HYDRAULIC PROPERTIES OF THE MADISON AQUIFER SYSTEM IN THE WESTERN RAPID CITY AREA, SOUTH DAKOTA

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 93-4008

Prepared in cooperation with the
CITY OF RAPID CITY

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By Earl A. Greene

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Rapid City, South Dakota
1993

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
1608 Mt. View Road
Rapid City, SD 57702

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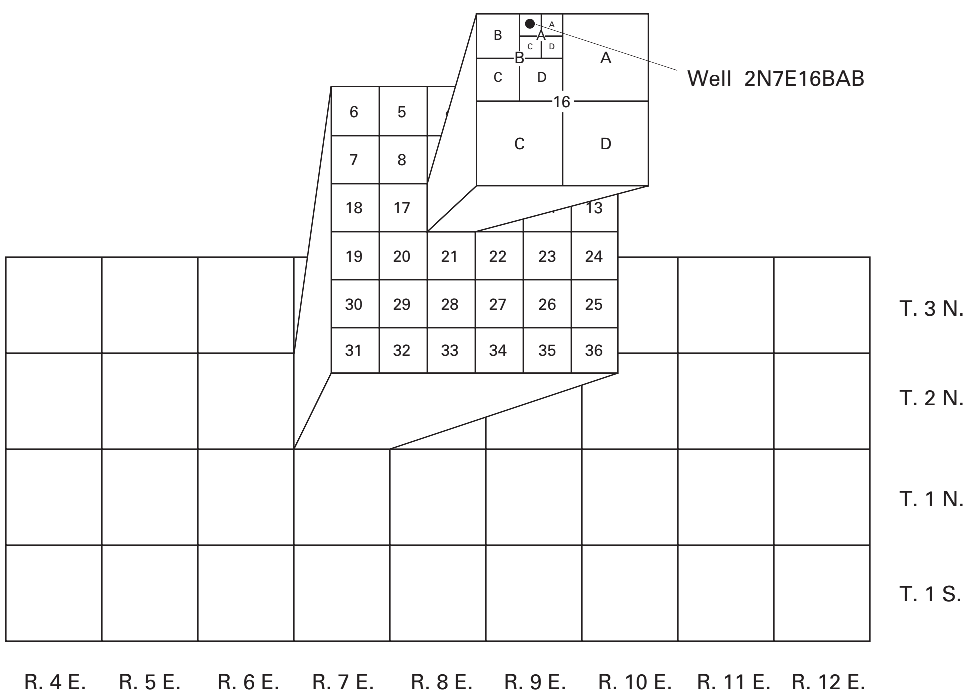
CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	square meter per day
gallon per minute (gal/min)	0.06309	liter per second
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

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.

WELL-NUMBERING SYSTEM

The well-numbering system used in this report is based on the rectangular system for subdivisions of public land. Each "number" (actually number-letter designation) indicates the location of the well with respect to township, range, and section. Number 2N7E16BAB indicates a well in T. 2 N., R. 7 E., sec. 16. The last three letters show the location within the section; the first letter (B) identifies the quarter section (160 acres); the second letter (A), the quarter-quarter section (40 acres); and the third letter (B) the quarter-quarter-quarter section (10 acres). Well 2N7E16BAB is in the NW quarter of the NE quarter of the NW quarter of section 16, township 2 north, range 7 east (see figure below). Where more than one well is located within a 10-acre tract, a number is added following the letter sequence to distinguish them.



HYDRAULIC PROPERTIES OF THE MADISON AQUIFER SYSTEM IN THE WESTERN RAPID CITY AREA, SOUTH DAKOTA

By Earl A. Greene

ABSTRACT

Available information on hydrogeology, data from borehole geophysical logs, and aquifer tests were used to determine the hydraulic properties of the Madison aquifer. From aquifer-test analysis, transmissivity and storage coefficient were determined for the Minnelusa and Madison aquifers, and vertical hydraulic conductivity (K_v') along with specific storage (Ss') for the Minnelusa confining bed.

Borehole geophysical well logs were used to determine the thickness and location of the Minnelusa aquifer, the lower Minnelusa confining bed, and the Madison aquifer within the Madison Limestone. Porosity values determined from quantitative analysis of borehole geophysical well logs were used in analyzing the aquifer-test data. The average porosity at the two aquifer-test sites is about 10 percent in the Minnelusa aquifer, 5 percent in the lower Minnelusa confining bed, and 35 percent in the Madison aquifer.

The first aquifer test, which was conducted at Rapid City production well #6, produced measured drawdown in the Minnelusa and Madison aquifers. Neuman and Witherspoon's method of determining the hydraulic properties of leaky two-aquifer systems was used to evaluate the aquifer-test data by assuming the fracture and solution-opening network is equivalent to a porous media. Analysis of the aquifer test for the Minnelusa aquifer yielded a transmissivity value of 12,000 feet squared per day and a storage coefficient of 3×10^{-3}. The specific storage of the Minnelusa confining bed was 2×10^{-7} per foot, and its vertical hydraulic conductivity was 0.3 foot per day. The transmissivity of the Madison aquifer at this site was 17,000 feet squared per day, and the storage coefficient was 2×10^{-3}.

The second aquifer test, which was conducted at Rapid City production well #5 (RC-5) produced measured drawdown only in the Madison aquifer. Hantush and Jacob's method of determining the hydraulic properties of leaky confined aquifers with no storage in the confining bed was used to evaluate the aquifer-test data by assuming the fracture and solution-opening network is equivalent to a porous media. The analysis of data from the RC-5 aquifer test showed that transmissivity was not equal in all directions. Hantush's method was used to determine the direction of radial anisotropy and magnitude of the major and minor axes of transmissivity. The major axis of transmissivity is at an angle of 42° east of north, and the transmissivity along this axis is about 56,000 feet squared per day. The minor axis of transmissivity is at an angle of 48° west of north, and the transmissivity along this axis is about 1,300 feet squared per day. The major axis of transmissivity intersects Cleghorn Springs, a large resurgent spring on the west edge of Rapid City. The shape of the potentiometric contours of the Madison aquifer near RC-5 agree with the orientation of the transmissivity ellipse. The average value of the storage coefficient from the isotropic analysis of the aquifer-test data was 3.5×10^{-4}, and the average vertical hydraulic conductivity of the lower Minnelusa confining bed was 9.6×10^{-3} foot per day.

INTRODUCTION

The Madison aquifer in the Rapid City area currently is being developed as a source of municipal water by the City of Rapid City, local water associations, and industry. The possibility exists that large-scale development of the Madison aquifer in the Rapid City area could adversely affect water levels in the Minnelusa and Madison aquifers and flow from resurgent springs in Rapid City.

Although the Madison aquifer is known to contain large quantities of water, it is still virtually undeveloped in the Rapid City area and elsewhere in the Black Hills because sufficient water for private use may be obtained from the shallower Minnelusa and Inyan Kara aquifers. For this reason, little is known about the hydrogeology of the Madison aquifer. Without knowledge about the hydrogeology of the Madison aquifer and its potential response to large-scale water withdrawals, sound ground-water management plans cannot be formulated. To address these unknowns, the U.S. Geological Survey, in cooperation with the City of Rapid City, is conducting an investigation of the hydrogeology of the Madison aquifer in the Rapid City area (fig. 1).

The general approach used to study the hydrogeology of the Madison aquifer system was to describe the geologic framework to include the upper part of the Minnelusa Formation as an aquifer, the lower part of the Minnelusa Formation as a confining bed, and the Madison aquifer. These three hydrogeologic units make up the Madison aquifer system.

The three specific objectives of the study of the Madison aquifer system near Rapid City are: (1) Describe the geologic framework, hydraulic properties of the rocks composing the framework, and geologic controls on ground-water movement; (2) simulate flow through the system to evaluate the effects of large-scale withdrawals from the Madison aquifer system on the ground-water and surface-water resources; and (3) investigate the geochemistry of the Madison aquifer system. This report addresses objective 1.

Purpose and Scope

The purpose of this report is to describe the hydraulic properties of the Madison aquifer system determined from analysis of aquifer tests conducted at Rapid City in 1990 by the U.S. Geological Survey. The hydrogeology of the sites, design and methodology of the tests, and test results are discussed. In addition, the geologic framework and hydrogeologic properties at each of the test sites are described on the basis of qualitative and quantitative interpretation of geophysical well logs.

Drawdown data were analyzed by appropriate analytical methods based on conceptual models of the Madison aquifer system at each of the aquifer test sites. The analysis of the aquifer tests provided information on the transmissivity and storage coefficient of the Minnelusa and Madison aquifers and on the vertical hydraulic conductivity and specific storage of the lower Minnelusa confining bed.

Previous Investigations

Many reports describe the general geology and hydrology of western South Dakota aquifers including the Black Hills area. Investigations of the geology and hydraulic properties of the Madison aquifer in the Rapid City

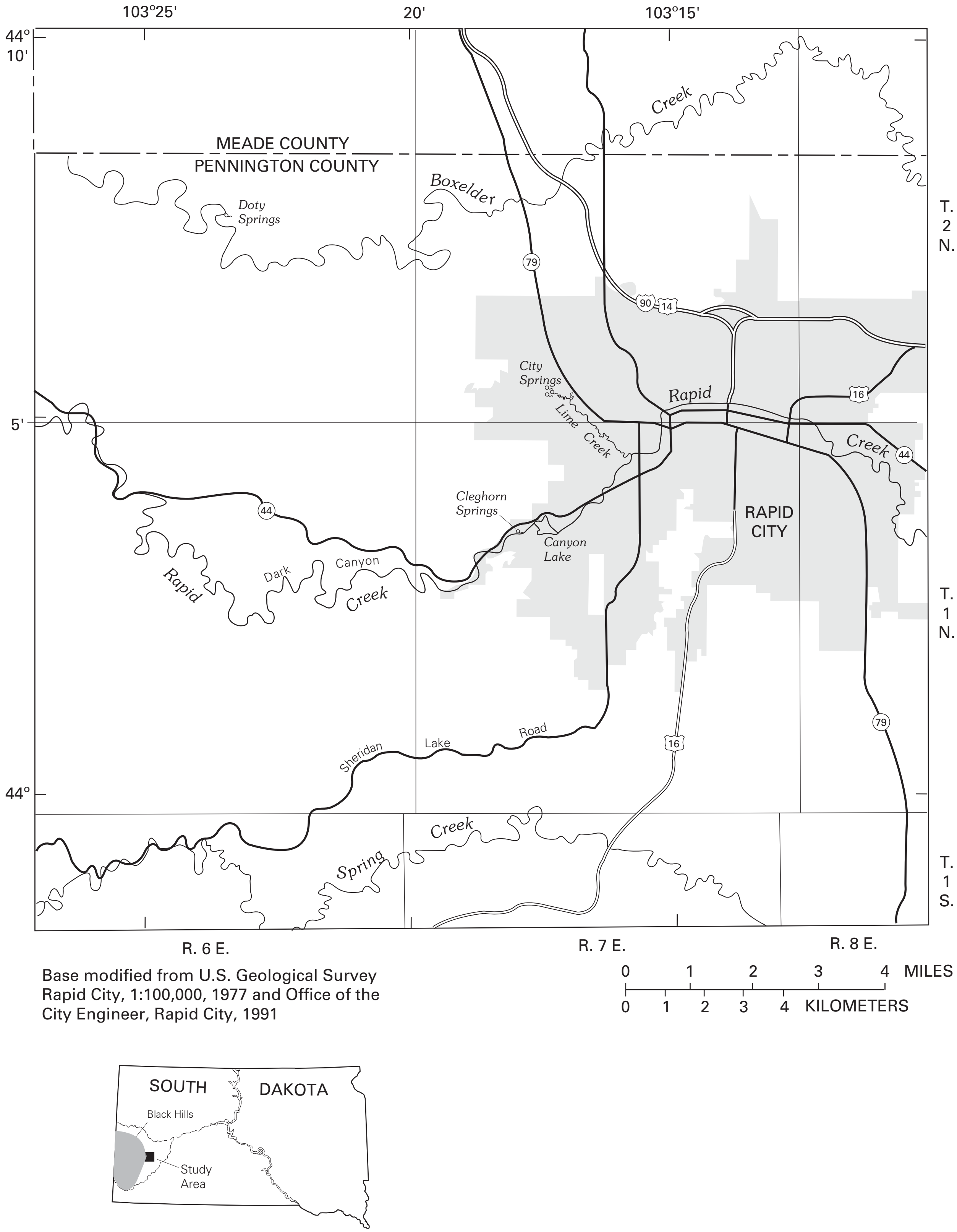


Figure 1.--Location of the study area.

area have been limited by the large depth (up to 4,200 ft) to the Madison Limestone.

Darton and Paige (1925) described the general geology of the Black Hills area. Cattermole (1969, 1972) mapped the geologic formations in the Rapid City area, including the Minnelusa Formation and Madison Limestone. Road logs by Rahn and others (1985), Gries and Steece (1985), and Redden (1985) illustrate the surficial geology along specific highways and roads within and near Rapid City.

A number of reports and papers have been published describing the ground-water resources of western South Dakota, including the Rapid City area of the Black Hills. Important publications on the ground-water resources of the Rapid City area include Darton (1909, 1918), Gries (1943, 1971), Peter (1985), and Downey (1984, 1986).

Ground-water flow directions and interconnection of sinkholes and springs in the vicinity of Rapid City were studied by Rahn and Gries (1973) using dye tests. Distribution and discharge of large springs in the Black Hills also were measured in this study.

Peter (1985) evaluated the bedrock aquifers (Inyan Kara, Minnelusa, and Madison aquifers) in the Rapid City area. Ground-water availability was evaluated on the basis of recharge and discharge rates, estimated aquifer transmissivities, storage coefficients, and reported well yields. Peter concluded that, of the three aquifers investigated, the Madison aquifer has the greatest potential for development.

Acknowledgments

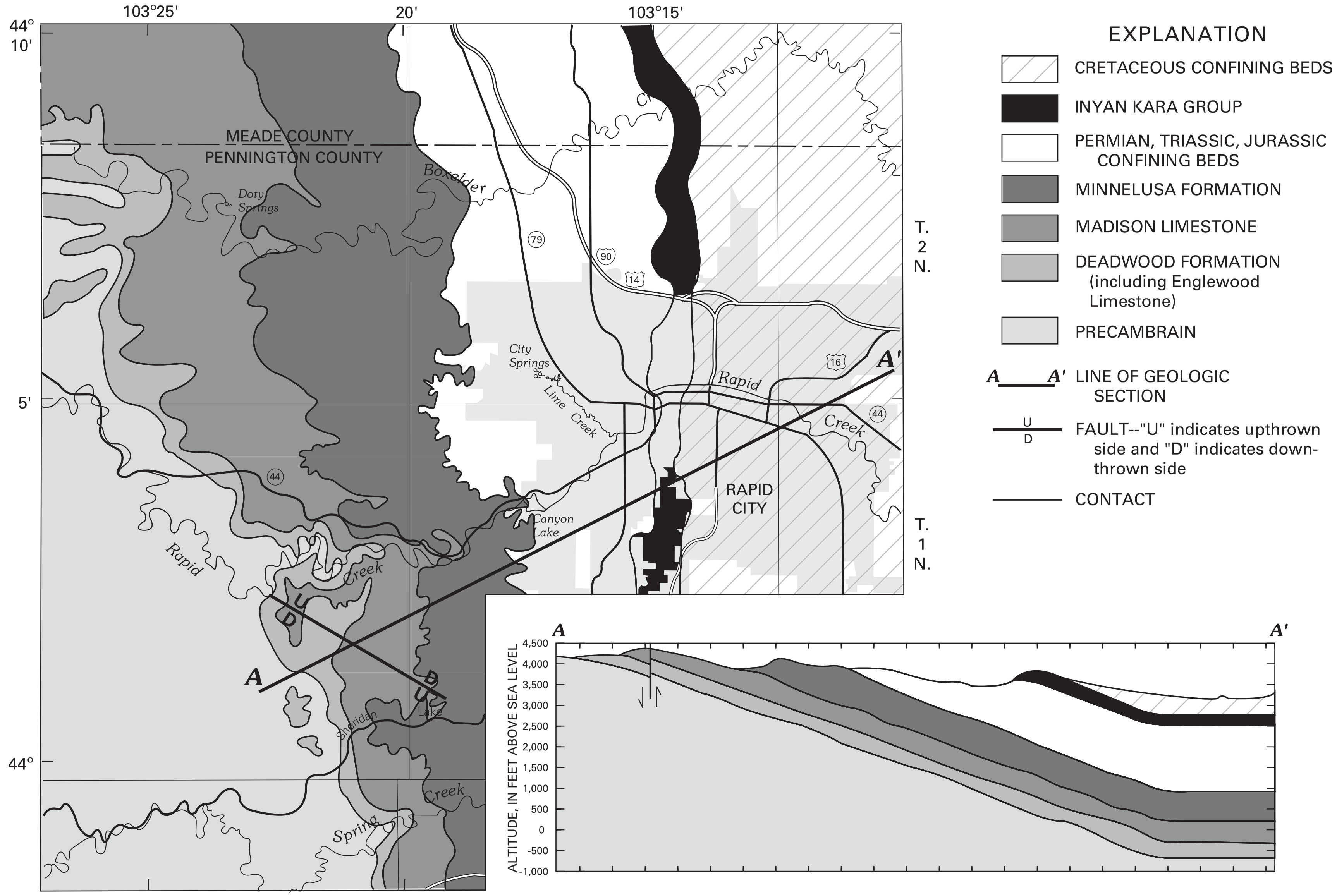
The author would like to thank Black Hills Power and Light, Westberry Trails Water Users Association, Chapel Lane Water Company, and Mr. and Mrs. Schleusener for the use of their wells during the aquifer tests. Jim Goodman and Ken Buhler, South Dakota Department of Environment and Natural Resources, cooperated with the U.S. Geological Survey on the location of State observation wells.

The author also would like to thank individuals of Taylor Drilling Company and the City of Rapid City who provided data, suggestions, or assistance; their help during the aquifer tests is greatly appreciated. Finally, the author thanks the U.S. Geological Survey Borehole Geophysical Research Group for their help in obtaining and interpreting geophysical logs of selected wells.

HYDROGEOLOGY

Geologic Setting

Rapid City is located at the central eastern flank of the Black Hills uplift. The Black Hills uplift, of Laramide age, is about 60 mi wide by 125 mi long. The core of the uplift is composed of hard, erosion-resistant undifferentiated Precambrian igneous and metamorphic rocks along with Precambrian and Cenozoic intrusive rocks. Surrounding the Precambrian core are outcrops of Paleozoic strata, which primarily are bands of dipping limestones, interbedded sandstones, and shales, including the Deadwood Formation, Madison Limestone, and Minnelusa Formation (fig. 2). A generalized geologic section (A-A' on fig. 2) shows the location of these formations and the dip of the Paleozoic and Mesozoic rocks.



Base modified from U.S. Geological Survey Rapid City, 1:100,000, 1977 and Office of the City Engineer, Rapid City, 1991

Geology modified from Ed DeWitt and others, 1989; E.E. McGregor and J.M. Cattermole, 1973; J.M. Cattermole, 1969, 1972; and N.H. Darton and Sidney Paige, 1925

Figure 2.--Generalized bedrock geology within the study area

The younger Paleozoic strata (Permian system) and older Mesozoic rocks of the Triassic and Jurassic systems are composed of shale with lesser amounts of limestone, siltstone, and sandstone. These units generally are considered confining beds in the study area, though water is obtained locally in a number of geologic units within these systems (table 1).

The outer rim of the uplift is composed of resistant sandstones and shales of the younger Mesozoic strata of the Cretaceous system. The sandstones, shales, and siltstone beds of the Inyan Kara Group form a hogback ridge dividing west and east Rapid City. The Fall River Formation and Lakota Formation of the Inyan Kara Group are considered aquifers within the study area.

The younger shales with lesser amounts of limestone and sandstones, of the Cretaceous system within the Mesozoic era, generally are considered to be confining beds within the study area except for the Newcastle Sandstone, which contains the Newcastle aquifer.

Minnelusa Aquifer

The Minnelusa Formation of Pennsylvanian and Permian age is exposed over approximately 31 mi^2 in the study area (fig. 2). Drillers' logs, geophysical logs, and previous published data indicate the thickness of the formation to be about 500 to 800 ft in the study area (Cattermole, 1969). The typical geophysical well-log response and interpreted lithology from these logs for the Minnelusa Formation, Opeche Formation, Minnekahta Limestone, Spearfish Formation, and alluvium are shown in figure 3.

Based on geophysical well-log interpretation and drillers' logs, the Minnelusa aquifer usually is contained within the upper 200 to 300 ft of the formation, and is composed of poorly to well-cemented, fine- to medium-grained sandstone with some limestone, dolomite, and shale. The lower part of the Minnelusa Formation is similar in lithology to the upper part, but has less sandstone and more limestone and dolomite. There usually is a thin shale zone at the base of the Minnelusa Formation (table 1, fig. 3).

The Minnelusa aquifer usually consists of the sandstones of the upper part of the Minnelusa Formation, though the sandstone beds in the middle to lower part of the formation have been utilized locally. The sandstone beds of the Minnelusa Formation are the most utilized aquifer in the study area.

The altitude of the potentiometric surface of the Minnelusa aquifer (fig. 4) ranges from about 3,500 ft in the western part of the study area to about 3,300 ft in the eastern part. The potentiometric surface in the eastern part of the study area is above the land surface indicating wells completed in the Minnelusa aquifer will flow in this area. Ground-water flow generally is from west to east.

The thickness of the confining layer overlying the Minnelusa aquifer varies from 0 ft at the surface exposure of the Minnelusa Formation west of Canyon Lake to about 1,800 ft near the east edge of the study area. This confining bed is composed of Permian-, Triassic-, and Jurassic-age shales and siltstones with some interbedded sandstone, limestone, and gypsum. The rock units in the confining layer include, in descending order, the Morrison Formation or Unkpapa Sandstone, Sundance Formation, Gypsum Spring Formation (where present), Spearfish Formation, Minnekahta Limestone, and Opeche Formation (table 1).

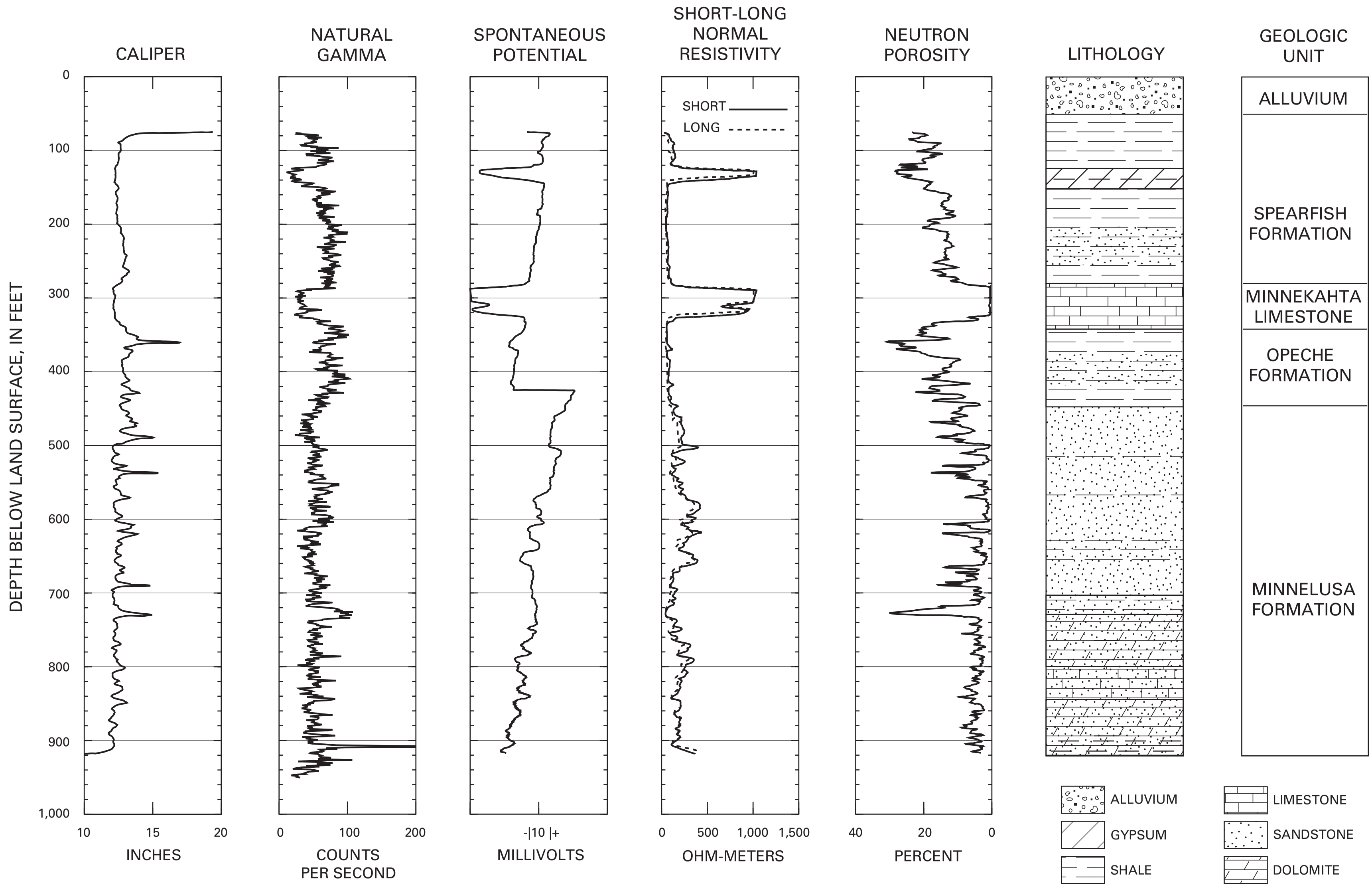
Table 1.--Generalized stratigraphic section of the Precambrian, Paleozoic, and Mesozoic bedrock formations and aquifers in the study area

[Modified from Rahn, 1985, 1987; Brown and others, 1984; Cattermole, 1969, 1972; and Darton and Paige, 1925]

Era	System	Series and Group	Geological unit	Thickness (feet)	Hydrology	Description
Mesozoic	Cretaceous	Upper Cretaceous	Pierre Shale	0-1,400	Confining beds. These rock units are generally too impermeable to serve as a ground-water source.	Shale, sandstone, marl, limestone, and bentonite. Gray to black.
			Niobrara Formation	100-265		
			Carlile Shale	370-800		
			Greenhorn Formation	225-360		
			Belle Fourche Shale	350-850		
			Mowry Shale	150-250		
		Lower Cretaeous	Newcastle Sandstone	25-45	Newcastle aquifer.	Sandstone, siltstone, and shale. Sandstone is light brown, fine- to medium-grained and poorly sorted. Siltstone and shale is brown to gray and interbedded with the sandstone. This unit is too thin to be a major aquifer in the study area.
			Skull Creek Shale	0-325	Confining bed.	Shale, dark-gray or black.
			Inyan Kara Group: Fall River Formation	50-500	Inyan Kara aquifer.	Sandstone interbedded with shale and siltstone. Sandstone, brown to light gray, coarse to very fine-grained. Shale, tan to gray. Siltstone, tan to gray.
			Inyan Kara Group: Fuson Shale			
			Inyan Kara Group: Lakota Formation			
	Jurassic		Morrison Formation	20-310	Confining beds. These rock units are generally too impermeable to serve as a ground-water source. Unkpapa Sandstone. Sandstone members of Sundance Formation and the Minnekahta Limestone are aquifers locally, where permeable	Shale, siltstone, sandstone, limestone, and gypsum. Shales and siltstones of the Morrison and Sundance Formations are gray, and red in the Gypsum Spring, Spearfish Formation. Sandstones of the Unkpapa Sandstone are buff to white, and fine grained. Limestone of the Minnekahta Limestone is light brown to gray or pink.
			Unkpapa Sandstone	0-200		
			Sundance Formation	150-530		
			Gypsum Spring Formation	0-50		
	Triassic		Spearfish Formation	250-700		
	Permian		Minnekahta Limestone	20-70		

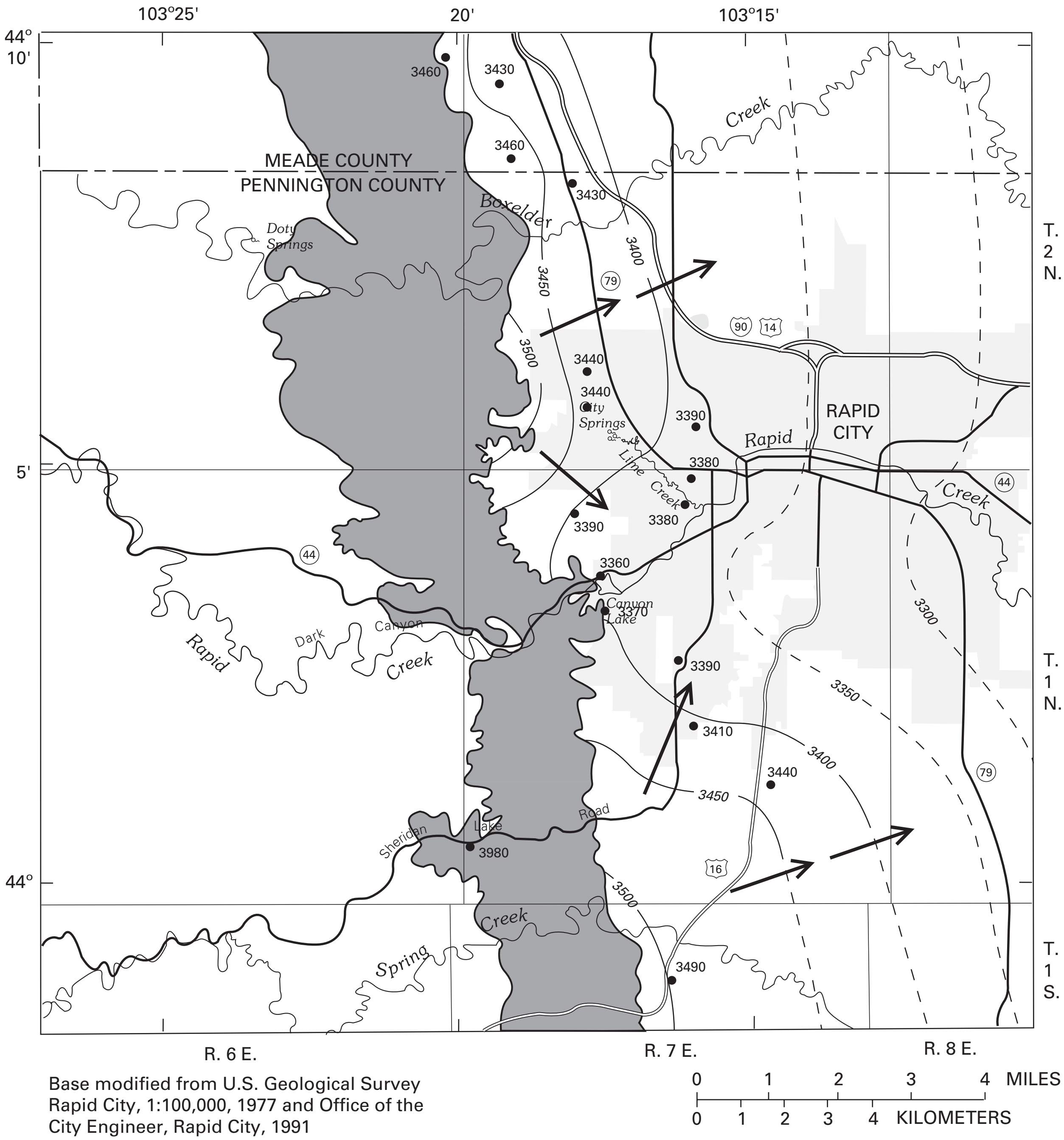
Table 1.--Generalized stratigraphic section of the Precambrian, Paleozoic, and Mesozoic bedrock formations and aquifers in the study area--Continued

Era	System	Series and Group	Geological unit	Thickness (feet)	Hydrology	Description
Paleozoic	Permian (Cont.)		Opeche Formation	50-160	Confining bed.	Shale, red.
	Pennsylvanian		Minnelusa Formation	350-800	Minnelusa aquifer. Upper sandstone beds about 200 to 300 feet thick.	Sandstone, limestone, dolomite, and shale; light brown to gray, weathers red. Generally medium to thick bedding, channeling and crossbedding common.
					Confining bed about 200 to 400 feet thick.	Limestone, dolomite, sandstone, and shale. Shale is interbedded with the limestone, dolomite, and sandstone. At base is 0 to 50 feet of red clayey shale.
	Mississippian		~~Unconformity~~ Madison Limestone or Pahasapa Limestone	300-450	Madison aquifer. Upper 100 to 200 feet.	Limestone, locally dolomite. Gray or buff, coarsely crystalline, massive and cavernous in upper part. Permeability from fractures and solution features.
					Confining bed.	Dolomitic, buff to tan, very finely crystalline. Some interbedded limestone. Lack of fractures and solution features generally distinguishes this part of the Madison as a confining bed.
	Devonian		Englewood Limestone	30-60	Confining beds.	Limestone, pink to lavender, very finely crystalline.
	Ordovician		~~Unconformity~~ Whitewood Dolomite or Limestone or Red River Formation	0-60		Dolomite and limestone, buff. The Whitewood Dolomite is the stratigraphic equivalent of the more extensive Red River Formation.
			Winnipeg Formation	0-100		Shale and Siltstone, green.
	Cambrian		~~Unconformity~~ Deadwood Formation ~~Unconformity~~	150-300	Deadwood aquifer.	Sandstone, shale, and local lenses of conglomerate. Sandstone, lavender, green, red to light brown, fine to very coarse grained. Shale, red to brown-gray.
Precambrian					Base of the hydrologic system.	Undifferentiated igneous and metamorphic rocks.



Natural gamma log provided by the U.S. Geological Survey Borehole Geophysical Research Group, Denver, Colorado.
Caliper, spontaneous potential, resistivity, and neuton porosity provided by Goodwll, Inc., Upton, Wyoming

Figure 3.--Typical caliper, natural gamma, spontaneous potential, short-long normal resistivity, and neutron porosity log response in the Spearfish Formation, Minnekahta Limestone, Opeche Formation, and the Minnelusa Formation at Rapid City well #5 (RC-5).



Base modified from U.S. Geological Survey Rapid City, 1:100,000, 1977 and Office of the City Engineer, Rapid City, 1991

EXPLANATION

SURFACE EXPOSURE OF THE MINNELUSA FORMATION

3400 — POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells, spring of 1991. Dashed where approximately located. Contour interval 50 feet. Datum is sea level.

DIRECTION OF GROUND-WATER FLOW

WELL COMPLETED IN THE MINNELUSA AQUIFER

Figure 4.--Potentiometric surface of the Minnelusa aquifer, spring 1991.

The lower part of the Minnelusa Formation consists of interbedded sandstones and dolomitic limestone (table 1, fig. 3) and is a confining bed separating the Minnelusa aquifer from the Madison aquifer (Peter, 1985; Kyllonen and Peter, 1987). No wells are reported to exist in this lower part of the Minnelusa Formation within the study area; therefore, little information exists on its hydraulic properties.

Recharge to the Minnelusa aquifer is from areal precipitation on surface exposures, streamflow losses to the aquifer where streams cross the exposure of the Minnelusa Formation, and possible upward leakage from the Madison aquifer. There probably is no downward leakage into the Minnelusa aquifer from the Inyan Kara aquifer because of the higher potentiometric surface of the Minnelusa aquifer and the low vertical hydraulic conductivity of the overlying confining beds.

Madison Aquifer

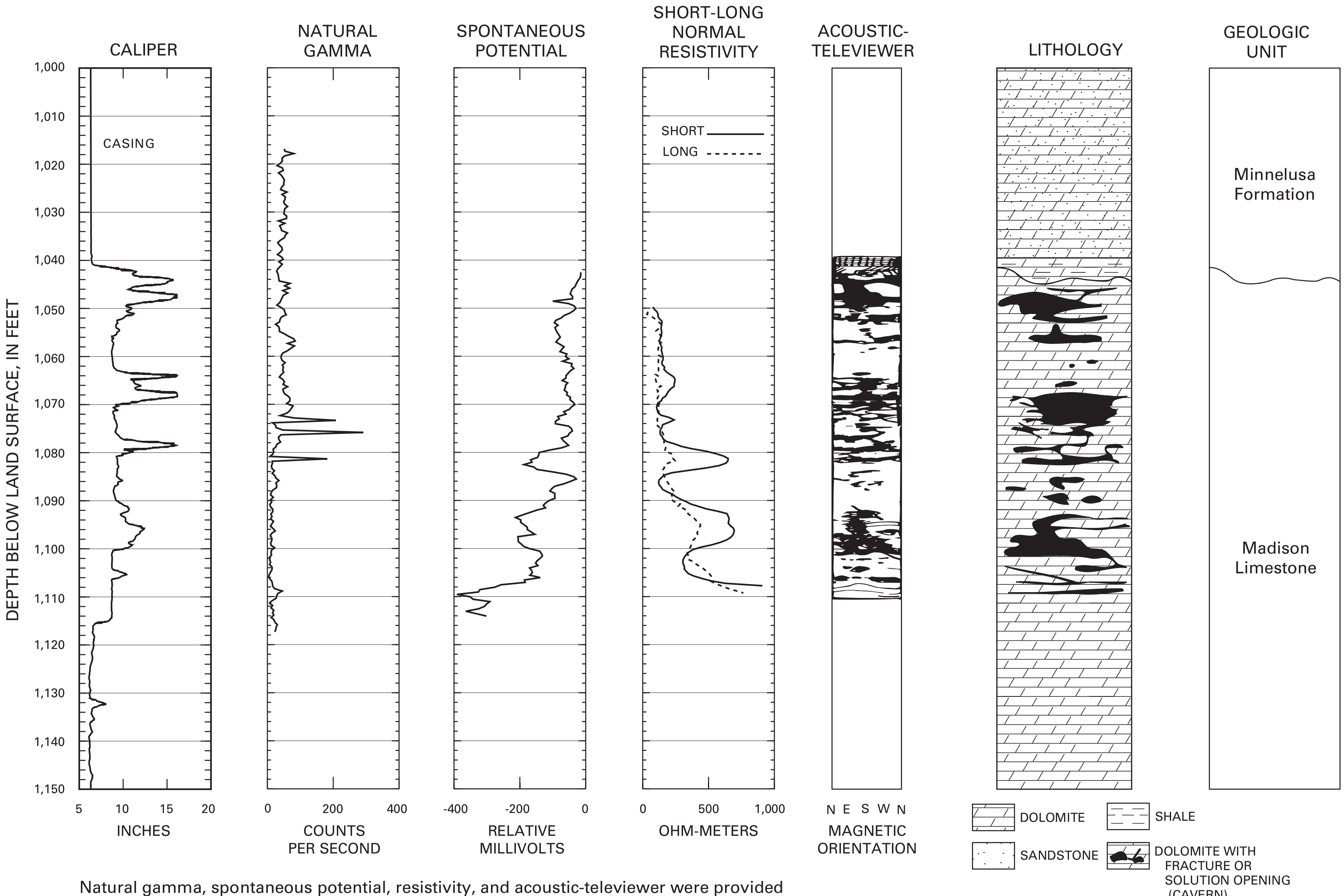
The Madison Limestone, also locally known as Pahasapa Limestone, is a massive limestone and dolomite of Mississippian age and is exposed at the surface over approximately 25 mi^2 of the study area (fig. 2). Unpublished drillers' logs, geophysical well logs, and previous published data indicate the thickness of the Madison Limestone to be about 300 to 450 ft (Cattermole, 1969).

The Madison aquifer usually is contained within the upper 100 to 200 ft of the formation where fractures or solution features have increased the permeability of the limestone or dolomite beds. The altitude of the top of the Madison aquifer varies from about 4,500 ft above sea level where it is exposed at the surface in the Black Hills to about 300 ft above sea level on the east side of the study area.

The thickness of the Madison Limestone at the U.S. Geological Survey Lime Creek observation well (LC), as determined from geophysical logs, the driller's log, and well cuttings, is about 340 ft and extends from about 1,042 ft to about 1,382 ft below land surface. Except for the caliper logs, the geophysical logs obtained in this well were only able to penetrate the upper part of the Madison Limestone where the formation contains fractures or solution openings. The caliper and acoustic-televiewer logs show the location and character of the fractures, caverns, and solution openings in the aquifer from 1,042 to 1,150 ft (fig. 5). From 1,150 ft to about 1,382 ft (contact with the Englewood Limestone), the drilling data and caliper log did not detect many solution openings or fractures.

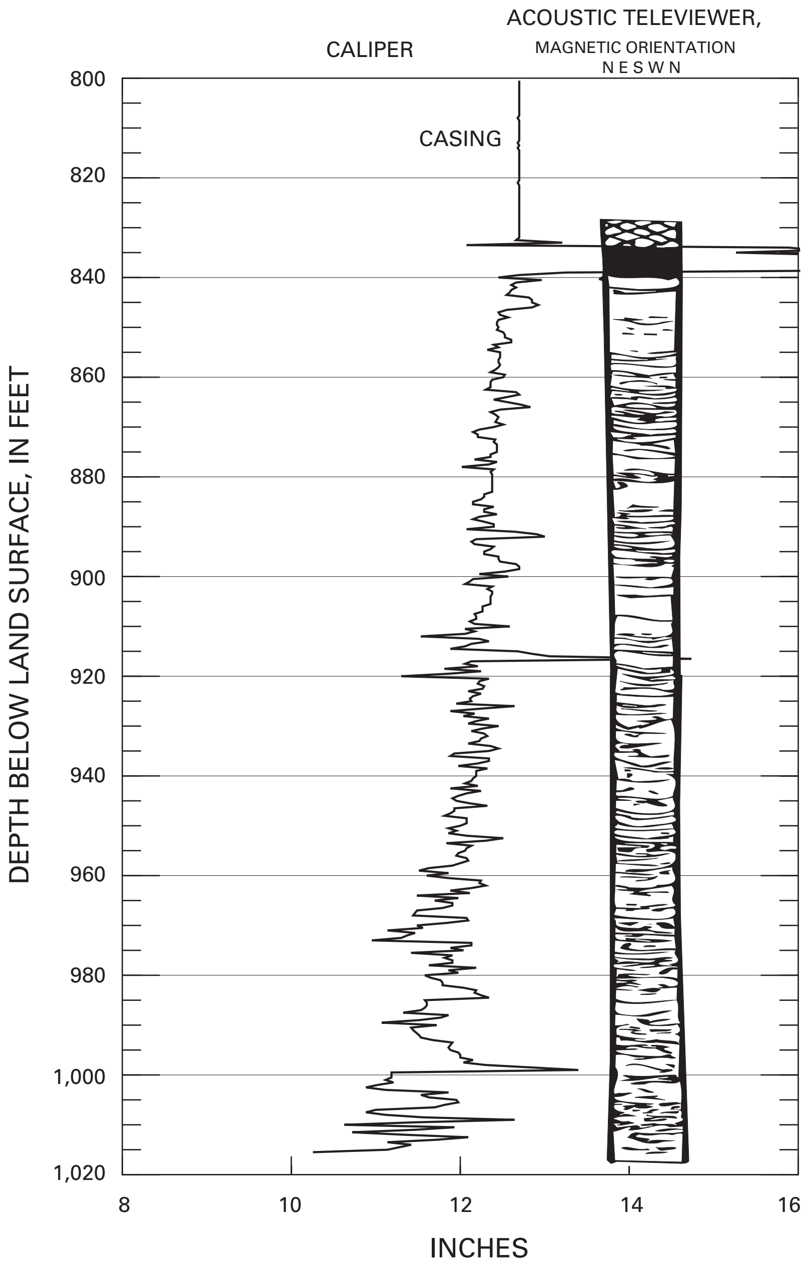
Ground-water flow in the Madison aquifer also may be controlled by fractures where the secondary permeability is made up of fractures instead of large solution openings (caverns). The caliper and acoustic-televiewer logs (fig. 6) of the Madison aquifer in Rapid City production well #6 (RC-6) show that the permeability of the aquifer at this location is made up of fractures and not large solution openings such as at well LC (fig. 5).

Analysis of geophysical well logs from wells drilled by municipalities and local water associations into the Madison aquifer in the vicinity of the study area generally indicates that the Madison Limestone near the outcrop has appreciable secondary permeability as a result of fractures or openings along bedding planes. These fractures have been enlarged as a result of calcite or dolomite dissolution through movement of ground water to form large caverns (fig. 5). These zones of fracture concentration and solution enlargement generally are associated with structural features resulting from the uplift.



Natural gamma, spontaneous potential, resistivity, and acoustic-televiewer were provided by the U.S. Geological Survey Borehole Research Group, Denver, Colorado

Figure 5.--Caliper, natural gamma, spontaneous potential, short-long normal resistivity, and acoustic-televiewer logs for an interval of the Madison aquifer in the U.S. Geological Survey Lime Creek (LC) observation well.



Geophysical well logs provided by the U.S. Geological Survey Borehole Research Group, Denver, Colorado

Figure 6.--Caliper and acoustic-televiewer logs for the Madison aquifer in Rapid City well #6 (RC-6).

The Madison aquifer generally has fewer solution openings but still contains numerous fractures in the eastern part of the study area (fig. 2). This decline in large solution openings probably is due to the lack of dissolution of dolomite and structural features associated with reduced ground-water circulation in the eastern part of the area.

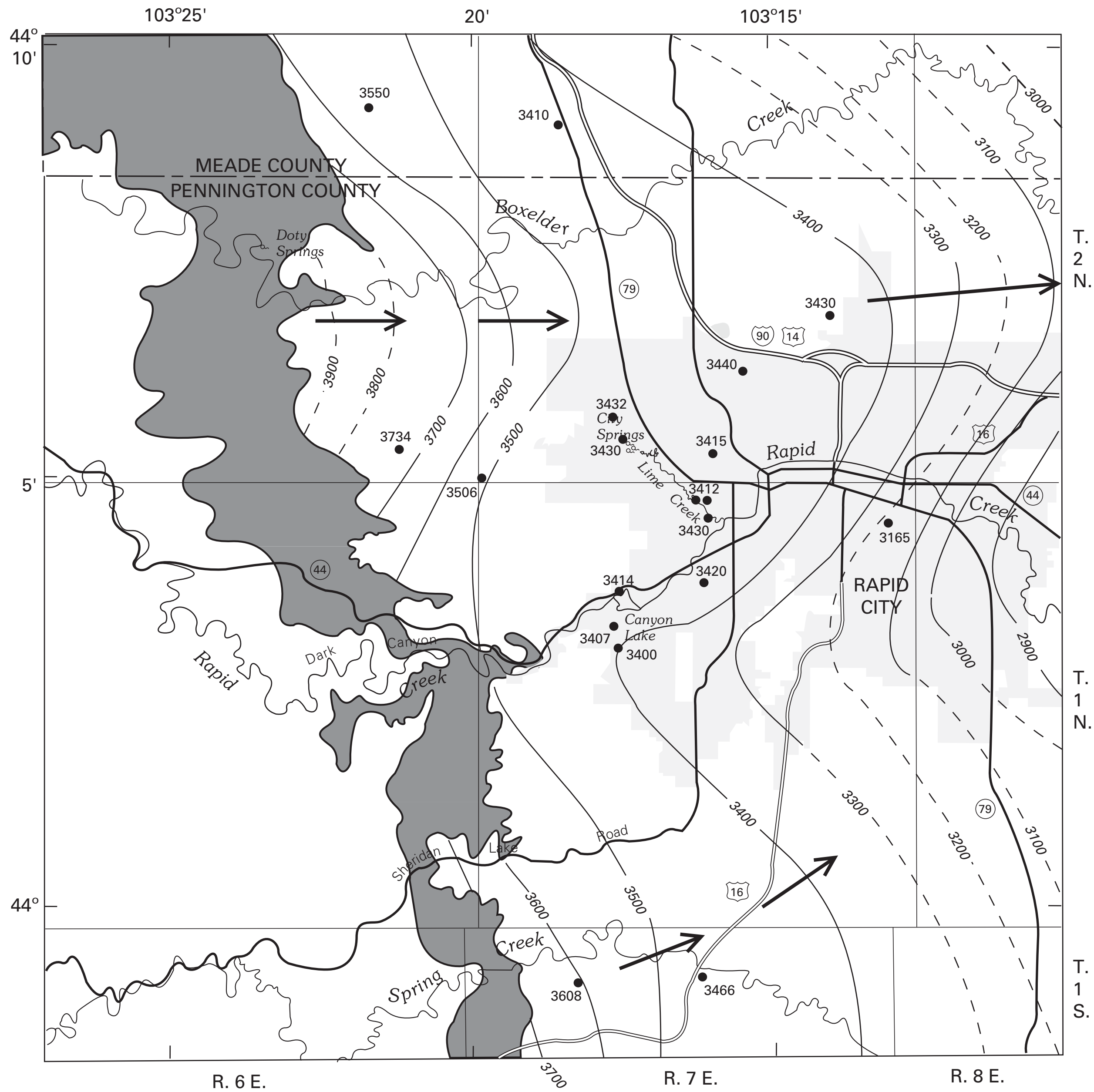
The interbedded limestone, dolomite, and shale beds of the lower Minnelusa Formation (fig. 3) are a leaky, confining layer separating the Minnelusa and Madison aquifers (Peter, 1985; Kyllonen and Peter, 1987). This confining layer ranges from 200 to 400 ft in thickness throughout the study area. The vertical hydraulic conductivity of this confining layer, as determined from core tests conducted in a test well in Crook County, Wyoming, varied from less than 2.4×10^{-5} to 1×10^{-2} ft/d (Blankennagel and others, 1977).

The lower confining layer separating the Madison aquifer from the Deadwood aquifer is the lower part of the Madison Limestone and the Englewood Limestone of Devonian and Mississippian age, respectively (Downey, 1984; Peter, 1985; Kyllonen and Peter, 1987). The Englewood Limestone is a limestone or dolomitic siltstone that has a lower vertical hydraulic conductivity than the Madison aquifer (Downey, 1984). From simulation, Downey estimates the vertical hydraulic conductivity of this confining layer to be about 5×10^{-7} ft/d. The undifferentiated Deadwood Formation and Englewood Limestone is exposed over approximately 8 mi^2 within the study area (fig. 2).

The altitude of the potentiometric surface of the Madison aquifer (fig. 7) ranges from about 3,900 ft in the western part of the study area to about 2,900 ft above sea level in the eastern part. The potentiometric surface of the Madison aquifer generally is above land surface in the western part of the study area and is below land surface in the eastern part. Ground-water flow generally is from west to east.

The Madison aquifer is recharged from precipitation falling directly on surface exposures of the Madison Limestone, streamflow loss where streams cross the exposed limestone, and possible upward leakage from the Deadwood aquifer. In the eastern part of the study area, the potentiometric surface of the Minnelusa aquifer is greater than the Madison aquifer (figs. 4 and 7), indicating possible downward leakage from the Minnelusa aquifer to the Madison aquifer.

The hydraulic heads are similar in the Minnelusa and Madison aquifers near the central part of the study area (fig. 8). This area indicates a possible greater hydraulic connection of the Minnelusa and Madison aquifers than in areas where the heads are substantially different. The similarity in heads could be due to the increased permeability of the lower Minnelusa (confining bed) from increased fracturing by folding and faulting.



Base modified from U.S. Geological Survey Rapid City, 1:100,000, 1977 and Office of the City Engineer, Rapid City, 1991

EXPLANATION

SURFACE EXPOSURE OF THE MADISON LIMESTONE

3400 — POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells, spring of1991. Dashed where approximately located. Contour interval 100 feet. Datum is sea level.

DIRECTION OF GROUND-WATER FLOW

WELL COMPLETED IN THE MADISON AQUIFER

Figure 7.--Potentiometric surface of the Madison aquifer, spring 1991.

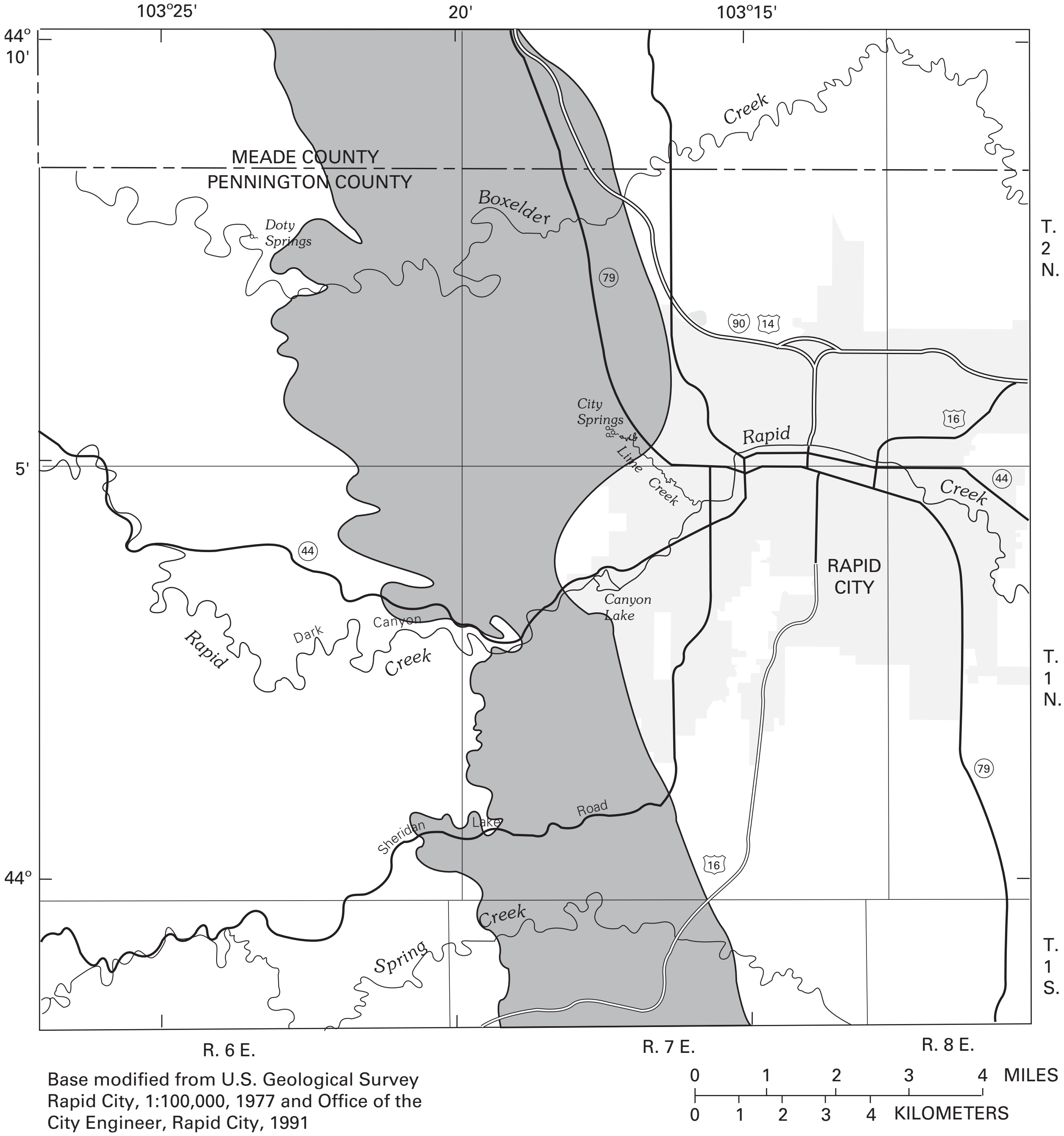


Figure 8.--Area (shaded) where the potentiometric heads in the Minnelusa and Madison aquifers are similar.

DATA-COLLECTION SITES (WELLS) AND STUDY METHODS

Description of Wells

Sixteen wells were used for borehole geophysical logging and aquifer testing to define the physical geometry and determine the hydraulic properties of the Madison aquifer. Production wells Rapid City #5 (RC-5) and Rapid City #6 (RC-6) and observation wells City Quarry #1 (CQ-1), City Quarry #2 (CQ-2), Canyon Lake #1 (CL-1), Canyon Lake #2 (CL-2), and Lime Creek (LC) were drilled by a private well-drilling contractor from September 1989 to February 1990. Additional public- or industrial-supply wells and existing observation wells were used during the aquifer tests only if they were completed in the Minnelusa or Madison aquifer. General data on wells used for the study are presented in table 2, and the well locations are shown in figure 9.

Production wells completed in the Minnelusa or Madison aquifers generally are large-diameter (10-14 in.) wells, cased in the upper part of the formations, and finished as open boreholes in the aquifers. Production wells may be fully or partially penetrating. Typical well construction details are illustrated in figure 10 by a schematic of well RC-5 completed in the Madison aquifer.

Observation wells completed in the Minnelusa or Madison aquifers are constructed similar to production wells. Generally, observation wells are cased with 7-in.-diameter steel casing in the upper formations and are 6-in. open-hole construction in the aquifer.

Aquifer Tests

Two constant-discharge aquifer tests were conducted in the Madison aquifer during the spring of 1990 at wells RC-6 and RC-5. The aquifer tests were designed to determine the transmissivity and storage coefficient of the Madison aquifer and to investigate the possible interconnection of the Minnelusa and Madison aquifers. The relative locations of the observation wells and the corresponding production wells are presented in figure 9. The radial distance of observation wells from the corresponding production wells, and the aquifer in which each well is completed, is given in table 3.

During the two aquifer tests, data were collected according to the standards for aquifer-test data collection and analysis (Stallman, 1971). Production-well pumping rates were maintained within 10 percent of the design pumping rate, water levels in non-flowing observation wells were measured to within 0.01 ft, shut-in pressures in flowing wells were measured to 0.1 pound per square inch or better depending on the scale of the pressure gage used, altitudes of measuring points were measured to 0.1 ft, and the distances from production wells to observation wells were measured to within 1 ft for wells less than 1 mi apart. Observation wells greater than 1 mi from the production well were measured from topographic maps with a scale of 1:24,000.

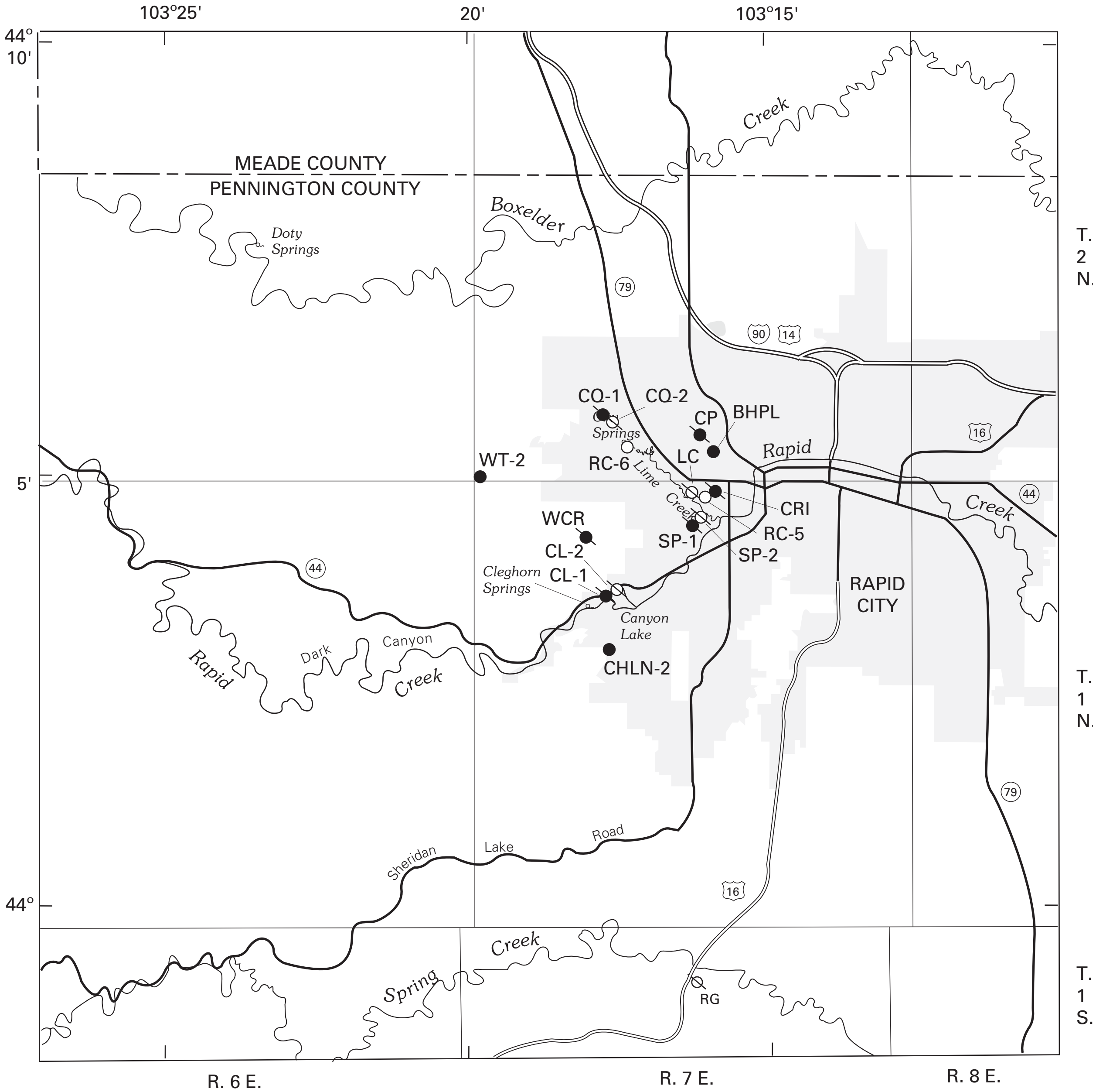
Weekly water-level data were collected to establish pre- and post-aquifer test water-level trends in the Minnelusa and Madison aquifers. In selected observation wells, daily water levels were measured. Water-level trends were established from February to September 1990 for the Minnelusa and Madison aquifers at the City Quarry site (CQ-1 and CQ-2) and from January to September 1990 at the Canyon Lake site (CL-1 and CL-2).

Table 2.--Data on wells used for borehole geophysical well logging and aquifer testing in the study area

[Location of wells shown in figure 9; --, no data]

Local identifier[1]	Local name and abbreviation	Owner	Type of well	Depth (feet)	Aquifer	Date drilled	Reported yield (gallons per minute)
1S 7E 3CDBD	Reptile Gardens (RG)	South Dakota	Observation	1,220	Madison	1986	--
1N 7E 3BABD	Camp Rapid Irrigation (CRI)	SD National Guard	Irrigation	600	Minnelusa	1987	90
1N 7E 3BBCD	Rapid City #5 (RC-5)	Rapid City	Public supply	1,292	Madison	1990	1,600
1N 7E 3BBCC	Lime Creek (LC)	USGS	Observation	1,391	Madison	1989	--
1N 7E 3BCDD	Sioux Park #1 (SP-1)	South Dakota	Observation	570	Minnelusa	1964	--
1N 7E 3BCDD2	Sioux Park #2 (SP-2)	South Dakota	Observation	1,170	Madison[2]	1965	--
1N 7E 5DBCA	West Camp Rapid (WCR)	SD National Guard	Observation	224	Minnelusa	1987	--
1N 7E 8ADDD	Canyon Lake #1 (CL-1)	South Dakota	Observation	115	Minnelusa	1989	--
1N 7E 8ADDD2	Canyon Lake #2 (CL-2)	South Dakota	Observation	700	Madison	1989	--
1N 7E17AADD	Chapel Lane #2 (CHLN-2)	Chapel Lane Water Co.	Public supply	820	Madison	1975	328
2N 7E31CCCA	Westberry Trails #2 (WT-2)	Westberry Trails Water Assoc.	Public supply	680	Madison	1971	25
2N 7E32ABB	City Quarry #1 (CQ-1)	South Dakota	Observation	175	Minnelusa	1989	--
2N 7E32ABB2	City Quarry #2 (CQ-2)	South Dakota	Observation	825	Madison	1989	--
2N 7E32ADDD	Rapid City #6 (RC-6)	Rapid City	Public supply	1,290	Madison	1990	700
2N 7E34BCCA	Cement Plant (CP)	South Dakota	Observation	400	Minnelusa	1964	--
2N 7E34BDCC	Black Hills Power and Light Co. (BHPL)	Black Hills Power and Light Co.	Industrial supply	1,275	Madison	1959	520

[1]Explained on page vii of text.
[2]Bottom 115 feet of the well is perforated in the Minnelusa confining bed.



Base modified from U.S. Geological Survey Rapid City, 1:100,000, 1977 and Office of the City Engineer, Rapid City, 1991

EXPLANATION

SP-1 — MINNELUSA OBSERVATION WELL--Letters and number indicate local abbreviation

CQ-2 — MADISON OBSERVATION WELL--Letters and number indicate local abbreviation

RC-6 — CITY PRODUCTION WELL COMPLETED IN THE MADISON AQUIFER--Letters and number indicate local abbreviation

WT-2 — PUBLIC/INDUSTRIAL SUPPLY WELL COMPLETED IN THE MADISON AQUIFER--Letters and number indicate local abbreviation

Figure 9.--Locations of the wells used for borehole geophysical logging and aquifer testing.

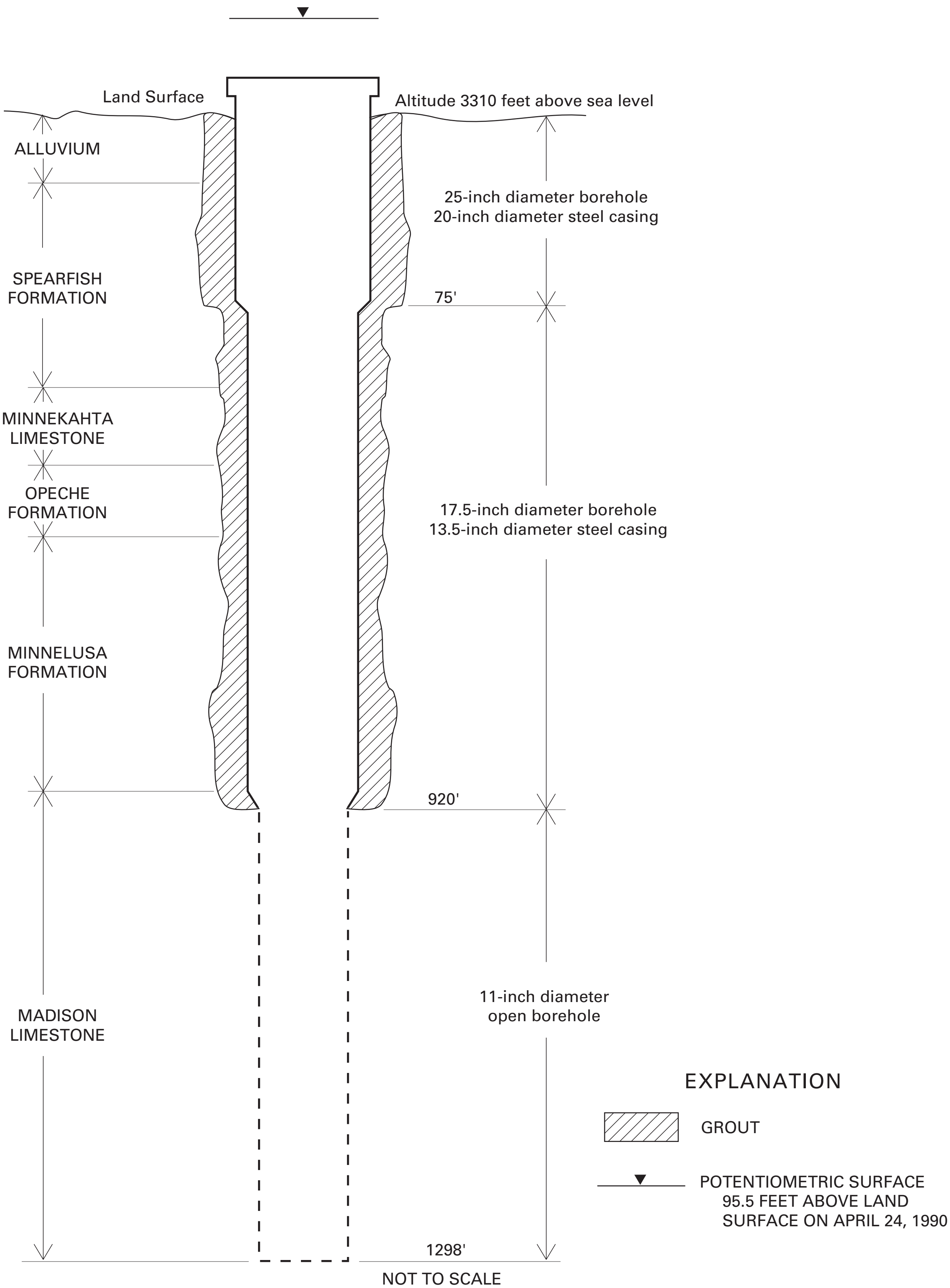


Figure 10.--Schematic showing construction details of Rapid City well #5 (RC-5) completed in the Madison aquifer.

Table 3.--Distance between observation wells and corresponding production well and the aquifer in which each well is completed

Production well	Observation well	Distance from production well (feet)	Aquifer
RC-5	--	--	Madison
	LC	685	Madison
	CRI	1,650	Minnelusa
	SP-1	1,700	Minnelusa
	SP-2	1,700	Madison
	BHPL	3,950	Madison
	CP	4,550	Minnelusa
	RC-6	7,200	Madison
	WCR	8,700	Minnelusa
	CL-1	8,900	Minnelusa
	CL-2	8,900	Madison
	CQ-1	10,250	Minnelusa
	CQ-2	10,250	Madison
	CHLN-2	11,700	Madison
	WT-2[1]	15,850	Madison
	RG	33,000	Madison
RC-6	--	--	Madison
	CQ-2	2,919	Madison
	CQ-1	2,930	Minnelusa
	CP[2]	5,900	Minnelusa
	BHPL[1]	6,600	Madison
	WCR	6,950	Minnelusa
	LC	7,150	Madison
	RC-5	7,200	Madison
	CRI	7,850	Minnelusa
	SP-1	8,600	Minnelusa
	SP-2	8,600	Madison
	WT-2	10,300	Madison
	CL-1	10,850	Minnelusa
	CL-2	10,850	Madison
	CHLN-2[1]	14,150	Madison
	RG	37,500	Madison

[1]Well owner needed water production from the well. Production was maintained at a constant rate as much as possible during the aquifer test.
[2]The well was inadvertently serviced during the aquifer test.

Hydrographs of water levels in the Minnelusa and Madison aquifers at the City Quarry site (fig. 11) indicate the two aquifers are hydraulically connected. Potentiometric heads of the Minnelusa and Madison aquifers are similar in this area (fig. 8). Separation of the heads in the aquifers from April 15 to about September 25, 1990, could be due to difference in areal recharge or summer withdrawal. There are a number of private wells located in the Minnelusa aquifer in the vicinity; many are used for lawn and garden watering during the summer months.

Hydrographs of water levels in the Minnelusa and Madison aquifers at the Canyon Lake site (fig. 12) indicate the aquifers are poorly connected hydraulically. This site is outside of the area where the potentiometric heads of the Minnelusa and Madison aquifers are similar (fig. 8).

Geophysical Logging

The primary purpose of the use of geophysical well logs was to investigate the hydrogeologic properties and define the physical geometry of the Madison aquifer system. Analysis of the logs provided information on location of the aquifer within the bedrock formation and thicknesses of the aquifers and confining beds at the aquifer test sites. As a further aid in analyzing the aquifer tests, porosity was estimated by quantitative interpretation (inversion) of the well logs.

The inversion of geophysical well logs relates the geophysical property measured in a sample volume of aquifer material to the hydraulic property of interest, such as porosity or permeability. This inversion involves the application of mathematical formulas following the correct assumptions where the background lithology remains uniform. Because of the "non-uniqueness" of geophysical log interpretation, more than one interpretation for a set of geophysical logs exists; therefore, the interpretation of a set of log data presented in this report may not be the only possible interpretation (Paillet and others, 1990).

HYDRAULIC PROPERTIES OF THE MADISON AQUIFER SYSTEM

Porosity

Minnelusa Aquifer and Confining Bed

A suite of geophysical well logs from wells RC-5 and RC-6 were analyzed to identify the sandstone beds (potential aquifers) and shale or dolomite beds (confining beds) (non-aquifers) within the Minnelusa Formation. Interpretation of the geophysical logs (fig. 13) and driller's log for well RC-6 indicates the upper part of the Minnelusa Formation (280-660 ft) contains relatively thick zones of sandstones. The lower part of the Minnelusa Formation (690-838 ft) below a shale bed (660-690 ft) is interbedded sandstone, dolomite, and shale.

Interpretation of the geophysical logs (fig. 14) and driller's log for well RC-5 indicates the sandstone beds are located in the upper part of the formation (440-550 ft). Sandstones are interbedded with dolomite from about 550 to 670 ft and dolomite from about 670 to 717 ft. Similar to well RC-6, there is a shale zone (717-732 ft) separating the upper and lower Minnelusa Formation. The lower part of the Minnelusa (732-915 ft) is interbedded sandstones, dolomites, and shales.

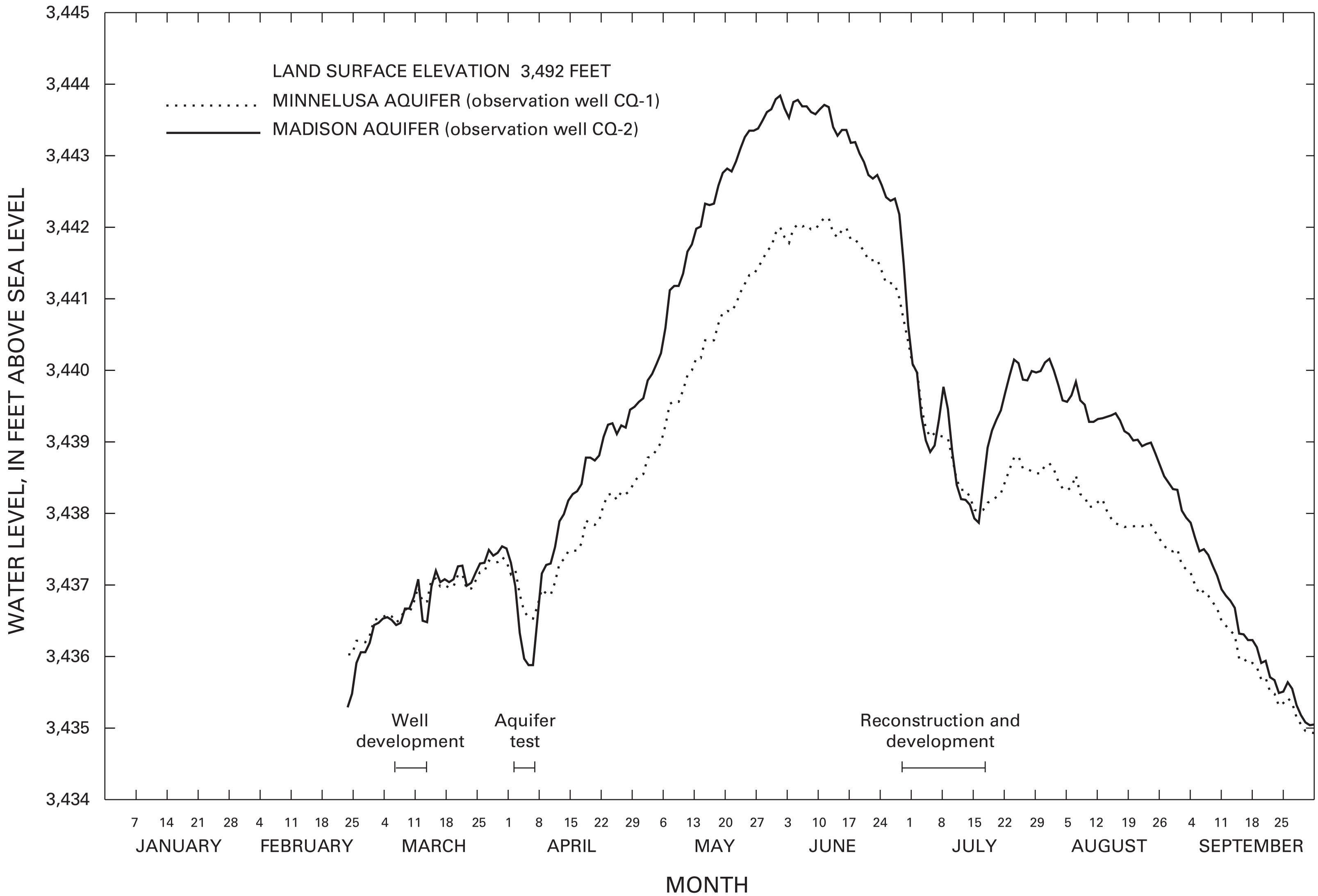


Figure 11.--Water-level trends at the City Quarry (CQ) site near Rapid City well #6 (RC-6) for the Minnelusa and Madison aquifers, February through September 1990.

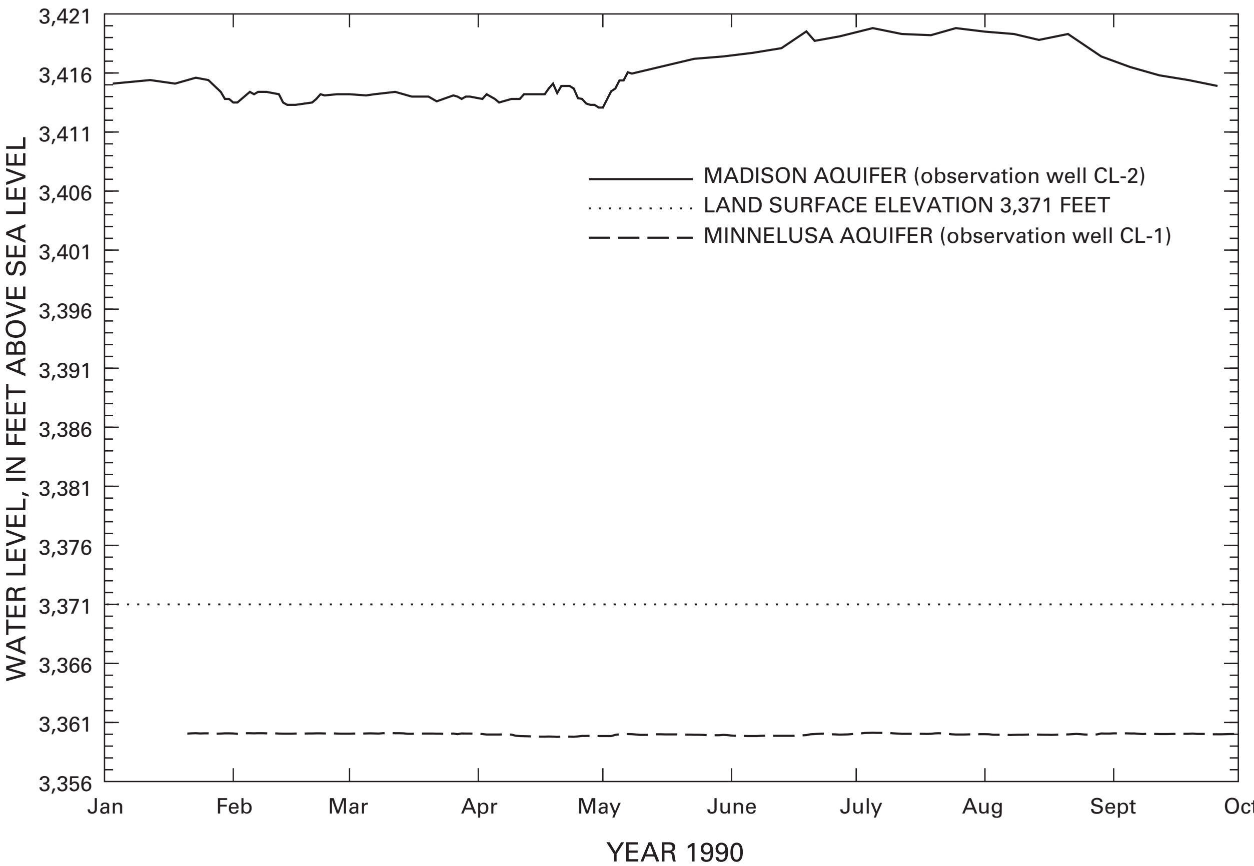
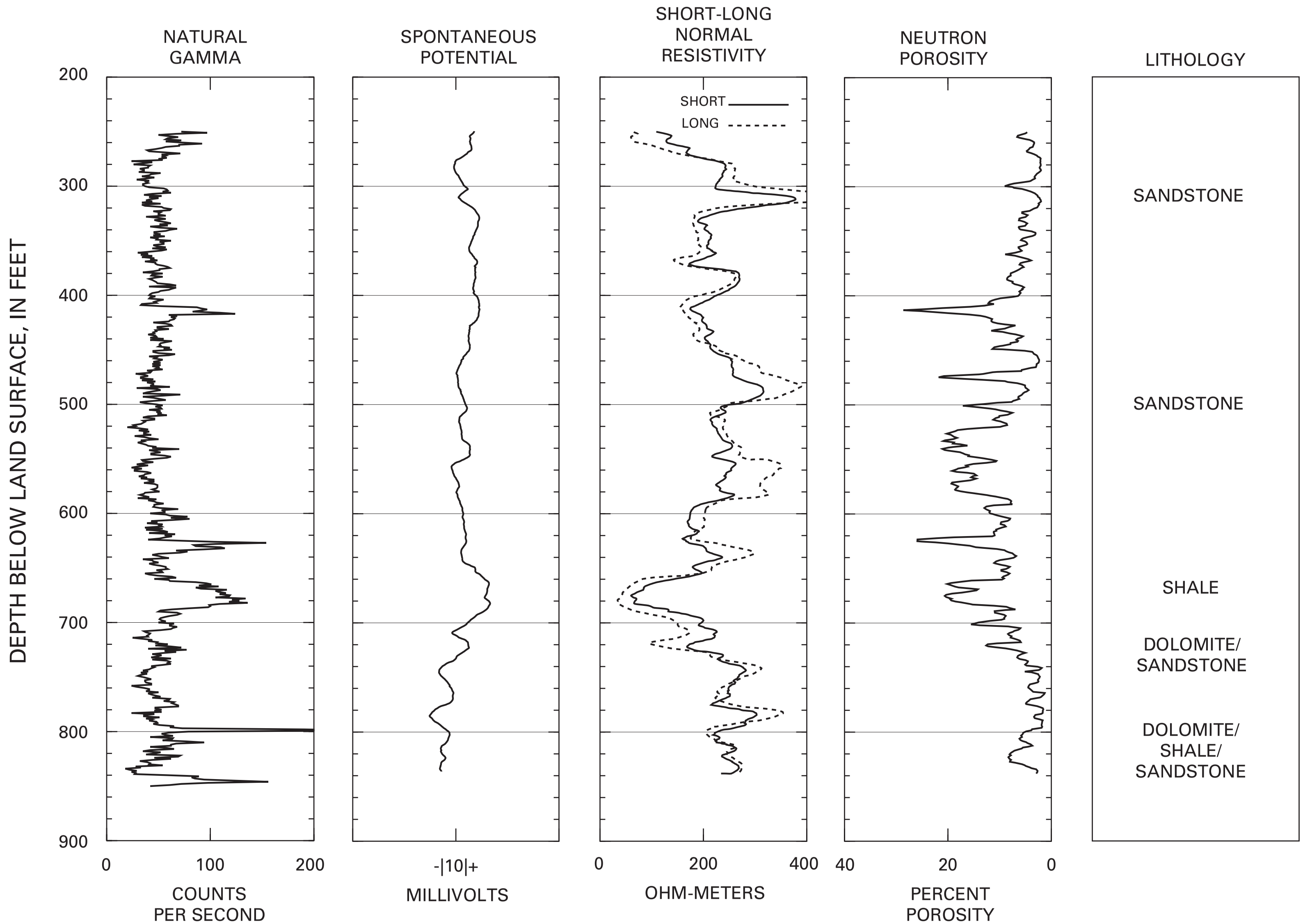
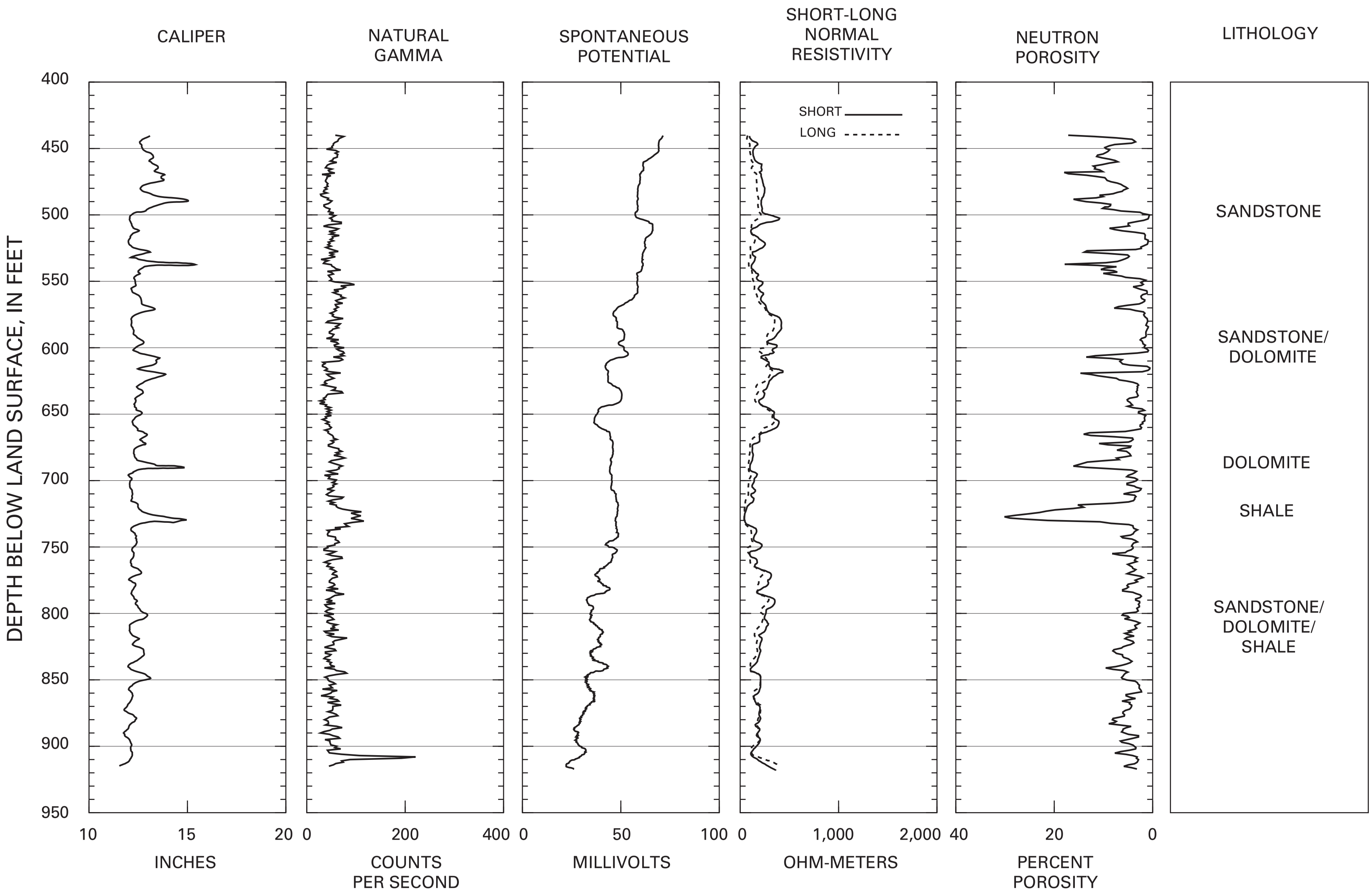


Figure 12.--Water-level trends of the Minnelusa and Madison aquifers at the Canyon Lake (CL) site, January through September 1990



Natural gamma log provided by the U.S. Geological Survey Borehole Research Group, Denver, Colorado. Spontaneous potential, resistivity, and neutron porosity logs provided by Goodwell, Inc., Upton, Wyoming.

Figure 13.--Natural gamma, spontaneous potential, short-long normal resistivity, and neutron porosity logs for Rapid City well #6 (RC-6), illustrating sandstone beds of the upper Minnelusa aquifer and lower Minnelusa confining bed.



Natural gamma log provided by the U.S. Geological Survey Borehole Research Group, Denver, Colorado. Spontaneous potential, resistivity, and neutron porosity logs provided by Goodwell, Inc., Upton, Wyoming.

Figure 14.--Caliper, natural gamma, spontaneous potential, short-long normal resistivity, and neutron porosity logs for Rapid City well #5 (RC-5), illustrating sandstone beds of the upper Minnelusa aquifer and lower Minnelusa confining bed.

Porosity values for the Minnelusa aquifer and lower Minnelusa Formation confining bed were estimated from the neutron porosity logs obtained at wells RC-6 and RC-5 (fig. 15). The neutron porosity log was corrected for shale content of the sample volume of the rock using the natural gamma log to distinguish between noneffective and effective porosities. The porosity of the rock measured by the neutron porosity log will be masked by the shale or clay (noneffective) porosity. Noneffective shale (clay) porosities may range from 20 to 60 percent as measured by the uncorrected neutron porosity log.

From interpretation of the borehole geophysical logs (figs. 13, 14, and 15), the sandstone beds in wells RC-6 and RC-5 contain the Minnelusa aquifer. The lower Minnelusa confining bed is composed of the sandstone, dolomite, and shale beds of the Minnelusa Formation. The corrected neutron porosity log in figure 15 helps determine the porosity distribution within the formation and provides the estimates of effective porosities of the aquifer and confining bed.

At well RC-6, the average effective porosity of the sandstone beds that make up the Minnelusa aquifer between 280 to 660 ft is about 10 percent. A relatively thick, poorly cemented sandstone bed from about 520 to 590 ft has an average effective porosity of about 15 percent. The lower Minnelusa confining bed (660-838 ft) has an average effective porosity of about 5 percent (figs. 13 and 15). The lower Minnelusa confining bed contains sandstone beds that have a large enough effective porosity to indicate they probably transmit water (fig. 15).

The Minnelusa aquifer at well RC-5 primarily consists of sandstone beds from 440 to 550 ft with an average effective porosity of about 5 percent. A relatively thick, poorly cemented sandstone bed from 460 to 500 ft has an effective porosity of about 10 percent (figs. 14 and 15).

The sandstones, dolomites, and shales that make up the Minnelusa confining bed from about 550 to 915 ft have an average effective porosity of about 5 percent. Many small intervals in this confining bed contain porosities less than 1 percent (figs. 14 and 15).

Madison Aquifer

Porosity for the Madison aquifer at wells RC-6 and LC was estimated from resistivity logs because neutron logs were not run in the Madison Limestone. Resistivity logs were not run at well RC-5; however, well LC is 685 ft away and porosity at the two sites is inferred to be similar (fig. 9).

The use of resistivity logs (short- and long-normal) to estimate the porosity of a rock formation requires a number of assumptions. The first assumption is that the short- or long-normal log resistivity values are equal to the actual formation resistivity (R_t). In actuality the short- or long-normal resistivity values may overestimate or underestimate the actual formation resistivity depending on combinations of electrode spacing and formation properties. Paillet and others (1990) discuss the relation of the short- and long-normal resistivity values to R_t, and when one or the other is a better estimate of R_t values. Along with determining R_t values, an estimate of the resistivity of the saturating fluid (R_w) is needed. Paillet and others (1990) and Keys (1990) describe methods to estimate R_w using spontaneous potential logs. An alternative method of estimating R_w is

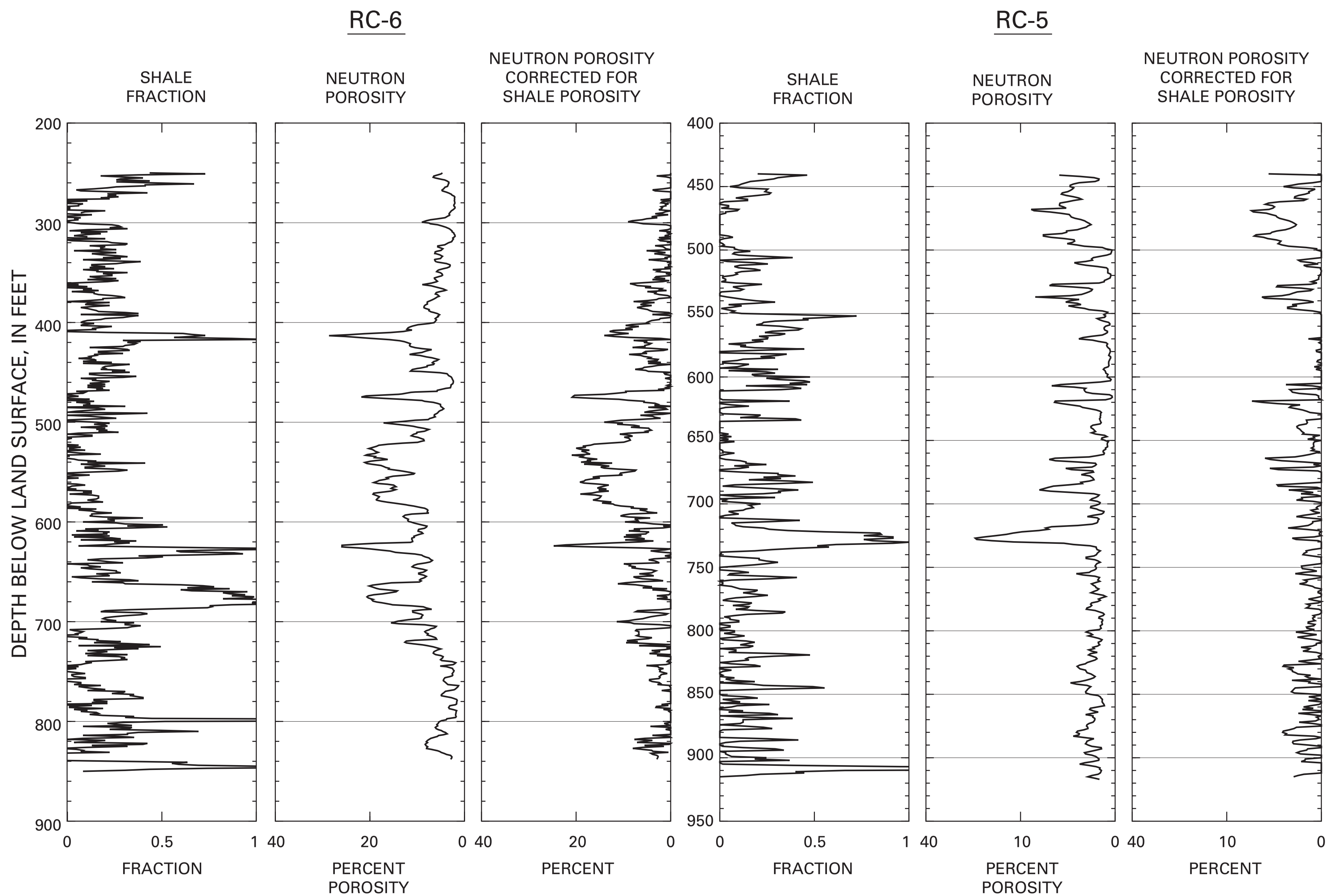


Figure 15.--Shale fraction estimated from the gamma log and then used to correct the neutron porosity log to estimate porosity for the Minnelusa Formation in Rapid City wells #6 (RC-6) and #5 (RC-5).

used in this report. When water-quality data are obtained, R_w (ohm-meters) can be related to specific conductance (microsiemens per centimeter) according to the relation (Keys, 1990).

$$R_w = \frac{10,000}{\text{Specific conductance}}$$

Specific conductance of the water from wells RC-6 and LC is about 333 microsiemens per centimeter; therefore, R_w for the Madison aquifer is equal to 30 ohm-meters at these sites. The ratio of R_t/R_w can be related to the formation factor (F), which is a property of the pore network according to the equation (Paillet and others, 1990).

$$F = \frac{R_t}{R_w}$$

The formation factor (F) can then be related to porosity (ϕ) of the formation using a generalized version of Archie's law for carbonates through the following equation (Archie, 1942).

$$F = \frac{1}{\phi^n}$$

where

F = formation factor, dimensionless;
ϕ = porosity, in decimal percent; and
n = 2 for carbonates.

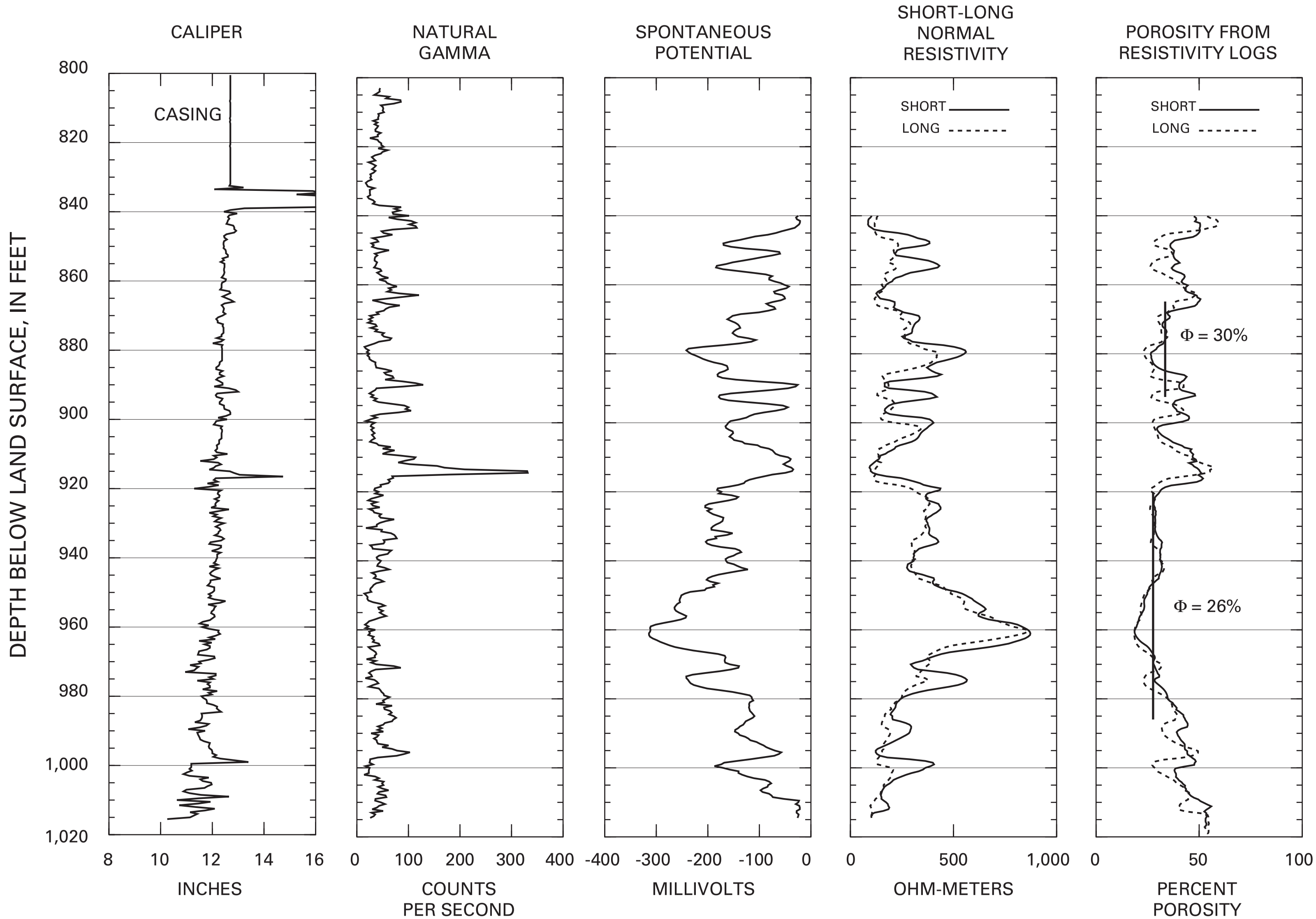
Inversion of the resistivity logs at wells RC-6 and LC provided estimates of the porosity in the Madison aquifer (figs. 16 and 17). The short-normal and long-normal resistivity logs provided similar estimates of porosity at well RC-6 (fig. 16), whereas the long-normal resistivity log at well LC was interpreted to be a better estimate of R_t than the short normal. This was because the long-normal log measures a greater volume of rock with the included fractures and solution openings than the short-normal (fig. 5).

The average effective porosity (ϕ) of the Madison aquifer for the entire borehole at wells RC-6 and LC (fig. 17) was similar at about 35 percent, as compared to about 10 percent in the Minnelusa aquifer at well RC-6. These effective porosity values determined for the Minnelusa and Madison aquifers are in the range of porosities that have been reported for sandstones and karstic limestones (Kruseman and de Ridder, 1991).

Transmissivity and Storage Coefficient

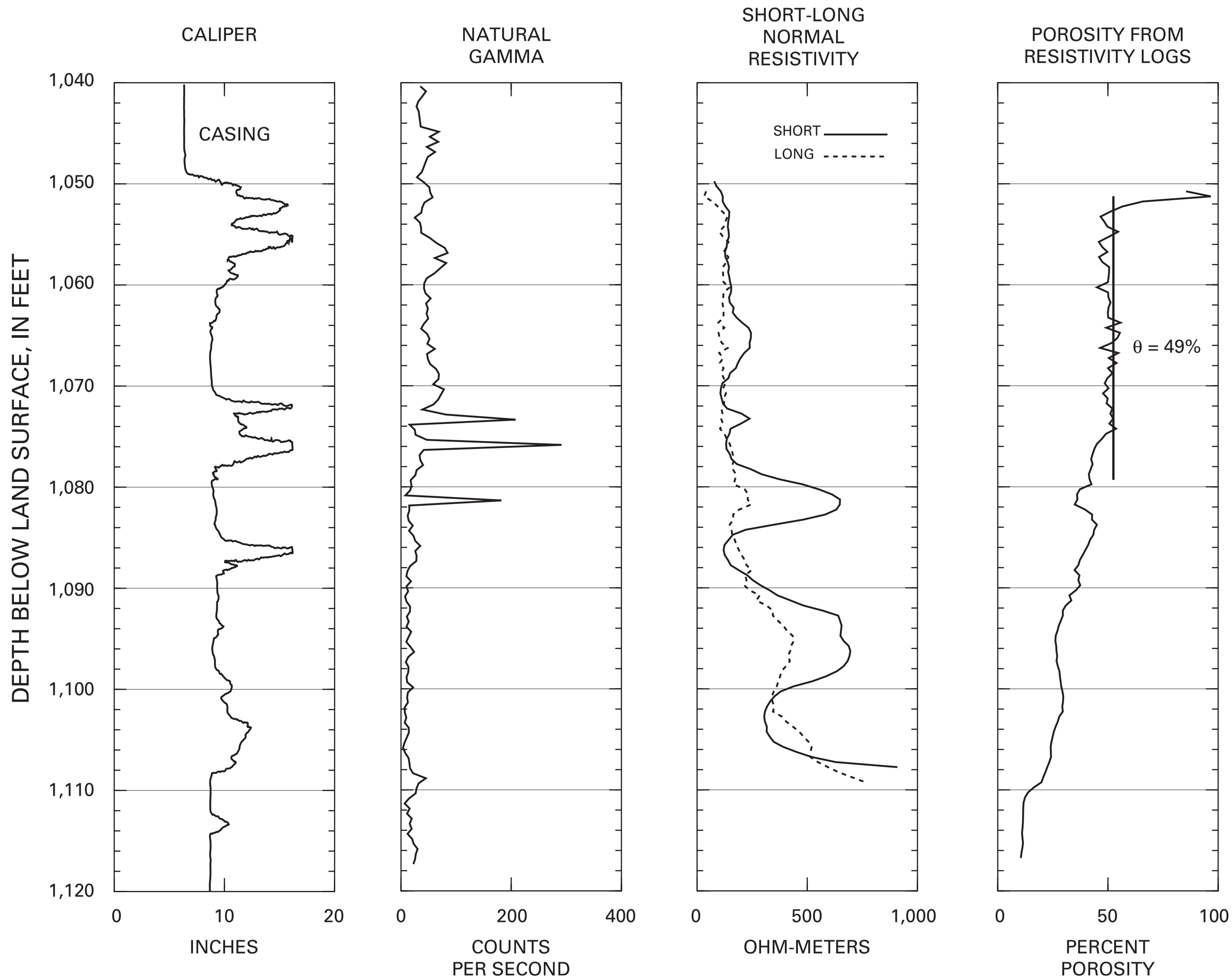
Well RC-6

A 4-day, constant-discharge aquifer test conducted at well RC-6 was designed to determine the transmissivity and storage coefficient of the Madison aquifer and to investigate the hydraulic connection of the Minnelusa and Madison aquifers. The pumping rate in the production well was maintained within ±5 percent of 680 gal/min. The drawdown phase of the aquifer test started on April 2, 1990, and ended 4 days later on April 6, when the pump was shut off and recovery was started. During the recovery period, data were collected until the water levels in the production well and observation wells were at the pre-aquifer test level.



Natural gamma, spontaneous potential, and resistivity logs were provided by the U.S. Geological Borehole Geophysical Research Group, Denver, Colorado.

Figure 16.--Caliper, natural gamma, spontaneous potential, short-long normal resistivity logs, and porosity calculated from the resistivity logs, for an interval of the Madison aquifer in Rapid City well #6 (RC-6).



Natural gamma and resistivity logs provided by the U.S. Geological Survey Borehole Geophysical Research Group, Denver, Colorado.

Figure 17.--Caliper, natural gamma, short-long normal resistivity logs, and porosity calculated from the resistivity logs, for an interval of the Madison aquifer at the Lime Creek (LC) observation well.

Twelve observation wells in the Minnelusa and Madison aquifers were measured during the aquifer test. Observation wells CQ-1 (Minnelusa aquifer) and CQ-2 (Madison aquifer) were the only two observation wells to respond to pumping of well RC-6. Radial distance from well RC-6 to well CQ-1 is 2,930 ft and to well CQ-2 is 2,919 ft. The aquifer-test data (table 5, Supplemental Data section at the end of this report) were used to determine the transmissivity and storage coefficient of the Minnelusa and Madison aquifers and the vertical hydraulic conductivity and specific storage of the lower Minnelusa confining bed.

Drawdown corrections

In application of analytical techniques to determine the hydraulic properties of an aquifer, the drawdown data must be corrected to account for the effects of partial penetration of the production well or observation wells. In addition, drawdown data must be corrected to account for external influences such as barometric pressure.

Well RC-6 penetrates 450 ft of the Madison Limestone. Because the thickness of the Madison aquifer in the Rapid City area is about 200 ft, this probably represents the entire thickness of the aquifer and for analysis purposes, well RC-6 is assumed to be fully penetrating. The observation wells in the Minnelusa aquifer (CQ-1) and Madison aquifer (CQ-2) are partially penetrating. Partial penetration induces vertical flow components in the well and causes increased head loss (greater drawdown). Partial-penetration effects decrease with radial distance from the production well and if the aquifer is isotropic and homogeneous, then partial-penetration effects can be considered to be negligible at a radial distance of 1.5 to 2 times the saturated thickness (Todd, 1980). The observation wells CQ-1 and CQ-2 are a distance of about six times the formation thickness from the production well; therefore, no correction was made for partial penetration.

It is known that water levels in wells completed in confined aquifers will fluctuate due to changes in atmospheric (barometric) pressure. An increase in barometric pressure causes a water-level decline, and a decrease in barometric pressure causes a water-level rise. Without applying this correction to aquifer-test data, an erroneous interpretation could result.

The response of water level to barometric pressure changes (barometric efficiency) in wells CQ-1, CQ-2, Sioux Park #1 (SP-1), Sioux Park #2 (SP-2), CL-1, and CL-2 (fig. 9, table 3) were established prior to aquifer testing by recording barometric pressure and water levels. From the known relation between change in barometric pressure and change in water level, the actual drawdown during the aquifer test was corrected for barometric pressure changes (Ferris and others, 1962; Kruseman and de Ridder, 1991).

Analytical model, assumptions, and boundary conditions

The choice of the theoretical model of ground-water flow is a crucial step in interpreting aquifer-test data. If the wrong model is chosen, the calculated hydraulic characteristics of an aquifer will be incorrect. Based on drillers' logs and geophysical well-log analysis (presented in the previous section), the Madison aquifer at well RC-6 and surrounding area has such a large fracture and solution opening density (secondary porosity) that ground-water flow at this site in response to pumping is considered analogous to movement through a porous media. Thus, the aquifer properties determined in the analysis are those for an equivalent porous media (Long and others, 1982).

The analytical model used to evaluate the aquifer-test data for RC-6 is based on Neuman and Witherspoon's method of determining the hydraulic properties of leaky two-aquifer systems (Neuman and Witherspoon, 1969a, 1969b). Their analytical model of ground-water flow assumes the production well is a line sink, completely penetrates the pumped aquifer (Madison), and discharges at a constant rate. The unpumped aquifer (Minnelusa) is not a constant head source; drawdown in the Minnelusa aquifer is due to pumping in the Madison aquifer. Ground-water flow is vertical in the confining bed (lower Minnelusa Formation) and is horizontal in the Minnelusa and Madison aquifers. The Minnelusa and Madison aquifers are homogeneous, isotropic, horizontal, and of infinite radial extent. A schematic of the conceptual model of flow for the two-aquifer system is presented in figure 18.

The equations governing ground-water flow, including boundary conditions and initial conditions are modified from Neuman and Witherspoon (1969a, 1969b) and numerical inversion by Moench and Ogata (1984):

Aquifer 1 = Subscript 1 (pumped aquifer)
Aquifer 2 = Subscript 2 (unpumped aquifer)
z = vertical distance above bottom of confining bed

PUMPED AQUIFER

$$\frac{\partial^2 s_1}{\partial r^2} + \frac{1}{r}\frac{\partial s_1}{\partial r} + \frac{K'_v}{T_1}\left.\frac{\partial s'}{\partial z}\right|_{z=0} = \frac{1}{\frac{K_1}{Ss_1}}\frac{\partial s_1}{\partial t}$$

$$s_1\,(r,0)=0$$

$$s_1\,(\bullet\,,t)=0$$

$$\lim_{r\to 0} r\frac{\partial s_1}{\partial r} = -\frac{Q}{2\pi T_1}$$

CONFINING BED

$$\frac{\partial^2 s'}{\partial z^2} = \frac{1}{\frac{K'_v}{Ss'}}\frac{\partial s'}{\partial t}$$

$$s'\,(r,z,0)=0$$

$$s'\,(r,0,t)=s_1\,(r,t)$$

$$s'\,(r,b',t)=s_2\,(r,t)$$

UNPUMPED AQUIFER

$$\frac{\partial^2 s_2}{\partial r^2} + \frac{1}{r}\frac{\partial s_2}{\partial r} - \frac{K'_v}{T_2}\left.\frac{\partial s'}{\partial z}\right|_{z=b'} = \frac{1}{\frac{K_2}{Ss_2}}\frac{\partial s_2}{\partial t}$$

$$s_2\,(r,0)=0$$

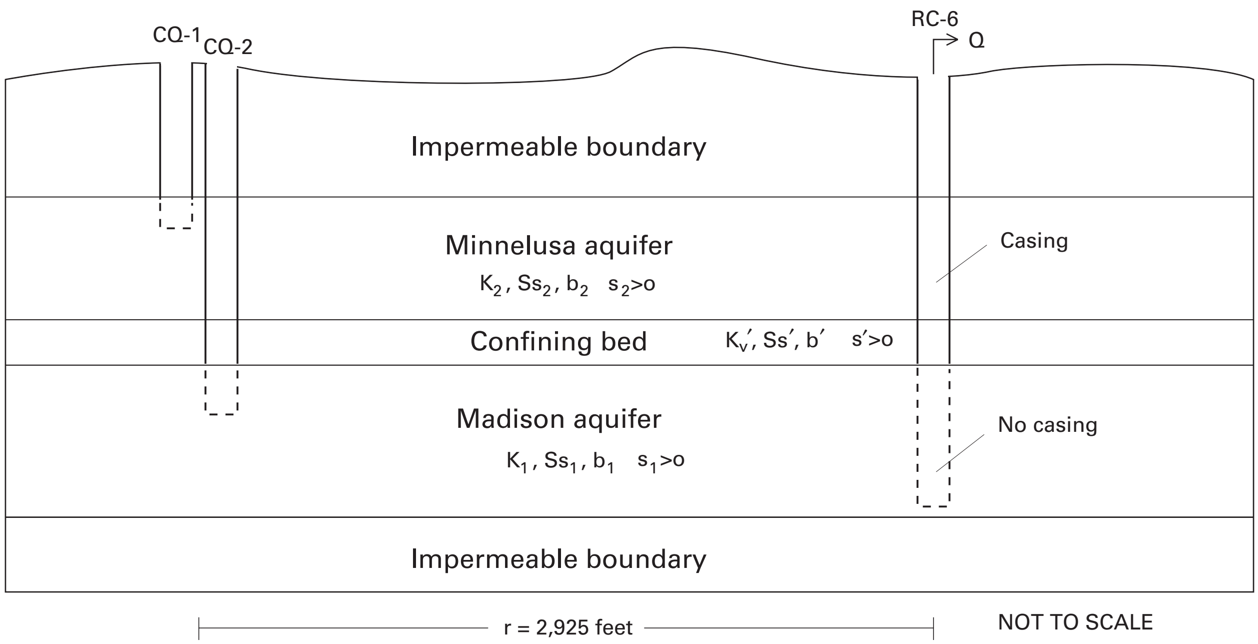
$$s_2\,(\bullet\,,t)=0$$

$$\lim_{r\to 0} \frac{\partial s_2}{\partial r} = 0$$

Applying LaPlace and Hankel transformations, the ground-water flow equation can be reduced to six (6) dimensionless variables:

$$t_D = \frac{K_1 t}{Ss_1 r^2} \qquad s_D = \frac{4\pi K_1 b_1}{Q}\, s_1 \qquad \beta_{11} = \frac{K'_v r}{4 K_1 b_1}\left(\frac{K_1 Ss'}{Ss_1 K'_v}\right)^{\frac{1}{2}}$$

$$\frac{r}{B_{11}} = \frac{r}{b_1}\left(\frac{K'_v b_1}{b' K_1}\right)^{\frac{1}{2}} \qquad \frac{r}{B_{21}} = \frac{r}{b_2}\left(\frac{K'_v b_2}{b' K_2}\right)^{\frac{1}{2}} \qquad \beta_{21} = \frac{K'_v r}{4 K_2 b_2}\left(\frac{K_2 Ss'}{Ss_2 K'_v}\right)^{\frac{1}{2}}$$



EXPLANATION

RC-6	Production well
CQ-1	Minnelusa aquifer (unpumped) observation well
CQ-2	Madison aquifer (pumped) observation well
Q	Constant discharge rate, cubic feet per day
K_2	Hydraulic conductivity of the unpumped aquifer, feet per day
Ss_2	Specific storage of the unpumped aquifer, foot^{-1}
b_2	Thickness of the unpumped aquifer, feet
s_2	Drawdown in the unpumped aquifer, feet
K'_v	Vertical hydraulic conductivity of the confining bed, feet per day
Ss'	Specific storage of the confining bed, foot^{-1}
b'	Thickness of the confining bed, feet
s'	Drawdown in the confining bed, feet
K_1	Hydraulic conductivity of the pumped aquifer, feet per day
Ss_1	Specific storage of the pumped aquifer, foot^{-1}
b_1	Thickness of the pumped aquifer, feet
s_1	Drawdown in the pumped aquifer, feet
r	Radial distance to the observation wells, feet

Figure 18.--Conceptual model of the multiple aquifer system for RC-6 aquifer test.

where

Q = constant discharge, cubic feet per day;
K_2 = hydraulic conductivity of the unpumped aquifer, feet per day;
Ss_2= specific storage of the unpumped aquifer, $foot^{-1}$;
b_2 = thickness of the unpumped aquifer, feet;
s_2 = drawdown in the unpumped aquifer, feet;
T_2 = transmissivity of the unpumped aquifer, feet squared per day;
K_v'= vertical hydraulic conductivity of the confining bed, feet per day;
Ss'= specific storage of the confining bed, $foot^{-1}$;
b' = thickness of the confining bed, feet;
s' = drawdown in the confining bed, feet;
K_1 = hydraulic conductivity of the pumped aquifer, feet per day;
Ss_1= specific storage of the pumped aquifer, $foot^{-1}$;
b_1 = thickness of the pumped aquifer, feet;
s_1 = drawdown in the pumped aquifer, feet;
T_1 = transmissivity of the pumped aquifer, feet squared per day;
r = radial distance to the observation wells, feet;
t_D = dimensionless time;
s_D = dimensionless drawdown;
t = time, days; and
z = vertical distance above the bottom of the confining bed, feet.

Type curves used for analysis were developed by a numerical inversion of the Laplace transform solution given by Moench and Ogata (1984) for the Neuman and Witherspoon two-aquifer system (1969a, 1969b). The solution to drawdown in the unpumped and pumped aquifers are controlled by four dimensionless parameters where: β_{11} and r/B_{11} control the pumped aquifer type curve and β_{21} and r/B_{21} control the unpumped-aquifer type curve. Dimensionless drawdown (s_D) in the pumped aquifer is independent of β_{21} and r/B_{21} for small values of dimensionless time (t_D). However, drawdown in the unpumped aquifer at all values of time are dependent on β_{11}, r/B_{11}, β_{21}, and r/B_{21}. At large values of time, drawdown in the pumped aquifer is significantly affected by drawdown in the unpumped aquifer.

Because of the large number of unknown parameters in the six dimensionless equations needed to build the type curves for this solution, the initial values used for thicknesses of the aquifers and confining beds (b_2, b',b_1, horizontal hydraulic conductivity (K_2 and K_1), and specific storage of the aquifers and confining bed (Ss_2, Ss', Ss_1) were obtained from the borehole geophysical well logs. Specific storage is defined as the storage coefficient of an aquifer or confining bed divided by its thickness. Specific storage has units of $foot^{-1}$.

The initial values of horizontal hydraulic conductivity of K_2 (Minnelusa aquifer) and K_1 (Madison aquifer) were determined from quantitative interpretation of the geophysical logs at RC-6 using equations relating porosity to hydraulic conductivity developed by Jorgensen (1988) and modified by Paillet and others (1990). Initial values for specific storage of the Minnelusa aquifer (Ss_2), lower Minnelusa confining bed (Ss'), and Madison aquifer (Ss_1) were estimated by using an equation given in Lohman (1972) relating porosity to the storage coefficient. The value for the storage coefficient was then divided by the thickness to obtain specific storage. Thickness for the Minnelusa aquifer (b_2) is 400 ft, lower Minnelusa confining bed (b') is 200 ft, and the Madison aquifer (b_1) is 200 ft.

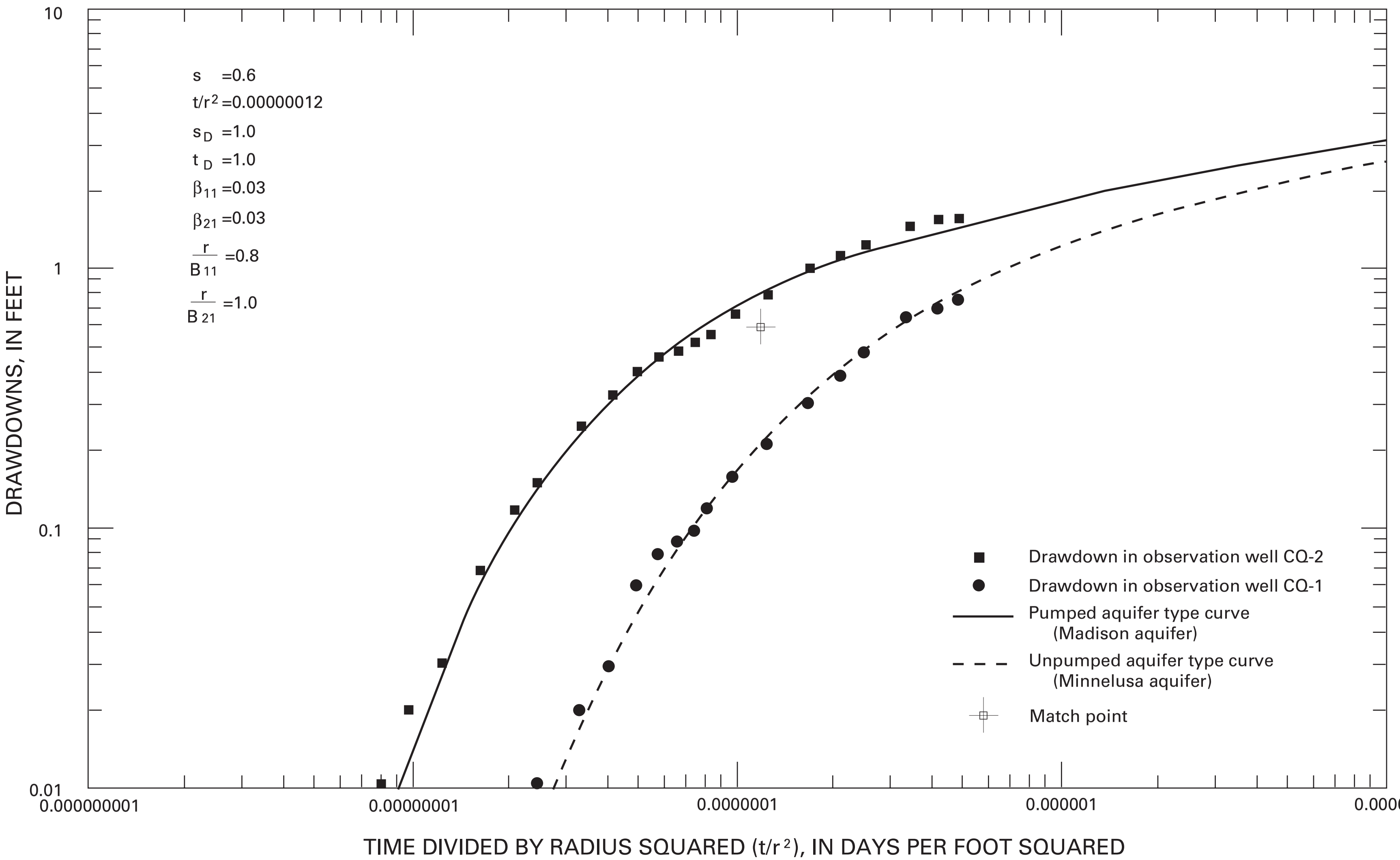


Figure 19.--Comparison of drawdown data for observation wells CQ-1 (Minnelusa aquifer) and CQ-2 (Madison aquifer) from RC-6 aquifer test superimposed on dimensionless drawdown (s_D) versus dimensionless time (t_D) type curves for the unpumped aquifer (Minnelusa aquifer) and pumped aquifer (Madison aquifer).

The values of hydraulic conductivity (K_2, K_v', K_1) and specific storage (Ss_2, Ss', Ss_1) in the aquifers and confining bed were varied to change the magnitudes of β_{11}, r/B_{11}, β_{21}, and r/B_{21} to produce the best type-curve fit for the aquifer-test data (fig. 19). The hydraulic properties of the Minnelusa and Madison aquifers and lower Minnelusa confining bed were estimated from this best-fit result. For the Minnelusa aquifer, hydraulic properties of transmissivity (T or K_2b_2) and storage coefficient (S or Ss_2b_2) calculated from the analysis of the aquifer test conducted at well RC-6 were T = 12,000 ft^2/d and S = 3 x 10^{-3}. The calculated values for the Minnelusa confining bed were specific storage (Ss') = 2 x 10^{-7} ft^{-1} and the vertical hydraulic conductivity (K_v') = 0.3 ft/d. The hydraulic properties of the Madison aquifer calculated from this aquifer test were T (or K_1b_1) = 17,000 ft^2/d and S (or $Ss_1b_{1)}$ = 2 x 10^{-3} (figs. 18 and 19).

Well RC-5

A 7-day constant-discharge aquifer test conducted at well RC-5, which began on April 24, 1990, was designed to determine the transmissivity and storage coefficient of the Madison aquifer and to investigate the hydraulic connection of the Minnelusa and Madison aquifers. In addition, the test was designed to determine if flow at Cleghorn Springs (fig. 9) was reduced by pumping well RC-5.

The pumping rate in the production well was maintained within ±4 percent of 1,700 gal/min until May 1, 1990, when the drawdown phase of the aquifer test ended. The pump was shut off and recovery was started. During the recovery period, data were collected until water levels in the production well and observation wells were at the pre-aquifer test levels.

Fourteen observation wells in the Madison and Minnelusa aquifers were measured during the duration of the aquifer test. Observation wells LC, SP-2, CL-2, BHPL (Black Hills Power and Light production well), and CHLN-2 (Chapel Lane #2), all in the Madison aquifer (fig. 9, table 2), responded to pumping well RC-5. Radial distances from well RC-5 to the observation wells that responded to pumping are given in table 3. No wells in the Minnelusa aquifer responded to pumping. The data (table 6, Supplemental Data section at the end of this report) from this test were used to determine the transmissivity and storage coefficient of the Madison aquifer, and vertical hydraulic conductivity (K_v') of the confining bed (lower Minnelusa Formation) separating the Minnelusa and Madison aquifers.

Since 1987, discharge at Cleghorn Springs has been monitored at three streamflow-gaging stations (0612600, 0612700, and 06412800) at the Cleghorn Springs State Fish Hatchery. Flow measured at the gaging stations may be affected by the hatchery operation, which uses flow from Cleghorn Springs and runoff from rainfall.

During the aquifer test, there was no measurable decrease in spring discharge at the three Cleghorn Springs gaging stations. Flow from Cleghorn Springs increased during the aquifer test, which probably was due to runoff from rainfall that started on April 23 and lasted throughout the duration of the aquifer test.

Drawdown corrections

Similar to the aquifer test conducted at well RC-6, the drawdown data were corrected for external influences and partial penetration of the production well and observations wells. After the drawdown data were corrected, analytical techniques to determine the hydraulic properties of the aquifer near well RC-5 were applied.

Well RC-5 penetrates about 380 ft of the Madison Limestone, which probably is close to the entire thickness of the formation at this site. Since the aquifer is contained in the upper 100 to 200 ft of the formation, well RC-5 is assumed to be fully penetrating. All of the observation wells used during the aquifer test partially penetrate the aquifer except wells LC and RC-6. Because all of the partially penetrating wells used in the aquifer test are at a radial distance greater than twice the saturated thickness of the Madison aquifer, partial-penetration effects are assumed to be negligible for analysis purposes (Todd, 1980).

Drawdown data in observation wells used during the aquifer test were analyzed and corrected for changes in barometric pressure. The barometric efficiency was determined for the observation wells similar to the method used for the observation wells from the RC-6 aquifer test. The actual drawdown during the aquifer test was corrected for water-level changes due to barometric pressure changes (Ferris and others, 1962; Kruseman and de Ridder, 1991).

Analytical model, assumptions, and boundary conditions

The choice of the theoretical model of ground-water flow is as crucial for this aquifer test as it was for the aquifer test at well RC-6. If the wrong model is chosen, the calculated hydraulic characteristics of the aquifer will be incorrect. Based on drillers' logs and geophysical well-log analysis (presented in the previous section), the secondary porosity of the Madison aquifer at well RC-5 and surrounding area is made up of a large fracture and solution opening density (fig. 5). Ground-water flow at this site in response to pumping is assumed to be analogous to movement through a porous media.

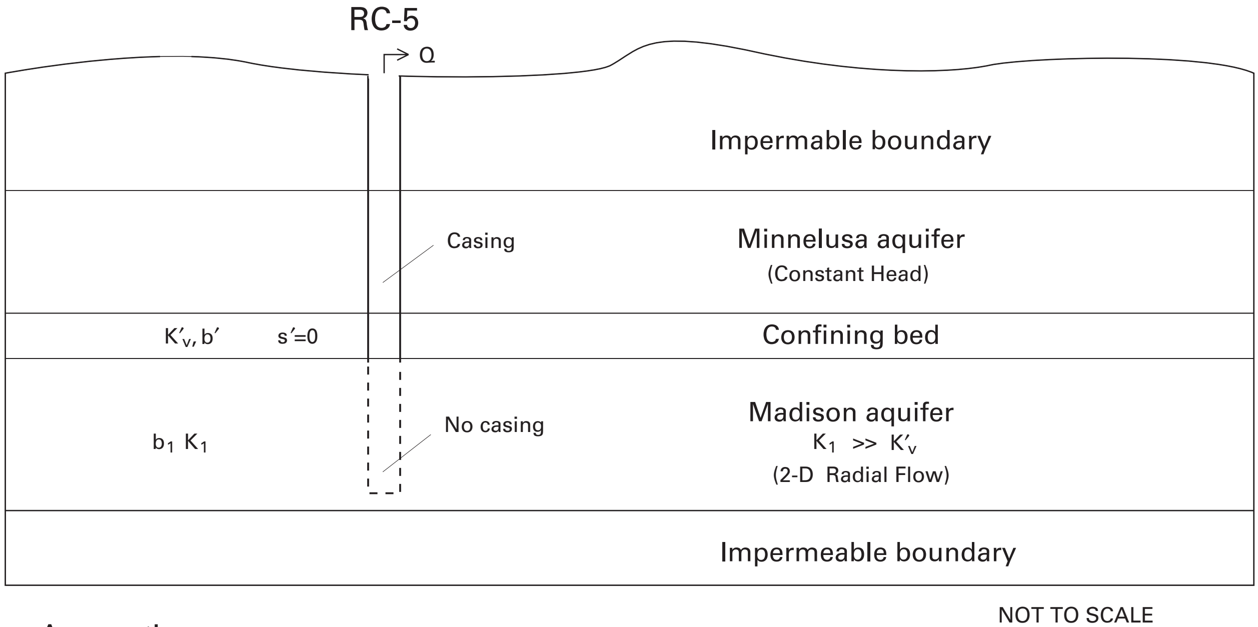
The analytical model used to evaluate the aquifer-test data is based on the Hantush and Jacob (1955) equation to describe drawdown near a fully penetrating production well in a leaky confined aquifer with leakage proportional to drawdown (fig. 20). The equation Hantush and Jacob (1955) developed to solve for drawdown is:

$$s = \frac{Q}{4\pi T} W(\mu, r/B)$$

$$W(\mu, r/B) = \int_{\mu}^{\infty} \left(\frac{1}{z}\right) e^{-z-\frac{r^2}{4B^2 z}} dz$$

$$\mu = r^2 S/4Tt$$

$$B = \sqrt{\frac{Tb'}{K'_v}}$$



Assumptions:

1. Well discharges at a constant rate (Q).
2. Well is of infinitesimal diameter and fully penetrates the aquifer.
3. Madison aquifer is overlaid everywhere by a confining bed having a uniform thickness (b') and vertical hydraulic conductivity (K'_v).
4. Confining bed is overlaid by a infinite constant-head plane source.
5. Hydraulic gradient across confining bed changes instantaneously with a change of head in the aquifer (no release of water from storage in the confining bed).
6. Flow in the aquifer is two-dimensional and radial in horizontal plane and flow in the confining bed is vertical. This assumption is approximated closely where the hydraulic conductivity of the aquifer (K_1) is sufficiently greater than the confining bed (K'_v).

Differential equation describing nonsteady radial flow in a homogeneous isotropic aquifer with leakage proportional to drawdown for aquifer test RC-5.

$$\frac{\partial^2 s_1}{\partial r^2} + \frac{1}{r}\frac{\partial s_1}{\partial r} - \frac{s_1 K'_v}{T b'} = \frac{S}{T}\frac{\partial s_1}{\partial t}$$

Boundary and initial conditions for aquifer test RC-5.

$s(\infty, t) = 0 \quad t \geq 0$	Initial drawdown is 0 everywhere in the Madison aquifer and drawdown is small at the large distances from the pumping well RC-5
$Q = \begin{cases} 0, & t < 0 \\ \text{constant} > 0, & t \geq 0 \end{cases}$	Discharge from RC-5 is constant and begins at t=0
$\lim_{r \to 0} r \frac{\partial s}{\partial r} = -\frac{Q}{2\pi T}$	Near RC-5 during pumping the flow toward the well is equal to discharge

Figure 20.--Conceptual model of the multiple aquifer system for RC-5 aquifer test (hydrology modified from M.S. Hantush and C.E. Jacob, 1955; J.E. Reed, 1980).

where

- s = drawdown in observation well, in feet;
- r = distance from production well to observation well, in feet;
- Q = pumping rate, in cubic feet per day;
- t = time after pumping started, in days;
- T = transmissivity of the pumped aquifer, in square feet per day;
- S = storage coefficient (volume of water instantaneously released from storage) of the pumped aquifer, dimensionless;
- K_v' = vertical hydraulic conductivity of the confining bed, in feet per day;
- b' = thickness of the confining bed, in feet; and
- z = variable of integration.

The Hantush-Jacob (1955) equation is based on the assumptions presented in figure 20. Assumption 5 usually will be true if the confining bed is thin, there is a slow decline in head of the pumped aquifer, and if there is a large hydraulic diffusivity (K_v'/Ss') in the confining bed (Cooper, 1963; Peters, 1987).

The field-data plots from five observation wells (LC, SP-2, BHPL, CL-2, and CHLN-2) are superimposed on the leaky confined aquifer type curves (fig. 21). The match points and coordinate values for each of the five curve matches are as follows:

Observation well	s (ft)	t/r^2 (minutes/ft^2)	W(μ, r/B)	1/μ	r/B
LC	16	2.4×10^{-5}	1	1	0.1
SP-2	10	2.4×10^{-5}	1	1	.3
BHPL	5.0	2.4×10^{-5}	1	1	.4
CL-2	.65	3.0×10^{-6}	1	1	.3
CHLN-2	.65	3.0×10^{-6}	1	1	.3

The hydraulic properties of the Madison aquifer and confining bed (lower Minnelusa Formation) were calculated by the following equations:

$$T = \frac{Q}{4\pi s} W(\mu, r/B),$$

$$K_v' = \frac{Tb'}{B^2}, \text{ and}$$

$$S = \frac{4Tt\mu}{r^2}$$

Results of calculations for all five observation well data sets are presented in table 4. In calculating K_v' for the confining bed, an average confining-bed thickness (b') of 200 ft was used. These thicknesses are based on borehole geophysical log analysis of production wells RC-6 and RC-5 and observation wells LC, CL-2, and CQ-2.

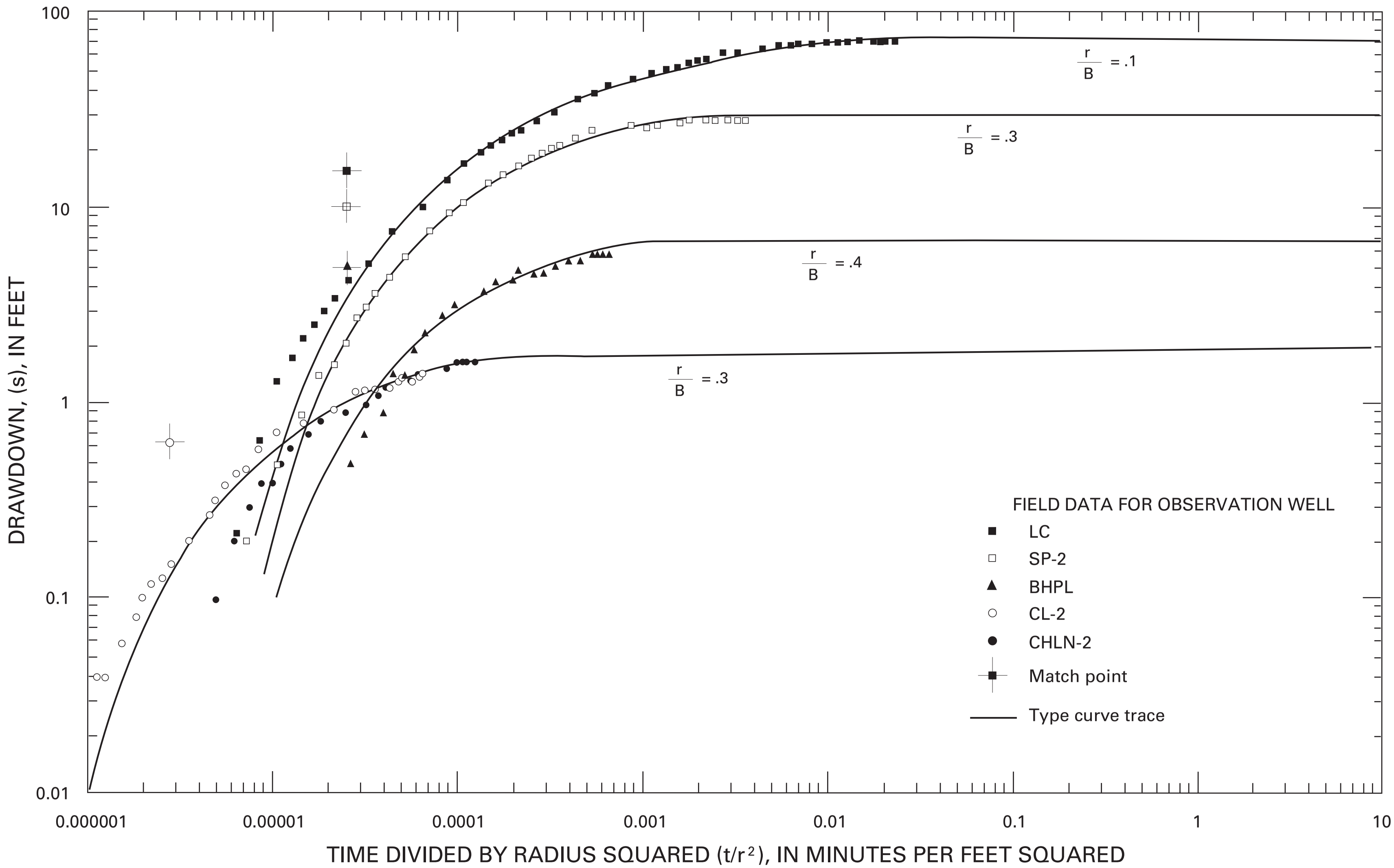


Figure 21.--Drawdown data for observation wells LC, SP-2, BHPL, CL-2, AND CHLN-2 superimposed on the best fit leaky confined aquifer type curve match for RC-5 aquifer test.

Table 4.--Hydraulic properties of the Madison aquifer determined from the analysis of the aquifer test conducted at well RC-5

[r, radial distance between the pumping well (RC-5) and observation well; T, transmissivity of the Madison aquifer; S, storage coefficient of the Madison aquifer; K_v', vertical hydraulic conductivity of the confining bed (lower Minnelusa Formation). Values for hydraulic properties are rounded to two significant digits]

Observation well	r (ft)	T (ft^2/d)	S dimensionless	K_v' (ft/d)
LC	685	1,600	1.0×10^{-4}	6.8×10^{-3}
SP-2	1,700	2,600	1.0×10^{-4}	1.6×10^{-2}
BHPL	3,950	5,200	1.0×10^{-4}	1.1×10^{-2}
CL-2	8,900	40,000	3.3×10^{-4}	9.1×10^{-3}
CHLN-2	11,700	40,000	3.3×10^{-4}	5.3×10^{-3}

The five field-data plots (fig. 21) would theoretically fall on the same curve if transmissivity was not anisotropic or leakage did not occur. The displacement of the plots from one another results because of directional transmissivities in the Madison aquifer and because leakage through the confining bed does not equally affect drawdown in the five wells.

Anisotropic analysis

The analysis of aquifer-test data from the RC-5 aquifer test (fig. 21) shows that transmissivity is not equal in all directions (anisotropic). Anisotropy is common in water-laid sedimentary and stratified formations and in aquifers that are fractured or composed of solution features (Madison aquifer).

Aquifers that are composed of fractures or solution features tend to be anisotropic. The differences in transmissivity of an anisotropic aquifer will control the shape of the drawdown cone. In anisotropic aquifers, the drawdown cone will form ellipses instead of concentric circles. Consequently, there will be a major and a minor direction (axes) of anisotropy and therefore a major axis and a minor axis of transmissivity. The transmissivity in the direction of the major axis may be 2 to 10 times greater than transmissivity in the direction of the minor axis (Hantush and Thomas, 1966) or more.

Methods to analyze anisotropy in leaky confined aquifers, where anisotropy is in the horizontal plane, are given by Hantush (1966a, 1966b) and further explained in Kruseman and de Ridder (1991). Hantush (1966b) presents the following equations to analyze for anisotropy on the horizontal plane, where the coordinate axes of x and y are parallel to the principal directions of anisotropy in a leaky confined aquifer:

$$s = \frac{Q}{4\pi T_e} W(\mu_{xy}, r/B')$$

$$\mu_{xy} = \frac{r^2 S}{4tT_r}$$

where

- s = drawdown in observation well, in feet;
- r = distance from production well to observation well, in feet;
- Q = pumping rate, in cubic feet per day;
- t = time after pumping started, in days;
- $T_e = \sqrt{T_x T_y}$ = effective transmissivity, in feet squared per day;
- T_x = transmissivity in the major direction of anisotropy, in feet squared per day;
- T_y = transmissivity in the minor direction of anisotropy, in feet squared per day;
- S = storage coefficient, dimensionless;
- T_r = transmissivity in the r direction, with r direction making the angle θ with the x axis, in feet squared per day;
- $B' = \frac{\sqrt{T_r b'}}{K_y'}$ dimensionless;
- b' = thickness of the confining bed, in feet; and
- K_v'= vertical hydraulic conductivity of the confining bed, in feet.

To determine the major and minor axes of transmissivity in the Madison aquifer from the RC-5 aquifer test, an anisotropic analysis was conducted using the aquifer-test data. The three closest observation wells (LC, SP-2, BHPL) to RC-5 are each in a different radial line and presented the best data for the anisotropic analysis. Because the ratios of T_i/S_i and B_i'/B_i' in the coefficients a and b are approximately equal, the following equation was used to determine the directions of the major and minor axes of transmissivity (Hantush, 1966b).

$$\tan 2\theta = \frac{-2\ (b-1)\ \sin^2 \alpha - (a-1)\sin^2 \beta}{(b-1)\ \sin 2\alpha - (a-1)\sin 2\beta}$$

where

- θ = two roots, one being the major axis of transmissivity (x axis) and the other the minor axis of transmissivity (y axis);
- α = angle to the second radial line of observation wells;
- β = angle to the third radial line of observation wells;
- $a = 0.5[(T_1/S_1/T_2/S_2) + (B_1'/B_1')^2]$; and
- $b = 0.5[(T_1/S_1/T_3/S_3) + (B_1'/B_3')^2]$

T_1, S_1, B_1' was set equal to BHPL; T_2, S_2, B_2' was equal to LC; and T_3, S_3, B_3' was equal to SP-2. After θ is determined, the ratio of T_x/T_y may be determined with the following equations (Hantush, 1966b):

$$n = \frac{\cos^2(\theta+\beta) - a\ \cos^2\ \theta}{a\ \sin^2\ \theta - \sin^2(\theta+\alpha)}$$

or

$$n = \frac{\cos^2(\theta+\alpha) - b\ \cos^2\ \theta}{b\ \sin^2\ \theta - \sin^2(\theta+\beta)}$$

where the value of n greater than 1 locates the major axis of transmissivity and is the ratio of T_x/T_y and the value of n less than 1 locates the minor axis.

Knowing the ratio of T_x/T_y and using the following equations after Hantush (1966b) where:

$$n = T_x/T_y = (T_e/T_y)^{1/2}$$

$$T_y = \frac{T_e}{\sqrt{n}}$$

and

$$T_x = \frac{(T_e)^2}{T_y}$$

T_e is equal to the average effective transmissivity of the ellipse. For this analysis, T_e was estimated using all of the wells from the isotropic analysis (fig. 21, table 4) and is the area-weighted average of transmissivity. T_e was calculated to be about 8,500 ft^2/d.

The ratio of T_x/T_y and the value for T_x are then used to determine the directional transmissivities (T_r) using the following equation (Hantush, 1966b):

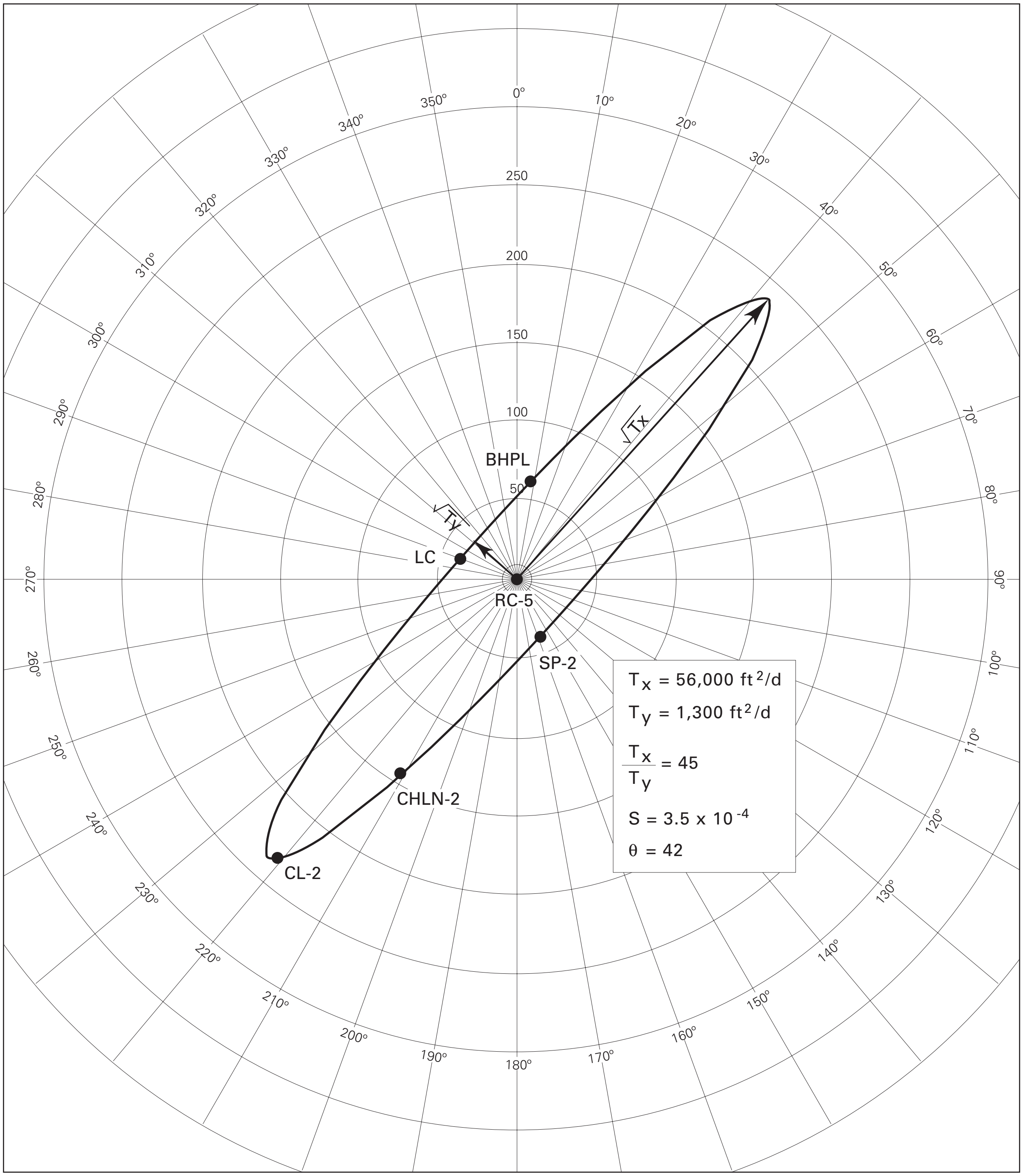
$$T_r = T_x/[\cos^2 \theta + (T_x/T_y) \sin^2 \theta]$$

where

- T_r = transmissivity in the r direction, with the r direction making the angle θ with the x axis, in feet squared per day;
- T_x = transmissivity in the major direction of anisotropy, in feet squared per day;
- T_y = transmissivity in the minor direction of anisotropy, in feet squared per day.

The results of this analysis of the aquifer test conducted at well RC-5 are presented in figure 22. The major axis of transmissivity is 56,000 ft^2/d at an angle of 42° east of north. The minor axis of transmissivity is 1,300 ft^2/d at an angle of 48° west of north. The average value of S from the isotropic analysis of the aquifer-test data is 3.5×10^{-4}. The average vertical hydraulic conductivity of the Lower Minnelusa confining bed is 9.6×10^{-3} ft/d.

The major axis of transmissivity intersects Cleghorn Springs and the valley where Rapid Creek enters the City of Rapid City. Comparison of the potentiometric contours of the Madison aquifer with the direction and shape of the theoretical transmissivity ellipse shows a good fit between contours of 3,500 ft and 3,400 ft. The low gradient between these contours supports the presence of a zone of high permeability in the direction of about 42° east of north, due to a fracture zone or extensive solution openings (fig. 23).



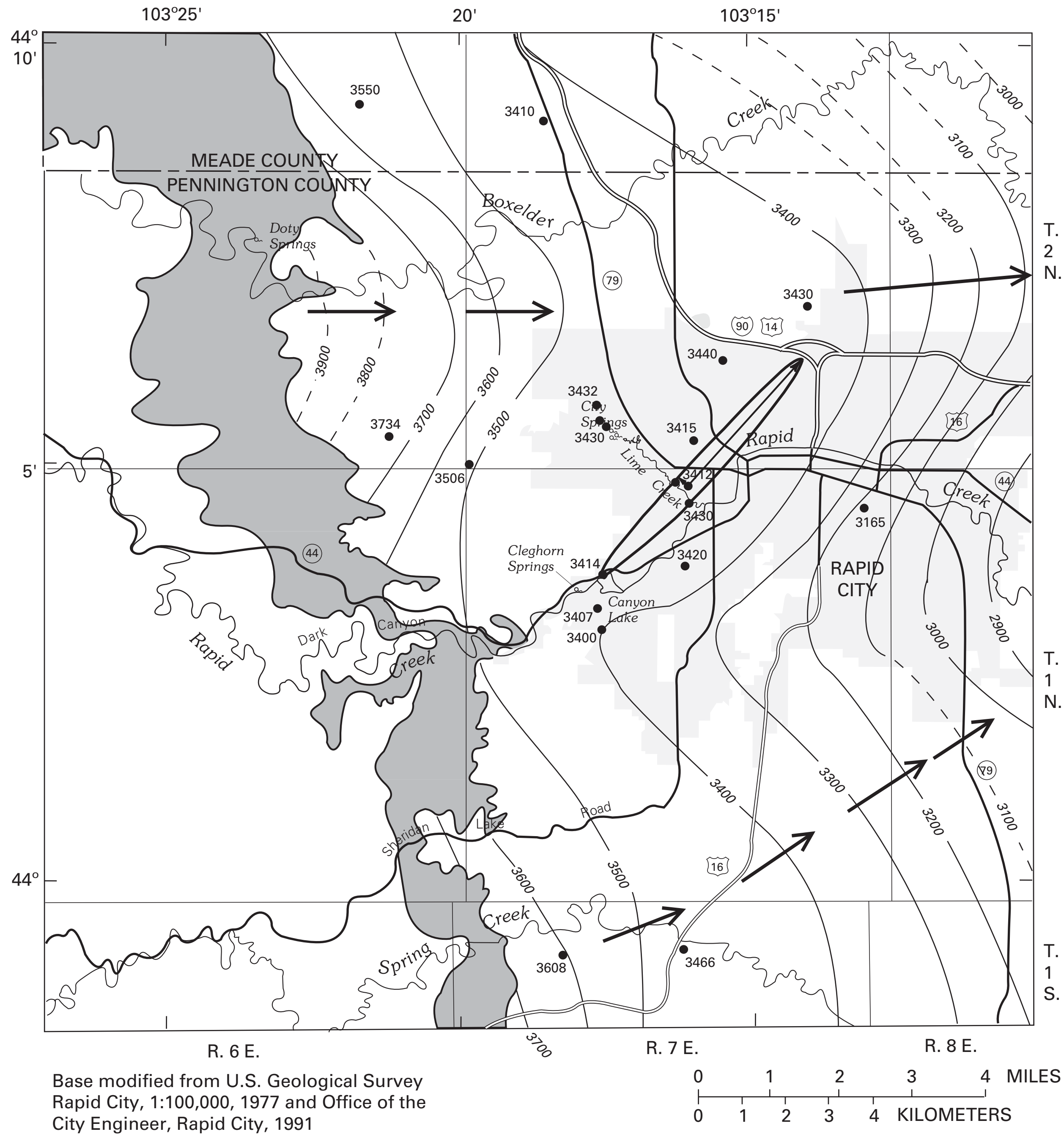
EXPLANATION

● LC DIRECTIONAL TRANSMISSIVITY ($\sqrt{Tr}$) AND WELL IDENTIFICATION

——— THEORETICAL TRANSMISSIVITY ELLIPSE, ($\sqrt{Tr}$)

0 50 100 $(ft^2/d)^{1/2}$

Figure 22.--Theoretical transmissivity ellipse showing the angle and magnitude of the major and minor axes of transmissivity from the anisotropic analysis of RC-5 aquifer test.



EXPLANATION

SURFACE EXPOSURE OF THE MADISON LIMESTONE

3400 — POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells, spring of 1991. Dashed where approximately located. Contour interval 100 feet. Datum is sea level.

DIRECTION OF GROUND-WATER FLOW

TRANSMISSIVITY ELLIPSE--See figure 22

WELL COMPLETED IN THE MADISON AQUIFER

Figure 23.--Overlay of the major and minor axes of transmissivity calculated from RC-5 aquifer test on the potentiometric-surface maps of the Madison aquifer.

SUMMARY AND CONCLUSIONS

This study consisted of investigating the hydrogeology, analyzing borehole geophysical well logs, designing and conducting two constant-discharge aquifer tests, and interpreting aquifer-test data in the Madison aquifer system in western Rapid City. The hydraulic properties of the Madison aquifer were investigated to determine transmissivity (T) and storage coefficient (S). In addition, from the aquifer-test analysis, transmissivity and storage coefficient were determined for the Minnelusa aquifer, while both vertical hydraulic conductivity (K_v') and specific storage (Ss') were estimated for the Minnelusa confining bed.

The Minnelusa Formation is overlain by a confining layer that varies in thickness from 0 ft at the surface exposure west of Canyon Lake to as much as 1,800 ft near the east edge of the study area. This confining layer is composed of Permian-, Triassic-, and Jurassic-age shales and siltstones with some interbedded sandstones, limestones, and gypsum.

The Minnelusa aquifer usually consists of sandstone beds in the upper 200 to 400 ft of the formation. These sandstone beds in the upper part of the formation are the most widely utilized aquifer in the study area. The altitude of the potentiometric surface of the Minnelusa aquifer ranges from about 3,500 ft above sea level in the west to about 3,300 ft above sea level in the eastern part of the study area.

The lower part of the Minnelusa Formation consists of interbedded sandstones and dolomitic limestones. This layer is a confining or semi-confining bed separating the Minnelusa aquifer from the Madison aquifer.

The altitude of the top of the Madison Limestone ranges from about 4,500 ft above sea level where it crops out at the surface in the western part of the study area to about 300 ft above sea level in the eastern part of the area. The Madison aquifer is contained within the upper 100 to 200 ft of the formation, where fractures or solution features have increased the permeability of the limestone or dolomite beds.

The altitude of the potentiometric surface of the Madison aquifer ranges from about 3,900 ft above sea level in the western part of the study area to about 2,900 ft in the eastern part. The potentiometric surface of the Madison aquifer generally is above land surface in the western part of the study area and is below the land surface in the eastern part. Ground-water flow generally is from west to east.

A quantitative analysis of borehole geophysical well logs from three wells was made to determine the location and thickness of the sandstone beds in the Minnelusa aquifer, the thickness of the lower Minnelusa confining bed, and the thickness of the Madison aquifer. Interpretation of the geophysical well logs also provided information on the nature of the fracture and solution openings of the Madison aquifer as an aid in analyzing the aquifer tests.

Porosity values for the Minnelusa aquifer, lower Minnelusa confining bed, and Madison aquifer were obtained from quantitative analysis of neutron and resistivity logs. The average porosity at the two aquifer-test sites is about 10 percent in the Minnelusa aquifer, 5 percent in the lower Minnelusa confining bed, and 35 percent in the Madison aquifer.

Two aquifer tests were conducted in the Madison aquifer system during the spring of 1990 to determine the hydraulic properties of transmissivity (T) and storage coefficient (S). The degree of hydraulic connection between the Minnelusa and Madison aquifers also was studied.

The first aquifer test was a 4-day constant-discharge test conducted at production well RC-6. Twelve observation wells in the Minnelusa and Madison aquifers were measured during the duration of the aquifer test. The analytical model used to evaluate the aquifer-test data is based on Neuman and Witherspoon's method of determining the hydraulic properties of leaky two-aquifer systems assuming the fracture and solution-opening network is equivalent to a porous media. Hydraulic properties of transmissivity (T) and storage coefficient (S) from analysis of the aquifer test conducted at well RC-6 for the Minnelusa aquifer were T = 12,000 ft^2/d and S = 3×10^{-3}. The calculated values for the Minnelusa confining bed were specific storage (Ss’) = 2×10^{-7} ft^{-1} and vertical hydraulic conductivity of the confining bed (K_v’) = 0.3 ft/d. The hydraulic properties of the Madison aquifer calculated from this aquifer test were T = 17,000 ft^2/d and S = 2×10^{-3}.

The second aquifer test was a 7-day constant-discharge test conducted at production well RC-5. Fourteen observation wells in the Minnelusa and Madison aquifers were measured during the duration of the aquifer test. The analytical model used to evaluate the aquifer-test data is based on Hantush and Jacob's method for leaky confined aquifers with no storage in the confining bed and assuming the fracture and solution-opening network is equivalent to a porous media. The analysis of data from the RC-5 aquifer test showed that transmissivity in the Madison aquifer is anisotropic, that is not equal in all radial directions. A method developed by Hantush was used to determine the direction of radial anisotropy and magnitude of the major and minor axes of transmissivity. The major axis of transmissivity is 56,000 ft^2/d at an angle of 42° east of north. The minor axis of transmissivity is 1,300 ft^2/d and is at an angle of 48° west of north. The average value of S from the isotropic analysis of the aquifer-test data was 3.5×10^{-4}. The average vertical hydraulic conductivity (K_v’) of the lower Minnelusa confining bed was 9.6×10^{-3} ft/d. The major axis of transmissivity intersects Cleghorn Springs and the valley where Rapid Creek enters the City of Rapid City and explains the shape of the potentiometric contours in the Madison aquifer.

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SUPPLEMENTAL DATA

Table 5.--Data for the RC-6 aquifer test

Production well RC-6		Observation well CQ-1		Observation well CQ-2	
Pumping rate (Q) = 680 gallons per minute		Distance from production well (r) = 2,930 feet		Distance from production well (r) = 2,919 feet	
Time since start of pumping (minutes)	Drawdown (feet)	Time since start of pumping (minutes)	Drawdown[1] (feet)	Time since start of pumping (minutes)	Drawdown[1] (feet)
0	0	0	0	0	0
4	151.2	4	0	4	0
5	197.2	5	0	5	0
6	202.9	6	0	6	0
7	208.8	7	0	7	0
8	200.7	8	0	8	0
9	190.9	9	0	9	0
10	194.2	10	0	10	0
15	206.6	15	0	15	0
20	223.6	20	0	20	0
30	244.6	30	0	30	0
40	260.1	40	0	40	0
50	268.4	50	0	50	0
60	277.2	60	0	60	0
90	311.0	90	0	90	0
100	314.0	100	0	100	.01
120	319.4	120	0	120	.02
150	337.4	150	0	150	.03
200	350.7	200	0	200	.07
250	359.7	250	0	250	.12
300	358.7	300	.01	300	.15
400	370.7	400	.02	400	.25
500	380.7	500	.03	500	.33
600	384.2	600	.06	600	.40
700	387.2	700	.08	700	.46
800	393.5	800	.09	800	.49
900	395.5	900	.10	900	.53
1,000	394.2	1,000	.12	1,000	.57
1,200	399.3	1,200	.16	1,200	.69
1,500	408.9	1,500	.21	1,500	.80
2,000	415.7	2,000	.31	2,000	1.01
2,500	417.0	2,500	.40	2,500	1.13
3,000	419.3	3,000	.49	3,000	1.27
4,000	417.4	4,000	.66	4,000	1.49
5,000	425.9	5,000	.72	5,000	1.57
5,760	426.4	5,760	.78	5,760	1.58

[1]Corrected for changes in barometric pressure.

Table 6.--Data for the RC-5 aquifer test

Production well RC-5		Observation well LC		Observation well SP-2	
Pumping rate (Q) = 1,700 gallons per minute		Distance from production well (r) = 685 feet		Distance from production well (r) = 1,700 feet	
Time since start of pumping (minutes)	Drawdown (feet)	Time since start of pumping (minutes)	Drawdown[1] (feet)	Time since start of pumping (minutes)	Drawdown[1] (feet)
0	0	0	0	0	0
1	76.0	1	0	1	0
2	94.0	2	0	2	0
3	98.0	3	0	3	0
4	104.2	4	.7	4	0
6	101.1	6	1.9	6	0
7	107.5	7	2.3	7	0
8	111.4	8	2.8	8	0
9	114.7	9	3.2	9	0
10	115.5	10	3.7	10	0
12	121.0	12	4.6	12	0
15	126.5	15	5.5	15	0
20	132.8	20	8.3	20	.2
30	144.7	30	10.8	30	.5
40	152.3	40	15.2	40	.9
50	156.7	50	18.0	50	1.4
60	160.2	60	20.8	60	1.6
70	156.8	70	22.8	70	2.1
80	155.4	80	24.5	80	2.8
90	158.5	90	26.1	90	3.2
100	161.6	100	27.2	100	3.7
120	168.0	120	30.2	120	4.6
150	170.4	150	34.2	150	5.8
200	176.5	200	39.2	200	7.9
300	180.5	300	46.1	300	10.9
400	183.4	400	50.5	400	13.4
500	190.3	500	54.5	500	15.0
600	190.0	600	57.4	600	17.1
700	194.4	700	59.8	700	18.5
800	196.6	800	61.9	800	19.6
900	197.6	900	63.5	900	21.0
1,000	201.2	1,000	65.1	1,000	21.7
1,200	200.2	1,200	68.8	1,200	23.3
1,500	207.9	1,500	69.9	1,500	24.5
2,000	200.1	2,000	72.7	2,000	25.3
2,500	202.0	2,500	73.4	2,467	26.5
3,021	206.5	2,920	74.3	2,960	26.5
3,545	206.4	3,017	74.6	3,013	26.8
3,960	214.4	3,720	75.3	3,345	26.8
4,560	215.3	4,520	75.7	4,500	27.7
5,106	214.6	5,115	77.2	5,015	28.6
5,585	212.8	5,775	77.1	6,086	28.8

Table 6.--Data for the RC-5 aquifer test--Continued

Production well RC-5, Pumping rate (Q) = 1,700 gallons per minute		Observation well LC, Distance from production well (r) = 685 feet		Observation well SP-2, Distance from production well (r) = 1,700 feet	
Time since start of pumping (minutes)	Drawdown (feet)	Time since start of pumping (minutes)	Drawdown[1] (feet)	Time since start of pumping (minutes)	Drawdown[1] (feet)
6,090	212.0	6,697	77.5	7,008	28.8
6,488	212.5	7,990	77.1	8,002	28.8
7,000	209.3	8,635	77.1	9,045	28.8
7,500	208.3	8,700	77.1	10,080	28.8
8,000	209.5	9,050	77.5		
8,580	208.7	10,080	76.7		
9,090	210.7				
9,540	209.7				
10,080	208.0				

Table 6.--Data for the RC-5 aquifer test--Continued

Observation well BHPL Distance from production well (r) = 3,950 feet		Observation well CL-2 Distance from production well (r) = 8,900 feet		Observation well CHLN-2 Distance from production well (r) = 11,700 feet	
Time since start of pumping (minutes)	Drawdown[1] (feet)	Time since start of pumping (minutes)	Drawdown[1] (feet)	Time since start of pumping (minutes)	Drawdown[1] (feet)
0	0	0	0	0	0
100	0	100	0	100	0
150	0	150	0	150	.04
180	0	180	0	180	.04
220	0	220	0	220	.06
260	0	260	0	260	.08
280	0	280	0	280	.10
315	0	315	0	315	.12
360	0	360	0	360	.13
400	.5	400	.1	400	.15
500	.7	500	.2	500	.20
600	.9	600	.3	600	.27
700	1.4	700	.4	700	.32
800	1.4	800	.4	800	.38
900	1.9	900	.5	900	.44
1,040	2.3	1,012	.6	1,010	.46
1,300	2.8	1,285	.7	1,200	.58
1,500	3.2	1,515	.8	1,500	.69
2,070	3.7	2,020	.9	2,100	.78
2,480	4.2	2,575	1.0	2,600	.82
3,000	4.4	3,000	1.1	2,996	.91
3,180	4.9	3,339	1.2	4,000	1.13
4,000	4.9	4,485	1.3	4,500	1.15
4,500	4.9	5,018	1.4	5,025	1.16
5,100	5.3	7,010	1.5	6,000	1.18
5,986	5.5	8,022	1.6	7,036	1.29
6,970	5.5	8,512	1.6	7,350	1.33
7,980	5.8	9,035	1.6	7,600	1.33
8,465	5.8	10,080	1.6	8,014	1.28
8,960	5.8			8,500	1.35
9,480	5.8			9,025	1.39
10,080	5.8			10,080	1.40

[1]Corrected for changes in barometric pressure.