Prepared in cooperation with the Wyoming State Engineer's Office

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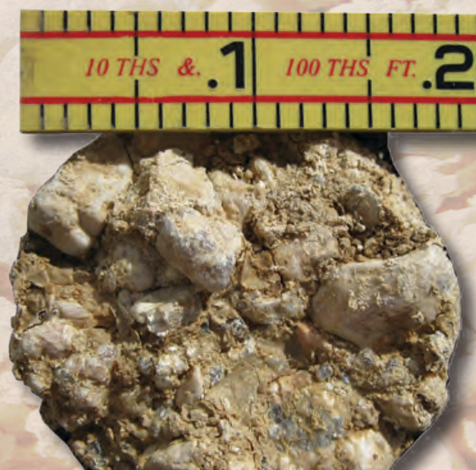

Scientific Investigations Report 2013–5242

U.S. Department of the Interior
U.S. Geological Survey

Front cover. Upper left: Steel bit and outer core barrel used to collect sediment core from the Ogallala Formation and White River Group.
Upper right: Sediment core collected from the Chadron Formation of the White River Group at 447 feet below land surface.
Lower right: Tri-cone drill bit used to drill wells.

Back cover. Upper right: Sediment core collected from the Ogallala Formation from 26.5 to 27 feet below land surface.
Lower left: Hydraulic mud-rotary drill rig used to collect sediment cuttings and core and install monitoring wells.

Geologic and Hydrogeologic Characteristics of the Ogallala Formation and White River Group, Belvoir Ranch near Cheyenne, Laramie County, Wyoming

By Timothy T. Bartos, Sharon F. Diehl, Laura L. Hallberg, and Daniel M. Webster

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U.S. Geological Survey
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Seth Davidson of the U.S. Geological Survey (USGS) installed and maintained instrumentation used to continuously measure groundwater levels in two monitoring wells installed for this study and prepared preliminary groundwater-level hydrographs; Kirk Miller and Scott Edmiston (USGS) also maintained groundwater-level instrumentation and prepared the groundwater-level hydrographs presented in this report. Rick Healy (USGS) analyzed unsaturated-zone sediment samples for chloride and assisted with use of the water-table fluctuation method to estimate groundwater recharge. Bob Michel (USGS) analyzed unsaturated-zone sediment samples for tritium. Colleague reviews by Janet Carter (USGS) and Pete McMahon (USGS) improved the quality of the report. Suzanne Roberts (USGS) is thanked for creating the illustrations.

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Plate

[in pocket]

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Conversion Factors and Datums

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
acre	4,047	square meter (m^2)
	Volume	
gallon (gal)	3.785	liter (L)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Radioactivity	
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
gallons per day per foot [(gal/d)/ft]	12.42	liters per day per meter [(L/d)/m]

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
micrometer (micron; µm)	0.00003937	inch (in.)
angstrom (Å)	0.000000003937	inch (in.)
meter (m)	3.281	foot (ft)
	Volume	
milliliter (mL)	0.03382	ounce, fluid (fl. oz)
liter (L)	0.2642	gallon (gal)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)/ft^2$]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (μg/L).

Abbreviated Water-Quality Units

μg/L	micrograms per liter
μS/cm	microsiemens per centimeter at 25 degrees Celsius
mg/L	milligrams per liter
NTRU	nephelometric turbidity ratio units
pCi/L	picocuries per liter
TU	tritium units

Chemical Abbreviations

$\delta^{18}O$	oxygen-18/oxygen-16 isotopic ratio
$\delta^{2}H$	deuterium/protium isotopic ratio
Al	aluminum
Ca	calcium
$CaCO_3$	calcium carbonate
Fe	iron
$FeTiO_3$	ilmenite
H	hydrogen
^{3}H	tritium
HCl	hydrochloric acid
Hornblende	$(Ca,Na)_2(Mg,Fe,Al)_5(Al,Si)_8O_{22}$
K	potassium
Mg	magnesium
Na	sodium
O	oxygen
Sericite	$K(Al,Fe,Mg)_2(SiAl)_4O_{10}(OH)_2 \cdot H_2O)$

SF_6	sulfur hexafluoride
Si	silica
Ti	titanium

Symbols and Abbreviations

<	less than
°2θ	degrees 2-theta
Å	angstrom
®	registered trademark
ADAPS	Automated Data Processing System
BLS	below land surface
CFC	chlorofluorocarbon
δ	delta
DO	dissolved oxygen
DOC	dissolved organic carbon
E	estimated concentration
EDS	energy-dispersive x-ray
GMWL	global meteoric water line
GRO	gasoline-range organics
GWSI	Groundwater Site Inventory database
HAL	Health Advisory Level
ICDD	International Center for Diffraction Data
IRL	interim reporting level
LRL	laboratory reporting level
LT-MDL	long-term method detection level
MCL	Maximum Contaminant Level
MRL	minimum reporting level
NWIS	National Water Information System
NWQL	National Water Quality Laboratory of U.S. Geological Survey
PVC	polyvinyl chloride
QA	quality assurance
QC	quality control
RASA	Regional Aquifer System Analysis (program of the U.S. Geological Survey)
RPD	relative percent difference
rpm	revolutions per minute

SEM	scanning electron microscope
SMCL	Secondary Maximum Contaminant Level
SP	spontaneous potential
SSLC	sample-specific critical level
SWAT	Soil and Water Assessment Tool
TCE	trichloroethene
TDS	total dissolved solids
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VSMOW	Vienna Standard Mean Ocean Water
VOC	volatile organic compound
WSEO	Wyoming State Engineer's Office
XRD	x-ray diffraction

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By Timothy T. Bartos, Sharon F. Diehl, Laura L. Hallberg, and Daniel M. Webster

Abstract

The geologic and hydrogeologic characteristics of Tertiary lithostratigraphic units (Ogallala Formation and White River Group) that typically compose or underlie the High Plains aquifer system in southeastern Wyoming were described physically and chemically, and evaluated at a location on the Belvoir Ranch in Laramie County, Wyoming. On the basis of this characterization and evaluation, three Tertiary lithostratigraphic units were identified using physical and chemical characteristics determined during this study and previous studies, and these three units were determined to be correlative with three identified hydrogeologic units composing the groundwater system at the study site—a high-yielding aquifer composed of the entire saturated thickness of the heterogeneous and coarse-grained fluvial sediments assigned to the Ogallala Formation (Ogallala aquifer); an underlying confining unit composed primarily of very fine-grained volcaniclastic sediments and mudrocks assigned to the Brule Formation of the White River Group and some additional underlying sediments that belong to either the Brule or Chadron Formation, or both (Brule confining unit); and an underlying low-yielding aquifer composed primarily of poorly sorted fluvial sediments assigned to the Chadron Formation of the White River Group (Chadron aquifer).

Despite widely varying sediment heterogeneity and consolidation, some limited hydraulic connection throughout the full vertical extent of the Ogallala aquifer was indicated but not conclusively proven by interpretation of similar chemical and isotopic characteristics, modern apparent groundwater ages, and similar hydraulic-head responses measured continuously in two Ogallala aquifer monitoring wells installed for this study at two different widely separated (83 feet) depth intervals. Additional work beyond the scope of this study, such as aquifer tests, would be required to conclusively determine hydraulic connection within the Ogallala aquifer.

Groundwater levels (hydraulic heads) measured continuously using water-level recorders in both monitoring wells completed in the Ogallala aquifer showed a consistent strong upward vertical gradient in the Ogallala aquifer, indicating the potential for water to move from deeper to shallower parts of the aquifer, regardless of the time of year and the presumed effects of pumping of public-supply and industrial wells in the area. Continuous measurement of groundwater levels in the shallowest monitoring well, installed near the water table, and examination of subsequently constructed water-level hydrographs indicated substantial groundwater recharge is likely during the spring of 2009 and 2010 from the ephemeral stream (Lone Tree Creek) located adjacent to the study site that flows primarily in response to spring snowmelt from the adjacent Laramie Mountains and surface runoff from precipitation events. Using the water-table fluctuation method, groundwater recharge was estimated to be about 13 inches for the period beginning in early October 2009 and ending in late June 2010, and about 4 inches for the period beginning in March 2011 and ending in early July 2011. Comparison of previously measured groundwater levels (hydraulic heads) and groundwater-quality characteristics in nearby monitoring wells completed in the Chadron aquifer with those measured in the two monitoring wells installed for this study in the Ogallala aquifer, combined with detailed lithologic characterization, strongly indicated the Brule confining unit hydraulically confines and isolates the Chadron aquifer from the overlying Ogallala aquifer, thus likely limiting hydraulic connection between the two units. Consequently, because of the impermeable nature of the Brule confining unit and resulting hydraulic separation of the Ogallala and Chadron aquifers, and compared with local and regional hydrostratigraphic definitions of the High Plains aquifer system, the groundwater system in Tertiary lithostratigraphic units overlying the Upper Cretaceous Lance Formation at the location studied on the Belvoir Ranch was defined as being composed of, from shallowest to deepest, the High Plains aquifer system (high-yielding Ogallala aquifer only, composed of the saturated Ogallala Formation); the Brule confining unit composed of the Brule Formation of the White River Group and an underlying fine-grained depth interval with sediments that belong to either the Brule or Chadron Formation, or both; and the low-yielding Chadron aquifer (composed of poorly sorted coarse-grained sediments with substantial fine-grained matrix material assigned to the Chadron Formation of the White River Group).

Introduction

The High Plains aquifer system is a nationally important water resource that underlies a 111-million-acre area [173,000 square miles (mi^2)] in parts of eight States—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (McGuire and others, 2003). By irrigating crops with groundwater from the High Plains aquifer system, the area that overlies the aquifer system has become one of the major agricultural regions in the world. In addition, the High Plains aquifer system also serves as the primary source of drinking water for most residents of the region. In 2000, the High Plains aquifer system had an estimated 2,980 million acre-feet (acre-ft) of drainable water in storage, making it one of the largest aquifers or aquifer systems in the world (McGuire and others, 2003).

The High Plains aquifer system is present in parts of five counties in southeast Wyoming. The High Plains aquifer system overlies an area of 8,190 mi^2 in southeast Wyoming (Gutentag and Weeks, 1980). Of Wyoming, 8 percent is located within the High Plains aquifer system, and 5 percent of the aquifer system is located within the State (Gutentag and Weeks, 1980). On the basis of withdrawals for irrigation, public-supply, and industrial use, the High Plains aquifer system is the most used source of groundwater in Wyoming (Boughton and others, 2006, fig. 4). Throughout much of southeastern Wyoming, the High Plains aquifer system is the predominant groundwater resource for agricultural (irrigation), municipal, industrial, stock, and domestic uses (Trihydro Corporation, 2006). Withdrawal of groundwater for irrigation is the largest use of water from the High Plains aquifer system in southeastern Wyoming (Trihydro Corporation, 2006).

In areas to the west, southwest, and northwest of Cheyenne city limits in Laramie County, the High Plains aquifer system is used heavily as a source of water for domestic, stock, public-supply, and industrial purposes. Production wells are located in these areas, and pumping of public-supply wells and possibly other types of wells in the area have resulted in groundwater declines (for example, Lowry and Crist, 1967; Black and Veatch, 2004; Wyoming State Engineer's Office, 2008). To improve understanding of the aquifer system in this area of heavy use, the U.S. Geological Survey (USGS), in cooperation with the Wyoming State Engineer's Office (WSEO), studied the geologic and hydrogeologic characteristics of the Tertiary lithostratigraphic units (Ogallala Formation and White River Group) composing or underlying the High Plains aquifer system.

The primary purpose of this report is to present the results of a recently completed investigation of the Tertiary lithostratigraphic units (Ogallala Formation and White River Group) composing or underlying the aquifer system on the Belvoir Ranch west of Cheyenne city limits and immediately south of an area with many production wells. The physical and chemical geologic and hydrogeologic properties of the Tertiary lithostratigraphic units composing or underlying the High Plains aquifer system were investigated using drilling, coring, detailed sediment description, monitoring well installation, and groundwater-quality sampling and analysis. The results of this detailed geologic and hydrogeologic characterization of the Ogallala Formation and White River Group are presented in this report. The report also provides an up-to-date overview of the High Plains aquifer system in southeastern Wyoming, and the findings will improve the understanding of the northern part of the High Plains aquifer system.

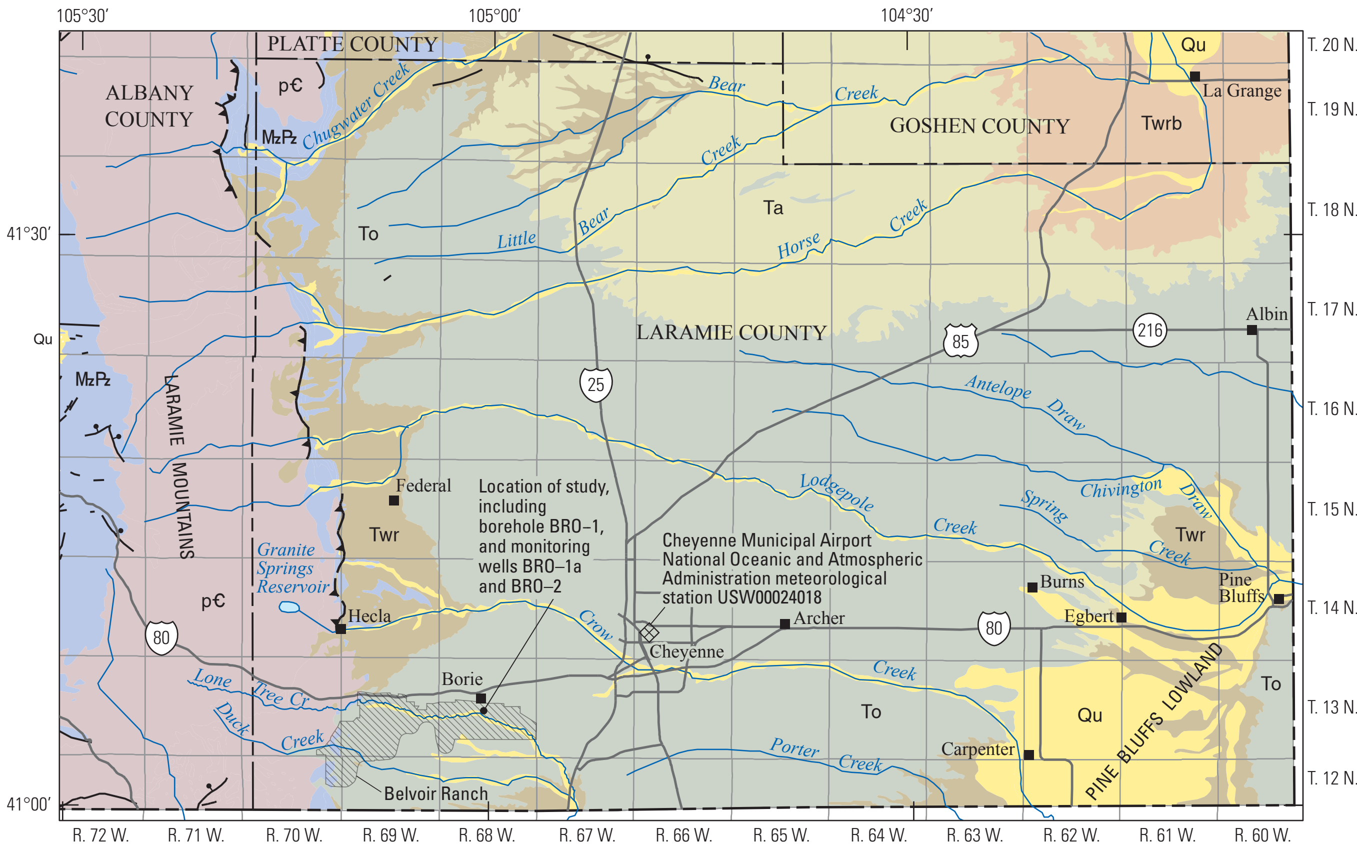
Description of Study Area

The study area is described in this section of the report. Brief descriptions of the geographic and geologic setting, production wells, and climate in the vicinity of the study area are presented.

Geographic and Geologic Setting

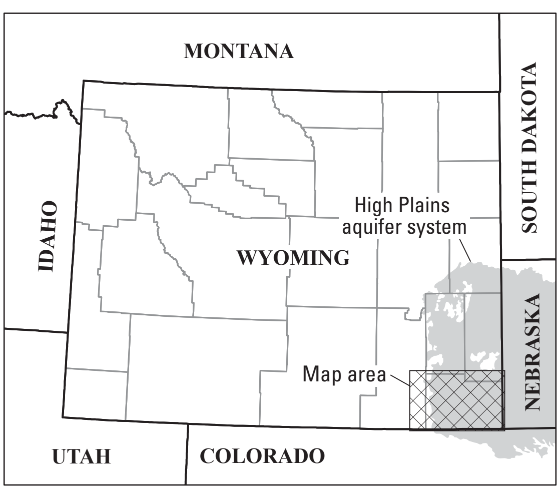
The study area is located on the Belvoir Ranch in southwestern Laramie County, about 7 miles (mi) southwest of the city of Cheyenne (fig. 1). Laramie County includes parts of the southern Rocky Mountains physiographic province (Laramie Mountains that extend along the western edge of the county and immediately west of the study area; fig. 1) and Great Plains physiographic province (most of the county) as described by Fenneman and Johnson (1946). The topography of the area east of the Laramie Mountains within the Great Plains physiographic province, which is most of Laramie County and includes the study area, has been described as a "high eastward-sloping" and "gently rolling surface of only moderate relief" underlain by Tertiary sedimentary rocks (Lowry and Crist, 1967, p. 6).

The Cheyenne area has been described as being on a broad tableland that forms part of the High Plains (physiographic feature, not aquifer system) east of the Laramie Mountains that is underlain by the Miocene-age Ogallala Formation deposited as an alluvial apron east of the Rocky Mountains (Mears, 1991; Cooley, 1991; Cooley and Crist, 1994, sheet 2). Erosion subsequent to Ogallala Formation deposition resulted in formation of "broad gravel-capped terraces and benches and shallow valleys of moderate relief that characterize the High Plains in southeastern Wyoming" (Cooley and Crist, 1994, sheet 2). Cooley and Crist (1994, sheet 2) noted that "these features include the valleys of Crow Creek and its tributaries in the Gangplank, a series of dissected slopes between the Laramie Mountains and Cheyenne." The Tertiary Ogallala Formation and White River Group or Formation south of Crow Creek form a gradual slope from the High Plains to the Laramie Mountains, and this gradual slope, referred to as the "Gangplank," is used by the Union Pacific Railroad and Interstate 80 as a route across the mountains with the least possible grade. In places along the Gangplank, Crow Creek and other streams have eroded all or parts of the Ogallala Formation.



Base modified from U.S. Bureau of the Census digital data, 2001, 1:100,000
Public Land Survey System data from Bureau of Land Management, 2007
Albers Equal-Area Conic projection
Standard parallels 29°30′ and 45°30′, central meridian 107°30′
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83)

Geology modified from Love and Christiansen, 1985



DESCRIPTION OF MAP UNITS

Lithostratigraphic units

Qu	Quaternary unconsolidated deposits—Locally part of High Plains aquifer system where saturated and hydraulically connected laterally or vertically to underlying Tertiary lithostratigraphic units
To	Ogallala Formation
Ta	Arikaree Formation
Twr	White River Group or Formation
Twrb	Brule Formation
Twrc	Chadron Formation (not shown on map)
MzPz	Mesozoic and Paleozoic sedimentary rocks
pЄ	Precambrian granitic and metamorphic rocks

(To, Ta, Twr, Twrb, Twrc: Regional Tertiary lithostratigraphic units composing or underlying the High Plains aquifer system)

EXPLANATION

Fault—Bar and ball on downthrown side

Thrust fault—Sawteeth on upper plate

Figure 1. Location of study on Belvoir Ranch, Laramie County, Wyoming, and generalized geology of the High Plains aquifer system in southeastern Wyoming.

The study area is located immediately east of the Laramie Mountains (fig. 1) on the northwestern margin of the Denver-Julesburg Basin (not shown), a large structural (synclinal) basin formed as a result of the late Cretaceous- to early Eocene-age Laramide orogeny (Snoke, 1993, and references therein). In the vicinity of the eastern flank of the Laramie Mountains, sedimentary rocks of late Cretaceous and older age are upturned sharply, but the unconformably overlying late Eocene- and early Oligocene-age White River Group or Formation and Miocene-age Ogallala Formation are upturned gently near the mountains (Cooley and Crist, 1981; Cooley and Crist, 1994, sheet 1, fig. 4).

The location selected for drilling, coring, and installation of monitoring wells in this study was located on a grass-covered terrace adjacent to and above an ephemeral stream originating in the Laramie Mountains known as Lone Tree Creek (figs. 1 and 2). Lone Tree Creek, part of the South Platte River drainage basin, flows onto the Ogallala Formation beginning west of and continuing east of the study area on the Belvoir Ranch (fig. 1). Because of proximity to the adjacent Laramie Mountains and the source of sediments composing the lithostratigraphic unit, the Ogallala Formation in the study area is very coarse grained along Lone Tree Creek and areas to the north in the vicinity of production wells (for example, Foley, 1942; Morgan, 1946; Cooley and Crist, 1994; JR Engineering, 2005; Trihydro Corporation, 2009), and generally is coarser than in most areas in southeastern Wyoming. Eastward from the Laramie Mountains, the Ogallala Formation becomes much finer grained, especially in the vicinity of the city of Cheyenne where the formation is represented by a predominantly fine-grained facies (Cooley and Crist, 1994). Because the Ogallala Formation is very coarse grained in the study area, the unit contains a high-yielding but heterogeneous aquifer along Lone Tree Creek (JR Engineering, 2005, 2007; Trihydro Corporation, 2009), and areas to the north and south. The saturated part of the Ogallala Formation in this area is considered an aquifer (Ogallala aquifer) by all investigators, and the unit contains the primary aquifer of the High Plains aquifer system in the area. Additional information on the geology and hydrology of the study area is provided in the

Figure 2. Drilling and coring of monitoring wells BRO–1a and BRO–2 at study location on Belvoir Ranch, Laramie County, Wyoming. Note study location is on a terrace immediately above Lone Tree Creek, and note coarse-grained sediments in the present-day stream channel in foreground of photograph.

"Overview of the Regional High Plains Aquifer System in Southeastern Wyoming" section.

Soils along the Lone Tree Creek channel bottom and riparian zone are "deeper in comparison to the surrounding terrace and hillslope areas and are classified as a sandy loam" (Lidstone and Associates, 2005, p. 3). The soil series is the Weed Loam (Lidstone and Associates, 2005, p. 3).

Production Wells

Immediately to the north and northeast of the study area and the Lone Tree Creek drainage, the Ogallala Formation is productive, but apparently heterogeneous, and thus production from wells completed in the unit is variable and limited to permeable water-bearing zones composed of sand and gravel beds, lenses, and stringers interbedded with finer-grained silt and clay (Theis, 1941; Foley, 1942; Morgan, 1946; Lowry and Crist, 1967; Weston Engineering, 1996a,b; Black and Veatch, 2004). Nevertheless, beginning in the late 1930s, the city of Cheyenne began to locate and install production wells into permeable zones of the Ogallala Formation in this area and subsequently continued to install wells until several areas were developed to the north (for example, Theis, 1941; Foley, 1942; Morgan, 1946; Lowry and Crist, 1967). Currently (2013), the city of Cheyenne owns and operates more than 30 production wells in four areas in the vicinity of Cheyenne (Black and Veatch, 2004, and references therein). Collectively, these four areas provided an average of about 30 percent of Cheyenne's annual public-water supply for the years 1991 to 2002 (Black and Veatch, 2004, p. 3-42). Most production wells to the west of Cheyenne withdraw water primarily from wells completed in permeable zones of the Ogallala Formation, although some contribution from the underlying White River Group or Formation is likely where screens penetrate the unit. In contrast, production wells to the northwest of Cheyenne near Federal are completed in the White River Group or Formation (Lowry and Crist, 1967; Black and Veatch and others, 1994; Black and Veatch, 2004) because erosion has removed the overlying Ogallala Formation (see area near Federal in fig. 1) and because the unit appears to be coarser grained than in the vicinity of Borie, especially in the lower part of the unit that appears to be more permeable/productive than in the upper part (for example, Lowry and Crist, 1967, p. 25). Many of the productive zones in the White River Group or Formation near Federal have been identified as localized sand and gravel channels (Black and Veatch, 2004).

In 2003, the city of Cheyenne purchased the Belvoir Ranch, which includes the area along Lone Tree Creek that includes the study area. High-yielding production wells already present on the ranch are now (2013) owned by the city of Cheyenne and are not used often (Wyoming State Engineer's Office, 2008). Additional production wells on the Belvoir Ranch along Lone Tree Creek could be developed (JR Engineering, 2005, 2007). Numerous high-yielding production wells used for industry are located to the south and east of the study area and within the vicinity of Borie and Belvoir Ranch (for example, Shepherd and Owens, 1981; JR Engineering, 2007; Wyoming State Engineer's Office, 2008). These high-yielding production wells, installed primarily in the Ogallala Formation from the late 1960s to 1990s, are used to supply water to a fertilizer plant located east of the study area (Wyoming State Engineer's Office, 2008, and references therein).

Numerous studies have been published describing various aspects of the geology and hydrogeology near Cheyenne. The annotated bibliography compiled by Ogle and Jordan (1997), supplemented with updates provided in Hallberg and Mason (2007), provides useful annotated descriptions of much of the available literature. Useful summaries of various aspects of the geology, hydrogeology, and development and use of production wells near Cheyenne are provided in several studies (Black and Veatch and others, 1994; Weston Engineering, 1996a; Jordan, 1998; Black and Veatch, 2004; Wyoming State Engineer's Office, 2008).

Climate

The climate in Laramie County, which is characteristic of the northern Great Plains, is semiarid with large temperature variations, cold winters, low precipitation, frequent winds, low humidity, and high evaporation. Mean annual precipitation (snow and rain) ranges from about 14 to 18 inches (in.) in the central and eastern parts of the county, including the study area along Lone Tree Creek, to as much as 24 in. in the Laramie Mountains on the western edge of the county (JR Engineering and others, 2008, unnumbered figure, p. 4–1).

Methods of Study

Methods used for collection and analysis of geologic, hydrogeologic, and groundwater-quality data are described in this section. Quality-assurance methods and quality-control data collected for the groundwater-quality samples also are described in this section.

Collection of Unsaturated-Zone Sediment Samples

Characterization of the Belvoir Ranch area began with drilling of a shallow borehole. A shallow [58.5 feet (ft) below land surface (BLS)] borehole (designated BRO–1) was installed first at the study site (fig. 1) by drilling and coring with a hollow-stem auger drilling rig to collect continuous unsaturated-zone core/sediment samples free of any drilling mud or fluids that could be introduced if hydraulic (mud) rotary drilling techniques were used. Coring using hollow-stem methods was very difficult and damaging to drilling/coring equipment because of the large size of Ogallala Formation sediments found at the site, which were composed of a large percentage of gravel-sized sediments. Consequently, because of the predominance of gravel-sized sediment, core could not be collected continuously from land surface to the full depth (58.5 ft BLS) of borehole BRO–1. For intervals where core could not be obtained, good returns of cuttings still allowed for detailed description of the sediment. From this coring, unsaturated-zone sediments were subsampled from 10 intervals and placed in sealed glass jars to analyze pore waters for tritium and moisture content, and unsaturated-zone sediments from an additional 10 adjacent intervals were subsampled from the core and placed in sealed metal containers to be analyzed for chloride and moisture content. Upon completion of BRO–1 drilling/coring, the borehole was sealed with bentonite grout.

Drilling, Coring, and Monitoring Well Installation

Following drilling and coring of borehole BRO–1 using hollow-stem methods, an adjacent (approximately 10 ft away) deep (540 ft BLS) borehole (BRO–2) was drilled and partially cored using mud rotary techniques and a 2.75-in. outside diameter, 10-ft long core barrel until the entire Tertiary section was penetrated and the underlying Upper Cretaceous Lance Formation was found. Attempts at coring of borehole BRO–2 using mud rotary techniques began at 58.5 ft BLS, the depth at which coring of borehole BRO–1 ended. Once again, coring was very difficult because of the continuing occurrence of gravel-sized sediments. Core returns were minimal because of nearly continuous jamming of the core barrel with large pebbles and cobbles; typically, a single large igneous or metamorphic pebble or cobble jammed into the core barrel would be the only material retrieved from a given core run. Numerous attempts were made at adjusting the position of the core barrel in relation to the drilling bit as well as other modifications to the drilling/coring process to improve core returns; all of these attempts were unsuccessful because of continual jamming of the core barrel with large sediments. Consequently, because of the predominance of gravel-sized sediment, coring was discontinued until finer-grained sediments were found that could be cored. Fortunately, because sediments were so coarse, cuttings returns were excellent and sediment samples were collected continuously and bagged/sealed for later description. This extremely coarse-grained sedimentary sequence was found continuously to a depth of about 272 to 275 ft BLS; at this depth, finer-grained sediments were found and continuous coring was begun. Core then was collected continuously from about 275 to about 485 ft BLS; because of equipment problems and resource constraints, the remaining depth of the borehole (485 to 540 ft BLS) was drilled instead of cored, and cuttings were collected continuously. Drilling was discontinued when the entire Tertiary section was penetrated and sediments of the underlying Upper Cretaceous Lance Formation were found. Upon penetration of an estimated 8 ft of the Upper Cretaceous Lance Formation, drilling was discontinued and equipment was removed from the borehole so geophysical logging (caliper, electrical/resistivity, spontaneous potential, natural gamma, and neutron) (see Geophysical Logs section) could be conducted in the open borehole.

Two monitoring wells, designated BRO–2 (USGS site 410507105003802) and BRO–1a (USGS site 410508105003801), were installed in the Ogallala Formation on May 26 and May 27, 2009, respectively. Wells were constructed and developed using procedures described in Lapham and others (1995). Based on lithology found during drilling/coring and results of geophysical logging, a screen interval (205.05 to 225.05 ft BLS) in a deep part of the sediments identified as the Ogallala Formation was selected and the cored borehole (BRO–2) was converted into a monitoring well (also identified as BRO–2) after sealing the deeper part of the borehole below the interval selected for screening with bentonite grout. Upon completion of monitoring well BRO–2, an adjacent "water table" monitoring well (BRO–1a) was installed to a depth of 122.38 ft BLS about 10 feet from monitoring well BRO-2. The depth to the top of the well screen interval (102.31 to 122.31 ft BLS) for monitoring well BRO–1a was selected to be several feet below the estimated water table at the time of drilling. The well screen was installed several feet below the water table to minimize atmospheric gaseous exchange that can occur as a result of the well screen being located above and "straddling" the water table; in addition, this allows the well screen to remain below the water table even if groundwater levels decline in the future.

Construction of both monitoring wells began with installation of steel surface casing to a depth of 20 ft BLS in monitoring well BRO–2 and to a depth of 16 ft BLS in monitoring well BRO–1a. The monitoring wells were constructed with factory cleaned and sealed, 2.5-in. diameter, threaded, flush-jointed, polyvinyl chloride (PVC) well casing and 2.5-in. diameter perforated, PVC-slotted, nonmetallic well screen (0.02-in. slot size), and o-rings were placed at each casing joint. Four 1.3-ft long stainless steel centralizers were placed at different depth intervals around the well casing and screen of the monitoring wells to centralize both in each borehole. Filter packs composed of 10/20 silica sand (public drinking-water supply quality) were installed with tremie pipes from the bottom of the wells to about 12 ft above the screened intervals in both monitoring wells; about 11 to 12 ft of hydrated bentonite pellets were installed above the filter packs to prevent the environmental seal from entering the filter pack. The environmental seal that was installed above the hydrated bentonite pellets to within about 3 ft BLS of both monitoring wells consisted of bentonite grout mixed onsite. After installation was complete, the monitoring wells were developed until discharge from each was visibly "clear" in appearance. The shallow monitoring well (BRO–1a) was developed using bailing, whereas the deeper monitoring well (BRO–2) was developed using an airlift method (Driscoll, 1986). Lockable outer steel protective housings were set on concrete bases poured around both wells to protect the PVC casing protruding above the land surface and to allow for protection of continuous water-level recorders installed in both wells. Detailed information describing well installation and construction for both wells was recorded and entered into the USGS National Water Information System (NWIS) Groundwater Site Inventory (GWSI) database (*http://waterdata.usgs.gov/wy/nwis/gw*). Construction information for monitoring well BRO–2 is shown on figure 3 and plate 1, and construction information for monitoring well BRO–1a is shown in figure 3.

Collection and Storage of Cuttings and Core

Immediately after collection, drill cuttings and core were wiped to remove drilling mud and tightly wrapped and sealed in multiple layers of heavy duty aluminum foil. Depth intervals from which cuttings and core were collected were measured carefully and recorded in a field notebook, and then depth information was recorded directly on the tightly wrapped aluminum foil using black permanent ink markers. Cuttings and core then were placed into labeled core boxes for archival purposes.

Lithologic Description

Brief descriptions of the methods used to describe the sediments collected from cuttings and core collected as part of the study are presented in this part of the report. The sediment descriptions were then used to characterize and define the lithology at the surface and in the subsurface at the study site.

Visual Description

Sediment characteristics from collected cuttings and core were described by viewing the cuttings and core in the office with a binocular microscope. Grain size was described using a binocular microscope and the modified Wentworth scale (Ingram and Johnson, 2006, p. 161); the relative proportions of different grain sizes composing the sediments for a given depth interval were estimated visually using a binocular microscope. Sediment rounding and sphericity were described using a binocular microscope and American Geological Institute comparison charts (Powers and Johnson, 2006, p. 167). Color and hue were described using Munsell soil color charts (Munsell, 2000). Other physical sediment characteristics (for example, sorting, cementation, and mineralogical and lithological composition) were described visually.

X-Ray Diffraction

Methods used to prepare and interpret 10 lithologic samples subsampled from cuttings and core for analysis using x-ray diffraction (XRD) are described in this section of the report. The XRD samples were prepared and analyzed at the USGS Chlorofluorocarbon Laboratory in Reston, Virginia. Crystal faces are denoted using standard Miller indices [for example, (001), (002), and (004)]. Miller indices form a notation system used to denote the different faces on a crystal (Moore and Reynolds, 1989).

Sediment Preparation

Sediment specimens were prepared for basic XRD analysis of crystalline material and cryptocrystalline clays. Whole samples were dried in air and then lightly crushed in a mortar and pestle before mounting for XRD analysis. The powders were mounted with random orientation of the crystallites on glass substrates after adding amyl acetate mixed with ethyl cellulous. This viscous mixture dries rapidly and minimizes preferred basal orientation of platy minerals to expose a-b axis peaks of the crystallites. Fractionated clays were mounted on glass substrates by mixing the sized separates with water, which was evaporated slowly on slides to obtain basal (c-axis) orientation. Three diagnostic treatments were conducted on oriented clay specimens to note c-axis response to characterize clay-mineral species. Each subsample was scanned untreated, glycol solvated overnight at 60 degrees Celsius (°C), followed by heating overnight at 550 °C. Detailed methodology for diagnostic identification of clays and related minerals is present in Moore and Reynolds (1989).

Grain-Size Fractionation

Sediments underwent grain-size fractionation that used hydrodynamic settling techniques based on Stokes' law (Boggs, 1987) but further modified for accelerated-particle settling with centrifugation according to the techniques of Jackson (1969). Although English units of measure are used in parts of this report, grain sizes and grain-size fractionation are presented using the metric scale (in millimeters and microns) because of use of the modified Wentworth scale for grain size (Ingram and Johnson, 2006, p. 161) and because of the small size of particles. Whole samples were dispersed in water with high-powered ultrasonification after adding Calgon® (sodium hexametaphosphate) dispersant, and then centrifuged at specified times and revolutions per minute (rpm) until no more of the target fraction could be isolated from the bulk slurry. In turn, the initial sized slurry was centrifuged for the next smallest grain size. This process was repeated sequentially down to the finest grain size to obtain a series of bracketed size separates. The initial particle size of less than (<) 1 micron or micrometer (µm) was centrifuged from the bulk dispersions at 3,000 rpm for 3 minutes. The resulting <1-µm slurries were centrifuged at 10,000 rpm for 10 minutes to separate <0.1-µm materials. Subsequently, the <0.1-µm slurries were centrifuged for 90 minutes at 20,000 rpm to isolate <0.03-µm ultrafine particulates. All solid material in the sized slurries was consolidated into pellets by final centrifugation at 20,000 rpm for 1 hour, except for the supernatant liquids that contained <0.03-µm materials. These slurries required centrifugation at 40,000 rpm for 2 hours or longer to consolidate the solid material for XRD analysis. Sediment preparation averaged

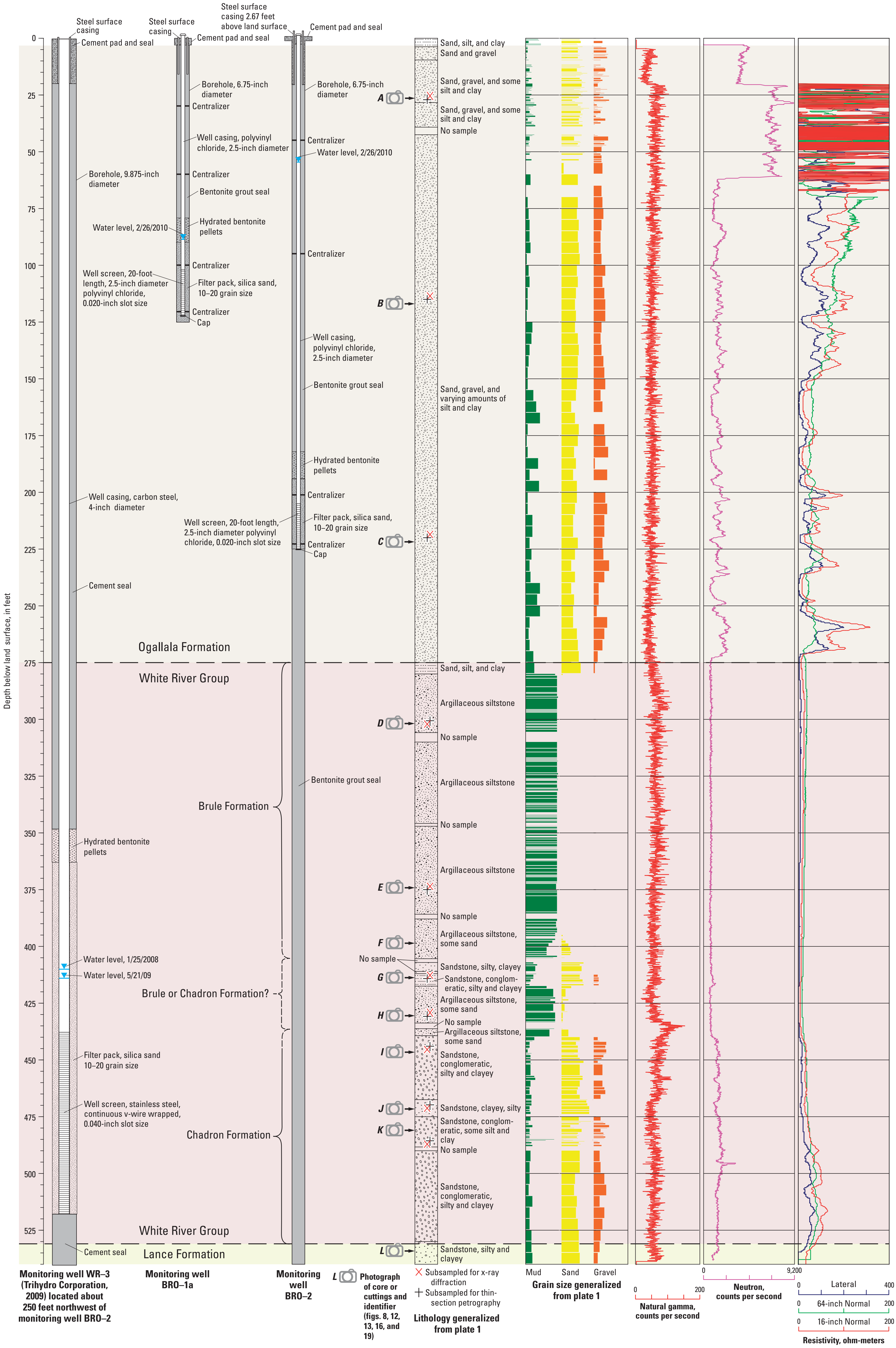


Figure 3. Well construction, generalized core description, and selected geophysical logs for monitoring wells BRO–1a and BRO–2, and well construction for monitoring well WR–3, Belvoir Ranch, Laramie County, Wyoming.

1.5 to 2.5 days per sample to provide sufficient material for XRD and other analytics. Minerals in relation to International Center for Diffraction Data (ICDD) reference numbers (International Center for Diffraction Data, 2002) and characteristic XRD reflections in degrees 2-theta (°2θ; angle of diffraction, recorded as °2θ by convention) are listed in table 1.

X-Ray Diffraction System Parameters

The XRD samples were analyzed on an automated PANalytical diffractometer using CuKα radiation (a type of monochromatic x-ray radiation used for x-ray diffraction) from a long-fine focus tube, spectrally isolated with a graphite crystal monochromator. Kilovolts were set at 45, and milliamps were set at 25. The soller slit was fixed at 1 degree (°), and the receiving slit was fixed at ¼°. The scan rate was 1 °2θ per minute, analyzed from 2 to 66 °2θ for standard analyses. The b-axis measurements obtained on randomly oriented <0.03-µm smectites were scanned at a ¼ °2θ per minute from 55 to 65 °2θ. Although English units of measure are used predominantly in this report, the XRD analysis uses the metric scale (such as angstroms, microns, and millimeters) because of the small scale of measurements.

Tabulated X-Ray Diffraction Results

The primary minerals identified in sediment samples were quartz, plagioclase, potassium feldspar, mica (primarily muscovite), calcite, dolomite, illite, kaolinite, chlorite, smectite, and hornblende (appendix 1). The mineral abundances in weight percent for whole samples and glycol-solvated scans of each fraction separated from XRD samples 1 to 10 are shown in appendix tables 1–1 to 1–5, whereas appendix tables 1–6 to 1–15 show the same abundances for each of the 10 samples separately from coarsest to finest grain size. Untreated and heated scans were used for diagnostic identification of the clay-mineral constituents, but were not used to calculate weight percent. Glycol-solvated scans provide the best resolution of closely spaced peaks for the minerals detected, and therefore, the most complete mineral assemblage for weight percent calculations. The angstrom values of the (060) peaks measured from randomly oriented <0.03-µm materials scanned at ¼ °2θ per minute to determine dioctahedral (aluminum-rich) and trioctahedral (magnesium-rich) phyllosilicate lattice types are listed in appendix table 1–16.

Semi-Quantification Method

Diffraction-peak intensity is proportional to weight percent, but does not necessarily pair highest intensity with highest weight percent in any unknown sample matrix. The direct relation between diffraction-peak intensity and weight percent can be affected substantially by preferred orientation, peak overlap, crystal order and disorder, mass absorption coefficients of each mineral, sample-mounting techniques, and diagnostic treatments.

Semiquantitative weight percent values from sediment samples were determined by an internal standard method embedded in the PANalytical High Score identification software. This technique calculates weight percent of the unknown constituents from analyses of standard materials that contain reference-intensity ratios. The ratios are determined from known quantities of corundum mixed with known quantities of the standard minerals. Reference-mineral analyses are stored

Table 1. Minerals, International Center for Diffraction Data reference file numbers, and important x-ray diffraction reflections.

[°2θ, degrees 2-theta]

Mineral	International Center for Diffraction Data reference number[1]	Characteristic x-ray diffraction reflections in °2θ[1]
Quartz (Q)	5–490	26.6, 20.8
Calcite (Cc)	5–586	29.4, 23.1
Dolomite (Dol)	28795	30.8, 24.0
Plagioclase (Plg)	9–466	27.9, 22.1
Potassium feldspar (Ks)	19–931 and 76–742	27.5, 27.1
Hornblende (Hb)	81–502	28.4, 10.4, 9.9
Chlorite (Chl)	12–243	6.2, 12.3, 25.1
Untreated smectite (Sm)	13–135	6.1, 17.7
Glycolated smectite (Sm)	12–219	5.1, 10.1
Heated smectite (Sm)	7–304	8.7, 17.1
Illite (Ill)	9–334	8.8, 17.9
Muscovite (Mica)	41115	8.9, 17.9
Kaolinite (Kao)	6–221	12.4, 24.8

[1]From International Center for Diffraction Data (2002).

in a database licensed by the ICDD (International Center for Diffraction Data, 2002). A rigorous assessment of the internal standard method of calculating XRD weight percent is provided by Chung (1974).

Diagnostic Clay-Mineral Identification

Diagnostic treatments on clays are used to discriminate lattice types that expand and collapse (smectites), nonswelling lattice types (illites, chlorites, and kaolinites), as well as structural types that become amorphous after heating (kaolinites). The positions of the principal diffraction peaks for ideal end-member reference clays after diagnostic treatments are shown in table 2. A brief description of diagnostic response is explained to emphasize a basic rationale for identification of clay-mineral constituents in multiphase sediment.

Most sediment typically contains at least three or more clay species that can respond differently when compared to end-member phases. The ideal illite (001) peak remains unaffected at 10.1 angstroms (Å) (8.8 °2θ) after glycol solvation and heating. Glycol expands most smectites from 15 Å (6.1 °2θ) to 17 Å (5.2 °2θ). Heating at 500 °C collapses smectite to 10 Å (8.7 °2θ). Kaolinite remains at 7.1 Å (12.4 °2θ) after glycolation, but becomes amorphous, and therefore resolves no peaks after heating at 500 °C. Chlorite (001) reflections remain at 14.3 Å (6.20 °2θ) after glycolation and heat treatment.

Kaolinite, chlorite, and smectite can be difficult to discriminate because their untreated basal peaks have considerable overlap with one another. Glycol solvation does not always expand the smectite (001) peak enough to completely resolve the (001) chlorite reflection at 14.3 Å (6.2 °2θ). The untreated (001) smectite peak position can vary from 13 Å (6.8 °2θ) to 15 Å depending on hydration state, often diffusing resolution of the principal chlorite reflection. The (002) (7.2 Å, 12.2 º2θ) and (004) (3.53 Å, 25.1 °2θ) chlorite peaks also overlap with the kaolinite (001) (7.14 Å, 12.4 °2θ) and (002) (3.57 Å, 24.9 °2θ) peaks. Kaolinite and chlorite discrimination is clarified by heat treatments that breakdown kaolinite to amorphous material, resolving only chlorite peaks left unaffected by heating. After heating, the (001) smectite peak at 14–15 Å (6.3–5.9 °2θ) generally collapses to the 10 Å (8.7 °2θ) illite-like structure, exposing the principal chlorite reflection. Collapsed smectite peaks overlap with principal illite reflections.

Thin-Section Petrography

Methods used to prepare and interpret 10 lithologic samples subsampled from cuttings and core for analysis using thin-section petrography are described in this section of the report. Most of the lithologic samples collected from cuttings or core were loose or friable; consequently, a composite sample was collected from poorly consolidated sediment samples and cemented with epoxy for thin sectioning. Clayey samples also were impregnated with epoxy.

Mineralogy was determined using polished thin sections under transmitted and reflected light microscopy. In addition, selected thin sections, as well as three-dimensional core samples, were examined with a JEOL 5800LV scanning electron microscope (SEM) equipped with an Oxford ISIS energy-dispersive x-ray (EDS) detector to determine basic mineralogy and identify textural features.

Point-count data, which give a percent area of minerals, are a supplement to XRD data, which provide data on bulk-mineral content. Point-count data group the minerals into their mineralogic assemblages, such as hornblende, quartz, iron oxides, and feldspar in metamorphic rock fragments, or polycrystalline quartz, plagioclase, and microcline in granitic rock fragments. Samples that are texturally soils were point counted for this study, but it is important to note that mineral abundance in soils normally is obtained by mineral separation, a process by which the matrix is separated from the finer-grained minerals, and weights are obtained on clays in contrast to grains. Point counts on the sediments examined in this study that are interpreted to likely be paleosols are not useful for true mineral count because the high area content of the matrix overwhelms mineral content. A minimum of 500 points were counted for each thin section.

Table 2. Diagnostic response of (001) x-ray diffraction peaks for ideal end-member reference clays used to characterize clay minerals in the Ogallala Formation and White River Group (Brule and Chadron Formations), Belvoir Ranch, Laramie County, Wyoming.

[°C, degrees Celsius; °2θ, degrees 2-theta; Å, angstrom]

Mineral species	Untreated position		Glycolated position		500 °C position	
	°2θ	Å	°2θ	Å	°2θ	Å
Montmorillonite (smectite)	6.1	14.73	5.2	16.99	8.7	10.19
Illite	8.8	10.1	8.8	10.1	8.8	10.1
Kaolinite	12.4	7.14	12.4	7.14	amorphous	amorphous
Chlorite	6.2	14.3	6.2	14.3	6.2	14.3

Geophysical Logs

After drilling and coring of monitoring well BRO–2 was completed, geophysical logs were collected in the 540-ft deep borehole filled with drilling fluid. Geophysical logs collected included caliper, natural gamma, spontaneous potential, lateral and normal resistivity, and neutron. Information describing these geophysical tools and methods of interpretation are provided in Keys (1990) and Hearst and others (2000); a brief summary of each geophysical logging method provided below is summarized from these two references as well as modified from Anderson and others (2009).

The caliper tool is a spring-loaded multi-arm device that provides an average measure of borehole diameter. Changes in borehole diameter may reflect drilling and construction procedures, relative consolidation of lithologic units, and other lithologic features such as fractures.

Natural gamma logs measure the natural gamma radiation emitted by sediments surrounding a borehole. Clayey minerals tend to accumulate radioisotopes through adsorption and ion exchange processes; consequently, zones of high natural gamma activity typically are interpreted as being clay rich, although many other lithologies (for example, shale and feldspathic sandstones) also are associated with high gamma activities.

Spontaneous potential (SP) logs measure electrical potentials that develop in boreholes at lithologic and water-quality interfaces. SP is largely a function of chemical reactions that occur within the wellbore fluids, and the type and amount of clay present. Electrochemical effects generally result from the migration of ions from more to less mineralized fluids.

Two types of resistivity tools were used to measure the electrical resistivity of rocks and water surrounding the borehole. Normal electrical resistivity measurements consisted of short-normal (16-in.) and long-normal (64-in.) resistivities. Short-normal and long-normal resistivity tools have two different volumes of investigation beyond the borehole. The long-normal measurement has a greater volume of investigation beyond the borehole and is affected less by drilling fluid than is the short-normal measurement. Lateral resistivity logs are similar to normal resistivity logs but utilize a different electrode configuration to measure electrical resistivity beyond the borehole fluid invaded zone. In general, electrical resistivity measurements are affected by clay content, rock porosity, and pore fluid dissolved-solids concentrations. Lower resistivities generally correspond to higher porosity or smaller grain size because the surface area associated with small grain size promotes electrical current transmission.

Neutron logs record the continuous measurement of the induced radiation produced by bombarding the surrounding geologic formation and fluid with neutrons from a sealed neutron source, which interact with surrounding atomic nuclei until they are captured. In groundwater environments, most neutron interactions are in response to the amount of hydrogen present; the amount of hydrogen present largely is a function of the water content of surrounding borehole sediments. Neutron logs commonly are used to qualitatively or quantitatively estimate saturated formation porosity. Neutron logs also commonly are used in relation to natural gamma logs, and these combined logs can indicate areas of high porosity associated with bound groundwater on clay surfaces. In this study, neutron logs are presented in the original units of counts per second to provide a qualitative measurement of sediment porosity.

Collection, Processing, and Storage of Groundwater-Level Measurements

USGS personnel instrumented the two monitoring wells installed for this study with pressure transducers and data loggers to continuously record water levels. The nested configuration of the monitoring wells provided information on vertical hydraulic-head (water-level) gradients within the Ogallala aquifer, and continuous monitoring of water levels was used to establish trends over time. Discrete and continuous water levels were measured and documented using methods described in Cunningham and Schalk (2011). Continuous water levels were measured using vented pressure transducers installed in both monitoring wells. Location, construction, lithologic, geophysical, well-completion information, and discrete water-level measurements were entered into and stored in the USGS NWIS GWSI database; continuous groundwater-level data were entered into and stored in the USGS NWIS Automated Data Processing System (ADAPS) database, and these data are available at *http://waterdata.usgs.gov/wy/nwis/gw/*.

Groundwater-Quality Sample Collection

Groundwater-quality samples were collected from monitoring well BRO–1a on June 24, 2010, and from BRO–2 on November 12, 2009. Samples were collected and processed in a mobile water-quality laboratory using groundwater sampling procedures described in Koterba and others (1995) and the USGS “National Field Manual for the Collection of Water-Quality Data” (U.S. Geological Survey, variously dated). Water was pumped into a sampling manifold and flow-through chamber in a mobile field laboratory until at least three well-casing volumes were purged at low rates and measurements of pH, specific conductance, temperature, turbidity, and dissolved oxygen (DO) stabilized. After field measurements stabilized, water was diverted to a sampling chamber consisting of a PVC frame enclosed in a plastic bag to minimize the potential of atmospheric contamination. Samples collected for all analyses except chlorofluorocarbons (CFCs), sulfur hexafluoride (SF_6), and dissolved gases were collected within the sampling chamber. All materials in contact with the water samples after being pumped out of the wells were either stainless steel or Teflon® (with the exception of water samples collected for CFCs, SF_6, and dissolved gases).

Samples to determine alkalinity, major-ion, trace-element, dissolved organic carbon (DOC), and nutrient concentrations were filtered onsite using a 0.45-µm pore-size, disposable-capsule filter. Samples analyzed for alkalinity, major ions, and trace elements were collected in precleaned plastic or glass bottles that were rinsed onsite with filtered groundwater. Samples analyzed for DOC were collected in baked amber-colored glass bottles. Samples to be analyzed for major cations and trace elements were preserved to a pH of less than 2 standard units using ultrapure nitric acid. Samples to be analyzed for DOC were preserved to a pH of less than 2 standard units using sulfuric acid. Samples for major anions, tritium (^3H), stable isotopes of oxygen and hydrogen, dissolved gases, CFCs, and SF_6 did not require preservation.

Groundwater samples analyzed for the volatile organic compound (VOC) trichloroethene (trichloroethylene or TCE) were not filtered and were collected in three pre-acidified 40-milliliter (mL) amber-colored glass vials with septa obtained from TestAmerica Laboratories, and the vials were filled without headspace. When filling the three vials, the flow rate was adjusted to about 100 mL per minute to minimize aeration of the samples. The VOC and gasoline-range organics (GRO) samples were chilled on ice immediately after collection, and shipped to TestAmerica Laboratories in Savannah, Georgia, within 24 hours.

Groundwater samples analyzed for CFCs were collected using procedures described by the USGS Reston Chlorofluorocarbon Laboratory in Reston, Va. (U.S. Geological Survey, 2009a). Interpretation of CFCs in groundwater is complex, so the reader is referred to other resources describing the collection, analysis, and interpretation of CFCs in groundwater for additional information (Busenberg and Plummer, 1992; Plummer and Friedman, 1999; Plummer and Busenberg, 2000; U.S. Geological Survey, 2009a).

Groundwater samples analyzed for SF_6 were collected using procedures described by the USGS Reston Chlorofluorocarbon Laboratory in Reston, Va. (U.S. Geological Survey, 2009b). The details of analytical and interpretive techniques used to estimate apparent ages using SF_6 are described in Busenberg and Plummer (1997, 2000).

Chemical Analyses and Data Reporting

Physical characteristics (water temperature, pH, turbidity, and DO) were measured in the field during collection of groundwater samples using methods described in the USGS "National Field Manual for the Collection of Water-Quality Data" (U.S. Geological Survey, variously dated). Alkalinity was determined onsite by incremental titration of a filtered water sample with sulfuric acid (Rounds and Wilde, 2001).

The USGS National Water Quality Laboratory (NWQL) in Denver, Colorado, analyzed groundwater samples for major ions, trace elements, nutrients, and DOC. Major ions and trace elements were analyzed using atomic-absorption spectrometry, colorimetry, ion-exchange chromatography, or inductively-coupled plasma/mass spectrometry (Fishman and Friedman, 1989; Faires, 1993; Fishman, 1993; McLain, 1993; Garbarino, 1999; Jones and Garbarino, 1999). Nutrients were analyzed using colorimetry (Fishman, 1993). DOC was analyzed using ultraviolet light-promoted persulfate oxidation and infrared spectrometry (Brenton and Arnett, 1993). TestAmerica Laboratories, Inc., was contracted to analyze groundwater samples for TCE and GRO. Groundwater samples were sent to TestAmerica Laboratories, Inc., in Savannah, Ga., for analysis of TCE using U.S. Environmental Protection Agency (USEPA) method 524.2 (Munch, 1995). GRO samples were sent to TestAmerica Laboratories, Inc., in Savannah, Ga., and were analyzed using USEPA SW846 method 8015B (U.S. Environmental Protection Agency, 1996).

The USGS Reston Chlorofluorocarbon Laboratory in Reston, Va., analyzed groundwater samples for dissolved gases (methane, carbon dioxide, nitrogen, oxygen, and argon) and CFCs (CFC–11, CFC–12, and CFC–113). Dissolved gases were analyzed using gas chromatography (Busenberg and Plummer, 1992), and measured concentrations were used to improve CFC and SF_6 age interpretations. The CFCs and SF_6 were analyzed using electron-capture gas chromatography (Busenberg and Plummer, 1992). Apparent groundwater ages were assigned by the Reston Chlorofluorocarbon Laboratory using CFC equilibrium partial pressures corrected for recharge temperatures with known historical atmospheric partial pressures (Busenberg and Plummer, 1992; Plummer and Friedman, 1999; Plummer and Busenberg, 2000).

In this report, standard nomenclature is used to describe the analyses of water samples for stable isotopes of oxygen and hydrogen. The composition of stable isotopes is reported using delta (δ) notation, which indicates parts per thousand or per mil. The value for δ in per mil (parts per thousand) is calculated using the following equation:

$$\delta = (Rx/Rs - 1) \times 1{,}000 \qquad (1)$$

where

Rx is the ratio of the heavy-to-light isotope of the sample, and

Rs is the ratio of the heavy-to-light isotope of the applicable reference standard (Clark and Fritz, 1997).

The USGS Reston Stable Isotope Laboratory analyzed groundwater samples for stable isotopes of hydrogen (δ^2H or deuterium/protium isotopic ratio) by hydrogen equilibrium (Coplen and others, 1991) and oxygen ($\delta^{18}O$ or oxygen-18/oxygen-16 isotopic ratio) by carbon-dioxide equilibrium (Epstein and Mayeda, 1953). Both δ^2H and $\delta^{18}O$ are reported in relation to Vienna Standard Mean Ocean Water (VSMOW). Tritium was analyzed at the USGS Isotope Tracers Project Laboratory in Menlo Park, California, using electrolytic enrichment (Ostlund and Dorsey, 1977).

Laboratory analytical results for most constituents were reported relative to laboratory reporting levels (LRLs), interim reporting levels (IRLs), or to minimum reporting levels (MRLs). The LRLs are set by the NWQL to minimize both false positive and false negative measurement errors (Childress and others, 1999). The LRLs are calculated statistically on a continual basis using quality-control data for a given analytical method to determine long-term method detection levels (LT-MDLs) (Childress and others, 1999). The LRLs are defined as twice the annual LT-MDLs. The IRL is a temporary reporting level used for new or custom schedules when long-term method detection level data are unavailable and a LRL has not been established (U.S. Geological Survey, 2004). The MRLs are the minimum concentrations of a constituent that can be reported reliably using a given analytical method (Timme, 1995). In this report, LRLs are reported for most constituents. The MRLs and LRLs can vary for the same constituent because of improvement in analytical methods or possible complications with individual analyses.

The NWQL reports some analytical results as estimated concentrations. Estimated concentrations are smaller than a minimum concentration that can be reported reliably by a given analytical method, but generally larger than the LT-MDL (Childress and others, 1999). Concentrations reported as estimated indicate that the constituent is present in the water sample, but there is some type of quantitative analytical uncertainty associated with the reported concentration. In this report, estimated concentrations in tables are designated with the placement of the letter “E” preceding the reported laboratory concentration.

Analytical results for tritium, a radioisotope, were reported in relation to a sample-specific critical level (SSLC). The SSLC is the “smallest measured concentration that is statistically different from the instrument background or analytical blank, and it serves as the detection threshold for deciding whether the radionuclide is present in a sample” (McCurdy and others, 2008, p. 4).

Quality Assurance and Quality-Control Samples

In addition to collection of environmental groundwater-quality samples from the two monitoring wells, three types of quality-control (QC) samples were collected as part of the quality-assurance (QA) program (Koterba and others, 1995). The QC samples included one office blank, one trip blank, and one replicate environmental sample. The QC samples were collected, preserved, and analyzed using the same methods and equipment as used for environmental samples. Collection and evaluation of QC samples, in addition to adherence to strict USGS sample collection, processing, and analysis procedures, composed the QA program.

Blank Samples

Two types of blank samples were collected to evaluate bias from the potential introduction of contamination to environmental samples during field sample collection, field-equipment cleaning, and laboratory analytical procedures. Specially prepared water for all blank samples was provided by the USGS, and was certified to be free of inorganic (inorganic-free blank water) and organic (organic-free blank water) constituents to concentrations less than NWQL LRLs or MRLs. A field-equipment blank was collected in the office after cleaning of the sampling equipment and before collection of environmental samples for this study (referred to herein as an “office blank”). The office blank was collected to determine if cleaning procedures removed constituents from sampling equipment and to ensure that field and laboratory methods had not contaminated environmental samples. After cleaning was completed, the office blank was collected by passing blank water through all sampling equipment and then collecting and preserving the sample using the same procedures as for environmental samples.

The office blank sample was collected before groundwater-quality sampling and was analyzed for major ions, trace elements, nutrients, and DOC (table 3). Major ions, nutrients, and dissolved organic carbon were not detected in the office blank. Seven trace elements were detected at very small concentrations in the office blank sample (barium, chromium, cobalt, copper, manganese, molybdenum, and nickel). Concentrations of five of seven detected trace elements (barium, chromium, manganese, molybdenum, and nickel) were measured at concentrations less than those measured in samples from monitoring wells BRO–1a and BRO–2. The detection of cobalt in the office blank at concentrations greater than those measured in samples from both monitoring wells, and the detection of copper in the office blank but not in the environmental groundwater sample from monitoring well BRO–2, indicate concentrations of these constituents could be biased high; however, the environmental concentrations measured in both monitoring wells were very small [slightly greater than or less than 1 microgram per liter (µg/L)] and likely of little environmental concern. Consequently, results of the office blank sample indicated that decontamination procedures were adequate, and that field and laboratory contamination of environmental samples by most inorganic constituents was minimal.

Trip blanks consisted of vials filled with organic-free blank water and sealed at TestAmerica Laboratories. Trip blanks were used to verify that VOC vials were not contaminated during storage, sampling, or shipment to or from TestAmerica Laboratories. No VOCs were detected in the trip blanks.

Replicate Sample

A replicate sample (also known as a duplicate sample) is a sample collected immediately after the primary groundwater sample (environmental sample); both samples are analyzed for the same constituents to assess combined effects of field and laboratory procedures on measurement variability (precision). The relative percent difference (RPD) was calculated to compare constituent concentrations measured in both samples using the following equation:

$$RPD = \text{absolute value}\left(\frac{sample1 - sample2}{\left(\frac{sample1 + sample2}{2}\right)}\right) \times 100 \qquad (2)$$

One replicate sample was collected and analyzed for major ions and related water-quality characteristics, trace elements, nutrients, DOC, radioisotopes (tritium), and stable isotopes (hydrogen and oxygen) (table 4). The RPDs were not calculated for inorganic sample pairs where one value was reported as less than the applicable reporting level (LRL, IRL, MRL, or SSLC) and the other value was reported as greater than the applicable reporting level (LRL, IRL, MRL, or SSLC). The RPDs for most constituents were less than or equal to 10 percent, and indicated very good precision (reproducibility) for most inorganic constituents. Seven trace elements had RPDs greater than 10 percent; however, most RPDs greater than 10 percent were attributable to small concentration differences that resulted in large RPDs because both environmental and replicate sample concentrations were very small.

Major-Ion Balances

Major-ion data were quality assured by calculating ion balances. The ion balance was calculated (in milliequivalents per liter) as the total dissolved-cation equivalence minus the total dissolved-anion equivalence divided by the total equivalence of ions dissolved in solution. The calculated balance for the groundwater sample collected from monitoring well BRO–1a was about 7 percent, whereas the calculated balance for the groundwater sample collected from monitoring well BRO–2 was about 4.5 percent, which was considered acceptable for the study.

Water-Quality Criteria

Natural processes and human activities can affect groundwater quality. The primary natural factors that can affect the type and quantities of dissolved constituents in groundwater include the source and chemical composition of recharge water, the lithologic and hydrologic properties of the geologic unit, the various chemical processes occurring within the geologic unit, the amount of time the water has remained in contact with the geologic unit (residence time), and the mixing of waters from different geologic units. Many different human activities can affect groundwater quality, the effects are often negative, and some can impair the quality of water in relation to some uses. Potential sources of groundwater contamination in the aquifers studied are few because the land is relatively undeveloped in the study area and used primarily for livestock grazing; however, groundwater-quality samples collected from some wells completed in the Ogallala aquifer on the Belvoir Ranch along Lone Tree Creek indicate contamination by TCE

Table 3. Summary of major ions and related water-quality characteristics, trace elements, nutrients, and dissolved organic carbon in office blank sample in relation to groundwater-quality samples collected from monitoring wells BRO–1a and BRO–2, Belvoir Ranch, Laramie County, Wyoming.

[USGS, U.S. Geological Survey; NWIS, National Water Information System; LRL, laboratory reporting level; <, less than; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; E, estimated concentration; IRL, interim reporting level]

Constituent or characteristic	USGS NWIS parameter code	Reporting level	Office blank concentration or value	Well BRO–1a concentration or value	Well BRO–2 concentration or value
Major ions and related water-quality characteristics, in milligrams per liter, dissolved (sample filtered through 0.45-micrometer filter)					
Calcium	00915	0.044 (LRL)	<0.04	52.6	51.6
Magnesium	00925	0.016 (LRL)	<0.016	5.05	5.91
Sodium	00930	0.10 (LRL)	<0.10	5.46	6.75
Potassium	00935	0.064 (LRL)	<0.06	1.8	1.73
Chloride	00940	0.12 (LRL)	<0.12	4.49	7.01
Sulfate	00945	0.18 (LRL)	<0.18	13.6	19.2
Fluoride	00950	0.08 (LRL)	<0.08	0.7	0.47
Silica	00955	0.058 (LRL)	<0.2	19.1	22.5
Hardness (mg/L as $CaCO_3$)	00900	calculated	<0.18	152	154

Table 3. Summary of major ions and related water-quality characteristics, trace elements, nutrients, and dissolved organic carbon in office blank sample in relation to groundwater-quality samples collected from monitoring wells BRO–1a and BRO–2, Belvoir Ranch, Laramie County, Wyoming.—Continued

[USGS, U.S. Geological Survey; NWIS, National Water Information System; LRL, laboratory reporting level; <, less than; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; E, estimated concentration; IRL, interim reporting level]

Constituent or characteristic	USGS NWIS parameter code	Reporting level	Office blank concentration or value	Well BRO–1a concentration or value	Well BRO–2 concentration or value
Trace elements, in micrograms per liter, dissolved (sample filtered through 0.45-micrometer filter)					
Aluminum	01106	3.4 (LRL)	<3.4	E1.9	<3.4
Antimony	01095	0.054 (LRL)	<0.05	0.08	0.08
Arsenic	01000	0.044 (LRL)	<0.04	0.91	1.4
Barium	01005	0.14 (LRL)	0.2	88	108
Beryllium	01010	0.012 (LRL)	<0.01	<0.01	<0.01
Boron	01020	2.8 (LRL)	<3	22	17
Cadmium	01025	0.02 (LRL)	<0.02	E0.02	<0.02
Chromium	01030	0.12 (LRL)	E0.08	0.36	0.12
Cobalt	01035	0.010 (LRL)	1.2	0.16	0.23
Copper	01040	1 (LRL)	1.3	1.4	<1
Iron	01046	6 (LRL)	<6	<6	<6
Lead	01049	0.030 (LRL)	<0.03	0.05	<0.03
Lithium	01130	0.44 (LRL)	<0.4	6	9.1
Manganese	01056	0.26 (LRL)	E0.2	0.7	0.5
Molybdenum	01060	0.028 (LRL)	0.04	0.9	0.6
Nickel	01065	0.12 (LRL)	0.39	1.1	0.66
Selenium	01145	0.040 (LRL)	<0.04	0.62	0.58
Silver	01075	0.010 (LRL)	<0.01	<0.01	<0.01
Strontium	01080	0.40 (LRL)	<0.40	188	217
Thallium	01057	0.020 (LRL)	<0.02	<0.02	<0.02
Uranium	22703	0.008 (LRL)	<0.01	1.51	2.01
Vanadium	01085	0.16 (LRL)	<0.16	2.5	3.8
Zinc	01090	2.8 (LRL)	<2.8	6.3	<2.8
Nutrients, in milligrams per liter, dissolved (sample filtered through 0.45-micrometer filter), and dissolved organic carbon					
Nitrate, as nitrogen	00618	calculated	<0.040	E1.57	<2.08
Nitrite, as nitrogen	00613	0.002 (IRL)	<0.002	E0.002	<0.002
Nitrate + nitrite, as nitrogen	00631	0.04 (LRL)	<0.04	1.57	2.08
Ammonia, as nitrogen	00608	0.02 (LRL)	<0.020	<0.02	E0.01
Organic nitrogen	00607	calculated	<0.10	<0.07	E0.02
Total nitrogen	62854	0.10 (LRL)	<0.10	1.64	2.11
Phosphorus, as phosphorus	00666	0.006 (LRL)	<0.006	0.022	0.032
Orthophosphate, as phosphorus	00671	0.008 (LRL)	<0.008	0.029	0.032
Dissolved organic carbon (mg/L as carbon)	00681	0.66 (LRL)	<0.7	1.1	E0.5

Table 4. Replicate data for major ions and related water-quality characteristics, trace elements, nutrients, dissolved organic carbon, radioisotopes, and stable isotopes in groundwater-quality samples collected from monitoring well BRO–1a, Belvoir Ranch, Laramie County, Wyoming.

[USGS, U.S. Geological Survey; NWIS, National Water Information System; LRL, laboratory reporting level; $CaCO_3$, calcium carbonate; MRL, minimum reporting level; E, estimated concentration; <, less than; NC, not calculated; IRL, interim reporting level; C, carbon; SSLC, sample-specific critical level; --, no data; per mil, parts per thousand]

Constituent or characteristic	USGS NWIS parameter code	Reporting level	Environmental sample	Replicate sample	Calculated relative percent difference
Major ions and related water-quality characteristics, in milligrams per liter unless otherwise noted					
Calcium	00915	0.044 (LRL)	52.6	52.5	0.2
Magnesium	00925	0.016 (LRL)	5.05	5.04	0.2
Sodium	00930	0.10 (LRL)	5.46	5.59	2.4
Potassium	00935	0.064 (LRL)	1.8	1.86	3.3
Chloride	00940	0.12 (LRL)	4.49	4.71	4.8
Sulfate	00945	0.18 (LRL)	13.6	13.6	0
Fluoride	00950	0.08 (LRL)	0.7	0.69	1.5
Silica	00955	0.058 (LRL)	19.1	19.1	0
Alkalinity (milligrams per liter as $CaCO_3$)	39086	calculated	115.9	115.9	0
Dissolved solids	70300	10 (MRL)	193	190	1.6
Sodium-adsorption ratio (SAR)	00931	calculated	0.19	0.2	5.1
Trace elements, in micrograms per liter unless otherwise noted					
Aluminum	01106	3.4 (LRL)	E1.9	3.7	64.3
Antimony	01095	0.054 (LRL)	0.08	0.09	11.8
Arsenic	01000	0.044 (LRL)	0.91	0.94	3.2
Barium	01005	0.14 (LRL)	88	88	0
Beryllium	01010	0.012 (LRL)	<0.01	<0.01	NC
Boron	01020	2.8 (LRL)	22	22	0
Bromide (mg/L)	71870	0.02 (IRL)	0.04	0.04	0
Cadmium	01025	0.02 (LRL)	E0.02	0.02	0
Chromium	01030	0.12 (LRL)	0.36	0.69	62.9
Cobalt	01035	0.010 (LRL)	0.16	0.27	51.2
Copper	01040	1 (LRL)	1.4	1.3	7.4
Iron	01046	6 (LRL)	<6	<6	NC
Lead	01049	0.030 (LRL)	0.05	0.05	0
Lithium	01130	0.44 (LRL)	6	6	0
Manganese	01056	0.26 (LRL)	0.7	0.9	25
Molybdenum	01060	0.028 (LRL)	0.9	1	10.5
Nickel	01065	0.12 (LRL)	1.1	1.1	0
Selenium	01145	0.040 (LRL)	0.62	0.57	8.4
Silver	01075	0.010 (LRL)	<0.01	<0.01	NC
Strontium	01080	0.40 (LRL)	188	185	1.6
Thallium	01057	0.020 (LRL)	<0.02	<0.02	NC
Uranium	22703	0.008 (LRL)	1.51	1.5	0.7
Vanadium	01085	0.16 (LRL)	2.5	2.6	3.9
Zinc	01090	2.8 (LRL)	6.3	E2.5	86.4

Table 4. Replicate data for major ions and related water-quality characteristics, trace elements, nutrients, dissolved organic carbon, radioisotopes, and stable isotopes in groundwater-quality samples collected from monitoring well BRO–1a, Belvoir Ranch, Laramie County, Wyoming.—Continued

[USGS, U.S. Geological Survey; NWIS, National Water Information System; LRL, laboratory reporting level; $CaCO_3$, calcium carbonate; MRL, minimum reporting level; E, estimated concentration; <, less than; NC, not calculated; IRL, interim reporting level; C, carbon; SSLC, sample-specific critical level; --, no data; per mil, parts per thousand]

Constituent or characteristic	USGS NWIS parameter code	Reporting level	Environmental sample	Replicate sample	Calculated relative percent difference
Nutrients, in milligrams per liter, and dissolved organic carbon					
Nitrate, as nitrogen	00618	calculated	E1.57	E1.56	0.6
Nitrite, as nitrogen	00613	0.002 (IRL)	E0.002	E0.002	0
Nitrate + nitrite, as nitrogen	00631	0.04 (LRL)	1.57	1.56	0.6
Ammonia, as nitrogen	00608	0.02 (LRL)	<0.02	<0.02	NC
Organic nitrogen	00607	calculated	<0.07	<0.02	NC
Total nitrogen	62854	0.10 (LRL)	1.64	1.59	3.1
Phosphorus, as phosphorus	00666	0.006 (LRL)	0.022	0.02	9.5
Orthophosphate, as phosphorus	00671	0.008 (LRL)	0.029	0.026	10.9
Dissolved organic carbon (mg/L as C)	00681	0.66 (LRL)	1.1	1.4	24
Radioisotopes and stable isotopes					
Tritium (picocuries per liter)	07000	0.32 (SSLC)	30.4	27.7	9.3
Deuterium/protium ratio (per mil)	82082	--	-117	-117	0
Oxygen-18/oxygen-16 ratio (per mil)	82085	--	-15.21	-15.22	0.1

(for example, JR Engineering, 2005). The TCE contamination on the Belvoir Ranch is from an upgradient former Atlas missile site (Wyoming Department of Environmental Quality, 2013).

Groundwater-quality data presented in this report are compared with several USEPA drinking-water standards for finished (treated) water established in the Safe Drinking Water Act (U.S. Environmental Protection Agency, 2012). The USEPA has established standards for physical properties and chemical constituents in drinking water that may have adverse effects on human health or that may cause cosmetic effects (for example, skin or tooth discoloration) or aesthetic effects (for example, color, taste, or odor). The Maximum Contaminant Level (MCL) is legally enforceable, health-based, and is the maximum permissible level for a constituent in drinking water that is delivered to a user of a public-water system (U.S. Environmental Protection Agency, 2012). The Health Advisory Level (HAL) is a nonenforceable standard that establishes acceptable constituent concentrations for different exposure periods (1 day, 10 day, long-term, and lifetime). A lifetime HAL is the concentration of a chemical below which would not result in any known or anticipated adverse noncarcinogenic health effects over a lifetime of exposure (70 years) (U.S. Environmental Protection Agency, 2012). An action level is a concentration of a chemical, which, if exceeded, requires treatment by the public-water supplier (U.S. Environmental Protection Agency, 2012). Secondary drinking-water regulations (U.S. Environmental Protection Agency, 2012), such as Secondary Maximum Contaminant Levels (SMCLs), are nonenforceable standards related to the cosmetic or aesthetic effects of drinking water and are the maximum recommended level for a constituent in drinking water. Although these USEPA standards only apply to drinking water supplied by public-water systems, not individual well owners, the concentrations are useful for comparison to evaluate the suitability of groundwater collected from wells for drinking.

Overview of the Regional High Plains Aquifer System in Southeastern Wyoming

The regional High Plains aquifer system in southeastern Wyoming is described in this section of the report. The Tertiary lithostratigraphic units composing or underlying the aquifer system are identified, the hydrostratigraphy is described and defined, and the physical and chemical characteristics of the units are described.

Lithostratigraphic Units

In southeastern Wyoming, the High Plains aquifer system can be composed of as many as four saturated Cenozoic lithostratigraphic units, including Quaternary-age unconsolidated deposits, the Miocene-age Ogallala Formation, the Miocene- and Oligocene-age Arikaree Formation, and the late Eocene- and Oligocene-age White River Group or Formation (fig. 4). The Cenozoic lithostratigraphic units unconformably overlie the Upper Cretaceous Lance Formation. The areal extent of the aquifer system and associated lithostratigraphic units in southeastern Wyoming are shown in figure 5.

Alternating episodes of fluvial (stream-laid) and eolian (windborne) deposition and erosion created the Cenozoic (Quaternary and Tertiary) sedimentary rocks composing the High Plains aquifer system in southeastern Wyoming. The Quaternary-age unconsolidated deposits (alluvium and terrace deposits) were deposited by eastward-flowing streams (Lowry and Crist, 1967). Alluvium was deposited from the erosion of the uplift to the west or in situ erosion of Tertiary rocks. Terrace deposits are erosional remnants of alluvium once deposited along former or current stream valleys. Tertiary rocks composing the aquifer system can be divided into two major groups: (1) an older, more homogenous group mostly composed of very fine- to fine-grained volcaniclastic rocks (derived from pyroclastic volcanic material and also described as and considered equivalent to "tuffaceous" or "vitric" in many publications) primarily of eolian origin, and secondarily of fluvial origin, represented by the late Eocene- to Oligocene-age White River Group or Formation and the Miocene- and Oligocene-age Arikaree Formation; and (2) a younger, coarser-grained and more heterogeneous group of rocks composed mostly of epiclastic (derived from weathering or erosion) rocks primarily of fluvial/alluvial origin, represented by the Ogallala Formation (Stanley, 1976, and references therein; Swinehart and others, 1985, and references therein; Swinehart and Diffendal, 1997, and references therein). Paleosols (fossil soils) occur in all three Tertiary lithostratigraphic units (Retallack, 1983; Swinehart and others, 1985, and references therein; Swinehart and Diffendal, 1997, and references therein; LaGarry, 1998; Terry, 1998).

The Ogallala Formation is a complex sequence of cuts and fills composed mostly of stream-laid (fluvial) sediments with minor amounts of volcanic ash. This complex alluvial sequence of cuts and fills is composed of a heterogeneous mixture of unconsolidated or weakly to firmly cemented gravel, sand, silt, and clay (when consolidated/cemented, these lithologies are equivalent to conglomerate, sandstone, siltstone, and mudstone, respectively) with minor amounts of volcanic ash (Foley, 1942; Morgan, 1946; Minick, 1951; Bjorklund, 1959; Moore, 1959; Denson and Bergendahl, 1961; Lowry and Crist, 1967; Stanley, 1971, 1976; Cassiliano, 1980; Cooley and Crist, 1981, 1994; Diffendal, 1984; Swinehart and others, 1985; Swinehart and Diffendal, 1997, and references therein). Thin lenses of well-cemented gravel, sand, and silt cemented primarily with calcium carbonate (caliche or calcrete) and less commonly with silica (silcrete) occur locally, and these lenses or beds are referred to as "mortar beds" in many publications; these cemented lenses or beds are resistant to erosion and commonly form ledges or caprocks. Lowry and Crist (1967, table 1) reported a maximum thickness of about 330 ft for the Ogallala Formation in Laramie County.

In contrast to the Ogallala Formation, the White River Group or Formation and Arikaree Formation are composed mostly of valley fills of eolian volcaniclastic material transported into Wyoming from explosive volcanism in areas located to the west (Sato and Denson, 1967; Stanley, 1976, and references therein; Singler and Picard, 1979a, b; Swinehart and others, 1985, and references therein; Swinehart and Diffendal, 1997, and references therein; Larson and Evanoff, 1998). Some stream-laid sediment also occurs in the units, most commonly at the bases of the lithostratigraphic units. Some of the eolian volcaniclastic material has been reworked and retransported as fluvial deposits.

The Arikaree Formation is composed of friable volcaniclastic, calcareous, very fine- to fine-grained sandstone interbedded with lenses of siltstone, and volcanic ash (Minick, 1951; Babcock and Bjorklund, 1956; Bjorklund, 1959; Moore, 1959; Denson and Bergendahl, 1961; Lowry and Crist, 1967; Sato and Denson, 1967; Stanley, 1976; Cassiliano, 1980; Cooley and Crist, 1981, 1994; Swinehart and others, 1985). Lowry and Crist (1967, table 1) reported a maximum thickness of about 450 ft for the Arikaree Formation in Laramie County.

The White River Group or Formation is characterized by massive, argillaceous (clayey), calcareous mudrocks (commonly siltstone), interbedded with minor amounts of locally occurring sandstone, conglomerate, and volcanic ash beds (Foley, 1942; Morgan, 1946; Gray, 1947; Brady, 1949; Minick, 1951; Rapp and others, 1953; Babcock and Bjorklund, 1956; Bjorklund, 1959; Moore, 1959; Denson and Bergendahl, 1961; Lowry and Crist, 1967; Sato and Denson, 1967; Denson and Chisholm, 1971; Crist and Borchert, 1972; Stanley, 1976; Singler and Picard, 1979a,b; Cassiliano, 1980; Cooley and Crist, 1981, 1994; Swinehart and others, 1985; Swinehart and Diffendal, 1997). In many locations, the "White River" is divided into an upper part (Brule Formation) and a lower part (Chadron Formation), and consequently, elevated to group rank. Lowry and Crist (1967, table 1) reported a maximum thickness of about 500 ft for the White River Formation in

Erathem	System	Series	Lithostratigraphic unit of Love and others (1993)	Hydrogeologic role/unit inferred from Lowry and Crist (1967)[3], Crist and Borchert (1972)[3], and numerous earlier studies[4] in southeastern Wyo.	Hydrogeologic unit of Borchert (1976) [Albin and LaGrange areas, Goshen and Laramie Counties, Wyo.]	Hydrogeologic unit of Lines (1976) and Hoxie (1977, 1979, 1983) [Wheatland Flats, Dwyer, and Muleshoe Flat areas, Platte County, Wyo.]	Hydrogeologic unit of Crist (1977) [Lusk area, Niobrara and northern Goshen Counties, Wyo.]	Hydrogeologic unit of Crist (1980) and Cooley and Crist (1981) [Laramie County, Wyo., and adjacent part of Colo.]		Hydrogeologic unit of Gutentag and Weeks (1980), Weeks and Gutentag (1981), Avery and Pettijohn (1984), and Gutentag and others (1984) [Parts of Colo., Kans., Nebr., N.Mex., Okla., S.Dak., Tex., and Wyo.]	
Cenozoic	Quaternary	Holocene and Pleistocene	Alluvial and terrace deposits	Local aquifers[5]	Not discussed	Not discussed	Alluvium locally in hydraulic connection where adjacent stream is perennial	Local aquifers[5]	Aquifer system[5]	Local aquifers[5]	High Plains aquifer system[5]
Cenozoic	Tertiary	Miocene	Ogallala Formation	Aquifer	Aquifer	Arikaree aquifer/aquifer system	Not present in study area	Aquifer	Aquifer system[5]	Aquifer	High Plains aquifer system[5]
Cenozoic	Tertiary	Miocene	Arikaree Formation	Aquifer	Aquifer	Arikaree aquifer/aquifer system	Aquifer	Aquifer	Aquifer system[5]	Aquifer	High Plains aquifer system[5]
Cenozoic	Tertiary	Oligocene	White River Group or Formation[1,2] — Brule Formation[2]	Aquifer/confining unit[6]	Aquifer/confining unit[6]	Aquifer/confining unit[6,7]	Not discussed	Aquifer[6]	Aquifer system[5]	Aquifer/confining unit[8]	
Cenozoic	Tertiary	Eocene[1]	White River Group or Formation[1,2] — Chadron Formation[1,2]	Aquifer/confining unit[6]	Not discussed	Not discussed	Not discussed	Aquifer[6]	Aquifer system[5]	Confining unit with local aquifers[9]	

Series	Hydrogeologic unit of Libra and others (1981) [Denver-Julesberg Basin, southeastern Wyo.]		Hydrogeologic unit of Crist (1983) [Wheatland Flats area, Platte County, Wyo.]		Hydrogeologic unit of Borchert (1985) [LaGrange area, Goshen and Laramie Counties, Wyo., and small area in western Nebr.]		Hydrogeologic unit of Wyoming Statewide Framework Plan (WWC Engineering and others, 2007, fig. 4-9) [Statewide]	Hydrogeologic unit used in this report (where White River Group or Formation is undivided) [southeastern Wyo. including Laramie County]		Hydrogeologic unit used in this report (where White River Group is divided into Brule and Chadron Formations) [southeastern Wyo. including Laramie County]	
Holocene and Pleistocene	Quaternary aquifers		Local aquifers[5]	Aquifer[10]	Local aquifers[5]	LaGrange aquifer[11]	Major aquifer-alluvial	Quaternary unconsolidated-deposit aquifers[5]	High Plains aquifer system[5,12]	Quaternary unconsolidated-deposit aquifers[5]	High Plains aquifer system[5,9,13]
Miocene (Ogallala Formation)	Major aquifer	Tertiary aquifer system	Not present in study area	Aquifer[10]	Not present in study area	LaGrange aquifer[11]	Major aquifer-sandstone	Ogallala aquifer	High Plains aquifer system[5,12]	Ogallala aquifer	High Plains aquifer system[5,9,13]
Miocene (Arikaree Formation)	Major aquifer	Tertiary aquifer system	Aquifer	Aquifer[10]	Not present or not part of LaGrange aquifer	LaGrange aquifer[11]	Major aquifer-sandstone	Arikaree aquifer	High Plains aquifer system[5,12]	Arikaree aquifer	High Plains aquifer system[5,9,13]
Oligocene (Brule Formation)	Confining unit with discontinuous aquifers[6]	Tertiary aquifer system	Not discussed		Aquifer	LaGrange aquifer[11]	Marginal aquifer	White River aquifer/confining unit[12]		Brule aquifer/confining unit[8]	
Eocene (Chadron Formation)	Confining unit with discontinuous aquifers[6]	Tertiary aquifer system	Not discussed		Aquifer	LaGrange aquifer[11]	Marginal aquifer	White River aquifer/confining unit[12]		Confining unit with local aquifers-Chadron aquifer/confining unit[9,13]	

Dashed line indicates possible hydraulic connection with underlying or overlying hydrogeologic unit.

[1]Historically, the Chadron Formation has been considered Oligocene in age (Love and others, 1993, and references therein). Revision of the Eocene-Oligocene boundary stratotype to about 34 million years before present or mega-annum (34 Ma) (for example, Berggren and others, 1992; Obradovich and others, 1995), and radiometric age-dating of ash beds in the White River Group or Formation in Wyoming indicating an age older than 34 Ma (Prothero and Swisher, 1992), infers the Chadron Formation is late Eocene in age (Swinehart and Diffendal, 1997).

[2]"White River" not elevated to Group rank (and not divided into Brule and Chadron Formations) and the unit is defined as a formation in parts of southeastern Wyoming including much of Laramie County (Love and Christiansen, 1985; Love and others, 1993; Ver Ploeg and others, 1998, 2000, and references therein).

[3]Hydrogeologic role of lithostratigraphic units defined for Laramie County (Lowry and Crist, 1967) and southeastern Laramie County (Crist and Borchert, 1972).

[4]See Knight and Morgan (1937), Burleigh and others (1938), Dockery (1940), Foley (1942), Morgan (1946), Babcock and Rapp (1952), Visher and Babcock (1953), Rapp and others (1953, 1957), Visher and others (1954), Babcock and Bjorklund (1956), Bjorklund (1959), Morris and Babcock (1960), Weeks (1960, 1964), Welder and Weeks (1965), and Herrmann (1972).

[5]Local aquifers in Quaternary unconsolidated deposits can be hydraulically connected laterally or vertically to underlying Tertiary aquifers of the High Plains aquifer system; where hydraulically connected, they are part of the aquifer system.

[6]Brule or Chadron Formations (all or upper part), or both, may be considered aquifers and in hydraulic connection with overlying Tertiary and Quaternary aquifers where permeable (coarse-grained deposits or zones of secondary permeability). Both formations function as lower confining unit(s) to overlying Tertiary and Quaternary aquifers where impermeable.

[7]Brule Formation of White River Group considered part of Arikaree aquifer/aquifer system in western part of study area where permeable.

[8]Brule Formation of White River Group considered an aquifer and part of High Plains aquifer system only where permeable (coarse-grained deposits or zones of secondary permeability) and in hydraulic connection with overlying Arikaree and Ogallala aquifers. Formation functions as lower confining unit to High Plains aquifer system where impermeable.

[9]Regionally, the U.S. Geological Survey does not consider the Chadron Formation to be part of the High Plains aquifer system, and the unit is classified as a confining unit or confining unit with local aquifers underlying the High Plains aquifer system; however, regional U.S. Geological Survey potentiometric-surface maps of the aquifer system include the formation where exposed at land surface in the Goshen Hole area in southeastern Wyoming (Gutentag and Weeks, 1980; Weeks and Gutentag, 1981; Avery and Pettijohn, 1984; and Gutentag and others, 1984).

[10]Aquifer divided into an "upper aquifer" composed of "saturated terrace deposits and the upper part of the Arikaree where the Arikaree is exposed in Wheatland Flats" and "alluvium along Rock Creek-Wheatland Creek, Sybille Creek, Laramie River, and Chugwater Creek," and a "lower aquifer composed of the saturated Arikaree Formation below a depth of 100 feet and all wells deeper than 100 feet" (Crist, 1983, p. 2). The division of the Arikaree Formation into two "zones or units" or aquifers reflects earlier work by Morris and Babcock (1960) and Weeks (1964).

[11]LaGrange aquifer composed of saturated alluvium and both the Brule and Chadron Formations of the White River Group. Ogallala Formation not present in study area. Arikaree Formation, where present in study area, is not part of LaGrange aquifer.

[12]Undivided White River Group or Formation and Brule and Chadron Formations of the White River Group considered aquifers and part of the High Plains aquifer system only where permeable (coarse-grained deposits or zones of secondary permeability). Units function as lower confining unit to High Plains aquifer system where impermeable.

[13]Chadron Formation (or parts of Chadron Formation) considered to be in hydraulic connection with and part of High Plains aquifer system in some areas in southeastern Wyoming by some investigators, most commonly where formation is exposed at land surface and located laterally or vertically adjacent to other Tertiary lithostratigraphic units (Ogallala, Arikaree, and Brule Formations) (for example, Rapp and others, 1957; Borchert, 1985).

Figure 4. Relation of Cenozoic lithostratigraphic units to hydrogeologic units, High Plains aquifer system, southeastern Wyoming.

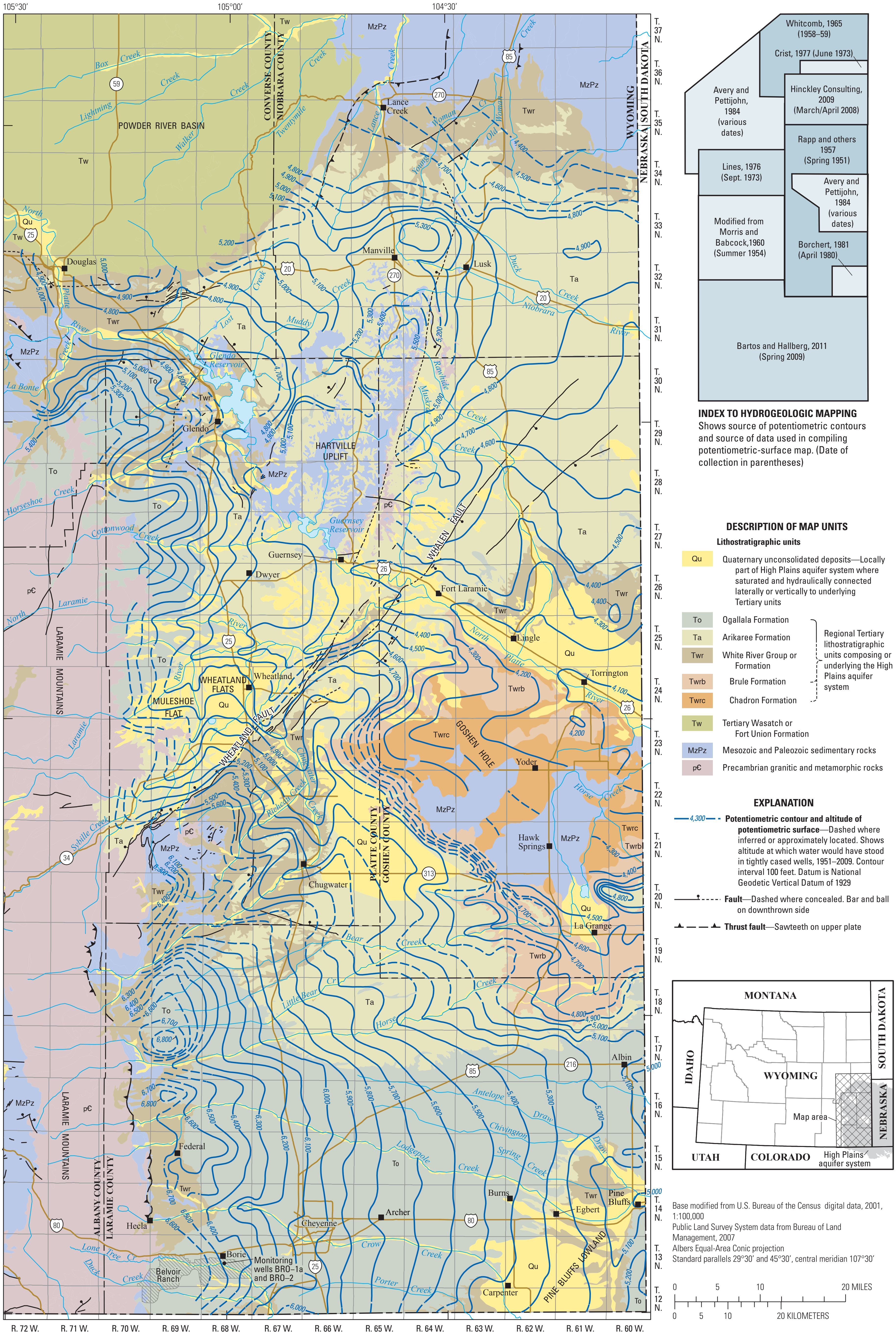


Figure 5. Generalized potentiometric-surface map of the High Plains aquifer system in southeastern Wyoming.

Laramie County. All three (or four if “White River” is divided) Tertiary lithostratigraphic units unconformably overlie the predominantly fluvial Upper Cretaceous Lance Formation.

Hydrostratigraphy

The relation of Cenozoic lithostratigraphic units to hydrogeologic units (hydrostratigraphy) is described in the context of regional and local scales in this section the report.

Regional Hydrostratigraphy

Aquifers in as many as four Cenozoic lithostratigraphic units—Quaternary unconsolidated alluvial and terrace deposits, Ogallala Formation, Arikaree Formation, and the White River Group or Formation—may compose the High Plains aquifer system in southeastern Wyoming (figs. 4 and 5). An aquifer system consists of two or more aquifers, commonly vertically stacked, that are grouped together because of physical connection or sharing of similar geologic and hydrologic characteristics that are best described and studied together. Although considered part of the aquifer system or units that underlie the aquifer system, depending on location, each of the four Cenozoic lithostratigraphic units also have been traditionally defined as an individual hydrogeologic unit (aquifer or confining unit) or hydrostratigraphic unit within or below the larger High Plains aquifer system, and that usage is retained herein (last two columns in fig. 4). The individual hydrogeologic units that compose the High Plains aquifer system can be connected hydraulically to varying degrees, depending on location. Hydraulic connection between the hydrogeologic units varies locally, but regionally the units are in sufficient hydraulic connection to compose a regional aquifer system (Crist, 1980; Cooley and Crist, 1981, 1994; Gutentag and Weeks, 1980; Libra and others, 1981; Weeks and Gutentag, 1981; Avery and Pettijohn, 1984; Gutentag and others, 1984) (fig. 4). Where Quaternary unconsolidated deposits are in hydraulic connection laterally or vertically to the underlying Tertiary aquifers, the deposits generally are considered locally part of the High Plains aquifer system by most investigators (fig. 4). The Tertiary lithostratigraphic units composing the aquifer system overlie one another, although not all are present throughout southeastern Wyoming and adjacent western Nebraska because of erosion or nondeposition (for example, fig. 6). Consequently, wells completed in the High Plains aquifer system in southeastern Wyoming obtain water from one or more of these lithostratigraphic units that varies by location and well construction (some wells are completed in more than one lithostratigraphic unit).

Historically, many different combinations or groupings of the four Cenozoic lithostratigraphic units composing the High Plains aquifer system have been used by many different investigators to define various aquifers and aquifer systems at different locations in southeastern Wyoming (fig. 4); the definition of the aquifers and aquifer systems varies because of the different Cenozoic lithostratigraphic units present at a given location, as well as different hydrogeologic characteristics of the units in the area evaluated and different interpretations of the degree of hydraulic interconnection between the units by different investigators. In many earlier studies, the degree of regional hydraulic interconnection between the different Tertiary hydrogeologic units composing the High Plains aquifer system generally went unrecognized but some earlier studies did recognize hydraulic connection between the units, especially in Laramie County. Lowry and Crist (1967, p. 28) noted that in areas where the Ogallala and Arikaree Formations were lithologically similar in Laramie County, “the water-bearing properties of the Ogallala and of the Arikaree are similar enough that the two formations may be considered as a [single] hydrologic unit.” In addition, the investigators indirectly noted the existence of an aquifer system in Laramie County, stating that “hydraulic connection between the Tertiary formations [in Laramie County] is sufficient to permit contouring a common water table” (Lowry and Crist, 1967, p. 39). Similarly, Crist and Borchert (1972) indicated that hydraulic connection between different Tertiary lithostratigraphic units, as well between Tertiary lithostratigraphic units and extensive alluvial and terrace deposits, in parts of southeastern Laramie County was sufficient to permit contouring a common water table. Crist (1980) was the first investigator to formally identify and propose a regional “aquifer” or “aquifer system” composed of all the Tertiary lithostratigraphic units in southeastern Wyoming, although his study was limited to Laramie County and the aquifer system was unnamed; in addition, Crist (1980) does state that part of the reason the Tertiary lithostratigraphic units were “grouped” together into an aquifer system for modeling purposes was because of difficulty differentiating the individual lithostratigraphic units throughout the county. Subsequently, Cooley and Crist (1981) and Libra and others (1981) also recognized a regional aquifer system composed of all Tertiary lithostratigraphic units in southeastern Wyoming; the aquifer system was unnamed in Cooley and Crist (1981) but was informally defined as the “Tertiary aquifer system” in Libra and others (1981, fig. II-5) (see “Hydrogeologic unit of Libra and others (1981)” column in fig. 4). In fact, numerous past and current reports use this informal “Tertiary aquifer system” nomenclature or variations thereof (“Tertiary aquifer” or “upper Tertiary aquifer”) to regionally define the High Plains aquifer system in southeastern Wyoming. Regional studies of the aquifer system in Cenozoic lithostratigraphic units in southeastern Wyoming and equivalent lithostratigraphic units in adjacent states by the USGS Regional Aquifer System Analysis (RASA) program led to formal naming and definition of the High Plains aquifer system (Gutentag and Weeks, 1980; Weeks and Gutentag, 1981; Avery and Pettijohn, 1984; Gutentag and others, 1984; Weeks and others, 1988). Figure 4 summarizes and synthesizes these and other previous studies, and attempts to unify regional aquifer and aquifer system nomenclature in southeastern Wyoming while essentially reflecting the formal definition of the regional High Plains aquifer system by the USGS RASA program (Gutentag and

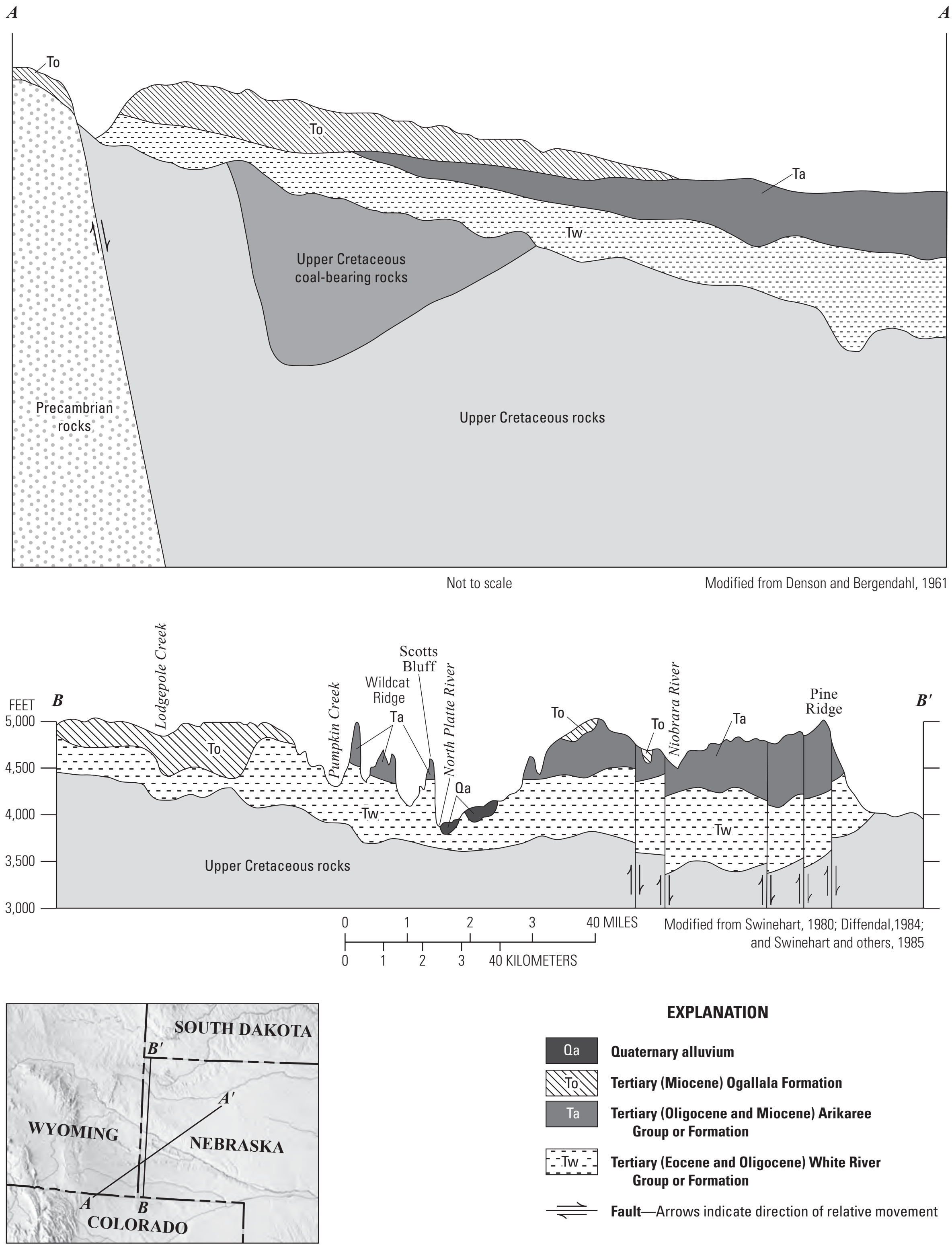


Figure 6. Simplified schematic showing relation of the Tertiary lithostratigraphic units composing the High Plains aquifer system, southeastern Wyoming to Nebraska panhandle (*A–A′*), and cross section across western Nebraska showing relation of Tertiary lithostratigraphic units composing the High Plains aquifer system (*B–B′*).

Weeks, 1980; Weeks and Gutentag, 1981; Avery and Pettijohn, 1984; Gutentag and others, 1984; Weeks and others, 1988); however, there are some notable discrepancies and contradictions between the regional USGS definition of the aquifer system and local definitions.

Discrepancies in regional aquifer and aquifer system nomenclature (hydrostratigraphy) arise primarily as a result of different interpretations of the hydrogeologic role of the White River Group or Formation in southeastern Wyoming. Although the Arikaree and Ogallala Formations are defined as aquifers within the High Plains aquifer system throughout their areal extent in southeast Wyoming and adjacent states by all investigators, the White River Group or Formation (or parts of the unit) is defined as either an aquifer or confining unit, depending upon local hydrogeologic characteristics and if the "White River" has been elevated to group rank and divided into the Brule and Chadron Formations (fig. 4). Most investigators, including the USGS RASA program, define the Brule Formation as an aquifer and part of the High Plains aquifer system only where locally permeable or in hydraulic connection with the overlying Ogallala or Arikaree Formations where present; where impermeable, the formation is defined as a confining unit underlying the High Plains aquifer system. Regionally, the USGS does not consider the Chadron Formation underlying the Brule Formation to be part of the High Plains aquifer system, and the unit is classified as a confining unit, confining unit with local aquifers, or an aquifer underlying the High Plains aquifer system (fig. 4); however, regional USGS potentiometric-surface maps group the Chadron Formation with the Brule Formation and show both units as part of the aquifer system where exposed at land surface in southeast Wyoming, primarily where the Chadron Formation is exposed at land surface in the Goshen Hole area (fig. 5) (Gutentag and Weeks, 1980; Gutentag and others, 1984; Weeks and Gutentag, 1981; Avery and Pettijohn, 1984; Weeks and others, 1988), inferring hydraulic connection with the rest of the aquifer system (see Chadron Formation outcrop area in Goshen Hole in fig. 5) and somewhat contradicting the USGS RASA regional definition of the aquifer system. In addition, some local studies (most of which were conducted by the USGS and shown in fig. 4) consider the Chadron Formation (or parts of the Chadron Formation), where locally permeable, to be in hydraulic connection with adjacent members of the aquifer system in some areas in southeast Wyoming, primarily where the formation is exposed at land surface and located laterally or vertically adjacent to other Tertiary lithostratigraphic units in the Goshen Hole area (for example, Rapp and others, 1957; Borchert, 1985) or where the "White River" is not elevated to group rank and is defined as a formation (for example, Crist, 1980; Cooley and Crist, 1981). Consequently, the definition of the High Plains aquifer system proposed herein (last two columns in fig. 4) acknowledges the regional definition of the system by the USGS RASA program, whereas also acknowledging likely local hydraulic connection of the White River Group or Formation (including the Chadron Formation) with other Cenozoic lithostratigraphic units commonly considered part of the aquifer system in parts of southeastern Wyoming.

Local Hydrostratigraphy

Broad classification of regional lithostratigraphic units as regional hydrogeologic or hydrostratigraphic units, as described in the previous section, is a convenient tool to describe and evaluate characteristics of the High Plains aquifer system at a regional scale; however, this approach is a simplification of a complex natural system and this classification is not always appropriate when evaluating the aquifer system or individual hydrogeologic units of the aquifer system at a local scale. Stratigraphic nomenclature commonly is not appropriate for classification of hydrogeologic units. Stratigraphic units are identified by numerous characteristics, including age and conformable or unconformable contacts, whereas hydrogeologic units (or hydrostratigraphic units) are defined primarily by the water-bearing characteristics of rocks within part of an individual stratigraphic unit (sometimes referred to as a "zone"), an entire stratigraphic unit, or a group of stratigraphic units (see Lohman and others, 1972). In addition, it should be noted that differences observed in lithology at the local scale may simply reflect a facies change within the same stratigraphic unit rather than an actual difference in stratigraphic units (and associated hydrogeologic/hydrostratigraphic units). Consequently, different water-bearing zones identified within the High Plains aquifer system may be reflective of different facies within the same stratigraphic unit rather than a different stratigraphic unit (and associated regional hydrostratigraphic unit). Ultimately, the scale of the study should be considered when defining hydrogeologic units (see discussion in Hansen, 1991, p. 65–76).

In southeastern Wyoming, local lithologies in each Tertiary lithostratigraphic unit of the High Plains aquifer system vary substantially, and consequently, hydrogeologic characteristics associated with the different lithologies (rock types) vary substantially as well. Because of this heterogeneity, aquifer and aquifer system geologic and hydrogeologic characteristics should be determined locally for many studies rather than relying on characteristics obtained from regional studies. For example, studies by Earth Technology Corporation (1984) and Cooley and Crist (1994) of the aquifer system near Cheyenne noted that even the Ogallala Formation was difficult to classify as a single hydrogeologic unit. In fact, because of hydraulic heads in water-bearing zones substantially varying over relatively short distances, Cooley and Crist (1994) concluded/inferred that even the Ogallala Formation could be considered its own aquifer system at the local scale. Therefore, the authors of this report believe the High Plains aquifer system in southeastern Wyoming was perhaps most succinctly described by a recent report (Wyoming State Engineers Office, 2008, p. 14) as a "complex aquifer system of multiple interconnected water-bearing zones with both primary and secondary permeability and not a sandbox."

High Plains Aquifer System Characteristics

The physical and chemical characteristics of the Tertiary lithostratigraphic units composing the High Plains aquifer system are summarized in this section of the report.

Physical Characteristics

As noted previously, the High Plains aquifer system is composed of as many as four Cenozoic lithostratigraphic units. Individual Tertiary hydrogeologic units composing the High Plains aquifer system are briefly described in the following subsections.

Ogallala Aquifer

The Ogallala aquifer, composed of the permeable parts of the Ogallala Formation, is present in parts of four counties in Wyoming, but the aquifer primarily is used in Laramie County in southeastern Wyoming (fig. 5). In Laramie County, the aquifer is used widely as a source of water for domestic, stock, industrial, public-supply, and irrigation purposes. The relation of the Ogallala aquifer to other underlying and overlying hydrogeologic units of the High Plains aquifer system is shown in figure 4.

Because of the heterogeneous nature of the Ogallala Formation, physical characteristics of the Ogallala aquifer are highly variable. Permeability of the Ogallala aquifer is primary (intergranular) and highly variable in southeastern Wyoming because of lithologic heterogeneity of the Ogallala Formation; transmissivity and well yields are highest where coarse-grained unconsolidated or poorly consolidated sand and gravel beds are present. Fine-grained sediments (clay, silt, and very fine sand) are very common within the Ogallala Formation, and wells completed in these sediments can be unsuccessful because of negligible or very low well yield (Knight and Morgan, 1937; Foley, 1942; Morgan, 1946; Lowry and Crist, 1967; Cooley and Crist, 1994); in addition, fine-grained sediments and zones of well-cemented sediments interbedded with coarse-grained water-bearing zones can result in widely varying hydraulic heads over short distances and locally confining or semiconfining conditions (for example, Cooley and Crist, 1994).

Arikaree Aquifer

The Arikaree aquifer, composed of the permeable parts of the Arikaree Formation (described in the "Lithostratigraphic Units" section), is present in parts of as many as five counties in southeastern Wyoming, and the aquifer is present at land surface throughout much of the High Plains aquifer system areal extent (fig. 5). The relation of the Arikaree aquifer to underlying and overlying hydrogeologic units of the High Plains aquifer system is shown in figure 4. The aquifer primarily is used as a source of water for domestic and stock use, and less commonly for public-supply and irrigation use (Trihydro Corporation, 2006). The Arikaree Formation (aquifer) is absent in areas west and south of Cheyenne because of erosion or nondeposition (Denson and Bergendahl, 1961; Bart, 1974, 1975; Cooley and Crist, 1981, 1994).

Although Ogallala aquifer properties are highly variable primarily because of lithologic heterogeneity, Arikaree aquifer properties may be highly variable because of differences in the type of permeability present. The lithology of the Arikaree Formation (excluding the basal conglomerate reported in some areas) primarily is poorly to moderately cemented very fine- to fine-grained sandstone and generally is relatively homogenous (Morris and Babcock, 1960; Whitcomb, 1965; Stanley, 1976; Borchert, 1976), especially when compared to the overlying Ogallala Formation (Borchert, 1976). Because of predominantly fine-grained aquifer sediments in the Arikaree Formation, well yields in the Arikaree aquifer generally are small to moderate at most locations; consequently, large well yields typically are obtained by penetrating large thicknesses of the aquifer (Rapp and others, 1957; Morris and Babcock, 1960; Weeks, 1964; Whitcomb, 1965). In most areas, permeability is primary (intergranular). Areas of high permeability and transmissivity reported in some studies may be attributable to secondary permeability development from localized fractures (Rapp and others, 1957; Morris and Babcock, 1960; Whitcomb, 1965) or concretionary zones (Whitcomb, 1965). Morris and Babcock (1960, p. 37) noted that the basal conglomerate in Platte County, where present, saturated, and poorly cemented, "may yield large quantities of water to wells;" however, the investigators also noted that "the basal conglomerate is well cemented in most places, and it is doubtful that much greater yield could be obtained from it than from the upper part of the formation."

In some areas within Laramie County, lithologic and hydrologic characteristics of the Ogallala and Arikaree aquifers can be very similar. Lowry and Crist (1967, p. 28) noted that the Arikaree Formation in Laramie County could be lithologically very similar to the Ogallala Formation in places and that "it is difficult to distinguish the contact between the two formations in many wells;" the investigators also noted that in areas where both units were lithologically "similar in appearance," water-bearing properties of both units were similar enough that the two formations may be considered as a single hydrogeologic unit. Similarly, Cooley and Crist (1981) also noted the difficulty in separating the two formations and noted that the contact between the Ogallala and Arikaree Formations in their fence diagrams for southeastern Wyoming "generally was determined rather arbitrarily."

White River Group or Formation

As described in the "Hydrostratigraphy" section of this report, the White River Group or Formation is defined as either an aquifer or a confining unit, based on local physical characteristics. Permeability in the White River Group or Formation is because of either the presence of primary permeability in locally occurring coarse-grained deposits such as sandstone lenses and stringers and occasional conglomerates, or more commonly, secondary permeability in various mudrocks (primarily siltstone) that compose most of the unit(s). Consolidated mudrocks such as siltstone in the Brule Formation of the White River Group generally yield small volumes of water; large yields are obtained only in zones with secondary permeability development. Numerous early studies attributed locally high well yields in the White River Group or Formation [Brule Formation] in southeastern Wyoming to secondary permeability development by fractures, joints, and fissures (Knight and Morgan, 1937; Burleigh and others, 1938; Dockery, 1940; Warner, 1947; Babcock and Rapp, 1952; Rapp and others, 1953, 1957; Babcock and Bjorklund, 1956; Bjorklund, 1959; Morris and Babcock, 1960). Secondary permeability in the White River Group or Formation of southeastern Wyoming and adjacent western Nebraska has been the source of much discussion, speculation, and investigation over the years; many of the interpretations conflict with one another.

Lowry (1966) and Lowry and Crist (1967) reevaluated these earlier studies suggesting that secondary permeability primarily was because of fractures, joints, and fissures. It should be noted that most geologic and hydrogeologic studies conducted in southeastern Laramie County in the Pine Bluffs Lowland area do not elevate the “White River” to group rank and consequently, define the unit as a formation and do not divide the upper part of the unit into the Brule Formation and the lower part into the Chadron Formation. Geologic studies and mapping immediately adjacent to the Pine Bluffs Lowlands area conducted immediately across the Wyoming-Nebraska State line show that the “White River” exposed at land surface in the area can be identified clearly as the Brule Formation (Swinehart and Diffendal, 1997, and references therein). Lowry (1966) and Lowry and Crist (1967) observed that many of the wells with large yields previously attributed to secondary permeability development were located in valleys of major drainages; a more detailed study led Lowry (1966) and Lowry and Crist (1967) to conclude that many of the wells also likely were completed in overlying Quaternary unconsolidated deposits (alluvium) composed of material derived from the “White River” [Brule Formation] rather than the formation itself. Consequently, because the large-yielding wells also were screened partially or completely in more permeable alluvium, “difficulty in differentiating the two has left the impression that the White River Formation [Brule Formation] is a much better aquifer than it really is” (Lowry, 1966, p. D219). In wells where a more detailed examination showed that large yields clearly were attributable to secondary permeability and not attributable to more permeable alluvium, Lowry (1966) and Lowry and Crist (1967) concluded that piping, rather than fractures, joints, and fissures, was the process primarily responsible for the locally high secondary permeability of the White River Formation [upper part or Brule Formation]. The investigators concluded that the piping likely occurred before deposition of the overlying alluvium or Ogallala Formation (favorable paleotopography) and that other conditions favorable for piping to occur include favorable grain-size distribution, mineralogy, and geochemistry; some of these conditions also were considered favorable to piping development in the Brule Formation of southeastern Wyoming in studies by Crist and Borchert (1972) and Borchert (1976).

Crist and Borchert (1972) used televiewer logs from wells to examine secondary permeability in the White River Formation [upper part or Brule Formation] in southeastern Laramie County. The investigators reported openings resembling caverns or tubes, but this interpretation also has been interpreted as asymmetric spalling of the borehole (Barrash and Morin, 1987).

Borchert (1976) used televiewer logs from wells to examine secondary permeability in the White River Formation [upper part or Brule Formation] in the Albin and La Grange areas of southeastern Wyoming. Dark regions were reported from examination of the televiewer logs, and these regions were interpreted as irregular cavities. In addition, investigators did not observe any features considered to be fractures other than possibly bedding plane fractures. Examination of the same dark regions in televiewer logs from another and more detailed study of the Brule Formation near Sidney, Nebraska (not shown, about 85 miles east of Cheyenne, Wyo.), led Barrash and Morin (1987, p. 452) to conclude that these regions also could be “artifacts because of drilling disturbance and/or removal of lateral support from structurally weak, intensely fractured material.”

At a study location near Sidney Draw west of Sidney, Nebr., Barrash and Morin (1987) conducted perhaps the most detailed study of permeability in the Brule Formation. Using many different geological, geophysical, and hydrogeological methods, the investigators concluded that (1) vertical hydraulic conductivity in the unfractured part of the Brule Formation is enhanced at some locations by several types of features, including abundant pedotubules (vertical features in the rocks such as preserved animal burrows), and horizontal hydraulic conductivity in the unfractured part of the formation that could be enhanced by subhorizontal parting planes; (2) acoustic televiewer logs can be used to identify zones of secondary permeability (fracture zones), and fracture zones correlate with locations of enlarged borehole diameter; and (3) televiewer images of fracture zones indicate fracture networks and voids (similar to some conclusions reached by Crist and Borchert, 1972, and Borchert, 1976), but the study could neither clearly support nor refute interpretation of piping for the origin or nature of the fractured zones as proposed in earlier studies (Lowry, 1966; Lowry and Crist, 1967; Crist and Borchert, 1972; and Borchert, 1976). Regardless of the source of permeability, all investigators conclude that permeability generally is low in the mudrocks that compose much of the White River Group or Formation unless secondary permeability is present.

Regional Groundwater Flow, Recharge, and Discharge

Groundwater in the High Plains aquifer system in southeastern Wyoming generally moves from west to east, but this pattern of flow is altered locally by groundwater divides, and by groundwater discharge to streams (fig. 5). In Laramie County, the altitude of the potentiometric surface declines from about 6,800 ft in the west to about 5,000 ft in the east (fig. 5; Bartos and Hallberg, 2011). Recharge is from infiltration and percolation of precipitation, losses (seepage) from ephemeral and perennial streams, and infiltrating irrigation water (Lowry and Crist, 1967). Discharge is by the movement of water to seeps and springs, streams, evapotranspiration, and withdrawal from wells (Lowry and Crist, 1967). Some groundwater also leaves the aquifer system in southeastern Wyoming as underflow, especially in the Quaternary unconsolidated-deposit aquifers (for example, Rapp and others, 1953; Bjorklund, 1959; Lowry and Crist, 1967).

Chemical Characteristics

Chemical characteristics of the High Plains aquifer system in southeastern Wyoming were summarized using major-ion composition and dissolved-solids concentrations. The dissolved-solids concentration commonly is called the salinity of the water and is classified as follows: fresh, less than 1,000 milligrams per liter (mg/L); slightly saline, 1,000–3,000 mg/L; moderately saline, 3,000–9,999 mg/L; very saline, 10,000–35,000 mg/L; and briny, more than 35,000 mg/L (Heath, 1983). The major-ion composition of groundwater sampled from different hydrogeologic units in the High Plains aquifer system in southeastern Wyoming was summarized using trilinear diagrams (fig. 7) (Piper, 1944). Calcium and bicarbonate were the predominant ions in water from the Ogallala and Arikaree aquifers, and thus, groundwater from these aquifers can be classified as primarily calcium-bicarbonate type (fig. 7*A*, *B*). Almost all waters from the Ogallala and Arikaree aquifers were classified as fresh (dissolved-solids concentrations less than 1,000 mg/L; fig. 7*A*, *B*).

Calcium-bicarbonate type waters also were common in the various “White River” hydrogeologic units, but unlike in waters from the Ogallala and Arikaree aquifers, sodium also was a predominant cation in many of the groundwater samples; therefore, many of the groundwater samples could be classified as a calcium-sodium-bicarbonate type or mixed cation-bicarbonate type waters (fig. 7*C*, *D*, and *E*). Most waters from the “White River” hydrogeologic units were fresh, but some waters were slightly saline (dissolved-solids concentrations ranging from 1,000 to 3,000 mg/L; fig. 7*C*, *D*, and *E*) and moderately saline (dissolved-solids concentrations ranging from 3,000 to 9,999 mg/L; fig. 7*C*, *D*, and *E*). Increasing dissolved-solids concentrations appear to correspond to increasing sodium and sulfate content (fig. 7*C*).

Geologic Characteristics

The geologic characteristics of the Ogallala Formation and White River Group or Formation at the study location (fig. 1) are described in this section. Characterization of the lithology and lithostratigraphy was derived by use of cuttings, core, and geophysical logs collected from borehole BRO–1 and monitoring well BRO–2, through which visual descriptions, samples for XRD and petrographic analyses, and lithostratigraphic descriptions were obtained.

Lithology and Lithostratigraphy

The term “lithology” herein refers to unconsolidated, semiconsolidated, or consolidated sediments collected during drilling and coring at the study location. Lithology is described at several scales: visual descriptions of all cuttings and core, including utilization of a binocular microscope (plate 1), supplemented with selected photographs; elemental composition of 10 ground-up samples using XRD (appendix tables 1–1 to 1–16); and petrographic analysis of 10 thin sections supplemented with SEM and further supplemented with selected photographs. In addition, the lithology and lithostratigraphy is evaluated in relation to the responses of various geophysical logging methods.

A detailed visual description of sediments from cuttings and core collected from borehole BRO–1 and monitoring well BRO–2 were combined with XRD analyses and petrographic descriptions to construct a detailed composite description of lithology (texture and composition) and lithostratigraphy at the site (plate 1); results of geophysical logging also are shown on plate 1 to facilitate detailed comparison with described lithology. Lithology from the detailed description shown on plate 1 is generalized and shown in relation to monitoring wells BRO–1a and BRO–2 construction, nearby monitoring well WR–3 construction, and selected geophysical logs on figure 3.

After lithologic and geophysical characterization was completed, identified lithologic units were assigned to lithostratigraphic units on the basis of comparisons with published descriptions of the Cenozoic sequence in southeastern Wyoming and western Nebraska. Numerous previous investigations in the vicinity of Cheyenne have characterized the lithology, lithostratigraphy, and hydrostratigraphy of the Cenozoic sequence using only qualitative drill cuttings descriptions and geophysical logs. Earlier studies have noted that a more quantitative approach to characterization of these units in the vicinity of Cheyenne is needed (for example, Weston Engineering, 1996a; Wyoming State Engineer’s Office, 2008). Building on previous investigations, this study attempts to provide a more quantitative and systematic characterization of the Cenozoic sequence along Lone Tree Creek in the vicinity of Cheyenne.

Soil Profile

Predominantly dark grayish brown to brown colored fine-grained sediments (clay, silt, and very fine sand) with roots and some organic matter comprised the upper 3.5 ft of material at the study site on Belvoir Ranch (plate 1). These sediments represent the soil profile at the study location (fig. 1).

Ogallala Formation

Characteristics of sediments collected from core and cuttings from the Ogallala Formation (about 3.5 to 275 ft BLS) at the study location are described in this section of the report. Sediment characteristics within this depth interval are described using visual techniques, XRD and thin-section petrography, and geophysical log characteristics. Finally, the resulting description of these characteristics is compared and contrasted with previously published descriptions and lithostratigraphy to assign sediments of this depth interval to the Ogallala Formation.

Visual Description

Sediments from 3.5 to about 275 ft BLS generally were very coarse—sand- and gravel-sized sediments generally predominated, and mud-sized sediments (silt and clay) generally composed a much smaller percentage of the sediments than sand- and gravel-sized sediments, although many depth intervals (zones) had mud-sized sediments that composed a much larger percentage of the sediment-size range (plate 1; fig. 3). Examples of intervals with a notably high percentage of fine-grained sediments are the 155- to 170-ft, 185- to 200-ft, and 240- to 255-ft depth intervals (plate 1; fig. 3). Coarse-grained sediments (sand- and gravel-sized) were of variable composition; igneous rock fragments (primarily granite, commonly pink-colored) and light- and dark-colored metamorphic rock fragments (quartzite, gneiss, and schist) composed a substantial percentage of the sediments (plate 1). Sedimentary rock fragments, indicative of immature sediments, were observed in some intervals, but were relatively uncommon. Comparison of the lithology of the igneous and metamorphic rock fragments with published descriptions of plutonic igneous rocks (Precambrian-age Sherman Granite) and associated metamorphic (metasedimentary and metavolcanic) rocks that occur in isolated masses within the extensive body of Sherman Granite composing the Laramie Mountains (for example, Frost and others, 1993, and references therein; Houston and Marlatt, 1997, and references therein) indicated that the rocks composing the sediments largely were derived from the adjacent Laramie Mountains. Morgan (1946, p. 12) attributed this anomalous accumulation of coarse-grained sediments to “an alluvial fan built up by Lone Tree Creek with the apex of the fan near the mouth of Lone Tree Canyon where the stream emerges from the mountains.”

Although both igneous and metamorphic rock fragments were present, plutonic igneous rock fragments composed of granitic clasts from the Sherman Granite were the most common, perhaps composing as much as three-quarters of the sand- and gravel-sized fraction in some depth intervals. Similarly, large percentages of igneous material were noted in gravel-sized sediments from gravel/conglomerate samples collected west of Cheyenne by Stanley (1971; 1976, fig. 13, p. 305). Both Stanley (1971, 1976) and Blackstone (1975) associated these sediments with the Ogallala Formation, and Stanley (1971, 1976) definitively showed that these coarse igneous and metamorphic rock fragments were derived from the Laramie Mountains immediately to the west and areas west of the Front Range south of the Laramie Mountains in northern Colorado. Using petrographic methods, Stanley (1976) determined that the granitic clasts that compose a large percentage of the sediments were derived primarily from the Sherman Granite of the Laramie Mountains, confirming and expanding on earlier petrographic descriptions by Minick (1951) and qualitative descriptions made by other investigators (Foley, 1942; Morgan, 1946; McGrew, 1953; Moore, 1959, 1963; Lowry and Crist, 1967; and see additional information in the “Lithostratigraphy” section that follows).

Although quartz was the most abundant mineral (as liberated grains and as quartzite), feldspar composed a large percentage of the sediment; consequently, sediments of this lithostratigraphic unit can be described as “arkosic.” In fact, numerous investigators have noted the “arkosic” character (Foley, 1942; Morgan, 1946; McGrew, 1953; Moore, 1963) or “feldspathic” character (Stanley, 1971, 1976; Stanley and Benson, 1979; Stanley and Faure, 1979) of these sediments.

The color and coarse-grained nature of the Ogallala Formation sediments is shown in photographs of core from one depth interval in borehole BRO–1 (26.5 to 27 ft BLS, fig. 8*A*) and cuttings from two greater depth intervals in monitoring well BRO–2 (115 to 120 ft BLS and 220 to 225 ft BLS, figs. 8*B* and *C*). Gravel-sized sediments (pebbles and cobbles) commonly were broken into smaller pieces (shattered) as a result of the drilling/coring process. Light- to dark-colored accessory minerals were relatively common (plate 1). Sediments (sand- and gravel-sized particles) generally were immature, as indicated by subrounded to subangular rounding and subprismoidal to subdiscoidal sphericity when not shattered by drilling (plate 1; figs. 8*A*–*C*) and uncommon sedimentary rock fragments. Orange, red, or yellow staining was observed in many depth intervals. Carbonate cementation was observed in many depth intervals (plate 1), but some of this material actually may be fine-grained matrix material.

The amount or degree of cementation (consolidation) was difficult to evaluate, particularly in the interval that was drilled rather than cored; however, evaluation of core from the upper 58.5 ft obtained using hollow-stem auger drilling methods indicated that cementation was highly variable and commonly limited to specific, discrete zones of relatively small thickness. During drilling, even with excellent cuttings returns, it was impossible to determine if intervals where drilling was difficult (as indicated by drill rig “bouncing” or “chattering”) were because of well-cemented/consolidated

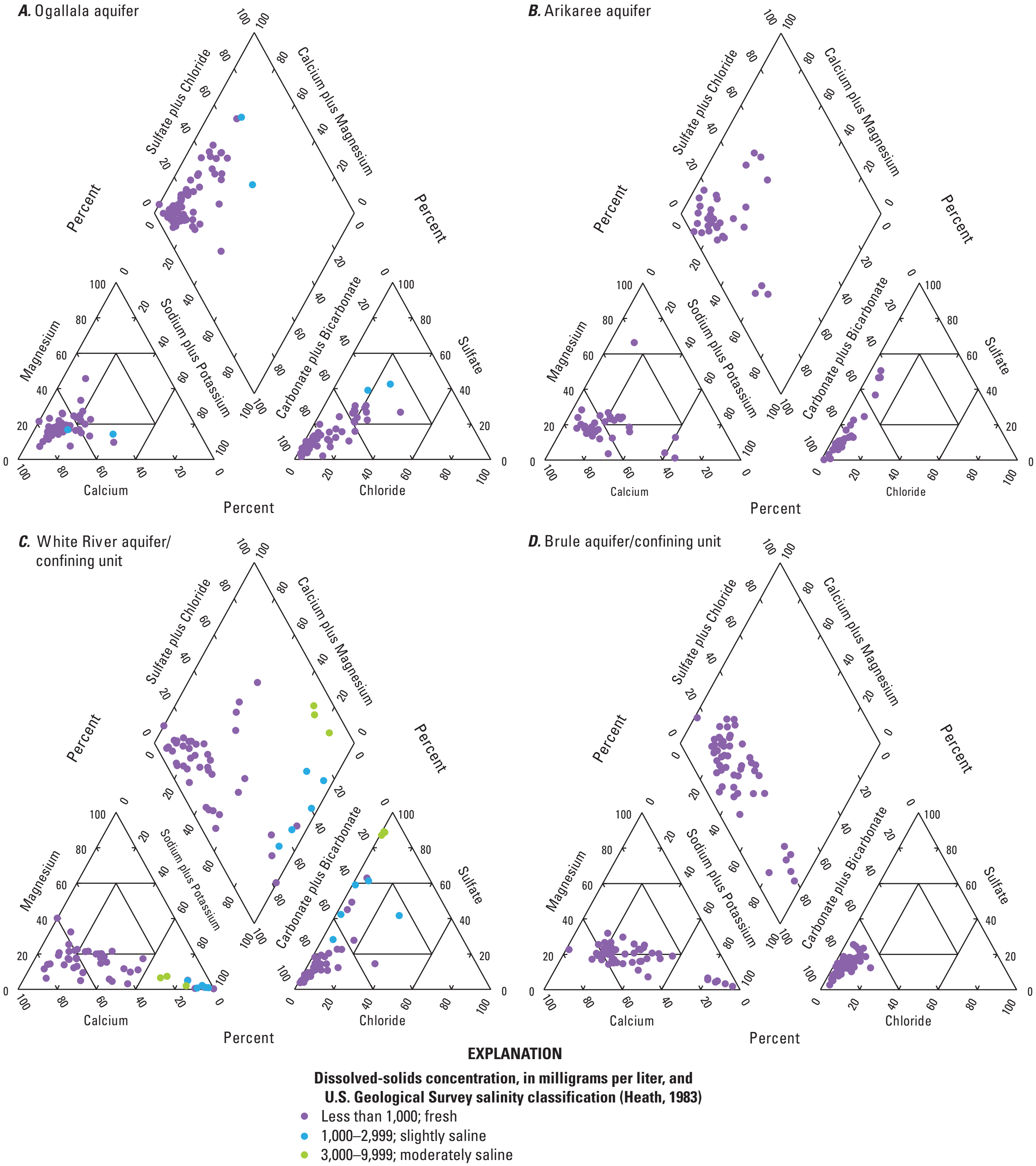


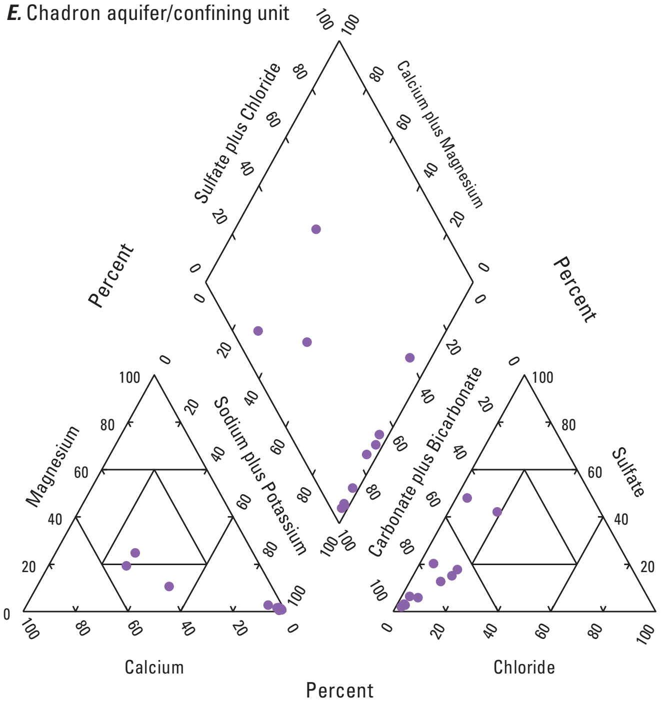
Figure 7. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for groundwater samples from the High Plains aquifer system, southeastern Wyoming.

zones or because of the difficulty of drilling through intervals with very large sediments (especially intervals with cobble-sized sediments). Consequently, on the basis of the overall unconsolidated to semiconsolidated nature of sediments, this upper coarse-grained lithostratigraphic unit from about 3.5 ft to about 275 ft BLS is perhaps best summarized as "unconsolidated to semi-consolidated sand and gravel (plate 1) with interbedded fine-grained sediments (silt and clay) with discrete zones of consolidation (cementation)" rather than lithified sediments ("rocks").

X-Ray Diffraction and Petrography

After visual description was complete, three intervals from this coarse-grained lithostratigraphic unit were subsampled for additional analysis using XRD (26.5–26.75, 115–120, and 220–225 ft BLS), and three adjacent intervals were subsampled for thin-section petrography (26.9–27, 115–120, and 220–225 ft BLS). Each of the intervals selected for XRD and thin-section petrography were adjacent to one another to facilitate use of both analytical methods to characterize the

E. Chadron aquifer/confining unit



EXPLANATION

Dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

- Less than 1,000; fresh
- 1,000–2,999; slightly saline
- 3,000–9,999; moderately saline

Figure 7. Trilinear diagrams showing major-ion composition and dissolved-solids concentrations for groundwater samples from the High Plains aquifer system, southeastern Wyoming.—Continued

sediments in essentially the same depth interval. Point-count data for the petrographic thin sections are listed in table 5.

The thin section constructed of core from the 26.9–27-ft depth interval of borehole BRO–1 indicates the sediments in this depth interval are best described as an unconsolidated, immature (subangular grains) gravel; the sample is poorly sorted with grain sizes ranging from micron-size matrix material to pebble- and cobble-size grains that are as large as 0.6-centimeter (cm; 0.2-in.) in diameter in the thin section. Constituent grains were sourced from granitic and metamorphic terrains. Although some liberated quartz grains were surrounded by clays and calcite cement, quartz, which is the most abundant constituent in the Ogallala Formation (table 5), occurred mainly in the granitic and schistose (metamorphic) rock fragments. Granite fragments were composed of polycrystalline quartz, potassium feldspar (twinning pattern indicated microcline), and plagioclase with accessory brown biotite or hornblende $[(Ca,Na)_2(Mg,Fe,Al)_5(Al,Si)_8O_{22}]$. Quartz grains had undulose ("wavy") extinction because of strain within the quartz lattice, which is a common optical property of quartz in igneous and metamorphic rocks. Other accessory minerals were minor pyroxene, epidote, and zircon grains. Potassium feldspars showed areas of myrmekitic texture, which is a mixture of vermiform quartz and plagioclase; this "wormy" texture may be diagnostic of their granitic source area.

Metamorphic rock fragments that were identified visually (as described in the previous "Visual Description" subsection for the Ogallala Formation and as identified on plate 1) were identified in thin section as schistose metamorphic rock fragments composed of layers of quartz, plagioclase, opaque iron-oxides (magnetite altering to hematite?), biotite, and hornblende. The XRD results for samples from the 26.5- to 26.75-ft depth interval (appendix tables 1–1 to 1–6) indicate chlorite in the fine fraction of the sample, but biotite and hornblende are visibly partially altered to chlorite in thin section, both in the foliated (preferential alignment) schistose rock fragments and as liberated grains.

Some minerals have undergone dissolution and replacement. Hornblendes have undergone partial dissolution and replacement in the very fine-grained carbonate cement (fig. 9*A*). Ferromagnesium minerals such as large liberated grains of hornblende have undergone partial dissolution and exhibit alteration, with iron-oxide rims that outline the former boundary of the grain (fig. 9*B*). The SEM micrograph (fig. 9*B*) is a close-up of a hornblende grain showing dissolution etching, secondary porosity (black void area), and the formation of an iron-oxide rind at the rim of the former extent of the grain. This dissolution texture demonstrates that elements that compose hornblende (for example, calcium, sodium, magnesium, iron, and aluminum) have gone into solution.

Coarse-grained plagioclase commonly is altered to clays; petrographically, the very fine-grained white clays in the altered plagioclase are called sericite $[K(Al,Fe,Mg)_2(SiAl)_4O_{10}(OH)_2 \cdot H_2O)]$, a very fine-grained mica with a similar chemistry and structure to kaolin. The

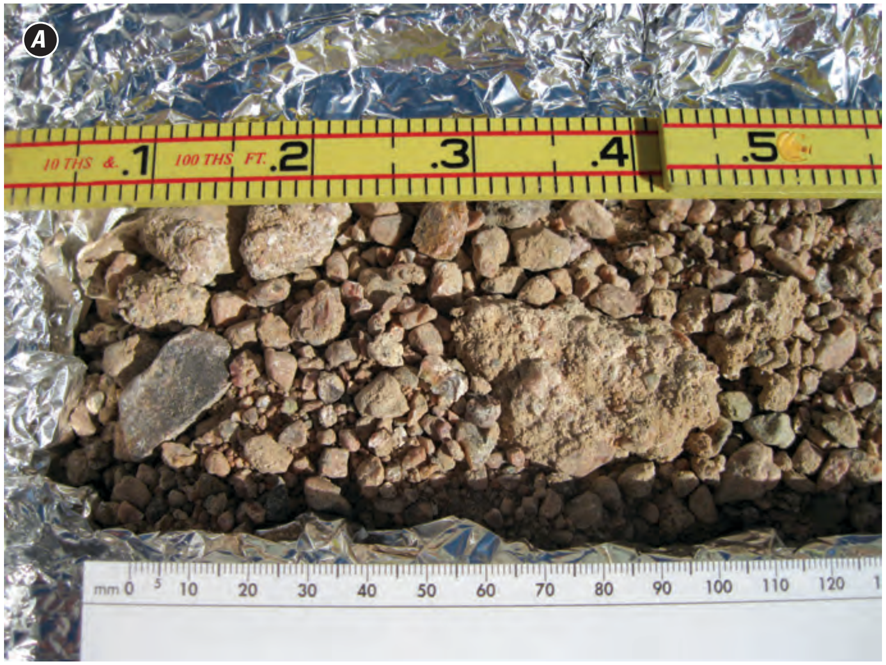


Figure 8. Core and cuttings from borehole BRO–1 and monitoring well BRO–2, Ogallala Formation, Belvoir Ranch, Laramie County, Wyoming. *A*, Core from 26.5 to 27 feet below land surface depth interval, borehole BRO–1; *B*, Cuttings from 115 to 120 feet below land surface depth interval, monitoring well BRO–2; and *C*, Cuttings from 220 to 225 feet below land surface depth interval, monitoring well BRO–2. (Photographs correspond with photograph identifiers *A*, *B*, and *C* on fig. 3.)

XRD results for samples from the 26.5–26.75-ft depth interval indicate the clay fraction in the sample to be smectite, illite, and kaolinite (appendix tables 1–1 to 1–6). Clays commonly coated constituent grains (fig. 9*C*), but grains and clays "floated" in a micritic (very fine grained) carbonate cement (figs. 9*A* and *C*).

The framework grains in this depth interval indicated sediments originated from a plutonic and metamorphic terrain, based on the presence of zircons, quartz with undulose extinction in granitic rock fragments, and fragments of foliated hornblende schist. Visual description and quantitative characterization using XRD and petrographic methods indicated sediments of this lithostratigraphic unit generally match the "rhyolite-bearing feldspathic sandstone petrofacies" attributed to the Ogallala Formation in southeastern Wyoming by Stanley (1976).

The thin section constructed from cuttings from the 115–120-ft depth interval of monitoring well BRO–2 indicates the sediments in this depth interval are best described as an unconsolidated immature gravel, with granule to pebble-size grains, and with linear metamorphic fragments as large as 0.8 cm (0.3 in.) in length. Point-count data for the petrographic thin section are listed in table 5. The framework constituents, primary and alteration mineralogy, and dissolution of grains are very similar to the thin section from the overlying 26.9–27-ft depth interval. Rock fragments composed the largest percentage of constituents (table 5) and are from variable sources—plutonic granitic rock fragments composed of quartz, potassium feldspar, and plagioclase (fig. 10*A*), which commonly have areas of myrmekitic texture and accessory hornblende, biotite, apatite, and zircon; metamorphic rock fragments identified as hornblende-biotite-quartz schist; and micritic- to coarse-grained carbonate-cemented rock fragments of varying lithology. Amphibole (probably hornblende) extensively has changed to green chlorite in rock fragments.

As noted in other depth intervals, ferromagnesium minerals such as hornblende and a brown mica, which could be biotite, have totally to partially altered to chlorite, and hornblende grains have undergone partial dissolution (fig. 10*B*). The serrations from dissolution etching (fig. 10*B*, identified with white leaders) at the edge of the etched grain are characteristic dissolution textures of these minerals.

Thin sections were not stained to differentiate calcite and dolomite. Dolomite was only identified using XRD in the bulk material sample from the 115–120-ft depth interval (appendix table 1–1), and rock fragments of micritic- to coarse-grained carbonate enclosing constituent grains appear to be calcite, as in the sample from the 26.9–27-ft depth interval. Dolomite may be a coarse-grained phase in granitic rock fragments. Calcite and dolomite are difficult to differentiate without staining techniques because both minerals exhibit the same cleavage and a characteristic pink reflective birefringence. The XRD analysis did not identify mica phases such as biotite, but the alteration product, chlorite, was identified in all grain-size fractions from the 115–120-ft depth interval, except for the bulk material (appendix tables 1–1 to 1–5, appendix table 1–7).

The petrographic thin section constructed from cuttings from the 220–225-ft depth interval of monitoring well BRO–2 indicates the sediments in this depth interval are best described as an unconsolidated immature gravel, with micron-sized clay matrix to pebble-size grains, as much as 0.8 cm (0.3 in.) in diameter in thin section. Point-count data for the thin section are listed in table 5. Rock fragments are diverse, from multiple source rocks and environments (fig. 11). Grains included (1) granitic rock fragments of potassium feldspar (microcline based on twinning pattern), plagioclase, quartz, and biotite; (2) sedimentary rock fragments of clay-dominant mudstone/shaley rock fragments (fig. 11*B*) and fossiliferous limestone partially replaced by silica (fig. 11*C*); and (3) metamorphic rock fragments of hornblende-biotite-quartz schist (fig. 11*D*).

Constituent grains were coated by a discontinuous micritic matrix of iron-oxide stained carbonate plus clays. Coarse-grained calcite cement appeared to have nucleated on the very fine-grained dark brown micrite; the equant coarse-grained calcite had loosely cemented larger grains (fig. 11*A*). Most constituent grains were metamorphic and granitic rock fragments. Siltstone rock fragments were mainly quartzose with some feldspar and clay matrix between grains. More labile (friable) and softer, shaley rock fragments composed of clays and silt-sized quartz and feldspar grains partially were compressed and deformed between the harder granitic and quartzite grains. The intact shaley rock fragments were characteristic of immature sands. The shaley fragments and clay matrix account for the high clay content recorded in XRD results for the 220–225-ft depth interval (appendix tables 1–1 to 1–5, appendix table 1–8).

The framework grains for the depth interval of about 3.5 to 275 ft BLS indicated sediments of this lithostratigraphic unit originated primarily from an igneous (plutonic) and metamorphic terrain, based on the presence of zircons, undulose quartz in granitic fragments, and fragments of foliated hornblende schist. These igneous and metamorphic rock fragments were mixed with grains from a sedimentary environment, as indicated by the presence of micritic carbonate grains. Because of the large amount of feldspars present, sediments of this unit, regardless of lithostratigraphic assignment, commonly are referred to as "arkoses" or "arkosic" in many previously published descriptions. Visual description and quantitative characterization using XRD and petrographic methods indicated that the sediments of this lithostratigraphic unit generally match the "rhyolite-bearing feldspathic sandstone petrofacies" attributed to the Ogallala Formation in southeastern Wyoming by Stanley (1976). Although many earlier studies (described in the following "Lithostratigraphy" section) noted that the sediments were derived from the Laramie Mountains, Stanley (1971, 1976) definitively indicated that these igneous and metamorphic sediments were derived from nearby uplifts, including the Laramie Mountains and their southward extension, the Front Range of Colorado, as well as areas west of the Front Range of Colorado, such as the North Park Basin (not shown).

Geophysical Log Characteristics

Because of the wide range of lithologies composing this lithostratigraphic unit (identified as the Ogallala Formation in the "Lithostratigraphy" section that follows), geophysical log responses were highly variable and most log types varied more in the Ogallala Formation than in other lithostratigraphic units (plate 1; fig. 3). Excellent correlation between described lithology/grain size and geophysical log response was observed for most log types. Most notably, depth intervals with a higher proportion of coarse-grained sediments (for example, gravels) were characterized by increases in resistivity and higher neutron counts, whereas intervals with a higher proportion of fine-grained (mud-sized) sediments were characterized by corresponding decreases in resistivity and lower neutron counts. In some ways, this pattern of alternating zones of higher and lower electrical resistivity and neutron counts, indicative of interbedded fine- and coarse-grained deposits, was easier to visualize when grain size was grouped into only three broad grain-size categories (mud, sand, and gravel; fig. 3) rather than when grouped into many more grain-size categories (plate 1).

Table 5. Point-count data for petrographic thin sections, borehole BRO–1 and monitoring well BRO–2, Belvoir Ranch, Laramie County, Wyoming.

[--, not present]

Depth interval (feet below land surface)	Percentage of constituent							
	Quartz	Plagioclase	Potassium feldspar	Biotite	Matrix (carbonate)	Matrix (clay)	Granitic rock fragment	Metamorphic rock fragment
Ogallala Formation								
26.9–27	25.4	17.2	22.8	0.4	28.2	--	--	5
115–120	16	14	25	--	--	--	--	35 (7 muscovite schist; 28 hornblende schist)
220–225	5	1	1	--	6	19	43	25 (hornblende schist)
Brule Formation of White River Group								
302.25–302.75	1	--	--	--	--	94 (micritic carbonate/clay/altered ash)	--	--
375.18–375.3	1	1	--	--	--	93 (micritic carbonate/clay/altered ash)	--	--
Brule or Chadron Formation of White River Group								
414.1–414.3	7	3	3	--	--	76	--	--
430.95–431.2	9	4	3	--	--	74	--	--
Chadron Formation of White River Group								
445.6–445.9	14	1	2	1	--	22 (10 gray/brown clay; 12 illuvial clay)	60	--
471.0–471.3	31	2	8	3 (2 brown mica; 1 altered to chlorite)	--	49	2	--
487.15	22 (includes polycrystalline quartz)	5	11	--	--	15 (9 gray/brown birefringent clay; 6 illuvial clay)	39	--

As expected, because of the highly variable and predominantly coarse-grained lithology and highly variable consolidation of the Ogallala Formation, caliper log response varied more than in any other lithostratigraphic unit. Natural gamma counts decreased from land surface to about 20 ft BLS, and from about 20 to 21 ft BLS, natural gamma counts increased slightly and then remained relatively uniform throughout the full thickness of the lithostratigraphic unit. Spontaneous potential (SP) was "jagged" in the upper 67 ft, and then gradually increased with depth to the bottom of the unit.

Lithostratigraphy

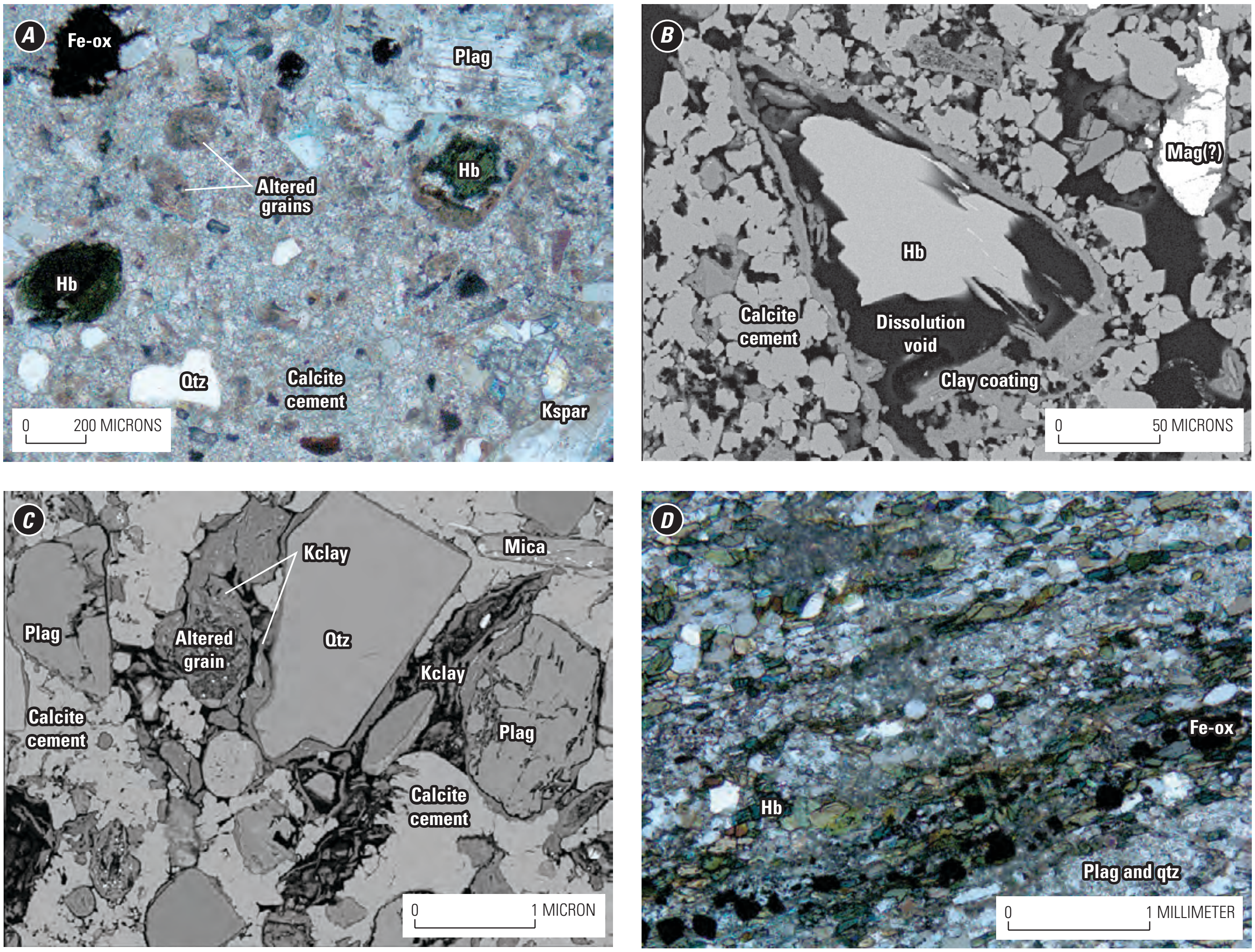
Detailed visual characterization coupled with utilization of petrographic and XRD techniques clearly showed that the sediments of this lithostratigraphic unit were derived primarily from the erosion of igneous and metamorphic terrain of the Laramie Mountains. Comparison of the sediment characteristics described previously in the subsections for the Ogallala Formation with previous studies (described within this subsection) indicates that sediments of this lithostratigraphic unit can be assigned to the Ogallala Formation (or the Ash Hollow Formation of the Ogallala Group). Numerous previous studies

Table 5. Point-count data for petrographic thin sections, borehole BRO–1 and monitoring well BRO–2, Belvoir Ranch, Laramie County, Wyoming.—Continued

[--, not present]

Depth interval (feet below land surface)	Percentage of constituent							
	Shale fragment	Hornblende	Quartz siltstone	Opaque (iron oxide and titanium oxide)	Carbonate grains	Lithic rock fragment	Chert	Void
Ogallala Formation								
26.9–27	--	0.4	--	0.6	--	--	--	--
115–120	--	2	4	--	4	--	--	--
220–225	--	--	--	--	--	--	--	--
Brule Formation of White River Group								
302.25–302.75	--	--	--	3	1 (coarse-grained calcite-filling void)	--	--	1 (open iron oxide-lined fracture)
375.18–375.3	--	--	--	3 (distinct iron-oxide nodule)	--		--	2
Brule or Chadron Formation of White River Group								
414.1–414.3	--	--	--	--	--	2	--	9
430.95–431.2	--	--	--	--	--	1	--	9
Chadron Formation of White River Group								
445.6–445.9	--	--	--	--	--	--	--	--
471.0–471.3	--	--	--	--	--	--	3	2
487.15	7	--	--	1	--	--	--	--

(summarized in the following descriptions) have shown that sediments of this lithostratigraphic unit, identified as the Ogallala Formation, were derived primarily from the erosion of igneous and metamorphic rocks of the Laramie Mountains, and secondarily from the southern extension of the Laramie Mountains, the Front Range of Colorado and areas to the west. To place this assignment in proper context, assignment of this lithostratigraphic unit to the Ogallala Formation is reviewed in the context of previous studies describing the equivalent Tertiary unit in the study area and southeastern Wyoming.



EXPLANATION

Fe-ox	Iron oxide	Mag	Magnetite
Hb	Hornblende	Plag	Plagioclase
Kclay	Potassic clay	Qtz	Quartz
Kspar	Potassium feldspar	?	Uncertain

Figure 9. Micrographs of samples from 26.9 to 27 feet below land surface, borehole BRO–1, Ogallala Formation, Belvoir Ranch, Laramie County, Wyoming. *A*, Transmitted light micrograph of patchy calcite and clay matrix enclosing granitic fragments and liberated grains of quartz, plagioclase and potassium feldspar, opaque minerals (probably magnetite altering to hematite), and ferromagnesium minerals such as mica and hornblende. Calcite partially has replaced constituent grains; *B*, Scanning electron microscope (SEM) micrograph of hornblende, which has undergone partial dissolution, leaving a clay and iron-oxide remnant skin. Calcite cement is blocky. Void areas (black) show fragmented clay skins where grains underwent total dissolution; *C*, SEM micrograph of quartz, feldspars, micas, and clays in calcite cement. Note the potassic clays coating constituent grains. Feldspar grains partially are altered to potassic clays, and some grains have undergone total dissolution, leaving fragments of clay coatings; and *D*, Transmitted light micrograph. Very coarse-sized rock fragments of hornblende schist are common.

Sediments of this lithostratigraphic unit, characterized by a predominance of material derived from the erosion of igneous and metamorphic terrains from the Laramie Mountains to the immediate west, the Front Range, and areas west of the Front Range in northern Colorado, have been assigned to the Ogallala Formation in the vicinity of and to the west of the city of Cheyenne since the 1940s. Most of these previous studies, like the study described herein, noted that the igneous (plutonic) rocks composing the formation are largely derived from the adjacent Laramie Mountains; some studies also noted that sediments composing this unit were derived from the Front Range of Colorado and areas to the west. Before the 1940s, the sedimentary rocks now known as the Ogallala Formation were originally mapped and described as or part of the Arikaree Formation by Darton and others (1910); Knight and Morgan (1937) and Theis (1941) retained this assignment, referring to these rocks throughout the Crow Creek drainage (including the study area; fig. 1) as the "Harrison (Arikaree) Formation" (the Harrison Formation is now known as one of several formations within the Arikaree Group of western Nebraska). The investigators noted that the formation was composed of fine- to coarse-grained sand and gravel in the western part of the Crow Creek drainage closest to the Laramie Mountains (including the study area), and that the formation became finer grained to the east.

Foley (1942) seems to be the first investigator to assign the sediments in the study area to the Ogallala Formation. Since first tentatively assigned (as indicated by a "?" designation throughout his report) to the Ogallala Formation by Foley (1942) and adopted by Morgan (1946), all subsequent geologic and hydrogeologic studies in the area appear to trace their assignment of these coarse-grained sediments to the Ogallala Formation back to the original assignment made by Foley (1942). Foley's (1942) tentative identification was based on comparison of the sediments in the vicinity of and to the west of the city of Cheyenne with exposures of the Ogallala Formation in western Nebraska. The investigator noted that original assignment of these sediments to the Arikaree Formation by Darton and others (1910) in the Cheyenne area was incorrect. Foley (1942, p. 28) noted that "the type locality of the Arikaree Formation is in the Pine Ridge escarpment in northwestern Nebraska," and "the post-Brule sediments in the Cheyenne area have strong topographic and lithologic affinities with the beds of the Ogallala (?) Formation directly to the east, and they are tentatively considered as Ogallala (?) Formation." Furthermore, Foley (1942) noted that the Ogallala Formation "is believed to be part of an extensive High Plains surface which was developed by heavily loaded rivers supplied chiefly from the Laramie Range to the west," as "indicated by the great diversity of texture, lateral shifting of channel deposits, and other features" (Foley, 1942, p. 28).

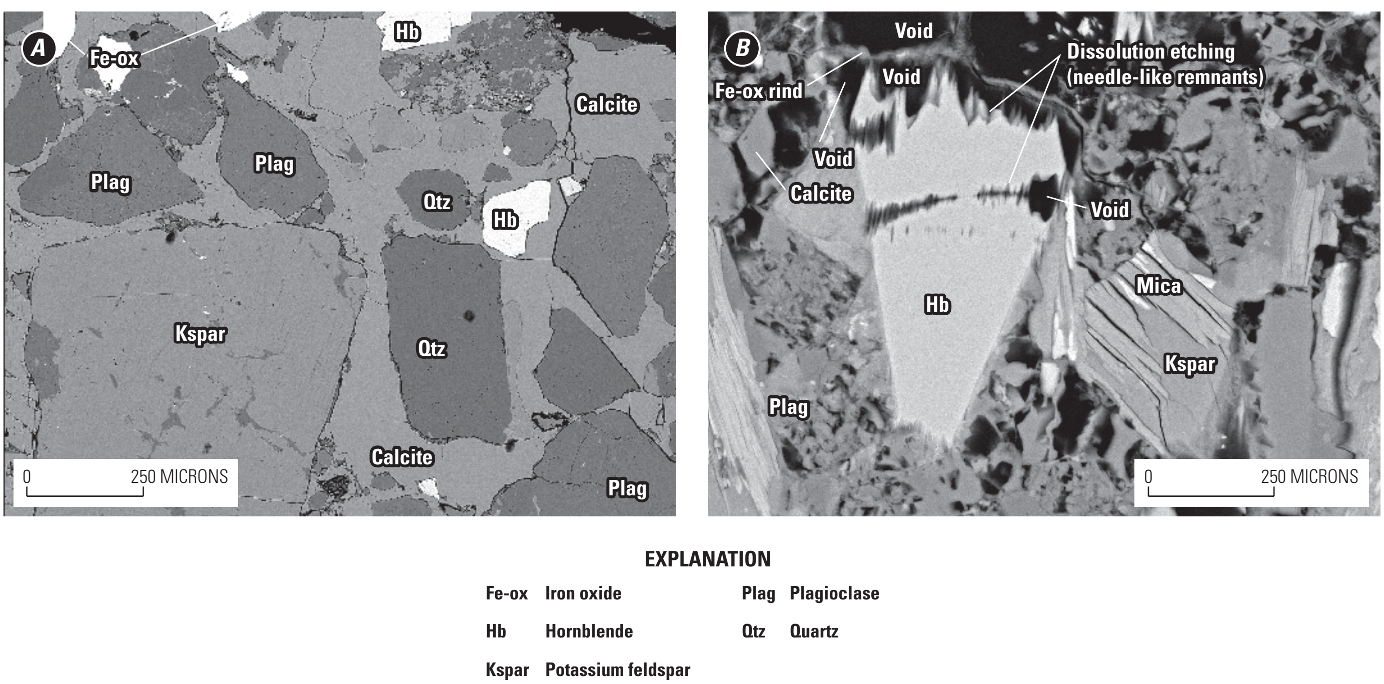
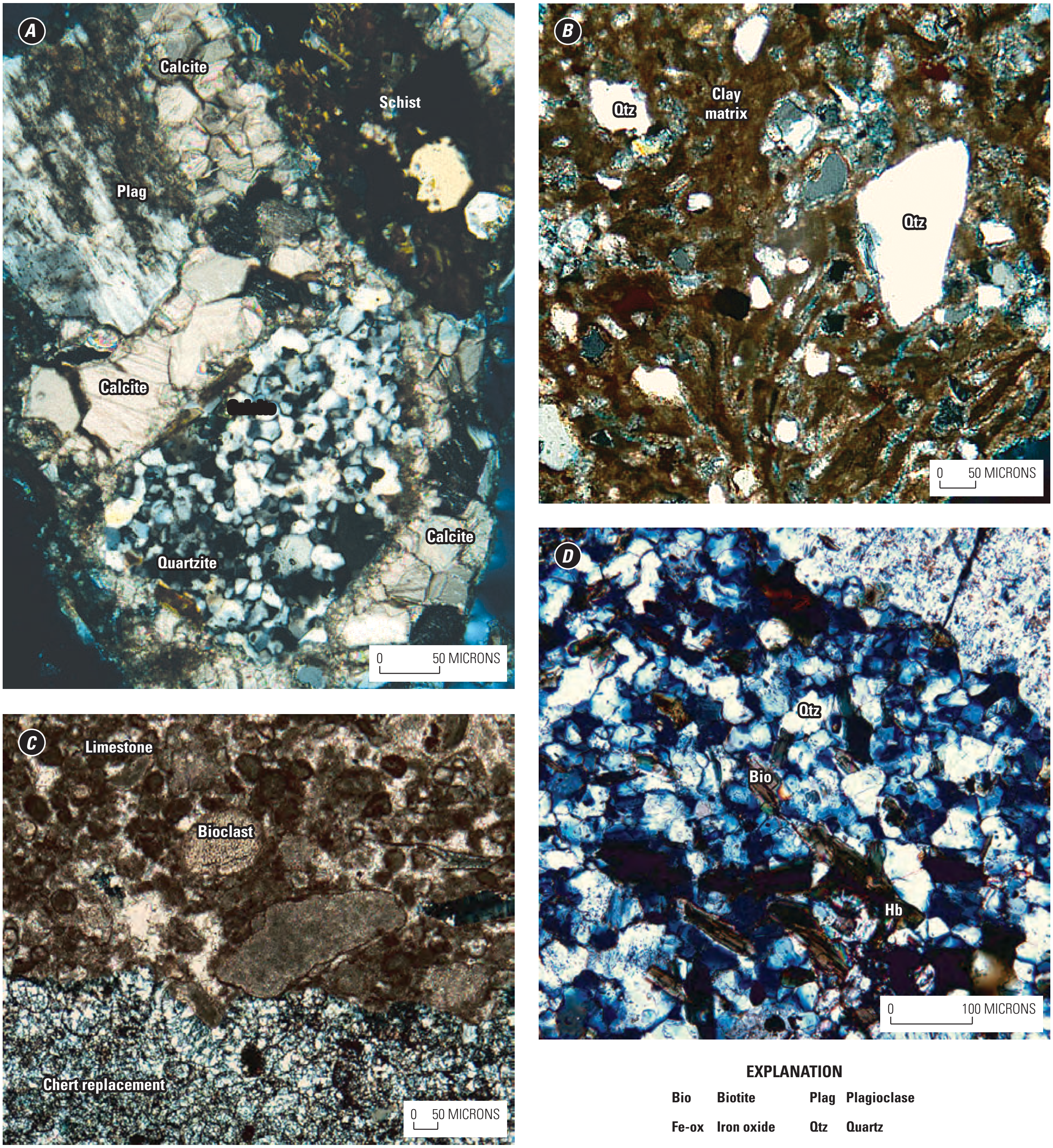


Figure 10. Micrographs of samples from 115 to 120 feet below land surface, monitoring well BRO–2, Ogallala Formation, Belvoir Ranch, Laramie County, Wyoming. *A*, Scanning electron microscope (SEM) micrograph of patchy magnetite-bearing calcite cement enclosing grains of quartz, potassium feldspar, plagioclase, iron-oxide grains, and hornblende; and *B*, SEM micrograph showing ferromagnesium minerals. Hornblende has undergone partial dissolution, evidenced by needle-like remnants adjacent to void spaces, and an iron-oxide rind that marks the former extent of the grain. The mica grain is fractured and altered along cleavage planes (exfoliation). Both minerals exhibit partial alteration to chlorite.



EXPLANATION

Bio	Biotite	Plag	Plagioclase
Fe-ox	Iron oxide	Qtz	Quartz
Hb	Hornblende		

Figure 11. Transmitted light micrographs of a sample from 220 to 225 feet below land surface, which contains rock fragments from multiple geologic source rocks and environments, monitoring well BRO–2, Ogallala Formation, Belvoir Ranch, Laramie County, Wyoming. *A*, Three rock fragments of quartzite, plagioclase, and biotite-hornblende-quartz schist cemented by coarse-grained calcite. Note the fine-grained dark brown micritic calcite cement around the quartzite grain; *B*, Iron-oxide stained, clay-rich shaley fragment; *C*, Fossiliferous carbonate grain partially replaced by silica; and *D*, Hornblende-biotite-quartz schist.

Subsequently, Morgan (1946) continued and expanded upon the work of Foley (1942). Like Foley, Morgan (1946, p. 11) noted that the gravel beds in the Ogallala Formation in the Cheyenne area were composed largely of sediments derived from erosion of the Laramie Mountains, and he noted the rocks “are composed almost entirely of disintegrated Sherman Granite with only minor amounts of other rock types.” Fine-grained sediments in the formation were said to be composed largely of reworked sediments of the underlying lithostratigraphic unit (identified as the Brule Formation of the White River Group). Morgan (1946, p. 11) noted that “water-bearing beds in the Ogallala Formation” were composed of “lenses, stringers, and irregular masses of sand and gravel which are interbedded with silt and clay,” and stated that the aquifers were “thickest and most permeable near the mountain front south of Crow Creek where the formation consists largely of sand and gravel.” This area includes the area along Lone Tree Creek studied and described herein. A more detailed study of the configuration of the coarse-grained deposits in the vicinity of Borie and in the area of the study described herein located along Lone Tree Creek led Morgan (1946, p. 12) to conclude that coarse-grained sand and gravels present in these areas were “part of an alluvial fan built up by Lone Tree Creek with the apex of the fan near the mouth of Lone Tree Canyon where the stream emerges from the mountains.”

Even after the work of Foley (1942) and Morgan (1946), some investigators (Gray, 1947; Brady, 1949) continued to use “Arikaree Formation” or “Harrison Formation” for mapping of the Tertiary deposits now known as the Ogallala Formation along the eastern flank of the Laramie Mountains in Laramie County. Based on lack of citation in the reference section of these mapping studies, it appears both investigators were unaware of the reassignment of these rocks to the Ogallala Formation by Foley (1942) and Morgan (1946). Brady (1949) mapped the eastern flank of the Laramie Mountains immediately north of the study area in the vicinity of Federal and Hecla, whereas Gray (1947) mapped the area immediately north of Brady’s study area in the vicinity of Lodgepole and Horse Creeks (figs. 1 and 5). The investigators noted that the “Arikaree Formation” adjacent to the Laramie Mountains was primarily a coarse-grained arkosic conglomerate composed of locally derived [Laramie Mountains] angular fragments of feldspar and Precambrian igneous and younger rocks.

Minick (1951) evaluated Tertiary stratigraphy in southeastern Wyoming and northeastern Colorado. Rocks of the lithostratigraphic unit described herein and equivalent rocks throughout southeastern Wyoming were identified as belonging to the Ash Hollow Formation rather than the Ogallala Formation. The Ash Hollow Formation is the uppermost formation of the Ogallala Group as defined in adjacent western Nebraska where the “Ogallala” is elevated to group rank and divided into several formations (for example, Diffendal, 1984; Swinehart and others, 1985, and references therein; Swinehart and Diffendal, 1997, and references therein). Subsequent investigators also have argued that rocks in southeastern Wyoming now identified as the Ogallala Formation (including the study area) would be more appropriately defined as the Ash Hollow Formation (McGrew, 1953; Cassiliano, 1980; Boyd, 1999). Minick (1951) noted that the coarse-grained deposits (conglomerates) of the Gangplank (not shown) were composed mainly of acidic rocks (Precambrian pebbles and cobbles) as well as pyroclastic (volcanic) rocks; Minick (1951) also noted that the pyroclastic rocks were rhyolitic and very similar to those described from an area in the Front Range of northern Colorado [Specimen Mountain in Rocky Mountain National Park (not shown)], suggesting northern and northeastern stream transport of sediments from this area to southeastern Wyoming at the time of Miocene deposition. Minick (1951, p. 19) provided detailed lithologic, petrologic, and petrographic descriptions of many rock specimens, reporting many characteristics that also were observed in the cuttings, core, and thin sections from the lithostratigraphic unit described previously for the BRO-1A and BRO-2 monitoring wells—predominance of similar mineral constituents including quartz, orthoclase and plagioclase feldspars, with minor amounts of magnetite, hematite, biotite, microcline, chalcedony, sericite, limonite, and kaolinite; flow-banded vitreous cryptocrystalline groundmass; particles showing fracturing, zoning, and marginal reaction rims; feldspars weathering to sericite and kaolinite; and magnetite with alteration to hematite.

Like Minick (1951), McGrew (1953) considered the rocks of this lithostratigraphic unit in the study area and southeastern Wyoming to be a western extension of the Ash Hollow Formation of the Ogallala Group present in adjacent western Nebraska. McGrew (1953, p. 64) noted that these deposits in Wyoming “represent the lower part of the Ash Hollow Formation as described for sediments in Nebraska by Lugn (1939), but include age equivalents of the basal Valentine Formation of the Ogallala Group in north-central Nebraska.” McGrew (1953, p. 64) also stated that the Ash Hollow Formation in southeastern Wyoming is “made up mostly of buff sand and clays, volcanic ash, stream gravels, and as the mountains [Laramie Mountains] are approached, much fresh arkose.” McGrew (1953, p. 64) noted that “the arkoses are quite obviously derived from the Sherman Granite of the Laramie Mountains and may well represent the debris developed during the cutting of the Sherman surface.” As observed earlier by Minick (1951), McGrew also noted that igneous (volcanic) rocks (defined as “volcanic pebbles”) in the sediments likely were derived from Specimen Mountain of Colorado, reflecting changing drainage patterns east of the Laramie Mountains during the time of deposition.

In contrast to Minick (1951) and McGrew (1953), Moore (1963) assigned these rocks to the Ogallala Formation. Moore (1963, p. 165) noted that sediments in the Ogallala Formation were coarser and more conglomeratic closer to the Laramie Mountains, the presumed sediment source, and that the formation contained “fragments of nearly every rock type present in the Laramie Range [Mountains].” Like Minick (1951) and McGrew (1953), Moore (1963) suggested that rhyolitic volcanic rocks in the sediments were derived from Specimen Mountain of Colorado.

Lowry and Crist (1967) described the geologic and hydrogeologic characteristics of all rocks in Laramie County, with an emphasis on the Cenozoic High Plains sequence. The investigators concurred with the work of Foley (1942) and Morgan (1946) and mapped the rocks of this unit in the study area and throughout Laramie County as the Ogallala Formation.

The work of Stanley (1971, 1976) is the most detailed and perhaps seminal lithologic/petrologic/petrographic examination of Tertiary lithostratigraphic units in southeastern Wyoming and parts of adjacent western Nebraska. On the basis of diagnostic clast types in all sand- and gravel-sized fractions, Stanley (1976) defined a petrofacies for the Ogallala Formation, as well as for all the lithostratigraphic units in the Cenozoic High Plains sequence, including the White River Group and Arikaree Formation. Stanley (1976, p. 297) believed that the depositional systems in southeastern Wyoming and adjacent Nebraska "are better defined by stratigraphic and geographic distribution of sandstone petrofacies in the Cenozoic High Plains sequence" rather than "by stratigraphic parameters or paleocurrent measurements." Four petrofacies were defined for the Cenozoic High Plains sequence, and the Ogallala Formation was assigned to the "rhyolitic-bearing feldspathic sandstone petrofacies." Using these petrofacies, Stanley (1971, 1976) definitively showed that Precambrian igneous (plutonic) and metamorphic sediments composing much of the Ogallala Formation in southeastern Wyoming were derived from nearby uplifts, including the Laramie Mountains in the vicinity of the study area, as well as from Cenozoic igneous (volcanic) sediments from the west side of the Front Range and the North Park Basin of northern Colorado.

Many previous investigators noted limitations between lithostratigraphic and biostratigraphic methods for definition and correlation of stratigraphic units in the Cenozoic High Plains sequence. Unfortunately, good fossil material has not been found in many of the units in much of southeastern Wyoming. In addition, the proximity of the study area to the source area (Laramie Mountains) for Ogallala Formation sediments resulted in high proportions of coarse-grained sediments that are not typical of the unit in other locations, and is not conducive to the preservation of fossils (Jordan, 1998). No fossil material has yet been reported for the study area; however, Cassiliano (1980) evaluated fossil assemblages along Horse Creek and Bear Creek in northern Laramie County (about 20 mi north of study area, fig. 5). Biostratigraphic interpretation of Tertiary lithostratigraphic units in this area by Cassiliano (1980) strongly indicates that some of the sediments in southeastern Wyoming currently (2013) described as the "Ogallala Formation" likely are equivalent to, and should possibly be referred to as the "Ash Hollow Formation of the Ogallala Group" of adjacent western Nebraska. Furthermore, Cassiliano (1980, p. 63) noted that Breyer (1975, fig. 1, p. 1) showed that "strata of the Ash Hollow Formation (Ogallala Group) can be traced from their type locality in southwestern Nebraska into southeastern Wyoming, "further supporting the extension of the Ash Hollow Formation of the Ogallala Group of southwestern Nebraska to adjacent southeastern Wyoming." Unfortunately, the lack of fossils makes it difficult to extend Cassiliano's biostratigraphic work to the study area and other areas in southeastern Wyoming.

Cooley and Crist (1981) constructed fence diagrams for the Cenozoic High Plains sequence throughout Laramie County and adjacent areas. The investigators assigned the coarse-grained rocks of the lithostratigraphic unit described herein to the Ogallala Formation. Subsequently, the same investigators conducted another study (Cooley and Crist, 1994) of the High Plains aquifer system from the Laramie Mountains to an area east of Cheyenne, including the area of this study. Like previous studies, the investigators noted that the coarse-grained nature of the Ogallala Formation near the Laramie Mountains is not representative of the formation throughout its extent in southeastern Wyoming, and that the predominant grain size in the formation changes and becomes finer grained eastward from the mountains; consequently, Cooley and Crist (1994) divided the Ogallala Formation from the Laramie Mountains to about 10 mi east of Cheyenne into three different facies, including a "conglomerate facies" adjacent to and composed of coarse-grained igneous and metamorphic sediments derived from the mountains. Sediments of this lithostratigraphic unit described herein are assumed to be equivalent to the conglomerate facies of the Ogallala Formation as described by Cooley and Crist (1994).

Swinehart and others (1985, fig. 5) constructed five geologic cross sections showing Tertiary lithostratigraphic units in southwestern Nebraska. One of the constructed geologic cross sections (fig. 6, section *B–B′*) was extended eastward into southeastern Wyoming. The "Ogallala" in southeastern Wyoming was identified as the Ash Hollow Formation of the Ogallala Group.

Jordan (1998) constructed geologic cross sections of the Cenozoic High Plains sequence to the west and northwest of Cheyenne, including the study area. The investigator assigned the coarse-grained lithostratigraphic unit to the Ogallala Formation.

Like Minick (1951) and McGrew (1953), Boyd (1999) believed that all use of the "Ogallala Formation" was incorrect in southeastern Wyoming. Boyd (1999) strongly argued that the rocks of this lithostratigraphic unit in the study area and southeastern Wyoming are a western extension of the Ash Hollow Formation of the Ogallala Group present in adjacent western Nebraska, and that "Ogallala Formation" should be abandoned.

The State of Wyoming geologic map (Love and Christiansen, 1985), a joint effort of the Wyoming State Geological Survey and USGS, defined the rocks of the lithostratigraphic unit in the study area and southeastern Wyoming as "Tertiary Miocene rocks-undifferentiated," perhaps reflecting the contentious nature of assigning the rocks to a lithostratigraphic unit. Subsequently, creation of the Statewide Phanerozoic chart by the Wyoming State Geological Survey and USGS (Love and others, 1993) resulted in assignment of these rocks to the Ogallala Formation, an assignment retained in the more recent 1:100,000 geologic maps (Ver Ploeg and others, 1998, 2000) that include the study area.

Ogle and Hallberg (2000) cored and subsequently described the lithology of Tertiary lithostratigraphic units to a depth of 380 ft BLS in the vicinity of the city of Cheyenne. In the detailed description of the lithology of the Ogallala Formation and White River Group or Formation, the investigators identified only the Ogallala Formation and the White River Group or Formation, and did not identify the Arikaree Formation between the two units.

Several recent studies (JR Engineering, 2005, 2007; Trihydro Corporation, 2009) were completed along Lone Tree Creek on the Belvoir Ranch, including the study area, using descriptions of drill cuttings and interpretation of geophysical logs from numerous test holes and test wells to evaluate locations for installation of high-yielding production wells in the area. The same coarse-grained lithostratigraphic unit described herein was assigned to the Ogallala Group or Formation, based primarily on reference to assignments by some of the studies described previously herein.

Brule Formation of the White River Group

Characteristics of sediments collected from core and cuttings from the Brule Formation of the White River Group (about 275 to 405.6 ft BLS) at the study location are described in this section of the report. Sediment characteristics within this depth interval are described using visual techniques, XRD and thin-section petrography, and geophysical log characteristics. Finally, the resulting description of these characteristics are compared and contrasted with previously published descriptions and lithostratigraphy to assign sediments of this depth interval to the Brule Formation of the White River Group.

Visual Description

In stark contrast to the coarse-grained sediments of the overlying Ogallala Formation, a thick, very fine-grained lithostratigraphic unit was cored from about 275 to 405.6 ft BLS. Sediments composing this lithostratigraphic unit consisted almost entirely of yellowish-brown and pale-brown-colored mud-sized sediments (clay and silt) (plate 1; fig. 3). Because of the very fine-grained nature of the sediments, visual estimation of the relative percentage of clay-sized as compared to silt-sized sediments was difficult and subjective; more quantitative techniques would be required to provide a quantitative estimation of relative percentages of each size. Subrounded to angular, subprismoidal to subdiscoidal sand-sized particles composed a very small percentage of the sediments (plate 1). More sand-sized sediment and occasional pebbles were found in the depth interval from 369.62 to 405.6 ft BLS (plate 1), but these sediments still composed a very small percentage overall. The fine grain size, as well as color, of the sediments is shown in photographs of core from three different depths (figs. 12*A* and *B*). Sediments become noticeably lighter in color upon drying (less brown and more white) (fig. 12*A*). Consolidation of sediments varied throughout the unit, ranging from very poorly to well cemented, but overall sediments from 275 to 405.6 ft BLS were poorly to moderately cemented. Occasional mica and dark-colored accessory minerals were observed in small percentages throughout much of the unit (plate 1). Carbonate cementation, as indicated by fizzing upon application of hydrochloric acid (HCl), was observed throughout the sequence.

Black to gray "flakes," ranging from less than 1 to 10 millimeters (mm; 0.04 to 0.4 in.) long, tentatively identified as biotite through visual examination and confirmed later with SEM, occurred sporadically throughout the entire sequence; in fact, occurrence of these biotite flakes was so visually notable throughout this sequence that this feature could be considered a diagnostic visual characteristic of this lithostratigraphic unit. Biotite flakes are shown in a photograph from a section of dry core from about 399.2 to 399.5 ft BLS (fig. 13).

On the basis of initial visual description, this lithostratigraphic unit was identified as predominantly a mudrock and classified as a siltstone or argillaceous siltstone, also a commonly published description of the Brule Formation (for example, Foley, 1942; Morgan, 1946; Denson and Bergendahl, 1961; Lowry, 1966; Lowry and Crist, 1967); using hand specimens collected during this study and cursory examination of hand specimens from other locations, the unit also could be just as easily classified as one of several types of mudrocks (for example, siltstone, claystone, silty claystone, or clayey siltstone) because of difficulty in visually determining the relative proportions of silt-size sediments in comparison to clay-sized sediments.

X-Ray Diffraction and Petrography

After visual description was completed (plate 1), two intervals from this fine-grained lithostratigraphic unit were subsampled for additional analysis using XRD (302.5–303.5 and 374.97–375.18 ft BLS), and two adjacent intervals were subsampled for thin-section petrography (302.25–302.375 and 375.18–375.3 ft BLS); each of the intervals selected for XRD and thin-section petrography were located adjacent to one another to facilitate use of both methods to characterize the sediments in essentially the same depth interval. Point-count data for the petrographic thin sections are listed in table 5.

The petrographic thin section constructed from core from the 302.25–302.375-ft depth interval of monitoring well BRO–2 indicates the sediments in this depth interval are best described as an altered, very fine grained, consolidated ash fall deposit or vitric (tuffaceous) siltstone (fig. 14*A*–*F*). The dominant identifiable constituents were shardy ash fall material that had undergone partial alteration (fig. 14*A*), but much of the ash fall material was isotropic under the petrographic microscope, indicating the shards were still volcanic glass. The shards largely were undeformed and retained common Y-shape and bubble-texture outlines (figs. 14*C*–*E*). Other minor constituent grains were quartz, potassium feldspar,

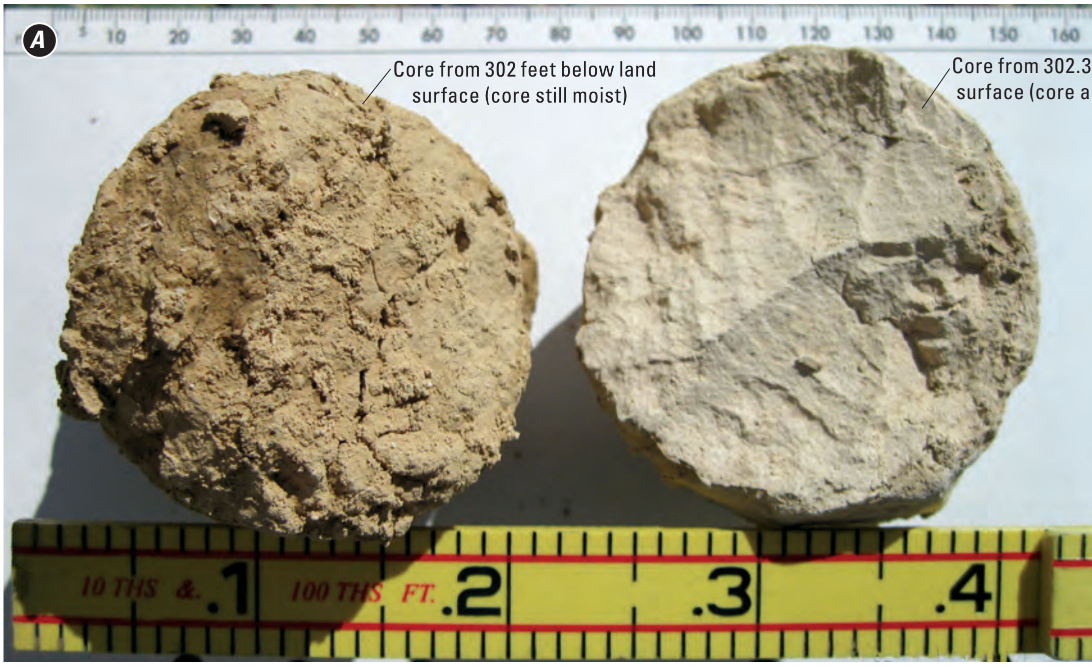


Figure 12. Photographs of core from monitoring well BRO–2, Brule Formation of White River Group, Belvoir Ranch, Laramie County, Wyoming. *A*, Core from about 302 feet (moist) and 302.3 feet (dry) below land surface and *B*, Core from about 374.6 feet below land surface. (Photographs correspond with photograph identifiers *D* and *E* on fig. 3.)

plagioclase, biotite, and opaque minerals such as ilmenite ($FeTiO_3$). Amorphous iron oxides and calcite coated open to closed fractures that cross cut the sample. Coarse-grained calcite commonly filled voids. Matrix was composed primarily of very fine-grained shards, which may account for the high quartz content in the adjacent XRD sample (appendix tables 1–1 to 1–5; appendix table 1–9), clays, and micritic carbonate.

Iron-oxide stained spheroids/nodules in the matrix were common and problematic in origin (figs. 14*B* and *F*). Some of the iron-oxide spheroidal shapes were filled partially by (1) very fine-grained dark brown clays, and then (2) a coarser-grained carbonate cement. This texture indicates that many of these spheroids were hollow, and a geopetal texture developed in which the void was filled first by a fine-grained dark material, followed by precipitation of a coarser-grained calcite cement (fig. 14*B*); such layering in a geopetal texture indicates original horizontality. Nodules in the thin section ranged from perfectly spherule to highly irregular in outline, which may indicate nodules of different origin. Many of the spherules retained very rounded outlines and have a central seed grain, which is indicative of accretionary lapilli in ash fall deposits, in which finer grained ash material agglomerates around a rotating larger grain (fig. 14*F*). Irregularly shaped nodules composed of amorphous iron oxides and the surrounding matrix indicate formation in situ.

The petrographic thin section constructed from core collected from the 375.18–375.3-ft depth interval of monitoring

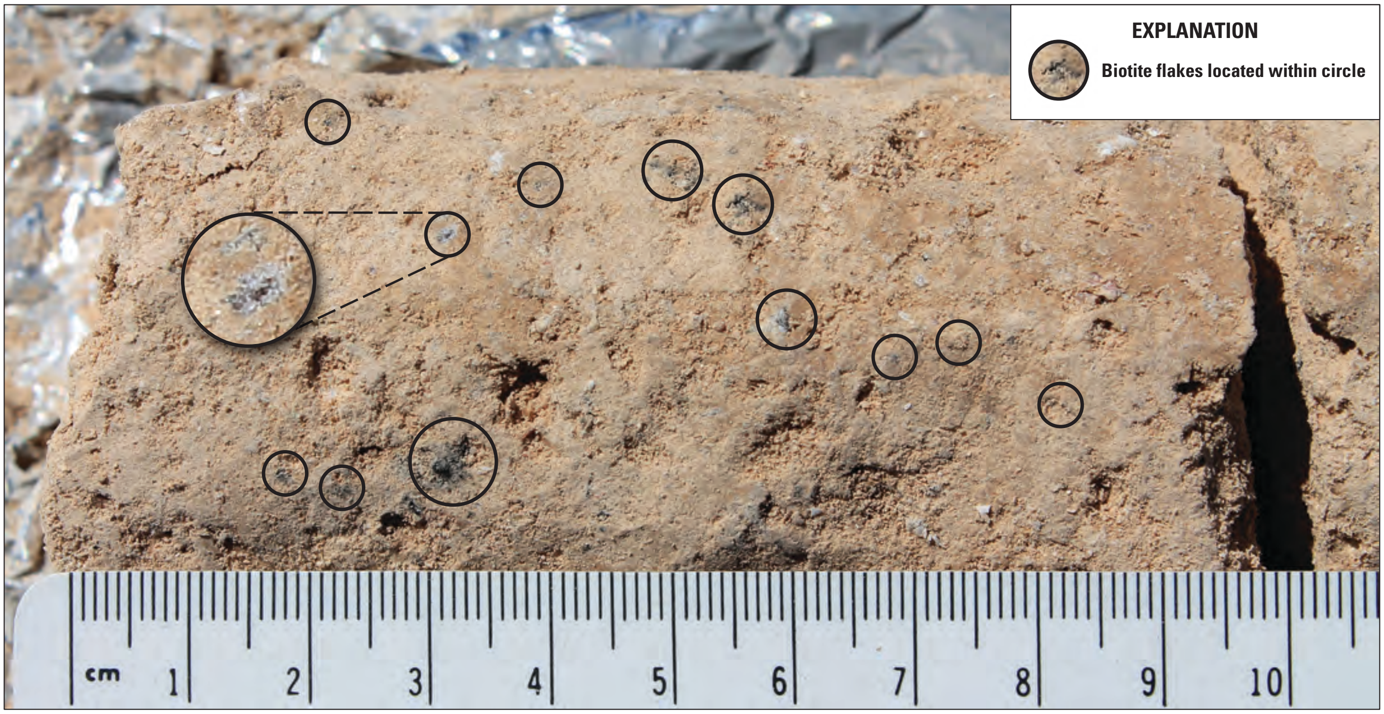


Figure 13. Photograph of core collected from 399.2–399.5 feet below land surface showing biotite flakes in the Brule Formation of the White River Group, monitoring well BRO–2, Belvoir Ranch, Laramie County, Wyoming. Photograph shows lateral view of core. (Photograph corresponds with photograph identifier *F* on figure 3.)

well BRO–2 indicates the sediments in this depth interval also are best described as an altered, very fine grained, consolidated ash fall deposit or vitric or tuffaceous siltstone (fig. 15*A*–*D*). The abundant ash material and silt-sized quartz was recorded in the high quartz content in the adjacent XRD sample from the 374.97–375.18-ft depth interval (appendix tables 1–1 to 1–5; appendix table 1–10). Abundant glassy bubble-textured shard and pumice fragments composed most of the matrix, which had largely altered to carbonate, amorphous iron oxides, or clays (fig. 15*A* and *B*). Some shards had undergone dissolution, leaving their remnant outlines in the matrix material, partially filled by secondary alteration minerals; for example, calcite partially had replaced larger shards, mimicking their shape. Cuspate or bubble-wall textured shard outlines were well preserved and did not show deformation because of compression or heat (fig. 15*D*). Most bubble texture was filled by very fine ash material, but where clusters of larger shards were agglomerated, void space in open bubble textures and between shardy material was "countable." Silt-sized grains include quartz, microcline, minor plagioclase, rarer brown biotite flakes, and opaque minerals identified as iron-oxide and titanium-oxide minerals (probably magnetite and ilmenite). Occasional strain-shadowed quartz and microcline grains were as large as 2 mm (0.08 in.), but this size of grain was the rare exception.

Amorphous iron oxides and clays formed aggregates and rounded to irregular-shaped nodules in the argillic matrix (fig. 15*A*). Iron-oxide nodules commonly enclosed shards that had been replaced by coarse calcite. The nodules incorporated silt grains as well as shards, and were cemented by iron oxides, clay, and carbonate. Open anastomosing fractures were lined by iron oxides.

Geophysical Log Characteristics

The contact between the fine-grained sediments of this lithostratigraphic unit (Brule Formation of the White River Group) and the overlying coarse-grained Ogallala Formation was characterized by sharp decreases in electrical resistivity and neutron counts (plate 1; fig. 3). In fact, the Brule Formation was recognized as having the lowest normal resistivity and lowest neutron counts, reflecting the elevated clay content and bound groundwater associated with this consistently fine-grained lithostratigraphic unit. After changing at the contact, log responses for normal resistivity and neutron counts were relatively uniform (consistent linear pattern) with increasing depth, although normal resistivity decreased slightly with increasing depth throughout the unit. Natural gamma increased moderately from about 272 to about 293 ft BLS and to counts higher than measured in the overlying Ogallala Formation, decreased from about 293 to 300 ft BLS to counts similar to those measured in the overlying Ogallala Formation, and was relatively uniform from about 300 ft BLS to the bottom of the unit. Caliper and SP log responses were relatively uniform with few deviations, although SP increased slightly

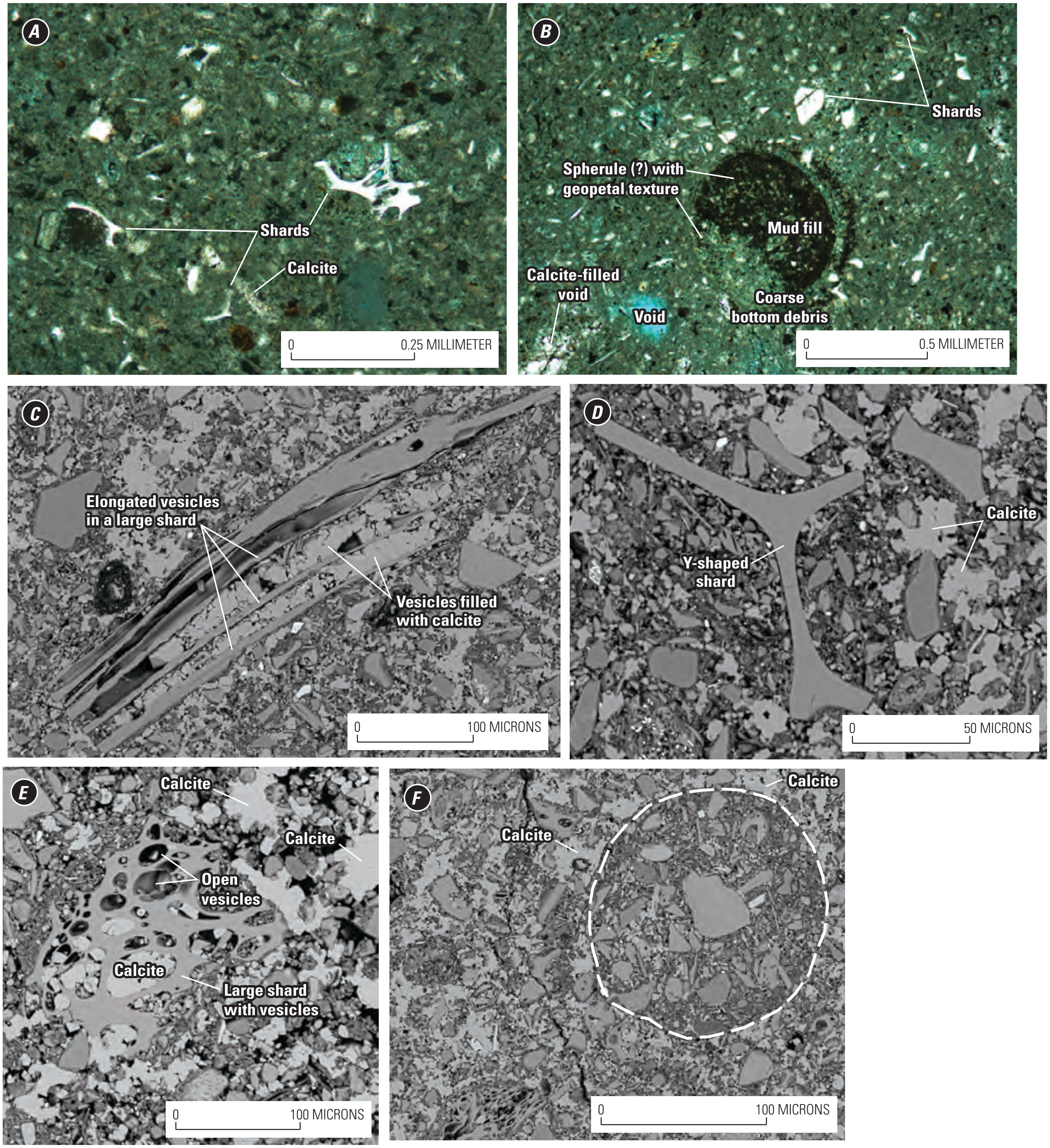


Figure 14. Transmitted light and scanning electron microscope (SEM) micrographs of thin section from 302.25 to 302.375 feet below land surface, monitoring well BRO–2, Brule Formation of White River Group, Belvoir Ranch, Laramie County, Wyoming. *A*, Transmitted light micrograph of glass shards in a very fine-grained matrix. Note curved bubble wall texture; *B*, Transmitted light micrograph of iron-oxide nodule; *C*, SEM micrograph of elongate parallel vesicles in a pumice shard. Vesicles partially are filled by calcite. Matrix is composed largely of glass shards, clays, quartz fragments, and calcite cement; *D*, SEM micrograph of a common Y-shaped shard; *E*, SEM micrograph of a volcanic shard demonstrating the variation in shape and degree of vesiculation (bubbles). Larger vesicles are filled with calcite; and *F*, SEM micrograph of concretionary iron-oxide nodule (?) outlined by dashed white line, containing shards and mineral grains. Calcite cement partially coats the nodule.

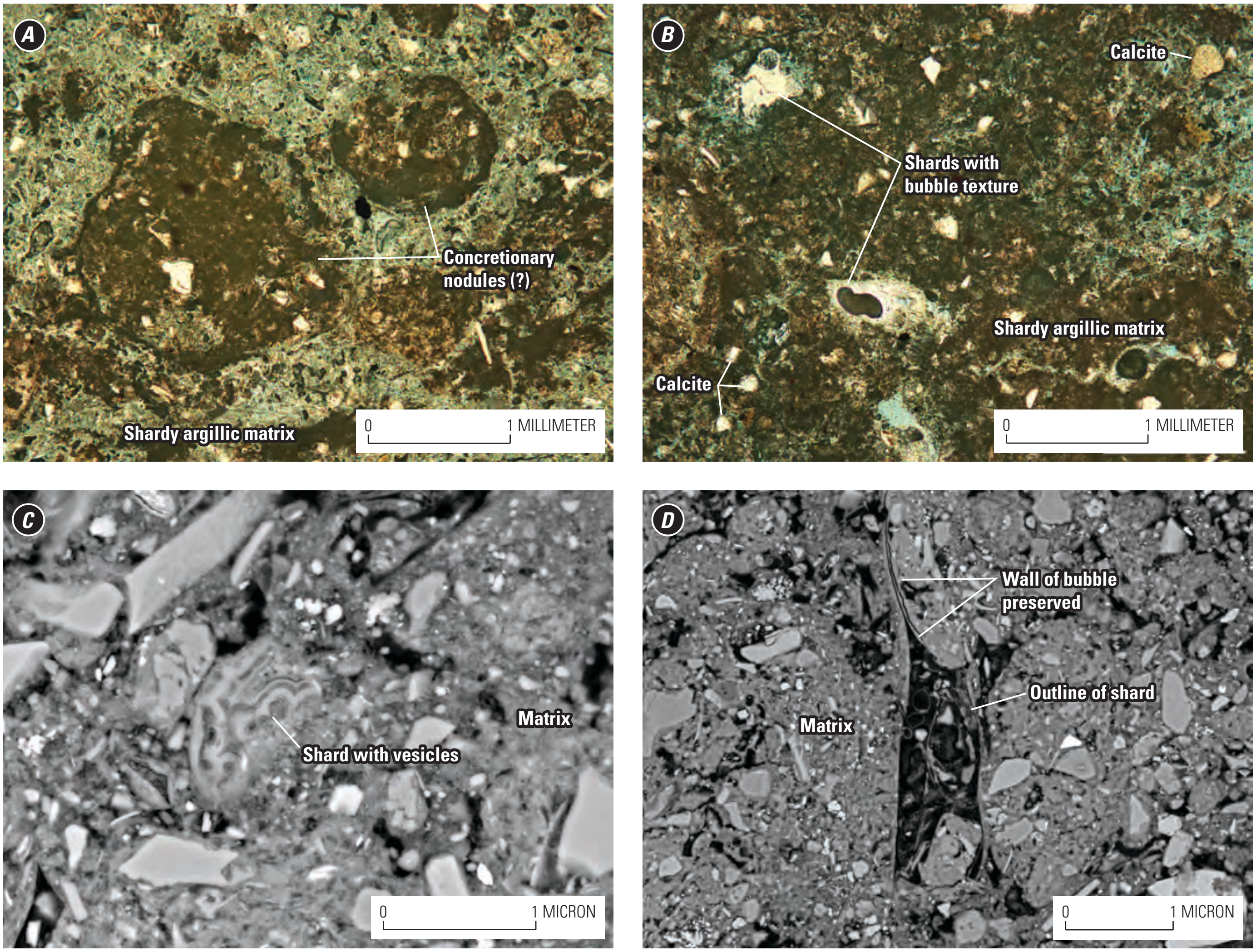


Figure 15. Transmitted light and scanning electron microscope (SEM) micrographs of samples from 375.18–375.3 feet below land surface, monitoring well BRO–2, Brule Formation of White River Group, Belvoir Ranch, Laramie County, Wyoming. *A*, Transmitted light micrograph. The sample is composed of abundant volcanic shardy material. Glassy matrix material is altered to clays and calcite. The sample is notable for numerous concretion-like masses—some are zoned, most are not. Nodule shapes range from rounded to highly irregular. Nodules contain shards and mineral grains such as quartz and feldspars; *B*, Transmitted light micrograph showing the fine-grained nature of the groundmass. Calcite filling voids is common; *C*, SEM micrograph showing a glassy volcanic fragment with bubble texture. The shapes and vesicularity (density of bubble texture) in the shards are highly variable (see fig. 14) and *D*, SEM micrograph showing a commonly shaped volcanic shard in which the outline of a fragile projection of bubble wall has been preserved.

with increasing depth throughout the unit, continuing the trend observed in the overlying Ogallala Formation.

Lithostratigraphy

Sediments of this lithostratigraphic unit, herein described visually as a vitric argillaceous siltstone, and petrographically determined to be a mudrock composed predominantly of volcaniclastic and altered volcaniclastic sediments, closely match detailed petrologic and petrographic descriptions of the predominant fine-grained lithology of the Brule Formation of the White River Group in southeastern Wyoming and western Nebraska (Denson and Bergendahl, 1961; Sato and Denson, 1967; Denson and Chisholm, 1971; Stanley, 1976; Stanley and Benson, 1979; Swinehart and others, 1985, and references therein; Swinehart and Diffendal, 1997, and references therein). In particular, similarly high percentages of volcaniclastic and altered volcaniclastic sediment, combined with the characteristic nature of the sediments (predominance of mud-sized sediment, retention of original volcanic shapes, and similar sediment alteration characteristics), essentially defines the unit petrographically in southeastern Wyoming and adjacent western Nebraska (Sato and Denson, 1967; Stanley, 1976; Stanley and Benson, 1979; Swinehart and others, 1985, and references therein). Most notably, Stanley and Benson (1979, p. 404) reported the same characteristics observed in this study, stating that "vitric siltstone and mudrock dominates the White River Group [Brule Formation]" and "these lithologies contain 40 to 80 percent rhyolitic shards, which exhibit bubble-wall junctures, rod shapes, or are pumiceous."

Almost all geologic studies from Foley (1942) to the present (2013) indicate the Arikaree Formation, rather than the White River Group or Formation, underlies the Ogallala Formation in southeastern Wyoming [as noted previously, studies before Foley (1942) identified both lithostratigraphic units known subsequently as the Ogallala and Arikaree Formations composing only one lithostratigraphic unit in southeastern Wyoming, the Arikaree or Harrison Formation]. An exception to this generalization for southeastern Wyoming is noted for the area that includes the vicinity of Cheyenne and areas immediately to the west and southwest, including the study area (Denson and Bergendahl, 1961; Lowry and Crist, 1967; Cooley and Crist, 1981, 1994) (fig. 6, section *A–A′*); these studies indicate the Arikaree Formation has been eroded and that the White River Group or Formation directly underlies the Ogallala Formation in the study area. Most subsequent studies have adopted this interpretation, but a few studies (Weston Engineering, 1996a; Wyoming State Engineers Office, 2008) have indicated that it has not been conclusively proven that the White River Group or Formation directly underlies the Ogallala Formation in the vicinity of Cheyenne and areas immediately to the west and southwest, including the study area, because of the absence of detailed and quantitative lithologic descriptions of core rather than drill cuttings. Although the Arikaree and Brule Formations in southeastern Wyoming and adjacent western Nebraska have many similar characteristics [for example, largely composed of fine-grained volcaniclastic eolian and fluvial sediments, commonly with retention of original volcanic shapes, as also was observed in this study, and similar lithologic and mineralogic composition (for example, Bart, 1974, 1975)], the Arikaree Formation generally is coarser grained than the Brule Formation and commonly is described as composed primarily of very fine- to fine-grained sandstone in southeastern Wyoming and adjacent western Nebraska (Sato and Denson, 1967; Denson, 1969; Denson and Chisholm, 1971; Lowry and Crist, 1967; Bart, 1974, 1975; Stanley, 1976; Swinehart and others, 1985, and references therein; Swinehart and Diffendal, 1997, and references therein). Collection and associated detailed description of core in this study indicates that the lithostratigraphic unit underlying the Ogallala Formation in the study area is much finer grained throughout the entire thickness of the unit than published descriptions of the Arikaree Formation, and the unit closely resembles published descriptions of the Brule Formation of the White River Group in southeastern Wyoming and adjacent western Nebraska as discussed previously. Conclusive identification of the Brule Formation underlying the Ogallala Formation in the study area confirms earlier studies indicating that the Arikaree Formation was eroded from the area before deposition of the Ogallala Formation (Denson and Bergendahl, 1961; Lowry and Crist, 1967; Cooley and Crist, 1981, 1994; Ogle and Hallberg, 2000) and refutes suggestions in later studies (Weston Engineering, 1996; Wyoming State Engineers Office, 2008) that it has not been determined that the White River Group directly underlies the Ogallala Formation in the study area and in the vicinity of Cheyenne and areas immediately to the west and southwest.

Brule or Chadron Formation of the White River Group

Characteristics of sediments collected from core and cuttings from the Brule or Chadron Formation of the White River Group (about 405.6 ft to 440.1 BLS) at the study location are described in this section of the report. Sediment characteristics within this depth interval are described using visual techniques, XRD and thin-section petrography, and geophysical log characteristics. Finally, the resulting description of these characteristics are compared and contrasted with previously published descriptions and lithostratigraphy. Although sediments of this depth interval are part of the White River Group, insufficient diagnostic characteristics made it difficult to determine which sediments in this depth interval should be assigned to the Brule Formation and which should be assigned to the Chadron Formation; therefore, sediments in this depth interval are identified as belonging to the "Brule or Chadron Formation of the White River Group" throughout this report.

Visual Description

Evaluation of continuous core collected from about 405.6 to 440.1 ft BLS indicated lithology in this depth interval varied more than the overlying lithostratigraphic unit identified as the Brule Formation of the White River Group. Sediment size and sorting varied substantially, but three generalized lithologic units were identified (plate 1; fig. 3): (1) a light yellowish brown silty and clayey sandstone from about 407 to 412.6 ft BLS, (2) a pale olive silty and clayey conglomeratic sandstone from 412.6 to 417.3 ft BLS (photograph of core from 414.3 ft BLS shown in fig. 16*A*), and (3) a light yellowish brown and brown sandy argillaceous siltstone from about 417.3 to 440.1 ft BLS (photograph of core from 430.6 ft BLS shown in fig. 16*B*). For all three units, sand- and gravel-sized sediments were immature, indicated by subrounded to angular rounding and subprismoidal to subdiscoidal sphericity (plate 1). Sediments generally ranged from moderately to poorly consolidated for the 407–412.6-ft depth interval, poorly to moderately consolidated for the 412.6–417.3-ft depth interval, and very poorly to moderately consolidated for the 417.3–440.1-ft depth interval. Black, red, or yellow staining was noted in both the 407–412.6-ft and the 412.6–417.3-ft depth intervals. Intact mudstone rock fragments, also indicative of immature sediments, were observed throughout the 407–412.6-ft depth interval, as well as from about 412.6 to 413.6 ft BLS in the upper part of the unit in the sandy argillaceous siltstone (417.3–440.1-ft depth interval). Mica and dark-colored accessory minerals were noted in small percentages throughout the

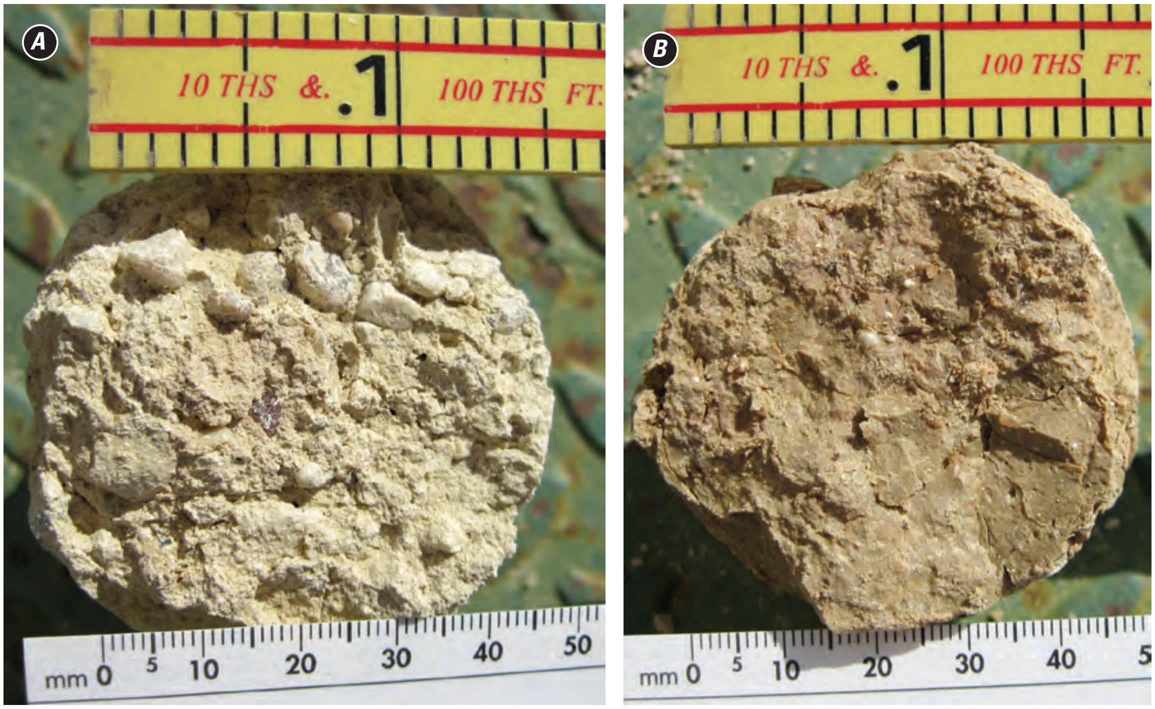


Figure 16. Photographs of core from monitoring well BRO–2, Brule or Chadron Formation of White River Group, Belvoir Ranch, Laramie County, Wyoming. *A*, Core from about 414.3 feet below land surface; and *B*, Core from about 430.6 feet below land surface. (Photographs correspond with photograph identifiers *G* and *H* on fig. 3.)

three lithologic units (plate 1). In contrast to the argillaceous vitric siltstone composing the overlying Brule Formation, biotite flakes were notably visually absent in the sandy argillaceous siltstone composing the 417.3–440.1-ft depth interval.

X-Ray Diffraction and Petrography

After visual description was complete, two intervals from this lithostratigraphic unit were subsampled for thin-section petrography (414.1–414.3 and 430.7–430.95 ft BLS) and two adjacent intervals were subsampled for additional analysis using XRD (413.8–414.1 and 430.95–431.20 ft BLS); each of the intervals selected for thin-section petrography and XRD were adjacent to one another to facilitate use of both methods to characterize the sediments in essentially the same depth interval. Point-count data for the petrographic thin sections are listed in table 5.

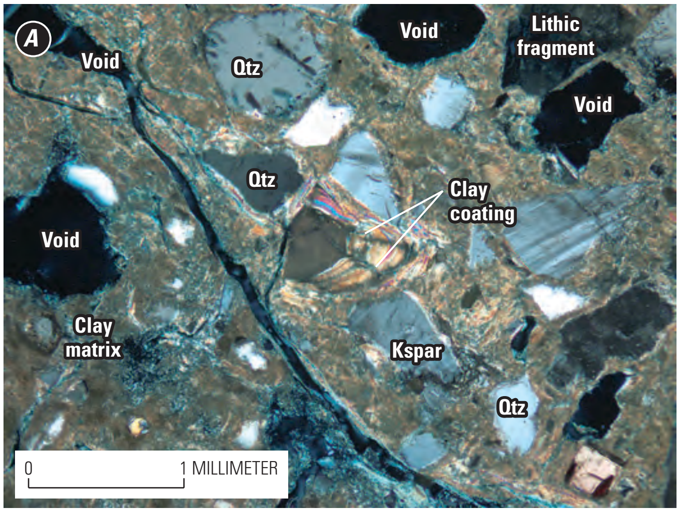
The petrographic thin section constructed from core collected from the 414.1–414.3-ft depth interval of monitoring well BRO–2 (fig. 17) indicates the sediments in this depth interval exhibit pedogenic features of a paleosol. Angular to subrounded constituent grains floated in an argillic matrix of orthogonally oriented clays. Constituent grains, rock fragments, voids, and fractures were coated and lined by platy clays. Clay coatings commonly had crescentric laminations (fig. 17*A*), which are characteristic of the deposition of infiltrated and transported clay by soil waters. Rounded reworked soil grains with illuvial clay and their own oriented clay matrix texture were contained within the “soil” itself.

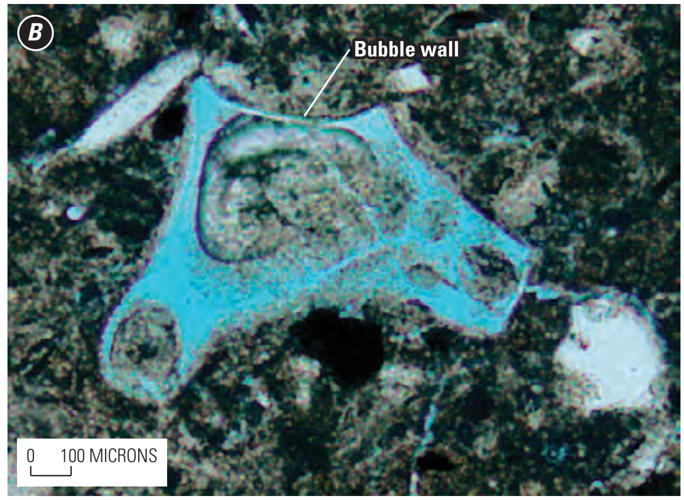
Open fractures and cracks formed a network through the clayey matrix (fig. 17). Irregularly shaped void spaces were common. As noted elsewhere in this section, this preserved open space may be original cracking, or the shrinkage cracking because of drying of the core.

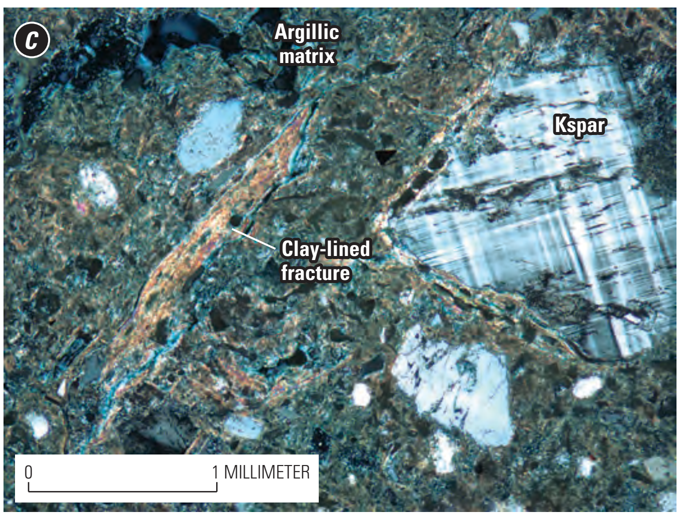
Volcaniclastic fragments were present, as indicated by the presence of shards with bubble textures (fig. 17*B*). Brown biotite, also identified in the overlying Brule Formation, is present. Analysis of the adjacent XRD sample showed that the bulk content of the sample is quartz and clay (413.8–414.1 ft BLS, appendix tables 1–1 to 1–5; appendix table 1–11), which is consistent with the argillic matrix and silicate grains.

The petrographic thin section constructed from core collected from the 430.7–430.95-ft depth interval of monitoring well BRO–2 indicates the sediments in this depth interval are an argillaceous siltstone. Sediments in the sample were highly altered to a very fine-grained clayey matrix, which had a vermiform crescent texture (fig. 18*A*). The dominant clay and quartz content also was observed in the adjacent XRD sample (430.95–431.20 ft BLS, appendix tables 1–1 to 1–5; appendix table 1–12).

Open dessication or shrinkage cracks cross cut the sample. Rare silicate grains with bubble texture appear to be formed after original pumice or shard material (fig. 18*B*); these grains were identified as pumice/shardy material on the







EXPLANATION

Kspar Potassium feldspar

Qtz Quartz

Figure 17. Scanning electron microscope (SEM) micrographs of samples from 414.1–414.4 feet below land surface, monitoring well BRO–2, Brule or Chadron Formation of the White River Group, Belvoir Ranch, Laramie County, Wyoming. *A*, Soil-like textures are shown by the laminated clay coatings around grains and voids. The black extinction bands (leaders) are a product of the strong continuous preferred orientation of clay particles; *B*, Plane light micrograph. Glassy shards with bubble texture are common constituents of volcanic origin preserved in the matrix; and *C*, Oriented clay lines fractures and coats grains. Potassium feldspar shows typical twinning pattern.

basis of their morphology and resemblance to volcaniclastic glass fragments seen in thin sections constructed from shallower parts of the core (for example, Brule Formation, 375.18–375.3-ft depth interval, fig. 15*C*).

Constituent grains floating in the clay matrix were potassium feldspar; plagioclase; quartz; chert grains; devitrified altered volcanic (?) rock fragments, many of which appeared to be partially to totally replaced by carbonate; and granitic fragments of quartz, feldspar, and sericitized plagioclase, minor amphibole, and zircon. Constituent grains were angular except for a few rounded sedimentary grains such as a 2-mm (0.08-in.) diameter, rounded, iron-oxide shaley rock fragment.

Geophysical Log Characteristics

Most geophysical log responses/measurements for sediments in this depth interval were very similar to those of the overlying Brule Formation, especially in the upper two lithologic units (light yellowish brown silty and clayey sandstone from about 407 to 412.6 ft BLS and pale olive silty and clayey conglomeratic sandstone from 412.6 to 417.3 ft BLS); however, subtle differences in log responses can be seen between and within the three lithologic units in this depth interval, and in comparison with overlying sediments of the Brule Formation (plate 1; fig. 3). Notably, subtle decreases in normal resistivity, SP, and neutron counts, relative to previous log responses observed in overlying sediments, were seen beginning at about 417 ft BLS, and once inflected/shifted, these responses remained constant (consistent linear pattern) with increasing depth to about 440 ft BLS. Caliper log deviation also was seen in this depth interval. Changes in natural gamma were more variable; counts decreased from about 416 to 421 ft BLS, increased from about 421 to 435 ft BLS, and decreased rapidly between about 435 to 440 ft BLS. The increase and corresponding decrease in natural gamma in the 434–436-ft depth interval was relatively “rapid,” resulting in a visually unique “spike.” Unfortunately, core or cuttings were not recovered from this depth interval so lithology could not be examined in relation to the natural gamma spike. These changes in geophysical log response, although generally subtle, coincided with and characterized the sandy argillaceous

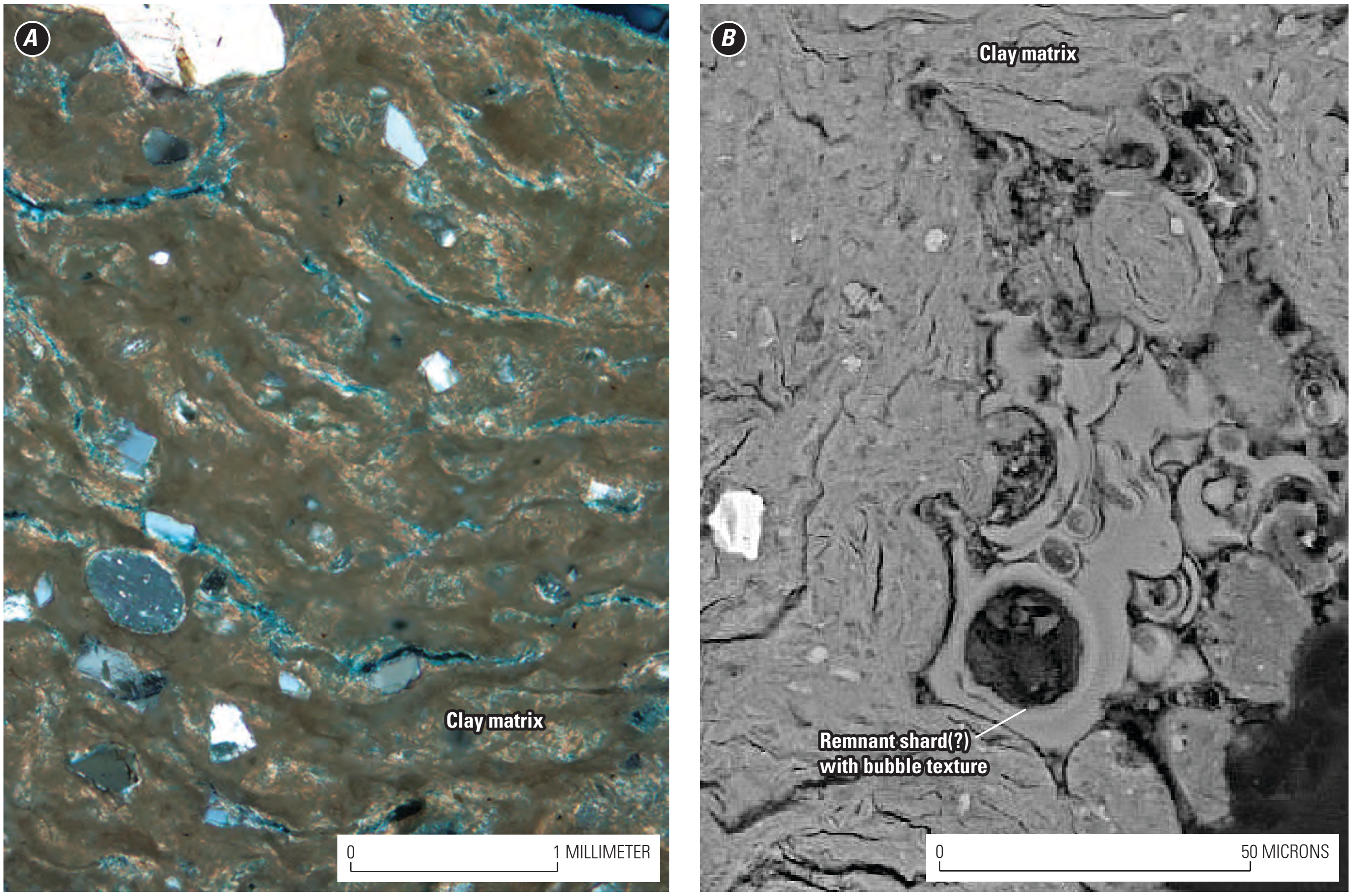


Figure 18. Micrographs of samples from 430.7 to 430.95 feet below land surface, monitoring well BRO–2, Brule or Chadron Formation of the White River Group, Belvoir Ranch, Laramie County, Wyoming. *A*, Transmitted light micrograph showing textured clay-rich sample with sparse constituent grains. Black areas are open fractures, probably shrinkage cracks; and *B*, Scanning electron microscope (SEM) micrograph of remnant shard with bubble texture.

siltstone in the 417.3–440.1-ft depth interval, and reflected lithologic change from the overlying coarser-grained silty and clayey conglomeratic sandstone in the 412.6–417.3-ft depth interval.

Lithostratigraphy

Identification of the overlying lithostratigraphic unit as the Brule Formation of the White River Group indicates lithologic units in this depth interval are either part of that unit, are part of the underlying Chadron Formation of the White River Group, or both. Although the Brule Formation is composed primarily of fine-grained (mud-sized) sediments of volcaniclastic origin, and the formation is predominantly composed of vitric (tuffaceous) mudrocks, coarse-grained alluvial deposits are known to occur throughout the unit, although commonly thin and more commonly near the middle of the formation in adjacent western Nebraska (Blodgett, 1974; Swinehart and others, 1985, and references therein).

Characteristics of lithologic units in this depth interval—overall coarser and more variable grain size compared to the overlying Brule Formation, and grain composition, presence of altered and unaltered volcaniclastics, and geophysical log characteristics generally similar to the overlying Brule Formation—were not considered diagnostic for assignment to either lithostratigraphic unit (Brule or Chadron Formation) of the White River Group. Notably, identification of altered and unaltered volcaniclastic sediments identified in both thin sections from this depth interval is not a diagnostic characteristic because volcaniclastic sediments reportedly occur in both the Brule and Chadron Formations in southeastern Wyoming and adjacent western Nebraska (see description in the following section); however, volcaniclastics generally occur less commonly in the Chadron Formation, and primarily in the upper part of the formation because the lower part is composed primarily of fluvial sediments derived from weathering of adjacent uplifts (Swinehart and others, 1985, and references therein; Swinehart and Diffendal, 1997, and references therein). As stated previously, geophysical log responses (most notably, normal resistivity logs) for this lithostratigraphic unit are very similar to log responses for the overlying

Brule Formation. Consequently, this lithostratigraphic unit is referred to as the “Brule or Chadron Formation of the White River Group” herein because characteristics of this unit are not diagnostic for definitive assignment to either formation of the White River Group.

Chadron Formation of the White River Group

Characteristics of sediments collected from core and cuttings from the Chadron Formation of the White River Group (about 440.1 to 532 ft BLS) at the study location are described in this section of the report. Sediment characteristics within this depth interval are described using visual techniques, XRD and thin-section petrography, and geophysical log characteristics. Finally, the resulting description of these characteristics are compared and contrasted with previously published descriptions and lithostratigraphy to assign sediments of this depth interval (440.1 to 532 ft BLS) to the Chadron Formation of the White River Group.

Visual Description

Sediments from the 440.1–488.4-ft depth interval were described using core (fig. 19*A–D*), whereas sediments from the 488.4–532-ft depth interval were described using cuttings. With the notable exception of an interbedded 10-ft-thick fine-grained lithologic unit and a few other thin fine-grained interbeds, lithologic units in the 440.1–532-ft depth interval can be described broadly as predominantly a matrix-supported (composed of varying amounts of silt and clay) conglomeratic sandstone. Within this broad lithologic characterization of this depth interval, three generalized lithologic units were identified (plate 1; fig. 3). Although described as ranging from unconsolidated/very poorly to moderately consolidated (plate 1), sediments throughout this entire sequence were poorly consolidated and could just as easily be classified as unconsolidated sediments rather than lithified sediments (“rocks”) (for example, fig. 19*C*). Drilling was stopped upon penetration of about 8 ft of sediments (from about 532 to 540 ft BLS) interpreted to be the underlying Upper Cretaceous Lance Formation (fig. 19*D*). Although not clear in this photograph (fig. 19*D*) because of drying before photography, sediments of the Upper Cretaceous Lance Formation were noticeably different in color than the overlying Chadron Formation, having a very distinctive and diagnostic yellowish color when wet; this distinctive color and color change from the overlying White River Group also has been noted in previous studies (for example, JR Engineering, 2005; Trihydro Corporation, 2009).

The first lithologic unit, a light olive brown to light yellowish brown, pale yellowish to gray, brown, pale yellow, or light olive-brown conglomeratic sandstone with varying amounts of silt and clay as matrix was present from about 440.1 to 467.3 ft BLS (plate 1). A photograph of core from about 447 ft BLS within this lithologic unit is shown in figure 19*A*. Sand-sized sediments were subrounded to angular, whereas pebbles were rounded to subrounded. Sphericity for all sediments ranged from subprismoidal to subdiscoidal. Red, orange, or yellow staining was observed throughout the lithologic unit. Clear quartz fragments were observed throughout this unit, as were rock fragments composed of pale-colored feldspars and pink and gray granitic fragments (plate 1). No dark metamorphic rock fragments were observed in this lithologic unit.

The second lithologic unit, a pale yellow to pale olive clayey and silty sandstone with occasional pebbles, was present from about 467.3 to 477 ft BLS (plate 1). A photograph of core from about 472 ft BLS is shown in figure 19*B*. Most sediments were subrounded to angular, but coarser-grained sediments were rounded to subrounded. Sphericity ranged from subprismoidal to subdiscoidal. Yellow or orange staining was noted in some intervals.

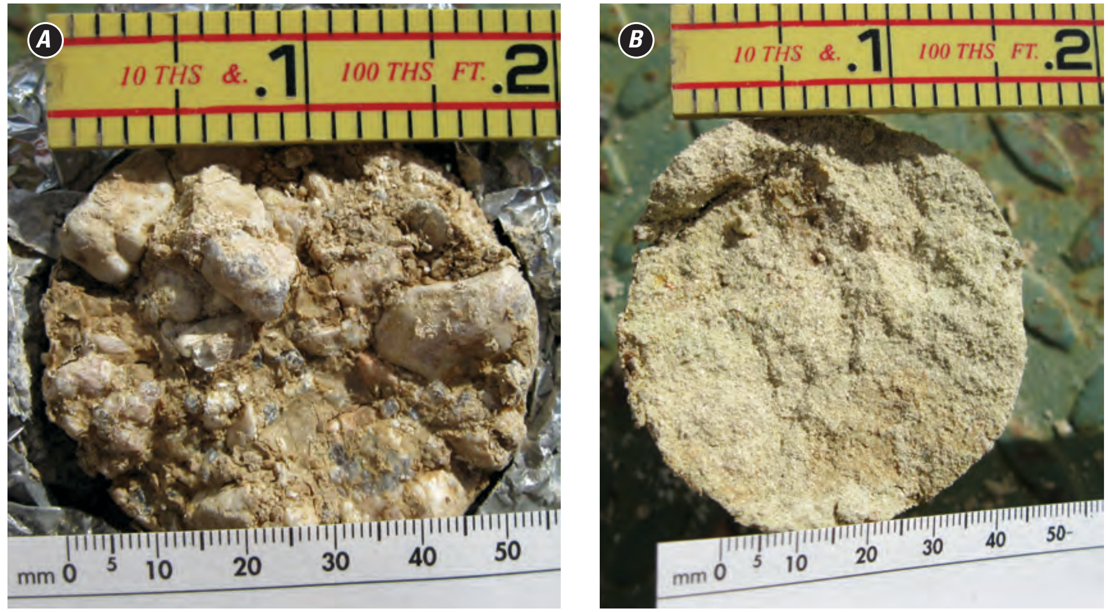
The third lithologic unit, a pale yellow, pale olive, olive yellow, brownish yellow, or light gray conglomeratic sandstone with varying amounts of silt and clay was present from about 477 to 532 ft BLS (plate 1). A photograph of core from one depth interval (482 ft BLS) within this lithologic unit is shown in figure 19*C*. Sand-sized sediments generally were subrounded to angular, but coarser-grained sediments were rounded to subrounded. Sphericity ranged from subprismoidal to subdiscoidal. Yellow, orange, and (or) red staining was noted in some intervals. Quartzitic, granitic, and mudstone rock fragments were noted throughout this unit; in addition, dark metamorphic rock fragments as seen in the Ogallala Formation were observed throughout the 477- to 532-ft depth interval.

Although not always considered a diagnostic characteristic for lithostratigraphic purposes, color throughout the depth interval from about 440.1 to 510 ft BLS was similar, characterized by an overall yellowish and green (olive) hue/color that was noticeably different from the sediments found at shallower depths and described previously. These sediments became increasingly darker olive or green with increasing moisture content; unfortunately, some of this darker olive or green color cannot be seen in photographs presented herein (fig. 19*A–C*) because some drying of the core occurred before detailed sample description, analysis, and photography was completed; as they dried, the sediments became more yellowish in color. Overall, the color of sediments in this sequence is distinctive and likely diagnostic, and contrasts with color in overlying lithologic and lithostratigraphic units.

X-Ray Diffraction and Petrography

After visual description was complete, three intervals from this lithostratigraphic unit were subsampled for additional analysis using XRD (446.0–446.4, 471.0–471.3, and 487.15–487.6 ft BLS) and three adjacent intervals were subsampled for thin-section petrography (445.6–445.9, 471.3–471.6, and 487.15 ft BLS); each of the intervals selected for XRD and thin-section petrography were adjacent to one another to facilitate use of both methods to characterize the

Figure 19. Photographs of core and cuttings from monitoring well BRO–2, Chadron Formation of the White River Group or Lance Formation, Belvoir Ranch, Laramie County, Wyoming. *A*, Core from about 447 feet below land surface, Chadron Formation of the White River Group; *B*, Core from about 472 feet below land surface, Chadron Formation of the White River Group; *C*, Core from about 482 feet below land surface, Chadron Formation of the White River Group; and *D*, Cuttings from 533–535 feet below land surface depth interval, Lance Formation. (Photographs correspond with photograph identifiers *I*, *J*, *K*, and *L* on fig. 3.)



sediments in essentially the same depth interval. Point-count data for the petrographic thin sections are listed in table 5.

The petrographic thin section constructed from core collected from the 445.6–445.9-ft depth interval of monitoring well BRO–2 indicates the sediments in this depth interval are best classified as an immature sandy gravel or conglomerate (depending on amount of cementation); this gravel/conglomerate was very poorly sorted with constituent grains ranging from micron-size matrix material to pebble-size centimeter-size (0.4-in. -size) rock fragments, which were subangular to rounded in shape (fig. 20). Constituent grains largely were coated by well-oriented clay coatings indicative of infiltrated illuvial clay (fig. 20). Open fractures, through matrix material and cross cutting larger grains, were lined by well-oriented illuvial clays, which is indicative of soil-like (paleosol) characteristics (fig. 20*B*).

Constituent grains from the 445.6–445.9-ft depth interval were granitic rock fragments composed of potassium feldspar, quartz, and plagioclase with minor biotite or zircon; strained, shadowed, polycrystalline quartz grains; and potassium feldspar grains. Matrix material was composed of liberated grains of feldspar, quartz, brown mica (biotite?) within fine-grained clays, and iron oxides. Potassium feldspar grains showed a typical cross-hatched twinning pattern (fig. 20*B*). Notably absent were metamorphic rock fragments such as hornblende and mica schist that were common in the shallower parts of the borehole, a characteristic also noted in the visual description of core throughout the 440.1–477-ft depth interval.

The petrographic thin section constructed from core collected from the 471.3–471.6-ft depth interval of monitoring well BRO–2 (fig. 21) indicates the sediments in this depth interval are immature, poorly sorted, with quartz, potassium feldspar, plagioclase; accessory grains of illuvial clay fragments; chert; devitrified volcanic (?) rock fragments; altered micas of brown biotite (?) and muscovite; green amphibole; and opaque minerals [magnetite or hematite (?)]. Mica, amphibole (hornblende), or opaque minerals were not identified in the adjacent XRD sample (471.0–471.3 ft BLS, appendix table 1–14). Because the percentage of clay matrix

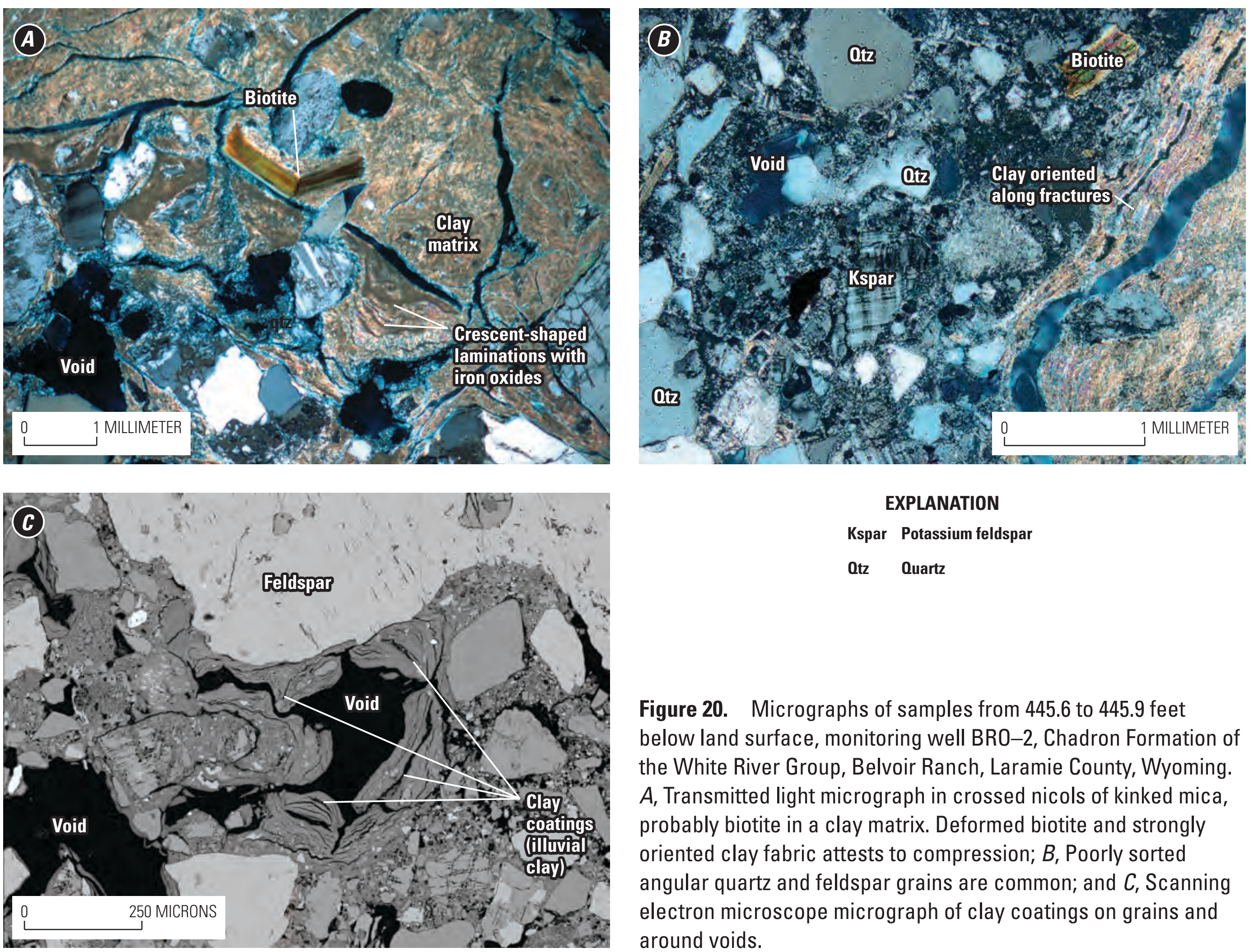
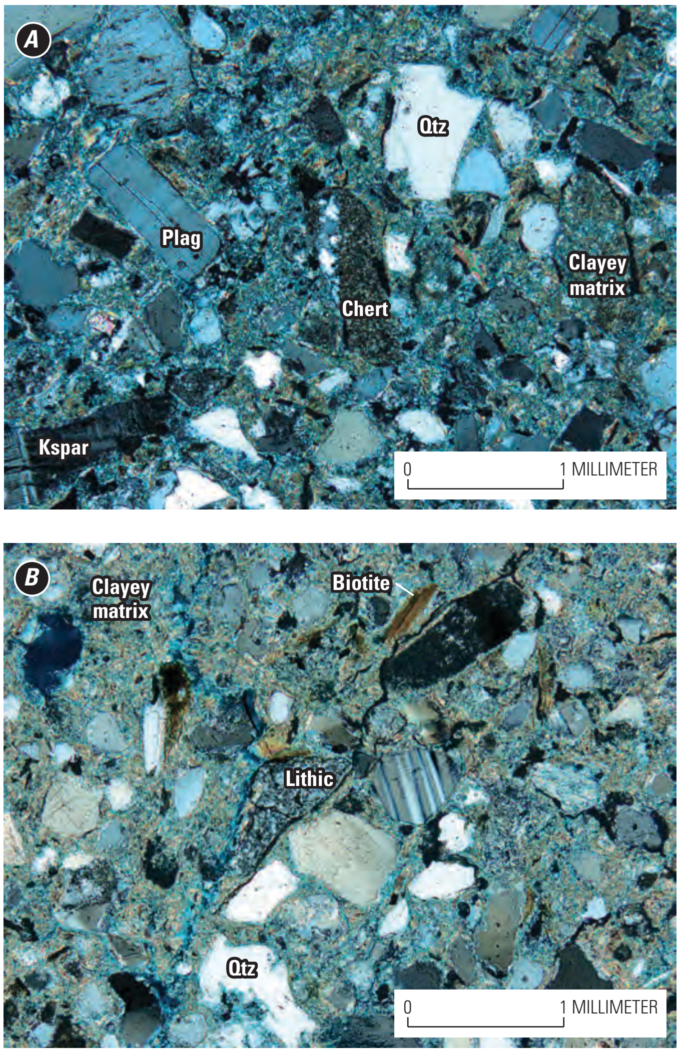


Figure 20. Micrographs of samples from 445.6 to 445.9 feet below land surface, monitoring well BRO–2, Chadron Formation of the White River Group, Belvoir Ranch, Laramie County, Wyoming. *A*, Transmitted light micrograph in crossed nicols of kinked mica, probably biotite in a clay matrix. Deformed biotite and strongly oriented clay fabric attests to compression; *B*, Poorly sorted angular quartz and feldspar grains are common; and *C*, Scanning electron microscope micrograph of clay coatings on grains and around voids.

material was large, composing 49 percent of the rock (table 5; fig. 21*A*), the thin-section sample was classified as a poorly sorted lithic and feldspathic argillaceous sandstone or a wacke by using classification of Williams and others (1982, fig. 13–1, p. 327) and modified from Dott (1964, p. 629).

Grains from the 471.3–471.6-ft depth interval were silt- to sand-sized; rock fragments were largely broken down to individual mineral grains, but granitic fragments of quartz plus feldspar were identifiable. Grains were coated by illitic clays; some areas/domains were more clay-rich than others (fig. 21*B*), and the matrix showed an orthogonal arrangement of platy brown-birefringent illitic clay between constituent grains. Kaolinite was identified in thin section as booklets of platy clays in close association with quartz. Kaolinite appeared to be an alteration product after feldspar that once was part of rock fragments with quartz. Granitic rock fragments commonly were broken down into constituent grains by alteration to clay along grain boundaries between feldspar and quartz grains. Micas such as muscovite were altered to iron oxides along cleavage planes. Micas commonly were kinked, deformed between harder constituent grains, and altered to iron-oxides along cleavage planes. Evaluation of void space was problematic because it was difficult to determine if shrinkage cracking around grains was original or occurred as the core dried. Very poorly sorted, immature unconsolidated to poorly cemented conglomerate, ranging from clays and fine-grained grains to cobble-sized grains, composed the thin section constructed from core from about 487.15 ft BLS (fig. 22*A*–*C*). Constituent grains included clayey/shaley fragments (fig. 22*B*), granitic fragments, epidote (?) and quartz rock fragments, and centimeter-size (0.4-in.-size) grains of individual potassium feldspar and polycrystalline quartz. Edges of clay-rich silt-bearing shaley fragments are penetrated by harder grains. Some clayey fragments had a vermiform, crescent texture similar to the thin section from the 430.7–430.95-ft depth interval. Other clayey fragments were rich in silt-size quartz, and their texture is similar to clay-rich domains in the thin section from the 471.3–471.6-ft depth interval, in which clays in fine-grained matrix material indicated an orthogonal alignment. This sample had features such as grains coated by layers of oriented illuvial clays that were similar to those found in soils (fig. 22*A*); however, as described previously, clay coatings may be because of pressure effects, and this sample was very coarse grained in comparison to other samples that had more soil-like characteristics. Granitic fragments consisted of quartz, potassium feldspar, plagioclase, and areas of myrmekitic texture (fig. 22*C*). Shaley fragments indicated that the sediment was immature, but the granitic, feldspar, and quartz rock fragments showed some rounding. Because the sediment was almost unconsolidated, void space could not be preserved, and therefore, was not point counted (table 5).



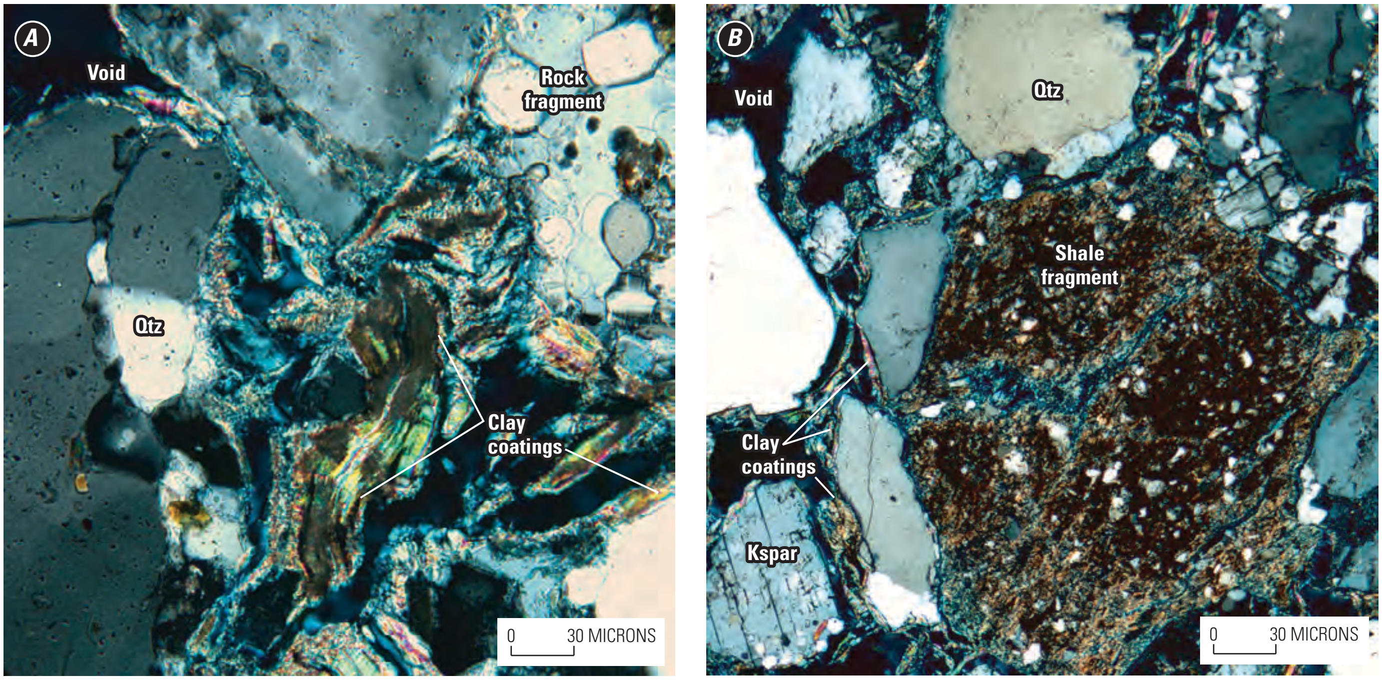
EXPLANATION

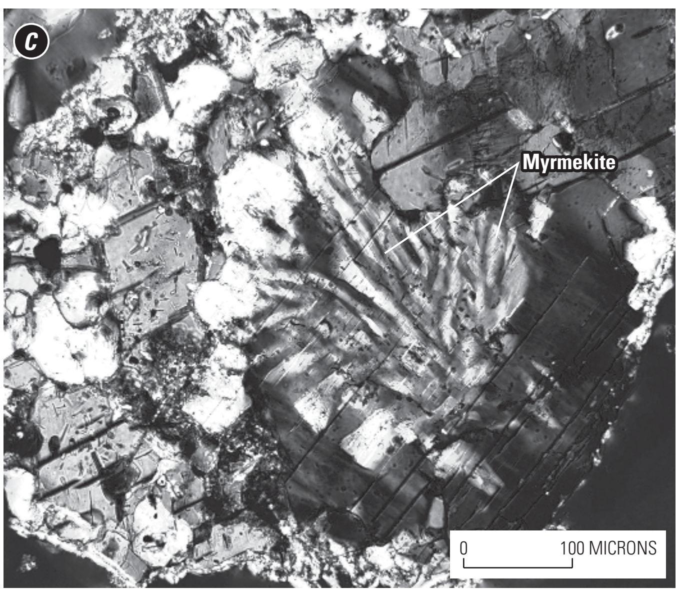
Kspar	Potassium feldspar
Plag	Plagioclase
Qtz	Quartz

Figure 21. Micrographs of samples from 471.3 to 471.6 feet below land surface, monitoring well BRO–2, Chadron Formation of the White River Group, Belvoir Ranch, Laramie County, Wyoming. *A*, Transmitted light micrograph of poorly sorted lithic and feldspathic argillaceous sandstone or a wacke; and *B*, Constituent grains are subrounded to angular, floating in domains of clay matrix.

Geophysical Log Characteristics

Geophysical log responses for sediments in the depth interval from 440.1 to 532 ft BLS differed from those seen in the three overlying lithologic units (405.6 to 440.1 ft BLS) that could not be confidently assigned to either the Brule or Chadron Formation of the White River Group (plate 1; fig. 3). The differing geophysical log responses observed in this depth interval were correlative with substantial changes from overlying finer-grained lithology, and combined, these characteristics were interpreted in this study to be indicative and a diagnostic characteristic of the Chadron Formation.





EXPLANATION

Kspar Potassium feldspar

Qtz Quartz

Figure 22. Transmitted light micrographs of samples from 487.15 feet below land surface, monitoring well BRO–2, Chadron Formation of the White River Group, Belvoir Ranch, Laramie County, Wyoming. *A*, Aligned clays coat grains and voids. Iron oxides (dark brown) occur with the clays; *B*, Shale fragments are common and may be deformed between harder granitic rock fragments; and *C*, Myrmekitic texture is common in the granitic rock fragments.

Normal resistivity counts, in comparison with the relatively uniform response observed in the overlying depth interval (405.6 to 440.1 ft BLS), increased moderately with increasing depth of the Chadron Formation until decreasing moderately beginning at about 519 ft BLS (plate 1; fig. 3). Resistivity continued to decrease steadily below 519 ft BLS and into the underlying silty and clayey sandstone of the Lance Formation. Log response varied between 487 and 519 ft BLS, reflecting alternating increases and decreases in resistivity associated with the larger proportion of gravel in the silty and clayey conglomeratic sandstone in this depth interval.

Neutron counts increased upon transition to the Chadron Formation, and then counts gradually increased with increasing depth until about 490 ft BLS (plate 1; fig. 3). With the exception of a spike at about 495.5 ft BLS, neutron counts decreased slowly with increasing depth from about 490 to 510 ft BLS. Log response was uniform from about 510 to 534 ft BLS, including the transition into the underlying Lance Formation. A small but relatively rapid decrease in neutron counts was observed in the 534–536-ft depth interval. Log response varied within the depth interval where counts gradually increased (440.1 to about 490 ft BLS), reflecting alternating increases and decreases in neutron counts. The increasing and decreasing neutron counts in this depth interval coincided with nearly identical changes in the resistivity logs.

Like the resistivity and neutron logs, natural gamma response reflected lithologic changes within the Chadron Formation. In fact, natural gamma counts and patterns generally correlated with the three generalized lithologic units identified in the 405.6 to 440.1-ft BLS depth interval that could not be confidently assigned to either the Brule or Chadron Formation of the White River Group as described previously. Highest natural gamma counts were associated with the silty and clayey conglomeratic sandstone in the 440.1–467.3-ft BLS depth interval, and lowest with the clayey and silty sandstone with occasional pebbles in the 467.3–477-ft BLS depth interval. Natural gamma counts for the silty and clayey conglomeratic sandstone in the 477–532-ft BLS depth interval were between those measured in the other two lithologic units in the Chadron Formation, and counts generally were the most uniform of all three lithologic units identified in the Chadron Formation. Natural gamma counts increased slightly transitioning into the underlying Lance Formation, possibly reflecting the increase in or characteristics of the finer-grained sediments associated with this different lithostratigraphic unit.

The SP increased slightly upon transition to the Chadron Formation, and then log response was uniform with increasing depth until about 488.4 ft BLS (plate 1); at this depth, SP decreased almost imperceptibly. Below this depth, log response remained uniform with increasing depth throughout the unit and into the underlying Lance Formation.

Lithostratigraphy

Characteristics of sediments in the three lithologic units in this depth interval (440.1 to 532 ft BLS) are noticeably different than those observed in the overlying 405.6–440.1-ft depth interval (much coarser grained; distinctive green color/hue; unique geophysical log characteristics; absence of volcaniclastic sediments in thin sections). In contrast to the overlying unit, these characteristics were interpreted to be diagnostic for assignment of these sediments to the lowermost lithostratigraphic unit of the White River Group, the Chadron Formation, for the following reasons described in this section.

Coarse-grained sediments in the "White River" adjacent to the Laramie Mountains in western Laramie County with characteristics similar to those observed in this study have been reported in numerous earlier studies (Dockery, 1940; Foley, 1942; Morgan, 1946; Gray, 1947; Brady, 1949; Haun, 1949; Minick, 1951). Several of these studies explicitly assign these coarse-grained sediments of the "White River" adjacent to the Laramie Mountains to the Chadron Formation, commonly noting the "arkosic" and "conglomeratic" characteristics of the sediments (Foley, 1942; Morgan, 1946; Gray, 1947; Brady, 1949). Foley (1942) assigned these arkosic and conglomeratic rocks to the basal part of the Chadron Formation. In the vicinity of Federal and Hecla (figs. 1 and 5), immediately north of the study area, Brady (1949, p. 17) assigned rocks known to compose the "White River" to the Chadron Formation; reported characteristics in Brady (1949) were very similar to those observed in this study—fine- to very coarse-grained sandy conglomerate with subrounded to angular pebbles of quartzite, feldspar, quartz, chert, granite, schist, basic igneous rocks, and small sedimentary rock fragments. In addition, Brady (1949) noted that the rounding of these sediments of the Chadron Formation indicates they were transported a short distance from the presumed sediment source, the Laramie Mountains; Brady (1949) also noted that composition indicates the sediments were derived primarily from the adjacent Precambrian igneous and metamorphic rocks of the Laramie Mountains. Characteristics of rocks in this lithostratigraphic unit observed in this study closely match the descriptions of the Chadron Formation identified in the Federal and Hecla areas immediately north of the study area (figs. 1 and 5) by several of these earlier investigators (Foley, 1942; Morgan, 1946; Brady, 1949). The coarse-grained "White River" sediments identified herein as the Chadron Formation also correspond to the coarse-grained deposits identified as being present in the "lower part" of the "White River Formation" by Lowry and Crist (1967, p. 25). Lowry and Crist (1967, p. W25) observed that within the vicinity of Federal, "logs of wells show…that the large yields of water are obtained from gravel channels in the White River Formation" that "are apparently limited to the lower part of the formation" and that "no large gravel channels have been found in the upper part of the White River."

According to the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 2005), color typically is not considered a definitive diagnostic characteristic for definition of lithostratigraphic units; however, the distinctive olive (green) hue/color of sediments throughout this depth interval (440.1 to 532 ft BLS) observed in this study is associated strongly with nearly all published descriptions of the Chadron Formation in southeastern Wyoming and adjacent western Nebraska [for example, McGrew, 1953; Babcock and Bjorklund, 1956; Rapp and others, 1957; Morris and Babcock, 1960; Moore, 1963; Whitcomb, 1965; Lowry and Crist, 1967 (described as lower part of the White River Formation); Singler and Picard, 1979a,b; Swinehart and others, 1985, and references therein; Swinehart and Diffendal, 1997, and references therein], as well as with published descriptions of the Chadron Formation or Member in areas to the north in east-central Wyoming [Douglas area (fig. 5) and Flagstaff Rim area (not shown in report)] (Emry, 1973; Evanoff, 1990; Evanoff and others, 1992). In fact, McGrew (1953, p. 63) noted that "the Chadron Formation can be recognized by its general grayish to *greenish color*," and Singler and Picard (1979b, p. 53) noted that "Chadron rocks display *mostly green hues* with some yellows and reds." North of the study area, Foley (1942, p. 34) noted that "exposures of the Chadron Formation between Lodgepole Creek and Horse Creek just to the north of the Federal area, indicate that in the basal part of the formation there may be unconsolidated gravels interbedded with *greenish* clay." Similarly, in his description of the White River Group in the vicinity of Horse Creek adjacent to the Laramie Mountains, Gray (1947, p. 11) also noted green-colored sediments in the Chadron Formation, reporting “interbedded red and *green* sandy clay.”

In the vicinity of southeastern Wyoming and adjacent western Nebraska, deposition of the Chadron Formation consisted of two depositional phases (Swinehart and others, 1985, and references therein; Swinehart and Diffendal, 1997, and references therein). The first phase was dominated by fluvial deposition, primarily in paleovalleys cut into Upper Cretaceous sedimentary rocks. This fluvial phase represents the lower part of the Chadron Formation and commonly is composed of coarse-grained sediments such as fine- and coarse-grained sandstones and locally occurring conglomerates interbedded with fine-grained mudrocks such as claystones and mudstones. Much less volcaniclastic sediment occurs in this fluvial phase of the Chadron Formation in southeastern Wyoming and adjacent western Nebraska than in the upper part of the Chadron Formation and the overlying Brule Formation (Swinehart and others, 1985, and references therein; Swinehart and Diffendal, 1997, and references therein), although volcaniclastic sediments are present in greater quantities in areas to the north in east-central Wyoming [Douglas area (fig. 5) and Flagstaff Rim area (not shown)] (Emry, 1973; Evanoff, 1990; Evanoff and others, 1992). Subsequent to the fluvial paleovalley filling phase, eolian deposition of rhyolitic volcanic ash from western volcanic eruptions contributed large quantities of volcaniclastic sediments to the Chadron Formation (and later, the Brule Formation) throughout southeastern Wyoming and western Nebraska; this volcaniclastic phase represents the upper part of the Chadron Formation and is composed primarily of vitric (tuffaceous) mudrocks (claystones, mudstones, and siltstones) with less common coarse-grained sediments or facies (Swinehart and others, 1985, and references therein; Swinehart and Diffendal, 1997, and references therein). The complete absence of volcaniclastic sediments throughout this depth interval (440.1 to 532 ft BLS), along with the much coarser-grained sediment size than the overlying depth interval (405.6 to 440.1 ft BLS), strongly indicates that this unit represents at least part of the Chadron Formation. Because volcaniclastic sediments were not found in this depth interval, the sediments likely are representative of the lower part of the Chadron Formation predominantly composed of fluvial deposits that were deposited before the deposition of large quantities of volcaniclastic sediments that dominate the upper part of the formation and the overlying Brule Formation.

Summary of White River Group Lithostratigraphy and Implications to Areal Extent in Southwestern Laramie County

In contrast to many previous studies in the vicinity of Cheyenne, this study indicates that sediments within the “White River” in the study area can be divided into two lithostratigraphic units identified herein as the Brule and Chadron Formations, based on unique and diagnostic lithologic and geophysical characteristics described previously herein, and comparison of these characteristics with published descriptions of these formations throughout or in parts of southeastern Wyoming (for example, McGrew, 1953; Moore, 1963; Stanley, 1976), in the vicinity of the Laramie Mountains just north of the study area in southwestern Laramie County (Gray, 1947; Brady, 1949), and in adjacent southwestern Nebraska (Swinehart and others, 1985, and references therein; Swinehart and Diffendal, 1997, and references therein).
As part of a recent study (Trihydro Corporation, 2009), six exploratory boreholes were drilled into the “White River Formation” at different locations on the Belvoir Ranch. The investigators collected drill cuttings and geophysical logs from all six exploratory boreholes. Two of the exploratory boreholes were converted into monitoring wells (designated WR–2 and WR–3), and both wells were screened in a “coarse-grained zone.” The coarse-grained zone also was identified in most of the exploratory boreholes. The investigators attributed the coarse-grained zone to the “lower White River Formation.” Drill cuttings descriptions and geophysical log characteristics from all six exploratory boreholes (four boreholes plus two additional boreholes subsequently converted into monitoring wells WR–2 and WR–3) provided in that study were compared with the more detailed and quantitative descriptions of the “White River” provided in this study. Qualitative drill cuttings descriptions and geophysical log characteristics of the coarse-grained zone in the lower part of the “White River” identified in monitoring wells WR–2 and WR–3 and in the exploratory boreholes of that study closely matched that described for the coarse-grained zone in monitoring well BRO–2 identified herein as the Chadron Formation. In fact, Trihydro Corporation (2009, p. 3–4) noted in several locations that the sediments in this coarse-grained zone were “consistent with descriptions of the Chadron Member of the White River Group.” Positive identification of both the Brule and Chadron Formations on the Belvoir Ranch along Lone Tree Creek would indicate possible elevation of the “White River” to group rank or formally recognizing two members of the “White River” in southeastern Wyoming where the unit is not elevated to group rank (as in east-central Wyoming near Douglas; see Emry, 1973; Evanoff, 1990; Evanoff and others, 1992), even though “lower” and “upper” parts of the “White River” are recognized in most parts of southeastern Wyoming and Laramie County that essentially are correlative with the Brule and Chadron Formations (Ver Ploeg and others, 1998). Identification of both units in multiple boreholes and wells in both studies indicates that the “White River Group,” composed of both the Brule and Chadron Formations, underlies much of the Lone Tree Creek area on the Belvoir Ranch. Furthermore, identification of the Brule and Chadron Formations in the subsurface of the study area in this study, determined to be correlative with characteristics observed in boreholes from different locations in the study by Trihydro Corporation (2009), combined with identification of both formations in the Federal and Hecla areas (figs. 1 and 5) in earlier mapping of surface exposures north of the study area (Brady, 1949; Gray, 1947), indicates the areal extent of both lithostratigraphic units can be extended southward from the Federal and Hecla areas

to the subsurface in the vicinity of the Belvoir Ranch along Lone Tree Creek.

Additional Lithologic Characterization

Some lithologic characteristics are best evaluated after sediments have been assigned to lithostratigraphic units. In this section of the report, additional petrographic characteristics are described, and bulk sample and clay mineralogy are described briefly in relation to depth and lithostratigraphic unit.

Petrography

The sediment sequence evaluated at the study area revealed epiclastic sediments eroded from predominately igneous (volcanic and plutonic) and metamorphic terrains with varying degrees of cementation interbedded with paleosols and volcaniclastic sediments represented by vitric (tuffaceous) mudrocks (ash fall deposits). Stanley and Benson (1979) noted the unusual preservation of pumice and glass shards in rocks from both the Ogallala Formation and White River Group. In this study, pumice and shards with preserved bubble outlines and characteristic triangular broken shard fragments were observed in several thin-section samples from the White River Group. Stanley and Benson (1979) also stated that because there was only minor intrastratal and alteration of detrital minerals, the "original detrital fabric or modes of the sandstone" have not been modified; however, several of the depth intervals from which thin sections were constructed showed morphological structures that are characteristic of soil horizons such as oriented clay-lined voids and orthogonal clay matrix fabrics. A modal count of the paleosol-like samples showed a range of clayey matrix of as much as 76 percent (table 5), which is much greater than modal counts from White River Group samples described in Stanley and Benson (1979). In addition, alteration of detrital grains was apparent by the partial dissolution of ferromagnesium minerals such as hornblende and development of iron-oxide remnant skin/rind (figs. 9*B* and 10*B*).

Characteristics observed in several thin-section samples from the White River Group were indicative of paleosols, but it could not be determined definitively because thin sections were only available for discrete depth intervals, and the lateral extent of these intervals beyond the borehole cannot be determined. Paleosols are common throughout the White River Group (Retallack, 1983; Swinehart and others, 1985; LaGarry, 1998; Terry, 1998). The identification of paleosols is mainly based on the micromorphologic observations of the characteristics of oriented clays in the matrix and illuvial clay coatings. Clay coatings around voids and grains occurred throughout the length of the thin-section samples. Clay coatings, also referred to in the report as clay cutans, clay skins, argillans, or illuvial clay, form from the transport and progressive deposition of clay around constituent grains as well as coating fractures (figs. 17*A* and fig. 20*B*) and voids (figs. 20*C*, 22*A*, and 22*B*). The presence of these well-layered and thinly laminated clay coatings indicates (1) past soil-water movement and transport and deposition of micron-sized (hundred-thousandth-inch-sized) clay particles, (2) redistribution of clay within a wet horizon (Fitzpatrick, 1993), or (3) both. Clay coatings in paleosols commonly exhibit crescent-shaped laminations lined with iron oxides (figs. 17*A* and 20*A*). Oriented platy clay minerals, which form illuvial clay coatings, are indicative of soil processes. Illuvial clay will exhibit black extinction bands under cross nicols; these polarized light features were observed in clay coatings in figures 20*A–C.* These clay coatings may become fragmented during the soil evolution process and are transported and incorporated as grains in sediments. Reworked grains of illuvial clay were observed in samples from the 414.1- and 471.3-ft depth intervals.

Cracking is a common feature of desiccated soils and mudstones; argillic layers are subject to expansion and shrinkage cracking because of wetting and drying cycles. Fractures in the clay-rich samples may be a remnant feature of the core sample itself, or the cracking may be because of drying and shrinkage of the clayey sample before epoxy impregnation for thin-section construction. All core samples were carefully wrapped with multiple layers of tight-covering foil to preserve moisture, so the complex system of cracks that is common in the paleosol samples may have been preserved. Some of the open cracks are lined with alteration textures and minerals such as iron oxides and clays (fig. 20*B*), which indicates that the cracks were active fluid pathways.

Dissolution of minerals was evident, especially of ferromagnesium minerals (figs. 9*B* and 10*B*). Leaching was evident by dissolution pitting as embayments into grains, or remnant serrate texture of grains (fig. 10*B*). Clay partially replaced constituent grains in many thin sections.

Many of the thin sections presented evidence of iron-oxide nodule formation (for example, fig. 15*A*). Nodule or concretion formation usually indicates wet conditions during formation, and nodules with zonation indicate that the sediment underwent wetting and drying cycles.

Bulk Sample and Clay Mineralogy in Relation to Depth and Lithostratigraphic Unit

Unique insights into bulk (whole) sample and clay mineralogy of sediments composing the Tertiary lithostratigraphic units were provided by this study. For example, sediments of the White River Group commonly are described as "bentonitic" because, as was observed in this study, a substantial percentage of the sediments composing the lithostratigraphic unit(s) are composed of devitrified (weathered volcanic glass) volcaniclastic (ash fall) sediments. Examination of different clay-sized fractions using XRD methods in this study allowed for a more definitive quantitative characterization of the clays commonly described as simply "bentonitic."

Bulk-sample mineralogy of the 10 XRD samples (appendix tables 1–1 to 1–15) indicated sediments typically representative of fluvial gravels, sands, silts, and clays derived from siliceous crystalline rocks dominated by quartz, plagioclase, and potassium feldspar, as well as trace to minor amounts of mica and mafic minerals. The weathered clay component was composed of smectite (montmorillonite), illite, and kaolinite. Variable amounts of calcite (5 to 27 percent) were detected in samples collected from the 302.5–303.5-foot and 374.97–375.28-foot depth intervals above the XRD sample from the 413.8–414.1-ft depth interval in the Brule or Chadron Formation; only one sample collected from the Ogallala Formation (115–120-ft depth interval sample) contained a trace of dolomite in addition to dominant calcite. No carbonate minerals were detected in XRD patterns of bulk samples collected from below the 413.8–414.1-ft depth interval (Brule or Chadron Formation), and no XRD samples below this depth interval effervesced after addition of HCl. Fresh mica at 10 Å was not confirmed in any of the bulk samples, though poorly resolved principal peaks at 10 Å with low intensity were presumed to be mostly illite. Chlorite was suspected but unconfirmed in bulk specimens because concentrations were too low. Trace levels of hornblende were detected in only three bulk samples.

The coarse-clay fraction included the bulk to 1-µm and <1.0–0.1-µm size brackets, which also contain residual quartz and feldspars (appendix tables 1–2 and 1–3). Some clay remained in the bulk to 1-µm fraction after separation of the <1-µm materials, indicating that most of these residual clay particles may be aggregates between 1.0 and 4.0 µm. Calcite detection increased substantially in the bulk to 1-µm separates in comparison to bulk samples, but substantially decreased in the <1.0–0.1-µm samples, indicating carbonate particle sizes around 1.0 µm. No calcite was detected by XRD in grain sizes <0.1 µm, and HCl acid spot tests were negative for presence of carbonate minerals in these finer fractions. Fresh mica was detected in bulk to 1.0-µm separates from samples between 220.0 and 431.2 ft BLS in addition to illite, but was not detected in any of the finer fractions. More chlorite and hornblende was detected in bulk to 1.0-µm separates than in the finer fractions, but detection became more consistent in finer fractions when compared to calcite and fresh mica.

The fine clay was contained in grain sizes of the <1.0–0.1-µm and <0.1–0.03-µm fractions. These separates dominantly contain smectite (appendix tables 1–3 and 1–4). Kaolinite content increased in samples collected from the 430.95–431.20-ft depth interval and below in transition from the depth interval identified as the Brule or Chadron Formation to the underlying Chadron Formation. Although somewhat inconsistent, increased kaolinite abundance may be associated with slightly higher plagioclase content. This “loose” relation is best observed in the <1.0–0.1-µm fractions, and may simply reflect more plagioclase available to weather to kaolinite.

When compared to <1.0–0.1-µm analyses (appendix table 1–3), the <0.1–0.03-µm fractions had slightly more kaolinite and less illite (appendix table 1–4). Sediments above the 430.95–431.20-ft depth interval generally contained 2 to 3 times more illite compared to lower depth intervals. Chlorite and hornblende were detected consistently in all depth intervals, but only in minor to trace amounts.

The ultrafine clay fraction was composed of particle sizes <0.03 µm (appendix table 1–5). These materials contained smectite pure enough to provide important characteristics of mineral phase and chemical composition when compared to end-member reference clays of similar nature. Smectite in XRD samples from this study were similar to the Ewing montmorillonite, which has been classified thoroughly by Khoury and Eberl (1981). The weight percentages of the <0.03-µm fraction for all depth intervals are shown in appendix table 1–5. The Ogallala Formation sample from the 115–120-ft depth interval (XRD sample 2, appendix table 1–5) was the purest smectite (100 percent), which represented the generally higher expandable clay purity observed in samples from the Ogallala Formation. Conversely, samples from the Chadron Formation (XRD samples 8, 9, and 10, appendix table 1–5) had less pure smectite (72 to 85 percent). Chadron Formation smectites also contained more kaolinite and traces of illite and chlorite.

The XRD scans of glycolated ultrafine (<0.03 µm) smectite from XRD samples (XRD sample 2, 115 to 120 ft BLS, and XRD sample 8, 446.0 to 446.4 ft BLS) compared to a well-crystallized dioctahedral montmorillonite from the Ewing pit, Amargosa Desert, Nevada, are shown in figure 23. Smectites in the Ogallala Formation and Chadron Formation resolved nine orders of basal reflections that closely corresponded to peaks resolved in the analysis of the Ewing specimen. Diffractograms of the (060) peaks obtained from randomly oriented <0.03-µm dioctahedral aluminous smectites from the same two XRD samples (XRD sample 2, 115 to 120 ft BLS, and XRD sample 8, 446.0 to 446.4 ft BLS), also compared to the Ewing montmorillonite are shown in figure 24. These scans resolved b-axis reflections of smectite at 1.50 Å, indicating aluminum-rich dioctahedral phases similar to the Ewing clay. The angstrom values of the (060) peaks for all 10 particulates for the <0.03-µm fraction, revealing their similarity to the Ewing type species. Regardless of purity, the ultrafine smectite in all 10 XRD samples can be described as an aluminous dioctahedral montmorillonite. The impurities are dioctahedral kaolinite and illite, and trioctahedral chlorite.

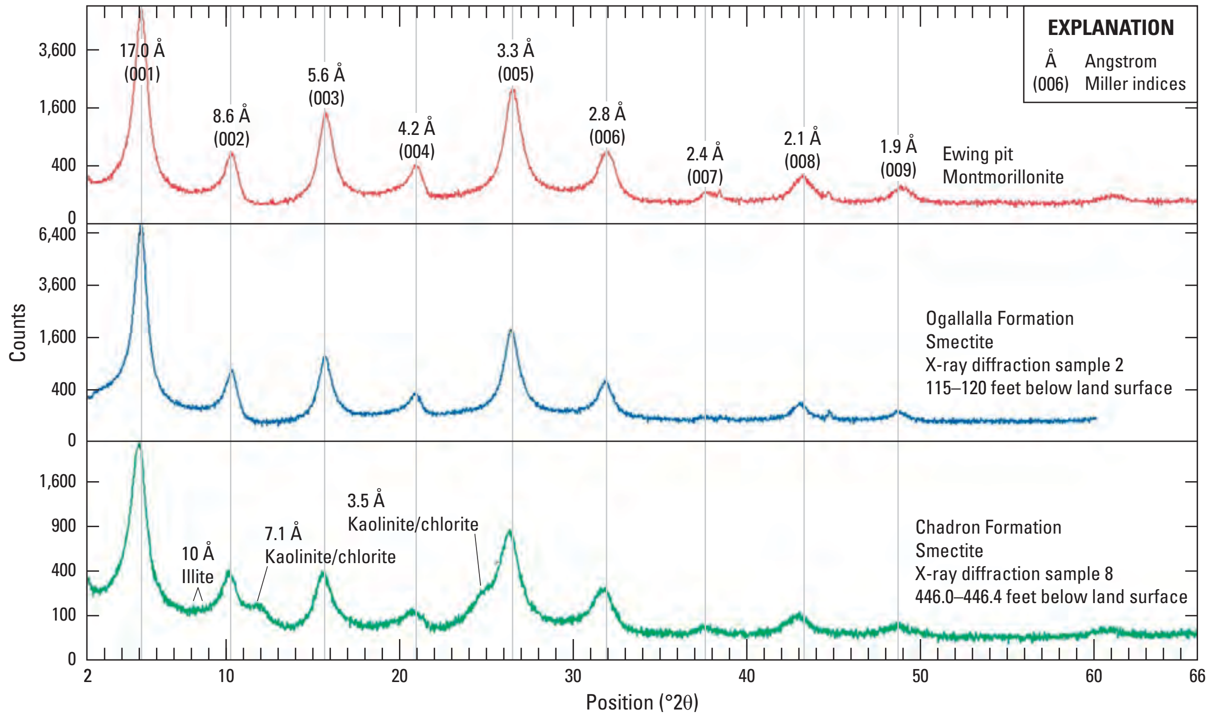


Figure 23. Diffractograms of oriented glycolated less than 0.03 micron (µm) smectites from the Ogallala and Chadron Formations compared to purified montmorillonite reference clay from the Ewing pit type locality in the Amargosa desert, Nevada. Sample 2 is the purest ultrafine material from the study area, whereas sample 8 contains traces of illite, kaolinite, and chlorite. Patterns scanned at 1 degree 2-theta (1 °2θ) per minute, CuKα radiation.

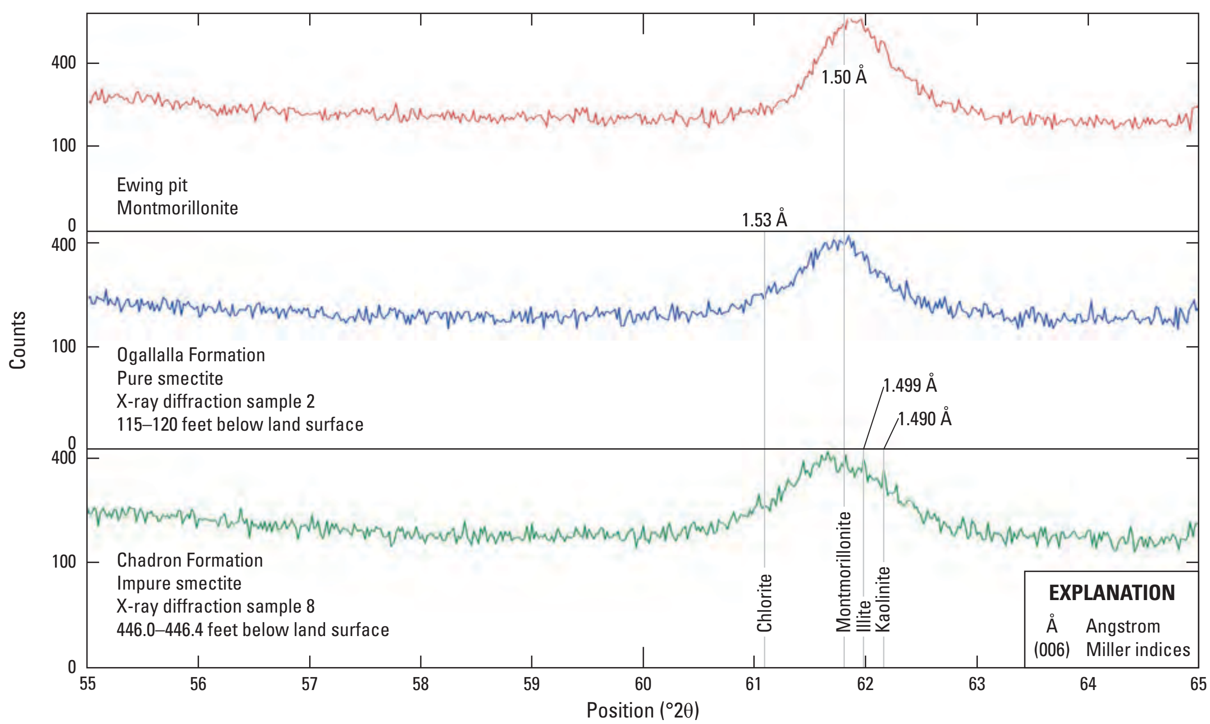


Figure 24. Diffractograms of (060) reflections from randomly oriented less than 0.03 micron (µm) dioctahedral aluminous smectites from the Ogallala and Chadron Formations compared to purified dioctahedral montmorillonite reference clay from the Ewing pit type locality in the Amargosa desert, Nevada. Sample 2 is the purest ultrafine material from the study area, whereas sample 8 contains traces of dioctrahedral illite, kaolinite, and trioctrahedral chlorite. Patterns scanned at 1 degree 2-theta (1 °2θ) per minute, CuKα radiation.

Hydrogeologic Characteristics

The hydrogeologic characteristics of the aquifers contained in Tertiary lithostratigraphic units at the study site are described in this section the report. Characteristics described in this section include groundwater levels, groundwater recharge, stable isotopes, apparent groundwater ages, and groundwater quality.

Groundwater Levels

Groundwater levels (hydraulic heads, which are water-level altitudes) are controlled by the balance between recharge to, storage in, and discharge from an aquifer. Aquifer sediment characteristics (for example, porosity, permeability, and thickness) and climatic and hydrologic factors (for example, timing and amount of recharge by precipitation, discharge to streams, and evapotranspiration) also control this balance. When recharge to an aquifer exceeds the rate of discharge, groundwater levels or hydraulic heads will increase (rise); conversely, when the rate of groundwater withdrawal or discharge is greater than the rate of groundwater recharge, water is removed from aquifer storage and groundwater levels or hydraulic heads will decrease (decline).

Groundwater levels (hydraulic heads) were measured continuously in monitoring wells BRO–1a and BRO–2, completed in the Ogallala aquifer, to assess fluctuations over time. From these continuous measurements, graphical representations of water levels (hydrographs) measured during the study are presented in figures 25 and 26 for October 2009 to June 2012. These hydrographs were plotted at the same scale in figure 25 and at different scales in figure 26 to facilitate different types of analysis. In addition, precipitation recorded at the Cheyenne airport (National Oceanic and Atmospheric Administration, 2012), located about 12 mi east of the study site, is plotted in relation to hydrographs in both figures. Precipitation data were used from the Cheyenne airport because available precipitation data for Belvoir Ranch were incomplete for the period of study (October 2009 to June 2012). It is realized that the timing and amount of precipitation may have differed between the study location and the Cheyenne airport, but the authors of this report believe these precipitation data reflected broader seasonal trends in the vicinity of Cheyenne, including the study area, and were sufficient to allow for examination of precipitation in relation to broader groundwater-level trends at the study location.

For 2010 and 2011, the hydrograph for monitoring well BRO–1a indicates that groundwater levels in the upper part of the Ogallala aquifer, reflective of the water table, vary seasonally (figs. 25 and 26). Groundwater levels increased during the spring of both 2010 and 2011, although the range and timing of the increase varied between years. For 2010, the water table was at its lowest level in January and at its highest level in late June/early July, whereas for the year 2011, the water table was at its lowest level in early March and at its highest level in late June/early July. The water-level increase observed in the spring of 2010 was substantially sharper and larger than in the spring of 2011. Groundwater levels decreased sharply from the highest level in late June/early July 2010 to about late September 2010, then decreased more gradually from late September 2010 until early March 2011, at which time groundwater levels began to increase again in the spring. After peaking in late June/early July 2011, groundwater levels declined continuously to June 2012; notably, groundwater levels never increased in spring 2012, in contrast with consistent groundwater level increases observed in the spring of both 2010 and 2011. Groundwater-level increases (recharge) for both 2010 and 2011 generally coincided with precipitation increases typically associated with spring, as measured at the Cheyenne airport (figs. 25 and 26). The absence of a groundwater-level increase in spring 2012 and the decrease in groundwater levels from late June/early July 2011 through July 2012 coincided with much lower spring precipitation in 2012 than in 2010 and 2011 (figs. 25 and 26). Qualitative correlation of spring 2010 and 2011 precipitation with relatively rapid increases in monitoring well BRO–1a water levels indicate that the deposits of the Ogallala Formation readily transmit water from the land surface to the water table at the study site. At first, this rapid water-table response to spring precipitation seemed somewhat surprising because it was expected that movement of percolating recharge waters through the thick unsaturated zone (about 90 ft) to the water table at the study site would take longer; thus, the rapid movement of water through the unsaturated zone presumably is because of the predominantly coarse-grained and relatively uncemented/unconsolidated character of Ogallala Formation sediments and proximity to the Lone Tree Creek stream channel. An additional description of the relation between Lone Tree Creek and groundwater recharge at the site is provided in the "Groundwater Recharge" section of the report. In addition to recharge from precipitation, other factors can contribute to and complicate interpretations of groundwater-level response, including evaporation, barometric pressure, antecedent moisture conditions, and loading because of the weight of the water and entrapped air in the soil horizon; evaluation of all these factors was beyond the scope of this study, but discussion of some of these factors can be found elsewhere (for example, Freeze and Cherry, 1979; Fetter, 1988).

The hydrograph for monitoring well BRO–2 shows that groundwater levels in the deeper part of the Ogallala aquifer varied substantially more than groundwater levels in the shallow part of the Ogallala aquifer near the water table screened by monitoring well BRO–1a, especially during specific times of the year (figs. 25 and 26). Groundwater-level fluctuations measured at well BRO–2 generally were characterized by relatively rapid decreases and subsequent increases (recoveries) of less than about 5 ft; the large fluctuations typically began in the spring (March or April) and ended in the fall (October or November). These fluctuations resemble the typical groundwater-level response observed when an aquifer is pumped (groundwater levels decrease) and then allowed to

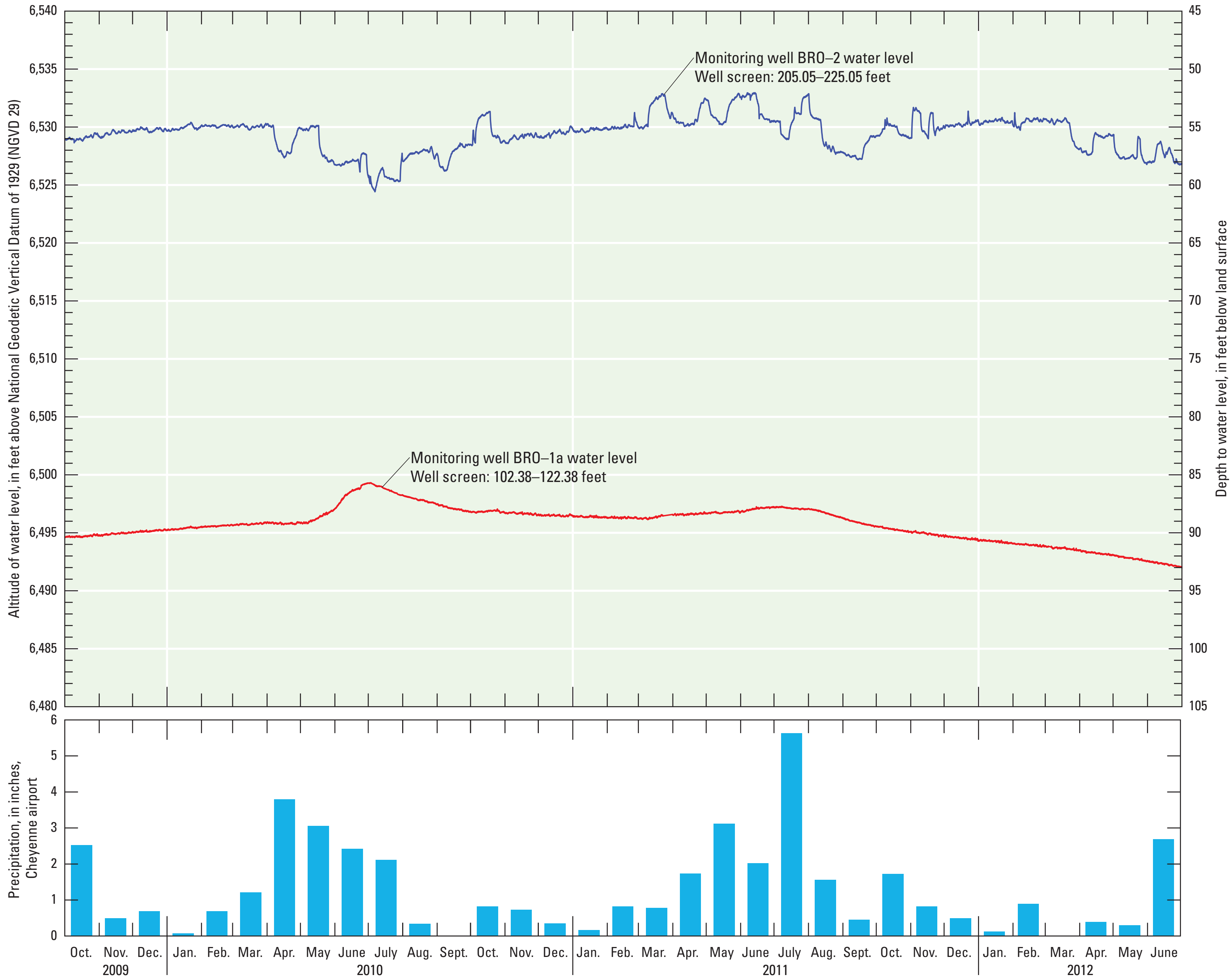


Figure 25. Water-level hydrographs for monitoring wells BRO–1a and BRO–2 completed in the Ogallala aquifer, with water-level altitudes plotted at same scale, and monthly precipitation at Cheyenne airport, from October 2009 through June 2012, Belvoir Ranch, Laramie County, Wyoming. Precipitation data from National Oceanic and Atmospheric Administration (2012).

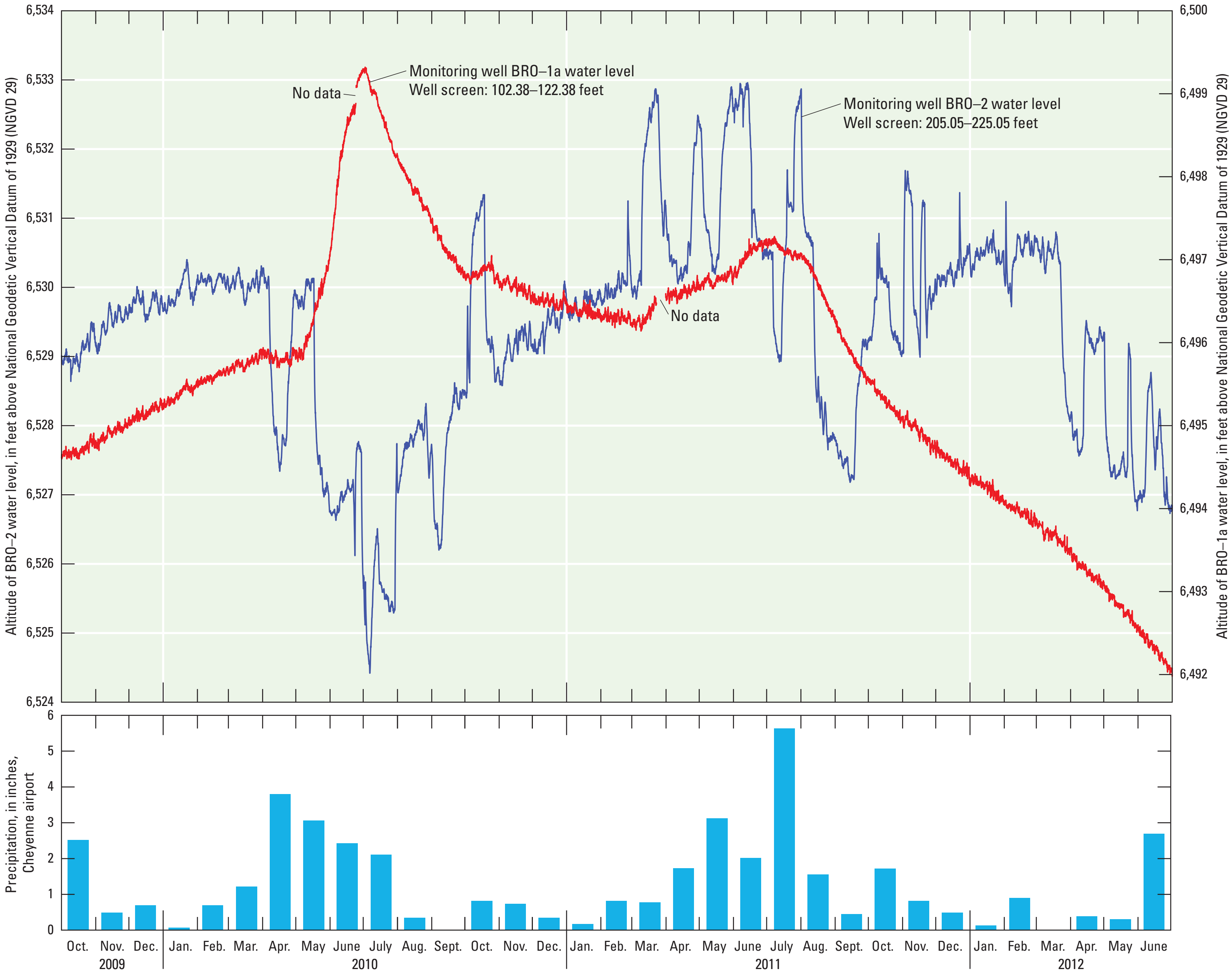


Figure 26. Water-level hydrographs for monitoring wells BRO–1a and BRO–2 completed in the Ogallala aquifer, with water-level altitudes plotted at different scales, and monthly precipitation at Cheyenne airport, from October 2009 through June 2012, Belvoir Ranch, Laramie County, Wyoming. Precipitation data from National Oceanic and Atmospheric Administration (2012).

recover after pumping subsequently is ended (groundwater levels increase); groundwater-level decreases in relation to pumping of production wells in the vicinity of Cheyenne have been noted as far back as the 1940s (Lowry and Crist, 1967), and these decreases continue to the present day (for example, Black and Veatch, 2004). Public-supply wells and industrial supply wells that pump at high rates from wells screened throughout much of the saturated thickness of the Ogallala Formation are present in the area (Black and Veatch, 2004; JR Engineering, 2007). In addition, some stock wells and high-yielding irrigation wells in the area are pumped or allowed to flow naturally during the summer irrigation season. Therefore, it is presumed that the observed groundwater-level declines reflect seasonal pumping of some of these wells. Some of the initial groundwater-level declines observed in monitoring well BRO–2 in the beginning of the spring of each year may correspond to the beginning of pumping or larger withdrawals of water from the public-supply wells in the area because of increased summertime water demand (Black and Veatch, 2004, p. 3–42). Examination of the timing and volume of pumping of nearby high-yielding production wells in relation to effects on groundwater levels in the area was beyond the scope of this study; however, some recent information on pumping of nearby production wells and resulting effects on groundwater levels in the area is provided in Black and Veatch (2004), JR Engineering (2007), and Wyoming State Engineer's Office (2008).

Despite large differences in seasonal hydraulic-head trends indicative of hydraulic isolation (fig. 25), small (tenths of a foot) short-term (weekly) groundwater-level fluctuations observed in monitoring well BRO–1a commonly subtly reflected much larger (1 ft or more) groundwater-level fluctuations observed in the deeper monitoring well BRO–2. These small groundwater-level fluctuations especially were reflected when hydraulic heads decreased presumably because of nearby pumping in the Ogallala aquifer, and also were reflected in some cases when the broader seasonal groundwater-level trends in the two monitoring wells were going in the opposite direction (one was increasing overall, whereas the other was decreasing overall) (fig. 26). The most visually obvious example of this subdued qualitative correlation can be seen in April 2010 (fig. 26). Before April 2010, groundwater levels in monitoring well BRO–1a increased continuously. Beginning in April 2010, groundwater levels measured in monitoring well BRO–2 decreased rapidly, presumably because of pumping of production wells in the area. The decrease in groundwater levels in monitoring well BRO–2 corresponded directly with an interruption in the groundwater level increase in monitoring well BRO–1a observed before April 2010, and groundwater levels in the well began to decrease slightly; this groundwater-level decrease corresponded with continuous decreases in groundwater levels observed in monitoring well BRO–2 for April. Once groundwater levels began to recover (increase) in monitoring well BRO–2 by the end of April 2010, a corresponding recovery (increase) also was observed in monitoring well BRO–1a.

This subtle qualitative correlation of hydraulic heads indicates but does not conclusively prove that some limited hydraulic connection may exist between deeper and shallower parts of the Ogallala aquifer. This limited hydraulic connection between deeper and shallower parts of the Ogallala aquifer is particularly likely when the aquifer is stressed by presumably seasonal pumping of nearby production wells that pump at high rates from well screens that cover much of the saturated thickness of the Ogallala Formation, and may exist despite layering/interbedding of coarser-grained and more permeable parts of the aquifer with finer grained and less permeable deposits and separation by about 83 ft of Ogallala Formation sediments between the top of the BRO–2 well screen to the bottom of the BRO–1a well screen at the study site. If some hydraulic connection exists between the deeper and shallower parts of the Ogallala aquifer, less permeable fine-grained layers and zones may not provide as much hydraulic confinement and isolation between different and more permeable parts of the aquifer as suggested previously (JR Engineering, 2007).

Hydraulic heads measured in monitoring well BRO–2 were much higher than those measured in monitoring well BRO–1a, indicating the hydraulic potential for upward movement of groundwater from the deeper part of the aquifer to the shallower part. The relative magnitude of the potential for this upward vertical groundwater flow was evaluated by calculating the vertical hydraulic gradient (fig. 27). The vertical hydraulic gradient is defined as the difference in hydraulic head in two wells screened at different depths in the aquifer, such as monitoring wells BRO–1a and BRO–2 divided by the distance between screened intervals. The units are dimensionless (ft/ft). The relative potential for upward or downward water movement in the aquifer is directly proportional to the magnitude of the hydraulic gradient. Positive hydraulic gradients indicate the potential for downward water movement and negative gradients indicate the potential for upward water movement. A negative vertical hydraulic gradient existed between monitoring wells BRO–1a and BRO–2 throughout the period of study (fig. 27). This negative hydraulic gradient varied temporally, apparently in relation to recharge and nearby production well pumping, but the gradient was always negative, indicating a consistent upward potential for groundwater movement from the deeper to the shallower part of the Ogallala aquifer at the study site. Directly to the east of the study site, the upward vertical hydraulic gradient, combined with lithologic changes, is sufficient that wells completed in the Ogallala aquifer flow. The upward vertical hydraulic gradient between the monitoring wells indicates that the recharge to the deeper part of the Ogallala aquifer in the study area (screened by well BRO–2) does not occur from downward leakage of surficial recharge within the Lone Tree Creek drainage, but rather as upward vertical underflow reflecting a longer groundwater-flow path with greater residence time and possibly located away from the immediately adjacent Lone Tree Creek stream channel.

Hydraulic head measured in the Chadron aquifer was examined in relation to hydraulic heads measured in

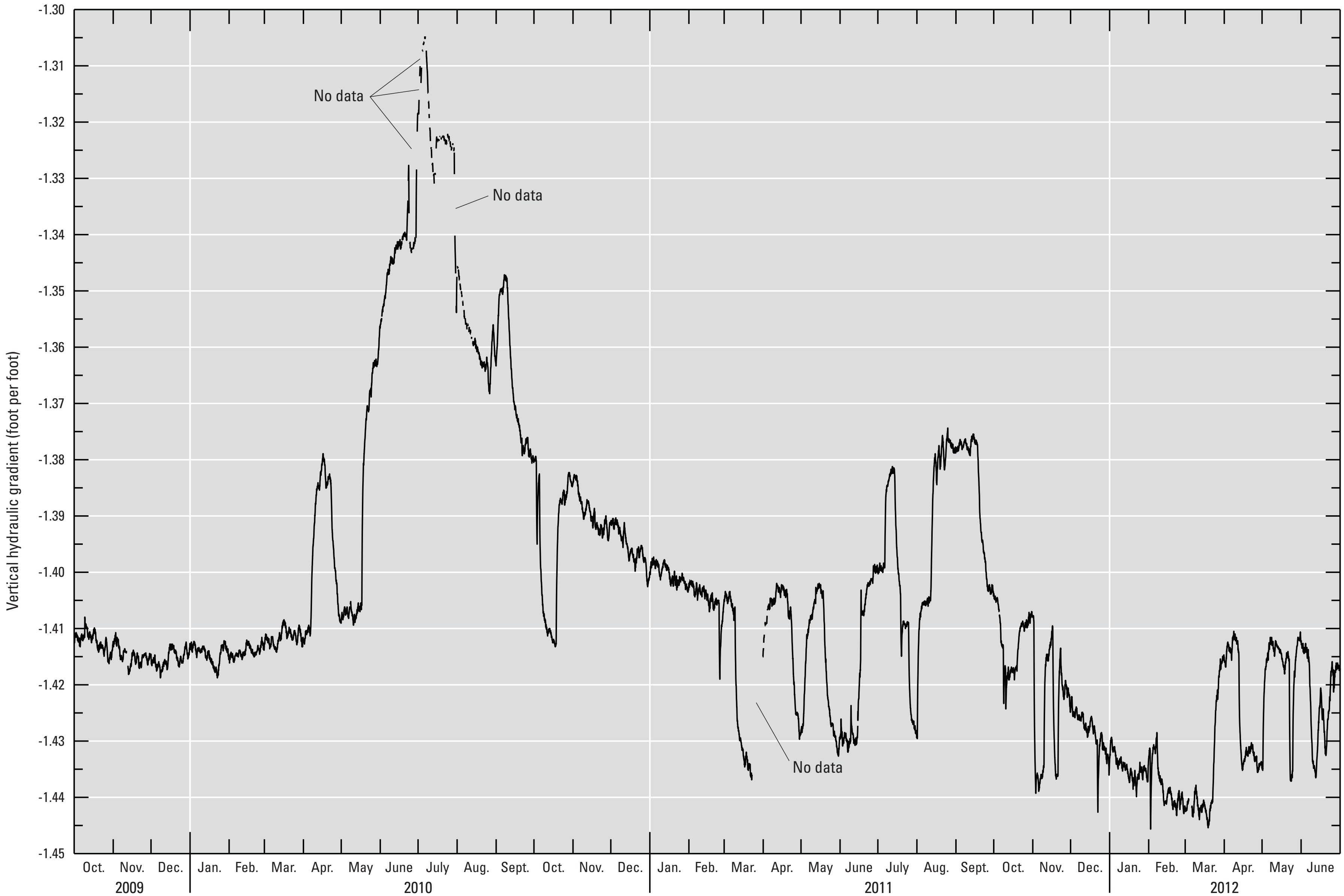


Figure 27. Vertical hydraulic gradient between monitoring wells BRO–1a and BRO–2 completed in the Ogallala aquifer, October 2009 through June 2012, Belvoir Ranch, Laramie County, Wyoming.

the Ogallala aquifer at the study site by using information obtained from a nearby monitoring well installed as part of another study (Trihydro Corporation, 2009). The monitoring well, identified as WR–3, is located only about 250 ft north of monitoring wells BRO–1a and BRO–2. Well construction for monitoring well WR–3 is shown in relation to construction for monitoring wells BRO–1a and BRO–2 in figure 3. Monitoring well WR–3 was installed in a coarse zone in the lower "White River Formation" identified using drill cuttings and geophysical logs. More detailed characterization of this same coarse zone as part of this study indicated that monitoring well WR–3 is screened over nearly the full thickness of sediments identified herein as the Chadron Formation of the White River Group. Trihydro Corporation (2009) identified this coarse zone in the lower "White River Formation" in many of their exploratory boreholes completed on the Belvoir Ranch along Lone Tree Creek. In fact, Trihydro Corporation (2009, p. 3–4) noted in several locations that the sediments in this coarse zone were "consistent with descriptions of the Chadron Member of the White River Group." Two discrete groundwater-level measurements were available from monitoring well WR–3. The earlier measurement (January 25, 2008) shown on figure 3 was obtained from Trihydro Corporation (2009, p. 3–4), whereas the more recent measurement (May 21, 2009) was obtained from the Cheyenne Board of Public Utilities (Victor Spencer, oral commun., 2009). Both measurements are shown on figure 3 in relation to selected discrete groundwater-level measurements from monitoring wells BRO–1a and BRO–2. The groundwater levels at monitoring well WR–3 were measured 16 months apart, and measurements were within 5 ft of one another. Comparison of the two available groundwater-level measurements at monitoring well WR–3 with discrete and continuous measurements at monitoring wells BRO–1a and BRO–2 clearly showed that hydraulic heads measured in the Chadron aquifer were substantially lower than hydraulic heads measured in the overlying Ogallala aquifer, based on the two available measurements from well WR–3. The substantially different hydraulic heads indicate that the overlying very fine-grained Brule Formation effectively hydraulically isolates and confines the Chadron aquifer from the overlying Ogallala aquifer at the location examined.

Groundwater Recharge

Attempts were made to estimate groundwater recharge at the study site using several different methods. Methods attempted included measurement and interpretation of tracers in the unsaturated zone (tritium and chloride) and use of the water-table fluctuation method.

Tritium and Chloride

Pore waters from 10 unsaturated-zone sediment samples were to be analyzed for tritium, and sediment samples from 10 adjacent depth intervals were to be analyzed for chloride to develop a vertical profile of these chemical "tracers" in the unsaturated zone at the study site. Vertical subsurface profiles of these tracers in areas with arid and semiarid climate can be used to determine the rates of vertical movement of water from the land surface through the unsaturated zone and to the saturated zone (deep percolation or recharge) (for example, Wood, 1999, and references therein; Scanlon, 2000, and references therein). Unfortunately, unsaturated-zone sediment characteristics at the site were not conducive to measurement of both tracers. Moisture content was insufficient for measurement of tritium in unsaturated-zone pore waters (Robert L. Michel, U.S. Geological Survey, written commun., 2009), and the coarse-grained sediments were flushed of sufficient amounts of chloride for use of the chloride mass-balance method (Richard W. Healy, U.S. Geological Survey, written commun., 2009).

Water-Table Fluctuation Method

Groundwater level increases observed in monitoring well BRO–1a in the spring of both 2010 and 2011 coincided with increases in spring precipitation and likely reflected active groundwater recharge contributed to the Ogallala aquifer from both diffuse and focused mechanisms. Diffuse recharge is "recharge that is distributed over large areas in response to precipitation infiltrating the soil surface and percolating through the unsaturated zone to the water table," whereas focused recharge is "the movement of water from a surface-water body such as streams, canals, or lakes to an underlying aquifer" (Healy, 2010, p. 3). Recharge to the shallow part of the Ogallala aquifer in the vicinity of monitoring well BRO–1a by infiltration and percolation of precipitation in the Lone Tree Creek drainage (diffuse recharge) likely is less than recharge to the aquifer by infiltration and percolation of water seeping directly from Lone Tree Creek (focused recharge) in the spring; consequently, increases in groundwater levels measured in monitoring well BRO–1a caused by infiltration and percolation from precipitation to the water table throughout the drainage (diffuse recharge) likely are obscured to some degree by the much greater rise in groundwater levels from infiltration and percolation of surface water seeping from Lone Tree Creek (focused recharge) to the upper part (water table) of the Ogallala aquifer. Proximity of monitoring well BRO–1a to the Lone Tree Creek (several hundred feet) channel (fig. 2), combined with likely minimal evapotranspiration because of time of year and minimal vegetation, indicates that groundwater recharge in the spring is likely primarily from the movement of water from the creek (seepage) to the water table. Except for occasional surface runoff from precipitation events during other times of the year (commonly convective summer storms), Lone Tree Creek (which generally is ephemeral in this reach) primarily flows in the spring and in response to (1) spring snowmelt runoff from the Laramie Mountains to the west, and (2) surface runoff of precipitation (melting snow and large spring and summer rainfall events) in the drainage directly adjacent to the creek, as observed visually several times during this study and as reported by previous investigators (Foley, 1942; Morgan, 1946; JR Engineering, 2007; Nunn and Turner, 2009). Evapotranspiration during the growing season because of vegetation likely is minimal because no trees or other vegetation except for short grasses are immediately adjacent to the Lone Tree Creek channel in the vicinity of the study area and the part of the drainage immediately upstream from the study area; the short grasses are present in the former and present-day stream channel and the terrace located immediately above the stream channel upon which monitoring wells BRO–1a and BRO–2 were constructed (fig. 2). Downstream from the study area where Lone Tree Creek flows, as a result of land-surface discharges from an artesian well and discharge from the Belvoir Reservoir during the irrigation season (JR Engineering, 2007), trees and other vegetation in addition to grasses are present immediately adjacent to the stream channel; evapotranspiration likely is much greater in this area than in the vicinity of and immediately upstream from the study area. Determination of the relative contributions of diffuse and focused recharge to the Ogallala aquifer at the study site was beyond the scope of the study, but an attempt was made to use groundwater levels measured at monitoring well BRO–1a to quantify recharge to the water table using the water-table fluctuation method.

The water-table fluctuation method (Healy and Cook, 2002, and references therein) provides an estimate of groundwater recharge by analysis of the graphical depiction of groundwater-level fluctuations measured in wells (groundwater-level hydrographs). The method is based on the assumption that a rise (increase) in water-table altitude (hydraulic head) measured in a shallow well is caused by the addition of recharge across the water table. The method is one of the most widely used techniques for estimating groundwater recharge because of its relative simplicity and “an insensitivity to the mechanism by which water moves through the unsaturated zone” (Healy and Cook, 2002, p. 91). Recharge is calculated by determining the water-level rise over a selected time period and then multiplying that measured rise by the specific yield of the sediments of interest. As summarized by the U.S. Geological Survey (2012), application of the method assumes that (1) the groundwater-level hydrograph depicts only natural water-table fluctuations caused by groundwater recharge and discharge; (2) specific yield is known and constant over the time period of the water-table fluctuations; and (3) the pre-recharge groundwater-level recession can be extrapolated to determine groundwater-level rise over the examined time period.

Two periods of groundwater-level rise measured in monitoring well BRO–1a and depicted in figure 26 were selected for calculation of recharge using the water-table fluctuation method—the water-level rise for the period beginning in early October 2009 and ending in late June 2010 (about 67 in.) and the water-level rise for the period beginning in March 2011 and ending in early July 2011 (about 19 in.). Specific yield of Ogallala Formation sediments at the site was not determined, so a reported average of about 20 percent for “coarse gravel” (Johnson, 1967, p. D1) was used in calculations. Use of the water-level rise for the former time period and a specific yield of 20 percent resulted in a focused recharge estimate of about 13 in., whereas use of the water-level rise for the latter time period and a specific yield of 20 percent resulted in a focused recharge estimate of about 4 in.

Recharge estimates for the High Plains aquifer system in Laramie County are available from several studies, including a few in the vicinity of Lone Tree Creek on the Belvoir Ranch. On the basis of measured flow of Lone Tree Creek for 1933 to 1938, focused recharge (streamflow loss or seepage) contributed to the Ogallala aquifer from Duck Creek, Goose Creek (not shown), and Lone Tree Creek in the vicinity of the Belvoir Ranch area was estimated by Foley (1942) to be about 2.5 million gallons per day [3.87 cubic feet per second (ft^3/s)]. Foley (1942, p. 51) speculated that diffuse recharge from precipitation to the Ogallala aquifer in the vicinity of Cheyenne likely averaged about 1 inch per year (in/yr) (about 6.5 percent of mean annual precipitation for the years 1933 to 1938), although the amount per year likely fluctuated considerably in response to annual precipitation. Morgan (1946) extended the work of Foley (1942) by using Foley’s recharge estimates in combination with detailed estimates of discharge from the Ogallala aquifer from all sources in the vicinity of Cheyenne. Morgan (1946, p. 19) estimated total recharge to the Ogallala aquifer from all sources in the vicinity of Cheyenne to be about 0.83 in/yr (about 5.5 percent of mean annual precipitation). This recharge estimate of 0.83 in/yr by Morgan (1946) was used subsequently by Rapp and others (1953, p. 22) to estimate recharge in the Egbert-Pine Bluffs-Carpenter area, by Lowry and Crist (1967, p. 22) to estimate recharge for all of Laramie County, and by Crist (1980) to construct and calibrate a groundwater-flow model of the High Plains aquifer system in Laramie County. Calibration of a large regional groundwater-flow model of the northern High Plains aquifer system as part of the USGS RASA program resulted in an estimate of composite recharge (recharge from all sources) for 1960 to 1980 of 0.2 to 0.4 in/yr in the vicinity of the study area (Luckey and others, 1986, fig. 28, p. 46). More recently, Nunn and Turner (2009) estimated diffuse groundwater recharge to the High Plains aquifer system on the Belvoir Ranch using field investigations and the Soil and Water Assessment Tool (SWAT) computer program (Neitsch and others, 2005). Nunn and Turner (2009, p. 69) concluded that “for the long-term average precipitation of 15.45 inches, this study suggests an average recharge of approximately 1.25 inches” (about 8 percent of long-term mean annual precipitation). Furthermore, the investigators noted that their study of recharge did not account for focused recharge from streams originating from the Laramie Mountains such as Lone Tree Creek, and concluded that focused recharge to the High Plains aquifer system from streams in the area warranted further investigation.

Estimates of focused recharge in the study area near Lone Tree Creek using the water-table fluctuation method in this study are very similar to a recharge estimate from a previous study evaluating statewide groundwater vulnerability to pesticides using a DRASTIC-like approach (Hamerlinck and Arneson, 1998a,b). DRASTIC is a systematic USEPA methodology that uses various hydrogeologic factors to evaluate pollution potential of any hydrogeologic setting (Aller and others, 1987). As part of the study by Hamerlinck and Arneson (1998a,b), groundwater recharge was estimated for the entire State of Wyoming as one of several geographic information system data layers used to construct an aquifer sensitivity map. Along Lone Tree Creek, groundwater recharge was estimated to range from 6 to 10 in/yr (Hamerlinck and Arneson, 1998a,b). Although not constructed as an annual total, recharge estimates using the water-table fluctuation method for the period beginning in early October 2009 and ending in late June 2010 (13 in.), and for the period beginning in March 2011 and ending in early July 2011 (4 in.), are very similar to the estimated annual recharge range reported by Hamerlinck and Arneson (1998a,b). Both recharge estimates reflect higher recharge to the High Plains aquifer system that would be expected in the vicinity of a stream overlying very coarse sediments with minimal soil and vegetation in the area (Lone Tree Creek) than in areas located upland and away from streams with soil and finer-grained sediments that compose most of the area overlying the aquifer system.

Stable Isotopes of Oxygen and Hydrogen

Collection of stable isotope ratios of oxygen-18/oxgen-16 ($\delta^{18}O$) and deuterium/protium ($\delta^{2}H$) in precipitation was not done as part of this study and no local values were available; therefore, paired $\delta^{18}O$ and $\delta^{2}H$ values in the groundwater samples from monitoring wells BRO–1a and BRO–2 (table 6) were plotted and compared to the global meteoric water line (GMWL; Craig, 1961) and two local meteoric water lines (North Platte, Nebr., Harvey and Welker, 2000; Pawnee National Grassland, Colo., Harvey, 2005; locations not shown in report). Paired $\delta^{18}O$ and $\delta^{2}H$ values in groundwater samples from monitoring wells BRO–1a and BRO–2 plotted closely together, plotted slightly below the GMWL and the two local meteoric water lines, and plotted away from other samples collected from different units of the High Plains aquifer system at different locations in Laramie County (fig. 28). This indicates that sampled waters from monitoring wells BRO–1a and BRO–2 likely were subject to similar recharge and evolutional paths, and thus the differences in the $\delta^{18}O$ and $\delta^{2}H$ values were minimal. In addition, plotting of the paired $\delta^{18}O$ and $\delta^{2}H$ values below the GMWL and the two local meteoric water lines indicates the water has undergone some fractionation, possibly because of evaporation (Drever, 1997).

Apparent Groundwater Age

Environmental tracers—tritium (^{3}H), three different chlorofluorocarbons (CFCs), and sulfur hexafluoride (SF_6)—were used to determine the apparent age of groundwater sampled from monitoring wells BRO–1a and BRO–2. These environmental tracers are present in the atmosphere at trace levels and can be valuable tools for understanding groundwater-flow systems by helping to determine or estimate areas and rates of recharge and discharge, residence time, direction of flow, flow velocities, contamination potential, and the time needed to flush contaminants from groundwater systems (Plummer and others, 1993; Clark and Fritz, 1997; Kendall and McDonnell, 1998; Plummer and Friedman, 1999; Cook and Herczeg, 2000). Introduced to the atmosphere either exclusively through anthropogenic activities (CFCs) or at activities or concentrations exceeding natural background levels after anthropogenic activities (tritium and SF_6), these tracers are useful for identifying and dating modern (after early 1950s) groundwater. The age of groundwater applies to the date of introduction of the environmental tracers to the water, and not to the age of the water itself; consequently, the age refers to the time elapsed since the water recharged the aquifer and was isolated from the source (atmosphere) of the tracer. Because age dates estimated from these environmental tracers may be affected by several factors, including mixing of waters of different ages, transport processes, chemical processes, and biogeochemical processes, groundwater ages commonly are referred to as “apparent ages.”

Tritium is a radioactive hydrogen isotope that undergoes radioactive decay with a half-life of 12.32 years (Lucas and Unterweger, 2000). Tritium activities are expressed in picocuries per liter (pCi/L) or tritium units (TU) where 1 TU is equal to 1 ^{3}H atom in 10^{18} atoms of hydrogen (Shapiro and others, 2012). Based on a half-life of 12.32 years, 1 TU is equal to about 3.22 pCi/L (Shapiro and others, 2012). Unlike other radioisotopes, tritium atoms can substitute for other hydrogen atoms in the water molecule. The incorporation of tritium directly into the water molecule makes tritium a useful tool for determining apparent groundwater age. Tritium is produced naturally by cosmic radiation in the upper atmosphere at very low levels and is incorporated into precipitation; however, large-scale atmospheric testing of thermonuclear devices beginning in the early 1950s and continuing through the early 1960s increased tritium levels by several orders of magnitude above natural levels, resulting in a global atmospheric spike in tritium concentrations measured in precipitation (Clark and Fritz, 1997). Atmospheric concentrations decreased by decay in the atmosphere and loss to the hydrologic cycle (primarily the oceans) after an international atmospheric test-ban treaty was signed in 1963 (Clark and Fritz, 1997). Before atmospheric testing of thermonuclear devices, the natural level of tritium in precipitation probably did not exceed about 26 pCi/L (8 TU) (Plummer and others, 1993). Activities probably will never completely return to lower natural levels because low levels of tritium continue to be released by other anthropogenic sources such as nuclear power plants and weapons plants (Clark and Fritz, 1997). If precipitation with tritium measured at an activity of 26 pCi/L or less recharged groundwater before 1952, those waters would have tritium present at an activity smaller than about 1 pCi/L in 2009 or 2010 (years that wells were sampled for this study) because of radioactive

Table 6. Summary of inorganic groundwater-quality samples collected from monitoring wells BRO–1a and BRO–2, Belvoir Ranch, Laramie County, Wyoming.

[USGS, U.S. Geological Survey; NWIS, National Water Information System; USEPA, U.S. Environmental Protection Agency; --, not applicable; SMCL, secondary maximum contaminant level; NTRU, nephelometric turbidity ratio units; mg/L, milligrams per liter; LRL, laboratory reporting level; MCL, Maximum Contaminant Level; $CaCO_3$, calcium carbonate; µS/cm, microsiemens per centimeter at 25 degrees Celsius; E, estimated concentration; <, less than; HAL, Health Advisory Level; IRL, interim reporting level; AL, action level; C, carbon; SSLC, sample-specific critical level; per mil, parts per thousand]

Characteristic or constituent	USGS NWIS parameter code	Reporting level	BRO–1a value or concentration (June 24, 2010)	BRO–2 value or concentration (Nov. 12, 2009)	USEPA drinking-water standards or health advisories[1]	Wyoming Class II agricultural water standard[2]	Wyoming Class III livestock water standard[2]
Physical characteristics							
Water temperature (degrees Celsius)	00010	--	14.0	11.4	--	--	--
pH, field (standard units)	00400	--	7.5	7.6	6.5–8.5 (SMCL)	4.5–9.0	6.5–8.5
Turbidity (NTRU)	63676	--	0.2	0.4	5 (SMCL)	--	--
Dissolved oxygen (mg/L)	00300	--	8.6	6.8	--	--	--
Major ions and related water-quality characteristics, in milligrams per liter unless otherwise noted, dissolved (sample filtered through 0.45-micrometer filter)							
Calcium	00915	0.044 (LRL)	52.6	51.6	--	--	--
Magnesium	00925	0.016 (LRL)	5.05	5.91	--	--	--
Sodium	00930	0.10 (LRL)	5.46	6.75	--	--	--
Potassium	00935	0.064 (LRL)	1.8	1.73	--	--	--
Chloride	00940	0.12 (LRL)	4.49	7.01	250 (SMCL)	100	2,000
Sulfate	00945	0.18 (LRL)	13.6	19.2	250 (SMCL)	200	3,000
Fluoride	00950	0.08 (LRL)	0.7	0.47	2 (SMCL) 4 (MCL)	--	--
Silica	00955	0.058 (LRL)	19.1	22.5	--	--	--
Dissolved solids	70300	10 (MRL)	193	215	500 (SMCL)	2,000	5,000
Alkalinity (mg/L as $CaCO_3$)	39086	--	116	117	--	--	--
Hardness (mg/L as $CaCO_3$)	00900	calculated	152	154	--	--	--
Specific conductance (µS/cm)	00095	--	306	321	--	--	--
Sodium-adsorption ratio (SAR)	00931	calculated	0.19	0.24	--	8	--
Trace elements, in micrograms per liter unless otherwise noted, dissolved (sample filtered through 0.45-micrometer filter)							
Aluminum	01106	3.4 (LRL)	E1.9	<3.4	50–200 (SMCL)	5,000	5,000
Antimony	01095	0.054 (LRL)	0.08	0.08	6 (MCL)	--	--
Arsenic	01000	0.044 (LRL)	0.91	1.4	10 (MCL)	100	200
Barium	01005	0.14 (LRL)	88	108	2,000 (MCL)	--	--
Beryllium	01010	0.012 (LRL)	<0.01	<0.01	4 (MCL)	100	--
Boron	01020	2.8 (LRL)	22	17	6,000 (HAL)	750	5,000
Bromide (mg/L)	71870	0.02 (IRL)	0.04	0.04	--	--	--
Cadmium	01025	0.02 (LRL)	E0.02	<0.02	5 (MCL)	10	50
Chromium	01030	0.12 (LRL)	0.36	0.12	100 (MCL)	100	50
Cobalt	01035	0.010 (LRL)	0.16	0.23	--	50	1,000
Copper	01040	1 (LRL)	1.4	<1	1,000 (SMCL) 1,300 (AL)	200	500

Table 6. Summary of inorganic groundwater-quality samples collected from monitoring wells BRO–1a and BRO–2, Belvoir Ranch, Laramie County, Wyoming.—Continued

[USGS, U.S. Geological Survey; NWIS, National Water Information System; USEPA, U.S. Environmental Protection Agency; --, not applicable; SMCL, secondary maximum contaminant level; NTRU, nephelometric turbidity ratio units; mg/L, milligrams per liter; LRL, laboratory reporting level; MCL, Maximum Contaminant Level; $CaCO_3$, calcium carbonate; µS/cm, microsiemens per centimeter at 25 degrees Celsius; E, estimated concentration; <, less than; HAL, Health Advisory Level; IRL, interim reporting level; AL, action level; C, carbon; SSLC, sample-specific critical level; per mil, parts per thousand]

Characteristic or constituent	USGS NWIS parameter code	Reporting level	BRO–1a value or concentration (June 24, 2010)	BRO–2 value or concentration (Nov. 12, 2009)	USEPA drinking-water standards or health advisories[1]	Wyoming Class II agricultural water standard[2]	Wyoming Class III livestock water standard[2]
Trace elements, in micrograms per liter unless otherwise noted, dissolved (sample filtered through 0.45-micrometer filter)—Continued							
Iron	01046	6 (LRL)	<6	<6	300 (SMCL)	5,000	--
Lead	01049	0.030 (LRL)	0.05	<0.03	15 (AL)	5,000	100
Lithium	01130	0.44 (LRL)	6	9.1	--	2,500	--
Manganese	01056	0.26 (LRL)	0.7	0.5	50 (SMCL)	200	--
Molybdenum	01060	0.028 (LRL)	0.9	0.6	40 (HAL)	--	--
Nickel	01065	0.12 (LRL)	1.1	0.66	100 (HAL)	200	--
Selenium	01145	0.040 (LRL)	0.62	0.58	50 (MCL)	20	50
Silver	01075	0.010 (LRL)	<0.01	<0.01	100 (HAL/SMCL)	--	--
Strontium	01080	0.40 (LRL)	188	217	4,000 (HAL)	--	--
Thallium	01057	0.020 (LRL)	<0.02	<0.02	2 (MCL)	--	--
Uranium	22703	0.008 (LRL)	1.51	2.01	30 (MCL)	--	--
Vanadium	01085	0.16 (LRL)	2.5	3.8	--	100	100
Zinc	01090	2.8 (LRL)	6.3	<2.8	2,000 (HAL) 5,000 (SMCL)	2,000	25,000
Nutrients, in milligrams per liter, dissolved (sample filtered through 0.45-micrometer filter), and dissolved organic carbon							
Nitrate, as nitrogen	00618	calculated	E1.57	2.08	10 (MCL)	--	--
Nitrite, as nitrogen	00613	0.002 (IRL)	E0.002	<0.002	1 (MCL)	--	10
Nitrate + nitrite, as nitrogen	00631	0.04 (LRL)	E1.57	2.08	10 (MCL)	--	100
Ammonia, as nitrogen	00608	0.02 (LRL)	<0.02	E0.01	30 (HAL)	--	--
Organic nitrogen	00607	calculated	<0.07	E0.02		--	--
Total nitrogen	62854	0.10 (LRL)	1.64	2.11		--	--
Phosphorus, as phosphorus	00666	0.006 (LRL)	0.022	0.032	--	--	--
Orthophosphate, as phosphorus	00671	0.008 (LRL)	0.029	0.032	--	--	--
Dissolved organic carbon (mg/L as C)	00681	0.66 (LRL)	1.1	E0.5	--	--	--
Radioisotopes and stable isotopes							
Tritium (picocuries per liter)	07000	0.32 (SSLC)	30.4	20.4	--	--	--
δ^2H (deuterium/protium ratio) (per mil)	82082	--	-117	-117	--	--	--
$\delta^{18}O$ (oxygen-18/oxygen-16 ratio) (per mil)	82085	--	-15.21	-15.19	--	--	--

[1]U.S. Environmental Protection Agency (2012).

[2]Wyoming Department of Environmental Quality (2005), table 1.

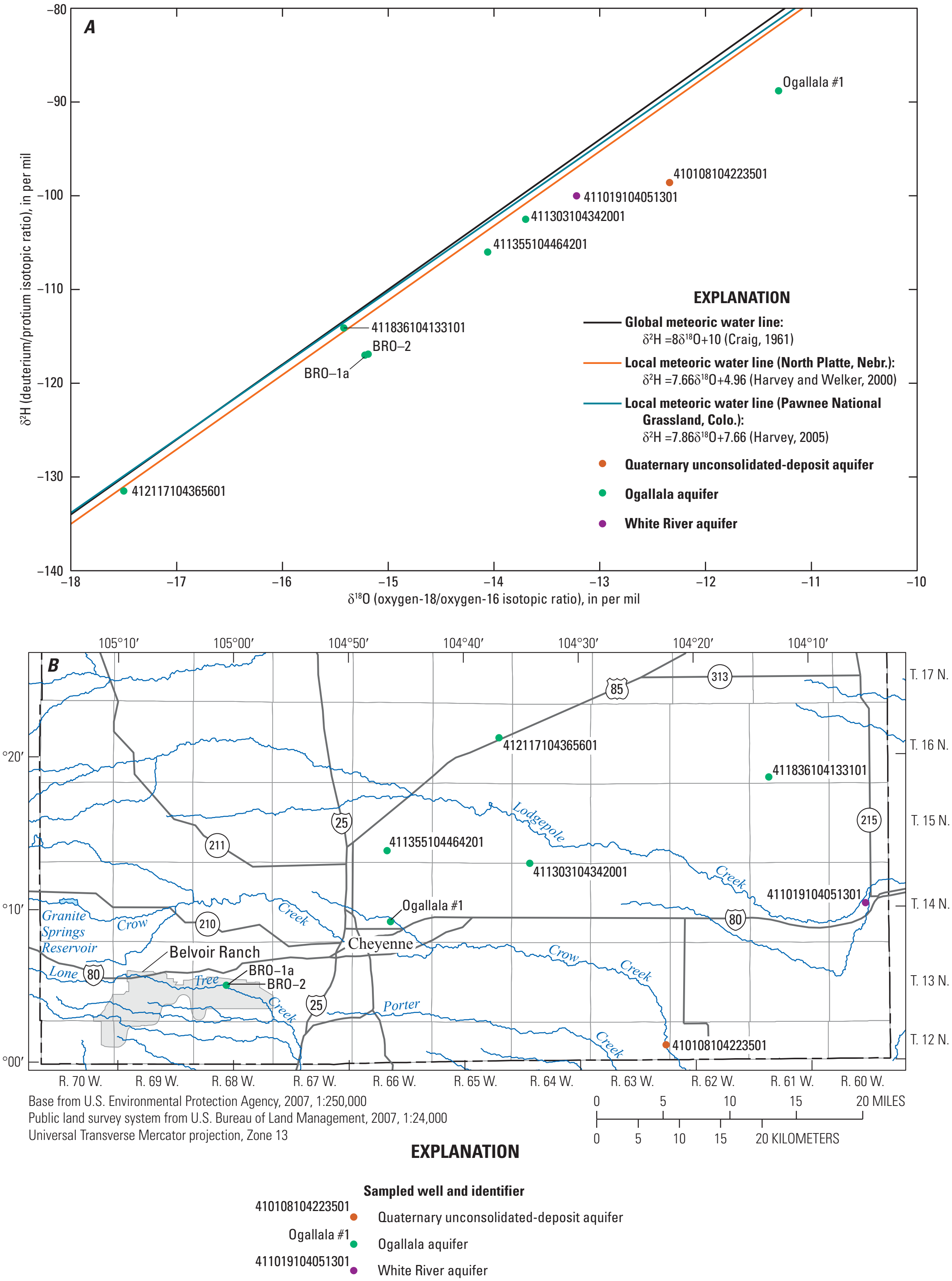


Figure 28. Relation between stable isotopes of oxygen and hydrogen for groundwater samples collected from the High Plains aquifer system compared to *A*, the global meteoric water line and two local meteoric water lines; and *B*, map showing location of sampled wells, Laramie County, Wyoming.

decay. Therefore, measurement of tritium at an activity level greater than about 1 pCi/L would indicate that at least some fraction of the sampled groundwater was recharged after the early 1950s.

CFCs are atmospherically stable synthetic gases used in a wide variety of products such as aerosol propellants, cleaning agents, solvents, refrigerants, as well as in the production of foam rubber and plastics. These gases began to be released into the atmosphere in the 1930s when originally introduced as refrigerants. Since the 1930s, atmospheric CFCs have been incorporated into the hydrologic cycle (Plummer and others, 1993; Plummer and Busenberg, 2000). Because the amount and rate at which CFCs accumulated in the atmosphere have been determined and can be compared with concentrations subsequently measured in groundwater samples, CFCs can be used as a tool to date young (less than 50 years) groundwater (Plummer and others, 1993; Plummer and Busenberg, 2000). Because estimation of groundwater age using CFCs is very sensitive to excess air and recharge temperature, groundwater samples were collected from both monitoring wells for analysis of dissolved gases to determine concentrations of excess air and recharge temperatures. Unfortunately, the dissolved-gas sample from monitoring well BRO–2 was damaged in transit to the laboratory, so dissolved gases only were available for the sample collected from monitoring well BRO–1a. The details of interpretive techniques used to estimate apparent groundwater ages using CFCs are complicated and not described herein, but details can be found in Busenberg and Plummer (1992), Plummer and Friedman (1999), and Plummer and Busenberg (2000).

The tracer SF_6 is a very stable gas mainly of anthropogenic origin and primarily used as an insulator in high-voltage switches; large-scale production of SF_6 began in the early 1950s (Busenberg and Plummer, 1997, 2000; Plummer and Friedman, 1999). Similar to CFCs, the amount and rate at which SF_6 accumulated in the atmosphere has been determined and can be compared with concentrations subsequently measured in groundwater samples (Busenberg and Plummer, 2000). The details of interpretive techniques used to estimate apparent groundwater ages using SF_6 are not described herein but are provided in Busenberg and Plummer (1997, 2000).

Tritium activities in groundwater samples collected from both monitoring wells (table 7; 30.4 pCi/L at BRO–1a and 20.4 pCi/L at BRO–2) were much greater than 1 pCi/L, indicating that at least some fraction of the sampled water from near the water table (BRO–1a) and from deeper in the Ogallala aquifer (BRO–2) was modern and recharged after the early 1950s (table 7). Differences in tritium activities may indicate some apparent age stratification in the Ogallala aquifer. The larger activity measured in monitoring well BRO–1a may reflect active groundwater recharge to the water table, as described previously in the "Groundwater Levels" section of the report, whereas the smaller activity measured in monitoring well BRO–2 may reflect a longer groundwater-flow path and greater residence time; however, the strong upward hydraulic gradient at the study site indicates that the tritium activity measured in BRO–1a and interpreted apparent age likely is a mixture of groundwater from the deeper part of the aquifer and active (and therefore, younger) recharge waters percolating downward through the unsaturated zone, which is described in greater detail in relation to interpreted CFC and SF_6 apparent ages in the following paragraphs. Alternatively, the larger tritium activity in monitoring well BRO–2 may reflect precipitation variation and (or) mixing of older waters with younger waters.

Interpretation of three different CFCs (CFC–11, CFC–12, CFC–113) measured in groundwater samples (table 7) supplemented with dissolved gases analyses from monitoring well BRO–1a indicates the apparent ages for water from both wells sampled were modern, and interpreted age assuming piston flow and corrected for excess air ranged from the mid- to late 1960s (BRO–2) to mid-1970s (BRO–1a) (table 7). Piston flow is "a simplified and idealized concept of groundwater flow in which groundwater moves in discrete packets by advection only, without hydrodynamic dispersion or mixing" (Shapiro and others, 2012, p. 10). Excess air is "atmospheric air (gases), beyond the amount that can be attributed to air/water solubility, that is incorporated into shallow groundwater during or following recharge…by air entrainment during infiltration and (or) by water-table fluctuations" (Shapiro and others, 2012, p. 9). Interpretation of CFC results from monitoring well BRO–2 indicated the groundwater sampled was a mixture of water of varying ages. Estimation of apparent groundwater age is complex for groundwater samples that are a mixture of water of varying ages. A mixture can be the result of many different processes, including convergence of different groundwater-flow paths to a pumping well with a long screen interval or an artifact of sampling a well with a screen that intersects water of variable age. Groundwater levels measured in both monitoring wells screened at two different depth intervals and described previously in the "Groundwater Levels" section indicated that nearby production well pumping presumably affects essentially the entire saturated thickness of the Ogallala aquifer at the study location. Pumping of groundwater from production wells that penetrate and are screened over nearly the entire saturated thickness of the Ogallala aquifer likely would result in intermixing of waters from many different zones of the aquifer with varying groundwater ages; thus, the CFC results indicating groundwater sampled from monitoring well BRO–2 is a mixture may reflect this intermixing.

Interpretation of SF_6 concentrations measured in groundwater samples supplemented with dissolved-gases analyses indicate the apparent ages for water from both wells sampled were young, and interpreted age assuming piston flow and corrected for excess air was 1972 for monitoring well BRO–2 and 1985 for monitoring well BRO–1a (table 7). Results from the USGS Reston Chlorofluorocarbon Laboratory indicated the interpreted apparent age for monitoring well BRO–2 was near the maximum age limit of the analytical method.

Apparent ages for groundwater sampled from both monitoring wells estimated using CFCs and SF_6 differed (table 7).

Table 7. Age tracer and supporting data and apparent groundwater age for groundwater samples collected from monitoring wells BRO–1a and BRO–2, Belvoir Ranch, Laramie County, Wyoming.

[All apparent groundwater ages calculated based on recharge altitude of 6,585 feet above National Geodetic Vertical Datum of 1929; pCi/L, picocuries per liter; cc/kg, cubic centimeters of gas per kilogram of water; °C, degrees Celsius; CFC, chlorofluorocarbon; pptv, parts per trillion per volume; SF_6, sulfur hexafluoride; U, analyzed for but not detected; NM, not measured because sample destroyed during transport to laboratory]

Well number (fig. 1)	Sample date (month/day/year)	Tritium[1] (pCi/L)	Dissolved gases[2] (milligrams per liter)					Excess air (cc/kg)	Recharge temperature calculated from dissolved gases (°C)	Calculated atmospheric mixing ratio corrected for excess air and recharge temperature[2]				Apparent groundwater age		
			Oxygen	Methane	Carbon dioxide	Nitrogen	Argon			CFC-11 (pptv)	CFC-12 (pptv)	CFC-113 (pptv)	SF_6 (pptv)	Tritium	CFCs	SF_6
BRO–1a	6/24/2010	30.4	[3]3.58	U	[3]9.05	[3]14.92	[3]0.55	0.6	9.8	[4]108.5	[4]258.6	[4]25.1	[5]1.55	After early 1950s	Mid-1970s[6]	1985
BRO–2	11/12/2009	20.4	NM	NM	NM	NM	NM	[7]2.0	[7]10	[4]29.1	[4]88.2	[4]9.3	[5]0.30	After early 1950s	Mid- to late-1960s[6] (mixture)[8]	[9]1972

[1]Analyzed by U.S. Geological Survey Tritium Laboratory, Menlo Park, California.

[2]Analyzed by U.S. Geological Survey Chlorofluorocarbon Laboratory, Reston, Virginia.

[3]Median of four samples.

[4]Median of three samples.

[5]Median of two samples.

[6]Apparent age estimated using CFC-11, CFC-12, and CFC-113.

[7]Estimated value because dissolved gases sample damaged during transport to laboratory.

[8]Possible mixture of young and old water.

[9]Near maximum age limit of analytical method.

This is not unusual and is the result of many factors, including different properties of the gases and behavior in the subsurface as well as inherently different assumptions and methods used for interpretation (for example, Plummer and others, 1993; Clark and Fritz, 1997; Kendall and McDonnell, 1998; Plummer and Friedman, 1999; Cook and Herczeg, 2000).

Interpretation of apparent groundwater age using all three tracers indicated vertical stratification of groundwater age at the site—groundwater from the shallower part of the Ogallala aquifer screened by monitoring well BRO–1a and representative of groundwater near the water table was younger than groundwater from the deeper part of the Ogallala aquifer screened by monitoring well BRO–2. Nevertheless, apparent ages estimated using CFCs and SF_6 for groundwater sampled from monitoring well BRO–1a were older than expected, considering that measured groundwater levels indicated that direct recharge to the water table is actively occurring. The older than expected apparent age is possibly the result of groundwater near the water table screened by monitoring well BRO–1a coming from both recharge percolating downward through the overlying unsaturated zone to the water table, as well as from groundwater that has moved from the immediately deeper part of the aquifer as a result of the strong upward vertical hydraulic gradient. In addition, resolution of the CFC and SF_6 methods may not be optimal because the depth to the water table of about 90 ft was large enough that CFC and SF_6 concentrations at the water table may be in equilibrium with atmospheric concentrations from previous years rather than the years (2009 and 2010) sampled (Cook and Solomon, 1995; Solomon and others, 1998; Busenberg and Plummer, 2000; Plummer and Busenberg, 2000). Apparent ages determined using CFCs and SF_6 data are based on the assumption that infiltrating water is in equilibrium with the atmosphere at the time of recharge. As unsaturated zone thickness increases, the likelihood increases that CFC and SF_6 concentrations in soil gas at the bottom of the thick unsaturated zone reflect older atmospheric concentrations rather than current atmospheric concentrations (Cook and Solomon, 1995; Solomon and others, 1998; Busenberg and Plummer, 2000; Plummer and Busenberg, 2000). This lag time for atmospheric CFCs and SF_6 to move through the 90-ft thick unsaturated zone may cause apparent ages to be older than the true age of recharge.

Groundwater-Quality Characteristics

Groundwater-quality characteristics are summarized in this section of the report. To aid in the determination of suitability for potential uses, groundwater-quality characteristics are compared to USEPA drinking-water standards and health advisories (U.S. Environmental Protection Agency, 2012), Wyoming Class II agricultural water standards (Wyoming Department of Environmental Quality, 2005, table 1), Wyoming Class III livestock water standards (Wyoming Department of Environmental Quality, 2005, table 1), and several additional commonly used guidelines. Ionic composition (water type) is described for groundwater-quality samples collected from this study, as well as in relation to samples collected in previous studies. In addition, ionic composition of groundwater samples collected from different lithostratigraphic/hydrogeologic units is compared.

Physical Characteristics

Physical characteristics measured in the field during collection of groundwater samples from both monitoring wells included water temperature, pH, turbidity, and DO (table 6). Water temperature was measured at 14.0 °C in the sample collected from well BRO–1a, and at 11.4 °C in the sample collected from well BRO–2. Field pH measurements in groundwater samples collected from monitoring wells BRO–1a and BRO–2 were alkaline (pH greater than 7.0) and were very similar (7.5 and 7.6 standard units, respectively). Turbidity measured in groundwater samples collected from both wells was very small [less than 0.5 nephelometric turbidity ratio units (NTRU)], and measurements were similar between the wells (0.2 NTRU at BRO–1a and 0.4 NTRU at BRO–2). Sampled groundwater from both wells was well oxygenated (oxic), with DO concentrations of 8.6 milligrams per liter (mg/L; BRO–1a) and 6.8 mg/L (BRO–2).

Major Ions and Related Groundwater-Quality Characteristics

Major ions constitute most of the dissolved constituents in groundwater and generally occur naturally as a result of recharge composition and interactions between water and soil or rock. Water samples were analyzed for the major ions of calcium, magnesium, sodium, potassium, chloride, sulfate, and fluoride. Silica, an uncharged species under typical pH conditions, is described with the major ions for convenience. Alkalinity as calcium carbonate ($CaCO_3$), a measure of the acid-buffering capacity of a filtered water sample, was determined onsite and in the laboratory. Bicarbonate and carbonate concentrations were calculated from alkalinity and pH values measured onsite (Hem, 1985).

No major ions or related water-quality characteristics were measured in groundwater samples collected from either well at concentrations larger than USEPA drinking-water standards or health advisories, Wyoming class II agricultural water standards, or Wyoming class III livestock standards (table 6). Dissolved-solids concentrations in groundwater samples from both wells were small (less than the USEPA SMCL of 500 mg/L) and very similar (193 mg/L at BRO–1a and 215 mg/L at BRO–2) (table 6). Compared to the USGS salinity classification (Heath, 1983, table 2, p. 65), water from both wells sampled was classified as fresh (dissolved-solids concentrations less than 1,000 mg/L).

Calculated hardness for groundwater samples collected from monitoring wells BRO–1a and BRO–2 was very similar (table 6; 152 and 154 mg/L as $CaCO_3$, respectively). Compared to the hardness scale of Durfor and Becker (1964), groundwater from both wells sampled was classified as hard (121 to 180 mg/L as $CaCO_3$).

Water Type

The major-ion composition of groundwater sampled from monitoring wells BRO–1a and BRO–2 completed in the Ogallala aquifer was classified by using a trilinear diagram (Piper, 1944) (fig. 29). Calcium and bicarbonate were the predominant ions in water from both wells sampled, and thus, groundwater from both wells can be classified as a calcium-bicarbonate type. Groundwater sampled from both wells plotted closely together on the trilinear diagram, indicating essentially the same ionic composition and little vertical variation with depth, despite the screen intervals being separated by nearly 83 ft of Ogallala Formation sediments.

The major-ion chemistry of groundwater sampled from the underlying Chadron aquifer was characterized and compared to groundwater sampled from the Ogallala aquifer during this study using groundwater samples collected from two nearby monitoring wells (monitoring wells WR–2 and WR–3) completed in the Chadron aquifer, sampled as part of a recent study conducted on the Belvoir Ranch along Lone Tree Creek (Trihydro Corporation, 2009), and discussed previously in the "Summary of White River Group Lithostratigraphy and Implications to Areal Extent in Southwestern Laramie County" section. One of the two wells, monitoring well WR–3, is located about 250 ft away from the study site; the second well, monitoring well WR–2, is located about 1.75 mi east of the study site (fig. 30). Samples collected from monitoring wells WR–2 and WR–3 were analyzed for major ions (Trihydro Corporation, 2009, appendix D). Using these analyses, the major-ion composition of groundwater sampled from monitoring wells WR–2 and WR–3 was plotted on the same trilinear diagram used to plot the major-ion composition of groundwater sampled from monitoring wells BRO–1a and BRO–2 (fig. 29). Groundwater sampled from monitoring wells WR–2 and WR–3 plotted closely together on the trilinear diagram, indicating essentially the same ionic composition. Ionic composition of waters from monitoring wells WR–2 and WR–3, screened throughout most of the saturated thickness of the Chadron Formation, were compositionally different than waters from monitoring wells BRO–1a and BRO–2 screened in discrete depth intervals in the overlying Ogallala Formation. In contrast to the calcium-bicarbonate waters of the Ogallala aquifer, calcium, sodium, and bicarbonate were the predominant ions in groundwater from the Chadron aquifer; consequently, groundwater from monitoring wells WR–2 and WR–3 can be classified as a calcium-sodium-bicarbonate type (fig. 29).

Groundwater samples from all four monitoring wells were plotted in relation to groundwater samples from the USGS NWIS database and to other samples (fig. 31) collected for previous studies (Gries and Bearlodge Ltd., Inc., 1989; Black and Veatch and others, 1994, and references therein; Weston Engineering, Inc., 1996a,b, 1998, 1999a,b, 2000; CH2M Hill and States West Water Resources Corporation, 1998; Benchmark Engineers, P.C., 2005; AVI Professional Corporation and others, 2008) from the Ogallala aquifer, White River aquifer, and the underlying Lance aquifer, which is contained in the Upper Cretaceous Lance Formation. These other samples were collected in the vicinity of Cheyenne (fig. 30). With a few exceptions, waters generally grouped into compositionally similar groups representative of their respective aquifers that were the same as seen in this study—the Ogallala aquifer was characterized by calcium-bicarbonate type waters, and the White River aquifer was characterized by calcium-sodium-bicarbonate type waters (fig. 31). Two groundwater samples from wells known to be at least partially open to the underlying Lance aquifer (Weston Engineering, Inc., 1996a, 1999b) also were plotted in figure 31. Ionic composition of waters sampled from both wells in the Lance aquifer compositionally were similar to one another but different than the ionic composition of waters from the Ogallala aquifer or White River aquifer; sodium and bicarbonate were the predominant ions so the waters from both wells in the Lance aquifer can be classified as sodium-bicarbonate type.

Trace Elements

Trace elements are a diverse group of constituents that generally occur naturally at small concentrations (less than 1 mg/L) in groundwater. Some trace elements (for example, iron and manganese) can be present at concentrations greater than the other trace elements, and are sometimes included with major ions. Trace elements commonly are collectively referred to as metals even though some trace elements, such as antimony, arsenic, and selenium, are semimetallic elements. Geochemical conditions commonly control measured concentrations of trace elements in groundwater rather than the abundance of the element in the rocks and minerals composing the aquifer (Hem, 1985). Health-based regulatory standards (MCLs) have been established by the USEPA for many trace elements because of toxicity to the human body. In addition, some trace elements, such as iron and manganese, can stain plumbing and laundry, so the USEPA has established secondary standards (SMCLs) for some trace elements for these and other aesthetic reasons.

All trace elements detected in groundwater from monitoring wells BRO–1a and BRO–2 were measured at small concentrations less than USEPA drinking-water standards or health advisories, Wyoming class II agricultural water standards, or Wyoming class III livestock standards (table 6). Beryllium, iron, silver, and thallium were not detected in groundwater sampled from either well. Five trace elements were detected at very small or estimated concentrations just above the laboratory reporting level (LRL) in water sampled from one but not the other well: aluminum, cadmium, copper, lead, and zinc.

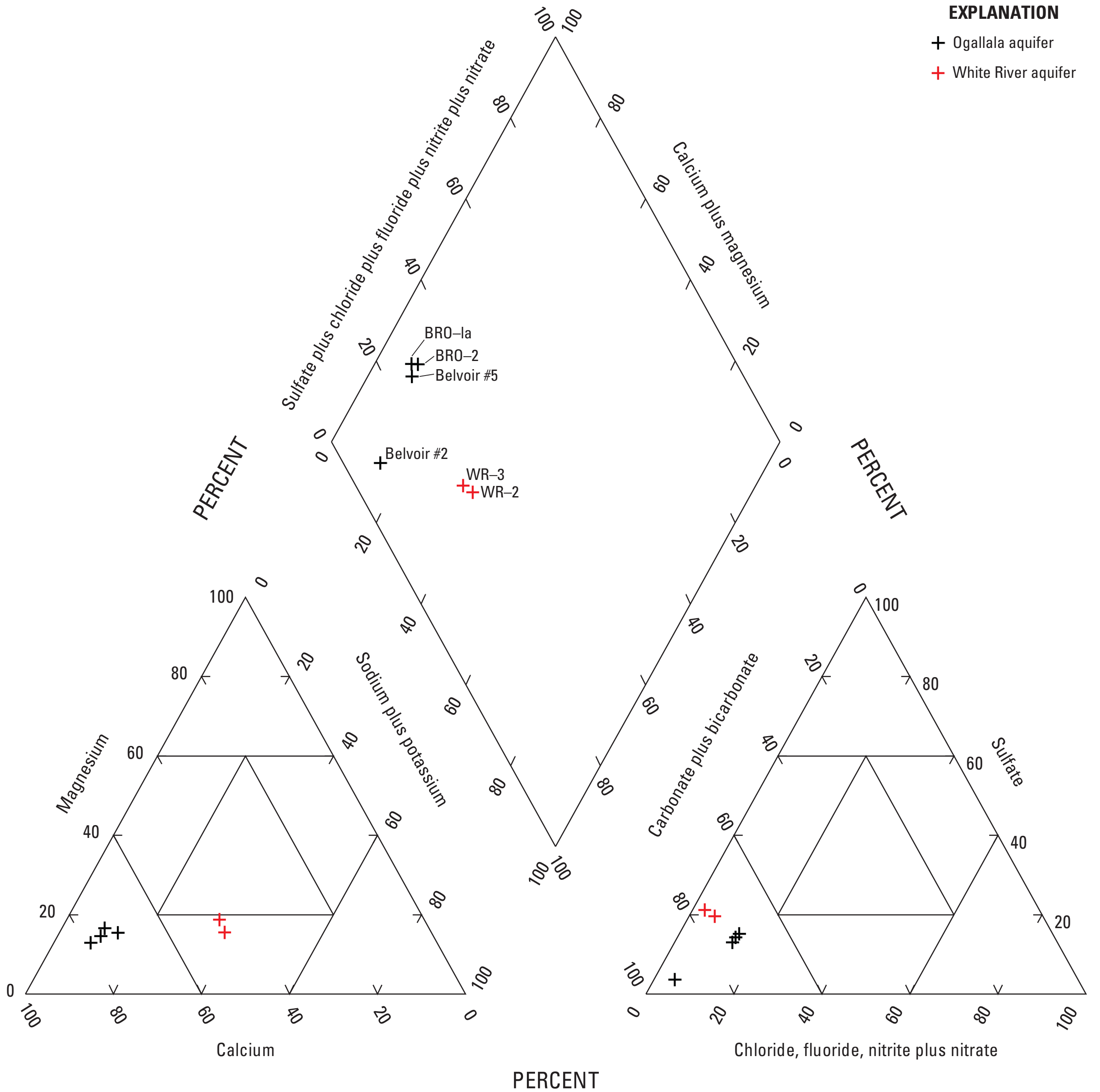


Figure 29. Trilinear diagram showing major-ion composition for groundwater samples from the Ogallala aquifer and White River aquifer, Belvoir Ranch, Laramie County, Wyoming. Location of wells shown in figure 30.

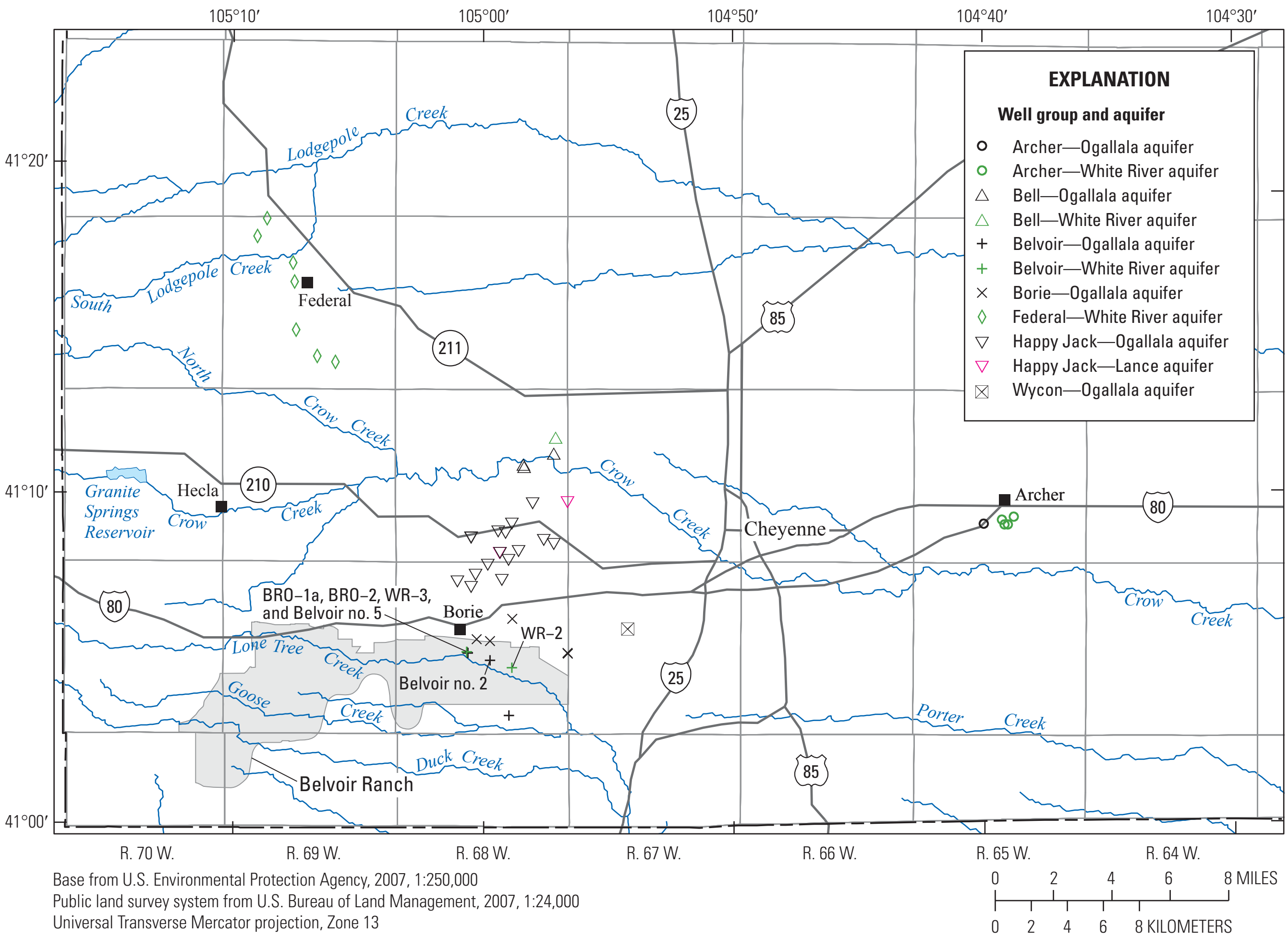


Figure 30. Location of sampled wells used in trilinear diagrams, Laramie County, Wyoming. Trilinear diagrams shown in figures 29 and 31.

Nutrients and Dissolved Organic Carbon

Groundwater samples from monitoring wells BRO–1a and BRO–2 were analyzed for different species of nitrogen and phosphorus. Small concentrations of both nutrients occur naturally in groundwater, but elevated concentrations commonly are associated with human (anthropogenic) activities. The most common anthropogenic sources of nitrogen and phosphorus in shallow groundwater are from leaching of fertilizers from agricultural lands, animal manure, or septic system effluent (Alley, 1993, and references therein).

Nitrate (an oxidized species of nitrogen in water) and phosphorus in water are of environmental and health concern. Nitrate and phosphorus discharged to surface waters can contribute to eutrophication. Large concentrations of nitrate in drinking water have been associated with potential adverse health effects including low oxygen levels in the blood of infants (“blue baby” syndrome, also known as infantile methemoglobinemia) (Fan and Steinberg, 1996), miscarriage (Centers for Disease Control and Prevention, 1996), and increased risk of non-Hodgkins lymphoma (Ward and others, 1996); however, the relation between nitrate in drinking water and infantile methemoglobinemia is still debated (for example, Avery, 1999).

As noted by Hem (1985, p. 124), “nitrogen occurs in water as nitrite or nitrate anions, in cationic form as ammonium, and at intermediate oxidation states as a part of organic solutes.” Consequently, groundwater samples were analyzed for several species of nitrogen, including both oxidized and reduced forms. Biogeochemical processes commonly control the species of nitrogen measured in groundwater (Hem, 1985). All nitrogen species concentrations described in this report are reported as equivalent concentrations of nitrogen. Groundwater samples were analyzed for total ammonia as nitrogen (referred to as “ammonia” in this report) that included ammonium ion and un-ionized ammonia. At the pH values measured in groundwater samples collected during this study, un-ionized ammonia was likely a small component of total ammonia (Hem, 1985).

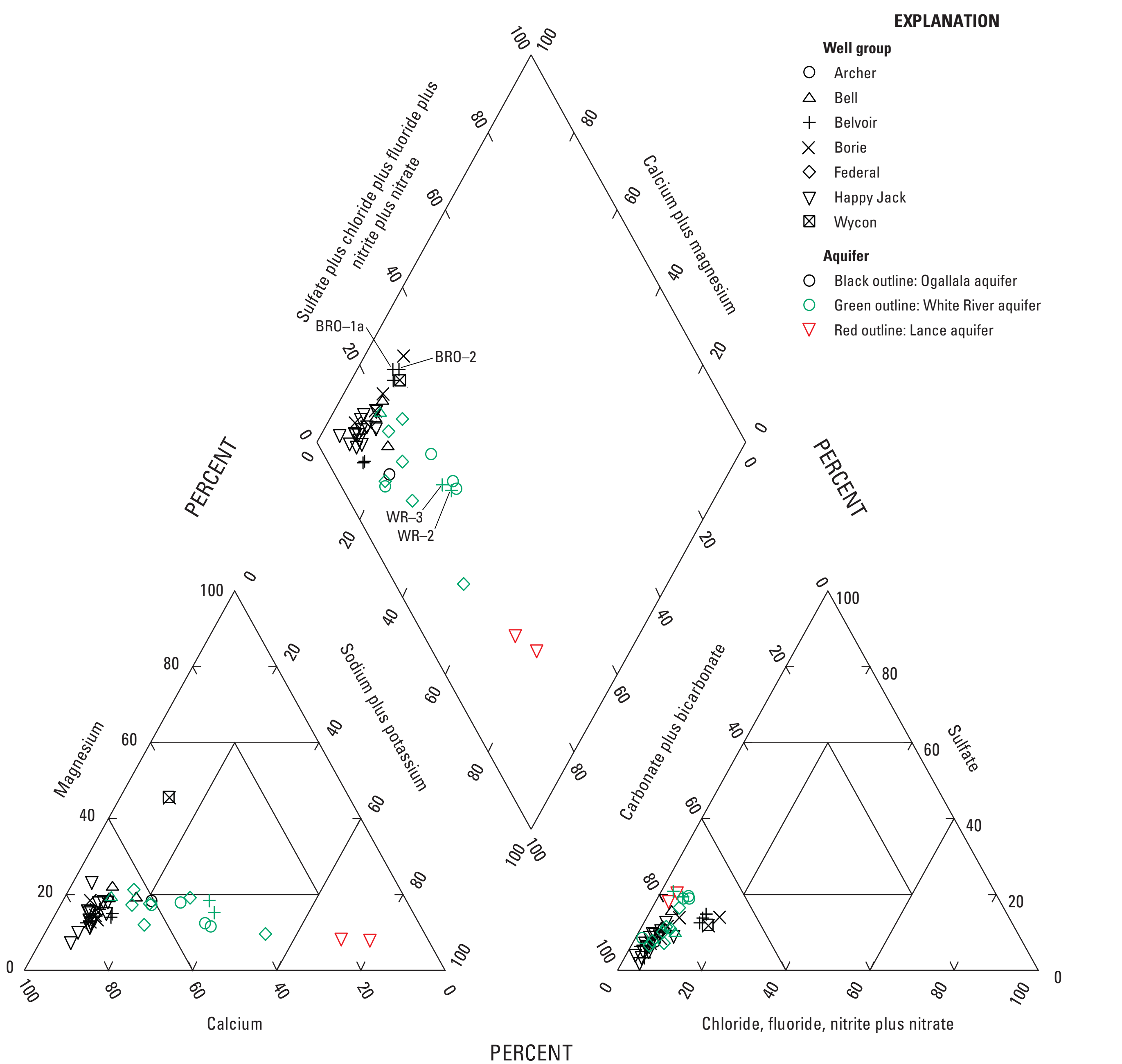


Figure 31. Trilinear diagram showing major-ion composition for groundwater samples from the Ogallala aquifer, White River aquifer, and Lance aquifer near Cheyenne, Laramie County, Wyoming. Location of wells shown in figure 30.

Nutrient concentrations were small in groundwater from both wells sampled, and all concentrations were much smaller than applicable USEPA drinking-water standards or health advisories (U.S. Environmental Protection Agency, 2012) or Wyoming class III livestock water standards (Wyoming Department of Environmental Quality, 2005, table 1) (table 6). Nitrite as nitrogen (nitrite) was not detected in groundwater sampled from well BRO–2, but was detected at the NWQL interim reporting level (IRL) of 0.002 mg/L in the sample from well BRO–1a; the BRO–1a detection was reported as an estimated concentration by the NWQL and was much smaller than the USEPA MCL of 1 mg/L. Because nitrite was not detected in groundwater from one well (BRO–2), measured at a very small concentration in the other well (BRO–1a), and either composed none or very little of the nitrite plus nitrate as nitrogen concentrations in both well samples (estimated 1.57 mg/L at BRO–1a and 2.08 mg/L at BRO–2), nitrite plus nitrate concentrations as nitrogen are referred to as “nitrate” herein.

Nitrate was the form of nitrogen detected most frequently and at the largest concentrations in groundwater from both wells sampled (table 6). Nitrate was measured at an estimated concentration of 1.57 mg/L in water sampled from well BRO–1a, and at a slightly greater concentration of 2.08 mg/L in well BRO–2. Ammonia as nitrogen (ammonia) was not detected in groundwater sampled from well BRO–1a, but was detected in the sample from well BRO–2 at an estimated concentration of 0.01 mg/L. Organic nitrogen was not detected in groundwater sampled from well BRO–1a, but was detected in well BRO–2 at an estimated concentration of 0.02 mg/L.

The detection of nitrate compared with most other species of nitrogen was expected because DO concentrations in groundwater from both wells sampled were indicative of oxic conditions (defined herein as DO concentrations larger than 0.5 mg/L); nitrate is the most common form of nitrogen in oxic groundwater and is stable over a wide range of geochemical conditions (Hem, 1985). The nitrate concentrations in samples from the monitoring wells (table 6) were much smaller than the USEPA MCL of 10 mg/L (U.S. Environmental Protection Agency, 2012). Concentrations of nitrate in ground water in the conterminous United States greater than 3 mg/L (Madison and Brunett, 1985), 2 mg/L (Mueller and Helsel, 1996), or 1.1 mg/L (Nolan and Hitt, 2003) have been suggested previously to be the result of human (anthropogenic) activities. Nitrate concentrations in groundwater samples from both wells (estimated concentration of 1.57 mg/L at BRO–1a and 2.08 mg/L at BRO–2) were slightly larger than the lowest estimate (1.1 mg/L) of concentrations that would be expected when influenced by human activities, and one sample was larger than the next highest estimate (2 mg/L), but both were less than the highest estimate (3 mg/L). Both nitrate concentrations that are slightly larger than would be expected when influenced by human activities are not surprising because a recent study indicates that nitrate concentrations in shallow groundwater beneath undeveloped parts of the High Plains aquifer system can be larger than expected in other geographic regions within the United States, primarily because of the presence of large natural nitrate deposits in the soil and subsoil of some arid and semiarid areas within the regional aquifer system (McMahon and Böhlke, 2006).

Dissolved phosphorus (total as phosphorus) was detected in groundwater from monitoring wells BRO–1a and BRO–2, but at very small concentrations (0.022 and 0.032 mg/L, respectively; table 6). Dissolved orthophosphate (as phosphorus) was detected in groundwater from both wells sampled, but at very small and similar concentrations (0.029 mg/L at BRO–1a and 0.032 mg/L at BRO–2; table 6). Phosphorus concentrations in groundwater usually are small because of low solubility and a tendency to adsorb to organic matter or metallic oxides in the subsurface (Hem, 1985). The USEPA has not established water-quality standards for phosphorus in groundwater; however, to reduce the possibility of eutrophication and resulting effects on aquatic life, USEPA recommends that total phosphorus concentrations in surface water should not be greater than 0.1 mg/L (as phosphorus) for flowing water not directly discharging into a lake or reservoir (U.S. Environmental Protection Agency, 1986). Phosphorus concentrations larger than 0.1 mg/L in groundwater can be a concern when groundwater discharges to surface water. Phosphorus concentrations in groundwater sampled from both monitoring wells were smaller than 0.1 mg/L.

Dissolved organic carbon (DOC) occurs naturally in groundwater, but elevated concentrations can indicate groundwater contamination from human sources (typically from septic system effluent) (Appelo and Postma, 2005). Much of the natural DOC in groundwater is from humic and fulvic acids generated by biogeochemical degradation of organic material in the soil profile above the aquifer or by degradation of organic matter within the aquifer deposits. Percolating waters (groundwater recharge) transport DOC in the soil zone to the water table. DOC concentrations in groundwater can affect trace-element solubility (through formation of complexes) and the redox state of groundwater (DOC is a common electron donor) (Chapelle, 2001). Concentrations of DOC measured in groundwater samples collected from monitoring wells BRO–1a and BRO–2 were small (1.1 mg/L and estimated 0.5 mg/L, respectively; table 6). These concentrations are within the range of 0 to about 3 mg/L reported for natural (uncontaminated) groundwater (Drever, 1997, fig. 6–1, p. 108).

Volatile Organic Compounds and Gasoline Range Organics

Volatile organic compounds (VOCs) generally are manmade chemicals in many commonly used products, such as plastics, paints, refrigerants, gasoline, fuel oils, lubricants, solvents, fumigants, pesticides, personal hygiene products, and disinfection byproducts. Many VOCs are highly soluble, mobile, and persistent in groundwater. In addition, many VOCs are suspected carcinogens or have some type of health risk associated with exposure (Zogorski and others, 2006, and references therein). Therefore, USEPA regulatory standards have been established for many VOCs in drinking water, including the VOC trichloroethene (also known as trichloroethylene or TCE). Gasoline-range organics (GRO) are a subset of petroleum hydrocarbons measured in the laboratory that included hydrocarbons in the C5–C10 range (5 to 10 carbon atoms).

Although not originally proposed as part of this study, samples were collected from monitoring wells BRO–1a and BRO–2 and analyzed for TCE and GRO (table 8) because the Wyoming Department of Environmental Quality needed additional information from the study area, which is located in an area where the Ogallala aquifer is known to be contaminated by TCE, as discussed previously in the “Water-Quality Criteria” section. The VOC TCE was detected in monitoring well BRO–1a at a concentration of 23 micrograms per liter (μg/L), which is greater than the USEPA MCL of 5 μg/L, but was not detected above the LRL of 0.37 μg/L in monitoring well BRO–2. GRO were not detected above the LRL of 11 mg/L in samples collected from either monitoring well.

Interpretation of the Groundwater System at the Study Site, Including Relation of Lithostratigraphy to Hydrostratigraphy, and in Relation to Definition of the High Plains Aquifer System

A groundwater system at any given location is defined by the aquifers and confining units that underlie the area (Heath, 1983, p. 14). Physical and chemical characteristics collected from the various units as part of this study were evaluated in relation to characteristics described in previous studies, and combined were used to interpret the groundwater system at the study site, including definition of Tertiary lithostratigraphic units (lithostratigraphy) as hydrogeologic units (hydrostratigraphy). Finally, identified Tertiary hydrogeologic units are defined as either composing or underlying the High Plains aquifer system in the study area along Lone Tree Creek.

Ogallala Aquifer

Physical characteristics described in previous studies and this study clearly indicate that the saturated part of the Ogallala Formation comprises an about 182-ft thick high-yielding aquifer (Ogallala aquifer) in the vicinity of Lone Tree Creek, as well as in areas immediately to the north and as far north as Federal. As was shown in this study, proximity to the source of sediments (Laramie Mountains) constituting the Ogallala Formation resulted in an anomalously thick accumulation of very coarse-grained (sand- and gravel-sized) sediments with overall poor consolidation (cementation) in the vicinity of Lone Tree Creek. Although some zones/depth intervals had a much higher percentage of fine-grained sediments, the predominant coarse-grained sediment size, combined with poor consolidation, has resulted in a very permeable and productive aquifer at the location studied along Lone Tree Creek. Development of monitoring well BRO–2 (with only a 20-ft long well screen) indicated potentially high well yields can be obtained from the Ogallala aquifer in the study area, because 825 gallons easily were removed from the well in 40 minutes [rate of about 20 gallons per minute (gal/min)]. Installation of numerous test holes and test wells along Lone Tree Creek as part of two studies (JR Engineering, 2005; Trihydro Corporation, 2009) indicated that the Ogallala aquifer sediments described in this study are present throughout the Lone Tree Creek drainage, and commonly are very coarse grained as was observed at the location of this study; however, high well yields (adequate for public-supply well purposes) could not be obtained at all locations because the coarse-grained sediments in the Ogallala Formation were not always as thick or were interbedded with thick beds of fine-grained sediments that were much less permeable. Heterogeneity in the Ogallala Formation in the vicinity of Cheyenne has been noted in numerous previous studies (for example, Foley, 1942; Morgan, 1946; Lowry and Crist, 1967; Black and Veatch and others, 1994; Weston Engineering, 1996a; Black and Veatch, 2004; Wyoming State Engineer's Office, 2008), and is described in a recent extensive compilation of geologic, geophysical, and hydrogeologic data for the area (Hallberg and Mason, 2007). This heterogeneity also is reflected by highly variable well yields. Yields of wells completed in the Ogallala aquifer on the Belvoir Ranch and surrounding areas vary substantially, reportedly ranging from 12 to 1,100 gal/min with yields dependent on local aquifer permeability (JR Engineering, 2007, p. 6).

Although aquifer testing of monitoring wells BRO–1a and BRO–2 was not conducted as part of this study, insight into Ogallala aquifer hydraulic properties in the vicinity of the study area is provided by two recent studies examining productivity of the aquifer and development potential in the Belvoir Ranch area along Lone Tree Creek (JR Engineering, 2005, 2007). As part of the study by JR Engineering (2005), the transmissivity of the Ogallala aquifer was estimated using a 24-hour constant-rate discharge test (aquifer test) of a test well (designated Belvoir no. 5) located about 190 ft north of

Table 8. Summary of trichloroethene and gasoline-range organics analyzed in groundwater-quality samples collected from monitoring wells BRO–1a and BRO–2, Belvoir Ranch, Laramie County, Wyoming.

[Concentrations greater than the laboratory reporting level are shown in **bold** type. USEPA, U.S. Environmental Protection Agency; µg/L, micrograms per liter; <, less than; MCL, Maximum Contaminant Level; C6–C10, range of carbon compounds included in the analysis; mg/L, milligrams per liter; --, not applicable]

Compound (units)	Common name/synonym	Laboratory reporting level	Well BRO–1a concentration (June 24, 2010)	Well BRO–2 concentration (November 12, 2009)	USEPA drinking-water standard
Trichloroethene (µg/L)	TCE, trichloroethylene	0.37	**23**	<0.37	[1]5 (MCL)
Gasoline-range organics (C6–C10) (mg/L)	GRO	11	<11	<11	--

[1]U.S. Environmental Protection Agency (2012).

monitoring wells BRO–1a and BRO–2. The test well was screened throughout much of the saturated thickness (110 to 150 ft BLS and 170 to 260 ft BLS) of the Ogallala aquifer. Using a "time versus drawdown" analytical method [method not stated in report, but interpreted to be the Jacob straight-line method (Fetter, 1988, p. 170–172)], transmissivity was estimated at 13,400 feet squared per day (ft^2/day), which is equivalent to 100,000 gallons per day per foot [(gal/d/ft)] and storativity was estimated at 0.01 (JR Engineering, 2005). Using water levels measured in the test well and two nearby test holes and a "distance versus drawdown" analytical method [method not stated in report, but interpreted to be a modification of Jacob straight-line method (Fetter, 1988, p. 172–173)], transmissivity was estimated at 10,854 ft^2/day [81,000 (gal/d)/ft] and storativity was estimated at 0.00001. In the more recent study (JR Engineering, 2007), 7-day aquifer tests were conducted using the Belvoir no. 5 test well and an additional test well (designated Belvoir no. 6) located about 2 mi to the east of Belvoir no. 5. Using water levels measured in the Belvoir no. 5 well and five observation wells and Cooper-Jacob time-drawdown and distance-drawdown analytical methods (Fetter, 1988, p. 170–174), "overall transmissivity" was estimated at 9,902 ft^2/day [73,900 (gal/d)/ft] and storativity was estimated to be 0.00027. Using water levels measured in the Belvoir no. 6 well and six observation wells and the Cooper-Jacob distance-drawdown analytical method, transmissivity was estimated at 5,682 ft^2/day [42,400 (gal/d)/ft]; using the Cooper-Jacob time-drawdown analytical method, transmissivity was estimated at 3,604 ft^2/day [26,900 (gal/d)/ft] and storativity was estimated to be 0.082. The investigators (JR Engineering, 2007, p. 10) noted that the storage value estimate for the Belvoir no. 5 test well indicated confined conditions, whereas the storage value estimate for the Belvoir no. 6 test well was "near the lower end of the range for an unconfined aquifer." All of these transmissivity estimates indicate the Ogallala aquifer can be highly productive/transmissive in the vicinity of the study area.

Installation of well screens at two different depth intervals in monitoring wells BRO–1a and BRO–2 installed for this study allowed for evaluation of characteristics from and hydraulic connection between two widely separated (about 83 ft) depth intervals in the Ogallala aquifer. Despite the presence of coarse-grained permeable zones with interbedded less permeable fine-grained layers and zones (aquifer stratification), limited hydraulic connection of deeper and shallower parts of the Ogallala aquifer at the study site was indicated, but not conclusively proven given data collected and interpreted previously herein. In addition, interpretation of these same data also indicated that the shallow part of the aquifer near the water table is not isolated from the land surface by intervening fine-grained sediments with varying degrees of consolidation (cementation) in the unsaturated zone of the Ogallala Formation. Subtle similarity of groundwater-level fluctuations in both monitoring wells, especially when hydraulic head declined presumably because of nearby production well pumping, and even when in some cases the broader groundwater level trends in the two monitoring wells were going in the opposite direction (one was increasing overall, whereas the other was decreasing overall), suggested but did not conclusively prove limited hydraulic connection of shallower parts of the aquifer with deeper parts. Apparent groundwater ages estimated using different methods indicated modern waters of similar ages in monitoring wells BRO–1a and BRO–2; the older apparent age of water sampled from monitoring well BRO–2 likely reflects a longer groundwater-flow path and thus, greater residence time. Stable isotopes of oxygen and hydrogen ($\delta^{18}O$ and δ^2H) measured in samples from both wells were nearly identical, indicating waters in both wells were subject to similar recharge or evolutional paths. Waters were well oxygenated in both wells, and measured concentrations were similar. Most groundwater-quality characteristics (for example, major ions, trace elements, and nutrients) were measured at very similar concentrations in samples from both wells, and the slightly higher concentrations of some constituents measured in the sample from monitoring well BRO–2 compared to the sample from well BRO–1a likely can be attributed to greater residence time associated with a longer groundwater-flow path. Water type was identical in samples from both wells, as indicated by waters plotting very close to one another on a trilinear diagram. Movement of waters from the land surface to the water table (active recharge) through the intervening unsaturated zone was indicated by flushing of chloride from unsaturated-zone sediments, groundwater levels in monitoring well BRO–1a responding relatively rapidly to seasonal recharge events, and modern apparent groundwater ages estimated using different tracer methods. Many of these characteristics indicate but do not conclusively prove that some limited hydraulic connection may exist between shallower and deeper parts of the Ogallala aquifer.

If the shallower and deeper parts of the Ogallala aquifer are interpreted to be in limited hydraulic connection, this interpretation would somewhat contrast with previous interpretations indicating hydraulic confinement and isolation of different and more permeable parts of the aquifer by finer-grained sediments at different depths in the aquifer (JR Engineering, 2005, 2007). Water-bearing zones with coarse-grained and permeable sediments (identified as "subaquifers" in JR Engineering, 2007, p. 13) interbedded with aquifer zones with predominantly fine-grained sediments were identified in the Ogallala aquifer using drill cuttings descriptions and geophysical logs, and water flow from discrete zones in the aquifer screened by a test well (designated TH–5) near Belvoir no. 5 was identified using hydrogeophysical techniques by previous investigators (JR Engineering, 2005, 2007) and led to their conclusion that the subaquifers hydraulically were confined and isolated from one another and presumably from the land surface by fine-grained sediments. Use of monitoring wells screened at two different depth intervals, more detailed Ogallala aquifer characterization, and the ability to build on these previous studies, indicated but did not conclusively prove limited aquifer interconnection in this study. Perhaps most notably, data collected from the Ogallala aquifer for these previous studies

(JR Engineering, 2005, 2007) were obtained from test wells with long well screens open to most of the saturated Ogallala aquifer thickness; consequently, measurements of different aquifer properties, such as hydraulic head and groundwater quality, reflect contribution from many different parts of the aquifer, and thus, measurements are an integration of properties from many different parts of the aquifer. Long well screen intervals were used because the purpose of these studies was to obtain information for construction of high-yielding production wells in the Ogallala aquifer along Lone Tree Creek; production wells typically are constructed with long well screens penetrating the full thickness of an aquifer to obtain the maximum amount of water from an aquifer in a given area (for example, Driscoll, 1986). In conclusion, data collected from shallower and deeper parts of the Ogallala aquifer and interpreted during this study cannot be used to determine conclusively if shallower and deeper parts of the Ogallala aquifer are in limited hydraulic connection. Additional work beyond the scope of this study such as aquifer tests would be required to conclusively determine hydraulic connection within the Ogallala aquifer.

Some similarity of aquifer characteristics between the shallower and deeper parts of the Ogallala aquifer may not have existed before development of production wells in the area; similar characteristics may be because of intermixing of waters from different parts of the aquifer as a result of pumping of nearby production wells with well screens open to nearly the full thickness of the aquifer in the area. Evaluation of the effects of production well pumping on the Ogallala aquifer in the vicinity of the study area was beyond the scope of this study, but considerable insight is provided by recent studies by JR Engineering (2007) and the Wyoming State Engineer's Office (2008).

Brule Confining Unit

As described previously in the "Aquifer System Characteristics" section, secondary permeability is present in the Brule Formation of the White River Group in parts of southeastern Wyoming. Detailed description of cores collected from the entire thickness of the Brule Formation as part of this study did not indicate any secondary permeability features (plate 1). Detailed characterization indicated the formation at the study area is very fine grained, composed primarily of volcaniclastic mudrocks (vitric or argillaceous siltstone) throughout its thickness (about 131 ft). In addition, the Brule Formation overlies about 35 ft of primarily fine-grained sediments from either the Brule or Chadron Formation, or both lithostratigraphic units. Combined, these fine-grained sediments compose a 166-ft thick confining unit separating the overlying Ogallala aquifer from the underlying Chadron aquifer. In addition to the very fine-grained lithology of this unit, additional evidence of the confining nature of this unit is provided by very different hydraulic heads and major-ion chemistry (water type) between the overlying Ogallala aquifer and underlying Chadron aquifer.

Chadron Aquifer

Based on sparse hydrologic data, the coarse-grained sediments of the White River Group identified as the Chadron Formation underlying the Brule confining unit tentatively are identified as an aquifer. Coarse-grained sediments in the lower part of the White River Group can be highly productive, as indicated by production wells completed in the unit in the vicinity of Federal [identified by Brady (1949) as the Chadron Formation] (for example, Lowry and Crist, 1967). Similar productive zones in the Chadron Formation have not been identified beneath the area between Borie and Crow Creek (for example, Lowry and Crist, 1967; Black and Veatch and others, 1994; Weston Engineering, 1996a; Black and Veatch, 2004); however, characterization of the White River Group below the Ogallala aquifer underlying this area is limited. Grain size observed in the core and cuttings obtained during this study for what is presumably the same unit along the Lone Tree Creek area identified as the Chadron Formation (aquifer) indicates that only small volumes of water possibly adequate for stock or domestic purposes might be able to be obtained from wells completed in the unit. Large volumes of water are unlikely to be obtained from the unit because sediments are sorted poorly, the coarse grains in the immature conglomeratic sandstone/sandy conglomerate present throughout much of the unit commonly are surrounded by substantial amounts of very fine-grained matrix (for example, fig. 19*A*; "wacke-like" sediments observed in thin section from the depth interval from 471.3–471.6 ft BLS, fig. 21), and some depth intervals have sediment characteristics indicative of paleosol development (fig. 20*B*), as described previously in the "Lithology and Lithostratigraphy" section. Furthermore, low aquifer productivity was indicated by low well yields observed during well purging associated with groundwater-quality sampling of monitoring wells WR–2 and WR–3 (Trihydro Corporation 2009). The investigators (Trihydro Corporation 2009, p. 3–7) concluded that well yields from the unit described herein as the Chadron aquifer were not sufficient for development of high-yield production wells, but it was likely that well yields from the unit in the vicinity of well WR–2 were sufficient for possibly developing "a small alternative water supply."

Comparison of previously measured groundwater levels (hydraulic heads) and groundwater-quality characteristics in nearby monitoring well WR–3 completed in the Chadron aquifer with those measured in the two monitoring wells installed for this study in the Ogallala aquifer (BRO–1a and BRO–2), combined with detailed lithologic characterization, strongly indicated that the 166 ft of fine-grained sediments overlying the Chadron aquifer, defined herein as the Brule confining unit, hydraulically confines and isolates the Chadron aquifer from the overlying Ogallala aquifer, thus likely limiting hydraulic connection between the two hydrogeologic units. As described previously in the "Groundwater Levels" section, comparison of groundwater levels measured in a nearby monitoring well (WR–3; Trihydro Corporation, 2009) with discrete and continuous groundwater levels measured in monitoring wells BRO–1a and BRO–2 clearly showed that hydraulic heads measured in the Chadron aquifer substantially were lower than measured in the overlying Ogallala aquifer. The substantially different hydraulic heads indicate the intervening thick Brule confining unit effectively hydraulically isolates and confines the Chadron aquifer from the overlying Ogallala aquifer at the location examined. Furthermore, ionic composition of waters from monitoring wells WR–2 and WR–3 (Trihydro Corporation, 2009), completed in what is defined herein as the Chadron aquifer, were compositionally different than Ogallala aquifer waters from monitoring wells BRO–1a and BRO–2 and other Ogallala aquifer wells in the vicinity of Cheyenne; waters from the Ogallala aquifer were classified as calcium-bicarbonate type, whereas waters from the Chadron aquifer were classified as a calcium-sodium-bicarbonate type (fig. 29).

Interpretation of Hydrostratigraphy in Relation to Definition of the High Plains Aquifer System

Finally, classification of Tertiary lithostratigraphic units as hydrogeologic units allows for a refined definition of the High Plains aquifer system at the study site along Lone Tree Creek. As was described previously in the “Local Hydrostratigraphy” section of the report, the hydrostratigraphy of the High Plains aquifer system should be evaluated and subsequently defined using local rather than regional hydrogeologic characteristics. Regionally, and locally throughout southeastern Wyoming, the saturated part of the Ogallala Formation is defined as an aquifer (Ogallala aquifer) and part of the High Plains aquifer system throughout its areal extent (figs. 4 and 5). It also is recognized by all investigators that some water-bearing zones are more permeable than others, and that individual water-bearing zones have varying degrees of hydraulic connection, as was noted herein in relation to Ogallala Formation (aquifer) characteristics in the Lone Tree Creek study area. The Brule Formation is defined as an aquifer only where permeable; where defined as an aquifer (Brule aquifer), the unit generally is considered part of the High Plains aquifer system only in areas where hydraulically connected with the overlying or adjacent Ogallala and Arikaree aquifers (figs. 4 and 5). Where impermeable, as was the case in this study, the Brule Formation is classified as a confining unit (Brule confining unit) that underlies the High Plains aquifer system (fig. 4). Consequently, because the Brule Formation was classified as a confining unit in this study, the High Plains aquifer system in the study area is composed only of the Ogallala aquifer. The Chadron Formation is not considered a part of the High Plains aquifer system in most regional studies, and in southeastern Wyoming, the unit only is considered part of the aquifer system where permeable (and defined as an aquifer) and in hydraulic connection with other overlying or adjacent permeable Tertiary hydrogeologic units (aquifers) that are part of the aquifer system, primarily in the Goshen Hole area (figs. 4 and 5). Although the coarse-grained zone of the White River Group identified as the Chadron Formation was defined as a low-yielding aquifer (Chadron aquifer) in this study, evaluation of all data collected during this study and previous studies strongly indicates that the aquifer is not in hydraulic connection with the overlying Ogallala aquifer through the intervening Brule confining unit and therefore, the unit is not considered part of the High Plains aquifer system (fig. 4). In conclusion, because of the impermeable nature of the Brule confining unit and resulting hydraulic separation of the Ogallala and Chadron aquifers, and compared with local and regional hydrostratigraphic definitions of the High Plains aquifer system (fig. 4), the groundwater system in Tertiary lithostratigraphic units overlying the Upper Cretaceous Lance Formation at the location studied on the Belvoir Ranch is defined as being composed of, from shallowest to deepest, the (1) High Plains aquifer system (high-yielding Ogallala aquifer only, composed of the saturated Ogallala Formation); Brule confining unit composed of the Brule Formation of the White River Group and an underlying fine-grained depth interval with sediments that belong to either the Brule or Chadron Formation, or both; and the low-yielding Chadron aquifer (composed of poorly sorted coarse-grained sediments with substantial fine-grained matrix material assigned to the Chadron Formation of the White River Group).

Summary

The geologic and hydrogeologic characteristics of Tertiary lithostratigraphic units (Ogallala Formation and White River Group) that typically compose or underlie the High Plains aquifer system in southeastern Wyoming were described physically and chemically, and evaluated at a location along Lone Tree Creek on the Belvoir Ranch in southwestern Laramie County, Wyoming. On the basis of detailed geologic characterization using visual description, x-ray diffraction, and thin-section petrography of cuttings and core, as well as geophysical logs obtained from a 540-foot (ft) deep exploratory borehole, and comparisons with previously published descriptions of Tertiary lithostratigraphic units in southeastern Wyoming and adjacent western Nebraska, three Tertiary lithostratigraphic units were identified at the study site. From shallowest to deepest, identified Tertiary lithostratigraphic units included the Ogallala Formation, the Brule Formation of the White River Group, and the Chadron

Formation of the White River Group. Sediments composing the 272-ft thick Ogallala Formation were characterized as an unconsolidated to semiconsolidated sand and gravel with interbedded fine-grained sediments (silt and clay) with discrete zones of consolidation (cementation); sediments were derived primarily from the erosion of igneous and metamorphic rocks from the Laramie Mountains. Sediments composing the about 131-ft thick Brule Formation of the White River Group were composed primarily of very fine-grained volcaniclastic mudrocks (vitric or argillaceous siltstone). Characterization of sediments identified as the Chadron Formation of the White River Group indicated the unit was about 92-ft thick and composed primarily of sandy conglomerate with sand- and gravel-sized sediments surrounded by substantial amounts of very fine-grained matrix. Thirty-five feet of White River Group sediments between the Brule and Chadron Formations could not be assigned confidently to either or both units. Evidence for paleosol development was seen in several thin sections constructed from sediments subsampled from the White River Group. Sediment samples from 10 depth intervals were examined using x-ray diffraction, and mineralogy and clay composition were characterized for five size fractions ranging from bulk-sized to less than 1 micron in size.

The three Tertiary lithostratigraphic units identified at the study site were determined to be correlative with three identified hydrogeologic units composing the groundwater system at the study site—a high-yielding aquifer composed of the entire saturated thickness (182 ft) of the heterogeneous and coarse-grained fluvial sediments assigned to the Ogallala Formation (Ogallala aquifer); an underlying 166-ft thick confining unit composed primarily of very fine-grained volcaniclastic sediments and mudrocks assigned to the Brule Formation of the White River Group and additional underlying sediments that belong to either the Brule or Chadron Formation, or both (Brule confining unit); and an underlying low-yielding aquifer composed primarily of poorly sorted fluvial sediments assigned to the Chadron Formation of the White River Group (Chadron aquifer).

Groundwater levels (hydraulic heads) measured continuously using water-level recorders in two monitoring wells completed in the Ogallala aquifer for this study presented a consistent strong upward vertical gradient in the Ogallala aquifer, indicating the potential for water to move from deeper to shallower parts of the aquifer, regardless of the time of year and the presumed effects of pumping of production wells in the area.

Continuous measurement of groundwater levels in the shallowest monitoring well, installed near the water table, and examination of subsequently constructed water-level hydrographs indicated substantial groundwater recharge is likely during the spring of 2009 and 2010 from the ephemeral stream (Lone Tree Creek) located adjacent to the study site that flows primarily in response to spring snowmelt from the adjacent Laramie Mountains and surface runoff from precipitation events. Using the water-table fluctuation method, groundwater recharge was estimated to be about 13 inches for the period beginning in early October 2009 and ending in late June 2010, and about 4 inches for the period beginning in March 2011 and ending in early July 2011.

Despite widely varying sediment heterogeneity and consolidation, some limited hydraulic connection throughout the full vertical extent of the Ogallala aquifer was indicated but not conclusively proven by interpretation of similar chemical and isotopic characteristics, modern apparent groundwater ages, and similar hydraulic head responses measured continuously in two Ogallala aquifer monitoring wells installed for this study at two different widely separated (83 ft) depth intervals. Additional work beyond the scope of this study such as aquifer tests would be required to conclusively determine hydraulic connection within the Ogallala aquifer.

Comparison of previously measured groundwater levels (hydraulic heads) and groundwater-quality characteristics in a nearby monitoring well completed in the Chadron aquifer with those measured in the two monitoring wells installed for this study in the Ogallala aquifer, combined with detailed lithologic characterization, strongly indicated that the Brule confining unit hydraulically confines and isolates the Chadron aquifer from the overlying Ogallala aquifer, thus likely limiting hydraulic connection between the two units.

Finally, classification of Tertiary lithostratigraphic units as hydrogeologic units allowed for a refined definition of the High Plains aquifer system at the study site along Lone Tree Creek. Because of the impermeable nature of the Brule confining unit and resulting hydraulic separation of the Ogallala and Chadron aquifers, and compared with local and regional hydrostratigraphic definitions of the High Plains aquifer system, the groundwater system in Tertiary lithostratigraphic units overlying the Upper Cretaceous Lance Formation at the location studied on the Belvoir Ranch was defined as being composed of, from shallowest to deepest, the (1) High Plains aquifer system (high-yielding Ogallala aquifer only, composed of the saturated Ogallala Formation); Brule confining unit composed of the Brule Formation of the White River Group and an underlying fine-grained depth interval with sediments that belong to either the Brule or Chadron Formation, or both; and the low-yielding Chadron aquifer (composed of poorly sorted coarse-grained sediments with substantial fine-grained matrix material assigned to the Chadron Formation of the White River Group).

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Appendix 1

Table 1–1. Quantitative mineral abundances, in weight percent, calculated from diffractograms of randomly oriented bulk material from x-ray diffraction (XRD) sample numbers 1–10, Belvoir Ranch, Laramie County, Wyoming.

[XRD, x-ray diffraction; Fm, Formation; tr, trace]

XRD sample number	Lithostratigraphic unit	Depth interval, feet below land surface	Percentage of constituent									
			Quartz	Plagioclase	Potassium feldspar	Calcite	Dolomite	Smectite	Illite	Kaolinite	Chlorite	Hornblende
1	Ogallala Fm	26.5–26.75	31	25	12	25	0	8	tr	tr	0	0
2	Ogallala Fm	115–120	39	28	11	11	3	3	3	2	0	0
3	Ogallala Fm	220–225	31	27	7	0	0	20	7	5	0	3
4	Brule Fm	302.5–303.5	45	9	15	5	0	10	7	9	0	0
5	Brule Fm	374.97–375.18	43	6	6	27	0	6	8	4	0	0
6	Brule or Chadron Fm	413.8–414.1	52	7	9	8	0	12	7	5	0	0
7	Brule or Chadron Fm	430.95–431.20	38	10	13	0	0	25	3	7	0	4
8	Chadron Fm	446.0–446.4	42	16	19	0	0	13	0	8	0	2
9	Chadron Fm	471.0–471.3	44	2	34	0	0	11	5	4	0	0
10	Chadron Fm	487.15–487.6	33	20	23	0	0	10	7	7	0	0

Table 1–2. Semi-quantitative mineral abundances, in weight percent, calculated from diffractograms of glycol solvated bulk to 1.0-micron fraction, oriented material separated from x-ray diffraction (XRD) sample numbers 1–10, Belvoir Ranch, Laramie County, Wyoming.

[XRD, x-ray diffraction; Fm, Formation]

XRD sample number	Lithostratigraphic unit	Depth interval, feet below land surface	Percentage of constituent									
			Quartz	Plagioclase	Potassium feldspar	Calcite	Dolomite	Smectite	Illite/ mica	Kaolinite	Chlorite	Hornblende
1	Ogallala Fm	26.5–26.75	23	19	8	25	0	8	4/0	3	3	8
2	Ogallala Fm	115–120	23	14	8	14	0	10	10/0	6	5	10
3	Ogallala Fm	220–225	30	17	13	6	0	14	4/12	2	1	1
4	Brule Fm	302.5–303.5	25	4	5	40	0	3	9/0	8	5	1
5	Brule Fm	374.97–375.18	24	15	12	22	0	17	1/3	1	5	0
6	Brule or Chadron Fm	413.8–414.1	44	7	8	0	0	22	8/4	3	2	2
7	Brule or Chadron Fm	430.95–431.20	27	19	13	0	0	16	6/12	3	2	2
8	Chadron Fm	446.0–446.4	21	5	6	0	0	27	5/0	24	2	0
9	Chadron Fm	471.0–471.3	49	17	14	0	0	10	5/0	5	0	0
10	Chadron Fm	487.15–487.6	25	19	6	0	0	23	10/0	14	0	3

Table 1–3. Semi-quantitative mineral abundances, in weight percent, calculated from diffractograms of glycol solvated less than 1.0–0.1-micron fraction, oriented material separated from x-ray diffraction (XRD) sample numbers 1–10, Belvoir Ranch, Laramie County, Wyoming.

[XRD, x-ray diffraction; Fm, Formation; tr, trace]

XRD sample number	Lithostratigraphic unit	Depth interval, feet below land surface	Percentage of constituent									
			Quartz	Plagioclase	Potassium feldspar	Calcite	Dolomite	Smectite	Illite/mica	Kaolinite	Chlorite	Hornblende
1	Ogallala Fm	26.5–26.75	0	0	0	7	0	58	27/0	4	3	1
2	Ogallala Fm	115–120	0	0	0	0	0	57	21/0	16	4	2
3	Ogallala Fm	220–225	0	0	0	0	0	62	16/0	10	12	0
4	Brule Fm	302.5–303.5	tr	2	1	7	0	56	26/0	8	1	1
5	Brule Fm	374.97–375.18	tr	tr	tr	0	0	68	14/0	8	7	3
6	Brule or Chadron Fm	413.8–414.1	tr	tr	tr	tr	0	71	11/0	6	6	6
7	Brule or Chadron Fm	430.95–431.20	0	0	0	0	0	56	7/0	27	7	3
8	Chadron Fm	446.0–446.4	5	8	6	0	0	51	5/0	24	1	0
9	Chadron Fm	471.0–471.3	10	3	0	0	0	53	7/0	22	5	0
10	Chadron Fm	487.15–487.6	25	12	5	0	0	36	6/0	13	3	0

Table 1–4. Semi-quantitative mineral abundances, in weight percent, calculated from diffractograms of glycol solvated less than 0.1–0.03-micron fraction, oriented material separated from x-ray diffraction (XRD) sample numbers 1–10, Belvoir Ranch, Laramie County, Wyoming.

[XRD, x-ray diffraction; Fm, Formation]

XRD sample number	Lithostratigraphic unit	Depth interval, feet below land surface	Percentage of constituent									
			Quartz	Plagioclase	Potassium feldspar	Calcite	Dolomite	Smectite	Illite/mica	Kaolinite	Chlorite	Hornblende
1	Ogallala Fm	26.5–26.75	0	0	0	0	0	64	17/0	12	7	0
2	Ogallala Fm	115–120	0	0	0	0	0	69	8/0	10	13	0
3	Ogallala Fm	220–225	0	0	0	0	0	78	12/0	10	0	0
4	Brule Fm	302.5–303.5	0	0	0	0	0	77	10/0	6	4	3
5	Brule Fm	374.97–375.18	0	0	0	0	0	69	18/0	13	0	0
6	Brule or Chadron Fm	413.8–414.1	0	0	0	0	0	80	16/0	2	2	0
7	Brule or Chadron Fm	430.95–431.20	0	0	0	0	0	55	7/0	25	8	5
8	Chadron Fm	446.0–446.4	0	0	0	0	0	51	8/0	35	6	0
9	Chadron Fm	471.0–471.3	0	0	0	0	0	60	5/0	31	4	0
10	Chadron Fm	487.15–487.6	0	0	0	0	0	53	10/0	29	8	0

Table 1–5. Semi-quantitative mineral abundances, in weight percent, calculated from diffractograms of glycol solvated less than 0.03-micron fraction, oriented material separated from x-ray diffraction (XRD) sample numbers 1–10, Belvoir Ranch, Laramie County, Wyoming.

[XRD, x-ray diffraction; Fm, Formation; tr, trace]

XRD sample number	Lithostratigraphic unit	Depth interval, feet below land surface	Percentage of constituent									
			Quartz	Plagioclase	Potassium feldspar	Calcite	Dolomite	Smectite	Illite/mica	Kaolinite	Chlorite	Hornblende
1	Ogallala Fm	26.5–26.75	0	0	0	0	0	93	0/0	0	7	0
2	Ogallala Fm	115–120	0	0	0	0	0	100	0/0	0	tr	0
3	Ogallala Fm	220–225	0	0	0	0	0	95	0/0	0	0	5
4	Brule Fm	302.5–303.5	0	0	0	0	0	88	8/0	2	2	0
5	Brule Fm	374.97–375.18	0	0	0	0	0	92	0/0	0	8	tr
6	Brule or Chadron Fm	413.8–414.1	0	0	0	0	0	99	0/0	0	0	1
7	Brule or Chadron Fm	430.95–431.20	0	0	0	0	0	92	0/0	0	7	1
8	Chadron Fm	446.0–446.4	0	0	0	0	0	72	2/0	24	2	0
9	Chadron Fm	471.0–471.3	0	0	0	0	0	85	tr/0	10	5	0
10	Chadron Fm	487.15–487.6	0	0	0	0	0	85	5/0	10	0	0

Table 1–6. Semi-quantitative mineral abundances, in weight percent, from coarsest to finest particle sizes calculated from diffractograms of randomly oriented bulk material and glycol solvated oriented materials from x-ray diffraction (XRD) sample number 1, Ogallala Formation, 26.5–26.75-foot depth interval below land surface, Belvoir Ranch, Laramie County, Wyoming.

[tr, trace; µm, micron; <, less than]

Size fraction	Percentage of constituent									
	Quartz	Plagioclase	Potassium feldspar	Calcite	Dolomite	Smectite	Illite	Kaolinite	Chlorite	Hornblende
Bulk	31	25	12	25	0	8	tr	tr	0	0
Bulk to 1.0 µm	23	19	8	25	0	8	4	3	3	8
<1.0–0.1 µm	0	0	0	7	0	58	27	4	3	1
<0.1–0.03 µm	0	0	0	0	0	64	17	12	7	0
<0.03 µm	0	0	0	0	0	93	0	0	7	0

Table 1–7. Semi-quantitative mineral abundances, in weight percent, from coarsest to finest particle sizes calculated from diffractograms of randmly oriented bulk material and glycol solvated oriented materials from x-ray diffraction (XRD) sample number 2, Ogallala Formation, 115–120-foot depth interval below land surface, Belvoir Ranch, Laramie County, Wyoming.

[µm, micron; <, less than; tr, trace]

Size fraction	Percentage of constituent									
	Quartz	Plagioclase	Potassium feldspar	Calcite	Dolomite	Smectite	Illite	Kaolinite	Chlorite	Hornblende
Bulk	39	28	11	11	3	3	3	2	0	0
Bulk to 1.0 µm	23	14	8	14	0	10	10	6	5	10
<1.0–0.1 µm	0	0	0	0	0	57	21	16	4	2
<0.1–0.03 µm	0	0	0	0	0	69	8	10	13	0
<0.03 µm	0	0	0	0	0	100	0	0	tr	0

Table 1–8. Semi-quantitative mineral abundances, in weight percent, from coarsest to finest particle sizes calculated from diffractograms of randomly oriented bulk material and glycol solvated oriented materials from x-ray diffraction (XRD) sample number 3, Ogallala Formation, 220–225-foot depth interval below land surface, Belvoir Ranch, Laramie County, Wyoming.

[µm, micron; <, less than]

Size fraction	Percentage of constituent									
	Quartz	Plagioclase	Potassium feldspar	Calcite	Dolomite	Smectite	Illite/ mica	Kaolinite	Chlorite	Hornblende
Bulk	31	27	7	0	0	20	7/0	5	0	3
Bulk to 1.0 µm	30	17	13	6	0	14	4/12	2	1	1
<1.0–0.1 µm	0	0	0	0	0	62	16/0	10	12	0
<0.1–0.03 µm	0	0	0	0	0	78	12/0	10	0	0
<0.03 µm	0	0	0	0	0	95	0/0	0	0	5

Table 1–9. Semi-quantitative mineral abundances, in weight percent, from coarsest to finest particle sizes calculated from diffractograms of randomly oriented bulk material and glycol solvated oriented materials from x-ray diffraction (XRD) sample number 4, White River Group/Brule Formation, 302.5–303.5-foot depth interval below land surface, Belvoir Ranch, Laramie County, Wyoming.

[µm, micron; <, less than; tr, trace]

Size fraction	Percentage of constituent									
	Quartz	Plagioclase	Potassium feldspar	Calcite	Dolomite	Smectite	Illite/mica	Kaolinite	Chlorite	Hornblende
Bulk	45	9	15	5	0	10	7/0	9	0	0
Bulk to 1.0 µm	25	4	5	40	0	3	9/0	8	0	1
<1.0–0.1 µm	tr	2	1	7	0	56	26/0	8	1	0
<0.1–0.03 µm	0	0	0	0	0	77	10/0	6	4	3
<0.03 µm	0	0	0	0	0	88	8/0	2	2	0

Table 1–10. Semi-quantitative mineral abundances, in weight percent, from coarsest to finest particle sizes calculated from diffractograms of randomly oriented bulk material and glycol solvated oriented materials from x-ray diffraction (XRD) sample number 5, White River Group/Brule Formation, 374.97–375.18-foot depth interval below land surface, Belvoir Ranch, Laramie County, Wyoming.

[µm, micron; <, less than; tr, trace]

Size fraction	Percentage of constituent									
	Quartz	Plagioclase	Potassium feldspar	Calcite	Dolomite	Smectite	Illite/mica	Kaolinite	Chlorite	Hornblende
Bulk	43	6	6	27	0	6	8/0	4	0	0
Bulk to 1.0 µm	24	15	12	22	0	17	1/3	1	5	0
<1.0–0.1 µm	tr	tr	tr	0	0	68	14/0	7	7	3
<0.1–0.03 µm	0	0	0	0	0	69	18/0	13	0	0
<0.03 µm	0	0	0	0	0	92	0/0	0	8	tr

Table 1–11. Semi-quantitative mineral abundances, in weight percent, from coarsest to finest particle sizes calculated from diffractograms of randomly oriented bulk material and glycol solvated oriented materials from x-ray diffraction (XRD) sample number 6, White River Group/Brule or Chadron Formation, 413.8–414.1-foot depth interval below land surface, Belvoir Ranch, Laramie County, Wyoming.

[µm, micron; <, less than; tr, trace]

Size fraction	Percentage of constituent									
	Quartz	Plagioclase	Potassium feldspar	Calcite	Dolomite	Smectite	Illite/mica	Kaolinite	Chlorite	Hornblende
Bulk	52	7	9	8	0	12	7/0	5	0	0
Bulk to 1.0 µm	44	7	8	0	0	22	8/4	3	2	2
<1.0–0.1 µm	tr	tr	tr	0	0	71	11/0	6	0	6
<0.1–0.03 µm	0	0	0	0	0	80	16/0	2	2	0
<0.03 µm	0	0	0	0	0	99	0/0	0	1	0

Table 1–12. Semi-quantitative mineral abundances, in weight percent, from coarsest to finest particle sizes calculated from diffractograms of randomly oriented bulk material and glycol solvated oriented materials from x-ray diffraction (XRD) sample number 7, White River Group/Brule or Chadron Formation, 430.95–431.20-foot depth interval below land surface, Belvoir Ranch, Laramie County, Wyoming.

[µm, micron; <, less than]

Size fraction	Percentage of constituent									
	Quartz	Plagioclase	Potassium feldspar	Calcite	Dolomite	Smectite	Illite/mica	Kaolinite	Chlorite	Hornblende
Bulk	38	10	13	0	0	25	3/0	7	0	4
Bulk to 1.0 µm	27	19	13	0	0	16	6/12	3	2	2
<1.0–0.1 µm	0	0	0	0	0	56	7/0	27	7	3
<0.1–0.03 µm	0	0	0	0	0	55	7/0	25	8	5
<0.03 µm	0	0	0	0	0	92	0/0	0	7	1

Table 1–13. Semi-quantitative mineral abundances, in weight percent, from coarsest to finest particle sizes calculated from diffractograms of randomly oriented bulk material and glycol solvated oriented materials from x-ray diffraction (XRD) sample number 8, White River Group/Chadron Formation, 446.0–446.4-foot depth interval below land surface, Belvoir Ranch, Laramie County, Wyoming, Belvoir Ranch, Laramie County, Wyoming.

[µm, micron; <, less than]

Size fraction	Percentage of constituent									
	Quartz	Plagioclase	Potassium feldspar	Calcite	Dolomite	Smectite	Illite/mica	Kaolinite	Chlorite	Hornblende
Bulk	42	16	19	0	0	13	0/0	8	0	2
Bulk to 1.0 µm	21	5	6	0	0	27	5/0	34	2	0
<1.0–0.1 µm	5	8	6	0	0	51	5/0	24	1	0
<0.1–0.03 µm	0	0	0	0	0	51	8/0	35	6	0
<0.03 µm	0	0	0	0	0	72	2/0	24	2	0

Table 1–14. Semi-quantitative mineral abundances, in weight percent, from coarsest to finest particle sizes calculated from diffractograms of randomly oriented bulk material and glycol solvated oriented materials from x-ray diffraction (XRD) sample number 9, White River Group/Chadron Formation, 471.0–471.3-foot depth interval below land surface, Belvoir Ranch, Laramie County, Wyoming.

[µm, micron; tr, trace; <, less than]

Size fraction	Percentage of constituent									
	Quartz	Plagioclase	Potassium feldspar	Calcite	Dolomite	Smectite	Illite/mica	Kaolinite	Chlorite	Hornblende
Bulk	44	2	34	0	0	11	5/0	4	0	0
Bulk to 1.0 µm	49	17	14	0	0	10	5/0	5	0	0
<1.0–0.1 µm	10	3	0	0	0	53	7/0	22	5	0
<0.1–0.03 µm	0	0	0	0	0	60	5/0	31	4	0
<0.03 µm	0	0	0	0	0	85	tr/0	10	5	0

Table 1–15. Semi-quantitative mineral abundances, in weight percent, from coarsest to finest particle sizes calculated from diffractograms of randomly oriented bulk material and glycol solvated oriented materials from x-ray diffraction (XRD) sample number 10, White River Group/Chadron Formation, 487.15–487.6-foot depth interval below land surface, Belvoir Ranch, Laramie County, Wyoming.

[µm, micron; <, less than]

Size fraction	Percentage of constituent									
	Quartz	Plagioclase	Potassium feldspar	Calcite	Dolomite	Smectite	Illite/mica	Kaolinite	Chlorite	Hornblende
Bulk	33	20	23	0	0	10	7/0	7	0	0
Bulk to 1.0 µm	25	19	6	0	0	23	10/0	14	3	0
<1.0–0.1 µm	25	12	5	0	0	36	6/0	13	3	0
<0.1–0.03 µm	0	0	0	0	0	53	10/0	29	8	0
<0.03 µm	0	0	0	0	0	85	5/0	10	0	0

Table 1–16. B-axis (060) phyllosilicate reflections in angstroms measured from x-ray diffraction (XRD) scans of randomly oriented less than 0.03-micron fraction material containing prominent smectite with minor to trace amounts of dioctahedral kaolinite and illite, and trioctahedral chlorite separated from High Plains aquifer system sediments, Belvoir Ranch, Laramie County, Wyoming.

[Values from 1.49 to 1.52 angstroms (Å) indicate dioctahedral species with aluminous octahedral layers (smectite, kaolinite, and illite) whereas values from 1.53 to 1.55 Å indicate trioctahedral phases containing octahedral layers enriched with magnesium (chlorite). XRD, x-ray diffraction; Fm, Formation; --, no data]

XRD sample number	Lithostratigraphic unit	Depth interval, feet below land surface	Smectite (060) Å	Kaolinite (060) Å	Illite (060) Å	Chlorite (060) Å
1	Ogallala Fm	26.5–26.75	1.51	--	--	1.53
2	Ogallala Fm	115–120	1.50	--	--	--
3	Ogallala Fm	220–225	1.50	--	--	--
4	Brule Fm	302.5–303.5	1.51	1.49	1.50	1.53
5	Brule Fm	374.97–375.18	1.50	--	--	1.53
6	Brule or Chadron Fm	413.8–414.1	1.50	--	--	1.53
7	Brule or Chadron Fm	430.95–431.20	1.51	--	--	1.53
8	Chadron Fm	446.0–446.4	1.50	1.49	1.49	1.53
9	Chadron Fm	471.0–471.3	1.51	1.49	1.50	1.54
10	Chadron Fm	487.15–487.6	1.51	1.49	1.50	1.54

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