GEOLOGIC AND HYDRAULIC CHARACTERISTICS OF SELECTED SHALY GEOLOGIC UNITS IN OKLAHOMA

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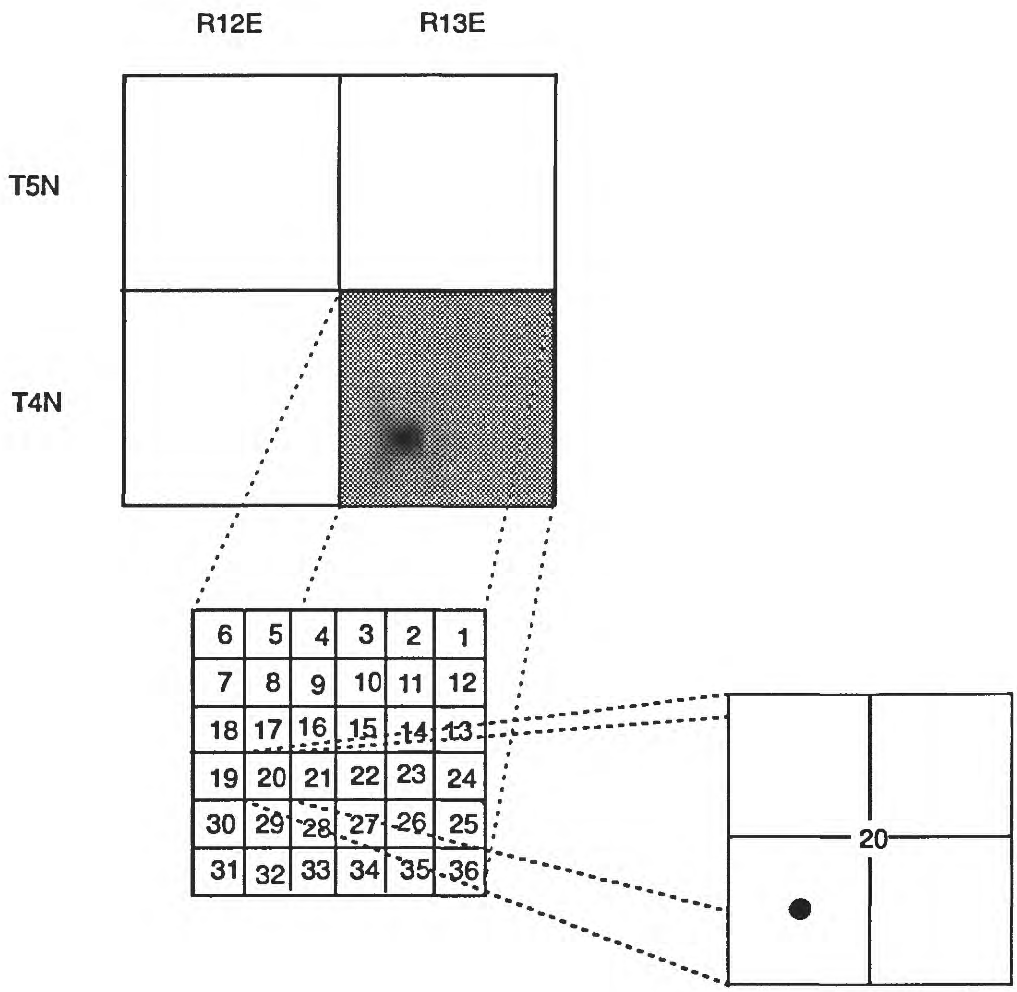
CONVERSION FACTORS

Multiply	By	To obtain
millimeter (mm)	0.03937	inch
centimeter (cm)	0.3937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
kilopascal (kPa)	0.145	pound per square inch
megapascal (MPa)	145.0	pound per square inch
meter per second (m/sec)	3.281	foot per second

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

EXPLANATION OF THE SITE-NUMBERING SYSTEM

Location of test wells are specified by a local site-numbering system. The local site-numbering system consists of the section number, township number, north or south and the range number, east or west. Each section is divided into 4 quarters referred to as NE, SE, NW, and SW. The diagram shown below illustrates the location of a test well described as: SW corner of section 20, T. 4 N., R. 13 E.



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ABSTRACT

Information was collected on the geologic and hydraulic characteristics of three shale-dominated units in Oklahoma—the Dog Creek Shale and Chickasha Formation in Canadian County, Hennessey Group in Oklahoma County, and the Boggy Formation in Pittsburg County. The purpose of this project was to gain insight into the characteristics controlling fluid flow in shaly units that could be targeted for confinement of hazardous waste in the State and to evaluate methods of measuring hydraulic characteristics of shales.

Permeameter results may not indicate in-place small-scale hydraulic characteristics, due to pretest disturbance and deterioration of core samples. The Dog Creek Shale and Chickasha Formation hydraulic conductivities measured by permeameter methods ranged from 2.8×10^{-11} to 3.0×10^{-7} meter per second in nine samples and specific storage from 3.3×10^{-4} to 1.6×10^{-3} per meter in four samples. Hennessey Group hydraulic conductivities ranged from 4.0×10^{-12} to 4.0×10^{-10} meter per second in eight samples. Hydraulic conductivity in the Boggy Formation ranged from 1.7×10^{-12} to 1.0×10^{-8} meter per second in 17 samples.

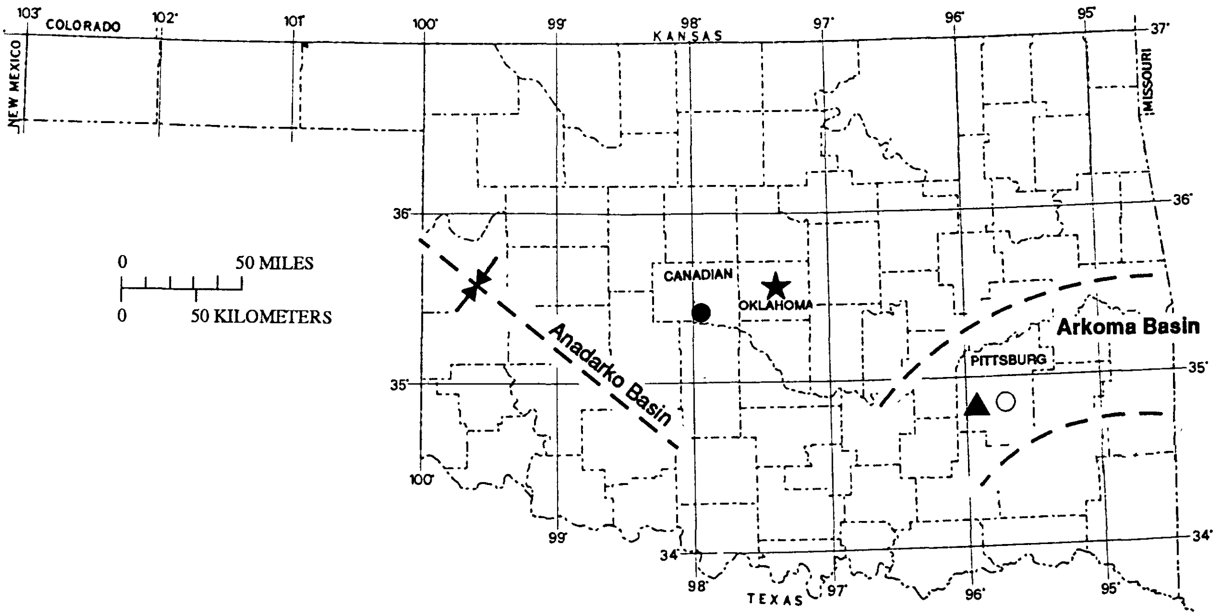
The hydraulic properties of isolated borehole intervals of average length of 4.5 meters in the Hennessey Group and the Boggy Formation were evaluated by a pressurized slug-test method. Hydraulic conductivities obtained with this method tend to be low because intervals with features that transmitted large volumes of water were not tested. Hennessey Group hydraulic conductivities measured by this method ranged from 3.0×10^{-13} to 1.1×10^{-9} meter per second; the specific storage values are small and may be unreliable. Boggy Formation hydraulic conductivities ranged from 2.0×10^{-13} to 2.7×10^{-10} meter per second and specific storage values in these tests also are small and may be unreliable. A substantially higher hydraulic conductivity of 3.0×10^{-8} meter per second was measured in one borehole 30 meters deep in the Boggy Formation using an open hole slug-test method.

INTRODUCTION

The transmission of fluid in shales is often dominated by geologic characteristics such as fractures and other types of secondary permeability features. Shales generally are perceived as strata of low permeability and therefore are often considered appropriate for near-surface geologic confinement of hazardous waste. Some studies have shown (Bredehoeft and others, 1983) flow through fractures in shaly formations on a regional scale that was undetected in local tests.

The purpose of this project was to gain insight into what are the characteristics controlling fluid flow in shaly units that could be targeted for confinement of hazardous waste in the State and to evaluate methods of measuring hydraulic characteristics of shales. Additional information on shaly units in Oklahoma is needed because of the range of possible geologic characteristics and because of the concern for protection of the State's water resources.

The U.S. Geological Survey in cooperation with the Oklahoma Geological Survey, collected information on the geologic and hydraulic characteristics of three shaly units in Oklahoma: the Dog Creek Shale and Chickasha Formation in Canadian County, the Hennessey Group in Oklahoma County, and the Boggy Formation in Pittsburg County (fig. 1). This information might facilitate the collection of geologic and



EXPLANATION

● Union City site (Dog Creek-Chickasha Formations) and Union City

★ Hefner site (Hennessey Group) and Oklahoma City

▲ McAlester site (Boggy Formation)

○ McAlester

Figure 1. Locations of sites in Oklahoma where the Dog Creek Shale and Chickasha Formation, Hennessey Group, and the Boggy Formation were studied.

hydraulic data in the selection of future sites for waste disposal involving these and other shaly units.

The terms claystone and shale were used inconsistently to describe cores and core samples of the fine-grained units. The term shale, as used in this report, would be inclusive.

Purpose and Scope

This report describes the geologic characteristics and hydraulic-test data of the Dog Creek Shale, Chickasha Formation, Hennessey Group, and the Boggy Formation. A generalized geologic log is presented for each unit, and bulk mineralogy and clay types determined by X-ray diffraction are described. Permeameter-derived measurements of hydraulic conductivity, in addition to specific storage, porosity, and water content of selected samples are given. In-place hydraulic conductivity and specific storage of the Hennessey Group and Boggy Formation also are given.

Acknowledgments

The authors thank the landowners, Oklahoma Brick Corporation, and McAlester Army Ammunition Depot for providing access to sites and permission for drilling. X-ray diffraction was performed by S. Tottempudi, B.L. Weaver, and D. Powell, at the University of Oklahoma in Norman, Oklahoma. James Greer provided drilling knowledge and field expertise. Chris Neuzil and Harold Olsen provided suggestions and comments. Permeameter tests were performed on core specimens by Harold Olsen at the U.S. Geological Survey core laboratory in Denver, Colorado.

METHODS OF INVESTIGATION

Continuous cores were obtained, examined, and described at each site. X-ray diffraction was used to determine clay and nonclay mineralogy in selected core samples. Hydraulic conductivity of all core samples was measured using constant-flow, steady-state permeameter methods. Specific storage, porosity, and water content were measured in selected cores samples. Hydraulic conductivity and specific storage of the Hennessey Group and Boggy Formation were measured in place by a pressurized slug-test method. Hydraulic conductivity of the Boggy Formation also was measured in one bore hole by an open-hole slug-test method.

Permeameter results may not indicate in-place conditions, due to pre-test disturbance and deterioration of core samples. Additionally, the difficulty of testing borehole intervals that have highly transmissive fractures appears to have biased borehole testing towards tighter zones.

Coring

The units were cored to a maximum depth of 61 meters by use of air-rotary and hydraulic-rotary drilling methods. Air-rotary coring used compressed air in combination with an alcohol-based gel at shallow depths until water was encountered, which required a switch to a mud-based system.

A generalized core description was prepared for each site to describe fractures. Special attention was given to fractures, as they could control the transmission of fluids in strata of low permeability. Fracture patterns and the presence or absence of secondary precipitates and slickensides on fracture faces were noted in an attempt to distinguish between pre-existing fractures and those created by the coring process. Fractures were observed in cores of the Hennessey Group, Dog Creek Shale, and Chickasha Formation and were extensive in the Boggy Formation, with the greatest fracture densities apparent at shallow depths.

Core sections chosen for permeameter tests were trimmed, wrapped in cheesecloth, and coated with a microcrystalline wax to prevent deterioration. The bore-hole description, depth, and orientation were noted on cores, which were stored in a cool area until shipped for testing at the U.S. Geological Survey laboratory in Denver, Colorado, and at the University of Oklahoma in Norman, Oklahoma.

Permeameter testing

The hydraulic properties of core specimens were measured by one of two constant-flow permeameter methods. Measurements were conducted on saturated, stress-controlled specimens over a range of effective stresses in either a triaxial cell (flexible-wall permeameter) or a back-pressured one-dimensional consolidometer (fixed-wall permeameter) using volume-controlled methods developed by Olsen and oth-

Table 1. Porosities and water content in core samples of the Dog Creek Shale and Chickasha and Boggy Formations and porosities of Pennsylvanian- and Permian-age shales (Manger, 1963)

[--, no data]

Source	Porosity	Water content gained during testing procedures
Pennsylvanian- and Permian-age shales (Manger, 1963)	10–19 percent, (7 samples)	--
Dog Creek Shale and Chickasha Formation	30–41 percent, (4 samples)	18–39 percent, (5 samples)
Boggy Formation	20–33 percent (3 samples)	26–42 percent (7 samples)

ers (1985, 1988, 1991) and Gill and others (1991). The triaxial cell was capable of measuring hydraulic conductivity with effective stress. The one-dimensional consolidometer system was capable of measuring both hydraulic conductivity with effective stress and compressibility with effective stress. Specific storage was calculated from the compressibility. Initial porosity was determined from the data of compressibility by backtracking to the effective stress equivalent to sample depth.

Most samples, especially from the Hennessey Group and Boggy Formation, were too stiff or friable to be trimmed adequately for the confining ring in the one-dimensional consolidometer. As a result, these samples were tested only for hydraulic conductivity in the triaxial cell.

Figure 2 shows the hydraulic-response curves of specific storage with effective stress and hydraulic conductivity with effective stress from a permeameter test of a core specimen of the Dog Creek Shale and Chickasha Formation. The ability of the rock to transmit fluid and store it decreases as compression is applied. The reported hydraulic conductivity and specific storage of a specimen were interpreted by estimating the effective stress applicable at in-place depth. Effective stress or overburden, the component of total stress that is applied to the rock grains, was estimated by subtracting the pore fluid pressure from the weight of the overlying rock and fluid (Freeze and Cherry, 1979). As shown in figure 2, by assuming a gradient of 0.0124 megapascals per meter, the overburden at 14.5 meters would produce an effective stress of 0.18 megapascals, which corresponds to a hydraulic conductivity of 7.5×10^{-8} meter per second and a specific storage of 1.6×10^{-3} per meter for the core specimen.

The range of effective stress over which hydraulic data were available was dependent on the permeameter method used. The one-dimensional consolidometer provided data from 0 to 3.5 megapascals (equivalent depths 0 to 280 meters), whereas the triaxial cell provided data from 0 to 1.7 megapascals (equivalent depths 0 to 140 meters). As the maximum depth of this study investigation was 61 meters, only effective stresses less than 1 megapascal are relevant to current conditions, but greater effective stresses could apply to past periods of deeper burial or other geologic settings.

The core sections chosen for laboratory tests were those that appeared intact, to avoid testing samples fractured by the coring operation and subsequent removal. However, examination under magnification showed that although cores appeared intact, slight fractures were present throughout the Dog Creek Shale, Chickasha Formation and Hennessey Group samples and extensively throughout the Boggy Formation samples (H. Olsen, USGS written commun., 1990).

The effects of the fractures are indicated by the porosities in the Dog Creek Shale and Chickasha and Boggy Formations samples (table 1). Porosity values, noticeably higher than porosities of Pennsylvanian-

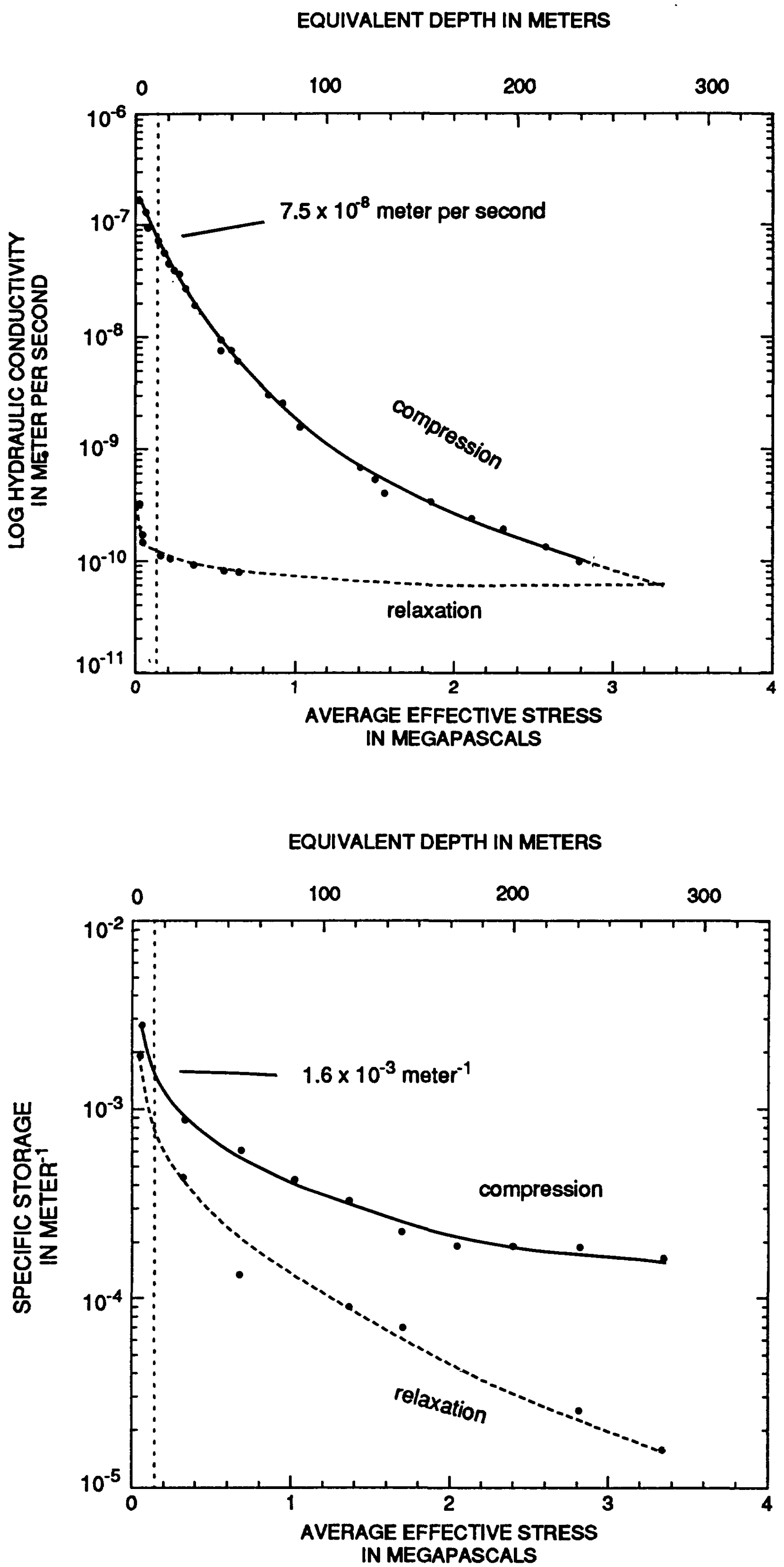


Figure 2. Hydraulic-response curve from volume-controlled hydraulic conductivity and compressibility measurements on a core specimen of the Dog Creek Shale and Chickasha Formation from DC-7, depth 14.5-14.6 meters. The reported values of hydraulic conductivity and specific storage were interpreted from the compressional phase of the response curves assuming a 0.0124 megapascals per meter stress gradient.

and Permian-age shales tabulated by Manger (1963), could result from fractures. Manger reports 7 samples from various shales, presumably not fractured and from depths of less than 305 meters, have total or effective porosities less than 20 percent.

It is unknown whether the microfractures observed in the core samples were pre-existing or were created by the drilling process, release of confining pressure, dehydration, or sample preparation. However, some degree of dehydration was apparent in the 12 Dog Creek Shale and Chickasha and Boggy Formations samples evaluated for water content. If it is assumed that the core specimens were fully saturated prior to testing because they were below the water table when retrieved, the volume of water contained by the specimens should decrease from the compressional forces applied during testing. Yet, data show that the volume of interstitial water in specimens was 18 to 42 percent higher after testing (table 1 and Appendix 3), implying that even though measures were taken to preserve the cores, some deterioration occurred prior to testing.

The effects of microfractures on small-volume laboratory tests could be substantial, as the microfractures would act as conduits for fluid flow. The effects of the microfractures can be seen in the discrepancies between the permeameter-derived hydraulic conductivities and historical data for unfractured argillaceous media at comparable porosities. Figure 3 shows the relation between laboratory-derived (permeameter) hydraulic conductivity and porosity data for a variety of natural argillaceous media, compiled by Neuzil (1994). Neuzil said (1994, p. 145) this plot "suggests a log-linear relation between permeability and porosity exists over an exceptionally wide range of consolidation states [with the data] falling within a band approximately three orders of magnitude wide***." Data from this study would be expected to fall within this band if porosities ranged from 10 to 40 percent. For porosities of 10 to 40 percent hydraulic conductivity is generally less than 10^{-9} meters per second. Many hydraulic conductivity values measured on the cores exceed his value. This would be consistent with the observation that core samples had microfractures. In-place, small-volume measurements of permeability might be less if fractures are not present.

The hydraulic response of the core specimens during compression tests is consistent with the cores being disturbed before tests. An intact core will show relatively little compaction during compression if the rock has been subjected to stresses of equal or greater magnitude during burial (Perloff and Boron, 1976). A relatively small compressibility would be anticipated if specimens were intact, because maximum overburden for the three shaly units probably exceeded 300 meters. Most samples from all three shaly units showed a large compressibility and a large decrease in hydraulic conductivity with compression, indicating that fluid movement at low effective stresses was primarily through microfractures in the core (H. Olsen, written commun., 1990).

Laboratory data indicate fractures play a role in controlling fluid flow within the core specimens of the shaly units. However, if the cores were disturbed before testing, the small-scale hydraulic-test results might not accurately describe the in-place hydraulic characteristics of the rocks at a larger scale as fracture patterns and density would be different. The hydraulic data from this study should be examined carefully when used to model regional or subregional scale ground-water movement.

Slug testing

In-place hydraulic conductivity and specific storage of the Hennessey Group and Boggy Formation were measured using a slug-test method based on techniques developed by Bredehoeft and Papadopulos (1980) with modifications suggested by Neuzil (1982). Conventional slug-test methods used for more permeable strata may be inappropriate for units of low-permeability, because of the slow flow rates and the time needed to observe a response. The method used reduces the test time by isolating and pressurizing the interval with a small volume of injected water. As a result, the hydraulic properties of the rocks are a function of the decline of pressure and not the decline of fluid level.

The location and vertical dimension of the borehole intervals to be tested were determined from core examination and geophysical logs, and uniform appearance. Four to five intervals of the Hennessey Group, averaging 4.5 meters in length, were isolated by packers and tested in two boreholes. Five intervals of the Boggy Formation were tested in one borehole.

The Boggy Formation also was slug tested over the upper 30 meters in one borehole—from the bottom of surface casing at 4.1 meters to total depth

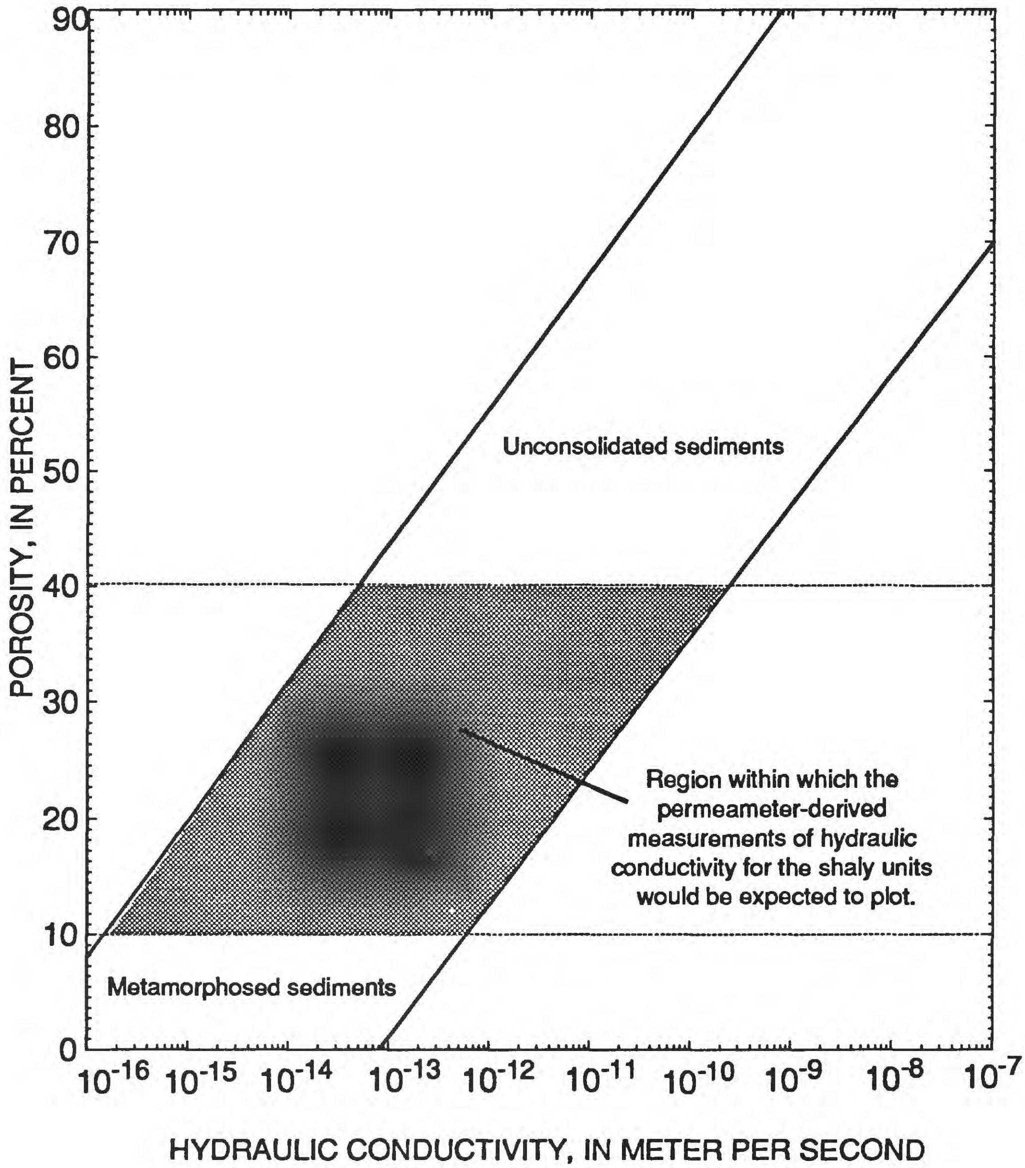


Figure 3. Band formed by historical laboratory-derived hydraulic conductivity versus porosity data for a variety of natural argillaceous media (Modified from: Neuzil, 1994).

drilled—using an open hole slug-test method. Data from this test provided information on the fracture permeability and the more permeable lenses that interval testing did not evaluate. No slug tests were performed on the Dog Creek Shale and Chickasha Formation.

The interval slug tests were restricted to zones of relatively low permeability. Intervals with fractures or other features that transmitted large volumes of water were difficult to test because of the rapid or instantaneous depressurization of confined fluid in the borehole.

The compressibility of the testing equipment should be accounted for during pressurized slug tests as discussed by Neuzil (1982). The resultant calculations of hydraulic conductivity and specific storage may be too low if the compressibility of only water is used. Measurements from interval slug tests of the Boggy Formation were calculated using the compressibility of the testing system described by Neuzil (1982), whereas for the Hennessey Group the compressibility of water was used. As a result, in-place hydraulic conductivities for the Hennessey Group may be too small, but may be accurate within an order-of-magnitude.

Specific storage values measured by the pressurized slug-test method are small. Inaccuracy of determined specific storage is inherent in the technique and has been recognized and discussed by other investigators (Cooper and others, 1967, Neuzil, 1986).

THE DOG CREEK SHALE AND CHICKASHA FORMATION, CANADIAN COUNTY (Union City Site)

The Union City site is located about 4 kilometers north northwest of Union City in south-central Canadian County (fig. 1). The Permian-age Dog Creek Shale crops out and is in the shallow subsurface at the site. It overlies the Chickasha Formation, that is encountered at depths below 21 to 24 meters in the boreholes drilled. The Dog Creek Shale consists mainly of reddish-brown shale, with thin interbeds of reddish-brown siltstone, and the Chickasha Formation is reddish-brown shale with many beds of reddish-brown siltstone, mudstone conglomerate, and sandstone. Total thickness of the Dog Creek Shale is about 60 meters in southern Canadian County (Fay, 1964, plate 1), and the Chickasha Formation also is estimated to be about 60 meters thick. Near-surface strata in southern Canadian County dip to the southwest about 4 meters per kilometer towards the axis of the Anadarko Basin (fig. 1), based on the structure of the underlying Blaine Formation (Jordan and Vosburg, 1963, plate 3, map A). Figure 4 shows the stratigraphic relation of the shaly units at the Union City and other study sites.

Geological Characteristics

Four test holes DC–1, 2, 7, and 8, drilled 61 meters deep, were cored in September 1986 near the Oklahoma Brick Co., located in sections 17 and 16, of T. 11 N., R. 7 W. (fig. 5). Cores from DC–1 and DC–2 were described to characterize the Dog Creek Shale and Chickasha Formation. Core from DC–1 was analyzed for clay and nonclay mineralogy. Permeameter tests were performed on cores from DC–7 and DC–8.

The section drilled at DC–1 and DC–2 consists of about 68 to 75 percent shale, about 18 to 19 percent siltstone and sandstone, and about 6 to 8 percent interbedded shale and siltstone. Each test hole penetrated 1.5 to 2.0 meters of soil overlying red-bed shales and siltstones of the Dog Creek Shale. The Dog Creek Shale, to a depth of 21 to 24 meters, consists mainly of reddish-brown, silty shale in DC–1 and DC–2. The shale grades to claystone with some highly silty shale. Shale beds typically are 0.6 to 3.0 meters thick and are interbedded with reddish-brown and some greenish-gray siltstone or sandstone beds that are commonly 0.3 to 1.5 meters thick. Zones of gypsum nodules are present at 1.5 to 3.0 meter intervals in the cores. Most of the shale is blocky or massive and lacks bedding, although barely perceptible stratification is locally present. Siltstone and sandstone interbeds are generally well layered and laminated in the Chickasha Formation below 21 to 24 meters with both horizontal bedding and small-scale crossbedding. Gypsum is present in both formations as scattered small nodules, thin beds, and throughout as thin veins of satin spar.

Shales in DC–1 and DC–2 are reddish brown and massive. Most of the shale is silty, ranging from slightly silty to very silty. Local zones of reduced iron oxides produce mottled orange, yellow, and gray rock. Scattered 1- to 3-millimeter-diameter light-gray spheres of rock are caused by reduction of iron oxides.

Dog Creek Shale and Chickasha Formation site[1]

System	Group	Stratigraphic unit
Permian	El Reno	Dog Creek Shale
		Chickasha Formation

1. Taken from Mogg and others (1960); Bingham and Moore (1975)

Hennessey Group site[2]

System	Group	Stratigraphic unit
Permian	Hennessey	Salt Plains Formation
		Kingman Siltstone
		Fairmont Shale
	Sumner	Garber Sandstone

2. Taken from Wood and Burton (1968); Bingham and Moore (1975)

Boggy Formation site[3]

System	Group	Stratigraphic unit
Pennsylvanian	Krebs	Boggy Formation
		Savanna Formation
		McAlester Formation
		Hartshorne Sandstone

3. Taken from Jones (1957); Marcher and Bergman (1983)

Figure 4. Geologic column showing stratigraphic position of the geologic units at study sites in Oklahoma.

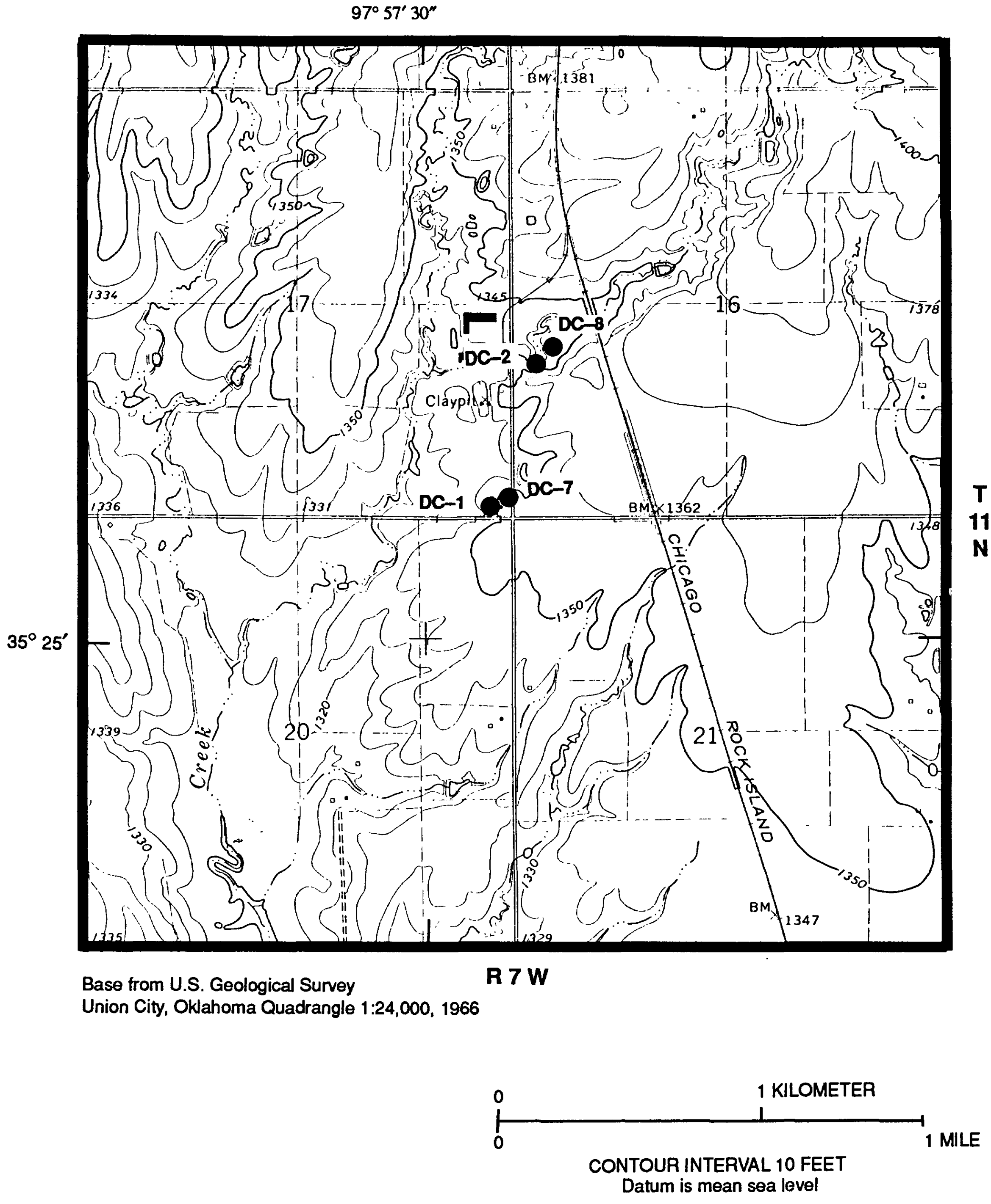


Figure 5. Locations of test holes (DC-1,2,7, and 8) in the Dog Creek Shale and Chickasha Formation at the Union City site, Canadian County, Oklahoma.

Siltstone beds are commonly argillaceous and reddish brown, although several of the beds are light gray to greenish gray. Some siltstones have small-scale crossbedding, but most siltstones have only barely perceptible evidence of horizontal bedding. These siltstone zones are correlative between the two cores (a distance of about 460 meters), and are tongues of the Chickasha Formation interfingering with the red-bed shales in the Dog Creek Shales.

Gypsum nodules are equidimensional to somewhat flattened, range in size from 1 to 30 millimeters, and are single or in zones 3 to 30 centimeters thick. Gypsum nodules are mainly in shale matrix and compose up to 50 percent of some zones. Vertical to subhorizontal veins of satin spar gypsum are present throughout the cored intervals, but are more numerous in the top 40 meters of both cores. Vein thicknesses range from 1 to 5 millimeters.

Red beds in DC–1 and DC–2 contain some fractures, particularly in the upper 18 meters of core. Hairline fractures usually range from vertical to 45 degrees dip, and many of them are filled with satin spar or lined with microcrystalline calcite or a black mineral that may be manganese oxide. Slickensides are on a few of the fracture surfaces.

Clay minerals in the Dog Creek Shale and Chickasha Formation (DC–1) are illite and kaolinite admixed with clay-sized quartz and feldspar (Appendix 1). The shrink/swell potential of these clays is low. Clay minerals reported in the Dog Creek Shale at other sites in Oklahoma are illite, kaolinite, mixed-layer chlorite-vermiculite, and mixed-layer chlorite-montmorillonite (Johnson and others, 1980). As reported by Hartronft and others (1967), at other sites in Canadian County, the plasticity of the Dog Creek Shale is medium, and shrink/swell potential is low to medium.

Hydraulic Characteristics

Depth to water was measured in each of the four test holes; measurements are listed in Appendix 2. Results from permeameter tests for the Dog Creek Shale and Chickasha Formation at the Union City site are listed in Appendix 3. Hydraulic conductivity ranged from 2.8×10^{-11} to 3.0×10^{-7} meter per second in nine samples. Figure 6 illustrates the variation of hydraulic conductivity with depth measured in cores. Specific storage ranged from 3.3×10^{-4} to 1.6×10^{-3} per meter in four samples.

HENNESSEY GROUP, OKLAHOMA COUNTY (Hefner site)

The Hefner site is located in northwestern Oklahoma County and the northwestern part of Oklahoma City; it is about 1.6 kilometers northwest of The Village, and about 0.5 kilometers north of the Lake Hefner dam and intake tower (figs. 1 and 7). Test holes are within 205 meters of the center of sec. 23, T. 13 N., R. 4 W.

Exposed and near-surface rocks at the Hefner site consist of Permian red-bed shales, siltstones, and sandstones of the Hennessey Group. The Hennessey Group has been subdivided in this area into the Salt Plains Formation, Kingman Siltstone, and Fairmont Shale (Bingham and Moore, 1975) (fig. 4). It is likely that parts of all three formations were cored and tested at this site, but the contacts between the formations could not be identified.

Geological Characteristics

The Hennessey Group consists mainly of red-brown shales interbedded with red-brown and orange-brown siltstones. It also contains some beds of greenish-gray shale and siltstone, and some beds of sandstone and lenses of gypsum. The Hennessey Group was deposited in mixed near-shore and shallow-marine environments, and grades westward into a thick sequence of red beds and evaporites in the Anadarko Basin (Jordan and Vosburg, 1963). The total thickness of the Hennessey Group in this area is about 90 meters. Near-surface strata in western Oklahoma County dip to the west-southwest at about 4 meters per kilometer towards the Anadarko Basin (Jordan and Vosburg, 1963).

Two test holes (HG–1 and HG–2), drilled about 61 meters deep, were cored in 1986 (fig. 7). HG–2 core was described to characterize the Hennessey Group, analyzed for clay and nonclay mineralogy, and tested for hydraulic characteristics. Interval-slug tests were performed in HG-1 and HG-2.

HG–2 encountered 6.4 meters of soil and surface clays and coring was started at that depth. The core consists of about 48 percent silty red-brown shales. Individual shale beds average about 3 meters thick, but range in thickness from 1 to 7 meters. The shales are massive or blocky and lack bedding planes.

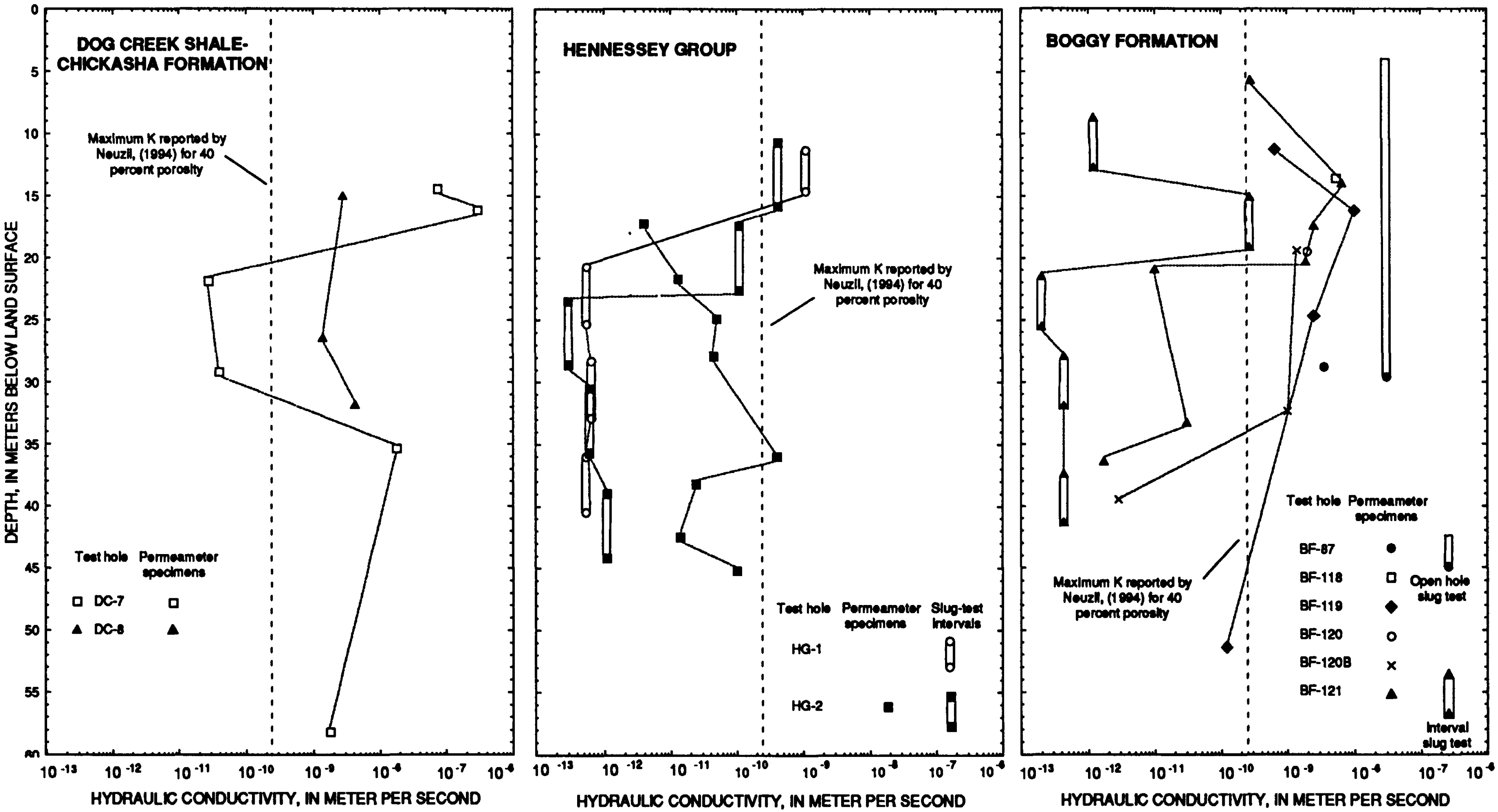


Figure 6. Plots showing hydraulic conductivity versus depth measured in core samples by use of constant-flow permeameter methods and in bore-hole intervals by use of slug-test methods.

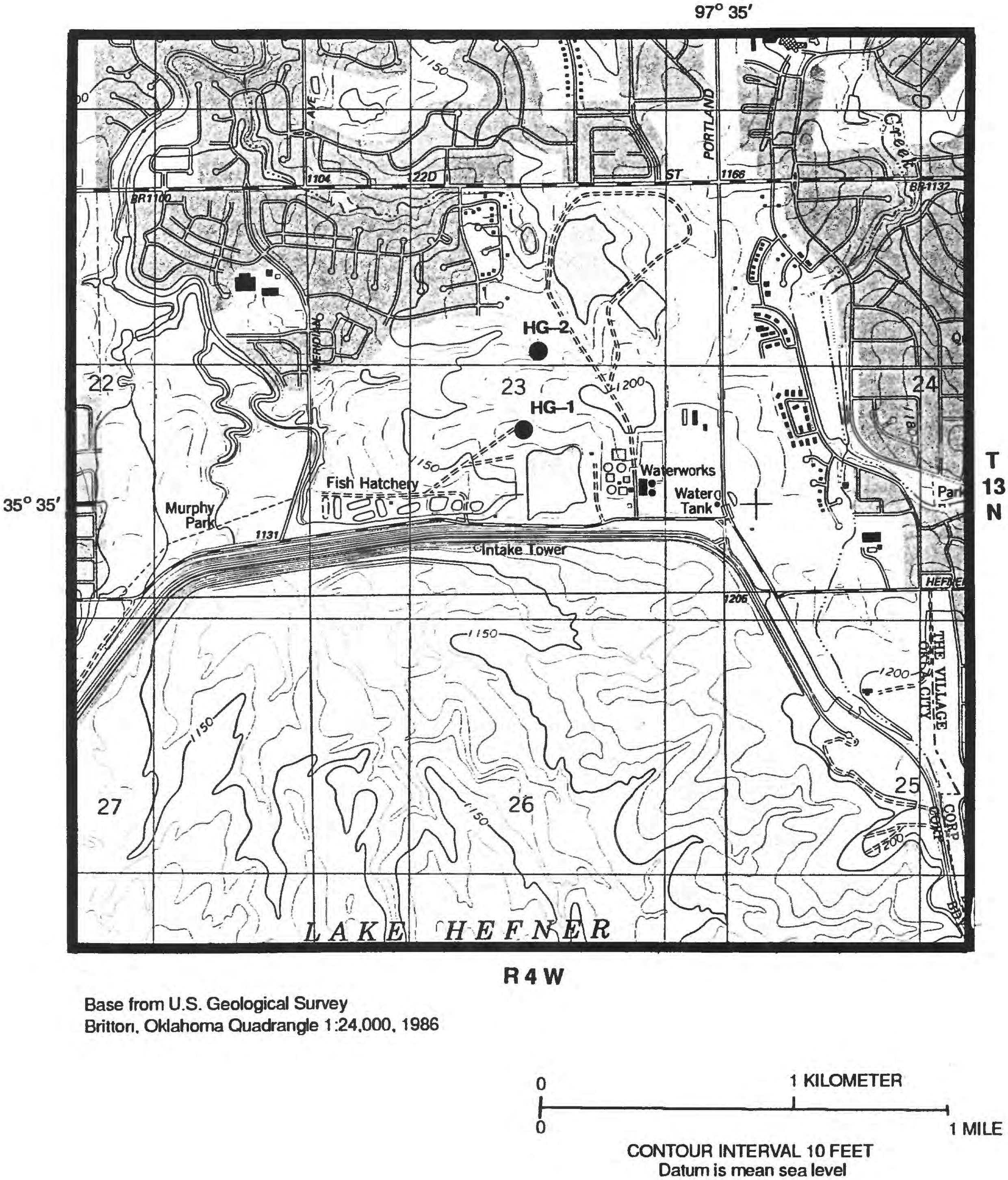


Figure 7. Locations of test holes (HG-1 and HG-2) in the Hennessey Group at the Hefner site, Oklahoma County, Oklahoma.

Small (1-3 millimeters) spheres of light-gray shale result from reduction of iron oxides.

Siltstone beds make up about 32 percent of HG–2. Most siltstones are red brown and clayey, although some are mottled blue green in part. Siltstone beds average about 2 meters thick in HG–2, but range from 6 centimeters to 7 meters thick. Most of the siltstones have evidence of bedding, and some of them have small-scale crossbedding.

Two sandstone beds near the bottom of HG–2 (below 48 meters) probably are in the upper part of the Garber Sandstone. The sandstones are red brown, very fine to fine grained, and are crossbedded. The upper sandstone is 5.5 meters thick, and the lower sandstone is 3.7 meters thick.

Similar to cores of the Dog Creek Shale and Chickasha Formation, cores of the Hennessey Group shales show fractures with slickensides and secondary precipitation of gypsum. Gypsum lenses, about 6 millimeters thick, are present at several depths from 19 to 24 meters, and slickensides are present at various depths from 6 to 37 meters. A black mineral, probably manganese oxide, stains slickenside surfaces near the top of the cores.

Dominant minerals in HG–2 are quartz and dolomite (Appendix 1). Dolomite is a significant component in all samples, except near the bottom of the core (44.5 meters); its relative proportion increases from 6.6 meters down to 20.9 meters where it is more abundant than quartz, and then decreases in the deeper samples. Feldspar is present in all seven samples from HG–2, and the principal clay minerals are illite and kaolinite. The shrink/swell potential of these clays is low. Clay minerals reported in the Fairmont Shale of the Hennessey Group elsewhere in Oklahoma are mainly mixed layer illite-chlorite-montmorillonite, illite, kaolinite, and chlorite (Johnson and others, 1980). Hartronft and others (1967) report at other sites in Oklahoma County, shale in the Hennessey has slight to medium plasticity, and a low to medium shrink/swell potential.

Hydraulic Characteristics

Depth-to-water measurements were taken the same day the test holes were completed. Measurements are listed in Appendix 2.

Hydraulic test results for the Hennessey Group at the Hefner site are listed in Appendix 3. Permeameter-derived hydraulic conductivity ranged from 4.0×10^{-12} to 4.0×10^{-10} meter per second in eight samples. Hydraulic conductivity measured by interval slug tests ranged from 3.0×10^{-13} to 1.1×10^{-9} meter per second in nine intervals. slug-test results suggest hydraulic conductivity values are highest at shallow depths in the Hennessey and decrease markedly below about 20 meters in HG–1 and about 23 meters in HG–2. The higher hydraulic conductivity values at shallow depths are consistent with the greater fracture density observed in cores at shallow depths. For two of the three zones below about 22 meters in HG–2, hydraulic conductivity was measured by both methods; slug tests were approximately one to three orders of magnitude smaller than permeameter measurements. Figure 6 illustrates the variance of hydraulic conductivity with depth and test method.

Measurements of specific storage obtained by interval slug tests range from 4.5×10^{-11} to 4.5×10^{-8} per meter; these values are small and may be unreliable.

BOGGY FORMATION, PITTSBURG COUNTY (McAlester site)

The McAlester site is located on the U.S. Army Ammunition Depot in southwestern Pittsburg County, approximately 8 kilometers southwest of the city of McAlester. Test holes were drilled in the SW corner of sec. 20, SE corner of sec. 25, SW corner of sec. 30, and the NW corner of sec. 30 in T. 4 N., R. 13 E., near road easements (fig. 8).

The rocks exposed near the McAlester site are Pennsylvanian-age shales and fine-grained sandstones of the upper part of the Krebs Group (Jones, 1957; Marcher and Bergman, 1983). The Krebs Group in this area is subdivided into the Hartshorne Sandstone (bottom), McAlester Formation, Savanna Formation, and Boggy Formation (top) (fig. 4). Only strata in the upper part of the Boggy Formation were cored at the McAlester site. Rock units that compose the Boggy Formation were deposited in fluvial/deltaic systems that extended southward and into the Arkoma basin (Visher and others, 1971). The Boggy Formation is composed of brown to dark-gray shale containing numerous thin sandstone beds and generally is very dense and fissile in part. The thickness of the Boggy Formation ranges from 610 to 1,220 meters. The structure near the McAlester site consists of tightly folded anticlines separated by broad, gently dipping synclines

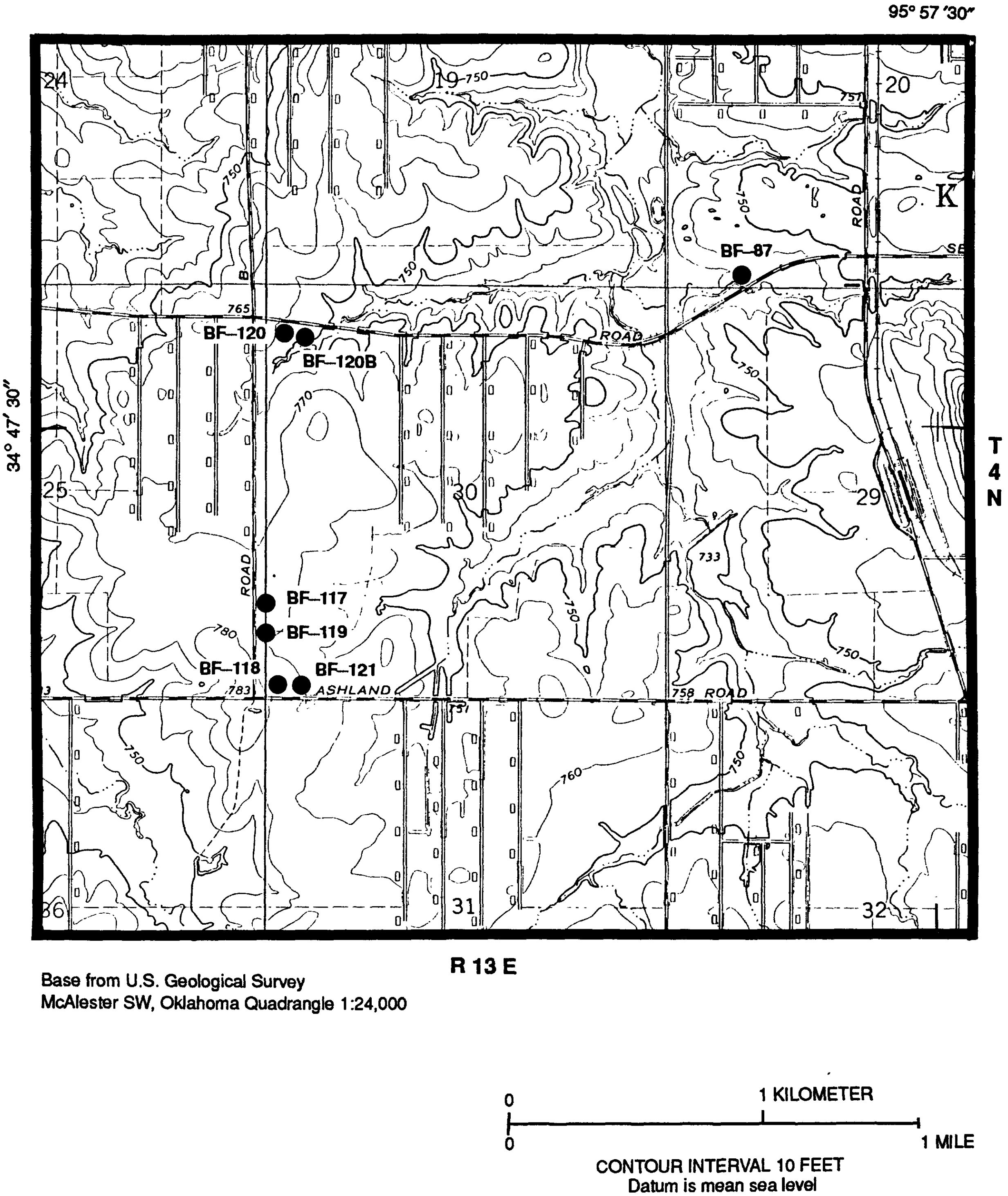


Figure 8. Locations of test holes (BF-87, 117, 118, 119, 120, 120B, and 121) in the Boggy Formation at the McAlester site, Pittsburgh County, Oklahoma.

trending northeast-southwest. Test holes are situated on the flank of a syncline with strata dipping at angles of 2 to 4 degrees to the north and northwest (Hendricks, 1937).

Geological Characteristics

Seven test holes were cored in 1988-89 at the McAlester site (fig. 8). The test holes are BF–87, 117, 118, 119, 120, 120B, and 121. Test holes BF–87, 117, 118, and 120 were cored to depths of 30 meters or less. Holes BF–119, 120B, and 121 were cored to depths of about 61 meters. Cores from BF–119, 120B, and 121 were described to characterize the Boggy Formation. Cores from BF–120 and BF–120B were analyzed for clay and nonclay minerals. Permeameter tests were performed on cores from BF–87, 118, 119, 120, 120B, and 121. Slug tests were performed on BF–87 and BF–121.

Information from BF–117 indicates that about 2 meters of brown, clay-rich soil overlies weathered shale. Shales make up the majority of the cored intervals in BF–119, 120B, and 121; they are slightly silty to silty and are dark gray below the weathered zone. The shales are locally fractured, generally with slickensides evident on the fracture surfaces. The fractures generally have dips of 30 degrees or less. Small ironstone nodules and bivalve fossils occur within some of the individual shale beds.

Intermittent and discontinuous beds of siltstone and sandstone are present throughout the length of the cores and compose the dominant lithology below 26 meters in BF–121. Most siltstones are light gray and clayey. Siltstone beds are generally less that 0.6 meters thick, but range from 0.4 to 10.0 meters thick. The thickest siltstone intervals are composed of alternating thin layers of shale, siltstone, and fine-grained sandstone. There is small-scale crossbedding within individual siltstone beds. About 10 percent of the cored interval in BF–121 consists of sandstone, whereas in cores from BF–119 and 120B less than 10 percent is sandstone. The sandstones are gray, very fine to fine grained, and crossbedded. Bed thickness varies from 9 centimeters to 3 meters.

Analyses of bulk samples collected for BF–120 and BF–120B indicate the dominant minerals in the Boggy Formation at the McAlester site are quartz and clays with a small amount of feldspar (Appendix 1). Calcite is significant in core samples down to 9.1 meters. Illite and kaolinite were the principal clay minerals found in the core samples. These two clay minerals have low shrink/swell potential. Clay minerals in the Boggy Formation reported at other locations in Oklahoma are illite, kaolinite, montmorillonite, and mixed layer illite-montmorillonite (Johnson and others, 1980). Hartronft and others (1970) report at other sites in Pittsburg County the plasticity of shale in the Boggy Formation is medium and the shrink/swell potential is low to moderate.

Hydraulic Characteristics

Depth-to-water measurements were made in five of the seven test holes and are listed in Appendix 2. There were no measurements in BF–118 or BF–121.

Hydraulic test results for the Boggy Formation at the McAlester site are listed in Appendix 3. Laboratory tests were performed on samples from shaly intervals of the cores (except the 51.3–51.5 meters sample from BF–119 which was siltstone). These measurements reflect the zones of lower permeability in the boreholes.

Hydraulic conductivity measured by permeameter methods ranged from a low of 1.7×10^{-12} to a high of 1.0×10^{-8} meter per second in 17 samples. Interval slug-test measurements ranged from 2.0×10^{-13} to 2.7×10^{-10} meter per second in five intervals. Figure 6 illustrates the variability of hydraulic conductivity with depth and test method. Fracture density in Boggy Formation cores was observed to be greatest at shallow depths and decreased with depth. Both permeameter and interval slug tests reflect a general decrease in permeability with depth. A hydraulic conductivity of 3.0×10^{-8} meter per second was measured over the entire borehole of BF–87, from bottom of surface casing at 4.1 meters to 30 meters deep, by an open-hole slug test. This value is 2 to 5 orders of magnitude greater than interval slug-test data in the other holes, and indicates the presence of zones of high permeability, which may be a result of fractures as cores showed similar lithology. The ability of these zones to transmit water was evident during the field work, formation water flowing into the borehole at times was problematic. A number of holes were abandoned because of instability. Specific storage measured by interval slug tests ranged from 4.6×10^{-9} to 4.6×10^{-7} per meter within five intervals; these values are small and may be unreliable.

SUMMARY

Information on the geologic and hydraulic characteristics of the Dog Creek Shale and Chickasha Formation, Hennessey Group, and Boggy Formation were collected to gain insight into the characteristics controlling fluid flow at sites studied and to evaluate methods of measuring hydraulic characteristics of shales. Cores indicate units consist primarily of shale and silty shale. Quartz and feldspar are the primary nonclay minerals in all samples of the three units. Dolomite is a significant component in all samples of the Hennessey Group; its relative proportion increases from 6.6 meters down to 20.9 meters where it is more abundant than quartz, and then decreases at the bottom of the core (44.5 meters). Calcite is significant in samples of the Boggy Formation down to 9.1 meters. Illite and kaolinite are the dominant clay minerals in the three units. Fractures were observed in cores of the Hennessey Group, Dog Creek Shale, and Chickasha Formation and were extensive in the Boggy Formation, with the greatest fracture densities apparent at shallow depths.

Permeameter results may not indicate in-place conditions, due to pre-test disturbance and deterioration of core samples. Dog Creek Shale and Chickasha Formation hydraulic conductivities measured by permeameter method ranged from 2.8×10^{-11} to 3.0×10^{-7} meter per second in nine samples and specific storage ranged from 3.3×10^{-4} to 1.6×10^{-3} per meter in four samples. Hennessey Group hydraulic conductivities ranged from 4.0×10^{-12} to 4.0×10^{-10} meter per second in eight samples, whereas for the Boggy Formation ranged from 1.7×10^{-12} to 1.0×10^{-8} meter per second in 17 samples.

The interval slug tests were restricted to zones of relatively low permeability. Intervals with fractures or other features that transmitted large volumes of water were difficult to test because of the rapid or instantaneous depressurization of confined fluid in the borehole. The Hennessey Group hydraulic conductivities measured by interval slug tests ranged from 3.0×10^{-13} to 1.1×10^{-9} meter per second and specific storage from 4.5×10^{-11} to 4.5×10^{-8} per meter in nine intervals. Boggy Formation hydraulic conductivities ranged from 2.0×10^{-13} to 2.7×10^{-10} meter per second and specific storage from 4.6×10^{-9} to 4.6×10^{-7} per meter in five intervals. A hydraulic conductivity of 3.0×10^{-8} meter per second was measured in BF-87 from bottom of surface casing at 4.1 meters to 30 meters deep by an open hole slug-test method. This value is 2 to 5 orders of magnitude greater than interval slug-test data in the other holes and indicates the presence of zones of high permeability, which may be a result of fractures as cores showed similar lithology. Measurements of specific storage are small and may be unreliable.

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APPENDICES

Appendix 1. Mineralogy and shrink/swell potential of selected samples of the Dog Creek Shale and Chickasha Formation in Canadian County, Hennessey Group in Oklahoma County, and the Boggy Formation in Pittsburgh County, Oklahoma

[Source S. Tottempudi and B. L. Weaver, University of Oklahoma, written commun.; >, greater than; >>, significantly greater than]

Depth (meters)	Minerals present	Clay shrink/swell potential
DC–1		
3.1	Quartz >> illite > feldspar > kaolinite	Low
8.4	Quartz >> illite, feldspar > kaolinite	Low
21.1	Quartz >> feldspar > illite > kaolinite	Low
42.0	Quartz >> feldspar > illite > kaolinite	Low
HG–2		
6.6	Quartz >> dolomite > feldspar, illite, kaolinite	Low
9.3	Quartz >> dolomite > feldspar, illite, kaolinite	Low
15.0	Quartz > dolomite > feldspar, illite, kaolinite	Low
20.9	Dolomite > quartz >> feldspar, illite, kaolinite	Low
34.5	Quartz > dolomite >> feldspar, illite, kaolinite	Low
44.5	Quartz >> feldspar > dolomite, illite, kaolinite	Low
59.6	Quartz >> feldspar, illite, kaolinite	Low
BF–120		
5.5	Quartz > calcite, illite, kaolinite > feldspar	Low
6.7	Quartz > calcite, illite, kaolinite > feldspar	Low
8.2	Quartz > calcite, illite, kaolinite > feldspar	Low
9.1	Quartz > calcite, illite, kaolinite > feldspar	Low
10.7	Quartz > illite, kaolinite > feldspar	Low
13.7	Quartz > illite, kaolinite > feldspar	Low
15.2	Quartz > illite, kaolinite > feldspar	Low
18.3	Quartz > illite, kaolinite > feldspar	Low
27.4	Quartz > illite, kaolinite > feldspar	Low
58.8	Quartz > *illite, kaolinite > feldspar*	*Low*
BF–120B		
21.3	Quartz > illite, kaolinite > feldspar	Low
30.5	Quartz > illite, kaolinite	Low
BF–120B (cont.)		
37.2	Quartz > illite, kaolinite	Low
45.7	Quartz > illite, kaolinite	Low

Appendix 2. Depth to water measured in test holes completed in the Dog Creek Shale and Chickasha Formation in Canadian County, Hennessey Group in Oklahoma County, and the Boggy Formation in Pittsburg County, Oklahoma

Test hole	USGS Site identification number	Date of test-hole completion	Surface elevation (meters above sea level)	Depth to water	Date of measurement
DC–1	352516097571901	September 3, 1986	411.5	6.1 meters	September 3, 1986
DC–2	352533097571401	September 10, 1986	411.5	2.7 meters	September 11, 1986
DC–7	352516097572001	July 17, 1987	413.0	4.3 meters	July 30, 1987
DC–8	352535097571501	August 5, 1987	411.5	4.0 meters	October 22, 1987
HG–1	353511097353501	September 1, 1988	358.1	12.2 meters	September 1, 1988
HG–2	353521097353501	October 1, 1988	356.6	15.2 meters	October 1, 1988
BF–87	344750095575701	February 4, 1987	224.0	2.1 meters	April 1, 1987
BF–117	344708095591301	March 24, 1987	233.2	23.8 meters	April 1, 1987
BF–119	344705095591101	December 7, 1987	236.2	9.4 meters	January 14, 1988
BF–120	344742095591101	January 27, 1988	231.6	9.1 meters	January 27, 1988
BF–120B	344742095590801	February 28, 1988	230.1	5.8 meters	February 28, 1988

Appendix 3. Results from hydraulic tests on selected intervals and samples of the Dog Creek Shale and Chickasha Formation in Canadian County, Hennessey Group in Oklahoma County, and the Boggy Formation in Pittsburg County, Oklahoma

[*K*, hydraulic conductivity in meter per second (m/sec); *Ss*, specific storage in meter^{-1} (m^{-1}); effective stress in megapascals (Mpa); initial and final water contents are percentage by weight; initial porosities are percentages and were determined from consolidation data, sample weight and volume measurements; 51-triax, 51-millimeter diameter triaxial cell; 58-triax, 58-millimeter diameter triaxial cell; 86-triax, 86-millimeter diameter triaxial cell; 102-triax, 102-millimeter diameter triaxial cell; flow length in all test specimens was 25 millimeters; orientation of samples was normal to bedding; -- no data]

Test hole and interval tested (meters below land surface)	Interval/sample description	Permeameter results								Slug-test results	
		K (m/sec)	Ss (m^{-1})	Average effective stress (Mpa)[1]	Initial water content	Final water content	Initial porosity	Final porosity	Test method	*K* (m/sec)	*Ss* (m^{-1})
DC–7											
14.5–14.6	Shale	7.5×10^{-8}	1.6×10^{-3}	0.18	--	--	39		1–D	--	--
16.2–16.3	Shale, slightly silty	3.0×10^{-7}	8.9×10^{-4}	0.20	--	--	41		1–D	--	--
21.8–22.0	Shale, silty, sandy	2.8×10^{-11}	7.2×10^{-4}	0.27	--	--	37		1–D	--	--
29.1–29.3	Sandstone, silty, slightly clayey	4.0×10^{-11}	--	0.36	7.1	10.3	--		51–triax	--	--
35.3–35.5	Siltstone, very sandy	1.8×10^{-8}	3.3×10^{-4}	0.44	--	--	30		1–D	--	--
58.1–58.3	Siltstone/sandstone	1.8×10^{-9}	--	0.72	7.3	12.0	--		51–triax	--	--
DC–8											
15.1–15.2	Shale, slightly silty	2.8×10^{-9}	--	0.19	12.8	15.8	--		86–triax	--	--
26.5–26.6	Shale, sandy, slightly silty	1.4×10^{-9}	--	0.33	8.6	11.0	--		51–triax	--	--
31.8–31.9	Shale, sandy, silty	4.2×10^{-9}	--	0.40	9.4	11.4	--		51–triax	--	--
HG–1											
11.3–14.6	--	--	--	--	--	--	--	--	--	1.1×10^{-9}	4.5×10^{-9}
20.7–25.3	--	--	--	--	--	--	--	--	--	5.6×10^{-13}	4.5×10^{-10}
28.3–32.9	--	--	--	--	--	--	--	--	--	6.5×10^{-13}	4.5×10^{-10}
36.0–40.5	--	--	--	--	--	--	--	--	--	5.4×10^{-13}	4.5×10^{-8}

Appendix 3. Results from hydraulic tests on selected intervals and samples of the Dog Creek Shale and Chickasha Formation in Canadian County, Hennessey Group in Oklahoma County, and the Boggy Formation in Pittsburg County, Oklahoma—Continued

Test hole and interval tested (meters below land surface)	Interval/sample description	Permeameter results								Slug-test results	
		K (m/sec)	Ss (m^{-1})	Average effective stress (Mpa)[1]	Initial water content	Final water content	Initial porosity	Final porosity	Test method	K (m/sec)	Ss (m^{-1})
HG–2											
10.7–15.8	Shale, silty with slickensides evident	--	--	--	--	--	--	--	--	4.2×10^{-10}	4.5×10^{-9}
17.2–17.4	Siltstone, clayey	4.0×10^{-12}	--	0.21	--	--	--	--	51–triax	--	--
17.4–22.6	Siltstone, clayey with occasional gypsum lenses	--	--	--	--	--	--	--	--	1.1×10^{-10}	4.5×10^{-8}
21.7–21.9	Siltstone	1.3×10^{-11}	--	0.27	--	--	--	--	51–triax	--	--
23.5–28.6	Shale, silty with fractures evident and occasional gypsum lenses	--	--	--	--	--	--	--	--	3.0×10^{-13}	4.5×10^{-8}
24.7–25.1	Shale, silty	5.0×10^{-11}	--	0.31	--	--	--	--	51–triax	--	--
27.9–28.0	Siltstone, clayey	4.5×10^{-11}	--	0.35	--	--	--	--	51–triax	--	--
30.5–35.7	Siltstone, clayey. Shale, silty at 35.2–35.7, slickensides evident	--	--	--	--	--	--	--	--	6.1×10^{-13}	4.5×10^{-11}
36.0–36.1	Shale, silty	4.0×10^{-10}	--	0.45	--	--	--	--	58–triax	--	--
38.2–38.3	Shale, silty	2.4×10^{-11}	--	0.47	--	--	--	--	58–triax	--	--
39.0–44.2	Interbedded siltstone and shale	--	--	--	--	--	--	--	--	1.1×10^{-12}	5.8×10^{-8}
42.5–42.6	Siltstone, clayey	1.4×10^{-11}	--	0.53	--	--	--	--	58–triax	--	--
45.2–45.3	Shale, silty	1.0×10^{-10}	--	0.56	--	--	--	--	58–triax	--	--

Appendix 3. Results from hydraulic tests on selected intervals and samples of the Dog Creek Shale and Chickasha Formation in Canadian County, Hennessey Group in Oklahoma County, and the Boggy Formation in Pittsburg County, Oklahoma—Continued

Test hole and interval tested (meters below land surface)	Interval/sample description	Permeameter results								Slug-test results	
		K (m/sec)	Ss (m^{-1})	Average effective stress (Mpa)[1]	Initial water content	Final water content	Initial porosity	Final porosity	Test method	K (m/sec)	Ss (m^{-1})
BF–87											
4.1–29.6	Shale, slightly silty in areas, fractures	--	--	--	--	--	--	--	--	[2] 3.0×10^{-8}	--
28.7–28.9	Shale, slightly silty, very fissile	3.5×10^{-9}	--	0.36	6.7	9.1	--	--	102–triax	--	--
BF–118											
13.5–13.8	Shale, very fissile	5.4×10^{-9}	--	0.17	8.9	12.4	--	--	102–triax	--	--
BF–119											
11.3–11.4	Shale, slightly silty, very fissile	6.4×10^{-10}	--	0.14	7.2	12.4	--	--	102–triax	--	--
16.0–16.3	Shale, slightly silty, very fissile	1.0×10^{-8}	--	0.20	7.4	11.1	--	--	86–triax	--	--
24.6–24.8	Shale, fissile	2.5×10^{-9}	--	0.31	5.8	8.0	--	--	86–triax	--	--
51.3–51.5	Siltstone, massive	1.2×10^{-10}	--	0.64	6.4	10.2	--	--	86–triax	--	--
BF–120											
19.3–19.8	Shale, fissile	2.0×10^{-9}	--	0.24	8.0	10.9	--	--	86–triax	--	--
BF–120B											
19.2–19.6	Shale, fissile	1.4×10^{-9}	--	0.24	--	--	--	--	86–triax	--	--
32.4–32.5	Shale, slightly silty, very fissile	1.0×10^{-9}	--	0.40	--	--	--	--	86–triax	--	--
39.5–39.6	Shale, silty, very fissile	2.8×10^{-12}	--	0.49	--	--	--	--	86–triax	--	--

Appendix 3. Results from hydraulic tests on selected intervals and samples of the Dog Creek Shale and Chickasha Formation in Canadian County, Hennessey Group in Oklahoma County, and the Boggy Formation in Pittsburg County, Oklahoma—Continued

Test hole and interval tested (meters below land surface)	Interval/sample description	Permeameter results								Slug-test results	
		K (m/sec)	Ss (m^{-1})	Average effective stress (Mpa)[1]	Initial water content	Final water content	Initial porosity	Final porosity	Test method	K (m/sec)	Ss (m^{-1})
BF–121											
5.7–5.9	Shale, slightly silty	2.8×10^{-10}	--	0.07	--	--	--	--	51–triax	--	--
8.8–12.8	Shale, slightly silty, fracture at 9.6 meters	--	--	--	--	--	--	--	--	1.2×10^{-12}	4.6×10^{-8}
14.0–14.2	Shale, slightly silty	6.5×10^{-9}	--	0.17	--	--	--	--	58–triax	--	--
15.2–19.2	Shale, slightly silty, thinly bedded, fractures at 18.2, 18.9, and 19.1 meters	--	--	--	--	--	--	--	--	2.7×10^{-10}	4.6×10^{-8}
17.4–17.6	Shale, slightly silty	2.5×10^{-9}	--	0.22	6.2	--	23	--	102–triax[3]	--	--
20.4–20.5	Shale, slightly silty	1.9×10^{-9}	--	0.25	5.6	--	20	--	102–triax[3]	--	--
21.0–21.1	Shale, slightly silty	1.0×10^{-11}	--	0.26	10.0	--	33	--	102–triax[3]	--	--
21.6–25.6	Shale, slightly silty, fracture at 22.6–22.9 meters	--	--	--	--	--	--	--	--	2.0×10^{-13}	4.6×10^{-9}
28.0–32.0	28.0–28.6 meters, very fine grained sandstone. 28.6–32.0 meters, silty shale with numerous fractures	--	--	--	--	--	--	--	--	4.3×10^{-13}	4.6×10^{-7}
33.4–33.5	Shale, very silty	3.0×10^{-11}	--	415	--	4.4	--	18	102–triax[3]	--	--
36.5–36.6	Shale, very silty	1.7×10^{-12}	--	453	--	3.6	--	14	102–triax[3]	--	--
37.5–41.4	Siltstone, shaley	--	--	--	--	--	--	--	--	4.3×10^{-13}	4.6×10^{-8}

[1] Pore pressure of several samples was determined to be over pressured and subsequently was corrected by subtracting two thirds of the base pore pressure from the total stress applied, resulting in an average effective stress reported.

[2] Open hole slug test performed over uncased borehole from bottom of surface casing at 4.1 meters to total depth drilled, 30 meters.

[3] The dual-carriage flow pump was used in combination with the triaxial system when testing these samples (Olsen and others, 1991, bottom of figure 7).