the Glorieta Sandstone in Kansas, Oklahoma, and Texas. Because the Glorieta Sandstone is as little as 500 feet below the overlying fresh-water formations, this disposal practice has become the subject of considerable controversy. Plate 4 shows the location of wells for which permits have been granted by the responsible State regulatory agencies in Kansas, Oklahoma, and Texas for disposal of wastes into the Glorieta Sandstone. Table 2 lists these wells and other pertinent information, such as maximum volume of waste that may be injected, pressures permitted, and injection intervals. These data were collected from the records of the Kansas State Board of Health, the Oklahoma Corporation Commission, and the Texas Water Development Board. Glorieta injection wells are not known to exist in Colorado and New Mexico. A total of 147 disposal locations were tabulated—29 in Kansas, 43 in Oklahoma, and 75 in Texas. A few of the injection-well permits may not have resulted, to date, in a waste-disposal operation. The locations shown on the map and listed in the table are for injections into the Glorieta only—many other injection wells utilize deeper formations.

State regulations for maximum injection pressure (measured at land surface) are: Kansas, 0.6 psi per ft (pounds per square inch per foot of depth to disposal zone); Oklahoma, 0.5 psi per ft and Texas, 0.4 psi per ft. Most of the injection operations into the Glorieta are reportedly at zero pressure; that is, injection is by gravity flow.

Because the Glorieta is overlain by rocks that are relatively impermeable, water in the Glorieta is confined under pressure and will rise in a conduit, such as a well, to some point above the top of the formation. The potentiometric surface of the Glorieta is an imaginary plane connecting all points of maximum rise of water from the Glorieta and usually is referred to mean sea level and expressed in feet above or below mean sea level. A map of the potentiometric surface should show the level to which water of a particular density would rise; should the density change at a particular point, the water would rise less or more at that point (less if the density becomes greater, more if the density becomes less). The upper limit of possible vertical movement of water from the Glorieta is determined by the position of the potentiometric surface. Information necessary for mapping the potentiometric surface of the water in the Glorieta is not available; therefore, the vertical distance that water from the Glorieta would be capable of rising above the formation is unknown. Vertical movement of injected fluids can occur either through natural openings, such as joints, faults, and solution channels, or artifical openings, such as well-bores, or both. Such vertical movement to an overlying fresh-water zone may occur if a conduit and sufficient pressure are present. Water from a disposal zone could ascend as illustrated schematically in figure 4.

In figure 4, the permeable injection zone represents any waste-disposal zone, such as a sandstone or porous limestone, capable of receiving the injected liquids. The overlying rocks, usually shale, have low permeability and do not transmit liquids easily. Well A represents a waste-disposal well injecting liquid waste into the permeable injection zone. Well B is an abandoned well in which steel casing was set and bonded to the sides of the well bore by a cement mixture. Well C represents an abandoned borehole in which no casing was set. Well C is most likely to provide a conduit for vertical movement of liquid between formations. A well such as C is likely to have caved in or become bridged in several places because the rocks, unsupported by casing, are not sufficiently rigid to resist collapse; nevertheless, openings may remain in and around the well to transmit fluid.

The schematic presentation assumes that no cement plug was set within the casing below the base of the fresh-water aquifer in wells B and C; or, if a plug was set, it did not seal the opening completely. It also assumes that the cemented casing in well B did not seal the borehole adequately. If a well, like example B, has deteriorated with time by corrosive action of fluids inside or outside, perforations may have developed to the extent that fluids can pass through it laterally at various horizons.

A difference in hydrostatic head such as that shown between well A and wells B and C could be caused by the difference in altitude at the top of the injection zone at these wells, by the injection pressure in well A, or both. If the head difference is sufficiently great, the potentiometric surface of the fluids in the injection zone may lie above the water table of the fresh-water aquifer. Under such conditions, if wells B and C have not been sealed completely, as described above, waste fluids will rise in them and enter the fresh-water aquifer as shown. Waste fluids would then

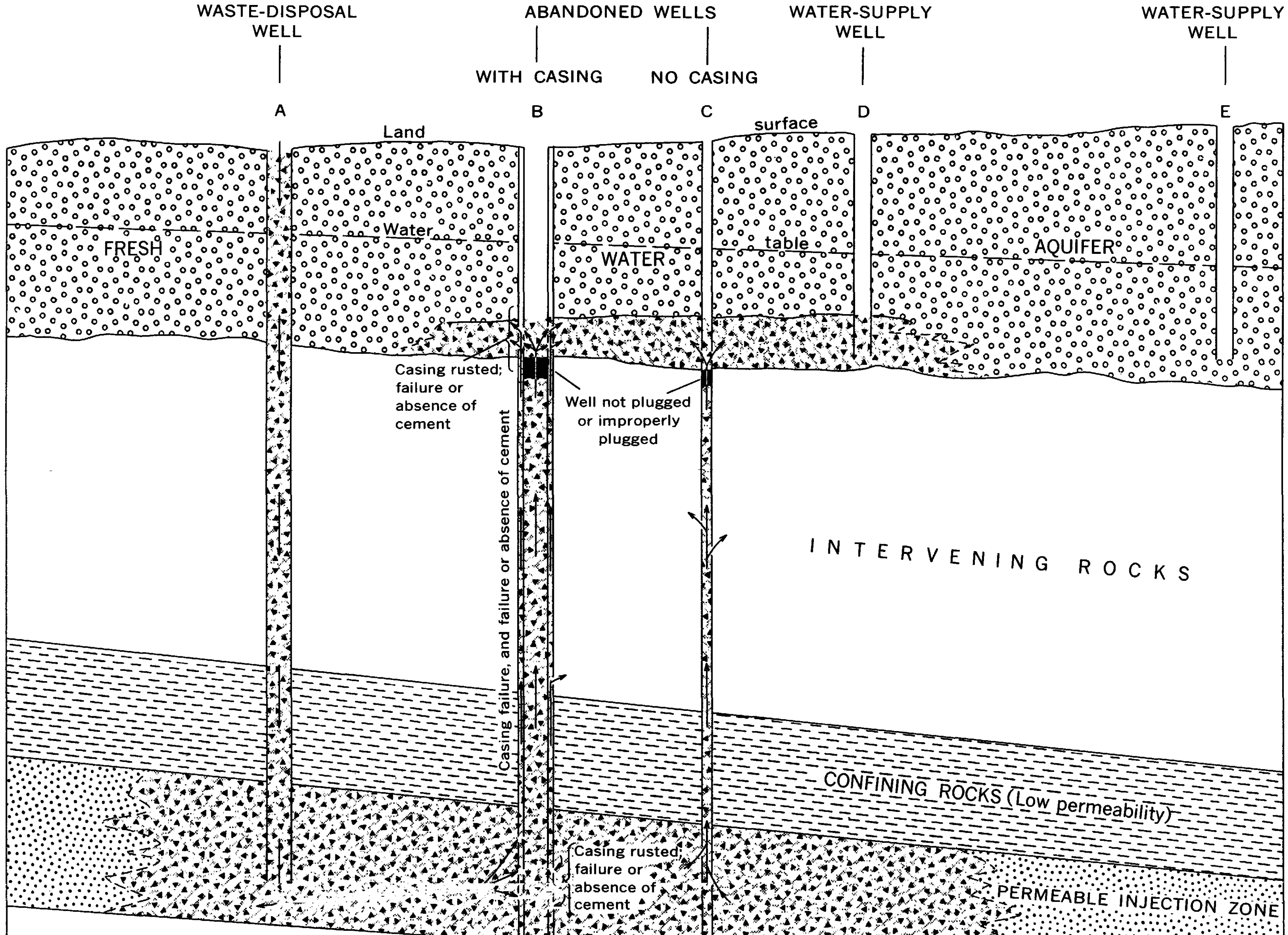

FIGURE 4.—Schematic diagram showing how waste water might enter a fresh-water aquifer through abandoned wells.

move laterally downgradient within the fresh-water aquifer and a downgradient water-supply well such as well D in the diagram would contain a mixture of native and injected water. A downgradient well, such as E, eventually would be affected. Downgradient travel of the foreign fluid would continue even if the source of leakage were located and corrected. The significance of interformation leakage at any point of withdrawal would depend on such factors as degree of dispersion, extent of dilution, and quality of the foreign fluid.

SUMMARY AND CONCLUSIONS

The geologic, hydrologic, and development data related to the Glorieta Sandstone and fresh-water aquifers now available can be summarized as follows:

Geologic data

1. The Glorieta Sandstone lies at depths ranging from as little as 500 feet to 1,600 feet below the base of the Ogallala Formation.
2. The rocks lying between the Glorieta Sandstone and fresh-water aquifers are of relatively impermeable types, but they have been subjected to solution and removal of salt beds, resulting in collapse of the overlying rocks. Where fracturing resulted from collapse, passages for upward movement of water from the Glorieta may exist. The extent of fracturing and the amount of subsequent closing of the fractures (as by chemical deposition or by gravitational settling of relatively soft rocks) is not known.

Hydrologic data

1. Because the hydrology of the Glorieta Sandstone has not been studied in detail, the position of the potentiometric surface of water in the Glorieta has not been determined. Knowledge of the potentiometric surface is necessary before the possibility of vertical movement of water within the Glorieta, and upward from the Glorieta, can be established.
2. Chemical analyses of water obtained from the Glorieta indicate that the water is high in chloride and dissloved solids; most samples contain more than 20,000 ppm of chloride, the approximate chloride content of sea water.
3. Water in the Ogallala Formation and in rocks of Cretaceous age is of good quality and is suitable for most uses.

Development data

1. The Ogallala Formation and the rocks of Cretaceous age are the major source of water for the area and provide water for irrigation, public supply, and domestic and stock use through more than 9,000 irrigation and public-supply wells and a large but undetermined number of other wells in the report area.
2. Permits have been issued for 147 disposal wells into the Glorieta Sandstone and most are in operation at this time.
3. Abandoned boreholes of several types penetrating the Glorieta Sandstone are present in the area. If improperly constructed initially, or if deteriorated since construction, these holes are possible conduits for the transmission of brine into overlying fresh-water zones, where the necessary upward hydraulic gradient exists or is created.

The data available to the U.S. Geological Survey and presented in this report are not sufficient to prove or disprove the presence of hydrologic interconnections between the Glorieta Sandstone and overlying fresh-water aquifers which might lead to undesirable mixing of the fluids they contain. The writers are unaware of any place in the report area where fresh-water aquifers have been affected by flow into them of injected brine or native saline fluids from the Glorieta Sandstone. However, the question of whether or not the highly important Ogallala and other fresh-water aquifers might eventually be affected by waste injection would appear to be important enough to justify further study. Such studies should include collection and interpretation of more comprehensive data on the following subjects:

1. Regional stratigraphy of the Glorieta Sandstone and its equivalents and the overlying rocks of Permian age, with empha-

sis on facies changes and weathering and solution of evaporites such as salt and gypsum.

2. Configuration of the fresh-water base.
3. Relation of regional stratigraphy to lateral movement of water within the basin.
4. Location of possible surface-discharge areas of water from the Glorieta Sandstone or its stratigraphic equivalents.
5. Amount of water in storage and transmissivity of the Glorieta Sandstone.
6. Data on head and density of water in the Glorieta Sandstone.
7. Additional data on water quality, including a monitoring program to detect any change in quality in the fresh-water aquifers.
8. Injection volumes and pressures.

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Table 1.—*Chemical analyses*

[Results in parts per million except pH. Analyses are reported as given by the source

Well location	Well depth (feet)	Production or sampled interval (feet)	Date of collection	Formation	Calcium (Ca)	Magnesium (Mg)
			COLORADO			
Baca County						
33S–42W–SE19	178		5–29–67	Ogallala	33	20
			KANSAS			
Grant County						
27S–35W–W/2				Glorieta		
30S–38W–NW5	310		7–16–69	Ogallala	53	15
Haskell County						
27S–34W–SW35				Glorieta		
28S–32W–W/2 17				do		
Morton County						
31S–39W–NE8				Glorieta		
34S–43W–8		1,020–1,022	5–3–60	do	600	243
Seward County						
31S–34W–S/2				Glorieta		
Stevens County						
31S–39W–SW25				Glorieta		
32S–35W–NE6				do		
36W–SE4				do		
33S–37W–NE14				do		
			NEW MEXICO			
Union County						
26N–35E–SE27			11–29–56	Ogallala	56	34
			OKLAHOMA			
Beaver County						
4N–27E–SE1	230		8–12–59	Ogallala	88	9.8
Cimarron County						
1N–5E–NE20	78		11– 9–38	Ogallala	46	24
Texas County						
5N–13E–3			[a]9– 1–59	Glorieta	685	227
27			[a]10–20–64	do	958	938
			[a]11– 8–64	do	1,046	953
			[a]8–13–65	do	1,044	944
			[a]3–16–66	do	1,036	874
5N–13E–20		1,300–1,500	1–19–65	do	[c]920	[c]1,142
2N–14E–NE24	404		5–16–61	Ogallala	43	27
			TEXAS			
Hansford County						
1,950 ft south and 2,080 ft east of sec. 63, block 45, H&TL Survey.				Glorieta	1,502	777

and are not necessarily rounded in accordance with U.S. Geological Survey standards]

Sodium (Na)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids	pH
			COLORADO—Continued			
28	218	--------	26	6.7	269	7.6
			KANSAS—Continued			
--------	--------	--------	--------	16,000	--------	--------
44	192	95	--------	17	344	--------
--------	--------	--------	--------	15,000	--------	--------
--------	--------	--------	--------	50,000	--------	--------
--------	--------	--------	--------	43,000	--------	--------
1,885	1,800	0	3,150	1,490	9,169	7.1
--------	--------	--------	--------	29,500	--------	--------
--------	--------	--------	--------	21,000	--------	--------
--------	--------	--------	--------	35,000	--------	--------
--------	--------	--------	--------	31,250	--------	--------
--------	--------	--------	--------	35,000	--------	--------
			NEW MEXICO—Continued			
b17	215	0	49	46	372	7.4
			OKLAHOMA—Continued			
11	252	--------	23	25	323	7.9
--------	--------	243	45	13	299	8.1
5,128	1,522	--------	7,059	10,196	--------	6.8
[b]21,500	1,917	0	7,894	30,496	63,200	7.2
[b]22,000	2,281	0	8,055	31,028	64,200	6.5
[b]21,163	2,160	0	8,600	29,800	62,900	--------
[b]19,750	2,262	0	7,765	29,786	62,960	7.2
[c]20,967	[c]2,123	--------	[c]8,200	[c]30,000	[c]63,252	--------
22	228	0	55	12	296	8.2
			TEXAS—Continued			
120,000	24	--------	6,676	184,392	313,480	4.0

Well location	Well depth (feet)	Production or sampled interval (feet)	Date of collection	Formation	Calcium (Ca)	Magnesium (Mg)
TEXAS—Continued						
Hutchinson County						
4 to 4½ miles west northwest of Stinnett.	---------	800–1,000	--------------	Glorieta	1,579	399
2½ miles west and 1 mile north of Stinnett.	---------	1,180–1,310	4–13–61	do	1,460	338
Moore County						
Sec. 1, block B–12, D&P Survey	---------	855	3–23–27	Glorieta	2,150	700
2¾ miles northeast of Dumas, Tex.	430	--------------	7–31–53	Ogallala	41	25

[a]Date of analysis.
[b]Sodium and potassium.
[c]Concentration in milligrams per liter.

of ground water—Continued

Sodium (Na)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids	pH
TEXAS—Continued						
17,580	72	----------	3,658	28,330	51,618	----------
20,400	52	0	3,550	31,900	57,700	6.9
[b]62,300	87	----------	6,010	97,500	168,747	----------
34	281	----------	43	6.8	326	8.0

Table 2.—*Information on wells or well sites where permits have been granted for injection into the Glorieta Sandstone*

[Wells 146 and 147 are industrial disposal wells; all others are oil-field brine disposal wells]

Permitted disposal: 1 barrel equals 42 U.S. gallons of liquid. Data listed for Kansas is the average of the maximum and minimum reported on the permit application; data listed for Texas is the maximum permitted disposal per day.
Injection pressure used: Zero indicates disposal by gravity instead of pumping under pressure; liquid level is at or below land surface.
Disposal interval: Data listed for Kansas is the top of the disposal zone.

Well No.	Location	Year permit issued	Permitted disposal (barrels per day)	Barrels injected per month (current)	Permitted injection pressure (psi at land surface)	Injection pressure used (psi at land surface)	Disposal interval (feet)
			KANSAS				
	Morton County						
1	31S–42W–3	1963	120	----------	300	0	970
2	15	1966	145	----------	150	35	1,072
3	32S–41W–24	1959	150	----------	500	0	750
4	42W–9	1968	400	----------	500	0	1,125
5	36	1969	500	----------	500	0	940
6	43W–17	1968	250	----------	500	0	1,200
7	33S–40W–8	1964	270	----------	0	0	1,088
8	41W–9	1965	275	----------	600	0	1,200
9	17	1965	125	----------	0	0	1,200
10	27	1968	40	----------	0	0	1,130
11	34S–40W–27	1968	50	----------	0	0	1,290
12	41W–33	1967	350	----------	600	0	1,030
13	42W–33	1965	260	----------	500	0	950
14	43W–20	1959	78	----------	150	0	910
15	29	1960	300	----------	500	0	825
16	35S–41W–18	1968	300	----------	450	0	1,130
17	43W–7	1963	400	----------	0	0	960
	Stevens County						
18	31S–35W–27	1967	575	----------	1,000	280	1,250
19	35S–36W–17	1967	275	----------	300	0	1,180
20	1	1969	200	----------	500	0	1,190
	Seward County						
21	32S–33W–27	1967	50	----------	500	0	1,005
22	33S–31W–23	1962	275	----------	600	0	1,100
23	36	1962	600	----------	500	210	1,000
24	----------------------	1963	275	----------	450	430	1,018
25	33W–27	1963	115	----------	0	0	990
26	28	1969	175	----------	100	0	1,220
27	34W–26	1961	225	----------	500	0	850
28	35S–31W–13	1967	1,250	----------	0	0	810
29	34W–4	1965	65	----------	100	0	1,140

Table 2.—*Information on wells or well sites where permits have been granted for injection into the Glorieta Sandstone*—Continued

Well No.	Location	Year permit issued	Permitted disposal (barrels per day)	Barrels injected per month (current)	Permitted injection pressure (psi at land surface)	Injection pressure used (psi at land surface)	Disposal interval (feet)
			OKLAHOMA				
	Cimarron County						
30	5N–8E–1	----	----	290	----	0	1,100–1,120
31	4N–8E–11	----	----	15,000	----	0	1,200–1,400
32	9E–26	----	----	3,600	----	50	1,072–1,202
33	1N–9E–22	----	----	5,700	----	400	1,090–1,118
34(not in use).	30	----	----	----	----	----	----
35(not drilled).	36	----	----	----	----	----	----
	Texas County						
36	6N–10E–14	----	----	660	----	0	1,016–1,134
37	17	----	----	3,000	----	0	1,097–1,117
38	35	----	----	8,970	----	0	1,116–1,236
39(not converted).	11E–19	----	----	----	----	----	----
40	6N–11E–31	----	----	4,800	----	250	1,058–1,150
41	13E–20	----	----	1,068	----	0	1,310–1,390
42	28	----	----	652	----	0	1,272–1,320
43	15E–34	----	----	3,100	----	400	1,159–1,359
44(not completed).	19E–13	----	----	----	----	----	1,400–1,500
45	5N–10E–2	----	----	19,960	----	0	1,050–1,400
46	12E–4	----	----	712	----	0	1,140–1,300
47	24	----	----	2,100	----	0	1,350–1,400
48	13E–3	----	----	650	----	0	1,253–1,380
49	20	----	----	9,640	----	0–50	1,360–1,370
50	27	----	----	0	----	0	1,150–1,350
51	29	----	----	0	----	0	----
52	32	----	----	1,240	----	0	1,150–1,250
53	14E–18	----	----	1,000	----	0	1,210–1,350
54	4N–12E–33	----	----	30	----	0	1,250–1,255
55	13E–1	----	----	----	----	0	Shut in
56	11	----	----	4,347	----	0	1,125–1,165
57	21	----	----	500	----	0	1,246–1,316
58	23	----	----	2,400	----	0	1,104–1,306
59	27	----	----	200	----	0	1,124–1,218
60	8	----	----	0	----	0	Shut in
61	18	----	----	3,741	----	0	1,165–1,185

Table 2.—*Information on wells or well sites where permits have been granted for injection into the Glorieta Sandstone*—Continued

Well No.	Location	Year permit issued	Permitted disposal (barrels per day)	Barrels injected per month (current)	Permitted injection pressure (psi at land surface)	Injection pressure used (psi at land surface)	Disposal interval (feet)
	OKLAHOMA—Continued						
	Texas County—Con.						
62	15E–22	--------	----------	10,767	----------	0–50	1,180–1,190
63	3N–12E–10	--------	----------	2,500	----------	0	1,064–1,280
64	14E–6	--------	----------	500	----------	0	1,160–1,180
65	17E–13	--------	----------	1,000	----------	0	1,098–1,118
66	18E–6	--------	----------	500	----------	0	1,110–1,130
67	7	--------	----------	1,500	----------	0	1,128–1,148
68	29	--------	----------	500	----------	0	1,046–1,066
69	2N–15E–16	--------	----------	1,776	----------	0	912–988
70	19E–16	--------	----------	4,000	----------	350	875–950
	Beaver County						
71	5N–22E–12	--------	----------	8,000	----------	35	1,270–1,300
72	1N–23E–2	--------	----------	900	----------	600	1,204–1,244
	TEXAS						
	Sherman County						
73	PSL, block 1, sec. 5	1962	20	----------	500	----------	1,000–1,300
74	T&NO, block 1–T, sec. 10.	1962	75	----------	500	----------	1,000–1,300
75	PSL, block 1, sec. 18	1965	10	----------	Gravity	----------	562–2,425
76	sec. 19	1962	----------	----------	----------	----------	1,155–1,402
77	GH&H, block 1–C, sec. 164.	1962	200–300	----------	Gravity	----------	1,090–1,620
78	sec. 201	1968	0–100	----------	Gravity	----------	1,086–1,330
79	sec. 88	1963	100	----------	Gravity	----------	1,250–1,270
80	sec. 164	--------	----------	----------	----------	----------	----------
81	sec. 120	1964	----------	----------	----------	----------	----------
82	sec. 32	1964	75	----------	Gravity	----------	950–2,500
83	block 2, sec. 14	1965	300	----------	500	----------	1,000–1,200
84	block 1–C, sec. 1.	1962	30	----------	150	----------	1,150–1,450
85	block 3–B, sec. 72.	1962	50	----------	Gravity	----------	1,140–1,270
86	sec. 52	1964	----------	----------	----------	----------	----------
87	sec. 56	1968	20–150	----------	Gravity	----------	1,092–1,280
88	sec. 53	1962	10	----------	----------	----------	900–1,400
89	sec. 52	1964	----------	----------	----------	----------	----------
90	sec. 3	1962	10	----------	150	----------	900–1,400
91	sec. 68	1967	150	----------	500	----------	1,120–1,280
92	block 3, sec. 41	1965	400	----------	500	----------	1,150–1,300
93	block 3–B, sec. 41.	--------	----------	----------	----------	----------	----------

Table 2.—*Information on wells or well sites where permits have been granted for injection into the Glorieta Sandstone*—Continued

Well No.	Location	Year permit issued	Permitted disposal (barrels per day)	Barrels injected per month (current)	Permitted injection pressure (psi at land surface)	Injection pressure used (psi at land surface)	Disposal interval (feet)
	TEXAS—Continued						
	Sherman County—Con.						
94	sec. 42	1963	10	--	Gravity	--	--
95	block 2–B, sec. 12	1965	500	--	Gravity	--	1,150–1,350
96	block 3–B, sec. 66.	1962	75	--	Gravity	--	1,145–1,285
97	sec. 66	--	--	--	--	--	--
98	T&NO, block 3–T, sec. 22.	1962	150	--	15	--	1,250–1,400
99	sec. 21	1964	10	--	Gravity	--	1,150–1,250
100	sec. 49	1965	50	--	Gravity	--	1,120–1,140
101	sec. 63	1964	300	--	Gravity	--	1,100–1,300
102	sec. 64	1964	300	--	Gravity	--	1,100–1,300
103	sec. 72	1963	100	--	300	--	1,100–1,500
	Hansford County						
104	W.C. RR, block 1, sec. 35	1962	100	--	Gravity	--	1,100–1,160
105	H&GN, block P, sec. 57	1962	20	--	Gravity	--	1,120–1,140
106	PSL, block 2, sec. 5	1962	--	--	--	--	--
107	GH&H, block 2, sec. 88	1966	100	--	500	--	1,120–1,300
108	H&TC, block 45, sec. 44	1963	100	--	250	--	--
109	sec. 47	1964	300	--	50	--	1,135–1,340
110	sec. 56	1963	50	--	100	--	1,495–5,300
111	sec. 78	1962	--	--	--	--	1,140–1,162
112	sec. 107	1962	100	--	Gravity	--	1,150–1,250
113	GH&H, block 2, sec. 118	1962	10	--	Gravity	--	1,135–1,165
114	sec. 122	1965	20	--	450	--	1,353–2,700
115	H&TC, block 45, sec. 153.	1965	40	--	Gravity	--	1,080–1,340
	Moore County						
116	T&NO, block 3–T, sec. 99.	1962	40	--	Gravity	--	1,150–1,275
117	sec. 102	1963	100	--	300	--	1,100–1,500
118	C.L. Porter, block M–2, sec. 11.	1965	300	--	580	--	1,160–1,325
119	T&NO, block 3–T, sec. 123.	1962	50	--	Gravity	--	1,175–1,240
120	H&GN, block Q, sec. 3	1966	100	--	Gravity	--	1,388–1,552
121	H.H. Ashbrook, block M–2, sec. 18.	1965	110	--	Gravity	--	1,250–1,500
122	G. Gober, block M–2, sec. 6.	1964	500	--	Gravity	--	1,100–1,300
123	T&NO, block 3–T, sec. 125.	1965	100	--	Gravity	--	1,150–1,300

Table 2.—*Information on wells or well sites where permits have been granted for injection into the Glorieta Sandstone*—Continued

Well No.	Location	Year permit issued	Permitted disposal (barrels per day)	Barrels injected per month (current)	Permitted injection pressure (psi at land surface)	Injection pressure used (psi at land surface)	Disposal interval (feet)
	TEXAS—Continued						
	Moore County—Con.						
124	AB&M, block M–16, sec. 16.	1962	125	------------	Gravity	------------	1,095–1,170
125	sec. 5	--------	------------	------------	------------	------------	------------
126	T&NO, block 3–T, sec. 183.	1965	850	------------	Gravity.	------------	1,050–1,400
127	sec. 184	1964	70	------------	Gravity	------------	1,030–1,100
128	sec. 200	1965	500	------------	Gravity	------------	1,054–1,064
129	B.O. Quarton, block 1–PD, sec. 1.	1963	50	------------	Gravity	------------	1,200–1,350
130	R.B. Newcome, block EB, sec. 7.	1963	30	------------	Gravity	------------	400–1,300
131	T&NO, block GT, sec. 48.	1968	200–800	------------	200	------------	878–966
132	T&NO, block 6–T, sec. 54.	1969	80–500	------------	Gravity	------------	850–975
133	sec. 53	1967	80–500	------------	250	------------	850–975
134	G&M, block 2, sec. 5	1963	10	------------	Gravity	------------	1,565–1,740
	Hutchinson County						
135	AB&M, block M–16, sec. 19.	1964	1,500	------------	Gravity	------------	1,000–1,300
136	R. Sikes, block M–23, sec. 54.	1962	150	------------	200	------------	1,251–1,332
137	sec. 54	1962	500	------------	Gravity	------------	1,176–1,232
138	H&TC, block 46, sec. 84	1962	5–10	------------	Gravity	------------	800–1,115
139	sec. 84	1965	150	------------	Gravity	------------	765–1,130
140	sec. 64	1962	250	------------	200–400	------------	868–888
141	A&B, block Y, sec. 35	1967	30	------------	Gravity	------------	650–797
142	M&C, block Y, sec. 4	1965	------------	------------	------------	------------	------------
	Carson County						
143	GB&CNG, block Y–2, sec. 16.	1966	------------	------------	Gravity	------------	800–810
144	AB&M, block Y–2, sec. 12.	1966	150	------------	375	------------	864–870
	Roberts County						
145	G&M, block C, sec. 94	1962	30	------------	350	------------	------------
	Moore County						
146	H&TC, block 44, sec. 399.	1965	25,000	------------	150	------------	1,116–1,236
147	sec. 362	1962	500	------------	250	------------	1,125–1,620