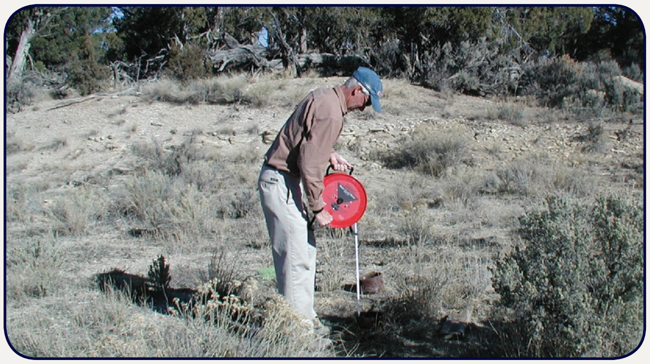
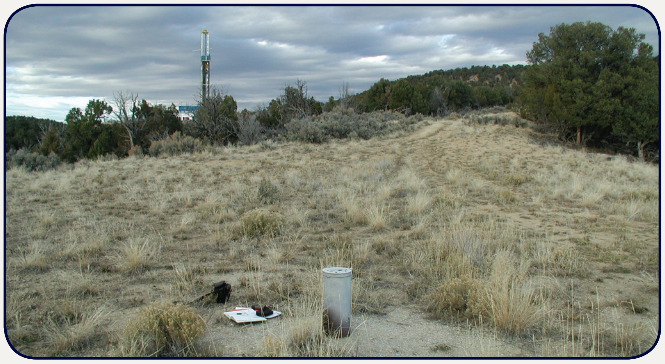
Prepared in cooperation with the Bureau of Land Management, White River Field Office

Chemistry and Age of Groundwater in Bedrock Aquifers of the Piceance and Yellow Creek Watersheds, Rio Blanco County, Colorado, 2010–12





Scientific Investigations Report 2013–5132

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

COVER:

Top, left: Piceance Creek near Ryan Gulch, Rio Blanco County, Colorado.
Photograph by U.S. Geological Survey.

Top, right: Wild horses in the Yellow Creek drainage, Rio Blanco County, Colorado.
Photograph by Kevin Dennehy, U.S. Geological Survey.

Middle, left: U.S. Geological Survey Geologist deploying a sampling device in a monitoring well, Rio Blanco County, Colorado.
Photograph by Richard Moscati, U.S. Geological Survey.

Middle, right: U.S. Geological Survey Hydrologic Technician measuring the water level in a monitoring well, Rio Blanco County, Colorado.
Photograph by Judith Thomas, U.S. Geological Survey.

Bottom, left: Monitoring well (foreground) located in the vicinity of a gas-well drilling pad (background).
Photograph by Judith Thomas, U.S. Geological Survey.

Bottom, right: View looking south in the Hunter Creek drainage, Rio Blanco County, Colorado.
Photograph by Peter McMahon, U.S. Geological Survey.

Chemistry and Age of Groundwater in Bedrock Aquifers of the Piceance and Yellow Creek Watersheds, Rio Blanco County, Colorado, 2010–12

By P.B. McMahon, J.C. Thomas, and A.G. Hunt

Prepared in cooperation with the Bureau of Land Management,
White River Field Office

Scientific Investigations Report 2013–5132

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

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2013

Suggested citation:
McMahon, P.B., Thomas, J.C., and Hunt, A.G., 2013, Chemistry and age of groundwater in bedrock aquifers of the Piceance and Yellow Creek watersheds, Rio Blanco County, Colorado, 2010–12: U.S. Geological Survey Scientific Investigations Report 2013–5132, 89 p., http://pubs.usgs.gov/sir/2013/5132/.

Contents

Figures

Tables

Appendix Figures

Appendix Tables

Conversion Factors

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
barrel, U.S. petroleum	159	liter (L)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
	Pressure	
atmosphere, standard (atm)	101.3	kilopascal (kPa)
bar	100	kilopascal (kPa)

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

$$°F=(1.8\times°C)+32$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

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

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

Abbreviations and Acronyms

‰	per mil or parts per thousand
cm^3STP/g	cubic centimeters at standard temperature and pressure per gram of water
$cm^3STP/g/yr$	cubic centimeters at standard temperature and pressure per gram per year
$cm^3STP/cm^2/yr$	cubic centimeters at standard temperature and pressure per square centimeter per year
DIC	dissolved inorganic carbon
DOC	dissolved organic carbon
MCL	maximum contaminant level
mg/L	milligrams per liter
µg/L	micrograms per liter
VCDT	Vienna Cañon Diablo Troilite
VPDB	Vienna Peedee belemnite
VSMOW	Vienna Standard Mean Ocean Water

Abbreviations and Acronyms Used in Appendix Figures

ft	feet
ft/min	feet per minute
O.D.	outside diameter
I.D.	inside diameter
EM res	electromagnetic resistivity
OTV MN	optical televiewer oriented to magnetic north
ATV MN	acoustic televiewer oriented to magnetic north
Y Cal	y-axis caliper
X Cal	x-axis caliper
HPFM	heat-pulse flowmeter
EMFM	electromagnetic flowmeter
Spec Cond	specific conductance
Temp Amb	ambient temperature
Deg C	degrees Celsius
Deg F	degrees Fahrenheit

Chemistry and Age of Groundwater in Bedrock Aquifers of the Piceance and Yellow Creek Watersheds, Rio Blanco County, Colorado, 2010–12

By P.B. McMahon, J.C. Thomas, and A.G. Hunt

Abstract

In 2011 and 2012, 14 monitoring wells completed in the Uinta and Green River Formations in the Piceance Creek and Yellow Creek watersheds in Rio Blanco County, Colorado, were sampled for field properties, major ions, nutrients, trace elements, noble gases, dissolved organic carbon, hydrocarbon molecular and isotopic compositions, volatile organic compounds, and a broad suite of stable and radioactive isotopes. Five of the wells were sampled quarterly in 2010 and 2011 for a smaller set of constituents to examine temporal changes in water quality. The chemical and isotopic constituents were selected to provide information on the overall groundwater quality, the occurrence and distribution of chemicals that could be related to the development of underlying natural-gas reservoirs, and to better understand groundwater residence times in the flow system.

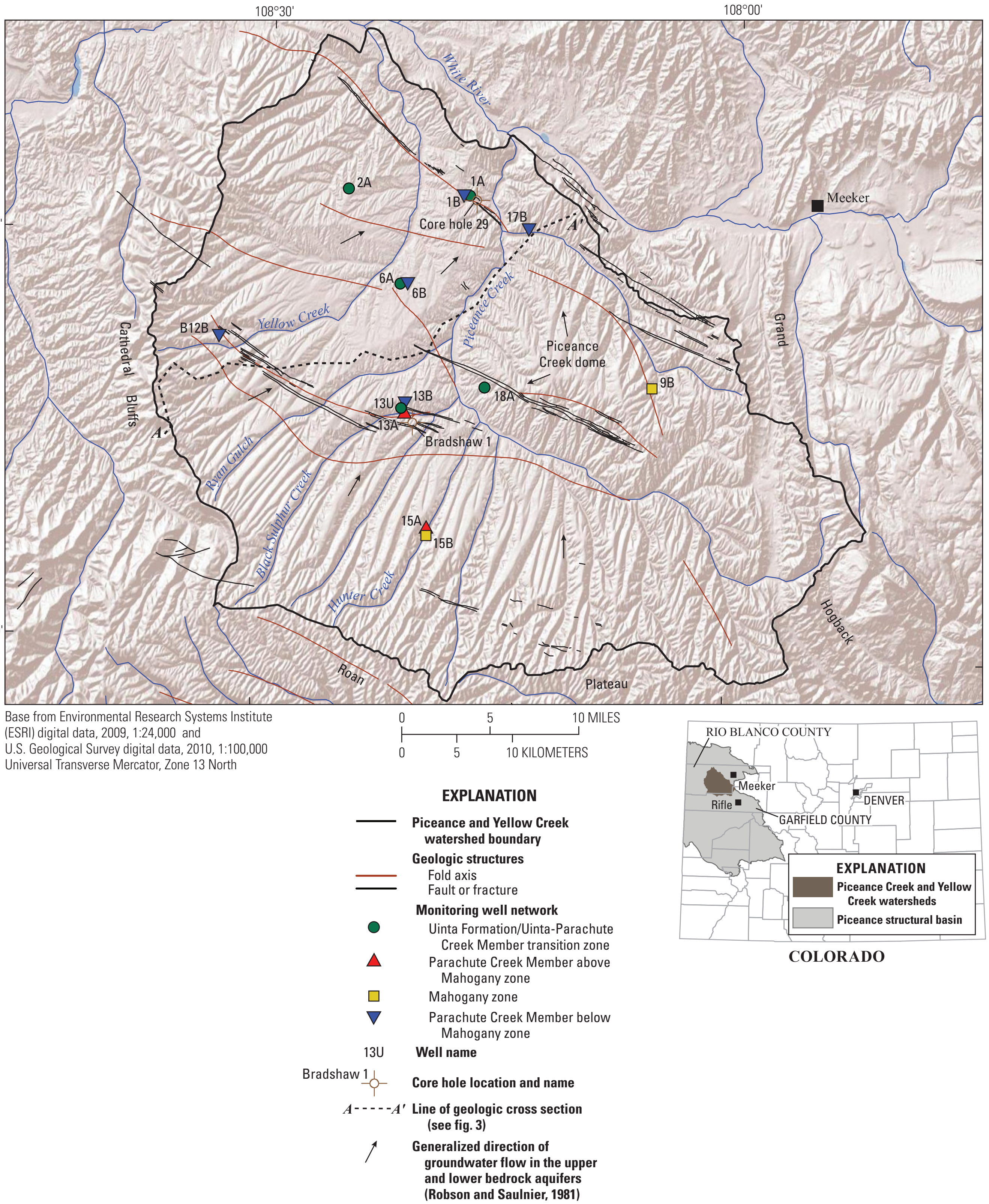
Water isotopic data indicate that the primary source of groundwater was precipitation that infiltrated into the aquifers at higher elevations along the watershed margins. The water generally evolved from a mixed-cation-bicarbonate-sulfate type water in recharge areas to a sodium-bicarbonate type water farther downgradient. Concentrations of dissolved solids ranged from 738 to 47,600 milligrams per liter (mg/L). The highest concentrations occurred in groundwater near the regional discharge area at the northern end of Piceance Creek.

Methane concentrations in groundwater ranged from less than 0.0005 to 387 mg/L. The methane was predominantly biogenic in origin, although the biogenic methane was mixed with thermogenic methane in water from seven wells. Water from one well contained 100 percent thermogenic methane that had an isotopic composition similar to that of some commercially produced natural gas in the Piceance Basin. Three BTEX compounds (benzene, toluene, and ethylbenzene) were detected in water from six of the wells, but none of the concentrations exceeded Federal drinking-water standards. Five of the six wells that produced water with BTEX also contained at least a small amount of thermogenic methane. The presence of thermogenic methane in the aquifers indicates a connection and vulnerability to chemicals in deeper geologic units, but how the methane got there is unclear because the relative contributions of nearby gas wells, geologic structure, and legacy contamination to hydrocarbon migration in the study area are not well understood. Ultimately, collection of baseline data prior to gas-well installation and collection of time-series data after gas-well installation is the best way to understand the roles of gas wells, geologic structure, and legacy contamination in hydrocarbon migration in the study area.

Groundwater ages in the aquifers were assessed with tritium, carbon-14, helium-4, and chlorine-36 data. Collectively, the data indicate that groundwater in high elevation recharge areas was essentially modern and became progressively older as it moved downgradient in the flow system. Data for halogenated volatile organic compounds indicate that some of the old groundwater was susceptible to contamination from human activity. Helium-4 data indicate that groundwater above the Mahogany zone had ages ranging from less than 1,000 years to about 20,000 years, whereas groundwater from within and below the Mahogany zone had ages greater than about 10,000 years, and most ages were greater than 20,000 years. Some groundwater ages in the lower aquifer near the regional discharge area at the northern end of Piceance Creek appeared to be greater than 50,000 years. The old groundwater ages have important implications from a water management perspective. The ages indicate that parts of the aquifers with long groundwater residence times could have century- to millennium-scale flushing times if they were contaminated. The presence of old groundwater in parts of the aquifers also indicates that these aquifers may not be useful for large-scale water supply because of low recharge rates.

Introduction

The primary aquifers in the Piceance Creek and Yellow Creek watersheds in Rio Blanco County, Colo., are bedrock aquifers in the Uinta and Green River Formations and alluvial aquifers in the major valleys. Most of the fresh groundwater is contained in the bedrock aquifers (Weeks and others, 1974). The watersheds are part of the larger Piceance structural basin in western Colorado (fig. 1). The aquifers are an important source of water for people living and working in the area and to streams and springs in the watersheds (Ortiz, 2002), which support a variety of plant and animal communities.



Base from Environmental Research Systems Institute (ESRI) digital data, 2009, 1:24,000 and
U.S. Geological Survey digital data, 2010, 1:100,000
Universal Transverse Mercator, Zone 13 North

Figure 1. Map showing location of the Piceance Creek and Yellow Creek watersheds in the Piceance structural basin, and locations of monitoring wells and core holes used in this study. [Geologic structure from Hail and Smith (1994, 1997).]

The Piceance and Yellow Creek watersheds contain rich energy resources in the forms of oil shale and natural gas (Dubiel, 2003; Johnson and others, 2010), as well as mineral resources such as nahcolite (Brownfield and others, 2010), a sodium bicarbonate evaporite mineral. The oil-shale deposit alone represents an in-place resource of about 1.5 trillion barrels of oil, making it the richest oil-shale deposit in the world (Johnson and others, 2010). Commercial development of the oil-shale resource has not begun as of 2013, whereas commercial production of natural gas in the Piceance Basin has occurred since at least the 1950s. Natural-gas reservoirs and (or) their development have the potential to affect the quality of shallow groundwater in the study area in several ways. Faults and fractures could serve as natural pathways for the movement of fluids from the deep reservoirs into shallow aquifers. At the land surface, leakage from pipelines or storage ponds could affect the quality of groundwater recharge. In the subsurface, lost circulation of drilling fluids into high-permeability zones could directly affect groundwater quality where the boreholes intersect aquifers. Leaky cement seals in the annular space of gas wells could allow deep fluids to migrate upward into shallow aquifers (Gorody, 2012). Differentiating between fluid-migration pathways of natural and human origin can be very difficult.

Several studies have examined the geochemistry of groundwater in the watersheds (for example, Welder and Saulnier, 1978; Robson and Saulnier, 1981; Slawson and others, 1982; Kimball, 1984; Day and others, 2010), mostly in relation to oil shale, but published studies of the geochemistry of shallow groundwater as it may relate to natural-gas reservoirs are scarce. Some monitoring of groundwater quality is being done by energy companies but little of that information is publically available (U.S. Geological Survey, 2012a). To begin to address this information gap and to obtain monitoring data during natural-gas development, the Bureau of Land Management (BLM), White River Field Office, asked the U.S. Geological Survey (USGS) to characterize the groundwater quality of shallow bedrock aquifers in the Piceance and Yellow Creek watersheds, with particular emphasis on chemical constituents that could be related to the development of underlying natural-gas reservoirs. This characterization provides information on current (2010–12) water-quality conditions in the aquifers against which future water-quality data could be compared. Such a comparison could help differentiate between water chemistry that might be expected in the aquifers on the basis of natural processes and chemistry that might be affected by energy-resource development.

Purpose and Scope

The purpose of this report is to characterize the chemistry and age of groundwater in bedrock aquifers in the Piceance and Yellow Creek watersheds, Rio Blanco County, Colo. (fig. 1). In 2011 and 2012, 14 monitoring wells were sampled for field properties, major ions, nutrients, trace elements, noble gases, dissolved organic carbon, hydrocarbon molecular and isotopic compositions, volatile organic compounds, and a broad suite of stable and radioactive isotopes. Five of the wells also were sampled quarterly in 2010 and 2011 for a smaller set of constituents to examine temporal changes in water quality. The chemical and isotopic constituents were selected to provide information on the overall groundwater quality, occurrence and distribution of chemicals that could be related to the development of underlying natural-gas reservoirs, and to better understand groundwater residence times in the flow system.

Description of Study Area

The study area is the Piceance and Yellow Creek watersheds within the Piceance structural basin in Rio Blanco County, Colo. (fig. 1). The watersheds, with a combined area of about 900 square miles, are bounded by the White River to the north and by upland areas to the east (Grand Hogback), south (Roan Plateau), and west (Cathedral Bluffs) (fig. 1). Elevations range from about 5,700 feet at the White River to over 8,000 feet on the Roan Plateau and Cathedral Bluffs.

Whereas most fresh groundwater in the bedrock occurs in the Uinta Formation and underlying Parachute Creek Member of the Green River Formation, most production of natural gas occurs below these formations in the Wasatch Formation, Mesaverde Group, and other geologic units (Johnson and Rice, 1990) (fig 2). Some gas wells drilled in the 1950s and 1960s were as shallow as about 2,500 feet below land surface and many wells drilled since the 1960s are in the 4,000- to 8,000-foot depth range (Colorado Oil and Gas Conservation Commission, 2012). The drilling of Mesaverde wells at depths of about 9,000 to 16,500 feet below land surface is anticipated to be the dominant gas-drilling activity in the study area in the foreseeable future (Bureau of Land Management, 2013). For comparison, the depth to the base of the deepest aquifer in the Parachute Creek Member generally is less than about 2,500 feet below land surface.

Detailed descriptions of the geology of the Green River and Uinta Formations can be found in Cashion and Donnell (1974), Hail (1990), Donnell (2009), Brownfield and others (2010), and Johnson and others (2010). In general, sediments of the Parachute Creek Member were deposited in Eocene Lake Uinta and consist of calcareous and dolomitic marlstone, limestone, calcareous sandstone, siltstone, and mudstone, with alternating lean and rich oil shale zones (fig. 2). Nahcolite occurs as nodules and thin beds, sometimes with halite, in parts of the L-5 and deeper zones of the Parachute Creek Member (Brownfield and others, 2010) (fig. 3). These intervals are sometimes collectively referred to as the saline zone (Robson and Saulnier, 1981; Welder and Saulnier, 1978). Nahcolite and probably halite also once occurred at shallower depths, but they have been mostly leached out (Johnson and Brownfield, 2013). The leached zone may be several hundred feet thick, depending on location in the study area. The greatest amount of leaching appears to have occurred toward the eastern, southern, and western margins of the study area and at shallower depths in the center of the study area

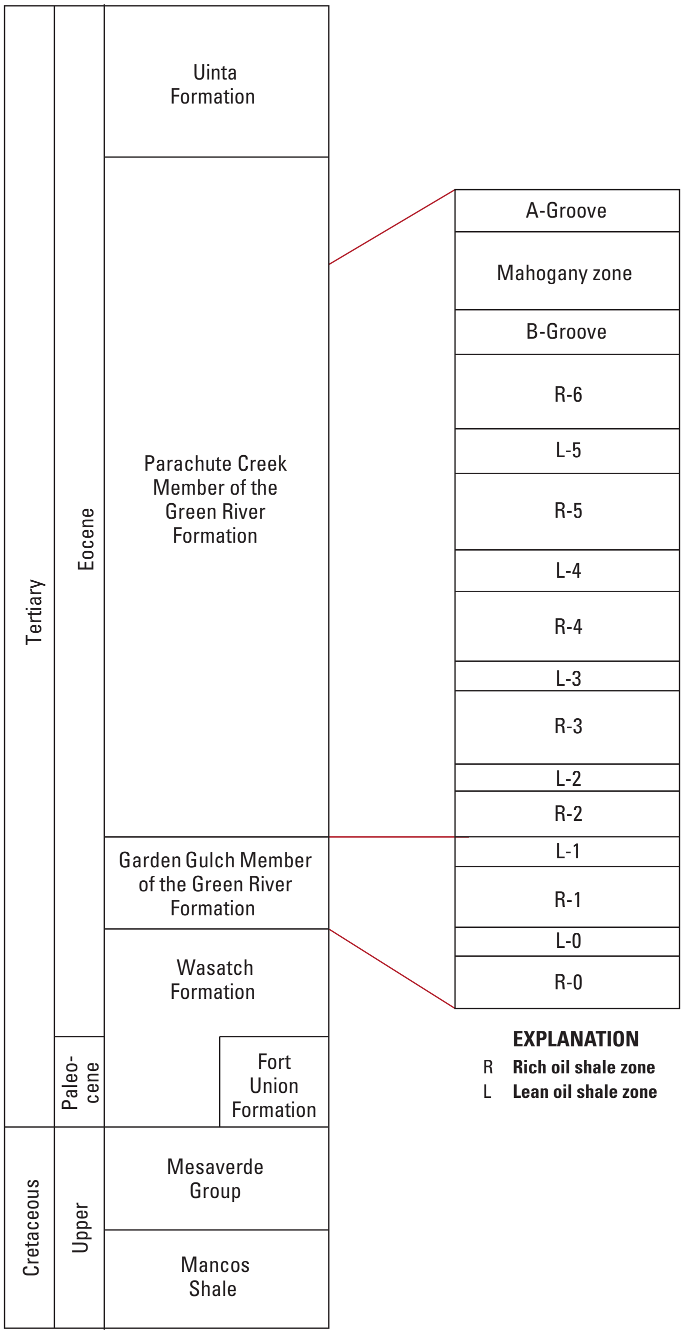


Figure 2. Generalized stratigraphic column for the study area. [Figure modified from Johnson and Rice (1990) and Johnson and others (2010).]

(Johnson and Brownfield, 2013) (fig. 3), probably as a result of dissolution by groundwater as it moved from the upland recharge areas toward regional discharge areas along Yellow and Piceance Creeks. The thickest sections of intact nahcolite occur in the center of the study area (fig. 3).

The Uinta Formation overlies the Parachute Creek Member; however, lower portions of the formation are complexly intertongued with upper portions of the Parachute Creek Member (Donnell, 2009) (fig. 3). Rocks of the Uinta Formation are a mix of sandstone, siltstone, mudstone, and marlstone and represent a southward prograding fluvial-deltaic system that filled Eocene Lake Uinta (Johnson, 1981). Because of this southward progradation of sedimentation, Uinta tongues become thinner to the south and tongues of the Parachute Creek Member become thicker to the south.

Fractures in marlstone and vugs and breccias from the dissolution of nahcolite and halite are the primary sources of porosity and permeability in the Parachute Creek Member and, thus, control groundwater flow (Coffin and others, 1971; Weeks and others, 1974; Day and others, 2010). Rich oil shale zones have a high kerogen content, which makes them more resistant to fracturing than lean zones (Weeks and others, 1974; Robson and Saulnier, 1981). In the 1970s, the USGS proposed a conceptual hydrogeologic model of the study area in which water-bearing zones in the Uinta Formation and Parachute Creek Member were divided into two aquifer systems, separated by the oil-shale rich Mahogany zone (figs. 2 and 3), which was considered to be a regionally extensive leaky confining layer (Coffin and others, 1971; Weeks and others, 1974; Robson and Saulnier, 1981). The upper bedrock aquifer system, consisting of water-bearing rocks of the Uinta Formation and Parachute Creek Member above the Mahogany zone, has unconfined and confined zones. The lower, mostly confined aquifer system consists of water-bearing rocks of the Parachute Creek Member below the Mahogany zone and above the saline zone. Permeability of the saline zone and the underlying Garden Gulch Member is very low, so they form the base of the fresh-water bearing aquifer system.

More recently, Shell Exploration & Production Company (Shell) proposed a revised conceptual hydrogeologic model of the west-central part of the study area. According to their model, there are three bedrock aquifer systems—an unconfined aquifer system in the Uinta Formation and two confined systems in the Parachute Creek Member (Day and others, 2010). The upper and lower confined aquifer systems are separated by a confining layer in the upper part of the R-5 zone and lower part of the L-5 zone, rather than the Mahogany zone (fig. 3). The upper confined aquifer system is separated from the Uinta Formation by a confining layer in the Parachute Creek Member above the A-Groove.

The detailed hydrogeologic data upon which the Shell model is based are not available throughout the study area, so it is unknown whether they are representative of the entire study area. As a result, this study uses the USGS hydrologic model for interpreting geochemical data. To the extent possible, however, wells in the upper aquifer system were further assigned either to the Uinta-Parachute Creek Member transition zone or the Parachute Creek Member above the Mahogany zone (fig. 3).

Normal annual precipitation in the study area ranges from about 12 to 25 inches, with the largest amounts falling in the upland areas (Weeks and others, 1974). Weeks and others (1974) estimated that the principal source of groundwater recharge was snowmelt in areas with elevations higher than 7,000 feet. Recharge occurs either as direct infiltration into bedrock aquifers or by recharge to small alluvial aquifers in

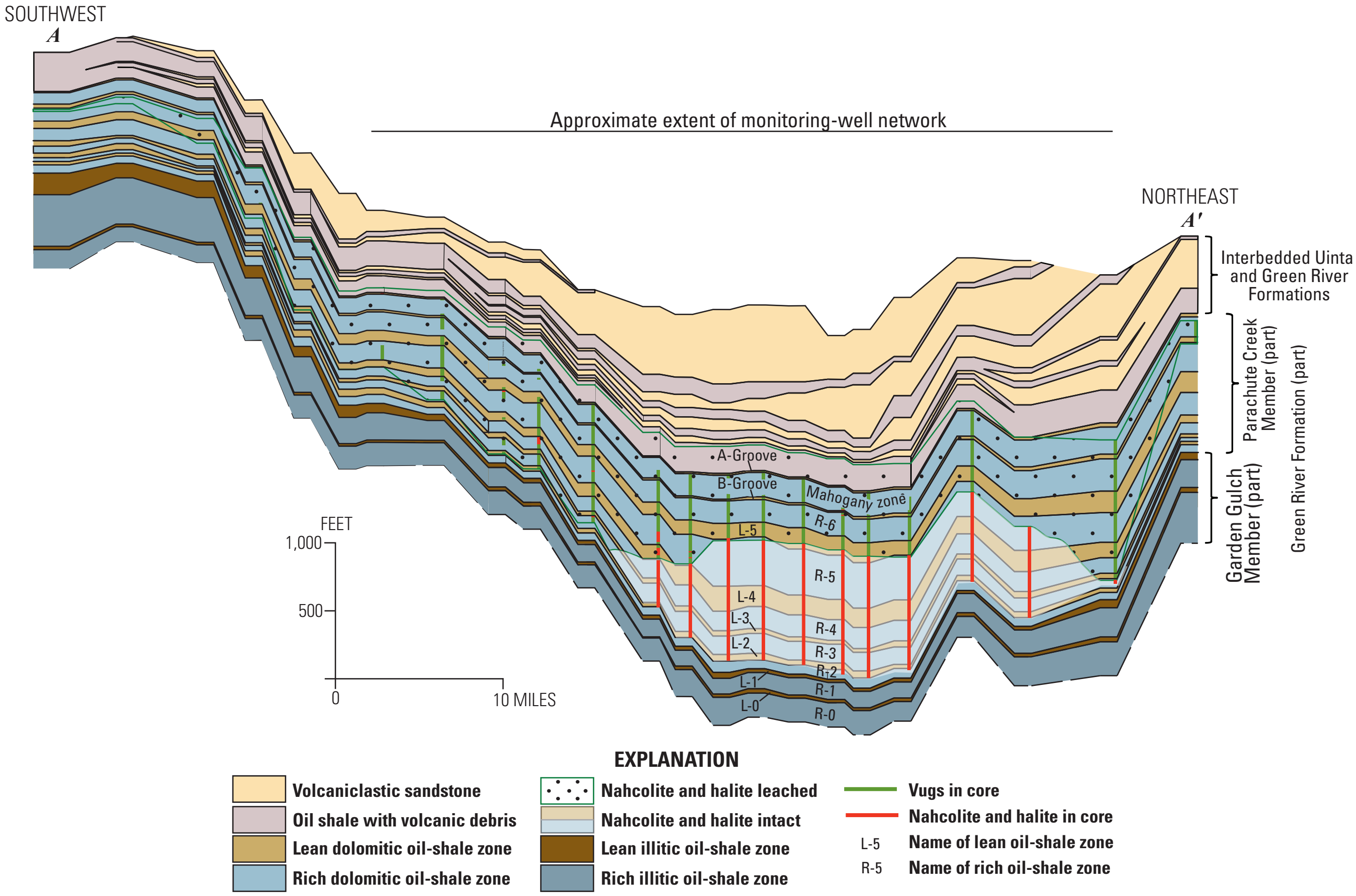


Figure 3. Geologic cross section through the study area. [Figure modified from Johnson and Brownfield (2013); See figure 1 for location of the cross section.]

the upper reaches of creeks, which then recharge bedrock aquifers (Robson and Saulnier, 1981; Day and others, 2010). Regardless of which hydrogeologic model (USGS or Shell) is considered, groundwater flow in the bedrock aquifers generally is from upland areas of the Roan Plateau and Cathedral Bluffs in the south and west, and toward Piceance Creek and lower Yellow Creek in the north and east (fig. 1) (Robson and Saulnier, 1981). Groundwater also flows radially away from Piceance Creek dome (fig. 1). The potential for downward movement of groundwater exists in upland areas along the eastern, southern, and western margins of the study area, and in the vicinity of Piceance Creek dome, and the potential for upward movement exists primarily along Piceance Creek and lower reaches of its tributaries (Robson and Saulnier, 1981).

Study Methods

Water samples were collected from 14 monitoring wells in August 2011 and 2012 (table 1). Five of the wells also were sampled quarterly in 2010 and 2011. The following sections provide details on the wells that were sampled, water-level measurements, and methods of sample collection and analysis.

Monitoring-Well Selection

Monitoring wells sampled for this study included 12 wells installed by the USGS in the 1970s, one well installed by the USGS in 2010 for this study (well 13U), and one well installed by Shell in 2002 (well B12B) (table 1). The 14 wells were selected to broadly encompass the area in which gas development is expected to continue and expand in the foreseeable future (Bureau of Land Management, 2013). Detailed information on construction of the USGS wells in the 1970s is in Welder and Saulnier (1978). Wells 13A and 13B, constructed in the 1970s, were modified by the USGS in 2010 to reduce the length of the open interval in the wells (Appendix figs. 1–1 and 1–2). Construction details for well 13U are in Appendix figure 1–3. Most of the selected wells are open to aquifers either above or below the Mahogany zone, but wells 9B and 15B appear to be open to parts of the Mahogany zone in addition to water-bearing zones below the Mahogany zone on the basis of isopach maps for the area (Johnson and others, 2010). Additional USGS wells installed in the 1970s were considered for use in this study (Welder and Saulnier, 1978), but they were not selected either because they could not be located in the field or because borehole geophysical logs collected from the wells during the reconnaissance phase of this project showed that they were not suitable for sampling.

Table 1. Location, construction, and geologic information for the monitoring wells.

[U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone]

Long well name	Short well name	Latitude	Longitude	USGS site number	Date drilled	Depth to water at time of sampling in August 2011 (feet below land surface)	Land-surface elevation (feet)	Well depth (feet below land surface)	Top of open interval (feet below land surface)	Bottom of open interval (feet below land surface)	Sample interval (feet below land surface)	Sampling device	Aquifer assignment for sample interval	Geologic interval in which sample interval is located (Welder and Saulnier, 1978; U.S. Geological Survey, 2010)
B12-31-199-B	B12B	39.916159	–108.547389	395458208325002	February 2002	328.0	7,458	491	407	491	407–491	Submersible pump	Lower aquifer	PCMB
TH75-1A	1A	40.038400	–108.285500	400218108170600	November 1975	199.2	6,143	1,060	182	1,060	550	Kemmerer	Upper aquifer	U-PCM
TH75-1B	1B	40.038150	–108.285330	400218108170601	December 1975	202.7	6,146	1,540	1,215	1,540	1,300	Kemmerer	Lower aquifer	PCMB
TH75-2A	2A	40.040806	–108.415361	400228108245400	November 1975	[1]578.8	6,719	1,122	402	1,122	761	Kemmerer	Upper aquifer	U-PCM
TH75-6A	6A	39.964480	–108.354230	395755108211400	August 1975	[2]280.5	6,439	1,260	111	1,260	400	Kemmerer	Upper aquifer	U-PCM
TH75-6B	6B	39.964770	–108.353700	395755108211401	August 1975	[2]281.7	6,438	1,755	1,381	1,755	1,440	Kemmerer	Lower aquifer	PCMB
TH75-9B	9B	39.88582	–108.08482	395310108050401	October 1975	458.4	7,350	1,575	1,297	1,575	1,325	Kemmerer	Lower aquifer	MZ
TH75-13A	13A	39.860160	–108.350310	395136108210000	December 1975	57.92	6,400	640	557	640	557–640	Submersible pump	Upper aquifer	PCMA
TH75-13B	13B	39.860060	–108.351200	395136108210001	January 1976	80.31	6,399	870	776	870	776–870	Submersible pump	Lower aquifer	PCMB
TH-13U	13U	39.860060	–108.351200	395136108210004	May 2010	59.54	6,400	250	159	239	159–239	Submersible pump	Upper aquifer	U-PCM
TH75-15A	15A	39.76144	–108.32014	394540108191201	June 1975	44.70	6,816	670	155	670	525	Kemmerer	Upper aquifer	PCMA
TH75-15B	15B	39.76116	–108.32037	394540108191202	June 1975	29.52	6,816	1,040	740	1,040	775	Kemmerer	Lower aquifer	MZ
TH75-17B	17B	40.012480	–108.221570	400045108131401	May 1975	65.32	6,100	2,400	893	2,400	1,050	Kemmerer	Lower aquifer	PCMB
TH75-18A	18A	39.881917	–108.263250	395255108154200	September 1975	415.4	6,740	810	108	810	600	Kemmerer	Upper aquifer	U-PCM

[1] Water level at time of drilling.

[2] Water level in June 2011.

Borehole Geophysics and Selection of Sample Interval

The USGS wells have long, uncased open intervals (278 to 1,507 feet long), with the exception of 13A, 13B, and 13U which were either modified after the original construction or newly constructed. Wells with long open intervals generally are not good wells to use for monitoring water chemistry because pumping them can integrate water from multiple water-bearing intervals in the sample. To address this issue, borehole geophysical logs (Appendix figs. 1–4 through 1–13), including heat-pulse and electromagnetic flow logs (Hess, 1986; Molz and others, 1994), were collected to determine the depths at which water entered and exited the open holes under nonpumping conditions. In 2008, Shell collected logs from some of the wells that were to be sampled for this study. In June 2011, USGS collected logs from the remaining wells that were to be sampled. Wells 6A and 6B were logged in 2008 and 2011; the flow-log data indicate that vertical flow patterns in the wells were very similar for the two measurement dates.

The water-bearing zones of primary interest to BLM are those in the Uinta Formation and in the A-Groove and B-Groove in the Parachute Creek Member (figs. 2 and 3). Thus, water entering open holes from those units, or as close to those units as possible, was targeted for sample collection using a Kemmerer discrete-depth sampler (discussed in the section “Sample Collection”). None of the wells had water entering the open hole from more than one of those units, so only a single depth was sampled in each well. Use of this discrete-depth sampling approach was intended to reduce the amount of mixing of water from different aquifers in the sample. Sample intervals selected on the basis of the geophysical measurements are listed in table 1.

Wells 13A, 13B, 13U, and B12B have short screened or open intervals and were sampled using submersible pumps.

Water-Level Measurements

Water levels were measured in the wells at the time of sample collection using either a steel tape or an electric tape. In addition, water levels were measured every 4 hours in wells 6A, 6B, 13A, 13B, and 13U using nonvented pressure transducers. Pressure readings were corrected for fluctuations in barometric pressure using data from a barometric pressure sensor installed at well 13U (Cunningham and Schalk, 2011).

Sample Collection

Samples were collected from the wells using dedicated submersible pumps (wells 13A, 13B, and B12B), a portable submersible pump (well 13U), or a Kemmerer sampler (all other wells). The dedicated pumps were made of stainless steel with galvanized metal discharge lines. The portable pump was made of stainless steel with a Teflon discharge line. The Kemmerer sampler was made of stainless steel with silicone seals and had a volume of 1.6 gallons. The Kemmerer sampler was deployed using an electric wireline system and tripod.

For wells that were pumped, a minimum of three casing volumes of water were purged from the wells prior to sample collection. Water samples were collected from the well discharge after readings of field properties (water temperature, specific conductance, pH, dissolved oxygen, and turbidity) had stabilized (as defined by Koterba and others, 1995). Concentrations of dissolved sulfide and alkalinity were measured in the field after the field properties were measured.

For wells that were sampled with the Kemmerer sampler, 40 to 120 minutes were required to lower the device to the sampling depth and retrieve it from the well. In August 2011, two trips in and out of each well were required to obtain sufficient volumes of water to make field measurements and fill sample bottles. One trip was required on most other sampling dates. Field properties were only measured once prior to sample collection because of limited water volumes and the time required to make multiple trips in and out of the well with the sampler.

In August 2011, water samples were collected from each of the 14 wells for the analysis of a broad suite of chemical and isotopic constituents that included major ions, nutrients, trace elements, dissolved organic carbon (DOC), BTEX compounds (benzene, toluene, ethylbenzene, and xylenes), hydrocarbon molecular compositions (methane through hexane), noble gases, dissolved carbon dioxide and nitrogen (N_2) gases, stable hydrogen and carbon isotopes of methane (δ^2H-CH_4 and $\delta^{13}C$-CH_4), stable hydrogen and oxygen isotopes of water (δ^2H-H_2O and $\delta^{18}O$-H_2O), tritium, stable carbon isotopes of dissolved inorganic carbon ($\delta^{13}C$-DIC), carbon-14 of DIC, chlorine-36/chloride ratio of dissolved chloride ($^{36}Cl/Cl$), stable oxygen and sulfur isotopes of sulfate ($\delta^{18}O$-SO_4 and $\delta^{34}S$-SO_4), and the isotopic composition of dissolved strontium ($^{87}Sr/^{86}Sr$). In August 2012, each of the 14 wells was sampled for many of these same constituents plus halogenated volatile organic compounds (hVOCs). Wells 6A, 6B, 13A, 13B, and 13U were further sampled approximately on a quarterly basis in 2010 and 2011 for major ions, methane concentrations, and BTEX compounds.

Water samples collected for the analysis of alkalinity, major ions, nutrients, trace elements, DOC, $\delta^{13}C$-DIC, carbon-14 of DIC, $\delta^{18}O$-SO_4, $\delta^{34}S$-SO_4 and $^{36}Cl/Cl$ were filtered in the field either with a GF/F glass fiber filter (2011 DOC sample), 0.45-micron Supor syringe filter (2012 DOC sample), or a 0.45-micron capsule filter (all other samples). Cation and trace element samples were acidified in the field with 7.5 normal nitric acid. DOC samples were acidified in the field with 37 percent hydrochloric acid. BTEX samples were acidified with 1:1 hydrochloric acid. Strontium isotope samples were filtered and acidified in the laboratory. Bottles used for samples of hydrocarbon molecular compositions, dissolved carbon dioxide and nitrogen (N_2) gases, hVOCs, δ^2H-CH_4, $\delta^{13}C$-CH_4, $\delta^{13}C$-DIC, and carbon-14 were filled to overflowing and then capped under water to minimize air bubbles and atmospheric contamination. Noble-gas samples were collected in copper tubes either at the land surface for the four pumped wells (Plummer and others, 2012) or down hole for the other wells using a sampling device developed by the USGS in cooperation with Auslog Ltd. (Australia) (Auslog Ltd. no longer in business). The Auslog sampling device allowed noble-gas sample tubes to be sealed down hole at the sample collection depth thus maintaining in situ hydrostatic pressure and minimizing sample degassing.

Rock samples were collected from three bore holes in the study area for analysis of their uranium and thorium contents. Two samples from the Uinta-Parachute Creek Member transition zone were collected from well 13U at the time it was drilled in 2010. Core from the other two holes was obtained from the USGS Core Research Center (*http://geology.cr.usgs.gov/crc/index.html*) located at the Denver Federal Center in Lakewood, Colo. Samples from the B-Groove, Mahogany zone, and A-Groove were collected from the Superior Oil Company Core Hole 29, located near well site 1, and from the Sinclair Oil and Gas Company core hole Bradshaw 1, located near well site 13 (fig. 1).

Sample Analysis

Selected field properties.—Dissolved oxygen was measured in the field using the Winkler titration method or the Indigo Carmine method (Hach Chemical Company, 2012a,b). Alkalinity was measured in the field by incremental titration using 1.6 or 8 normal sulfuric acid. Sulfide was measured in the field using the methylene blue method (Hach Chemical Company, 2012c).

Inorganic ions.—Major ions, trace elements, and nutrients were measured by standard methods of the USGS National Water Quality Laboratory in Lakewood, Colo. (Fishman, 1993; Fishman and Friedman, 1989; Patton and Kryskalla, 2011; Garbarino and others, 2006).

Organic constituents.—BTEX compounds were measured at the USGS National Water Quality Laboratory in Lakewood, Colo. (Connor and others, 1998). DOC samples collected in 2011 were measured at the USGS National Water Quality Laboratory in Lakewood, Colo. (Brenton and Arnett, 1993) and those collected in 2012 were measured at the USGS laboratory in Reston, Va. (Cozzarelli and others, 2011). hVOCs were measured by capillary column gas chromatography with electron-capture detection (GC-ECD) at the USGS Chlorofluorocarbon Laboratory in Reston, Va. (U.S. Geological Survey, 2012c).

Isotopes.—$\delta^{2}H-H_2O$ and $\delta^{18}O-H_2O$ were measured at the USGS Stable Isotope Laboratory in Reston, Va. (U.S. Geological Survey, 2012b) and reported relative to Vienna Standard Mean Ocean Water (VSMOW). $\delta^{18}O-SO_4$ and $\delta^{34}S-SO_4$ were measured at the USGS Stable Isotope Laboratory in Reston, Va. (U.S. Geological Survey, 2012b) and reported relative to VSMOW and Vienna Cañon Diablo Troilite (VCDT), respectively. δ^{13}C-DIC and carbon-14 were measured at the Woods Hole Oceanographic Institute Accelerator Mass Spectroscopy Laboratory in Woods Hole, Mass. (Woods Hole Oceanographic Institute, 2013). δ^{13}C-DIC is reported relative to Vienna Peedee belemnite (VPDB), and carbon-14 is reported in percent modern carbon (pmc) (not normalized for ^{13}C fractionation) (Mook and van der Plicht, 1999; Plummer and others, 2004). The reported instrument background level for carbon-14 was 0.36 pmc. $\delta^{2}H-CH_4$ and $\delta^{13}C-CH_4$ were measured at Isotech Laboratoies, Champaign, Ill., and reported relative to VSMOW and VPDB, respectively (Isotech Laboratories, 2013). Tritium was measured either at the USGS Noble Gas Laboratory in Denver, Colo. (Bayer and others, 1989), or the USGS Tritium Laboratory in Menlo Park, Calif. (Thatcher and others, 1977). ^{36}Cl/Cl was measured at the PRIME Laboratory at Purdue University in West Lafayette, Ind. (Purdue University PRIME Laboratory, 2013). ^{87}Sr/^{86}Sr was measured at the USGS Solid-Source Mass Spectrometry Laboratory in Menlo Park, Calif. (Bullen and others, 1996). With the exception of carbon-14, tritium, ^{36}Cl/Cl, and ^{87}Sr/^{86}Sr, isotope results are reported using the standard delta (δ) notation, in per mil (‰, parts per thousand). For example, the oxygen isotopic composition of a water sample ($\delta^{18}O-H_2O$) is defined as:

$$\delta^{18}O\text{-}H_2O = ((^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{ref} - 1)\times1{,}000 \qquad (1)$$

where

$^{18}O/^{16}O$ is the ratio of oxygen-18 to oxygen-16 in the sample and a reference (ref) material (VSMOW in this example).

Dissolved gases.—Concentrations of major gases (N_2, carbon dioxide, argon, methane), in milligrams per liter (mg/L), were measured at the USGS Chlorofluorocarbon Laboratory in Reston, Va. using gas chromatography (U.S. Geological Survey, 2012c). Concentrations of hydrocarbon gases (methane through hexane), in mole percent, were measured at the Isotech Laboratory, Champaign, Ill. (Isotech Laboratories, 2013). Concentrations of noble gases (helium, neon, argon, krypton, xenon), in cubic centimeters at standard temperature and pressure per gram of water (cm^3STP/g), and helium-3/helium-4 ratios relative to the helium-3/helium-4 ratio in air (R/R_a), were measured at the USGS Noble Gas Laboratory in Denver, Colo. (Bayer and others, 1989; Beyerle and others, 2000; and Hunt and others, 2010). Concentrations of methane, in milligrams per liter, also were measured at the Noble Gas Laboratory using mass spectrometry (Hunt and others, 2010).

Uranium and thorium in rock samples.—Rock samples were crushed and pulverized prior to digestion on a 140°C hotplate in sealed Teflon containers using sequential treatments with nitric and hydrofluoric acids (48 hour digestion), hydrochloric and nitric acids (1 hour digestion), and hydrochloric acid (12 hour digestion). Uranium and thorium concentrations in the acid leachate were measured at the USGS Inductively Couple Plasma-Mass Spectrometry Facility in Lakewood, Colo. (U.S. Geological Survey, 2013).

Quality Control

Five types of quality control (QC) samples were collected by field personnel: source solution blanks, equipment blanks, field blanks, field replicates, and spikes. The purpose of blank samples is to test for sample contamination during various stages of sample collection, processing, shipping, and analysis. Blank samples are collected by processing laboratory-certified blank water through the sampling equipment using the same techniques as used to collect environmental samples in the field. Inorganic and organic blank waters were obtained from the USGS National Water Quality Laboratory. Source solution blanks were collected at the office and in the field to verify the blank water was contaminant free. Equipment blanks were collected at the office prior to equipment being taken to the field to verify that the sampling equipment was clean. Field blanks were collected in the field to verify that procedures for cleaning sampling equipment between wells were adequate. The purpose of replicate samples is to quantify variability associated with the sampling and analysis methods. Field replicate samples were collected immediately following the collection of the environmental samples. Relative percent difference between the environment and replicate samples was calculated using equation 2:

$$\text{Relative percent difference} = |C_{env} - C_{rep}| \times 100/((C_{env} + C_{rep})/2) \quad (2)$$

where

$|C_{env} - C_{rep}|$ is the absolute value of the difference between concentrations of analytes in the environmental and replicate samples, and

$(C_{env} + C_{rep})/2$ is the average concentration of the analyte in the environmental and replicate samples.

The purpose of spike samples is to quantify the recovery efficiency of the analytical method for selected analytes of interest, BTEX in this case. The spike sample was prepared by collecting a replicate environmental sample and, in the laboratory, adding a known mass of each target analyte to the sample. Percent recovery was calculated using equation 3:

$$\text{Percent recovery} = (C_{ms} - C_{env}) \times 100/C_{spike} \quad (3)$$

where

C_{ms} is the measured analyte concentration in the spiked environmental sample,

C_{env} is the measured analyte concentration in the environmental sample, and

C_{spike} is the expected analyte concentration in the spiked sample.

QC results are listed in Appendix tables 2–1 through 2–3.

Major-ion balances, in percent difference, were calculated for each sample using equation 4 (as implemented in NETPATH using all available cation and anion data (Plummer and others, 1994):

$$\text{Major-ion balance} = (\Sigma\text{cations} - \Sigma\text{anions}) \times 100/(\Sigma\text{cations} + \Sigma\text{anions}) \quad (4)$$

where

Σcations is the sum of the concentrations of dissolved cations (in milliequivalents per liter) and

Σanions is the sum of the concentrations of dissolved anions (in milliequivalents per liter).

Thirty-nine of the 43 environmental samples had major-ion balances less than an absolute value of 5 percent (table 2). Of the four samples with major-ion balances greater than an absolute value of 5 percent, two of them were from one well (13B) that contained exceptionally high concentrations of sulfide (about 50 mg/L). Oxidation of sulfide to sulfate in the sample bottle could have affected the major-ion balances (which had an excess of anions).

Groundwater Levels

Depth to water in the wells ranged from about 30 feet below land surface at well site 15B to about 590 feet at site 2A (table 2). Overall, the median depth to water was 201 feet below land surface. Pressure tranducers installed in the wells at sites 6 and 13 provided information on temporal variability in water levels and vertical hydraulic gradients at those sites. Water levels in wells 6A, 6B, and 13B generally declined during the first 12 to 15 months of measurement (fig. 4). The maximum water-level decline at site 6 was about 4 feet and it was about 5 feet at site 13. Water levels in wells completed above the Mahogany zone (6A, 13U, 13A) generally exhibited more temporal variability, and thus the wells appeared to be hydraulically better connected to the near-surface hydrologic system (precipitation/recharge), than wells completed below the Mahogany zone (6B, 13B). The hydraulic gradient at site 6 was consistently downward from the Uinta-Parachute Creek Member transition zone to the Parachute Creek Member below the Mahogany zone. At site 13, the gradient relative to the Parachute Creek Member above the Mahogany zone (well 13A) was upward into the Uinta-Parachute Creek Member transition zone (13U) and downward into the Parachute Creek Member below the Mahogany zone (13B).

The downward hydraulic gradient across the Mahohany zone at site 13 (0.0997 on August 14, 2012) was about 60 times larger than the downward gradient at site 6 (0.0016 on August 17, 2012). Such variability in the gradient across the Mahogany zone, although based on limited data, implies that the confining properties of the Mahogany zone are not uniform across the study area. A large gradient across the Mahogany zone also was observed at site 15 (–0.0352 on August 20, 2012), although the gradient was upward.

Table 2. Field properties, major-ion, nutrient, and trace-element data for water collected from the monitoring wells.

[U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; ft, feet; °C, degrees Celsius; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; NTU, nephelometric turbidity units; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; µg/L, micrograms per liter; ng/L, nanograms per liter; <, less than; >, greater than; --, no data]

Well name	Geologic interval in which sample interval is located	Collection date	Collection time	Depth to water (feet below land surface)	Field measurements		
					Specific conductance (µS/cm at 25 °C)	pH	Water temperature (°C)
B12B	PCMB	8/22/2011	1200	328.00	1,325	7.41	14.3
B12B	PCMB	8/15/2012	1100	319.54	1,212	7.50	14.5
1A	U-PCM	8/18/2011	1500	199.15	1,175	7.83	20.0
1A	U-PCM	8/16/2012	1100	199.39	1,165	7.80	13.2
1B	PCMB	8/18/2011	1200	202.70	52,000	7.77	18.0
1B	PCMB	8/16/2012	1400	203.52	51,900	7.59	15.5
2A	U-PCM	8/23/2011	1130	580.00	1,700	7.45	18.0
2A	U-PCM	8/21/2012	1100	593.10	1,708	7.52	15.5
6A	U-PCM	8/25/2010	1000	278.41	1,532	8.30	12.0
6A	U-PCM	11/3/2010	1100	278.50	1,462	8.43	11.1
6A	U-PCM	6/2/2011	1000	280.49	1,524	8.37	13.8
6A	U-PCM	8/16/2011	1000	280.91	1,530	8.41	14.2
6A	U-PCM	8/17/2012	1400	281.38	1,528	8.47	14.8
6B	PCMB	8/25/2010	1300	280.69	1,340	8.28	14.2
6B	PCMB	11/3/2010	1500	280.55	1,305	8.38	13.1
6B	PCMB	6/2/2011	1500	281.67	1,360	8.51	16.1
6B	PCMB	8/16/2011	1600	280.91	1,360	8.35	15.1
6B	PCMB	8/17/2012	1100	282.79	1,361	8.46	14.6
9B	MZ	8/20/2011	1100	458.44	1,550	7.99	17.2
9B	MZ	8/18/2012	1100	458.54	1,576	7.91	14.8
13A	PCMA	8/24/2010	1400	57.68	1,430	7.66	16.9
13A	PCMA	11/2/2010	1310	58.60	1,355	7.82	16.0
13A	PCMA	6/1/2011	1130	57.80	[1]1,387	[1]7.68	[1]15.4
13A	PCMA	8/17/2011	1200	57.92	1,416	7.78	17.1
13A	PCMA	8/14/2012	1100	57.92	1,393	7.72	16.6
13B	PCMB	8/24/2010	1600	77.38	1,370	7.70	17.8
13B	PCMB	11/2/2010	1410	76.12	1,280	7.82	17.1
13B	PCMB	6/1/2011	1500	78.45	1,335	7.74	18.0
13B	PCMB	8/17/2011	1400	80.31	1,350	7.80	18.5
13B	PCMB	8/14/2012	1200	80.31	1,341	7.70	18.5
13U	U-PCM	8/24/2010	1200	61.12	1,675	7.35	14.6
13U	U-PCM	11/2/2010	1210	60.50	1,655	7.43	11.2
13U	U-PCM	6/1/2011	1300	59.33	1,730	7.34	14.4
13U	U-PCM	8/17/2011	1100	59.54	1,820	7.30	14.3
13U	U-PCM	8/14/2012	1300	60.78	1,774	7.27	14.0
15A	PCMA	8/19/2011	1300	44.70	2,230	7.75	17.5
15A	PCMA	8/20/2012	1400	46.35	2,197	7.76	14.1
15B	MZ	8/19/2011	1000	29.52	2,330	8.09	17.0
15B	MZ	8/20/2012	1000	29.56	2,310	8.03	12.2
17B	PCMB	8/21/2011	1030	65.32	6,420	7.50	18.5
17B	PCMB	8/19/2012	1000	66.61	6,352	7.38	17.5
18A	U-PCM	8/21/2011	1600	415.38	1,605	7.52	18.0
18A	U-PCM	8/18/2012	1600	413.62	1,587	7.55	15.8

Table 2. Field properties, major-ion, nutrient, and trace-element data for water collected from the monitoring wells.—Continued

[U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; ft, feet; °C, degrees Celsius; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; NTU, nephelometric turbidity units; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; µg/L, micrograms per liter; ng/L, nanograms per liter; <, less than; >, greater than; --, no data]

Well name	Collection date	Field measurements				Residue on evaporation at 180 °C (dissolved solids) (mg/L)	Calcium, filtered (mg/L)	Magnesium, filtered (mg/L)
		Turbidity (NTU)	Dissolved oxygen (mg/L)	Sulfide (mg/L)	Alkalinity (mg/L as $CaCO_3$)			
B12B	8/22/2011	1.2	5.3	<0.1	322	833	82.2	52.9
B12B	8/15/2012	0.7	5.1	<0.1	375	817	84.0	48.9
1A	8/18/2011	3.7	<0.5	<0.1	498	738	16.1	40.7
1A	8/16/2012	1.3	<0.5	<0.1	497	742	16.6	40.0
1B	8/18/2011	33	<0.5	<0.1	37,510	47,600	4.89	2.09
1B	8/16/2012	65	<0.5	<0.1	37,400	46,900	3.21	2.02
2A	8/23/2011	3.2	0.7	<0.1	508	1,140	60.3	97.7
2A	8/21/2012	15	<0.5	0.1	702	1,140	61.9	101
6A	8/25/2010	2.8	1.0	--	281	1,020	8.76	13.3
6A	11/3/2010	1.4	1.2	--	269	1,000	9.14	13.4
6A	6/2/2011	0.6	1.2	--	294	1,010	8.84	14.2
6A	8/16/2011	0.9	0.9	--	283	1,010	8.50	13.1
6A	8/17/2012	3.2	0.9	<0.1	296	1,000	8.77	13.4
6B	8/25/2010	7.1	<0.5	>2.0	645	854	3.25	2.34
6B	11/3/2010	>50	<0.5	>3.2	660	844	3.32	2.22
6B	6/2/2011	4.0	<0.5	>4.8	543	835	3.83	2.92
6B	8/16/2011	7.6	<0.5	8.6	644	859	3.40	2.48
6B	8/17/2012	10	<0.5	3.3	425	882	4.20	3.33
9B	8/20/2011	4.1	<0.5	0.2	810	913	7.08	3.69
9B	8/18/2012	4.3	<0.5	0.3	860	984	7.77	4.00
13A	8/24/2010	4.2	<0.5	0.6	478	941	25.9	54.0
13A	11/2/2010	1.7	<0.5	0.6	422	932	25.7	53.1
13A	6/1/2011	[1]30	[1]<0.5	[1]0.8	[1]446	[1]960	[1]32.9	[1]58.1
13A	8/17/2011	1.1	<0.5	0.4	431	924	24.5	54.6
13A	8/14/2012	2.0	<0.5	0.6	459	938	25.8	54.8
13B	8/24/2010	--	<0.5	--	745	855	14.6	15.7
13B	11/2/2010	>50	<0.5	--	698	869	15.2	17.0
13B	6/1/2011	80	<0.5	--	769	873	17.2	19.5
13B	8/17/2011	36	<0.5	47	731	876	15.2	18.2
13B	8/14/2012	70	<0.5	52	748	856	18.0	18.9
13U	8/24/2010	0.3	<0.5	1.8	490	1,150	60.1	77.6
13U	11/2/2010	0.3	<0.5	2.4	479	1,210	67.6	84.1
13U	6/1/2011	0.4	<0.5	2.7	521	1,240	71.3	94.9
13U	8/17/2011	0.4	<0.5	3.4	514	1,270	68.3	92.8
13U	8/14/2012	0.3	<0.5	4.1	513	1,250	71.7	92.6
15A	8/19/2011	4.5	<0.5	8.0	804	1,390	6.59	4.85
15A	8/20/2012	8.0	<0.5	11	1,051	1,380	7.41	4.84
15B	8/19/2011	26	<0.5	<0.1	852	1,460	3.93	4.20
15B	8/20/2012	18	<0.5	<0.1	1,123	1,470	4.03	4.28
17B	8/21/2011	2.5	<0.5	<0.1	3,346	4,340	6.22	5.84
17B	8/19/2012	6.4	<0.5	<0.1	3,437	4,300	6.48	6.17
18A	8/21/2011	1.2	<0.5	17	488	1,100	37.7	89.1
18A	8/18/2012	5.7	<0.5	22	518	1,090	39.4	91.5

Table 2. Field properties, major-ion, nutrient, and trace-element data for water collected from the monitoring wells.—Continued

[U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; ft, feet; °C, degrees Celsius; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; NTU, nephelometric turbidity units; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; µg/L, micrograms per liter; ng/L, nanograms per liter; <, less than; >, greater than; --, no data]

Well name	Collection date	Sodium, filtered (mg/L)	Potassium, filtered (mg/L)	Chloride, filtered (mg/L)	Bromide, filtered (mg/L)	Sulfate, filtered (mg/L)	Fluoride, filtered (mg/L)	Silica, filtered (mg/L)
B12B	8/22/2011	131	0.544	12.0	0.0698	325	0.597	24.8
B12B	8/15/2012	140	0.492	11.1	0.0690	289	0.496	23.6
1A	8/18/2011	200	0.480	11.1	0.0881	138	0.551	22.3
1A	8/16/2012	207	0.428	11.2	0.0856	142	0.445	20.5
1B	8/18/2011	18,600	49.7	4,610	--	<9.00	66.4	23.7
1B	8/16/2012	18,900	41.6	4,070	<0.5	<9.00	70.3	16.1
2A	8/23/2011	199	0.523	6.48	0.0360	299	0.168	28.9
2A	8/21/2012	217	0.473	10.7	<0.01	308	0.096	29.1
6A	8/25/2010	307	0.479	11.6	0.0890	458	0.236	11.6
6A	11/3/2010	301	0.514	11.7	0.0897	450	0.259	12.2
6A	6/2/2011	322	0.535	12.0	0.0814	452	0.206	12.9
6A	8/16/2011	313	0.554	11.5	0.0976	453	0.226	11.9
6A	8/17/2012	311	0.492	11.4	0.0997	453	0.173	11.2
6B	8/25/2010	301	0.617	11.3	0.0830	32.0	18.2	12.7
6B	11/3/2010	309	0.695	11.8	0.0806	12.8	18.7	13.3
6B	6/2/2011	330	0.588	12.2	0.0978	135	13.6	12.8
6B	8/16/2011	331	0.691	11.7	0.0890	61.6	18.8	12.1
6B	8/17/2012	312	0.466	11.9	0.0946	264	6.90	10.6
9B	8/20/2011	365	0.823	14.0	<0.01	0.199	16.5	11.3
9B	8/18/2012	378	0.747	14.7	0.0581	0.644	17.4	11.4
13A	8/24/2010	216	0.272	6.45	0.0610	316	2.36	23.1
13A	11/2/2010	213	0.264	6.67	0.0613	312	2.41	24.0
13A	6/1/2011	[1]222	[1]0.261	[1]6.72	[1]0.0591	[1]329	[1]1.76	[1]27.4
13A	8/17/2011	218	0.346	6.44	0.0670	322	2.45	23.7
13A	8/14/2012	233	0.294	6.49	0.0620	314	2.32	22.6
13B	8/24/2010	284	0.670	10.0	0.0700	2.31	4.72	14.4
13B	11/2/2010	280	0.571	9.84	0.0695	46.4	4.22	15.0
13B	6/1/2011	307	0.504	9.91	0.0817	94.6	4.43	16.4
13B	8/17/2011	293	0.555	9.45	0.0694	38.5	4.56	14.7
13B	8/14/2012	296	0.523	9.08	0.0817	88.0	4.27	14.5
13U	8/24/2010	194	0.479	9.07	0.063	428	0.330	35.7
13U	11/2/2010	202	0.488	7.69	0.0651	465	0.352	38.6
13U	6/1/2011	226	0.494	7.91	0.0708	506	0.360	37.7
13U	8/17/2011	221	0.505	7.95	0.0651	515	0.381	36.7
13U	8/14/2012	220	0.483	7.97	0.0696	475	0.257	36.6
15A	8/19/2011	509	1.76	116	0.317	29.4	19.1	10.5
15A	8/20/2012	530	1.55	114	0.349	27.8	12.8	10.1
15B	8/19/2011	553	1.28	105	0.129	<0.45	23.6	10.5
15B	8/20/2012	569	1.30	105	<0.02	1.65	22.3	10.3
17B	8/21/2011	1,620	5.56	329	0.453	<0.9	33.0	14.4
17B	8/19/2012	1,750	5.72	327	<0.05	<0.9	26.3	13.7
18A	8/21/2011	207	0.369	6.45	0.0516	434	1.93	28.4
18A	8/18/2012	213	0.313	5.98	0.0556	426	1.90	28.8

Table 2. Field properties, major-ion, nutrient, and trace-element data for water collected from the monitoring wells.—Continued

[U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; ft, feet; °C, degrees Celsius; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; NTU, nephelometric turbidity units; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; µg/L, micrograms per liter; ng/L, nanograms per liter; <, less than; >, greater than; --, no data]

Well name	Collection date	Nitrogen, total, filtered (mg/L)	Ammonia, filtered (mg N/L)	Nitrite, filtered (mg N/L)	Nitrite + nitrate, filtered (mg N/L)	Ortho-phosphate, filtered (mg P/L)	Organic carbon, filtered (mg/L)
B12B	8/22/2011	0.173	0.0255	0.00507	0.045	0.0187	4.4
B12B	8/15/2012	--	--	--	--	--	3.0
1A	8/18/2011	0.250	0.213	<0.001	<0.02	0.0135	1.6
1A	8/16/2012	--	--	--	--	--	4.2
1B	8/18/2011	--	--	--	--	--	--
1B	8/16/2012	30.1	28.1	<0.002	<0.08	4.65	17
2A	8/23/2011	0.300	0.256	<0.001	<0.02	0.0201	2.2
2A	8/21/2012	--	--	--	--	--	6.6
6A	8/25/2010	--	--	--	--	--	--
6A	11/3/2010	--	--	--	--	--	--
6A	6/2/2011	--	--	--	--	--	--
6A	8/16/2011	0.214	0.127	<0.001	0.089	0.0147	1.3
6A	8/17/2012	--	--	--	--	--	2.7
6B	8/25/2010	--	--	--	--	--	--
6B	11/3/2010	--	--	--	--	--	--
6B	6/2/2011	--	--	--	--	--	--
6B	8/16/2011	0.825	0.689	<0.001	<0.02	0.0169	2.3
6B	8/17/2012	--	--	--	--	--	3.5
9B	8/20/2011	0.941	0.786	<0.001	<0.02	0.0174	1.9
9B	8/18/2012	--	--	--	--	--	1.6
13A	8/24/2010	--	--	--	--	--	--
13A	11/2/2010	--	--	--	--	--	--
13A	6/1/2011	--	--	--	--	--	--
13A	8/17/2011	0.272	0.297	<0.001	<0.02	0.0292	1.8
13A	8/14/2012	--	--	--	--	--	1.9
13B	8/24/2010	--	--	--	--	--	--
13B	11/2/2010	--	--	--	--	--	--
13B	6/1/2011	--	--	--	--	--	--
13B	8/17/2011	0.670	0.480	0.00123	<0.02	0.0120	1.6
13B	8/14/2012	--	--	--	--	--	2.5
13U	8/24/2010	--	--	--	--	--	--
13U	11/2/2010	--	--	--	--	--	--
13U	6/1/2011	--	--	--	--	--	--
13U	8/17/2011	0.260	0.246	<0.001	<0.02	0.0377	1.4
13U	8/14/2012	--	--	--	--	--	3.0
15A	8/19/2011	2.54	2.16	<0.001	<0.02	0.0400	2.9
15A	8/20/2012	--	--	--	--	--	2.0
15B	8/19/2011	1.47	1.22	<0.001	<0.02	0.0211	4.6
15B	8/20/2012	--	--	--	--	--	1.7
17B	8/21/2011	7.24	6.65	0.0347	<0.02	0.0592	5.6
17B	8/19/2012	--	--	--	--	--	4.7
18A	8/21/2011	0.318	0.211	<0.003	<0.02	<0.02	1.9
18A	8/18/2012	--	--	--	--	--	3.9

Table 2. Field properties, major-ion, nutrient, and trace-element data for water collected from the monitoring wells.—Continued

[U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; ft, feet; °C, degrees Celsius; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; NTU, nephelometric turbidity units; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; µg/L, micrograms per liter; ng/L, nanograms per liter; <, less than; >, greater than; --, no data]

Well name	Collection date	Aluminum, filtered (µg/L)	Antimony, filtered (µg/L)	Arsenic, filtered (µg/L)	Barium, filtered (µg/L)	Beryllium, filtered (µg/L)	Boron, filtered (µg/L)	Cadmium, filtered (µg/L)
B12B	8/22/2011	<1.7	0.48	6.3	46.8	0.0073	86.1	0.056
B12B	8/15/2012	--	--	--	--	--	--	--
1A	8/18/2011	2.29	<0.027	1.1	38.2	0.0154	86.8	0.025
1A	8/16/2012	--	--	--	--	--	--	--
1B	8/18/2011	<42	<0.675	3.3	3,960	1.48	7,620	1.19
1B	8/16/2012	--	--	--	--	--	--	--
2A	8/23/2011	--	--	--	--	--	--	--
2A	8/21/2012	--	--	--	--	--	--	--
6A	8/25/2010	--	--	--	--	--	--	--
6A	11/3/2010	--	--	--	--	--	--	--
6A	6/2/2011	--	--	--	--	--	--	--
6A	8/16/2011	<1.7	<0.027	0.065	10.5	<0.006	65.9	0.025
6A	8/17/2012	--	--	--	--	--	--	--
6B	8/25/2010	--	--	--	--	--	--	--
6B	11/3/2010	--	--	--	--	--	--	--
6B	6/2/2011	--	--	--	--	--	--	--
6B	8/16/2011	2.66	<0.027	0.64	281	0.0324	356	<0.016
6B	8/17/2012	--	--	--	--	--	--	--
9B	8/20/2011	1.82	<0.027	0.16	315	0.0741	1,710	<0.016
9B	8/18/2012	--	--	--	--	--	--	--
13A	8/24/2010	--	--	--	--	--	--	--
13A	11/2/2010	--	--	--	--	--	--	--
13A	6/1/2011	--	--	--	--	--	--	--
13A	8/17/2011	<1.7	<0.027	<0.022	15.5	0.0083	150	<0.016
13A	8/14/2012	--	--	--	--	--	--	--
13B	8/24/2010	--	--	--	--	--	--	--
13B	11/2/2010	--	--	--	--	--	--	--
13B	6/1/2011	--	--	--	--	--	--	--
13B	8/17/2011	1.99	<0.027	0.037	3,280	0.0398	246	<0.016
13B	8/14/2012	--	--	--	--	--	--	--
13U	8/24/2010	--	--	--	--	--	--	--
13U	11/2/2010	--	--	--	--	--	--	--
13U	6/1/2011	--	--	--	--	--	--	--
13U	8/17/2011	1.93	<0.027	0.049	12.3	0.0096	129	<0.016
13U	8/14/2012	--	--	--	--	--	--	--
15A	8/19/2011	5.73	<0.027	0.16	220	0.133	4,020	0.026
15A	8/20/2012	--	--	--	--	--	--	--
15B	8/19/2011	4.60	0.036	0.18	907	0.167	4,960	0.026
15B	8/20/2012	--	--	--	--	--	--	--
17B	8/21/2011	34.1	<0.081	0.39	2,370	2.06	5,110	0.105
17B	8/19/2012	--	--	--	--	--	--	--
18A	8/21/2011	3.97	<0.027	0.73	17.2	0.0232	125	<0.016
18A	8/18/2012	--	--	--	--	--	--	--

Table 2. Field properties, major-ion, nutrient, and trace-element data for water collected from the monitoring wells.—Continued

[U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; ft, feet; °C, degrees Celsius; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; NTU, nephelometric turbidity units; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; µg/L, micrograms per liter; ng/L, nanograms per liter; <, less than; >, greater than; --, no data]

Well name	Collection date	Chromium, filtered (µg/L)	Cobalt, filtered (µg/L)	Copper, filtered (µg/L)	Iron, filtered (µg/L)	Lead, filtered (µg/L)	Lithium, filtered (µg/L)
B12B	8/22/2011	<0.06	0.108	<0.5	42.6	<0.015	29.4
B12B	8/15/2012	--	--	--	38.9	--	--
1A	8/18/2011	0.153	0.157	<0.5	51.0	0.029	62.4
1A	8/16/2012	--	--	--	35.5	--	--
1B	8/18/2011	5.18	<0.5	<12.5	585	<0.375	2,610
1B	8/16/2012	--	--	--	566	--	--
2A	8/23/2011	--	--	--	168	--	--
2A	8/21/2012	--	--	--	123	--	--
6A	8/25/2010	--	--	--	E3.6	--	--
6A	11/3/2010	--	--	--	7.3	--	--
6A	6/2/2011	--	--	--	5.6	--	--
6A	8/16/2011	<0.06	0.026	<0.5	<3.2	<0.015	70.4
6A	8/17/2012	--	--	--	7.8	--	--
6B	8/25/2010	--	--	--	80.8	--	--
6B	11/3/2010	--	--	--	153	--	--
6B	6/2/2011	--	--	--	37.8	--	--
6B	8/16/2011	0.100	<0.02	<0.5	14.6	<0.015	37.0
6B	8/17/2012	--	--	--	49.4	--	--
9B	8/20/2011	<0.06	<0.02	<0.5	402	<0.015	326
9B	8/18/2012	--	--	--	108	--	--
13A	8/24/2010	--	--	--	12.5	--	--
13A	11/2/2010	--	--	--	8.0	--	--
13A	6/1/2011	--	--	--	[1]387	--	--
13A	8/17/2011	<0.06	<0.02	<0.5	10.3	0.016	61.4
13A	8/14/2012	--	--	--	12.5	--	--
13B	8/24/2010	--	--	--	11.7	--	--
13B	11/2/2010	--	--	--	6.7	--	--
13B	6/1/2011	--	--	--	46.5	--	--
13B	8/17/2011	0.066	<0.02	<0.5	<3.2	<0.015	123
13B	8/14/2012	--	--	--	16.4	--	--
13U	8/24/2010	--	--	--	156	--	--
13U	11/2/2010	--	--	--	113	--	--
13U	6/1/2011	--	--	--	70.8	--	--
13U	8/17/2011	0.086	0.021	<0.5	43.9	<0.015	80.3
13U	8/14/2012	--	--	--	38.2	--	--
15A	8/19/2011	1.16	<0.02	<0.5	17.0	<0.015	673
15A	8/20/2012	--	--	--	12.1	--	--
15B	8/19/2011	0.060	0.040	2.18	169	0.063	803
15B	8/20/2012	--	--	--	189	--	--
17B	8/21/2011	0.300	0.06	<1.5	115	0.095	569
17B	8/19/2012	--	--	--	152	--	--
18A	8/21/2011	0.538	0.021	<0.5	22.3	<0.015	44.2
18A	8/18/2012	--	--	--	58.1	--	--

Table 2. Field properties, major-ion, nutrient, and trace-element data for water collected from the monitoring wells.—Continued

[U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; ft, feet; °C, degrees Celsius; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; NTU, nephelometric turbidity units; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; µg/L, micrograms per liter; ng/L, nanograms per liter; <, less than; >, greater than; --, no data]

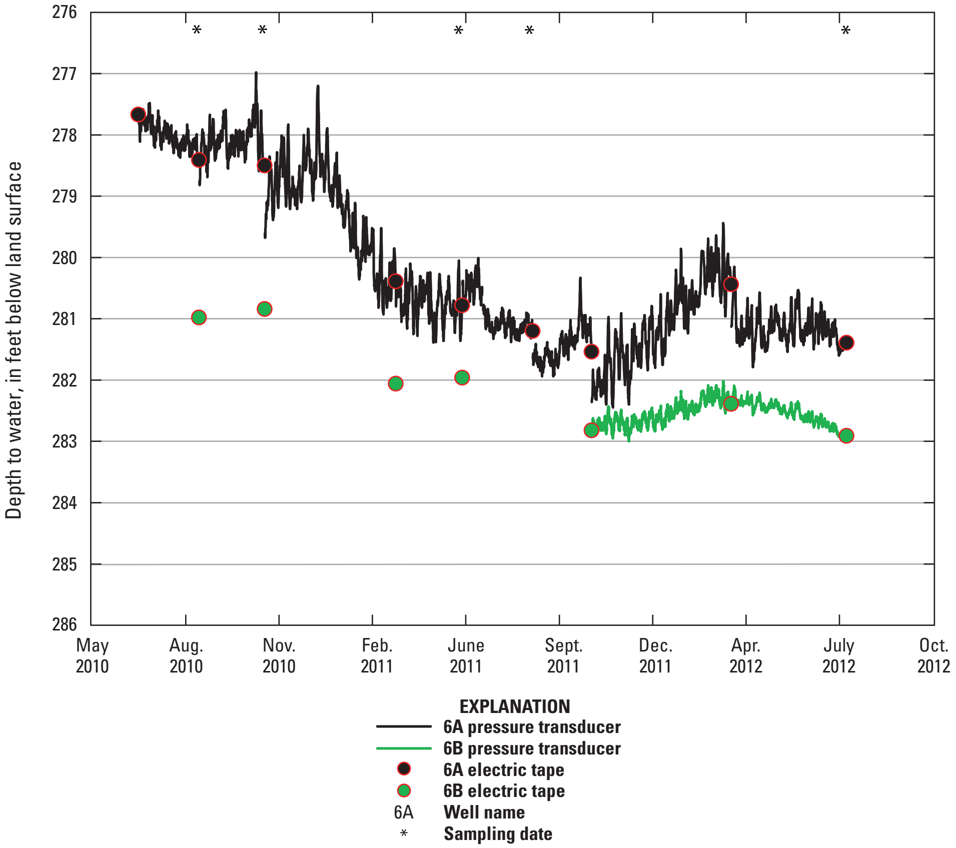
Well name	Collection date	Manganese, filtered (µg/L)	Mercury, unfiltered (ng/L)	Methyl mercury, unfiltered, (ng/L)	Molybdenum, filtered (µg/L)	Nickel, filtered (µg/L)	Selenium, filtered (µg/L)	Silver, filtered (µg/L)
B12B	8/22/2011	11.1	0.09	<0.04	18.0	1.05	0.373	<0.005
B12B	8/15/2012	10.8	--	--	--	--	--	--
1A	8/18/2011	6.98	0.75	0.09	4.65	2.50	<0.03	0.008
1A	8/16/2012	5.29	--	--	--	--	--	--
1B	8/18/2011	<8.00	4.96	--	1.26	5.26	0.815	2.35
1B	8/16/2012	6.08	--	--	--	--	--	--
2A	8/23/2011	5.76	--	--	--	--	--	--
2A	8/21/2012	4.85	--	--	--	--	--	--
6A	8/25/2010	5.32	--	--	--	--	--	--
6A	11/3/2010	5.71	--	--	--	--	--	--
6A	6/2/2011	5.81	--	--	--	--	--	--
6A	8/16/2011	5.53	3.68	0.43	4.06	1.08	<0.03	<0.005
6A	8/17/2012	4.16	--	--	--	--	--	--
6B	8/25/2010	7.94	--	--	--	--	--	--
6B	11/3/2010	8.35	--	--	--	--	--	--
6B	6/2/2011	16.3	--	--	--	--	--	--
6B	8/16/2011	16.0	7.61	0.33	0.783	0.175	<0.03	<0.005
6B	8/17/2012	12.5	--	--	--	--	--	--
9B	8/20/2011	10.1	0.70	0.07	0.804	0.249	<0.03	<0.005
9B	8/18/2012	3.47	--	--	--	--	--	--
13A	8/24/2010	1.67	--	--	--	--	--	--
13A	11/2/2010	1.34	--	--	--	--	--	--
13A	6/1/2011	[1]6.87	--	--	--	--	--	--
13A	8/17/2011	1.46	<0.04	<0.04	0.019	3.13	<0.03	0.010
13A	8/14/2012	1.18	--	--	--	--	--	--
13B	8/24/2010	14.0	--	--	--	--	--	--
13B	11/2/2010	7.47	--	--	--	--	--	--
13B	6/1/2011	5.31	--	--	--	--	--	--
13B	8/17/2011	4.12	0.75	<0.04	<0.014	0.168	0.064	0.008
13B	8/14/2012	6.43	--	--	--	--	--	--
13U	8/24/2010	47.9	--	--	--	--	--	--
13U	11/2/2010	31.3	--	--	--	--	--	--
13U	6/1/2011	22.2	--	--	--	--	--	--
13U	8/17/2011	18.5	0.13	<0.04	0.058	0.132	<0.03	0.015
13U	8/14/2012	11.6	--	--	--	--	--	--
15A	8/19/2011	6.94	3.24	0.17	0.079	0.226	0.036	0.021
15A	8/20/2012	2.99	--	--	--	--	--	--
15B	8/19/2011	1.39	1.32	0.05	0.147	1.30	<0.03	0.015
15B	8/20/2012	1.19	--	--	--	--	--	--
17B	8/21/2011	2.12	0.64	0.26	0.181	2.10	0.120	0.119
17B	8/19/2012	2.04	--	--	--	--	--	--
18A	8/21/2011	5.64	3.17	0.15	0.028	0.523	<0.03	0.009
18A	8/18/2012	3.94	--	--	--	--	--	--

Table 2. Field properties, major-ion, nutrient, and trace-element data for water collected from the monitoring wells.—Continued

[U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; ft, feet; °C, degrees Celsius; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; NTU, nephelometric turbidity units; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; µg/L, micrograms per liter; ng/L, nanograms per liter; <, less than; >, greater than; --, no data]

Well name	Collection date	Strontium, filtered (µg/L)	Thallium, filtered (µg/L)	Uranium, filtered (µg/L)	Vanadium, filtered (µg/L)	Zinc, filtered (µg/L)	Major-ion balance (percent)
B12B	8/22/2011	3,040	<0.01	3.31	1.57	39.1	2.4
B12B	8/15/2012	--	--	--	--	--	1.8
1A	8/18/2011	4,620	<0.01	0.292	<0.08	1.69	–1.2
1A	8/16/2012	--	--	--	--	--	–0.4
1B	8/18/2011	1,060	<0.250	<0.100	2.94	<35.0	–4.9
1B	8/16/2012	--	--	--	--	--	–2.9
2A	8/23/2011	--	--	--	--	--	9.6
2A	8/21/2012	--	--	--	--	--	0.3
6A	8/25/2010	--	--	--	--	--	–2.0
6A	11/3/2010	--	--	--	--	--	–1.5
6A	6/2/2011	--	--	--	--	--	0.0
6A	8/16/2011	1,400	<0.01	0.037	<0.08	4.07	–1.0
6A	8/17/2012	--	--	--	--	--	–2.0
6B	8/25/2010	--	--	--	--	--	–4.9
6B	11/3/2010	--	--	--	--	--	–3.4
6B	6/2/2011	--	--	--	--	--	0.3
6B	8/16/2011	875	<0.01	0.013	<0.08	<1.4	–2.3
6B	8/17/2012	--	--	--	--	--	–2.2
9B	8/20/2011	558	<0.01	0.010	<0.08	1.78	–2.6
9B	8/18/2012	--	--	--	--	--	–3.7
13A	8/24/2010	--	--	--	--	--	–4.4
13A	11/2/2010	--	--	--	--	--	–1.1
13A	6/1/2011	--	--	--	--	--	0.2
13A	8/17/2011	7,600	<0.01	0.010	<0.08	19.6	–1.5
13A	8/14/2012	--	--	--	--	--	–0.3
13B	8/24/2010	--	--	--	--	--	–3.7
13B	11/2/2010	--	--	--	--	--	–3.6
13B	6/1/2011	--	--	--	--	--	–6.1
13B	8/17/2011	4,640	<0.01	0.007	<0.08	1.52	–3.0
13B	8/14/2012	--	--	--	--	--	–6.0
13U	8/24/2010	--	--	--	--	--	–3.4
13U	11/2/2010	--	--	--	--	--	–1.1
13U	6/1/2011	--	--	--	--	--	0.1
13U	8/17/2011	11,300	<0.01	0.020	<0.08	<1.4	–1.5
13U	8/14/2012	--	--	--	--	--	1.1
15A	8/19/2011	1,260	<0.01	0.005	0.105	<1.4	4.5
15A	8/20/2012	--	--	--	--	--	–3.3
15B	8/19/2011	1,300	<0.01	0.014	<0.08	12.5	7.5
15B	8/20/2012	--	--	--	--	--	–2.5
17B	8/21/2011	515	<0.03	0.082	<0.24	5.82	–4.4
17B	8/19/2012	--	--	--	--	--	–1.4
18A	8/21/2011	5,880	<0.01	0.042	0.095	2.24	–2.5
18A	8/18/2012	--	--	--	--	--	–2.1

[1] The packer in well 13A (see Appendix figure 1–1) was not operating properly on this date so the reported concentrations may not be comparable to the concentrations on the other sample dates.



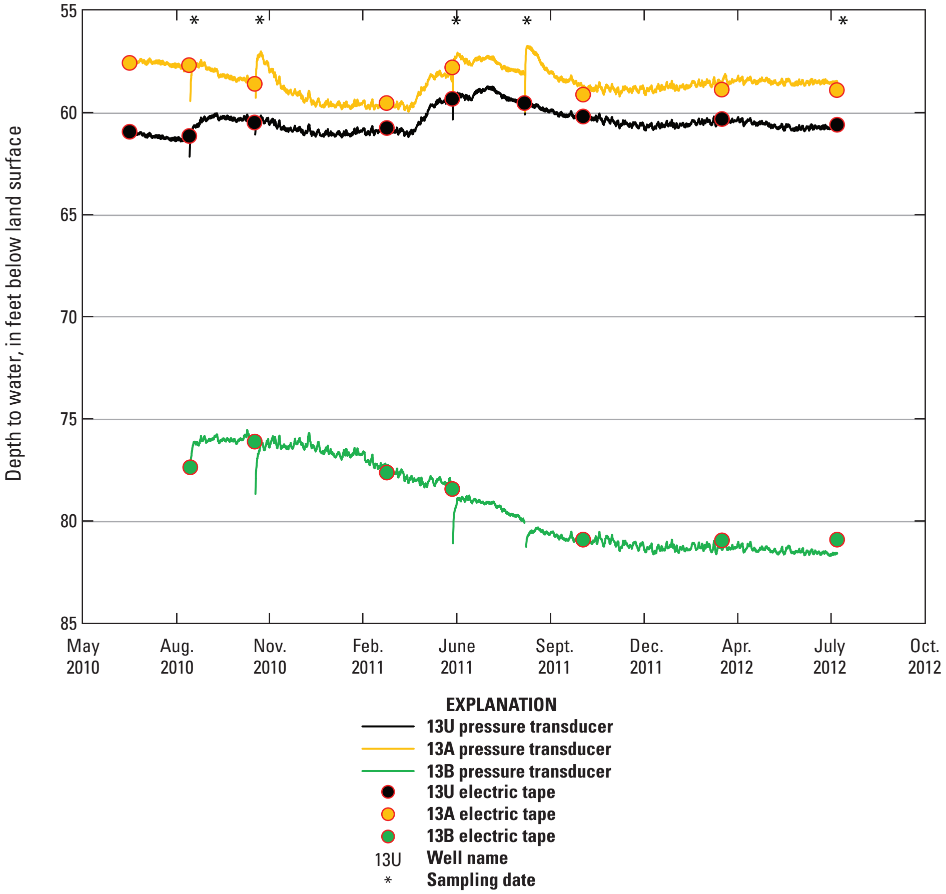


Figure 4. Graphs showing groundwater levels in relation to time in selected wells.

Sources of Groundwater

Isotopic values for water collected from the monitoring wells plot close to the values for snow collected by the USGS from sites on the Grand Mesa and Dunkley Pass, located about 60 miles to the south and northeast of the study area, respectively (Ingersoll and others, 2009) (fig. 5 and table 3). This finding is consistent with results from previous studies in which it was reported that the primary source of groundwater in the bedrock aquifers was precipitation, mostly in the form of snow, that infitrates into bedrock aquifers at higher elevations along the watershed margins (Weeks and others, 1974; Robson and Saulnier, 1981; Day and others, 2010). The small positive $\delta^{18}O$ shift for groundwater compared to snow indicates that the water may have undergone a small amount of evaporation prior to recharging the aquifers or that snow in the study area is slightly different isotopically from the snow samples plotted in figure 5. Samples of produced water from the Mesaverde Group in southwestern Wyoming and Garfield County, Colo., had isotopic values that were much more positive than those from the bedrock aquifers (fig. 5). The Wyoming and Garfield County water samples are from wells located about 110 miles north and 35 miles southeast of the study area, respectively (U.S. Department of Energy, 2012; U.S. Geological Survey, 2012a). If the isotopic composition of those samples is representative of water in the Mesaverde Group and other deep gas-producing zones in the study area, then the data indicate that those zones were not an important source of water near the monitoring wells. Although some major-ion data for produced waters in the study area are available from the Colorado Oil and Gas Conservation Commission (2012), the lack of more complete chemical and isotopic data for produced waters represents an important limitation of this study. Such information for the study area would improve the ability to identify the presence of water from deeper geologic units if it were to occur in the bedrock aquifers.

Redox Processes

Redox processes transfer, or donate, electrons from one chemical species to another species that accepts them. The electron donor is “oxidized” and the electron acceptor is “reduced” by the transfer. Redox processes in groundwater usually are catalyzed by naturally occurring microbes that use the energy produced by the process. In groundwater, organic carbon is the most common electron donor. If dissolved oxygen is present, it is the preferred electron acceptor because reduction of dissolved oxygen produces more energy than reduction of other chemical species that commonly occur in groundwater. The atmosphere is the source of the dissolved oxygen in groundwater, so the redox conditions in an aquifer near where recharge occurs usually are oxic (defined here as having a dissolved oxygen concentration of at least 0.5 mg/L).

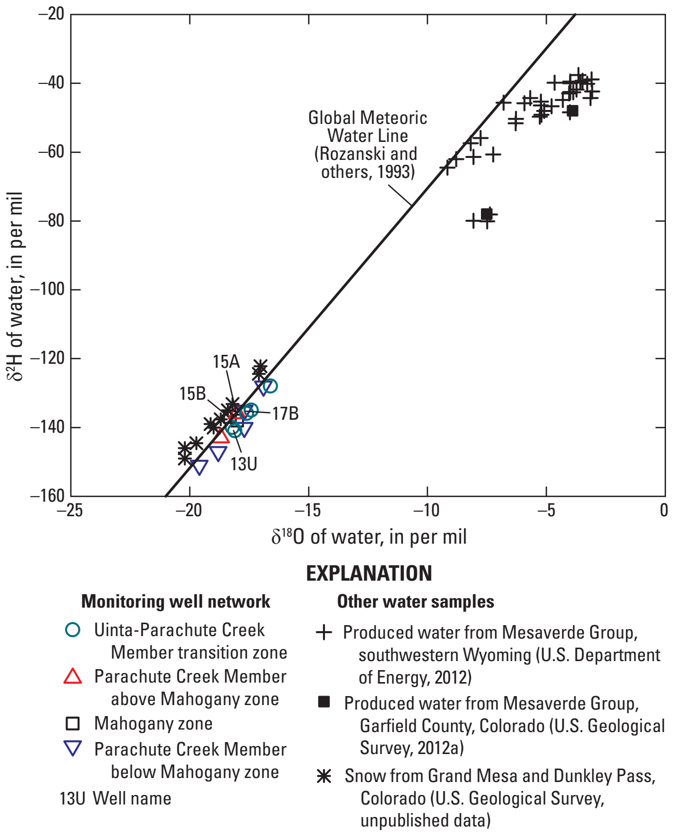


Figure 5. Graph showing stable isotopic composition of water collected from the monitoring wells in 2011 compared to the stable isotopic compositions of snow and water from the Mesaverde Group.

As groundwater moves through the aquifer along a flow path, the dissolved oxygen in the groundwater gradually is consumed by redox processes. Once all of the dissolved oxygen is consumed, other chemical species can accept electrons and become reduced. If nitrate is present, it will become the preferred electron acceptor until it in turn is consumed. This pattern continues, with manganese, iron, sulfate, and finally carbon dioxide acting as electron acceptors until they are consumed, in that order. Microbial reduction of sulfate and carbon dioxide occur under highly anoxic conditions and produce hydrogen sulfide and methane, respectively (Chapelle and others, 1995).

Only two wells, B12B and 6A, produced water that was consistently oxic. The water from B12B was very oxic, containing concentrations of dissolved oxygen greater than 5 mg/L in 2011 and 2012, whereas the water from 6A had concentrations ranging from 0.9 to 1.2 mg/L (table 2). Well 2A produced water with 0.7 mg/L of dissolved oxygen in 2011, but in 2012 the concentration was less than 0.5 mg/L. The remaining wells only produced anoxic water. Well B12B is located near the Cathedral Bluffs along the western margin of the study area at an elevation of 7,458 feet and is considered to be the best example of recently recharged groundwater in the dataset.

Table 3. Isotopic data for water collected from the monitoring wells.

[U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; ‰, per mil; VSMOW, Vienna Standard Mean Ocean Water; TU, tritium units; pmc, percent modern carbon; DIC, dissolved inorganic carbon; 1σ, 1 standard deviation; VPDB, Vienna Peedee Belemnite; VDCT, Vienna Cañon Diablo Troilite; <, less than; --, no data]

Well name	Geologic interval in which sample interval is located	Collection date	δ^{2}H, water (‰, VSMOW)	δ^{18}O, water (‰, VSMOW)	Tritium, water (TU)	Tritium, water, 1σ error (TU)	Carbon-14, DIC (pmc)	Carbon-14, DIC, 1σ error (pmc)	δ^{13}C-DIC (‰, VPDB)	δ^{2}H, methane (‰, VSMOW)	δ^{13}C, methane (‰, VPDB)	δ^{13}C, ethane (‰, VPDB)	δ^{34}S, sulfate (‰, VCDT)	δ18O, sulfate (‰, VSMOW)	^{87}Sr/^{86}Sr	^{36}Cl/Cl (10^{-15})	^{36}Cl/Cl, 1σ error (10^{-15})
B12B	PCMB	8/22/2011	–128	–16.93	0.9	0.09	20.76	0.12	–9.73	--	--	--	+16.23	–4.70	0.70931	--	--
1A	U-PCM	8/18/2011	–135	–17.41	<0.04	--	5.08	0.07	–9.39	--	--	--	+16.36	+0.31	0.70846	--	--
1B	PCMB	8/18/2011	–140	–17.66	0.06	0.09	--	--	--	–292	–64.22	--	--	--	0.71238	--	--
2A	U-PCM	8/23/2011	–136	–17.63	<0.04	--	2.48	0.04	–11.15	–187	–42.11	--	+17.64	–1.59	0.70863	--	--
6A	U-PCM	8/25/2010	--	--	<0.04	--	--	--	--	--	--	--	--	--	--	--	--
6A	U-PCM	8/16/2011	–141	–18.05	<0.04	--	1.89	0.04	–6.17	--	--	--	+10.25	–6.99	0.70870	--	--
6B	PCMB	8/25/2010	--	--	<0.04	--	--	--	--	--	--	--	--	--	--	--	--
6B	PCMB	8/16/2011	–147	–18.78	<0.04	--	1.59	0.03	–3.70	–293	–73.84	--	+18.29	–2.26	0.71113	--	--
6B	PCMB	8/17/2012	--	--	--	--	--	--	--	--	--	--	--	--	--	1,086	28
9B	MZ	8/20/2011	–138	–17.97	<0.04	--	0.44	0.02	+7.95	–294	–63.50	--	--	--	0.71143	--	--
9B	MZ	8/18/2012	--	--	--	--	--	--	--	--	--	--	--	--	--	156	7
13A	PCMA	8/24/2010	--	--	<0.04	--	--	--	--	--	--	--	--	--	--	--	--
13A	PCMA	8/17/2011	–143	–18.68	0.4	0.14	0.51	0.03	–5.13	–186	–51.21	--	+13.85	+0.27	0.70866	--	--
13A	PCMA	8/14/2012	--	--	<0.05	--	--	--	--	--	--	--	--	--	--	882	17
13B	PCMB	8/24/2010	--	--	<0.04	--	--	--	--	--	--	--	--	--	--	--	--
13B	PCMB	8/17/2011	–150	–19.51	--	--	<0.4	--	–9.31	–275	–62.51	--	--	--	0.70995	--	--
13B	PCMB	8/14/2012	--	--	--	--	--	--	--	–269	–62.33	--	--	--	--	874	27
13U	U-PCM	8/24/2010	--	--	<0.04	--	--	--	--	--	--	--	--	--	--	--	--
13U	U-PCM	8/17/2011	–140	–18.15	<0.04	--	<0.4	--	–9.36	–165	–35.29	--	+14.68	+0.52	0.70808	--	--
13U	U-PCM	8/14/2012	--	--	--	--	--	--	--	–161	–35.04	–24.8	--	--	--	868	40
15A	PCMA	8/19/2011	–136	–18.01	<0.04	--	<0.4	--	+3.53	–257	–65.30	--	--	--	0.71025	--	--
15A	PCMA	8/20/2012	--	--	--	--	--	--	--	–260	–64.45	--	--	--	--	--	--
15B	MZ	8/19/2011	–137	–18.32	0.06	0.18	<0.4	--	+4.83	–297	–70.42	--	--	--	0.71188	--	--
17B	PCMB	8/21/2011	–135	–17.69	<0.04	--	<0.4	--	+8.70	–282	–58.68	--	--	--	0.71286	--	--
18A	U-PCM	8/21/2011	–128	–16.61	<0.04	--	1.29	0.04	–11.1	–223	–58.63	--	+14.20	+0.85	0.70879	--	--
18A	U-PCM	8/18/2012	--	--	--	--	--	--	--	–208	–58.70	--	--	--	--	918	50

The redox data indicate that groundwater evolved from being oxic with high concentrations of sulfate and low concentrations of methane in recharge areas, to being anoxic with high sulfate and low methane concentrations farther downgradient in the upper aquifer system, to being highly anoxic with much smaller sulfate and much higher methane concentrations farther downgradient in the lower aquifer system. Sulfate reduction and methanogenesis appeared to be important redox processes in the lower aquifer system on the basis of elevated concentrations of sulfide and (or) methane in samples from that zone (tables 2 and 4). The largest sulfide concentration was 52 mg/L (well 13B) and the largest methane concentration was 387 mg/L (well 17B). Both samples were from the Parachute Creek Member below the Mahogany zone.

Methane concentrations generally were less than 1 mg/L when sulfate concentrations were greater than 100 mg/L and they were greater than 10 mg/L when sulfate concentrations were less than 100 mg/L (fig. 6). The former condition existed primarily above the Mahogany zone (fig. 6). The latter condition existed primarily in and below the Mahogany zone. This inverse relation between sulfate and methane concentrations results from the fact that at elevated sulfate concentrations sulfate reducing microbes can outcompete methanogens for electron donors such as organic carbon that are needed to support their metabolism (Lovley and Klug, 1986).

Lovely and Klug (1986) showed that sulfate reducing microbes can outcompete methanogens at sulfate concentrations as low as about 3 mg/L in some aquatic sediments. The data from this study indicate that the threshold sulfate concentration above which methanogenesis generally did not occur may be higher, possibly in the range of 50 to 100 mg/L. Previous studies showed that the sulfate-concentration threshold increases in organic-carbon rich environments (Isa and others, 1986; Vroblesky and others, 1996). Rocks in the Parachute Creek Member of the Green River Formation are very rich in organic carbon, commonly containing more than 10 weight percent organic carbon (Tuttle, 2009).

The inverse relation between sulfate and methane concentrations did not appear to apply to the sample from well 13U, completed in the Uinta-Parachute Creek Member transition zone. This is because essentially 100 percent of the methane in that sample was thermogenic in origin (from a deep, nonbiological source) rather than biogenic in origin (produced locally in the aquifer system by methanogenic microbes). The origin of methane in the water samples is discussed in the section “Hydrocarbon Chemistry.”

Major-Ion Chemistry

Concentrations of dissolved solids in the water samples ranged from 738 to 47,600 mg/L (table 2). For comparison, the Federal secondary drinking-water standard for dissolved solids is 500 mg/L (U.S. Environmental Protection Agency, 2012). The highest concentrations occurred in samples from wells 17B (4,340 mg/L) and 1B (47,600 mg/L), which were completed below the Mahogany zone and located near the regional discharge area at the northern end of Piceance Creek (fig. 1). For the remaining samples, concentrations of dissolved solids ranged from 738 to 1,470 mg/L.

The groundwater generally evolved from a mixed-cation-bicarbonate-sulfate type water in recharge areas of the Uinta-Parachute Creek Member transition zone to a sodium-bicarbonate type water in the Parachute Creek Member above the Mahogany zone, Mahogany zone, and Parachute Creek Member below the Mahogany zone (fig. 7). Water from well B12B, which was completed in the Parachute Creek Member below the Mahogany zone, was more similar in composition to water from the Uinta-Parachute Creek Member transition zone than to water from below the Mahogany zone. This is because B12B is located in a higher elevation recharge area near the margin of the study area, whereas the other wells completed in the Parachute Creek Member below the Mahogany zone are located farther downgradient in the study area (fig. 1). At the pH of the groundwater samples (7.27 to 8.51, median=7.76), nearly all the DIC was in the form of bicarbonate.

Recharge-area water acquired its sulfate from the oxidation of sulfide minerals such as pyrite (Kimball, 1984). Mineralogic and isotopic data from Tuttle and Goldhaber (1993) and Tuttle (2009) indicate that the Parachute Creek Member contains an abundance of sulfide minerals that are enriched in sulfur-34 ($\delta^{34}S$ from about +10 to +49‰) compared to marine sulfide minerals, but the rocks contain essentially no primary sulfate minerals. The $\delta^{34}S\text{-}SO_4$ values in groundwater that contained dissolved oxygen (wells 2A, 6A, and B12B) ranged from +10.25 to +17.64‰ (table 3), which are consistent with the sulfate being derived from the oxidation of isotopically enriched sulfide minerals. Protons (acidity) generated during sulfide-mineral oxidation could react with calcite, dolomite, and possibly nahcolite minerals to produce dissolved calcium, magnesium, sodium, and bicarbonate (Kimball, 1984).

The data indicate that several chemical reactions could be responsible for the evolution of groundwater to a sodium-bicarbonate type water as water moved downgradient from the recharge areas. The samples were at equilibrium or oversaturated with respect to calcite and dolomite, and undersaturated with respect to nahcolite, with the possible exception of water from well 1B, which contained exceptionally high concentrations of sodium and bicarbonate and was near equilibrium with respect to nahcolite (fig. 8*A*). WATEQ4F (Ball and Nordstrom, 1991), as implemented in NETPATH (Plummer and others, 1994), was used to calculate the mineral saturation indices. Nahcolite ($NaHCO_3$) would dissolve in groundwater that is undersaturated with respect to that mineral, producing dissolved sodium (Na^+) and bicarbonate (HCO_3^-) in a 1:1 molar ratio (eq. 5),

$$NaHCO_3 \rightarrow Na^+ + HCO_3^- \tag{5}$$

similar to the observed ratio of sodium and bicarbonate concentrations in the aquifers (fig. 8*B*), but nahcolite dissolution would not account for the observed reduction in concentrations of calcium and magnesium with increasing bicarbonate concentrations (fig. 8*C*).

Table 4. Hydrocarbon data for water collected from the monitoring wells.

[U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; µg/L, micrograms per liter; %, percent recovery; mg/L, milligrams per liter; <, less than; --, no data]

Well name	Geologic interval in which sample interval is located	Collection date	Collection time	Carbon dioxide (mg/L)[1]	Carbon dioxide (mole percent)	Methane (mg/L)[1]	Methane (mole percent)	Ethane (mole percent)	Ethylene (mole percent)	Propane (mole percent)	Propylene (mole percent)	Iso-butane (mole percent)	N-butane (mole percent)
B12B	PCMB	8/22/2011	1200	34.316	6.08	0.0042	0.130	<0.0001	0.0057	0.0007	--	0.0020	<0.0001
B12B	PCMB	8/15/2012	1100	32.427	--	0.0069	--	--	--	--	--	--	--
1A	U-PCM	8/18/2011	1500	15.517	2.91	0.0418	0.212	<0.0001	<0.0001	<0.0001	--	<0.0001	<0.0001
1A	U-PCM	8/16/2012	1100	15.053	--	0.0369	--	--	--	--	--	--	--
1B	PCMB	8/18/2011	1200	--	35.80	[2]75.9	63.17	0.0354	<0.0001	<0.0001	--	<0.0001	<0.0001
1B	PCMB	8/16/2012	1400	687.7	--	40.0	--	--	--	--	--	--	--
2A	U-PCM	8/23/2011	1130	40.754	8.23	0.1392	1.07	0.0007	<0.0001	<0.0001	--	<0.0001	<0.0001
2A	U-PCM	8/21/2012	1100	41.384	--	0.0737	--	--	--	--	--	--	--
6A	U-PCM	8/25/2010	1000	2.794	--	<0.0005	--	--	--	--	--	--	--
6A	U-PCM	11/3/2010	1100	2.709	--	<0.0005	--	--	--	--	--	--	--
6A	U-PCM	6/2/2011	1000	2.579	--	0.0006	--	--	--	--	--	--	--
6A	U-PCM	8/16/2011	1000	2.530	0.41	<0.0005	0.007	<0.0001	<0.0001	<0.0001	--	<0.0001	<0.0001
6A	U-PCM	8/17/2012	1400	2.831	--	0.0014	--	--	--	--	--	--	--
6B	PCMB	8/25/2010	1300	5.636	--	57.4	--	--	--	--	--	--	--
6B	PCMB	11/3/2010	1500	5.318	--	55.3	--	--	--	--	--	--	--
6B	PCMB	6/2/2011	1500	4.386	--	43.2	--	--	--	--	--	--	--
6B	PCMB	8/16/2011	1600	5.309	0.23	49.0	76.76	0.0047	<0.0001	<0.0001	--	<0.0001	<0.0001
6B	PCMB	8/17/2012	1100	2.266	--	19.0	--	--	--	--	--	--	--
9B	MZ	8/20/2011	1100	--	0.61	[2]150	93.75	0.0105	<0.0001	<0.0001	--	<0.0001	<0.0001
9B	MZ	8/18/2012	1100	24.853	--	85.9	--	--	--	--	--	--	--
13A	PCMA	8/24/2010	1400	17.482	--	0.2543	--	--	--	--	--	--	--
13A	PCMA	11/2/2010	1310	17.565	--	0.2297	--	--	--	--	--	--	--
13A	PCMA	6/1/2011	950	--	--	--	--	--	--	--	--	--	--
13A	PCMA	6/1/2011	1130	[4]22.386	--	[4]0.7386	--	--	--	--	--	--	--
13A	PCMA	8/17/2011	1200	17.531	2.78	0.1940	0.900	0.0094	<0.0001	0.0024	--	0.0012	0.0024
13A	PCMA	8/14/2012	1100	16.850	3.53	0.2132	0.878	0.0066	<0.0001	<0.0001	0.0004	<0.0001	<0.0001
13B	PCMB	8/24/2010	1600	17.135	--	42.6	--	--	--	--	--	--	--
13B	PCMB	11/2/2010	1410	30.304	--	54.7	--	--	--	--	--	--	--
13B	PCMB	6/1/2011	1500	44.257	--	49.0	--	--	--	--	--	--	--
13B	PCMB	8/17/2011	1400	29.330	1.32	60.0	95.11	0.1120	<0.0001	0.0297	--	0.0051	0.0032
13B	PCMB	8/14/2012	1200	29.819	1.78	53.9	93.82	0.1030	<0.0001	0.0235	0.0001	0.0034	0.0021
13U	U-PCM	8/24/2010	1200	49.068	--	17.4	--	--	--	--	--	--	--
13U	U-PCM	11/2/2010	1210	51.043	--	15.9	--	--	--	--	--	--	--
13U	U-PCM	6/1/2011	1300	51.857	--	17.5	--	--	--	--	--	--	--
13U	U-PCM	8/17/2011	1100	53.314	6.03	16.8	52.53	1.58	<0.0001	0.0203	--	0.0036	0.0007
13U	U-PCM	8/14/2012	1300	51.682	7.24	15.9	56.19	1.76	<0.0001	0.0237	<0.0001	0.0047	0.0003
15A	PCMA	8/19/2011	1300	--	1.44	[2]112	83.99	0.0335	<0.0001	0.0021	--	<0.0001	<0.0001
15A	PCMA	8/20/2012	1400	43.443	1.75	68.8	85.25	0.0379	<0.0001	0.0024	0.0002	0.0003	0.0002
15B	MZ	8/19/2011	1000	--	0.77	[2]106	87.22	0.0055	<0.0001	<0.0001	--	<0.0001	<0.0001
15B	MZ	8/20/2012	1000	27.539	--	72.5	--	--	--	--	--	--	--
17B	PCMB	8/21/2011	1030	255.7	11.23	[2]387	85.61	0.0264	<0.0001	0.0005	--	<0.0001	<0.0001
17B	PCMB	8/19/2012	1000	240.6	--	46.0	--	--	--	--	--	--	--
18A	U-PCM	8/21/2011	1600	26.077	4.78	0.2126	1.05	0.0064	<0.0001	<0.0001	--	<0.0001	0.0006
18A	U-PCM	8/18/2012	1600	25.483	6.19	0.2913	1.43	0.0075	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Table 4. Hydrocarbon data for water collected from the monitoring wells.—Continued

[U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; µg/L, micrograms per liter; %, percent recovery; mg/L, milligrams per liter; <, less than; --, no data]

Well name	Collection date	Iso-pentane (mole percent)	N-pentane (mole percent)	Hexanes + (mole percent)	Methane/ (ethane + propane)	Toluene (µg/L)	Benzene (µg/L)	Ethyl-benzene (µg/L)	o-xylene (µg/L)	Tert-butyl methyl ether (µg/L)	Xylene, total (µg/L)	m- and p-xylene (µg/L)	d-8-toluene (%)[3]
B12B	8/22/2011	<0.0001	<0.0001	<0.0001	186	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	91.0
B12B	8/15/2012	--	--	--	--	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	90.5
1A	8/18/2011	<0.0001	<0.0001	<0.0001	--	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	89.7
1A	8/16/2012	--	--	--	--	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	91.5
1B	8/18/2011	<0.0001	<0.0001	<0.0001	1,784	<0.2	<0.2	<0.2	<0.2	<0.4	<0.4	<0.4	62.5
1B	8/16/2012	--	--	--	--	<0.2	<0.2	<0.2	<0.2	<0.4	<0.4	<0.4	74.9
2A	8/23/2011	<0.0001	<0.0001	<0.0001	1,529	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	92.3
2A	8/21/2012	--	--	--	--	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	90.9
6A	8/25/2010	--	--	--	--	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	91.8
6A	11/3/2010	--	--	--	--	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	94.1
6A	6/2/2011	--	--	--	--	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	85.4
6A	8/16/2011	<0.0001	<0.0001	<0.0001	--	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	88.3
6A	8/17/2012	--	--	--	--	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	91.1
6B	8/25/2010	--	--	--	--	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	95.9
6B	11/3/2010	--	--	--	--	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	94.2
6B	6/2/2011	--	--	--	--	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	83.6
6B	8/16/2011	<0.0001	<0.0001	<0.0001	16,332	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	90.1
6B	8/17/2012	--	--	--	--	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	90.3
9B	8/20/2011	<0.0001	<0.0001	<0.0001	8,929	0.2	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	89.4
9B	8/18/2012	--	--	--	--	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	93.5
13A	8/24/2010	--	--	--	--	5.9	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	93.9
13A	11/2/2010	--	--	--	--	3.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	93.1
13A	6/1/2011	--	--	--	--	[4]3.9	[4]<0.1	[4]<0.1	[4]<0.1	[4]<0.2	[4]<0.2	[4]<0.2	84.4
13A	6/1/2011	--	--	--	--	[4]2.6	[4]1.0	[4]<0.1	[4]<0.1	[4]<0.2	[4]<0.2	[4]<0.2	76.0
13A	8/17/2011	0.0012	0.0018	<0.0001	76	2.7	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	89.8
13A	8/14/2012	<0.0001	<0.0001	<0.0001	133	2.9	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	91.3
13B	8/24/2010	--	--	--	--	7.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	93.8
13B	11/2/2010	--	--	--	--	9.2	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	94.0
13B	6/1/2011	--	--	--	--	12.2	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	83.8
13B	8/17/2011	0.0009	<0.0001	<0.0001	671	3.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	89.9
13B	8/14/2012	0.0004	<0.0001	<0.0001	742	1.4	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	90.6
13U	8/24/2010	--	--	--	--	<0.1	0.4	<0.1	<0.1	<0.2	<0.2	<0.2	87.8
13U	11/2/2010	--	--	--	--	<0.1	0.6	<0.1	<0.1	<0.2	<0.2	<0.2	90.1
13U	6/1/2011	--	--	--	--	<0.1	1.0	<0.1	<0.1	<0.2	<0.2	<0.2	76.4
13U	8/17/2011	0.0007	0.0005	<0.0001	33	<0.1	1.1	<0.1	<0.1	<0.2	<0.2	<0.2	83.8
13U	8/14/2012	<0.0001	<0.0001	0.0003	32	<0.1	0.7	<0.1	<0.1	<0.2	<0.2	<0.2	85.8
15A	8/19/2011	<0.0001	<0.0001	<0.0001	2,359	<0.1	0.6	<0.1	<0.1	<0.2	<0.2	<0.2	83.8
15A	8/20/2012	<0.0001	<0.0001	<0.0001	2,115	<0.1	0.6	0.2	<0.1	<0.2	<0.2	<0.2	84.9
15B	8/19/2011	<0.0001	<0.0001	<0.0001	15,858	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	87.5
15B	8/20/2012	--	--	--	--	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	90.4
17B	8/21/2011	<0.0001	<0.0001	<0.0001	3,183	0.2	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	85.9
17B	8/19/2012	--	--	--	--	0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	90.2
18A	8/21/2011	<0.0001	<0.0001	<0.0001	164	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	90.1
18A	8/18/2012	<0.0001	<0.0001	<0.0001	191	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	91.0

[1] Analysis done by gas chromatography.

[2] Analysis done by mass spectrometry.

[3] Octdeuterotoluene is a surrogate compound added to the sample in the laboratory to evaluate BTEX recovery efficiency.

[4] The packer in well 13A (see Appendix figure 1–1) was not operating properly on this date so the reported concentrations may not be comparable to the concentrations on the other sample dates.

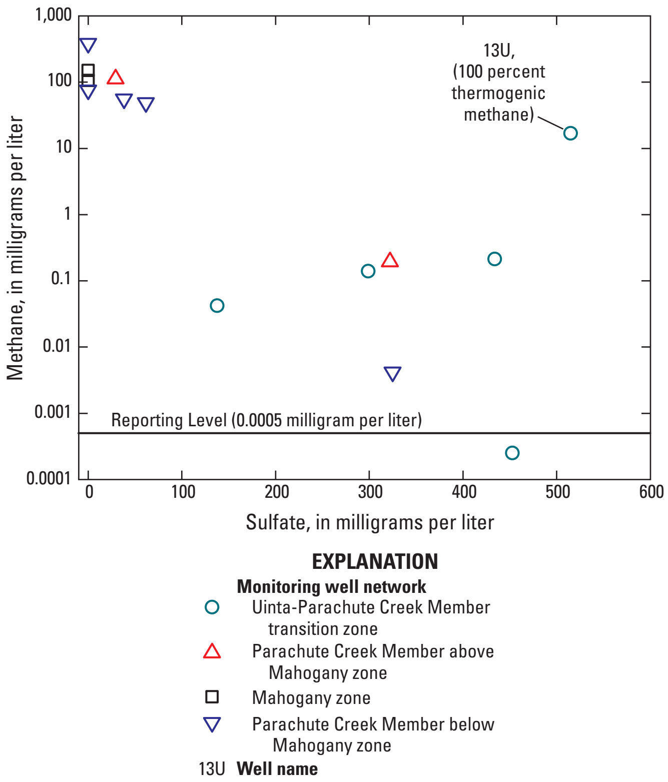


Figure 6. Graph showing methane concentrations in relation to sulfate concentrations for water samples collected from the monitoring wells in 2011.

The loss of calcium and magnesium from solution with increasing bicarbonate concentrations could be accounted for by ion exchange. Even though the groundwater was at equilibrium or oversaturated with respect to calcite and dolomite (fig. 8*A*), carbon dioxide produced by redox reactions such as sulfate reduction could drive additional dissolution of those minerals. Sulfate (SO_4^{2-}) reduction coupled to the oxidation of organic carbon (represented here as CH_2O) produces hydrogen sulfide (H_2S) and carbon dioxide (CO_2) (eq. 6).

$$SO_4^{2-} + 2CH_2O + 2H^+ \rightarrow H_2S + 2CO_2 + 2H_2O \qquad (6)$$

Sulfate concentrations decreased substantially with increasing bicarbonate concentrations (fig. 8*D*), as would be expected on the basis of the stoichiometry of equation 6, and hydrogen sulfide was detected in many of the samples (table 2). Exchange of the calcium and magnesium released from calcite ($CaCO_3$) and (or) dolomite ($CaMg(CO_3)_2$) dissolution with sodium adsorbed to clay minerals (NaX) would produce dissolved sodium and bicarbonate in a 1:1 molar ratio (eqs. 7 and 8),

$$CaCO_3 + CO_2 + H_2O + 2NaX \rightarrow 2Na^+ + 2HCO_3^- + CaX_2 \qquad (7)$$

$$\begin{aligned} CaMg(CO_3)_2 + 2CO_2 + 2H_2O + 4NaX \rightarrow 4Na^+ \\ + 4HCO_3^- + CaX_2 + MgX_2 \end{aligned} \qquad (8)$$

as was observed in the aquifers (fig. 8*B*).

The four samples (1B, 15A, 15B, 17B) with the highest bicarbonate concentrations plot above the 1:1 line in fig. 8*B* because they apparently contained sodium from other sources in addition to nahcolite and (or) exchangeable sodium on clays. Each of those samples had a chloride concentration greater than 100 mg/L, whereas the median concentration in the remaining samples was 10 mg/L, indicating that dissolution of halite (NaCl) could have been the other major sodium source. Wells 1B and 17B are completed in the Parachute Creek Member below the Mahogany zone and are located near the regional discharge area at the northern end of Piceance Creek and probably represent some of the most deeply circulated groundwater sampled for this study. Interestingly, 15A and 15B are located upgradient from wells that produced water with low chloride concentrations (fig. 1).

Chloride/bromide mass ratios for the samples were plotted relative to the ratios for halite in the Parachute Creek Member (fig. 9). The bromide concentration in the 2011 sample from well 1B could not be quantified by the ion chromatography method used to analyze the sample and the concentration in the 2012 sample was less than 0.5 mg/L, resulting in a chloride/bromide ratio greater than 8,140 in figure 9. The data for 1B, 9B, and 15B are consistent with the interpretation that halite dissolution added chloride to those samples (fig. 9). For 15A and 17B, the data indicate that chloride was added to those samples from halite dissolution and possibly from mixing with a small amount of high-chloride water having a relatively low chloride/bromide mass ratio.

Produced waters from the Mesaverde Group in southwestern Wyoming and Garfield County are examples of water with relatively low chloride/bromide ratios (fig. 9). The chloride and bromide concentrations in water from well 15A could be accounted for by a hypothetical mixture containing more than 98 percent water from 15B and less than 2 percent produced water similar in composition to those shown in figure 9. Such a small percentage of produced water in the mixture would not be discernible in the water isotopic data (fig. 5). This is only a hypothetical mixing scenario because it is unknown whether the produced-water data shown in fig. 9 are representative of water in deeper geologic units in the study area. Data from the Colorado Oil and Gas Conservation Commission (2012) indicate that chloride concentrations in produced water from the study area were similar to the produced water shown in figure 9, but no bromide data were reported. Nevertheless, the sample from 15A did contain trace amounts of propane and butane and the sample from 17B contained trace amounts of propane (table 4), which are indicative of interaction with fluid from deeper sources (Rowe and Muehlenbachs, 1999; Osborn and others, 2011). In contrast, the samples from 1B, 9B, and 15B did not have detectable concentrations of propane or butane. The hydrocarbon data are discussed in more detail in the section “Hydrocarbon Chemistry.”

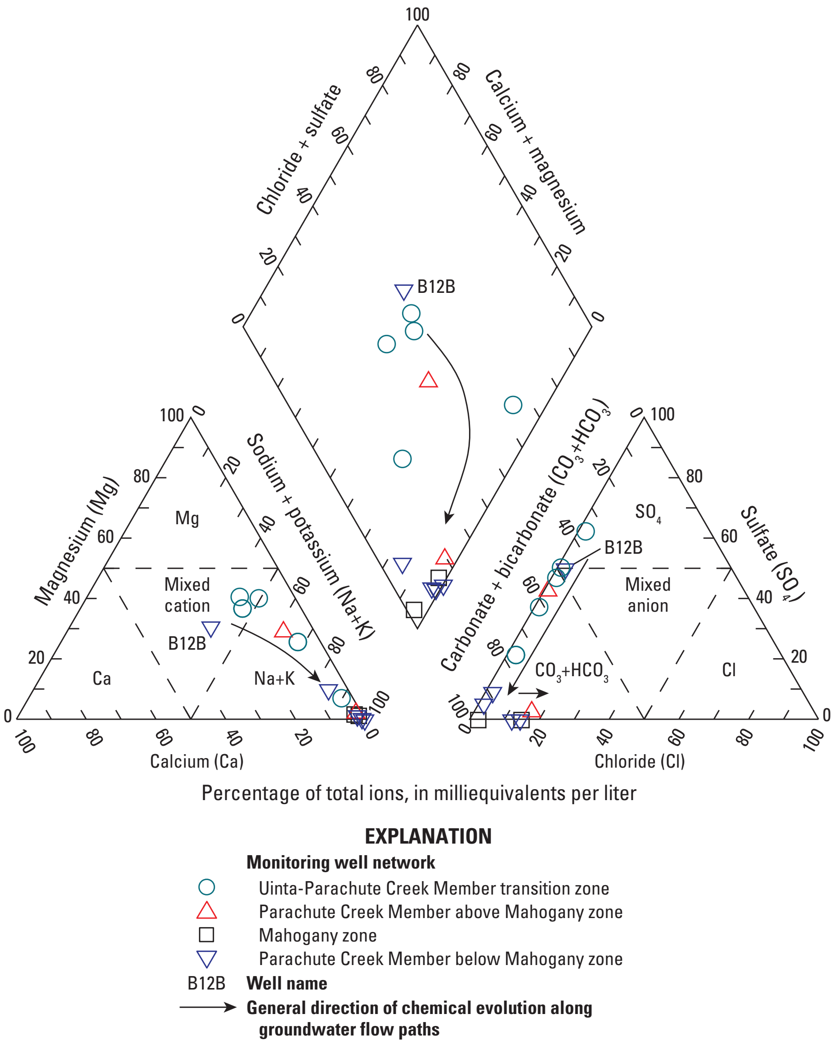


Figure 7. Trilinear diagram showing water types for water samples collected from the monitoring wells in 2011.

Minor- and Trace-Element Chemistry

Concentrations of fluoride ranged from about 0.1 to 70 mg/L (table 2). The Federal drinking-water standard (Maximum Contaminant Level, MCL) for fluoride is 4 mg/L (U.S. Environmental Protection Agency, 2012). For iron and manganese, concentrations ranged from less than about 3 to 585 micrograms per liter (µg/L) and from about 1 to 48 µg/L, respectively. There are no MCLs for iron and manganese. The highest concentrations of arsenic (6.3 µg/L, MCL=10 µg/L) and uranium (3.31 µg/L, MCL=30 µg/L) occurred in the highly oxic water from well B12B.

Concentrations of barium exhibited a strong positive correlation with fluoride concentrations (fig. 10), based on a least-squares linear regression (Helsel and Hirsch, 2002), as did concentrations of boron. Lower concentrations of barium and fluoride generally occurred in water samples from the Uinta-Parachute Creek Member transition zone and the Parachute Creek Member above the Mahogany zone. Water samples from the Mahogany zone and Parachute Creek Member below the Mahogany zone generally had higher concentrations of both elements. Samples from wells 1B, 13B, and 17B exceeded the barium (2 mg/L) and fluoride (4 mg/L) MCLs (fig. 10). Samples from four additional wells exceeded the fluoride MCL but not the barium MCL.

Concentrations and isotopic compositions of strontium also exhibited distinct spatial patterns. All the water samples from the Uinta-Parachute Creek Member transition zone and the Parachute Creek Member above the Mahogany zone had strontium concentrations greater than 1,250 µg/L and strontium-87/strontium-86 isotopic ratios (^{87}Sr/^{86}Sr ratios) less than 0.71025 (fig. 11 and table 3). The ^{87}Sr/^{86}Sr ratios for those samples plot within the range of values for carbonate minerals from the same geologic intervals (fig. 11) (Davis and others, 2009), suggesting that the dissolved strontium was derived from dissolution of those minerals. As noted previously, the major-ion data also indicate an important role for carbonate-mineral dissolution in the aquifers. Most of the samples from the Mahogany zone and the Parachute Creek

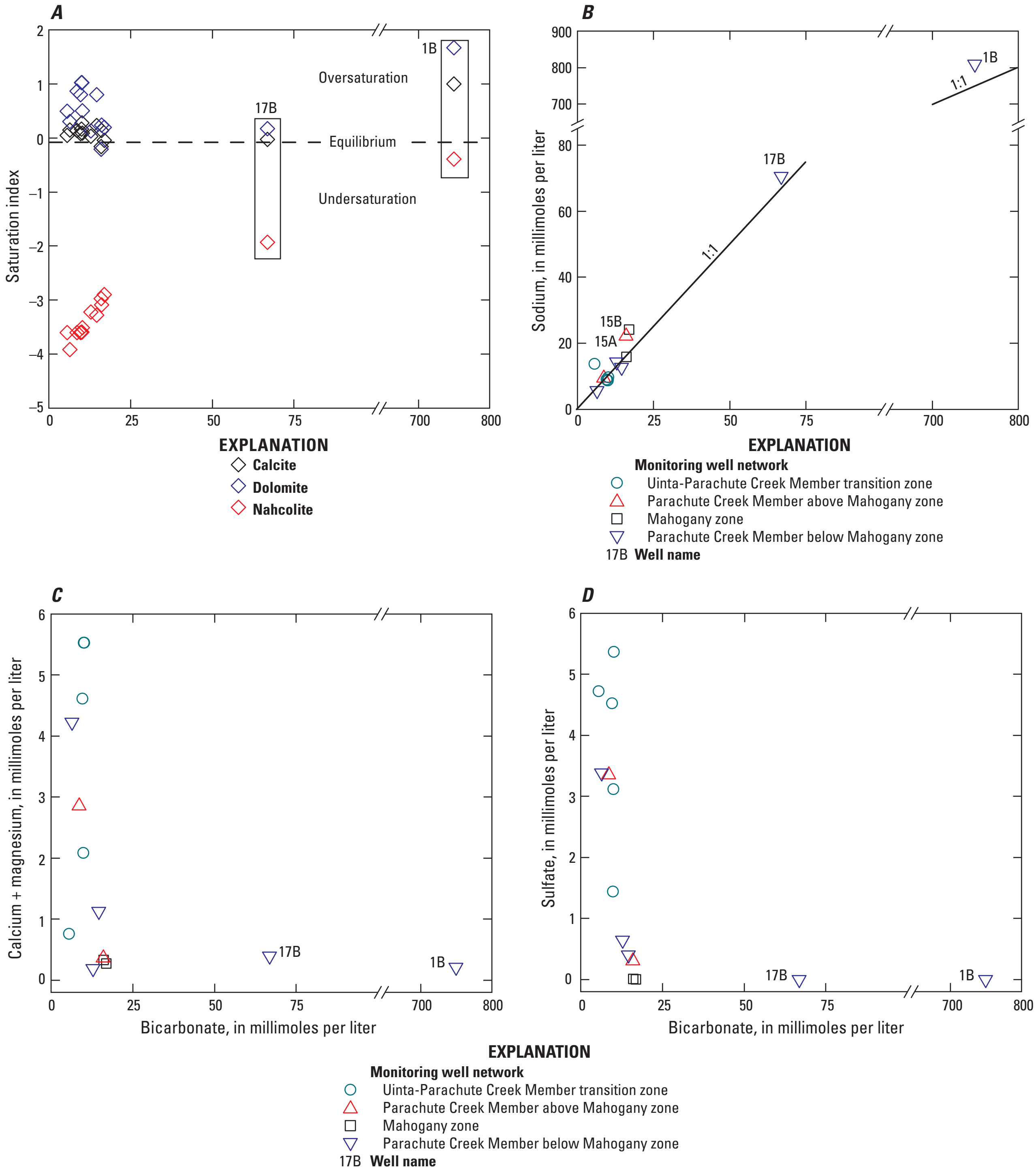


Figure 8. Graphs showing *A*, saturation indexes for calcite, dolomite, and nahcolite; *B*, concentrations of sodium; *C*, calcium+ magnesium; and *D*, sulfate in relation to bicarbonate concentrations for water samples collected from the monitoring wells in 2011.

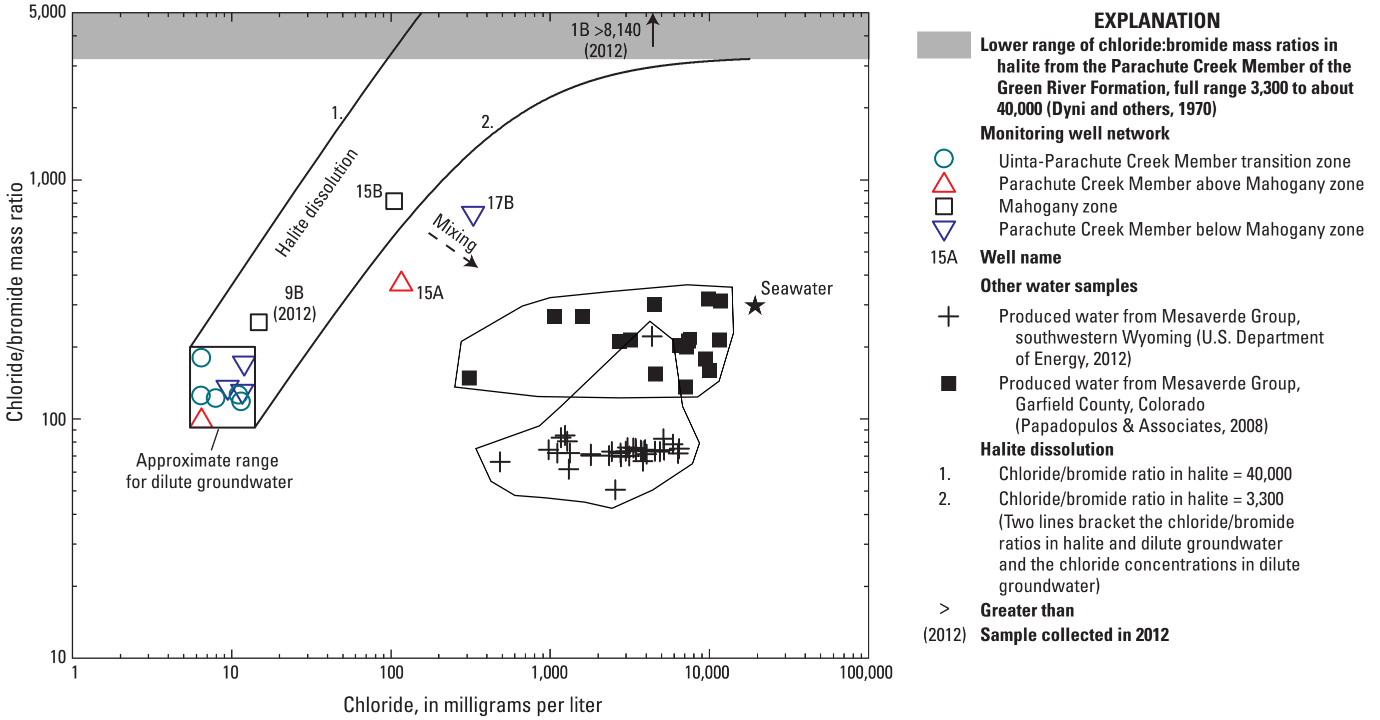


Figure 9. Graph showing chloride/bromide mass ratios in relation to chloride concentrations for water samples collected from the monitoring wells in 2011, except as noted.

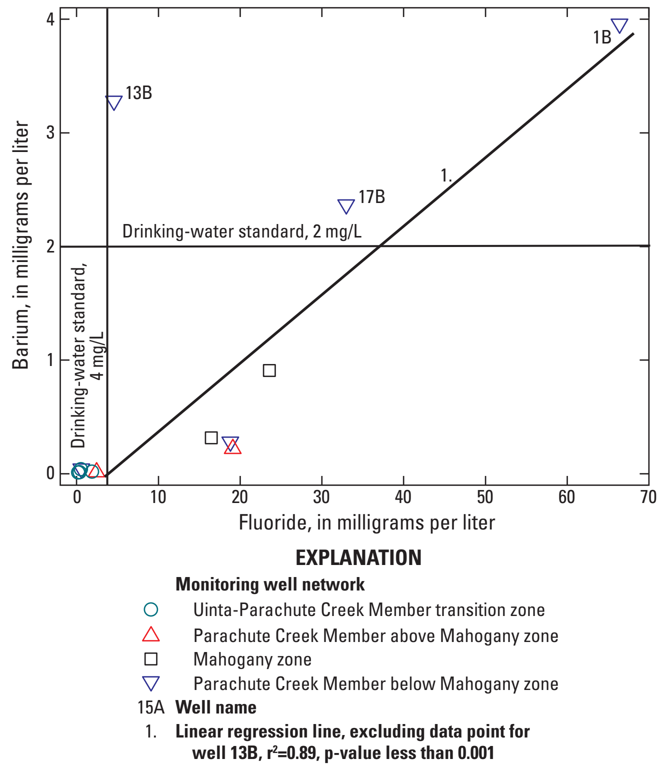


Figure 10. Graph showing barium concentrations in relation to fluoride concentrations for water samples collected from the monitoring wells in 2011.

Member below the Mahogany zone had strontium concentrations less than 1,300 µg/L and $^{87}Sr/^{86}Sr$ ratios greater than 0.71113 (fig. 11 and table 3). The $^{87}Sr/^{86}Sr$ ratios for those samples broadly correspond to the values for carbonate minerals from the deeper geologic intervals (fig. 11). The samples from wells 1B and 17B had the highest $^{87}Sr/^{86}Sr$ ratios of all the water samples (fig. 11), and they were higher than any of the ratios reported for carbonate minerals in the Green River Formation by Davis and others (2009) (fig. 11). The data plot in the same field as some of the water samples collected from the L3, L4, and L5 zones (fig. 2) by Posey and others (2009) in the west central part of the study area. The strontium data indicate that water from these deeper zones moved upward in the regional discharge area where wells 1B and 17B are located.

Hydrocarbon Chemistry

Two groups of hydrocarbons were analyzed for this study: the hydrocarbon gases methane through hexane and BTEX compounds. Both constituent groups are components of the fluids produced from natural-gas wells in the study area, and as such, they are useful indicators of connections between the bedrock aquifers and deeper formations. The results of those analyses are presented below.

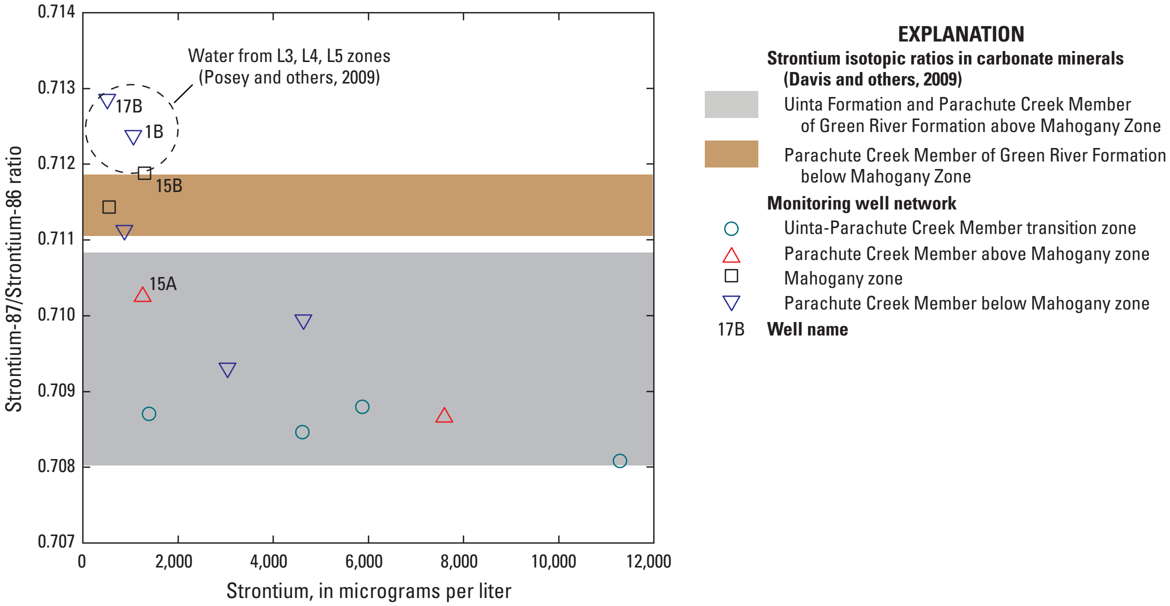


Figure 11. Graph showing strontium-87/strontium-86 ratios in relation to strontium concentrations for water samples collected from the monitoring wells in 2011.

Methane

Methane concentrations in groundwater ranged from less than 0.0005 to 387 mg/L (table 4). There currently is no Federal drinking-water standard for methane, but water containing methane at concentrations greater than about 28 mg/L could result in an immediate explosive hazard if used or stored in confined spaces (Eltschlager and others, 2001). In 2011, 7 of the 14 wells produced water with methane concentrations greater than 28 mg/L. Four samples had concentrations that exceeded 100 mg/L (9B, 15A, 15B, and 17B). These concentrations are higher than the methane concentrations reported for groundwater in some other gas-producing regions of the United States. Osborn and others (2011) reported a maximum methane concentration of 64 mg/L in water from drinking-water wells in the Marcellus Shale region of Pennsylvania. Kresse and others (2012) reported a maximum methane concentration of about 29 mg/L in the Fayetteville Shale region of Arkansas. The U.S. Environmental Protection Agency (2011) and Wright and others (2012) reported maximum methane concentrations of about 23 to 27 mg/L in monitoring wells in the Wind River Basin near Pavillion, Wyo. URS Corporation (2006) reported a maximum methane concentration of about 37 mg/L in various types of water wells in the Mamm Creek area of Garfield County, Colo.

The methane was predominantly biogenic in origin, although the biogenic methane was mixed with thermogenic methane in water from seven wells (fig. 12). Hydrocarbon gas molecular compositions and δ^{13}C data for methane (δ^{13}C-CH$_4$) indicate that methane in water from wells 6B, 9B, and 15B was essentially 100 percent biogenic, whereas methane in water from 13U was 100 percent thermogenic and had a δ^{13}C composition similar to some commercially produced natural gas in the Piceance Basin (Johnson and Rice, 1990). The highest concentrations of biogenic methane occurred in samples from the lower aquifer system and were probably produced by microbial degradation of oil shale contained therein. In contrast, the thermogenic methane was produced by nonbiological processes in deeper geologic units below the aquifer systems (Johnson and Rice, 1990).

Methane in water from 13A and 18A appeared to be a mixture of biogenic and thermogenic methane (fig. 12). The total methane concentrations in 13A and 18A, however, were mostly less than 0.5 mg/L, so the amount of thermogenic methane in those samples was quite low. The fraction of thermogenic methane was less in the samples from 13B, but the total methane concentration in 13B was consistently greater than 40 mg/L. Thus, the actual concentration of thermogenic methane probably was higher in 13B than it was in 13A and 18A. Samples from 15A and 17B plot in or near the field for biogenic methane but they still contained small amounts of heavier hydrocarbons like propane and butane (table 4), indicating that although the methane was largely biogenic trace amounts of thermogenic methane probably were present in those samples. The sample from B12B could not be plotted in figure 12 because its methane concentration was too low to measure δ^{13}C-CH$_4$, but the hydrocarbon gas composition of that sample (table 4) indicates it probably was mostly thermogenic in origin. Hydrocarbon molecular and isotopic compositions were reanalyzed in some of the samples collected in 2012 and those data are consistent with the 2011 data (fig. 12 and table 3).

Vitrinite reflectance data indicate that the Green River Formation in the study area was never buried deeply enough to generate thermogenic methane (Johnson and Nuccio, 1986; Johnson and Rice, 1990), so thermogenic methane in water from the monitoring wells is considered to have been generated in deeper geologic units and subsequently migrated upward into the Green River Formation (Johnson and Rice, 1990). Potential migration pathways for thermogenic methane in the monitoring wells are discussed in the section “Hydrocarbon Migration.”

The primary metabolic pathways for biogenic methane production are carbon dioxide reduction and acetate fermentation (Whiticar, 1999). The carbon dioxide reduction pathway appears to be the predominant production mechanism for biogenic methane in the samples on the basis of the δ^2H data for methane and water (table 3) (Whiticar, 1999). The $\delta^{13}C$ data for dissolved inorganic carbon ($\delta^{13}C$-DIC) are consistent with this interpretation. Microbial reduction of carbon dioxide to methane often results in an increase in the $\delta^{13}C$ values of the unreacted DIC because of the large isotopic fractionation associated with the process (Balabane and others, 1987; Whiticar, 1999). Samples highly enriched in biogenic methane (9B, 15B, and 17B) had $\delta^{13}C$-DIC values of +4.83 to +8.70 per mil, whereas methane-poor samples from wells such as 2A, 6A, and 18A had $\delta^{13}C$-DIC values of –11.15 to –6.17 per mil (table 3).

Times-series concentration data for methane are available for five wells. Concentrations were relatively constant at three of the wells (6A, 13A, and 13U), were more variable but with no clear trend at one well (13B), and decreased substantially at one well (6B) (fig. 13*A*). The concentration of thermogenic methane in water from 13U was relatively constant over time, possibly indicating a stable source for the methane in that location in the Black Sulphur Creek drainage. There was a significant (p=0.002) inverse correlation between methane and sulfate concentrations in water from 6B (fig. 13*B*). The cause of the recent increase in sulfate concentration at that location is unknown but apparently the increase in concentration was large enough to inhibit biogenic methane production (Lovley and Klug, 1986).

Methane concentrations generally increased with groundwater age, or residence time, as implied by a cross plot of methane and helium-4 concentrations (fig. 14). Helium-4 accumulates in groundwater as the residence time of water in an aquifer increases so older water usually contains more helium-4 than younger water (see the section “Helium-4”) (Andrews and others, 1985; Torgersen and Clarke, 1985; Plummer and others, 2012). Methane concentrations were much lower in samples of relatively young water collected from above the Mahogany zone than in older water collected from within or below the Mahogany zone, with some notable exceptions. The sample from well B12B had a very low methane concentration, even though that well was completed below the Mahogany zone, because it was located in the recharge area. The sample from 1B had a very low helium-4 concentration even though it had high methane because the sample was substantially degassed (see the section “Helium-4”). The sample from 13U had a high methane concentration even though the well was completed above the Mahogany zone, but the methane in that water was thermogenic in origin and unrelated to methanogenesis in the aquifers. The increase in concentrations of biogenic methane with groundwater age makes sense microbiologically because the longer groundwater resides in the aquifers the more time there is for methanogenesis to occur and for methane to accumulate.

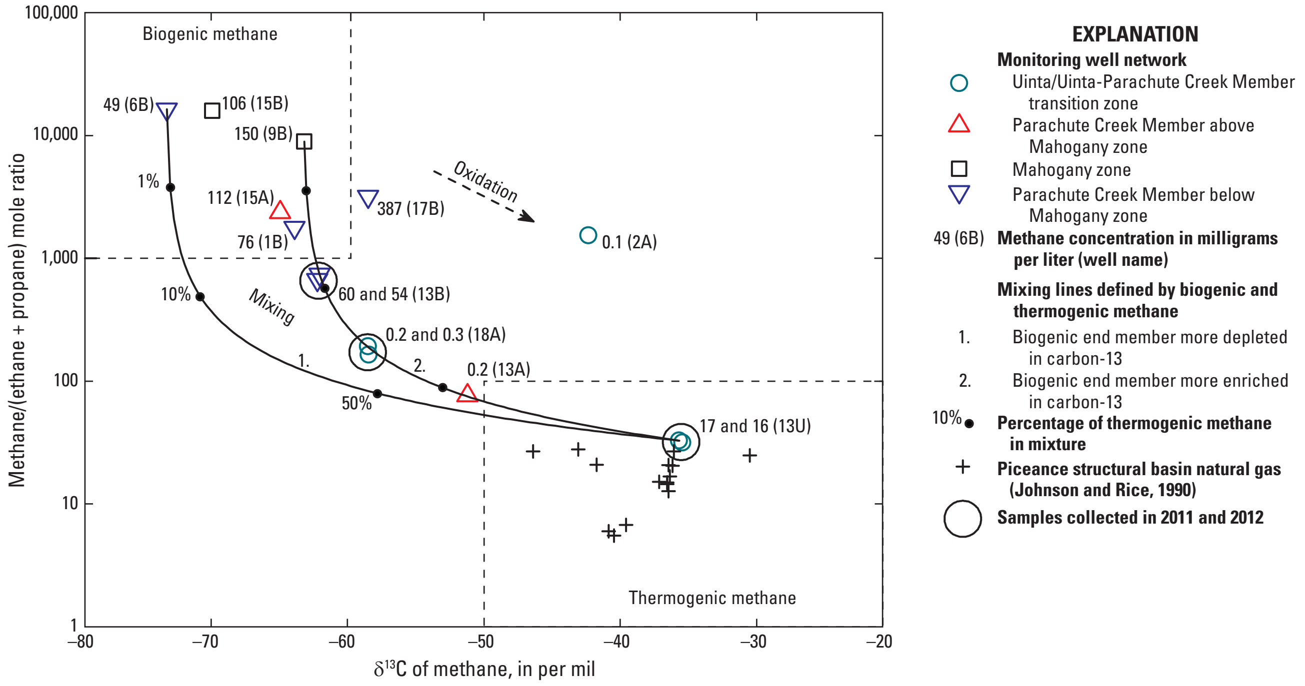


Figure 12. Graph showing hydrocarbon gas composition in relation to the stable carbon isotopic composition of methane for water samples collected from the monitoring wells in 2011; $\delta^{13}C$, stable carbon isotope compositions. [Selected wells were resampled in 2012 to evaluate temporal variability in the data. The boundaries of the biogenic and thermogenic methane fields are modified from Bernard and others (1976) and Whiticar (1999).]

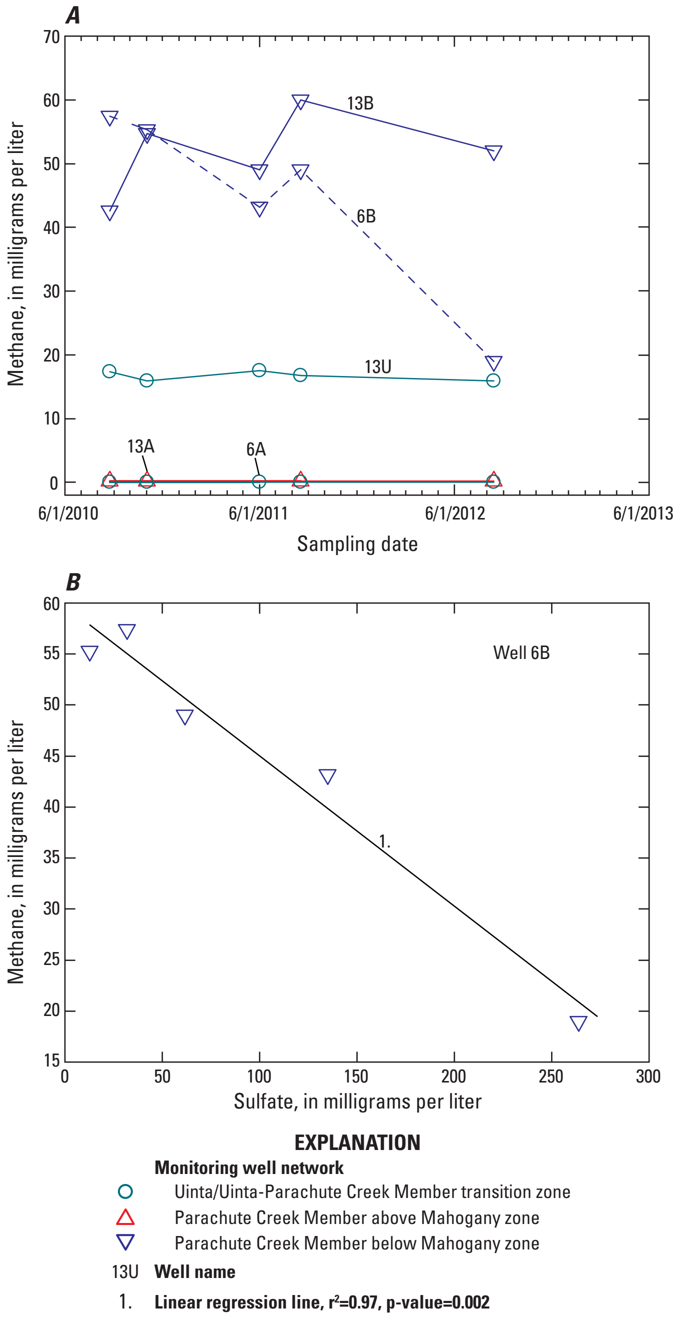


Figure 13. Graphs showing methane concentrations in relation to *A*, sampling date; and *B*, sulfate concentrations for selected monitoring wells.

BTEX

Three BTEX compounds (benzene, toluene, and ethylbenzene) were detected in water from six of the monitoring wells. Toluene was detected in 9B, 13A, 13B, and 17B, benzene was detected in 13U, and benzene and ethylbenzene were detected in 15A (fig. 1 and table 4). At 9B, toluene was only detected in the 2011 sample. At 15A, ethylbenzene was only detected in the 2012 sample. None of the BTEX concentrations exceeded an MCL. The highest benzene concentration was measured in 13U (1.1 µg/L, MCL=5µg/L). The highest toluene concentration was measured in 13B (12.2 µg/L, MCL=1,000 µg/L). The highest ethylbenzene concentration was measured in 15A (0.2 µg/L, MCL=700 µg/L).

The low-level BTEX detections in water collected with the Kemmerer sampler cannot be explained simply by air-water equilibration in the sampler or unpumped well. Based on a general study-area elevation of 6,500 feet, mean annual air temperature of 5 °C, and data for atmospheric concentrations of BTEX in rural areas undergoing natural-gas development in Colorado (Gilman and others, 2013), the BTEX concentrations in water that could be produced by air-water equilibration would be less than the BTEX reporting levels listed in table 4 (Staudinger and Roberts, 2001). Rather, the data indicate a widespread occurrence of trace quantities of BTEX compounds in the bedrock aquifers.

Well site 13 in the Black Sulphur Creek drainage was the only multi-well site with BTEX detections in more than one well. Time-series data from 13A, 13B, and 13U indicate that toluene and benzene persisted in groundwater at that location during the two years of record (fig. 15), although the concentrations of toluene exhibited relatively high variability over time. The thickness of the groundwater zone containing BTEX at that site could be at least 700 feet on the basis of the depths of the nested wells (table 1) and the chemical data.

BTEX compounds occur naturally in deep gas-bearing zones in the study area as indicated by their presence in produced waters (Colorado Oil and Gas Conservation

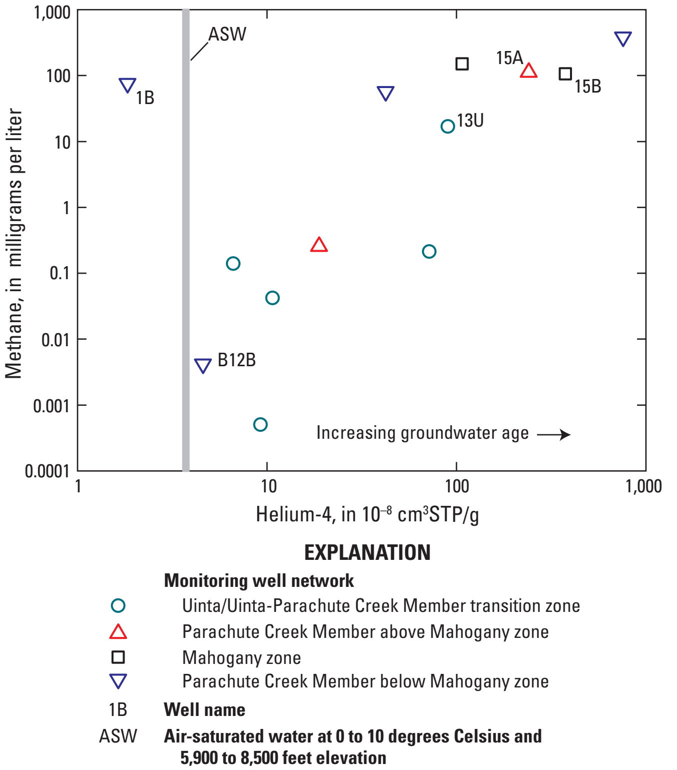


Figure 14. Graph showing methane concentrations in relation to helium-4 concentrations for water samples collected from the monitoring wells in 2011; cm^{3}STP/g, cubic centimeters at standard temperature and pressure per gram of water.

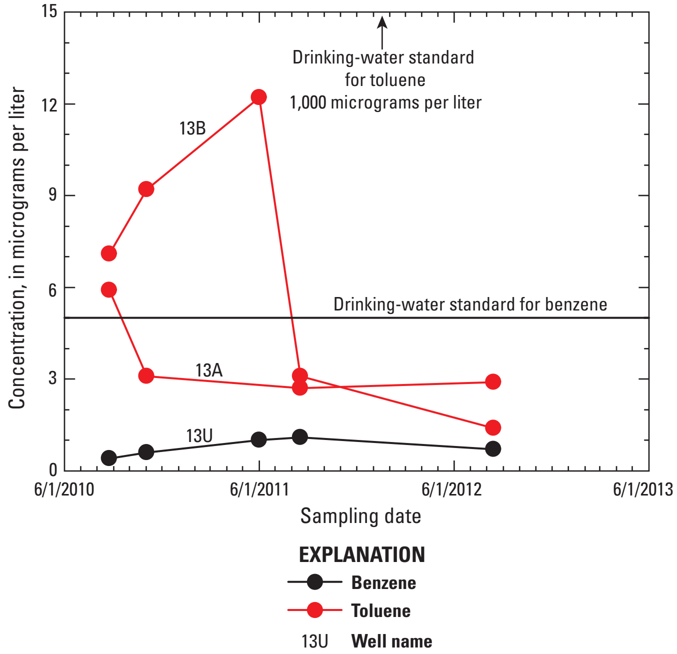


Figure 15. Graph showing benzene and toluene concentrations in relation to sampling date for water samples collected from wells 13A, 13B, and 13U.

Commission, 2012), so those deep zones are one possible source of BTEX in the groundwater. Recent recharge from the land surface, from fuel spills for example, is less likely to be the source because groundwater-age data, discussed in the section “Groundwater Age,” indicate that all the samples that contained BTEX apparently were recharged hundreds or thousands of years ago. Landon and Belitz (2012) concluded that trace concentrations of benzene in California groundwater in the vicinity of oil and gas fields were derived from subsurface sources because the groundwater was old, based on tritium data, similar to most groundwater in the Piceance study area. Five of the six wells in this study that produced water with BTEX also contained at least a small fraction of thermogenic methane, as indicated by hydrocarbon gas compositions and $\delta^{13}C$ data for methane. Taken together, the methane and BTEX data indicate that deep fluids interacted with groundwater in the bedrock aquifers, which is discussed in the section “Hydrocarbon Migration.”

Birdwell and Lewan (2010) indicated that it might be possible to leach BTEX from oil shale in the Parachute Creek Member at room temperature (about 25 °C), although it is not clear from that study if the BTEX was actually formed at room temperatures. If BTEX can be formed at room temperature from oil shale then some or all of the detected BTEX could have been produced in situ instead of having migrated from depth. In situ production seems less likely on the basis of the co-occurrence of BTEX and thermogenic methane in many of the samples. Nevertheless, additional study, possibly using compound-specific isotopic measurements, might help to distinguish between low- and high-temperature generation of BTEX.

Hydrocarbon Migration

In general, the two most likely migration pathways for thermogenic methane in the study area are movement along natural geologic structures (faults, fractures, or fold axes) and movement through improperly sealed boreholes of gas wells. Whereas hydrocarbon migration can occur naturally along geologic structures (Johnson and Rice, 1990), migration through boreholes is related to human activity. It is conceivable that an improperly sealed gas well intersecting a fault or fracture could result in a hybrid pathway. Regardless of the migration pathway, the presence of thermogenic gas in the aquifers indicates a connection and vulnerability to chemicals in deeper formations in the study area (Warner and others, 2012).

Distances from the monitoring wells to the nearest gas well and mapped geologic structure, and the number of gas wells and mapped geologic structures in a 1,500-foot radius (buffer zone) of the monitoring wells, were used to examine potential migration pathways for thermogenic methane and BTEX. Fold axes were included in the analysis because fractures and (or) thinning of stratigraphic layers could be associated with them. A 1,500-foot radius was chosen following the approach of the USGS National Water Quality Assessment Program (Koterba, 1998). However, the area contributing water to wells can be quite complex (Starn and others, 2010), so additional hydrologic analysis of buffer-zone geometries and sizes should be done if more data become available. The shortest distance between a gas well and monitoring well was 58 feet (well site 13) and the shortest distance to a mapped geologic structure was 636 feet (well site 1) (table 5). A maximum of 10 gas wells and 2 geologic structures were located in the buffer zones.

The 2011 monitoring results were divided into two groups: (1) water samples with BTEX detections and (or) methane/(ethane + propane) ratios less than 1,000 and (2) water samples with no BTEX detections and methane/(ethane + propane) ratios greater than 1,000. Group-1 samples are considered to contain hydrocarbons from below the Parachute Creek Member and group-2 samples do not. Most group-1 samples had more gas wells than geologic structures located within 1,500 feet of the wells (fig. 16). Most of the group-2 samples did not have any gas wells located within 1,500 feet of the wells. These data indicate that hydrocarbon migration could be associated with gas wells in some locations, such as at well sites 13 and 18 (fig. 16).

Monitoring well 18A had 10 gas wells and no known geologic structures in its buffer zone. The total amount of methane in water from 18A in 2011 and 2012 was small, but the methane appeared to be a mixture of biogenic and thermogenic gas (fig. 12). The well warrants further monitoring because most of the gas wells in the buffer zone were completed recently (since 2007). Other potentially important features were located outside the buffer zone but upgradient from the well. These include at least two fault or fracture zones (fig. 1) and a gas-producing zone in the Green

Table 5. Number and proximity of gas wells and geologic structures (faults, fractures, and fold axes) to the monitoring wells.

[ft, feet; BTEX, benzene, toluene, ethylbenzene, and xylene; µg/L, micrograms per liter; na, not applicable; <, less than]

Well name	Distance to nearest gas well (ft)[1]	Number of gas wells in 1,500-ft radius of monitoring well[1]	Type of gas well in 1,500-ft radius (number of wells)[1]	Number of laterally drilled gas-well holes in 1,500-ft radius of well[2]	Distance to nearest geologic structure (ft)[3]	Number of geologic structures in 1,500-ft radius of well[3]	Methane/ (ethane + propane)[4]	Total BTEX concentration (µg/L)[4]
B12B	1,183	1	Producing(1)	0	1,042	1	186	<0.1
1A	7,274	0	na	0	636	2	--	<0.1
1B							1,784	<0.2
2A	4,750	0	na	0	7,795	0	1,529	<0.1
6A	6,150	0	na	0	3,439	0	--	<0.1
6B							16,332	<0.1
9B	110	2	Abandoned(1), Producing(1)	0	946	1	8,929	0.2
13A	58	7	Abandoned(2), Producing(5)	4	1,180	1	76	2.7
13B							671	3.1
13U							33	1.1
15A	300	1	Abandoned (1)	2	16,590	0	2,359	0.6
15B							15,858	<0.1
17B	140	1	Abandoned(1)	0	6,519	0	3,183	0.2
18A	244	10	Abandoned (1), Producing(9)	7	2,720	0	164	<0.1

[1] Oil and gas well data downloaded 12/4/2012 (Colorado Oil and Gas Conservation Commission, 2012). Only wells with unique facility identification numbers and latitude/longitude were counted.

[2] Bottom-hole locations downloaded 12/4/2012 (Colorado Oil and Gas Conservation Commission, 2012).

[3] Geologic structure information from Hail and Smith (1994, 1997).

[4] 2011 monitoring data (see table 4).

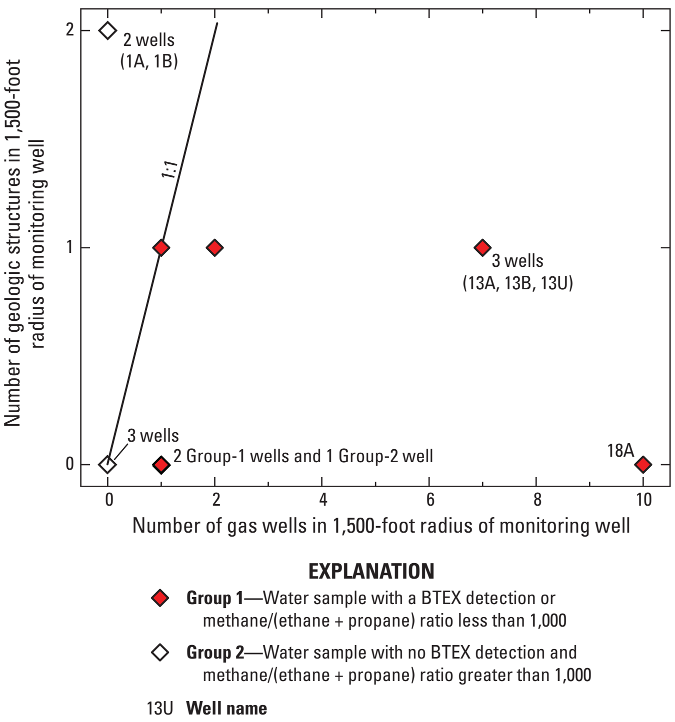


Figure 16. Graph showing number of geologic structures (faults, fractures, or fold axes) in relation to the number of gas wells in a 1,500-foot radius of the monitoring wells for group 1 and group 2 water samples collected from the monitoring wells in 2011.

River Formation that was developed several decades ago (Johnson and Rice, 1990). Monitoring data are not available to determine if these features contributed to the hydrocarbon chemistry of water from 18A.

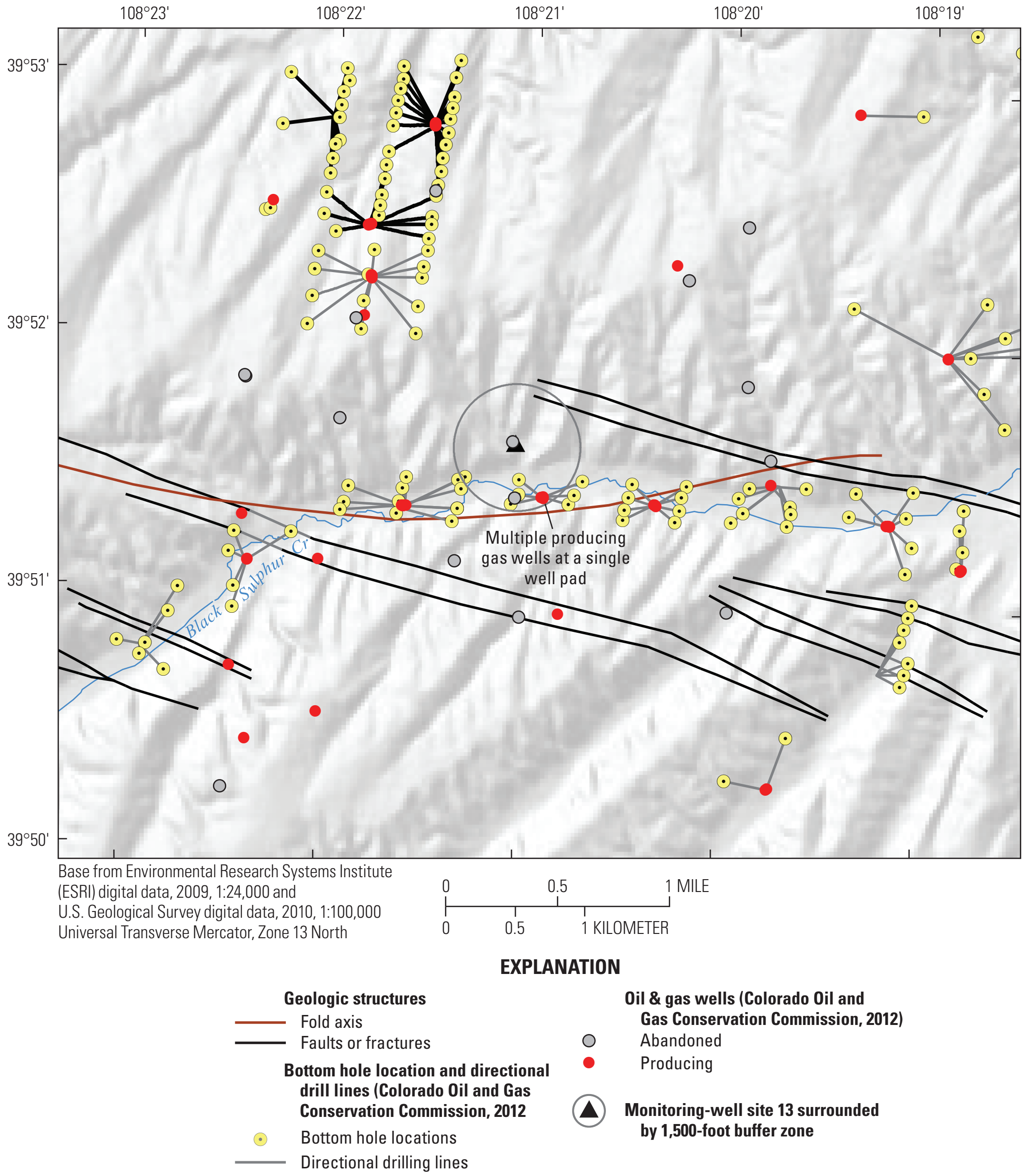
Well site 13 had seven gas wells and one geologic structure in its buffer zone. The monitoring wells at site 13 were essentially colocated with an abandoned gas well (Sulphur Creek No. 1) (fig. 17), whereas the nearest geologic structure was located 1,180 feet away. Sulphur Creek No. 1 was completed to a depth of 7,522 feet in the Mesaverde Group in 1957 and it was plugged and abandoned in 1990 (Facility number 228311; Colorado Oil and Gas Conservation Commission, 2012).

In 1956, a drill-stem test done on Sulphur Creek No. 1 indicated a strong gas show in the depth interval from 1,045 to 1,165 feet below land surface in the Parachute Creek Member below the Mahogany zone (Colorado Oil and Gas Conservation Commission, 2012), which is only 175 feet deeper than the bottom of the sample interval in well 13B. Downhole video collected from 13B in 2008 by Shell showed vigorous bubbling at the water surface in the well, indicating the zone tapped by 13B may have been in connection with the slightly deeper gas show. The water sample collected from 13B in August 2011 contained 60 mg/L methane but only a small fraction (possibly less than 10 percent) of it appeared to be thermogenic (fig.12). If the gas show contained thermogenic methane and was in connection with the monitoring well then it seems likely that most of the methane in 13B would be thermogenic. A more likely scenario is that the gas show contained biogenic methane. Data from this study indicate that substantial amounts of biogenic methane were present in the Parachute Creek Member below the Mahogany zone. The available data are more consistent with the interpretation that thermogenic gas and BTEX in water from the monitoring wells at site 13 were related to the nearby gas well(s) (fig. 17) or other potentially important features located outside the buffer zone but upgradient from the well. These other features include several faults or fractures (fig. 1) and an old test site for in-situ oil-shale retorting. Between 1966 and 1968, an in-situ oil-shale retorting test was conducted at a site located about 5 miles upgradient from well site 13. The test involved injecting natural gas into the Parachute Creek Member to generate oil from the shale, but the test was stopped because too much natural gas was lost to the formation (U.S. Congress Office of Technology Assessment, 1980). Monitoring data are not available to determine if these features contributed to the hydrocarbon chemistry of water from well site 13.

The manner in which hydrocarbons migrated to the wells at sites 13 and 18 is unclear because the relative contributions of nearby gas wells, geologic structure, and legacy contamination to hydrocarbon migration in the study area are not well understood. Collection of additional water-quality data around nearby gas wells, geologic structures, and the old test site would help test these potential migration pathways. Ultimately, collection of baseline data prior to gas-well installation and collection of time-series data after gas-well installation is the best way to understand the roles of gas wells, geologic structure, and legacy contamination in hydrocarbon migration in the study area.

Groundwater Age

Groundwater age refers to the time since water recharged an aquifer. Estimates of groundwater age are used for many purposes including the evaluation of aquifer susceptibility to contamination from human activities, estimating contaminant flushing times in aquifers, and identifying old groundwater that may not be recharged in our current (Holocene) climate regime. Ages based on the concentrations of tracers such as carbon-14 and helium-4 in groundwater are referred to as apparent ages because they are often based on simplifying assumptions regarding the effects of mixing, dispersion, and other processes affecting the tracer concentrations (Plummer and Busenberg, 2000; Cook and Böhlke, 2000). This section of the report examines apparent groundwater ages on the basis of tritium, hVOC, carbon-14, helium-4, and chlorine-36 data.



Base from Environmental Research Systems Institute (ESRI) digital data, 2009, 1:24,000 and
U.S. Geological Survey digital data, 2010, 1:100,000
Universal Transverse Mercator, Zone 13 North

Figure 17. Map showing locations of gas wells and geologic structures (faults, fractures, and fold axes) in the vicinity of monitoring well site 13. [Geologic structure from Hail and Smith (1994, 1997).]

Tritium

Tritium is a radioactive isotope of hydrogen with a half-life of 12.32 years (Lucas and Unterweger, 2000). Small concentrations of tritium are produced naturally by interactions between the atmosphere and cosmic rays, but large amounts of tritium also were injected into the atmosphere by the above-ground testing of nuclear weapons that started in the early 1950s and peaked in the early 1960s. Tritium is an excellent tracer of water movement because it is part of the water molecule. In general, tritium in groundwater originates from precipitation. Tritium concentrations were used to distinguish between old and modern groundwater. For the purposes of this study, water samples that contained less than 0.5 tritium units (TU) were considered to be old (nearly all sampled water recharged before the early 1950s) and samples that contained at least 0.5 TU were considered to be modern (recharged since the early 1950s), or to contain a mixture of modern and old water (McMahon and others, 2011). The sample from well B12B contained 0.9 TU (table 3), indicating that it contained some modern water. Water from the remaining wells contained less than 0.5 TU and was considered to be old. The presence of tritium in water from B12B is consistent with its location in a higher elevation recharge area. The sample may have contained about 10 to 20 percent modern water on the basis of the measured tritium and noble gas concentrations, and assuming tritium concentrations in local precipitation had a history similar to that in Salt Lake City, Utah (the nearest long-term record of tritium in precipitation) (Schlosser and others, 1989; Manning and others, 2005).

Halogenated VOCs

hVOCs are mostly anthropogenic chemicals that are widely used for such things as solvents, refrigerants, blowing agents, degreasers, and chemical feedstock (Deeds and others, 2012). Gas chromatography with electron-capture detection (GC-ECD) can detect hVOCs in water at concentrations sometimes two to more than four orders of magnitude lower than commonly used GC methods with mass spectrometry (Plummer and others, 2008). Because of the widespread use of hVOCs, and the high sensitivity of GC-ECD to them, several studies have used GC-ECD measurements of hVOCs in groundwater as sensitive indicators of whether groundwater is susceptible to contamination from human activity (Shapiro and others, 2004; Plummer and others, 2008; Deeds and others, 2012). In those studies, hVOC concentrations in groundwater commonly were two to four orders of magnitude lower than their Federal drinking-water standards, indicating they were not health concerns but that the groundwater was susceptible to contamination from human activity. hVOCs have been detected at very low concentrations in groundwater that was considered old on the basis of tritium data (Deeds and others, 2012). In this study, groundwater samples collected in 2012 were analyzed for hVOCs using GC-ECD to examine whether the apparently old water was susceptible to contamination from human activity.

Concentrations of 25 hVOCs measured in groundwater and quality assurance samples are listed in Appendix table 2–4. If an hVOC was detected in an equipment or field blank, it was not considered a detection in an environmental sample unless the concentration was five times greater than the concentration in the blank (U.S. Environmental Protection Agency, 1989). Thirteen hVOCs were detected after applying this screening criterion: 1,1,2,2-tetrachloroethane (1,1,2,2-PCA); 1,1,2-trichloroethane (1,1,2-TCA); 1,2-dichloroethane (1,2-DCA); chloroethane (CA); tetrachloroethene (PCE); trichloroethene (TCE); 1,1-dichloroethene (1,1-DCE); CFC-11; CFC-12; CFC-113; chloroform; methyl chloride; and methyl iodide. Chloroform, methyl chloride, and methyl iodide are not considered further because they have significant natural sources (Keene and others, 1999; Albers and others, 2011). PCE and TCE also may have natural sources but those sources are consider minor compared to the human sources (Chuck and others, 2005).

For the 10 remaining hVOCs, concentrations of detected compounds ranged from 10 to 216,000 picograms per kilogram of water (pg/kg), with a median of 1,890 pg/kg. None of the concentrations exceeded a Federal drinking-water standard. 1,1,2-TCA was the most commonly detected hVOC (6 detections) and 1,1-DCE had the highest detected concentration. The one sample that contained tritium (B12B) had three hVOC detections (fig. 18), consistent with the presence of at least a fraction of modern recharge in the sample. All the other samples that had hVOC detections had tritium activities less than 0.5 TU (old water). It is conceivable that the samples of old water with relatively low total hVOC concentrations still could have been contaminated during sample collection, handling, or analysis (even though a screening criterion was applied to the samples), but that possibility seems less likely for samples 1A and 1B that had the highest numbers of detections and total hVOC concentrations (fig. 18).

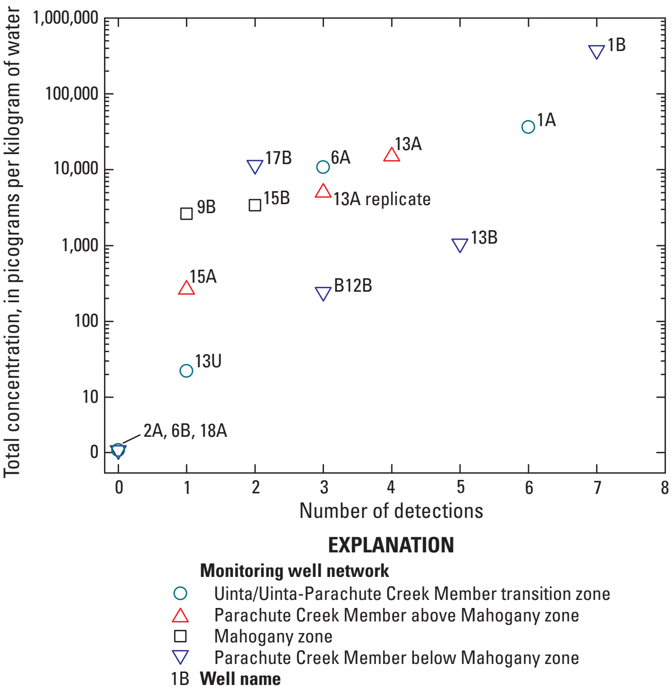


Figure 18. Graph showing total concentration of halogenated volatile organic compounds (hVOCs) in relation to the number of hVOCs detected in water samples collected from the monitoring wells in 2012.

Although the hVOC sample size for this study was small, the occurrence of more hVOCs, and at higher concentrations, in some samples of old water than in the sample of young water is counter to what was observed in California groundwater (Deeds and others, 2012). Deed and others (2012) detected more hVOCs in shallow, young groundwater in California than in deep, old groundwater and attributed that pattern to the presence of hVOCs in modern recharge from the land surface. The hVOC data for 1B in particular, a well in which the top of the open interval was about 1,200 feet below land surface, could be evidence for the introduction of hVOCs into the deep subsurface by other processes. One hypothesis is that vertical leakage along a wellbore from land surface or the upper aquifer to the lower aquifer introduced trace levels of hVOCs to the groundwater without adding measurable amounts of tritium (Deeds and others, 2012). A second hypothesis is that hVOCs entered the lower aquifer from subsurface activities, such as the drilling or operation of wells, and were subsequently transported downgradient to the monitoring well. Highly chlorinated compounds like PCE, TCE, 1,1,2,2-PCA, and 1,1,2-TCA, all of which were detected in 1B, are readily degraded to less chlorinated hVOCs by microbial processes in highly anoxic water (Vogel, 1994). The presence of these particular hVOCs in 1B and other samples with similar anoxic redox conditions could indicate either a nearby source or relatively rapid transport from a more distant source. The exact source of hVOCs in the lower aquifer cannot be determined on the basis of the available data, but the data do indicate that parts of the lower aquifer apparently were susceptible to human activity.

Carbon-14

Carbon-14 is a radioactive isotope of carbon with a half-life of 5,730 years (Kalin, 2000). Like tritium, small amounts of carbon-14 are produced naturally by interactions between the atmosphere and cosmic rays and large amounts were injected into the atmosphere by the above-ground testing of nuclear weapons. Carbon-14 in groundwater generally is derived from carbon dioxide in the atmosphere that interacts with soils and plants to produce dissolved inorganic and organic carbon. Radiocarbon dating of dissolved inorganic carbon (DIC) in groundwater has been widely used to determine apparent groundwater ages on the timescale of about 1,000 to 40,000 years (see review by Kalin, 2000).

The carbon-14 activity of DIC in the water samples ranged from less than 0.4 to about 21 percent modern carbon (pmc) (table 3). Carbon-14 activity could not be measured in water from 1B because of matrix-interference problems encountered during the analysis. The highest carbon-14 activities occurred in water samples from above the Mahogany zone, with some exceptions. The highest carbon-14 activity overall was in the sample from B12B (located in the recharge area but completed below the Mahogany zone). Water from 13U and 15A had carbon-14 activities less than 0.4 pmc even though those wells were completed above the Mahogany zone. The low carbon-14 activity in water from 15A may indicate mixing with older water from within or below the Mahogany zone because the hydraulic gradient between 15A and 15B was upward, and the chemistry of water from the two wells was similar. Water from 13U did not appear to contain water from deeper zones on the basis of the water isotopes and chloride/bromide ratios. This sample is discussed further in the section "Helium-4."

Kimball (1984) measured carbon-14 activities in some of these same wells; those activities generally were higher than the values measured in this study. Kimball (1984) reported carbon-14 activities in water from wells 13B, 15A, and 15B of 26.1, 6.9, and 5.2 pmc, respectively, whereas the activities reported here were less than 0.4 pmc. It is unclear exactly when Kimball (1984) collected samples from the wells or if they were affected by well installation in the mid 1970s.

The computer program NETPATH (Plummer and others, 1994) was used to develop mass-balance models of the changes in water chemistry between recharge and downgradient wells. The number of plausible mass-balance models for each downgradient well was constrained using mineralogic data, mineral saturation indices, and isotopic data for dissolved species and solid phases containing carbon. In NETPATH, mass-balance results were used to adjust carbon-14 activities for mass transfers involving carbon occurring in the groundwater system prior to sample collection. It was assumed that the water sample from B12B was representative of recharge water and all other wells were considered to be the downgradient wells in the NETPATH models. This assumption implies that the chemistry of recharge water did not change substantially over space and time. The limited number of complete chemical and isotopic analyses for groundwater in the recharge areas makes it difficult to evaluate this assumption. Moreover, it is possible that the carbon-14 activity of recharge varied over long times due to variations in the Earth's geomagnetic field strength and solar fluctuations (Mazaud and others, 1991; Bard and others, 1993).

Up to 8 constraints and 13 mineral phases were considered in the mass-balance models (table 6). The mineral phases were selected on the basis of mineralogic studies of rocks in the study area (Kimball, 1984; Hail, 1990; Tuttle, 2009). Not all the constraints and phases were used in each model. $\delta^{13}C$ data for calcite, dolomite, and organic carbon are from Tuttle (2009) and $\delta^{13}C$ data for nahcolite are from Reitsema (1980). The $\delta^{13}C$ composition of siderite was assumed to equal that of calcite because siderite probably precipitated from the same pool of DIC. The $\delta^{13}C$ composition of carbon dioxide in groundwater was assumed to equal that of organic carbon because the carbon dioxide probably was generated from organic carbon by redox reactions. The $\delta^{13}C$ data for methane are listed in table 3. The carbon-14 activity of each of these carbon-bearing phases was assumed to equal 0 pmc.

Radiocarbon dating with NETPATH requires three values of carbon-14 activity in DIC; the carbon-14 activity in recharge (A_o), the carbon-14 activity at the downgradient well

Table 6. Constraints, mineral phases, and isotopic data used in NETPATH (Plummer andothers, 1994) mass-balance models.

[‰, per mil; VPDB, Vienna Peedee Belemnite; na, not applicable; --, no data]

Constraint	Mineral phase	$\delta^{13}C$, mineral phase (‰, VPDB)	Source of isotopic data
Calcium	Calcite	+4 to +8	Tuttle, 2009
Carbon	Dolomite	+4 to +8	Tuttle, 2009
Fluoride	Siderite	+4 to +8	na[1]
Iron	Nahcolite	+10	Reitsema, 1980
Magnesium	Organic carbon	–30 to –25	Tuttle, 2009
Sodium	Carbon dioxide	–30 to –25	na[2]
Sulfur	Goethite	na	na
Redox	Pyrite	na	na
--	Fluorite	na	na
--	Albite	na	na
--	Halite	na	na
--	Magnesium/ sodium exchange	na	na
--	Calcium/ sodium exchange	na	na

[1] Assumed to have the same isotopic composition as calcite.

[2] Assumed to have the same isotopic composition as organic carbon.

adjusted for carbon inputs and outputs along the flow path but not for radioactive decay (A_{nd}), and the carbon-14 activity measured in the downgradient well (A) (Plummer and others, 1994). The value of A_{nd} is dependent on the value of A_o and the carbon mass transfers calculated in the mass-balance models. Radiocarbon ages are then calculated using equation 9.

$$\text{Radiocarbon age} = (5{,}730/\mathit{ln}2)\mathit{ln}(A_{nd}/A) \qquad (9)$$

For unadjusted radiocarbon ages, A_o=A_{nd}. In this study, A_o was assumed to equal the carbon-14 activity in water from well B12B (~21 pmc). Mulitple lines of evidence support the use of an A_o value on the order of about 20 pmc. Kimball (1984) reported a radiocarbon value of 30 pmc for a high-elevation spring in the study area that was considered to be representative of recent recharge on the basis of its tritium content. Additional estimates of A_o were made using the models of Fontes and Garnier (1979) and Eichinger (1983), as implemented in NETPATH. The following assumptions were made in parameterizing these models; closed system dynamics (Plummer and others, 1990), carbon-14 activity and δ^{13}C of carbonate minerals of 0 pmc and 8 per mil, respectively, and carbon-14 activity and δ^{13}C of unsaturated-zone carbon dioxide of 50 pmc and –30 per mil, respectively. The carbon-14 activity of carbon dioxide is sometimes set at 100 pmc in these models (Plummer and others, 1990; Manning, 2009), but a value of 50 pmc was chosen because of the thin modern soils, abundance of old (Eocene) organic carbon in the unsaturated zone, and the thickness of the unsaturated zone (median=201 feet). Carbon-14 activities of unsaturated-zone carbon dioxide in some other semiarid regions were much less than 100 pmc. Thorstenson and others (1983) reported carbon-14 activities of unsaturated-zone carbon dioxide as low as about 2 pmc at depths of about 30 feet in the Great Plains of North Dakota and Michel and McMahon (2008) reported carbon-14 activities of unsaturated-zone carbon dioxide as low as about 57 pmc at depths of about 135 feet in the High Plains of Colorado. The values of A_o calculated using the Fontes and Garnier (1979) and Eichinger (1983) models were 23 and 22 pmc, respectively, similar to the value measured in B12B.

Unadjusted radiocarbon ages ranged from 11,700 years for water from well 1A to greater than 33,000 years for the samples with carbon-14 activities less than 0.4 pmc (table 7). A radiocarbon age was not calculated for water from B12B, but that water was assumed to have an apparent age of about 100±50 years on the basis of its location in the flow system, its tritium and helium-4 contents, and its helium-3/helium-4 ratio. In many cases, the unadjusted ages likely overestimate the actual ages because carbonate mineral dissolution and organic-carbon oxidation coupled to sulfate reduction dilute the DIC pool with carbon that was free of carbon-14.

Mineral mass transfers calculated by NETPATH indicate that substantial amounts of inorganic and organic carbon entered and (or) left the groundwater system between the recharge and downgradient wells (table 7). Many of the models required calcite precipitation, dolomite and (or) nahcolite dissolution, ion exchange, and organic carbon oxidation to achieve mass balance (table 7). Organic carbon oxidation was primarily associated with sulfate reduction and methanogenesis, as indicated by the presence of elevated concentrations of sulfide and methane in many of the samples (tables 2 and 4), and by the inverse relation between sulfate and bicarbonate concentrations (fig. 8*D*). Many of the models also required some addition or loss of carbon dioxide, which probably indicates that the concentration of DIC in recharge was not precisely represented by water from well B12B (Plummer and Sprinkle, 2001). As a check on the mass-balance accounting of this carbon turnover, the measured and modeled δ^{13}C-DIC values at the downgradient wells were compared. The values generally compared well across a wide range of δ^{13}C-DIC values (about –11 to +8 per mil) (table 7). For samples that had carbon-14 activities greater than 0.4 pmc, radiocarbon ages adjusted for this carbon mass transfer ranged from 5,000 to 23,000 years for the NETPATH, Fontes and Garnier (1979), and Eichinger (1983) models (table 7), which are about 4,000 to 13,000 years younger than the unadjusted ages. For two of the three samples from above the Mahogany zone (1A and 2A), the average ages from the three adjustment models were less than 10,000 years, whereas both samples from within or below the Mahogany zone had average ages greater than 10,000 years. The oldest adjusted radiocarbon age was for sample 9B, about 23,000 years. The carbon-14 activity of 9B was close to the instrument background level of about 0.4 pmc. The uncertainty in these age estimates is about ±1,000 years on the basis of the range of adjusted ages for each well (table 7). Additional uncertainty in the radiocarbon ages may be associated with the validity of the chosen A_o value and the validity of the mass balance models used to calculate A_{nd}.

Diffusion of carbon-14 from aquifers to confining layers, or from fractures to rock matrix, can give the appearance of radioactive decay of carbon-14 and result in radiocarbon ages that are biased old (Sanford, 1997; Bethke and Johnson, 2002). Although diffusion was not explicitly included in the radiocarbon-age adjustments, it could result in age reductions of 50 percent or more in some settings (Sanford, 1997). Even if that were the case in the study area, the radiocarbon ages for the downgradient wells would still be in excess of several thousand years in most cases.

Helium-4

The radiocarbon ages were further evaluated in the context of the helium-4 data (table 8). Helium-4 is a stable isotope of helium. The primary sources of helium-4 in groundwater are: (1) water equilibration with the atmosphere at the time of recharge (air-saturated water, ASW), (2) air-bubble entrainment in groundwater during recharge (excess air), (3) decay of uranium- and thorium-bearing minerals in the aquifer (in-situ production), and (4) fluxes from external subsurface sources such as the mantle, deeper formations in the crust, and adjacent confining layers (external flux). Outward diffusion of helium-4 trapped in mineral grains is another potential source

Table 7. Mass-balance results and radiocarbon ages for water collected from the monitoring wells in 2011.

[mmol/kg, millimoles per kilogram of water; DIC, dissolved inorganic carbon; ^{14}C, carbon-14; ‰, per mil, VPDB, Vienna Peedee Belemnite; pmc, percent modern carbon; <, less than; >, greater than; na, not applicable; --, no data]

Variable	Downgradient well[1]											
	1A	2A	6A[5]	6B	9B	13A[5]	13B	13U	15A	15B	17B[5]	18A
Modeled phase mass transfer (mmol/kg)[2]												
Calcite	–2.65	–2.39	na	–4.73	–2.30	na	–3.88	–1.99	–0.40	–0.56	na	–2.60
Dolomite	1.00	1.85	na	2.28	na	na	2.10	1.64	na	na	na	1.49
Siderite	0.50	na	na	na	na	na	na	na	1.41	–1.65	na	na
Nahcolite	na	na	na	na	6.15	na	na	na	5.62	7.75	na	na
Organic carbon	3.36	0.61	na	10.42	17.36	na	11.76	0.15	12.71	11.29	na	0.18
Carbon dioxide	na	1.98	na	–1.60	–2.38	na	–1.85	2.88	–2.93	na	na	2.37
Goethite	0.48	0.14	na	1.24	1.70	na	0.76	na	na	3.35	na	na
Pyrite	–0.97	–0.14	na	–1.24	–1.69	na	–0.76	na	–1.42	–1.69	na	na
Fluorite	na	na	na	0.48	0.42	na	0.10	na	0.49	0.61	na	na
Albite	na	2.96	na	na	na	na	na	3.92	na	na	na	3.31
Halite	na	na	na	na	na	na	na	na	2.94	2.63	na	na
Magnesium/sodium exchange	1.50	na	na	4.36	2.03	--	3.53	na	na	na	na	na
Calcium/sodium exchange	na	na	na	na	na	na	na	na	3.96	4.01	na	na
Saturation index,[3] isotopic values, and unadjusted radiocarbon age												
Calcite	0.17	0.28	0.05	0.03	0.14	0.14	0.23	0.08	–0.16	–0.04	–0.03	0.08
Dolomite	1.02	1.00	0.49	0.13	0.24	0.87	0.80	0.50	–0.21	0.20	0.17	0.79
Siderite	–0.31	–9.52	--	–1.51	0.24	–1.17	--	–1.29	–1.73	0.46	–0.02	–2.61
Nahcolite	–3.92	–3.59	–3.60	–3.22	–3.09	–3.60	–3.28	–3.51	–2.97	–2.90	–1.93	–3.60
δ^{13}C DIC—measured (‰, VPDB)	–9.39	–11.15	–6.17	–3.70	+7.95	–5.13	–9.31	–9.36	+3.53	+4.83	+8.7	–11.10
δ^{13}C DIC—modeled (‰, VPDB)	–10.5	–10.1	na	–3.7	+7.6	na	–9.0	–11.3	+3.8	+5.6	na	–10.86
^{14}C DIC—measured (pmc)	5.08	2.48	1.89	1.59	0.44	0.51	<0.4	<0.4	<0.4	<0.4	<0.4	1.29
Unadjusted radiocarbon age (years)	11,700	17,700	19,900	21,300	32,000	30,700	>33,000	>33,000	>33,000	>33,000	>33,000	23,100
Adjusted radiocarbon age (years)												
Fontes and Garnier (1979) model[4]	7,000	5,000	na	12,000	23,000	na	na	na	na	na	na	19,000
Eichinger (1983) model[4]	7,000	5,000	na	12,000	23,000	na	na	na	na	na	na	18,000
NETPATH	6,000	12,000	na	11,000	22,000	na	na	na	na	na	na	18,000

[1] Well B12B is the upgradient well in each case and its measured ^{14}C activity was 21 pmc.

[2] Positive value for dissolution, negative value for precipitation.

[3] Saturation indexes were calculated using NETPATH, except for nahcolite, which was calculated using PHREEQC (Parkhurst and Appelo, 1999).

[4] Assuming a closed system with unsaturated zone carbon dioxide δ^{13}C and ^{14}C values of –30 per mil and 50 pmc, respectively, except for well 2A where a ^{14}C value of 20 pmc was assumed.

[5] Satisfactory mass-balance models were not found.

Table 8. Noble-gas data for water collected from the monitoring wells.

[U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; mg/L, milligrams per liter; cm^3STP/g, cubic centimeters at standard temperature and pressure per gram of water; 1σ, 1 standard deviation; R/R_a, $(helium\text{-}3/helium\text{-}4)_{sample}/(helium\text{-}3/helium\text{-}4)_{air}$; <, less than; --, no data]

Well name	Geologic interval in which sample interval is located	Collection date	Collection time	Nitrogen (mg/L)[1]	Argon (mg/L)[1]	Helium (10^{-8} cm^3 STP/g)[2]	Neon (10^{-7} cm^3 STP/g)[2]	Argon (10^{-4} cm^3 STP/g)[2]	Krypton (10^{-8} cm^3 STP/g)[2]	Xenon (10^{-8} cm^3 STP/g)[2]	Nitrogen (10^{-2} cm^3 STP/g)[2]	R/R_a[2]
B12B	PCMB	8/22/2011	1200	17.83	0.6243	4.60	1.81	3.24	8.37	1.08	1.25	0.932
B12B	PCMB	8/15/2012	1100	18.11	0.6118	5.75	2.15	3.43	8.10	1.22	1.37	0.936
1A	U-PCM	8/18/2011	1500	18.70	0.6949	10.7	2.21	3.92	9.32	1.33	1.55	0.483
1A	U-PCM	8/16/2012	1100	19.08	0.7000	--	--	--	--	--	--	--
1B	PCMB	8/18/2011	1200	--	--	1.84	0.03	0.16	1.00	0.13	<0.01	0.025
1B	PCMB	8/16/2012	1400	0.8012	0.0364	2.85	0.06	0.05	--	--	0.01	0.020
2A	U-PCM	8/23/2011	1130	15.21	0.5532	6.66	1.74	3.16	7.79	1.17	1.29	0.604
2A	U-PCM	8/21/2012	1100	15.75	0.5461	--	--	--	--	--	--	--
6A	U-PCM	8/25/2010	1000	19.70	0.7006	--	--	--	--	--	--	--
6A	U-PCM	11/3/2010	1100	19.83	0.7028	--	--	--	--	--	--	--
6A	U-PCM	6/2/2011	1000	19.67	0.6986	--	--	--	--	--	--	--
6A	U-PCM	8/16/2011	1000	19.66	0.7015	9.25	2.04	3.46	8.55	1.32	1.30	0.580
6A	U-PCM	8/17/2012	1400	19.92	0.7026	--	--	--	--	--	--	--
6B	PCMB	8/25/2010	1300	19.08	0.7392	42.4	2.29	3.75	8.87	1.19	1.45	0.143
6B	PCMB	11/3/2010	1500	18.72	0.7753	--	--	--	--	--	--	--
6B	PCMB	6/2/2011	1500	19.77	0.7724	--	--	--	--	--	--	--
6B	PCMB	8/16/2011	1600	16.97	0.6463	--	--	--	--	--	--	--
6B	PCMB	8/17/2012	1100	20.50	0.7019	--	--	--	--	--	--	--
9B	MZ	8/20/2011	1100	--	--	107	1.44	3.01	8.35	0.88	1.26	0.054
9B	MZ	8/18/2012	1100	8.28	0.2995	--	--	--	--	--	--	--
13A	PCMA	8/24/2010	1400	21.59	0.7529	18.8	2.55	4.38	10.4	1.44	1.81	0.334
13A	PCMA	11/2/2010	1310	21.61	0.7635	--	--	--	--	--	--	--
13A	PCMA	6/1/2011	950	--	--	--	--	--	--	--	--	--
13A	PCMA	6/1/2011	1130	[3]21.92	[3]0.7659	--	--	--	--	--	--	--
13A	PCMA	8/17/2011	1200	20.55	0.7357	--	--	--	--	--	--	--
13A	PCMA	8/14/2012	1100	22.50	0.7669	18.7	2.47	4.14	9.55	1.38	2.13	0.292
13B	PCMB	8/24/2010	1600	22.43	0.8364	--	--	--	--	--	--	--
13B	PCMB	11/2/2010	1410	1.540	0.0987	--	--	--	--	--	--	--
13B	PCMB	6/1/2011	1500	2.840	0.1923	--	--	--	--	--	--	--
13B	PCMB	8/17/2011	1400	1.699	0.1010	--	--	--	--	--	--	--
13B	PCMB	8/14/2012	1200	1.657	0.0889	--	--	--	--	--	--	--
13U	U-PCM	8/24/2010	1200	13.11	0.5645	92.9	1.77	3.58	10.3	1.48	1.54	0.072
13U	U-PCM	11/2/2010	1210	13.45	0.5713	--	--	--	--	--	--	--
13U	U-PCM	6/1/2011	1300	13.03	0.5599	--	--	--	--	--	--	--
13U	U-PCM	8/17/2011	1100	12.64	0.5507	90.2	1.73	3.44	8.44	1.26	1.30	0.065
13U	U-PCM	8/14/2012	1300	9.109	0.4245	73.8	1.39	3.45	9.04	1.50	1.44	0.065
15A	PCMA	8/19/2011	1300	--	--	241	1.90	3.44	--	1.13	1.51	0.021
15A	PCMA	8/20/2012	1400	14.31	0.5247	--	--	--	--	--	--	--
15B	MZ	8/19/2011	1000	--	--	376	1.59	3.41	7.88	1.01	1.32	0.027
15B	MZ	8/20/2012	1000	18.49	0.6863	--	--	--	--	--	--	--
17B	PCMB	8/21/2011	1030	1.462	0.0618	759	0.75	1.75	4.20	0.45	0.33	0.012
17B	PCMB	8/19/2012	1000	1.300	0.0528	--	--	--	--	--	--	--
18A	U-PCM	8/21/2011	1600	19.30	0.6761	71.9	1.86	3.79	8.44	1.11	1.57	0.068
18A	U-PCM	8/18/2012	1600	19.60	0.6677	--	--	--	--	--	--	--

[1] Analysis done by gas chromatography.

[2] Analytical uncertainties (1σ) for helium, neon, argon, krypton, xenon, nitrogen, and R/R_a were 1, 2, 2, 3, 3, 2, and 1 percent, respectively.

[3] The packer in well 13A (see Appendix figure 1–1) was not operating properly on this date so the reported concentrations may not be comparable to the concentrations on the other sample dates.

of helium-4 (Solomon and others, 1996), but it is considered to be negligible in the study area because of the age (Eocene) of the sediments. The combination of helium-4 from in-situ production and external fluxes is termed excess helium-4. Whereas helium-4 in groundwater from ASW and excess air are fixed at the time of recharge, excess helium-4 accumulates in groundwater as it ages and can sometimes be used to determine groundwater age. Helium-4 can potentially be used to determine apparent groundwater ages on the timescale of about 100 to 10^6 years (Plummer and others, 2012).

Excess helium-4 is calculated as the difference between the measured helium-4 concentration in the sample and the concentrations in ASW and excess air. Concentrations of helium-4 in groundwater from air equilibration and excess air can be calculated if the elevation of the recharge area, recharge temperature, total amount of excess air, and salinity of recharge are known. Two end members for recharge elevation were considered for each sample—the elevation of the water table at the well location and the maximum elevation at the watershed margin (8,500 feet). The salinity of recharge water was assumed to be 0 parts per thousand. Recharge temperature and excess air were subsequently calculated on the basis of the noble gas and nitrogen gas data and the unfractionated air (UA) and closed equilibrium (CE) models for excess air (Aeschbach-Hertig and others, 1999; Ballentine and Hall, 1999; Manning and Solomon, 2003). Calculations of recharge temperature and excess air were performed using a model that minimizes the sum of the weighted squared difference (χ^2) between measured and modeled noble gas concentrations (Manning, 2009, 2011). One standard deviation (1σ) uncertainties in the model-calculated parameters were calculated using a Monte Carlo method with 3,000 realizations (Manning, 2009, 2011).

Noble-gas recharge temperatures ranged from 0.4 to 8.2 °C, and concentrations of excess air ranged from 0 to 0.0072 $\mathrm{cm^3STP/g}$ (table 9). Recharge temperature and excess-air concentrations for the samples from wells 1B, 9B, and 17B could not be determined with the models because degassing in these methane-rich samples apparently stripped some noble gases from solution. The amount of degassing was substantial in the samples from 1B and 17B when viewed in the context of the expected concentrations of neon and argon in water at various recharge temperatures and with various amounts of excess air (fig. 19). Andrews and others (1991) reported similarly depleted neon and argon concentrations in methane-rich groundwater from the Milk River aquifer in Canada; however, those samples retained their high helium-4 concentrations. In the case of 1B, the helium-4 was nearly completely stripped from solution, which was not observed in the other high-methane samples (fig. 14).

How noble gases were so extensively stripped from 1B is unknown, but one hypothesis is that the water had been previously injected into the saline zone for the purpose of in-situ leach mining of nahcolite. The areas of in-situ mining are located about 6 miles upgradient from well site 1. The in-situ mining process injects heated water (at least 240 °F) into the saline zone (P. Daggett, Bureau of Land Management, oral commun., 2013). Depending on how the water is heated and injected, this temperature could be sufficiently high to completely strip noble gases from solution. The hVOC data indicate that water from 1B was influenced by human activity, but monitoring closer to the area of nahcolite mining would be needed to further evaluate this hypothesis.

Calculated concentrations of excess helium-4 ranged from 0.36×10^{-8} to 754×10^{-8} $\mathrm{cm^3STP/g}$ (table 9). These concentrations are as much as 220 times greater than the concentration of helium-4 in ASW at 0 to 10 °C and an elevation of 5,900 to 8,500 feet, and they indicate that substantial amounts of excess helium-4 accumulated in some of the samples. Most of the samples from recharge areas (B12B) and from above the Mahogany zone (1A, 2A, 6A, and 13A) contained relatively low concentrations of excess helium-4. Most of the samples from within and below the Mahogany zone (6B, 9B, 15B, and 17B) contained much higher concentrations of excess helium-4. Water from wells 13U, 15A, and 18A also contained relatively high concentrations of excess helium-4. Concentrations of excess helium-4 in water from 9B and 17B were estimated on the basis of the average recharge temperature of 4 °C and average concentration of excess air of 0.0022 $\mathrm{cm^3STP/g}$ from the other samples; however, because of degassing, the concentrations of excess helium-4 in these samples underestimates the actual concentrations, particularly in 17B.

Calculated concentrations of excess helium-4 were not very sensitive to the recharge elevation used in the model (table 9). The relative percent difference in concentrations of excess helium-4 between a sample with a recharge elevation equal to the elevation of the water table and the same sample with a recharge elevation of 8,500 feet ranged from 0 to 8 percent.

Helium-3/helium-4 ratios can be used to determine the contributions of mantle and crustal sources to excess helium-4 because of the large difference in ratios between mantle (~1×10^{-5}; Ozima and Podosek, 1983) and crustal helium (~2×10^{-8}; Mamyrin and Tolstikhin, 1984). In figure 20, helium-3/helium-4 ratios were plotted in relation to the ratio of helium-4 in ASW to total helium-4 in the sample. X-axis values that approach 0 indicate that essentially all the helium-4 in the sample was excess helium-4. An x-axis value of 1 indicates that all the helium-4 was from the atmosphere. Almost all the helium-4 in the sample from well B12B, located in the recharge area, was from the atmosphere and its helium-3/helium-4 value approached that of ASW (fig. 20). Samples from farther downgradient and deeper in the flow system contained much more excess helium-4 than B12B, and their helium-3/helium-4 ratios approached the value for crustal helium. A least-squares linear regression fit to the data yielded a y-intercept value of 2.1×10^{-8} (fig. 20), which is essentially identical to the helium-3/helium-4 ratio of crustal helium. The data indicate that the excess helium-4 was from crustal sources (within and (or) outside the aquifer), which simplifies the use of helium-4 for groundwater age dating.

Table 9. Recharge temperatures, concentrations of excess air and excess helium-4, and helium-4 ages for water collected from the monitoring wells.

[ft, feet; °C, degrees Celsius; cm^{3}STP/g, cubic centimeters at standard temperature and pressure per gram of water; 1σ, 1 standard deviation; Ae, initial trapped air volume; EA, excess air; F, excess air fractionation factor; χ^2, chi-squared; --, no data; cm^{3}STP/g/yr, cubic centimeters at standard temperature and pressure per gram per year; cm^{3}STP/cm^2/yr, cubic centimeters at standard temperature and pressure per square centimeter per year; CE, closed-system equilibration; UA, unfractionated air]

Well name	Sample date	Recharge elevation (ft)	Excess air model	Noble gas recharge temperature (°C)	±1σ error (°C)	Ae (cm^{3}STP/g)	F	EA (cm^{3}STP/g)	χ^2 ceiling	χ^2	Excess helium-4 (10^{-8} cm^{3}STP/g)	±1σ error (10^{-8} cm^{3}STP/g)	Helium-4 age (years)[1,2]	Comments
B12B	8/22/2011	7,130	CE	8.2	1.8	0.0033	0.52	0.0014	3.84	0.34	0.36	0.12	90	
B12B	8/22/2011	8,500	CE	6.9	2.2	0.0057	0.60	0.0019	3.84	0.76	0.39	0.12	100	
1A	8/18/2011	5,944	CE	3.8	0.6	0.0027	0.00	0.0027	3.84	1.11	5.47	0.17	1,400	
1A	8/18/2011	8,500	CE	1.6	1.1	0.0074	0.40	0.0039	3.84	1.43	5.57	0.20	1,500	
1B	8/18/2011	5,943	--	--	--	--	--	--	--	--	--	--	--	Substantial degassing
1B	8/18/2011	8,500	--	--	--	--	--	--	--	--	--	--	--	Substantial degassing
2A	8/23/2011	6,139	CE	7.9	0.5	0.0006	0.00	0.0006	5.99	5.36	2.65	0.12	700	
2A	8/23/2011	8,500	CE	5.2	0.5	0.0011	0.00	0.0011	5.99	3.01	2.63	0.12	700	
6A	8/16/2011	6,158	UA	4.4	0.6	--	--	0.0019	3.84	1.01	4.46	0.16	1,200	
6A	8/16/2011	8,500	UA	2.1	0.7	--	--	0.0025	3.84	0.50	4.44	0.15	1,200	
6B	8/25/2010	6,157	UA	4.9	0.7	--	--	0.0033	3.84	0.22	36.9	0.44	9,600	
6B	8/25/2010	8,500	UA	2.1	0.7	--	--	0.0038	3.84	0.06	36.8	0.44	9,600	
9B	8/20/2011	6,892	--	--	--	--	--	--	--	--	[3]102	--	27,000	some degassing
9B	8/20/2011	8,500	--	--	--	--	--	--	--	--	[3]102	--	27,000	some degassing
13A	8/24/2010	6,342	CE	2.3	2.4	0.0212	0.54	0.0063	5.99	1.45	13.0	0.26	3,400	
13A	8/24/2010	8,500	CE	0.4	2.6	0.0227	0.50	0.0072	5.99	2.19	13.1	0.25	3,400	
13U	8/17/2011	6,340	CE	4.9	0.5	0.0003	0.00	0.0003	5.99	0.26	86.3	0.91	[4]22,000	
13U	8/17/2011	8,500	CE	2.6	0.5	0.0008	0.00	0.0008	5.99	0.21	86.3	0.91	[4]22,000	
15A	8/19/2011	6,771	UA	6.9	0.6	--	--	0.0016	3.84	1.63	237	2.41	62,000	
15A	8/19/2011	8,500	UA	5.0	0.6	--	--	0.0021	3.84	2.85	237	2.48	62,000	
15B	8/19/2011	6,786	UA	5.6	0.3	--	--	0.0000	3.84	4.04	372	3.80	97,000	some degassing
15B	8/19/2011	8,500	UA	3.0	0.6	--	--	0.0001	3.84	2.64	372	3.77	97,000	some degassing
17B	8/21/2011	6,035	--	--	--	--	--	--		--	[3]754	--	[5]196,000	Substantial degassing
17B	8/21/2011	8,500	--	--	--	--	--	--		--	[3]754	--	[5]196,000	Substantial degassing
18A	8/21/2011	6,325	UA	3.3	0.7	--	--	0.0009	3.84	5.57	67.7	0.74	18,000	
18A	8/21/2011	8,500	UA	0.9	0.6	--	--	0.0014	3.84	6.59	67.7	0.73	18,000	

[1] Assumes excess helium-4 was only from in situ production. Uncertainty of the helium-4 ages is about ±35 percent.

[2] In-situ helium-4 production rate of $(4.26\pm1.59)\times10^{-11}$ cm^{3}STP/g/yr.

[3] Assumes recharge temperature of 4°C and excess air concentration of 0.0022 cm^{3}STP/g.

[4] The helium-4 age would be 4,000 years if, in addition to in situ production, there was an external helium-4 flux of 3.2×10^{-8} cm^{3}STP/cm^2/yr.

[5] Sample substantially degassed, age may be older.

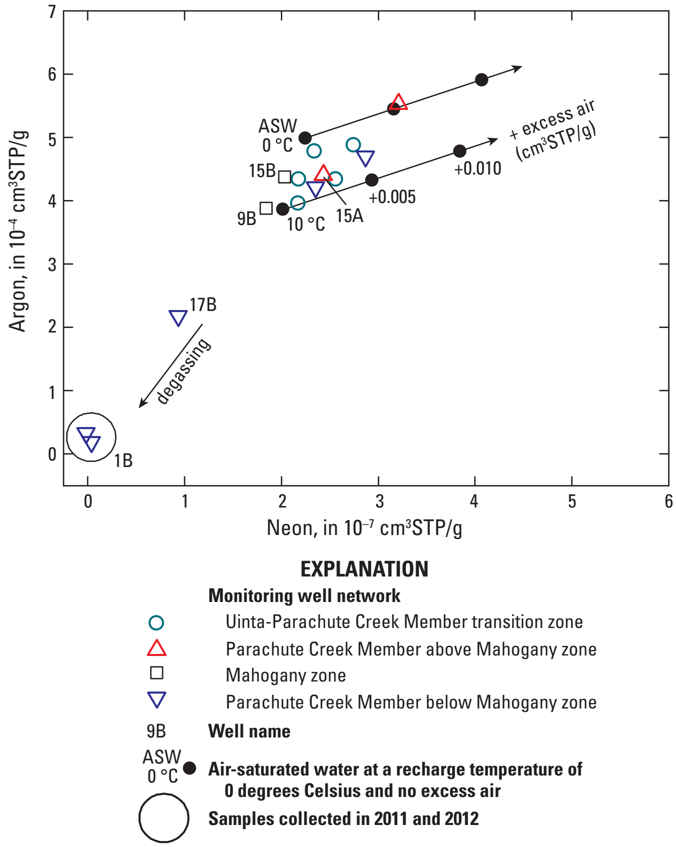


Figure 19. Graph showing argon concentrations in relation to neon concentrations for water samples collected from the monitoring wells in 2011, except as noted; cm^{3}STP/g, cubic centimeters at standard temperature and pressure, per gram of water. [Recharge elevations were assumed to equal the elevation of the water table at each site. Concentrations were normalized to sea level for plotting purposes.]

Initial helium-4 age estimates were made by assuming all the excess helium-4 was generated in the aquifer (in-situ production). The in-situ helium-4 production rate (R, in cubic centimeters at standard temperature and pressure per gram per year, cm^{3}STP/g/yr) was calculated according to equation 10 (Andrews and Lee, 1979; Stute and others, 1992; Plummer and others, 2012):

$$R = (\Lambda_{He})(\rho_r/\rho_w)(C_U P_U + C_{Th} P_{Th})((1-n)/n_{eff}) \qquad (10)$$

where

Λ_{He}	is the helium release factor from the rock (assumed to be unity, Andrews and Lee, 1979; Stute and others, 1992);
ρ_r and ρ_w	are the rock and water densities, respectively;
C_U and C_{Th}	are the concentrations of uranium and thorium in the rock, respectively;
P_U and P_{Th}	are the helium-4 production rates from uranium and thorium decay, respectively; and
n and n_{eff}	are the total and effective porosities of the rock, respectively.

The rock and water densities were assumed to be 2.6 and 1 gram per cubic centimeter, respectively. Concentrations of uranium and thorium were measured in eight rock samples (table 10), and averaged about 5.3±3.1 and 8.1±2.5 parts per million, respectively. These concentrations are similar to previously reported concentrations of uranium and thorium in the Parachute Creek Member (Dean and others, 1981). The values of P_U and P_{Th} are 1.19×10^{-13} and 2.88×10^{-14} cm^{3}STP/µg/yr, respectively (Andrews and Lee, 1979). The values of n and n_{eff} were assumed to be 0.05 (Robson and Saulnier, 1981). Substitution of these values into equation 10 results in a value for R equal to $(4.3\pm1.6)\times10^{-11}$ cm^{3}STP/g/yr. Helium-4 ages were then calculated according to equation 11:

$$\text{Helium-4 age} = (\text{Concentration of excess helium-4})/R \qquad (11)$$

Uncertainty in the helium-4 ages was about ±35 percent, mostly due to variability in uranium and thorium concentrations in the rocks. Additional uncertainty could be associated with the porosity values, which are not well constrained for the study area.

The helium-4 ages generally exhibited good agreement with the adjusted radiocarbon ages (fig. 21), implying that in-situ production alone could account for the excess helium-4

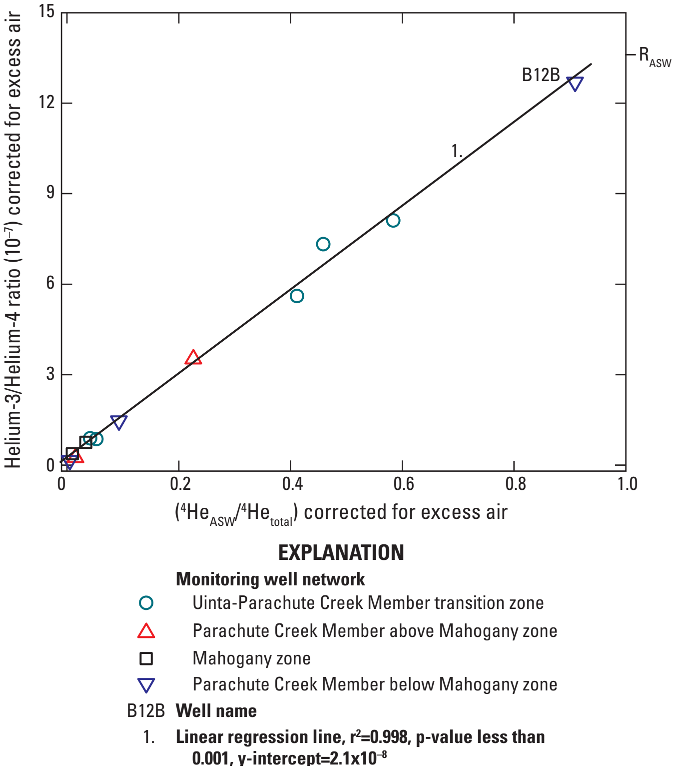


Figure 20. Graph showing helium-3/helium-4 ratios in relation to the ratio of helium-4 in air-saturated water to total helium-4 in the sample for water samples collected from the monitoring wells in 2011; ASW, air-saturated water; ^{4}He$_{ASW}$, helium-4 in ASW; ^{4}He$_{total}$, total helium-4 in the sample; R$_{AWS}$, helium-3/helium-4 ratio of AWS.

Table 10. Concentrations of uranium and thorium in selected rock samples.

[U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; ft, feet; 1σ, 1 standard deviation; ppm, parts per million]

Core hole name	Sample depth (ft below land surface)	Geologic interval in which sample interval is located	Uranium (ppm)	Thorium (ppm)
Sinclair Oil Bradshaw 1	718	PCMA	3.30	4.52
Sinclair Oil Bradshaw 1	764	MZ	4.54	7.86
Sinclair Oil Bradshaw 1	893	PCMB	4.46	8.52
Superior Oil core hole 29	962	PCMA	5.66	8.22
Superior Oil CH-29	1,054	MZ	4.28	4.41
Superior Oil CH-29	1,210	PCMB	12.7	9.02
USGS TH-13U	20 to 25	U-PCM	3.80	11.3
USGS TH-13U	40 to 45	U-PCM	3.70	10.66
average ± 1σ			5.30±3.1	8.06±2.5

in the samples for which adjusted carbon-14 ages were available. This interpretation is consistent with the hydrocarbon gas composition of those samples, which showed that they contained little or no thermogenic methane. Natural gas commonly contains carbon dioxide, helium, and other noble gases (Ballentine and others, 2002). Thus, the presence of thermogenic gas in the samples also could be considered evidence for an external flux of helium.

Helium-4 ages ranged from about 22,000 to 196,000 years for four samples (13U, 15A, 15B, and 17B) that could not be assigned radiocarbon ages because of their low carbon-14 activities (table 9). Of those four samples, only 13U had a large fraction of thermogenic methane (100 percent) (fig. 12), indicating a probable external helium flux at that well. If some of the helium-4 in 13U was produced outside the aquifer then the helium-4 age for 13U would be younger than 22,000 years. Major-ion and ^{87}Sr/^{86}Sr data indicate that water from 13U may be relatively young. 13U had high concentrations of calcium, magnesium, and sulfate, low sodium concentrations, and a low ^{87}Sr/^{86}Sr ratio (tables 2 and 3), similar to other chemically unevolved samples from above the Mahogany zone (1A, 2A, 13A) that had helium-4 ages less than 4,000 years. The low carbon-14 activity in 13U compared to other samples from above the Mahogany zone could be due in part to the addition of carbon-14 depleted carbon dioxide associated with thermogenic gas to the groundwater. Johnson and Rice (1990) reported carbon dioxide concentrations of 0.6 to 8.5 mole percent in 10 natural gas samples collected from wells in the same township in which 13U is located. 13U had the highest carbon dioxide concentrations of all the samples from above the Mahogany zone (table 4).

Although the magnitude of the external helium flux at 13U is unknown, a flux of about 3×10^{-8} $cm^3STP/cm^2/yr$ would result in a helium-4 age of about 4,000 years at 13U, assuming a porosity of 5 percent and an aquifer thickness of 120 feet (Day and others, 2010). This flux actually is quite small in comparison to the fluxes in many other geologic settings (see reviews by Torgersen, 2010 and Kulongoski and Hilton, 2011), and indicates that only a very small helium flux would be needed to produce a helium-4 age for 13U that is similar to the ages of other samples from above the Mahogany zone that were not impacted by thermogenic gas. On the basis of this discussion, a helium-4 age younger than 22,000 years (possibly less than 4,000 years) is favored for 13U.

The other three samples that could not be assigned radiocarbon ages (15A, 15B, and 17B) had the oldest helium-4 ages of all the samples (greater than 60,000 years) (table 9). Water from 15A may represent a mixture of relatively young water from above the Mahogany zone and much older water from within or below the Mahogany zone because the hydraulic gradient between 15A and 15B was upward and the chemistry of water from the two wells was similar (table 2). Moreover, chloride/bromide ratios indicate that 15A may have mixed with a small amount of deeper formation water associated with natural gas (fig. 9).

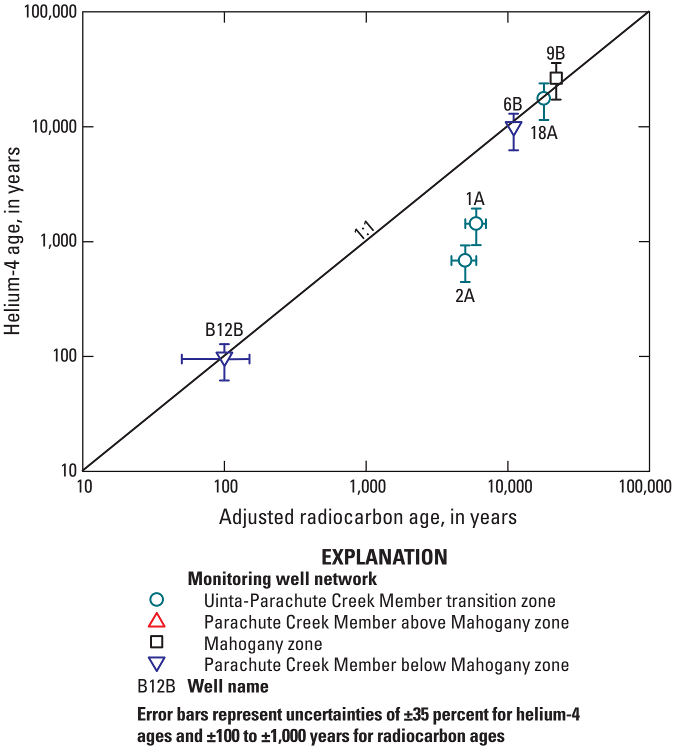


Figure 21. Graph showing helium-4 ages in relation to adjusted radiocarbon ages for the case of no external helium flux.

The other two samples, 15B and 17B, had high chloride concentrations and high $^{87}Sr/^{86}Sr$ ratios (fig. 11) that are characteristic of deeply circulated groundwater in the study area. Thus, having the oldest ages associated with these samples is conceptually consistent with the chemical and isotopic data. Also, 17B is located near the regional discharge area where the oldest ages would be expected. The sample from 17B contained a very small amount of propane (thermogenic gas), although the methane/Σ(ethane + propane) ratio was large (fig. 12), which indicates that 17B was affected to a small degree by an external gas flux that could have contained helium-4. Even a very small external helium flux could be important at long time scales such as may apply to 17B. For example, a flux of 3×10^{-9} $cm^3STP/cm^2/yr$ (10 times smaller than the hypothetical flux at 13U) would reduce the age of 17B from 196,000 to 125,000 years. A flux equal to that at 13U would result in an age of 35,000 years. Despite the uncertain role of an external helium flux at 17B, the groundwater age is still old in comparison to the age at other sites and probably exceeds 50,000 years.

It is less clear why groundwater at 15B should be so old given its upgradient location in the flow system (fig. 1). It would be helpful to have more samples in that part of the study area to better understand the flow system. Also, it would be helpful to have a better understanding of the chemistry of produced waters in the study area to better recognize where they may have mixed with groundwater in the bedrock aquifers.

Overall, the helium-4 ages are considered to be the most complete data set for characterizing groundwater age distributions in the aquifers given the generally good agreement between the helium-4 and radiocarbon ages and given that helium-4 ages could be determined for more samples than could radiocarbon ages. However, the data set is small. Additional studies of groundwater age would improve the understanding of age distributions in the aquifers, resulting in a better understanding of the flow system.

Chlorine-36

Chlorine-36 is a radioactive isotope of chlorine with a half-life of about 301,000 years. Chlorine-36 can potentially be used to determine apparent groundwater ages on the timescale of about 50,000 to 10^6 years (Plummer and others, 2012). The primary natural sources of chlorine-36 in groundwater are cosmogenic chlorine-36 in precipitation, weathering release from mineral surfaces in recharge areas that have interacted with cosmic radiation in the atmosphere, and production in the subsurface (Phillips, 2000). Like tritium and carbon-14, large amounts of chlorine-36 also were injected into the atmosphere by the above-ground testing of nuclear weapons.

In 2012, $^{36}Cl/Cl$ ratios were measured in water samples from a total of six wells, four were collected from wells that in 2011 had carbon-14 activities less than 1 pmc and two were collected from wells that had carbon-14 activities between 1 and 2 pmc. For five of the wells, $^{36}Cl/Cl$ ratios ranged from about 870×10^{-15} to $1{,}090\times10^{-15}$ (fig. 22 and table 3). Replicate samples collected from 13U had ratios of about 670×10^{-15} to 870×10^{-15} (Appendix table 2–2). These ratios are within the range of values expected for groundwater recharge in the Rocky Mountains (Davis and others, 2003; Posey and others, 2009), and they do not indicate extensive radioactive decay of chlorine-36 that would be expected in very old water. Although the carbon-14 and helium-4 data from these wells indicate groundwater ages as old as about 20,000 years, the amount of chlorine-36 decay that would occur in water of this age is small owing to the long half life of chlorine-36 and essentially within the range of variability in the measured $^{36}Cl/Cl$ ratios. Thus, for five of the samples, the $^{36}Cl/Cl$ ratios do not appear to contradict the radiocarbon and helium-4 ages.

In the sample from well 9B, the $^{36}Cl/Cl$ ratio was substantially lower than the ratios for the other samples and the 9B chloride concentration was higher than for the other samples (fig. 22). Chloride/bromide ratios indicate that the elevated chloride concentration in sample 9B was likely due to halite dissolution (fig. 9). Halite dissolution in groundwater generally adds nonradioactive chloride to solution. Possible chlorine-36 ages for 9B were calculated using equation 12 (Bentley and others, 1986; Phillips and others, 1986):

$$\text{Chlorine-36 age} = -(1/\lambda_{36})\,ln[C(R-R_{se})/C_o(R_o-R_{se})] \qquad (12)$$

where

λ_{36} is the chlorine-36 decay constant (2.30×10^{-6}/yr),
C is the measured chloride concentration,
C_o is the chloride concentration in recharge,
R is the measured $^{36}Cl/Cl$ ratio,
R_o is the $^{36}Cl/Cl$ ratio in recharge, and
R_{se} is the $^{36}Cl/Cl$ ratio in groundwater at equilibrium with chlorine-36 production and decay in the aquifer (referred to as secular equilibrium).

R_{se} was assumed to equal 10×10^{-15} on the basis of the rock type in the study area (Phillips, 2000).

If the values for C_o and R_o were assumed to be 6 mg/L and 870×10^{-15}, respectively, which generally represent recharge less affected by evaporation (fig. 22), then the chlorine-36 age of 9B would be about 380,000 years. This age is substantially older than the radiocarbon and helium-4 ages for water from that well (tables 7 and 9). Although the noble gas sample from 9B was degassed to some extent (fig. 19), the loss of helium-4 is not likely to have been large enough to explain the discrepancy in helium-4 and chlorine-36 ages. The helium-4 concentration in 9B would have to be about 20 times higher than the measured value to match the chlorine-36 age, assuming only in-situ helium-4 production, which implies an amount of degassing that does not appear

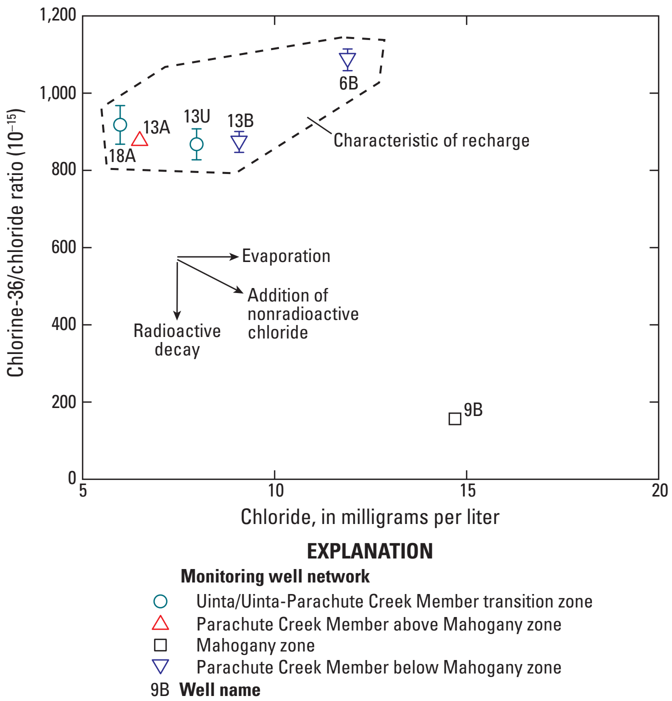


Figure 22. Graph showing chlorine-36/chloride ratios in dissolved chloride in relation to chloride concentrations for water samples collected from selected monitoring wells in 2012. [Error bar represents 1 standard deviation uncertainty.]

likely on the basis of the argon and neon data (fig. 19) and the concordance of carbon-14 and helium-4 ages for that sample (fig. 21). Another possible explanation for the discordance in chlorine-36 and helium-4 ages is that C_o was less than 6 mg/L. Kimball (1984) reported chloride concentrations in groundwater from the Uinta Formation as low as 2.6 mg/L. If C_o was 2.6 to 3 mg/L, then the chlorine-36 age would be about 18,000 to 80,000 years, which is in much closer agreement with the helium-4 age of 27,000 years. If C_o was 6 mg/L, then R_o would have to be about 400×10^{-15} to achieve concordance between the chlorine-36 and helium-4 ages. Such a low value for R_o seems unlikely on the basis of the chlorine-36 data from this study (fig. 22) and other studies in the area (Posey and others, 2009).

Summary of Groundwater Ages

Collectively, the tritium, carbon-14, helium-4, and chlorine-36 data indicate that groundwater was essentially modern in high elevation recharge areas and became progressively older as it moved downgradient in the flow system (fig. 23). hVOC data indicate that some of the old groundwater was susceptible to contamination from human activity, although whether that susceptibility was associated with activity at the land surface or subsurface activity is unknown. Helium-4 data indicate that groundwater from above the Mahogany zone had ages from less than 1,000 years to about 20,000 years, whereas groundwater from within and below the Mahogany zone had ages greater than about 10,000 years, and most ages were greater than 20,000 years (table 9). Some groundwater ages in the lower aquifer near the regional discharge area at the northern end of Piceance Creek appeared to be greater than 50,000 years. Old groundwater in the discharge area circulated deeply in the flow system and had the highest concentrations of dissolved solids in the aquifers (fig. 23), indicating the groundwater probably dissolved soluble minerals such as nacholite and halite in the saline zone.

The apparently old groundwater ages have important implications from a water management perspective. The ages indicate that parts of the aquifers with long groundwater residence times could have century- to millennium-scale flushing times if they were contaminated (fig. 23). In the case of well site 13, where thermogenic methane and BTEX could be related to nearby gas wells or legacy contamination, apparent groundwater ages were on the order of several thousand years. The presence of old groundwater in parts of the aquifers also indicates that these aquifers may not be useful for large-scale water supply because of low recharge rates.

Study Limitations

Results of this study should be considered in the context of some important limitations of the study design and data availability. Fourteen monitoring wells were used to characterize groundwater chemistry and age in the 900 square-mile study area. This small number of wells represents a limitation in the ability to analyze the spatial variability of water chemistry and age in the bedrock aquifers. Ten of the 14 wells had long open intervals, which is not ideal for monitoring water quality because of the potential for mixing water from multiple zones. Although geophysical logging and depth-dependent sampling were used to target zones where water entered the open intervals, it is not known whether those inflow zones changed with time or if they represent the most permeable zones in the intervals. Ideally, a study would sample monitoring wells designed with short open intervals that target the most permeable zones in an aquifer.

Few data on the chemical and isotopic composition of produced waters from the study area were available, thus limiting the ability to determine their spatial variability and recognize if water from deeper formations entered the bedrock aquifers. Similarly, few data on the molecular and isotopic composition of natural gas from the study area were available. Such data would be useful for determining the variability in gas compositions and possibly identifying which of the producing gas zones contributed thermogenic methane to the bedrock aquifers (Gorody, 2012).

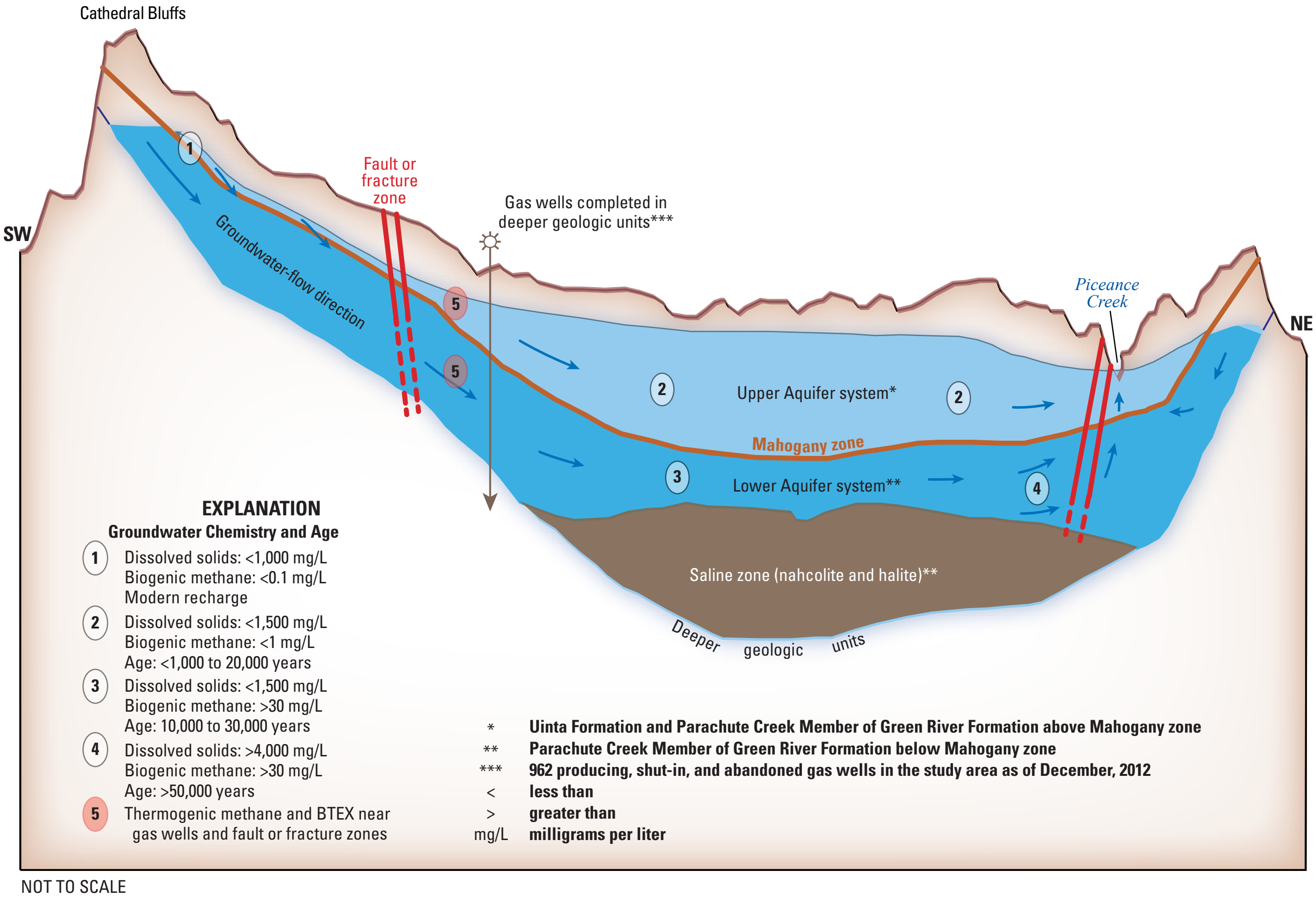


Figure 23. Schematic cross section of the groundwater-flow system in the bedrock aquifers and the evolution of groundwater chemistry and age along flow paths. [Topography and aquifer boundaries modified from Day and others (2010). Gas well data downloaded from the Colorado Oil and Gas Conservation Commission (2012) on December 4, 2012. Chemistry and ages from this study.]

Summary and Conclusions

The primary aquifers in the Piceance Creek and Yellow Creek watersheds in Rio Blanco County, Colorado, are bedrock aquifers in the Uinta and Green River Formations and alluvial aquifers in the major valleys. The Piceance and Yellow Creek watersheds contain rich energy resources in the forms of oil shale and natural gas, as well as mineral resources such as nahcolite. Several studies have examined the geochemistry of groundwater in the watersheds, mostly in relation to oil shale, but published studies on the geochemistry of shallow groundwater and how it may relate to underlying natural-gas reservoirs are scarce. To begin to address this information gap and to obtain monitoring data during natural-gas development, the Bureau of Land Management, White River Field Office, asked the U.S. Geological Survey to characterize the groundwater quality of shallow bedrock aquifers in the Piceance and Yellow Creek watersheds, with particular emphasis on chemical constituents that could be related to the development of underlying natural-gas reservoirs.

In 2011 and 2012, 14 monitoring wells were sampled for field properties, major ions, nutrients, trace elements, noble gases, dissolved organic carbon, hydrocarbon molecular and isotopic compositions, volatile organic compounds, and a broad suite of stable and radioactive isotopes. Five of the wells were sampled quarterly in 2010 and 2011 for a smaller set of constituents to examine temporal changes in water quality. The chemical and isotopic constituents were selected to provide information on the overall groundwater quality, occurrence, and distribution of chemicals that could be related to the development of underlying natural-gas reservoirs, and to better understand groundwater residence times in the flow system.

Water isotopic data indicate that the primary source of groundwater was precipitation that infiltrated into the bedrock aquifers at higher elevations along the watershed margins.

Deeper gas-producing zones were not an important source of water near the monitoring wells. Redox data indicate that groundwater evolved from being oxic with high concentrations of sulfate and low concentrations of methane in recharge areas, to being anoxic with high sulfate and low methane concentrations farther downgradient in the upper aquifer system, to being highly anoxic with much smaller sulfate and much higher methane concentrations farther downgradient in the lower aquifer system. Concentrations of dissolved solids in the water samples ranged from 738 to 47,600 mg/L. The highest concentrations occurred in samples from wells located near the regional discharge area at the northern end of Piceance Creek. The groundwater generally evolved from a mixed-cation-bicarbonate-sulfate type water in recharge areas of the Uinta-Parachute Creek Member transition zone to a sodium-bicarbonate type water farther downgradient. Chloride/bromide ratios indicate that mixing with small (less than 2 percent) amounts of water from deeper geologic units may have occurred in some wells. Concentrations of barium and boron exhibited strong positive correlations with fluoride concentrations. Water samples from the Mahogany zone and Parachute Creek Member below the Mahogany zone generally had the highest concentrations, with several of them exceeding Federal drinking-water standards for barium and fluoride.

Methane concentrations in groundwater ranged from less than 0.0005 to 387 mg/L. The methane was predominantly biogenic in origin, although the biogenic methane was mixed with thermogenic methane in water from seven wells. Water from one well contained 100 percent thermogenic methane that had an isotopic composition similar to that of some commercially produced natural gas in the Piceance Basin. The highest concentrations of biogenic methane occurred in the lower aquifer system and were probably produced by microbial degradation of oil shale contained therein. In contrast, the thermogenic methane was produced by nonbiological processes in deeper geologic units below the aquifer systems. Three BTEX compounds (benzene, toluene, and ethylbenzene) were detected in water from six of the wells, but none of the concentrations exceeded a Federal drinking-water standard. Five of the six wells that produced water with BTEX also contained at least a small amount of thermogenic methane. The presence of thermogenic methane in the aquifers indicates a connection and vulnerability to chemicals in deeper geologic units in the study area, but how the methane got there is unclear because the relative contributions of nearby gas wells, geologic structure, and legacy contamination to hydrocarbon migration in the study area are not well understood. Ultimately, collection of baseline data prior to gas-well installation and collection of time-series data after gas-well installation is the best way to understand the roles of gas wells, geologic structure, and legacy contamination in hydrocarbon migration in the study area.

The distribution of groundwater ages in the aquifers was assessed with tritium, halogenated volatile organic compounds, carbon-14, helium-4, and chlorine-36 data. Collectively, the data indicate that groundwater was essentially modern in high elevation recharge areas and became progressively older as it moved downgradient in the flow system. Halogenated volatile organic compounds data indicate that some of the old groundwater was susceptible to contamination from human activity, although whether that susceptibility was associated with activity at the land surface or subsurface activity is unknown. Helium-4 data indicate that groundwater from above the Mahogany zone had ages from less than 1,000 years to about 20,000 years, whereas groundwater from within and below the Mahogany zone had ages greater than about 10,000 years, and most ages were greater than 20,000 years. Some groundwater ages in the lower aquifer near the regional discharge area at the northern end of Piceance Creek appeared to be greater than 50,000 years. The apparently old groundwater ages have important implications from a water management perspective. The ages indicate that parts of the aquifers with long groundwater residence times could have century- to millennium-scale flushing times if they were contaminated. The presence of old groundwater in parts of the aquifers also indicates that these aquifers may not be useful for large-scale water supply because of low recharge rates.

Results of this study should be considered in the context of some important limitations of the study design and data availability. Fourteen monitoring wells were used to characterize groundwater chemistry and age in the 900 square-mile study area. This small number of wells represents a limitation in the ability to analyze the spatial variability of water chemistry and age in the bedrock aquifers. Few data on the chemical and isotopic composition of produced waters from the study area were available, thus limiting the ability to understand their spatial variability and recognize if water from deeper formations entered the bedrock aquifers. Similarly, few data on the molecular and isotopic composition of natural gas from the study area were available. Such data would be useful for understanding the variability in gas compositions and possibly identifying which of the producing gas zones contributed thermogenic methane to the bedrock aquifers.

Acknowledgments

The report was improved by the constructive reviews of Ronald Johnson (USGS), Justin Kulongoski (USGS), Bob Lange (BLM), and Andrew Manning (USGS). Geophysical logs and water-quality data provided by Shell Exploration and Production Company are greatly appreciated.

References Cited

Aeschbach-Hertig, W., Peeters, F., Beyerle, U., and Kipfer, R., 1999, Interpretation of dissolved atmospheric noble gases in natural waters: Water Resources Research, v. 35, p. 2779–2792.

Albers, C.N., Jacobsen, O.S., Flores, E.M.M., Pereira, J.S.F., and Laier, T., 2011, Spatial variation in natural formation of chloroform in the soils of four coniferous forests: Biogeochemistry, v. 103, p. 317–334.

Andrews, J.N., Drimmie, R.J., Loosli, H.H., and Hendry, M.J., 1991, Dissolved gases in the Milk River aquifer, Alberta, Canada: Applied Geochemistry, v. 6, p. 393–403.

Andrews, J.N., Goldbrunner, J.E., Darling, W.G., Hooker, P.J., Wilson, G.B., Youngman, M.J., Eichinger, L., Rauert, W., and Stichler, W., 1985, A radiochemical, hydrochemical and dissolved gas study of groundwaters in the Molasse Basin of Upper Austria: Earth and Planetary Science Letters, v. 73, p. 317–332.

Andrews, J.N., and Lee, D.J., 1979, Inert gases in groundwater from the Bunter Sandstone of England as indicators of age and paleoclimatic trends: Journal of Hydrology, v. 41, p. 233–252.

Balabane, M., Galimov, E., Hermann, M., and Letolle, R., 1987, Hydrogen and carbon isotope fractionation during experimental production of bacterial methane: Organic Geochemistry, v. 11, p. 115–119.

Ball, J.W., and Nordstrom, D.K., 1991, User's manual for WATEQ4F, with revised thermodynamic data base and test cases for calculating speciation of major, trace, and redox elements in natural waters: U.S. Geological Survey Open-File Report 91–183, 189 p.

Ballentine, C.J., Burgess, R., and Marty, B., 2002, Tracing fluid origin, transport and interaction in the crust: Reviews in Mineralogy and Geochemistry, v. 47, p. 539–614.

Ballentine, C.J., and Hall, C.M., 1999, Determining paleotemperature and other variables by using an error-weighted, nonlinear inversion of noble gas concentrations in water: Geochimica et Cosmochima Acta, v. 63, p. 2315–2336.

Bard, E., Arnold, M., Fairbanks, R.G., and Hamelin, B., 1993, ^{230}Th–^{234}U and ^{14}C ages obtained by mass spectrometry on corals: Radiocarbon, v. 35, p. 191–199.

Bayer, R., Schlosser, P., Bonisch, G., Rupp, H., Zaucker, F., and Zimmek, G., 1989, Performance and blank components of a mass spectrometric system for routine measurement of helium isotopes and tritium by ^{3}He ingrowth method, *in* Sitzungsberichte der Heidelberger Akademie der Wissenschaften. Mathematisch-naturwissenschaftliche Klasse: Heidelberg, Springer, p. 241–279.

Bentley, H.W., Phillips, F.M., and Davis, S.N., 1986, Chlorine-36 in the terrestrial environment, *in* Fritz, P. and Fontes, J-C., eds., Handbook of environmental isotope geochemistry: Amsterdam, Elsevier, v. 2, p. 427–480.

Bernard, B.B., Brooks, J.M., and Sackett, W.M., 1976, Natural gas seepage in the Gulf of Mexico: Earth and Planetary Science Letters, v. 31, p. 48–54.

Bethke, C.M., and Johnson, T.M., 2002, Ground-water age: Ground Water, v. 40, p. 337–339.

Beyerle, U., Aeschbach-Hertig, W., Imboden, D.M., Baur, H., Graph, T., and Kipfer, R., 2000, A mass spectrometric system for the analysis of noble gases and tritium from water samples: Environmetnal Science & Technology, v. 34, p. 2042–2050.

Birdwell, J.E., and Lewan, M.D., 2010, Leaching of hazardous substances from retorted oil shale during high temperature water flushing: Geological Society of America Annual Meeting, Denver, Colorado, November 1, 2010, paper 134–4, accessed December 10, 2012, at *https://gsa.confex.com/gsa/2010AM/finalprogram/session_26129.htm*.

Brenton, R.W., and Arnett, T.L., 1993, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of dissolved organic carbon by uv-promoted persulfate oxidation and infrared spectrometry: U.S. Geological Survey Open-File Report 92–480, 12 p.

Brownfield, M.E., Mercier, T.J., Johnson, R.C., and Self, J.G., 2010, Nahcolite resources in the Green River Formation, Piceance Basin, Colorado, *in* U.S. Geological Survey Oil Shale Assessment Team, eds., Oil-shale assessment of the Piceance Basin, Colorado: U.S. Geological Survey Digital Data Series DDS–69–Y, chap. 2, 57 p., accessed February 14, 2012, at *http://pubs.usgs.gov/dds/dds-069/dds-069-y/*.

Bullen, T.D., Krabbenhoft, D.P., and Kendall, C., 1996, Kinetic and mineralogic controls on the evolution of groundwater chemistry and ^{87}Sr/^{86}Sr in a sandy silicate aquifer, northern Wisconsin, USA: Geochimica et Cosmochimica Acta, v. 60, p. 1807–1821.

Bureau of Land Management, 2013, Reasonable foreseeable development scenario for oil and gas activities in the BLM White River Field Office, Rio Blanco, Moffat, and Garfield Counties, Colorado: accessed June 13, 2013, at *http://www.blm.gov/co/st/en/BLM_Programs/land_use_planning/rmp/white_river/documents/RFD.html*.

Cashion, W.B., and Donnell, J.R., 1974, Revision of nomenclature of the upper part of the Green River Formation, Piceance Creek Basin, Colorado, and eastern Uinta Basin, Utah: U.S. Geological Survey Bulletin 1394–G, 20 p.

Chapelle, F.H., McMahon, P.B., Dubrovsky, N.M., Fujii, R.F., Oaksford, E.T., and Vroblesky, D.A., 1995, Deducing the distribution of terminal electron-accepting processes in hydrologically diverse groundwater systems: Water Resources Research, v. 31, p. 359–371.

Chuck, A.L., Turner, S.M., and Liss, P.S., 2005, Oceanic distributions and air-sea fluxes of biogenic halocarbons in the open ocean: Journal of Geophysical Research (Oceans), v. 110, doi:10.1029/2004JC002741.

Coffin, D.L., Welder, F.A., and Glanzman, R.K., 1971, Geohydrology of the Piceance Creek structural basin between the White and Colorado Rivers, northwestern Colorado: U.S. Geological Survey Hydrologic Atlas 370, 2 sheets.

Colorado Oil and Gas Conservation Commission, 2012, Colorado Oil and Gas Information System: accessed October 13, 2012, at *http://cogcc.state.co.us/*.

Connor, B.F., Rose, D.L., Noriega, M.C., Murtagh, L.K., and Abney, S.R., 1998, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of 86 volatile organic compounds in water by gas chromatography/mass spectrometry, including detections less than reporting limits: U.S. Geological Survey Open-File Report 97–829, 78 p.

Cook, P.G., and Böhlke, J.K., 2000, Determining timescales for groundwater flow and solute transport, *in* Cook, P.G., and Herczeg, A., eds., Environmental tracers in subsurface hydrology: Boston, Kluwer Academic Publishers, p. 1–30.

Cozzarelli, I.M., Böhlke, J.K., Masoner, J., Breit, G.N., Lorah, M.M., Tuttle, M.L.W., and Jaeschke, J.B., 2011, Biogeochemical evolution of a landfill leachate plume, Norman, Oklahoma: Ground Water, v. 49, p. 663–687.

Cunningham, W.L., and Schalk, C.W., comps., 2011, Groundwater technical procedures of the U.S. Geological Survey: U.S. Geological Survey Techniques and Methods 1–A1, 151 p. (available only online at *http://pubs.usgs.gov/tm/1a1/*)

Davis, S.N., Moysey, S., Cecil, L.D., and Zreda, M., 2003, Chlorine-36 in groundwater of the United States—Empirical data: Hydrogeology Journal, v. 11, p. 217–227.

Davis, S.J., Mix, H.T., Wiegand, B.A., Carroll, A.R., and Chamberlain, C.P., 2009, Synorogenic evolution of large-scale drainage patterns—Isotopic paleohydrology of sequential Laramide Basins: American Journal of Science, v. 309, p. 549–602.

Day, M., Hansen, E., Gulliver, T., and McKinzie, B., 2010, Northwest Piceance Creek Basin hydrogeology, *in* Proceedings of the 30th Oil Shale Symposium, Golden, Colorado, October 18–20, 2010, accessed February 21, 2012, at *http://www.costar-mines.org/oss/30/paper/Paper_14-02-Hansen_Erik.pdf*.

Dean, W.E., Pitman, J.K., and Harrach, G.H., 1981, Geochemical and mineralogical analyses of U.S. Geological Survey oil-shale core CR-2, Piceance Creek Basin, Colorado: U.S. Geological Survey Open-File Report 81–596, 91 p.

Deeds, D.A., Kulongoski, J.T., and Belitz, K., 2012, Assessing California groundwater susceptibility using trace concentrations of halogenated volatile organic compounds: Environmental Science & Technology, v. 46, p. 13128–13135.

Donnell, J.R., 2009, Intertonguing of the lower part of the Uinta Formation with the upper part of the Green River Formation in the Piceance Creek Basin during the late stages of Lake Uinta: U.S. Geological Survey Scientific Investigations Report 2008–5237, 25 p.

Dubiel, R.F., 2003, Geology, depositional models, and oil and gas assessment of the Green River total petroleum system, Uinta-Piceance Province, eastern Utah and western Colorado, *in* U.S. Geological Survey Uinta-Piceance Assessment Team, compilers, Petroleum systems and geologic assessment of oil and gas in the Uinta-Piceance Province, Utah and Colorado: U.S. Geological Survey Digital Data Series DDS–069–B, chap. 5, 45 p., accessed February 14, 2012, at *http://pubs.usgs.gov/dds/dds-069/dds-069-b/*.

Dyni, J.R., Hite, R.J., and Raup, O.B., 1970, Lacustrine deposits of bromine-bearing halites, Green River Formation, northwestern Colorado, *in* Third Symposium on Salt: The Northern Ohio Geological Society, Inc., p. 166–180.

Eichinger, L., 1983, A contribution to the interpretation of ^{14}C groundwater ages considering the example of a partially confined sandstone aquifer: Radiocarbon, v. 25, p. 347–356.

Eltschlager, K.K., Hawkins, J.W., Ehler, W.C., and Baldassare, Fred, 2001, Technical measures for the investigation and mitigation of fugitive methane hazards in areas of coal mining: Office of Surface Mining Reclamation and Enforcement, 125 p., accessed February 8, 2013, at *http://www.techtransfer.osmre.gov/ARsite/Publications/Methane%20Manual.pdf*.

Fishman, M.J., 1993, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of inorganic and organic constituents in water and fluvial sediments: U.S. Geological Survey Open-File Report 93–125, 217 p.

Fishman, M.J., and Friedman, L.C., 1989, Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 545 p.

Fontes, J.C., and Garnier, J.M., 1979, Determination of the initial ^{14}C activity of the total dissolved carbon—A review of the existing models and a new approach: Water Resources Research, v. 15, p. 399–413.

Garbarino, J.R., Kanagy, L.K., and Cree, M.E., 2006, Determination of elements in natural-water, biota, sediment and soil samples using collision/reaction cell inductively coupled plasma-mass spectrometry: U.S. Geological Survey Techniques and Methods, book 5, sec. B, chap.1, 88 p.

Gilman, J.B., Lerner, B.M., Kuster, W.C., and de Gouw, J.A., 2013, Source signature of volatile organic compounds from oil and natural gas operations in northeastern Colorado: Environmental Science & Technology, v. 47, p. 1297–1305.

Gorody, A.W., 2012, Factors affecting the variability of stray gas concentration and composition in groundwater: Environmental Geosciences, v. 19, p. 17–31.

Hach Chemical Company, 2012a, Analysis of dissolved oxygen by the azide modification of the Winkler Method: accessed February 27, 2012, at *http://www.hach.com/dissolved-oxygen-reagent-set-digital-titrator-300-ml/product-downloads?id=7640193983&callback=qs*.

Hach Chemical Company, 2012b, Analysis of dissolved oxygen by the Indigo Carmine Method: accessed February 27, 2012, at *http://www.hach.com/dissolved-oxygen/parameter-products?productType=instruments&usEpa=false&parameterId=7639974407&hideObsolete=false*.

Hach Chemical Company, 2012c, Analysis of dissolved sulfide by the Methylene Blue Method: accessed February 27, 2012, at *http://www.hach.com/quick.search-download.search.jsa?keywords=methylene%20blue*.

Hail, W.J., 1990, Geology of the lower Yellow Creek area, northwestern Colorado: U.S. Geological Survey Bulletin 1787–O, 45 p.

Hail, W.J., and Smith, M.C., 1994, Geologic map of the northern part of the Piceance Creek basin, northwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–2400, 1 map.

Hail, W.J., and Smith, M.C., 1997, Geologic map of the southern part of the Piceance Creek basin, northwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–2529, 1 map.

Helsel, D.R., and Hirsch, R.M., 2002, Statistical methods in water resources: U.S. Geological Survey Techniques of Water Resources Investigations, book 4, chapter A3, 522 pages.

Hess, A.E., 1986, Identifying hydraulically conductive fractures with a slow-velocity borehole flowmeter: Canadian Geotechnical Journal, v. 23, p. 69–78.

Hunt, A.G., Lambert, R.B., and Fahlquist, Lynne, 2010, Sources of groundwater based on helium analyses in and near the freshwater/saline-water transition zone of the San Antonio segment of the Edwards aquifer, south-central Texas, 2002–03: U.S. Geological Survey Scientific Investigations Report 2010–5030, 15 p.

Ingersoll, G.P., Mast, M.A., Campbell, D.H., Clow, D.W., Nanus, L., and Turk, J.T., 2009, Rocky Mountain snowpack physical and chemical data for selected sites, 1993–2008: U.S. Geological Survey Data Series 369, 90 p.

Isa, Z., Grusenmeyer, S., and Verstraete, W., 1986, Sulfate reduction relative to methane production in high-rate anaerobic digestion, microbiological aspects: Applied and Environmental Microbiology, v. 51, p. 580–587.

Isotech Laboratories, 2013, Analytical services: accessed April 4, 2013, at *http://www.isotechlabs.com/analytical/isotope/*.

Johnson, R.C., 1981, Stratigraphic evidence for a deep Eocene Lake Uinta, Piceance Creek basin, Colorado: Geology, v. 9, p. 55–62.

Johnson, R.C., and Brownfield, M.E., 2013, Nahcolite and halite deposition through time during the saline mineral phase of Eocene Lake Uinta, Piceance Basin, western Colorado: U.S. Geological Survey Open-File Report 2013–1114, 71 p.

Johnson, R.C., Mercier, T.J., Brownfield, M.E., Pantea, M.P., and Self, J.G., 2010, An assessment of in-place oil shale resources in the Green River Formation, Piceance Basin, Colorado, *in* U.S. Geological Survey Oil Shale Assessment Team, eds., Oil-shale assessment of the Piceance Basin, Colorado: U.S. Geological Survey Digital Data Series DDS–069–Y, chap. 1, 197 p., accessed February 14, 2012, at *http://pubs.usgs.gov/dds/dds-069/dds-069-y/*.

Johnson, R.C., and Nuccio, V.F., 1986, Structural and thermal history of the Piceance Creek Basin, western Colorado, in relation to hydrocarbon occurrence in the Mesaverde Group, *in* Spencer, C.W., and Mast, R.F., eds., Geology of tight gas reservoirs: American Association of Petroleum Geologists, Studies in Geology 24, p. 165–206.

Johnson, R.C., and Rice, D.D., 1990, Occurrence and geochemistry of natural gases, Piceance Basin, northwest Colorado: American Association of Petroleum Geologists Bulletin, v. 74, p. 805–829.

Kalin, R.M., 2000, Radiocarbon dating of groundwater systems, *in* Cook, P.G., and Herczeg, A.L., eds., Environmental tracers in subsurface hydrology: Boston, Kluwer Academic Publishers, p. 111–144.

Keene, W.C., Khalil, M.A.K., Erickson, D.J., McCulloch, A., Graedel, T.E., and others, 1999, Composite global emissions of reactive chlorine from anthropogenic and natural sources–reactive chlorine emissions inventory: Journal of Geophysical Research (Atmosphere), v. 104, p. 8429–8440.

Kimball, B.A., 1984, Groundwater age determinations, Piceance Creek basin, Colorado, *in* Proceedings of the First Canadian/American Conference on Hydrogeology, Practical Applications of Groundwater Geochemistry, Banff, Alberta, Canada, June 22–26, 1984: Worthington, Ohio, National Water Well Association, p. 267–283.

Koterba, M.T., 1998, Ground-water data-collection protocols and procedures for the National Water-Quality Assessment Program—Collection, documentation, and compilation of required site, well, subsurface, and landscape data for wells: U.S. Geological Survey Water-Resources Investigations Report 98–4107, 91 p.

Koterba, M.T., Wilde, F.D., and Lapham, W.W., 1995, Ground-water data-collection protocols and procedures for the National Water-Quality Assessment Program—Collection and documentation of water-quality samples and related data: U.S. Geological Survey Open-File Report 95–399, 113 p.

Kresse, T.M., Warner, N.R., Hays, P.D., Down, A., Vengosh, A., and Jackson, R.B., 2012, Shallow groundwater quality and geochemistry in the Fayetteville Shale gas-production area, north-central Arkansas, 2011: U.S. Geological Survey Scientific Investigations Report 2012–5273, 31 p.

Kulongoski, J.T., and Hilton, D.R., 2011, Applications of groundwater helium, *in* Baskaran, M., ed., Handbook of environmental isotope geochemistry: Berlin, Springer-Verlag Publishers, p. 285–304.

Landon, M.K., and Belitz, K., 2012, Geogenic sources of benzene in aquifers used for public supply, California: Environmental Science & Technology, v. 46, p. 8689–8697.

Lovley, D.R., and Klug, M.J., 1986, Model for the distribution of sulfate reduction and methanogenesis in freshwater sediments: Geochimica et Cosmochimica Acta, v. 50, p. 11–18.

Lucas, L.L., and Unterweger, M.P., 2000, Comprehensive review and critical evaluation of the half-life of tritium: Journal of Research of the National Institute of Standards and Technology, v. 105, p. 541–549.

Mamyrin, B.A., and Tolstikhin, I.N., 1984, Helium isotopes in nature: New York, Elsevier, 273 p.

Manning, A.H., 2009, Ground-water temperature, noble gas, and carbon isotope data from the Española Basin, New Mexico: U.S. Geological Survey Scientific Investigations Report 2008–5200, 69 p.

Manning, A.H., 2011, Mountain-block recharge, present and past, in the eastern Española Basin, New Mexixo, USA: Hydrogeology Journal, v. 19, p. 379–397.

Manning, A.H., and Solomon, D.K., 2003, Using noble gases to investigate mountain-front recharge: Journal of Hydrology, v. 275, p. 194–207.

Manning, A.H., Solomon, D.K., and Thiros, S.A., 2005, ^{3}H/^{3}He age data in assessing the susceptibility of wells to contamination: Ground Water, v. 43, p. 353–367.

Mazaud, A., Laj, C., Bard, E., Arnold, M., and Tric, E., 1991, Geomagnetic field control of ^{14}C production over the last 80 ky—implications for the radiocarbon time scale: Geophysical Research Letters, v. 18, p. 1885–1888.

McMahon, P.B., Plummer, L.N., Böhlke, J.K., Shapiro, S.D., and Hinkle, S.R., 2011, A comparison of recharge rates in aquifers of the United States based on groundwater age data: Hydrogeology Journal, v. 19, p. 779–800.

Michel, R.L., and McMahon, P.B., 2008, Use of carbon-14 and CFCs to study gas movement and reactions in the unsaturated zone: European Geophysical Union Annual Meeting, Geophysical Research Abstracts, v. 10, 1607–7962/gra/EGU2008–A–01387.

Molz, F.J., Bowman, G.K., Young, S.C., and Waldrop, W.R., 1994, Borehole flowmeters—field application and data analysis: Journal of Hydrology, v. 163, p. 347–371.

Mook, W.G., and van der Plicht, J., 1999, Reporting ^{14}C activities and concentrations: Radiocarbon, v. 41, p. 227–239.

Osborn, S.G., Vengosh, A., Warner, N.R., and Jackson, R.B., 2011, Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing: Proceedings of the National Academy of Sciences, v. 108, p. 8172–8176.

Ortiz, R.F., 2002, Baseline characterization of water quality and mass loading in Piceance Creek, Rio Blanco County, Colorado, December 2000: U.S. Geological Survey Water-Resources Investigations Report 02–4134, 41 p.

Ozima, M., and Podosek, F.A., 1983, Noble gas geochemistry: Cambridge, England, Cambridge University Press, 367 p.

Papadopulos & Associates, 2008, Phase II hydrogeologic characterization of the Mamm Creek field area Garfield County, Colorado: A report prepared for the Board of County Commissioners, Garfield County, Colorado, 58 p.

Parkhurst, D.L., and Appelo, C.A.J., 1999, User's guide to PHREEQC (version 2)—A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations: U.S. Geological Survey Water-Resources Investigations Report 99–4259, 326 p.

Patton, C. J., and Kryskalla, J. R., 2011, Colorimetric determination of nitrate plus nitrite in water by enzymatic reduction, automated discrete analyzer methods: U.S. Geological Survey Techniques and Methods, book 5, chap. B8.

Phillips, F.M., 2000, Chlorine-36, *in* Cook, P.G., and Herczeg, A., eds., Environmental tracers in subsurface hydrology: Boston, Kluwer Academic Publishers, p. 299–348.

Phillips, F.M., Bentley, H.W., Davis, S.N., Elmore, D., and Swanick, G.B., 1986, Chlorine-36 dating of very old groundwater—2. Milk River aquifer, Alberta, Canada: Water Resources Research, v. 22, p. 2003–2016.

Plummer, L.N., Bexfield, L.M., Anderholm, S.K., Sanford, W.E., and Busenberg, E., 2004, Geochemical characterization of groundwater flow in the Santa Fe Group aquifer system, Middle Rio Grande basin, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 03–4131, 395 p.

Plummer, L.N., Busby, J.F., Lee, R.W., and Hanshaw, B.B., 1990, Geochemical modeling of the Madison Aquifer in parts of Montana, Wyoming, and South Dakota: Water Resources Research, v. 26, p. 1981–2012.

Plummer, L.N., and Busenberg, E., 2000, Chlorofluorocarbons—Tools for dating and tracing young groundwater, *in* Cook, P.G., and Herczeg, A., eds., Environmental tracers in subsurface hydrology: Boston, Kluwer Academic Publishers, p. 441–478.

Plummer, L.N., Busenberg, E., Eberts, S.M., Bexfield, L.M., Brown, C.J., Fahlquist, L.S., Katz, B.G., and Landon, M.K., 2008, Low-level detections of halogenated volatile organic compounds in groundwater—Use in vulnerability assessments: Journal of Hydrologic Engineering, v. 13, p. 1049–1068.

Plummer, L.N., Eggleston, J.R., Andreasen, D.C., Raffensperger, J.P., Hunt, A.G., and Casile, G.C., 2012, Old groundwater in parts of the upper Patapsco aquifer, Atlantic Coastal Plain, Maryland, USA—Evidence from radiocarbon, chlorine-36, and helium-4: Hydrogeology Journal, v. 19, p. 779–800.

Plummer, L.N., Prestemon, E.C., and Parkhurst, D.L., 1994, An interactive code (NETPATH) for modeling NET geochemical reactions along a flow PATH–Version 2.0: U.S. Geological Survey Water-Resources Investigations Report 94–4169, 135 p.

Plummer, L.N., and Sprinkle, C.L., 2001, Radiocarbon dating of dissolved inorganic carbon in groundwater from confined parts of the Upper Floridan aquifer, Florida, USA: Hydrogeology Journal, v. 9, p. 127–150.

Posey, H.H., Finley, J., and Quast, K., 2009, Interpreting groundwater in Eocene aquifers by isotopic measurements, Piceance Basin, Colorado: 29th Oil Shale Symposium, Colorado School of Mines, October, 2009, accessed October 10, 2012, at *http://www.ceri-mines.org/presentations2.htm*.

Purdue University PRIME Laboratory, 2013: accessed April 4, 2013, at *http://www.physics.purdue.edu/primelab/*.

Reitsema, R.H., 1980, Dolomite and nahcolite formation in organic rich sediments—Isotopically heavy carbonates: Geochimica et Cosmochimica Acta, v. 44, p. 2045–2049.

Robson, S.G., and Saulnier, G.J., Jr., 1981, Hydrogeochemistry and simulated solute transport, Piceance Basin, Northwestern Colorado: U.S. Geological Survey Professional Paper 1196, 65 p.

Rowe, D., and Muehlenbachs, A., 1999, Low-temperature thermal generation of hydrocarbon gases in shallow shales: Nature, v. 398, p. 61–63.

Rozanski, K., Araguás-Araguás, L., and Gonfiantini, R., 1993, Isotopic patterns in modern global precipitation, *in* Swart, P.K., Lohmann, K.C., McKenzie, J., and Savin, S., eds., Climate change in continental isotopic records: American Geophysical Union, Geophysical Monograph 78, p. 1–36.

Sanford, W.E., 1997, Correcting for diffusion in carbon-14 dating of groundwater: Ground Water, v. 35, p. 357–361.

Schlosser, P., Stute, M., Sonntag, C., and Münnich, K.O., 1989, Tritiogenic ^{3}He in shallow groundwater: Earth and Planetary Science Letters, v. 94, p. 245–256.

Shapiro, S.D., Busenberg, E., Focazio, M.J., and Plummer, L.N., 2004, Historical trends in occurrence and atmospheric inputs of halogenated volatile organic compounds in untreated groundwater used as a source of drinking water: Science of the Total Environment, v. 321, p. 201–217.

Slawson, G.C., Kelly, K.E., and Everett, L.G., 1982, Evaluation of groundwater pumping and bailing methods—Application in the oil shale industry: Groundwater Monitoring and Remediation, v. 2, p. 27–32.

Solomon, D.K., Hunt, A., and Poreda, R.J., 1996, Source of radiogenic helium-4 in shallow aquifers—Implications for dating young groundwater: Water Resources Research, v. 32, p. 1805–1813.

Starn, J., Bagtzoglou, A.C., and Robbins, G.A., 2010, Using atmospheric tracers to reduce uncertainty in groundwater recharge areas: Ground Water, v. 48, p. 858–868.

Staudinger, J., and Roberts, P.V., 2001, A critical compilation of Henry's Law constant temperature dependence relations for organic compounds in dilute aqueous solutions: Chemosphere, v. 44, p. 561–576.

Stute, M., Sonntag, C., Deák, J., and Schlosser, P., 1992, Helium in deep circulating groundwater in the Great Hungarian Plain—Flow dynamics and crustal and mantle helium fluxes: Geochimica et Cosmochimica Acta, v. 56, p. 2051–2067.

Thatcher, L.L., Janzer, V.J., and Edwards, K.W., 1977, Methods for determination of radioactive substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, chap. A–5, 95 p.

Thorstenson, D.C., Weeks, E.P., Hass, H., and Fisher, D.W., 1983, Distribution of gaseous $^{12}CO_2$, $^{13}CO_2$, and $^{14}CO_2$ in the sub-soil unsaturated zone of the western U.S. Great Plains: Radiocarbon, v. 25, p. 315–346.

Torgersen, T., 2010, Continental degassing flux of ^{4}He and its variability: Geochemistry, Geophysics, and Geosystems, v. 11, doi:10.1029/2009GC002930.

Torgersen, T., and Clarke, W.B., 1985, Helium accumulation in groundwater, I. An evaluation of sources and the continental flux of crustal ^{4}He in the Great Artesion Basin, Australia: Geochimica et Cosmochimica Acta, v. 49, p. 1211–1218.

Tuttle, M.L. 2009, A collection of chemical, mineralogical, and stable isotopic compositional data for Green River oil shale from depositional center cores in Colorado, Utah, and Wyoming: U.S. Geological Survey Open-File Report 2009–1274, 18 p.

Tuttle, M.L., and Goldhaber, M.B., 1993, Sedimentary sulfur geochemistry of the Paleogene Green River Formation, western USA—Implications for interpreting depositional and diagenetic processes in saline alkaline lakes: Geochimica et Cosmochimica Acta, v. 57, p. 3023–3039.

URS Corporation, 2006, Phase I—Hydrogeologic characterization of the Mamm Creek Field area in Garfield County: Prepared for the Board of County Commissioners, Garfield County, Colorado, 86 p.

U.S. Congress Office of Technology Assessment, 1980, An assessment of oil shale technologies: accessed January 25, 2013, at *http://www.princeton.edu/~ota/disk3/1980/8004_n.html*.

U.S. Department of Energy, 2012, Rocky Mountain Basins produced water database: accessed May 15, 2012, at *http://www.netl.doe.gov/technologies/oil-gas/Software/database.html*.

U.S. Environmental Protection Agency, 1989, Data evaluation, chap. 5 of Risk assessment guidance for Superfund—Volume I—Human health evaluation manual (part A): Washington, D.C., Office of Emergency and Remedial Response, U.S. Environmental Protection Agency Report EPA/540/1–89/002, 30 p., accessed July 17, 2012, at *http://www.epa.gov/oswer/riskassessment/ragsa/pdf/ch5.pdf.*

U.S. Environmental Protection Agency, 2011, Investigation of groundwater contamination near Pavillion, Wyoming: U.S. Environmental Protection Agency Report EPA–600–R–00–000, 104 p., accessed July 25, 2012, at *http://www.epa.gov/region8/superfund/wy/pavillion/*.

U.S. Environmental Protection Agency, 2012, National Primary Drinking Water Regulations: accessed October 11, 2012, at *http://water.epa.gov/drink/contaminants/index.cfm*.

U.S. Geological Survey, 2010, Oil shale and nahcolite resources of the Piceance Basin, Colorado—Piceance Basin oil shale database: accessed February 21, 2012, at *http://pubs.usgs.gov/dds/dds-069/dds-069-y/*.

U.S. Geological Survey, 2012a, Piceance Basin water-quality data repository: accessed February 21, 2012, at *http://rmgsc.cr.usgs.gov/cwqdr/Piceance/*.

U.S. Geological Survey, 2012b, Reston stable isotope laboratory: accessed June 3, 2010, at *http://isotopes.usgs.gov/*.

U.S. Geological Survey, 2012c, Reston chorofluorocarbon laboratory: accessed June 3, 2010, at *http://water.usgs.gov/lab/*.

U.S. Geological Survey, 2013, Inductively coupled plasma-mass spectrometry (ICP-MS) facility: accessed April 4, 2013, at *http://crustal.usgs.gov/laboratories/icpms/index.html*.

Vogel, T.M., 1994, Natural bioremediation of chlorinated solvents, *in* Handbook of bioremediation: Ann Arbor, Lewis Publishers, p. 201–225.

Vroblesky, D.A., Bradley, P.M., and Chapelle, F.H., 1996, Influence of electron donor on the minimum sulfate concentration required for sulfate reduction in a petroleum hydrocarbon-contaminated aquifer: Environmental Science & Technology, v. 30, p. 1377–1381.

Warner, N.R., Jackson, R.B., Darrah, T.H., Osborn, S.G., Down, A., Zhao, K., White, A., and Vengosh, A., 2012, Geochemical evidence for possible natural migration of Marcellus Formation brine to shallow aquifers in Pennsylvania: Proceedings of the National Academy of Sciences, v. 109, p. 11961–11966.

Weeks, J.B., Leavesley, G.H., Welder, F.A., and Saulnier, G.J., Jr.,1974, Simulated effects of oil-shale development on the hydrology of Piceance Basin, Colorado: U.S. Geological Survey Professional Paper 908, 84 p.

Welder, F.A., and Saulnier, G.J., Jr., 1978, Geohydrologic data from twenty-four test holes drilled in the Piceance Basin, Rio Blanco County, Colorado, 1975–76: U.S. Geological Survey Open-File Report 78–734, 140 p.

Whiticar, M.J., 1999, Carbon and hydrogen isotope systematics of bacterial formation and oxidation of methane: Chemical Geology, v. 161, p. 291–314.

Woods Hole Oceanographic Institute, 2013, NOSAMS, National Ocean Sciences Accelerator Mass Spectrometry Facility. The Sample Preparation Laboratory: accessed April 4, 2013, at *http://www.whoi.edu/page/live.do?pid=43315*.

Wright, P.R., McMahon, P.B., Mueller, D.K., Clark, M.L., 2012, Groundwater-quality and quality-control data for two monitoring wells near Pavillion, Wyoming, April and May 2012: U.S. Geological Survey Data Series 718, 26 p.

Appendixes

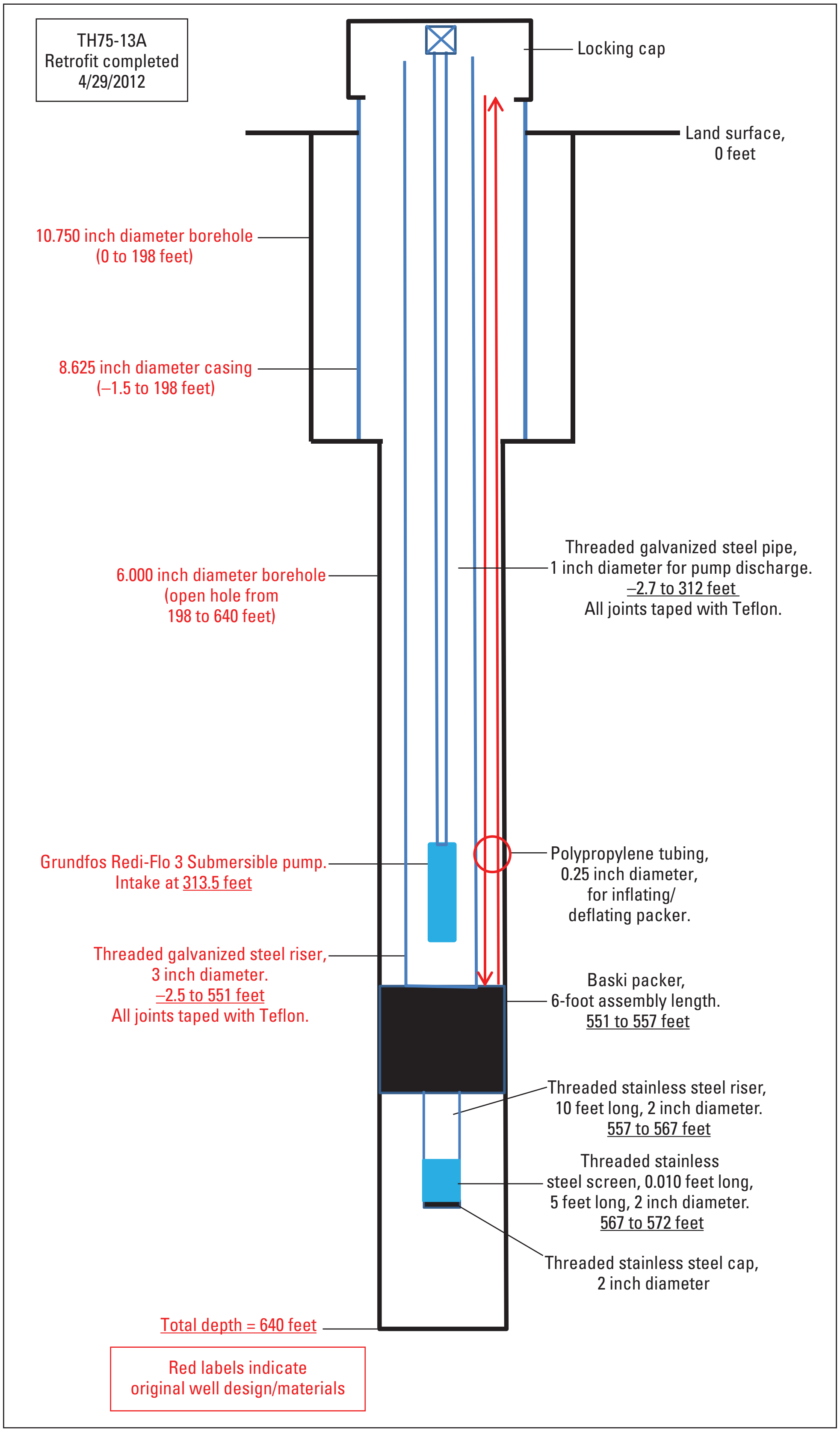


Figure 1–1. Construction details for monitoring well 13A.

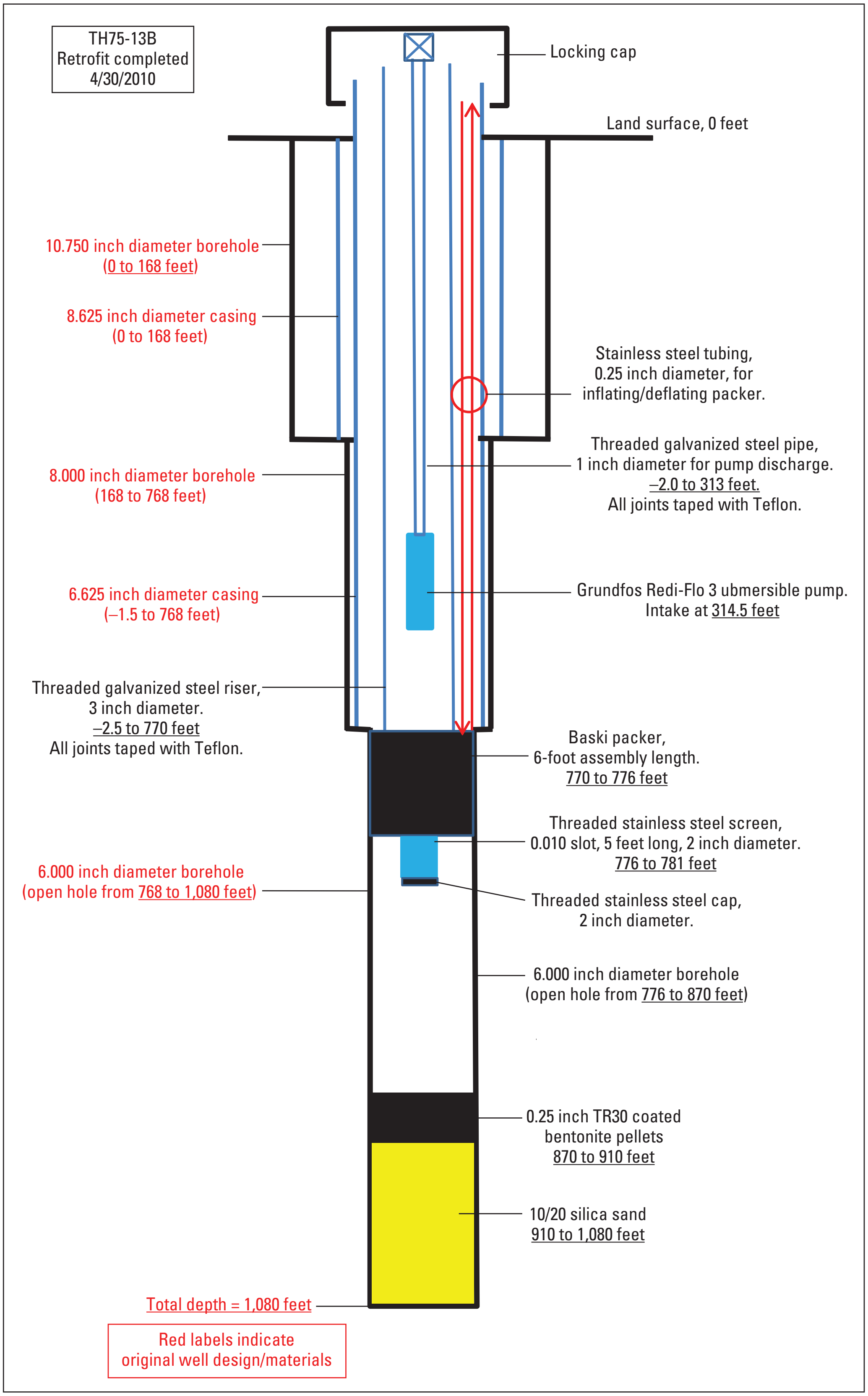


Figure 1–2. Construction details for monitoring well 13B.

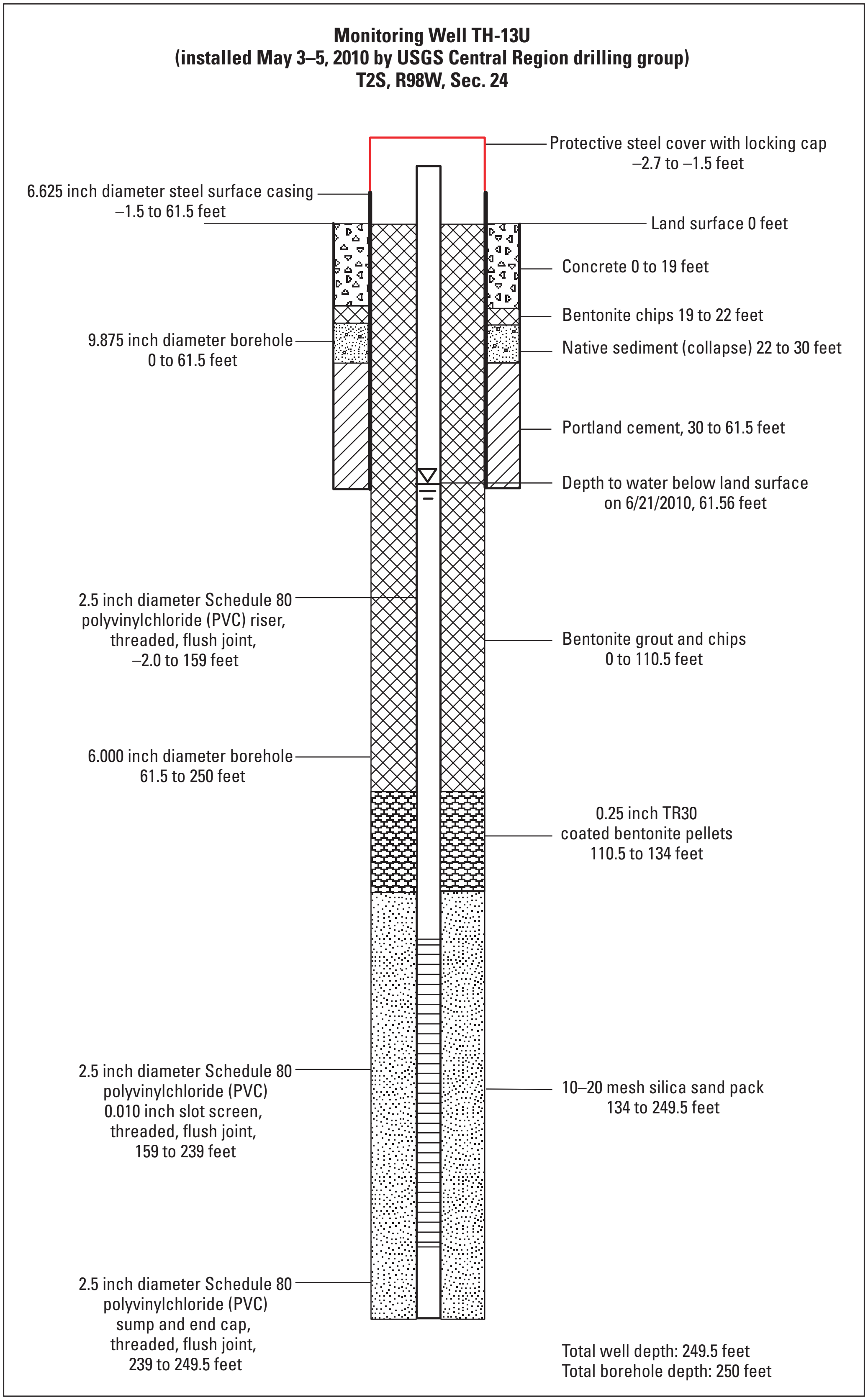
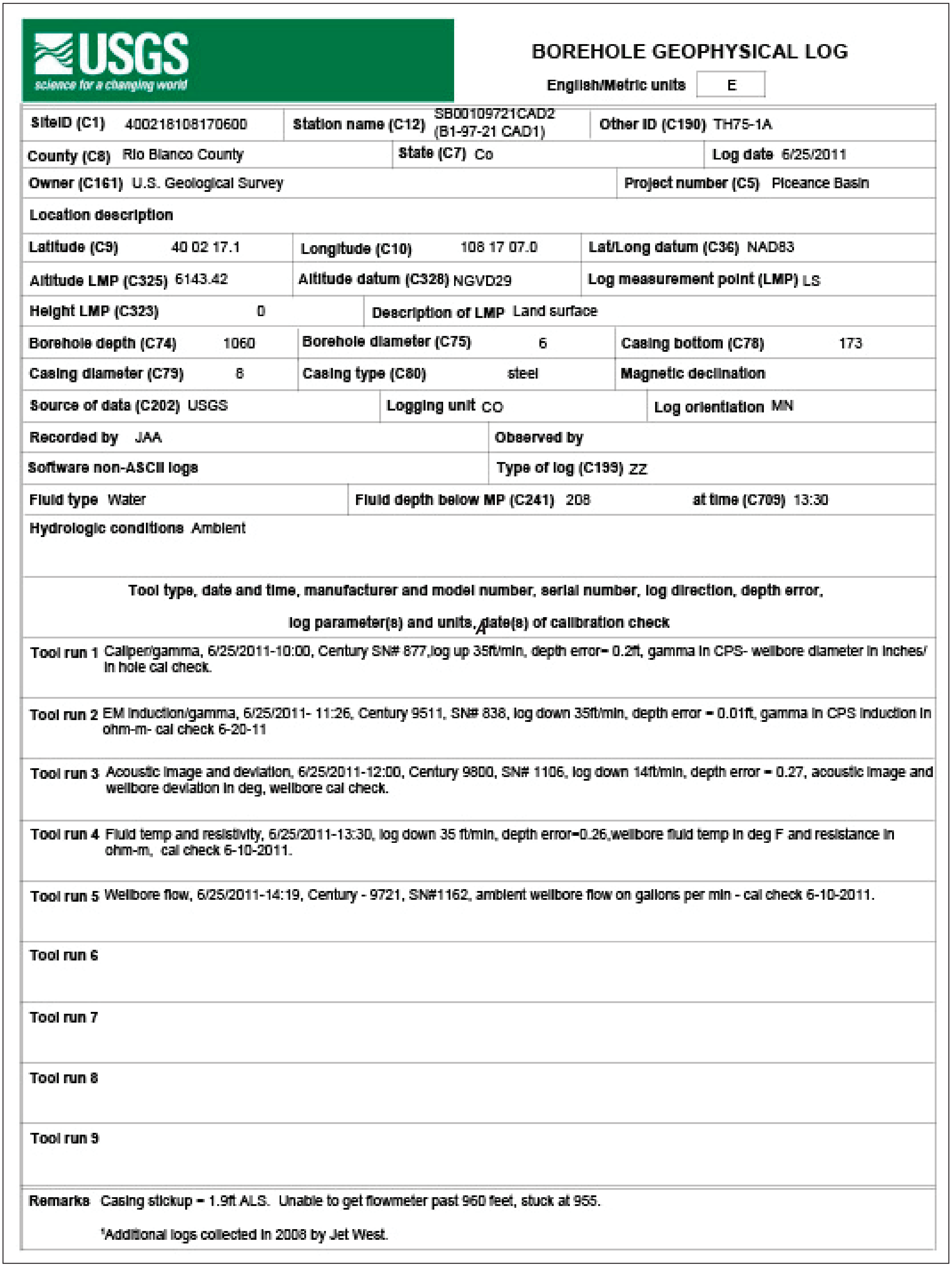


Figure 1–3. Construction details for monitoring well 13U.



USGS
science for a changing world

BOREHOLE GEOPHYSICAL LOG

English/Metric units E

SiteID (C1) 400218108170600
Station name (C12) SB00109721CAD2 (B1-97-21 CAD1)
Other ID (C190) TH75-1A
County (C8) Rio Blanco County
State (C7) Co
Log date 6/25/2011
Owner (C161) U.S. Geological Survey
Project number (C5) Piceance Basin
Location description
Latitude (C9) 40 02 17.1
Longitude (C10) 108 17 07.0
Lat/Long datum (C36) NAD83
Altitude LMP (C325) 6143.42
Altitude datum (C328) NGVD29
Log measurement point (LMP) LS
Height LMP (C323) 0
Description of LMP Land surface
Borehole depth (C74) 1060
Borehole diameter (C75) 6
Casing bottom (C78) 173
Casing diameter (C79) 6
Casing type (C80) steel
Magnetic declination
Source of data (C202) USGS
Logging unit CO
Log orientation MN
Recorded by JAA
Observed by
Software non-ASCII logs
Type of log (C199) ZZ
Fluid type Water
Fluid depth below MP (C241) 208
at time (C709) 13:30
Hydrologic conditions Ambient

Tool type, date and time, manufacturer and model number, serial number, log direction, depth error, log parameter(s) and units, date(s) of calibration check

Tool run 1 Caliper/gamma, 6/25/2011-10:00, Century SN# 677,log up 35ft/min, depth error= 0.2ft, gamma in CPS- wellbore diameter in inches/ in hole cal check.

Tool run 2 EM induction/gamma, 6/25/2011- 11:26, Century 9511, SN# 838, log down 35ft/min, depth error = 0.01ft, gamma in CPS induction in ohm-m- cal check 6-20-11

Tool run 3 Acoustic image and deviation, 6/25/2011-12:00, Century 9800, SN# 1106, log down 14ft/min, depth error = 0.27, acoustic image and wellbore deviation in deg, wellbore cal check.

Tool run 4 Fluid temp and resistivity, 6/25/2011-13:30, log down 35 ft/min, depth error=0.26,wellbore fluid temp in deg F and resistance in ohm-m, cal check 6-10-2011.

Tool run 5 Wellbore flow, 6/25/2011-14:19, Century - 9721, SN#1162, ambient wellbore flow on gallons per min - cal check 6-10-2011.

Tool run 6

Tool run 7

Tool run 8

Tool run 9

Remarks Casing stickup = 1.9ft ALS. Unable to get flowmeter past 960 feet, stuck at 955.

[1]Additional logs collected in 2008 by Jet West.

Figure 1–4. Geophysical logs for monitoring well 1A.

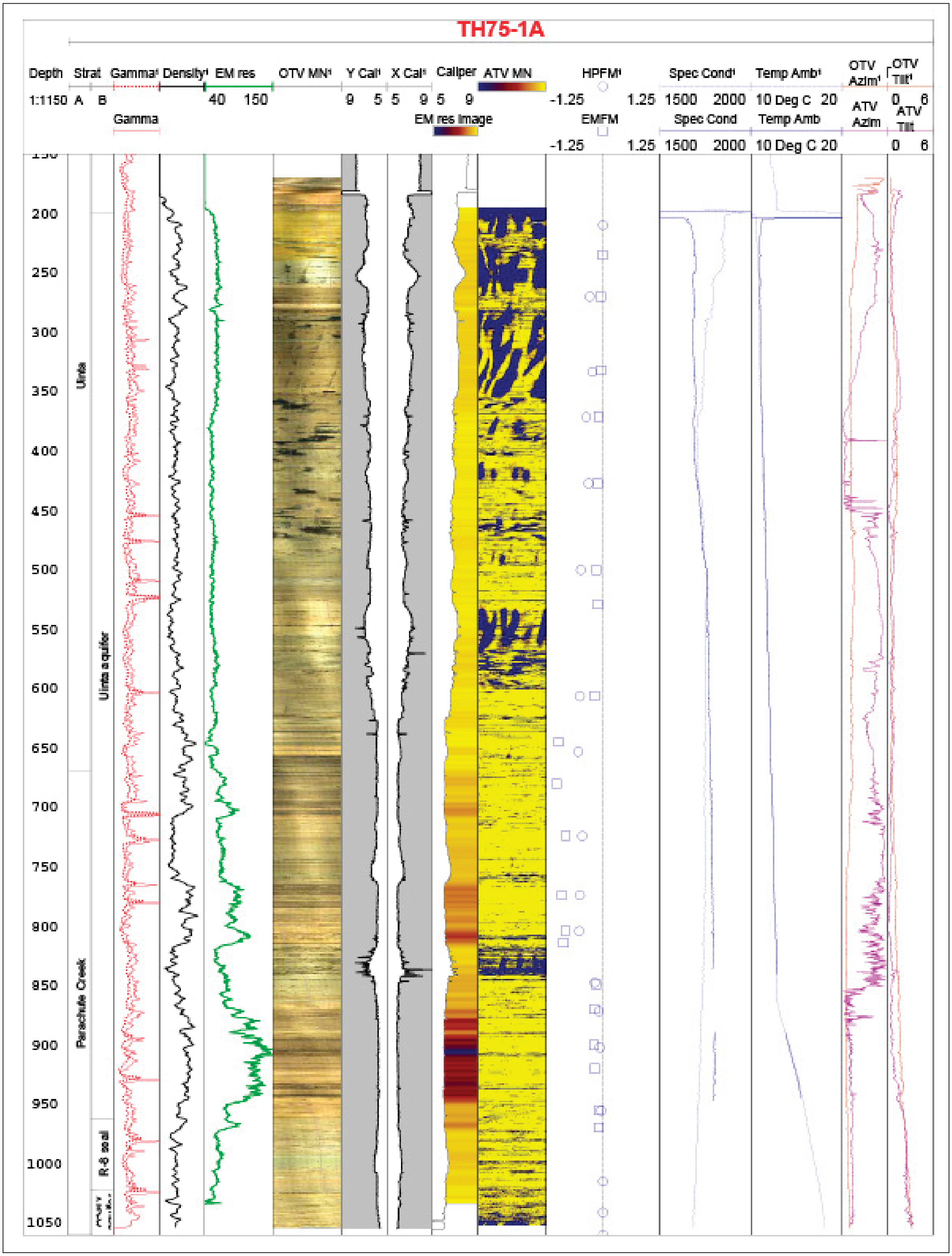
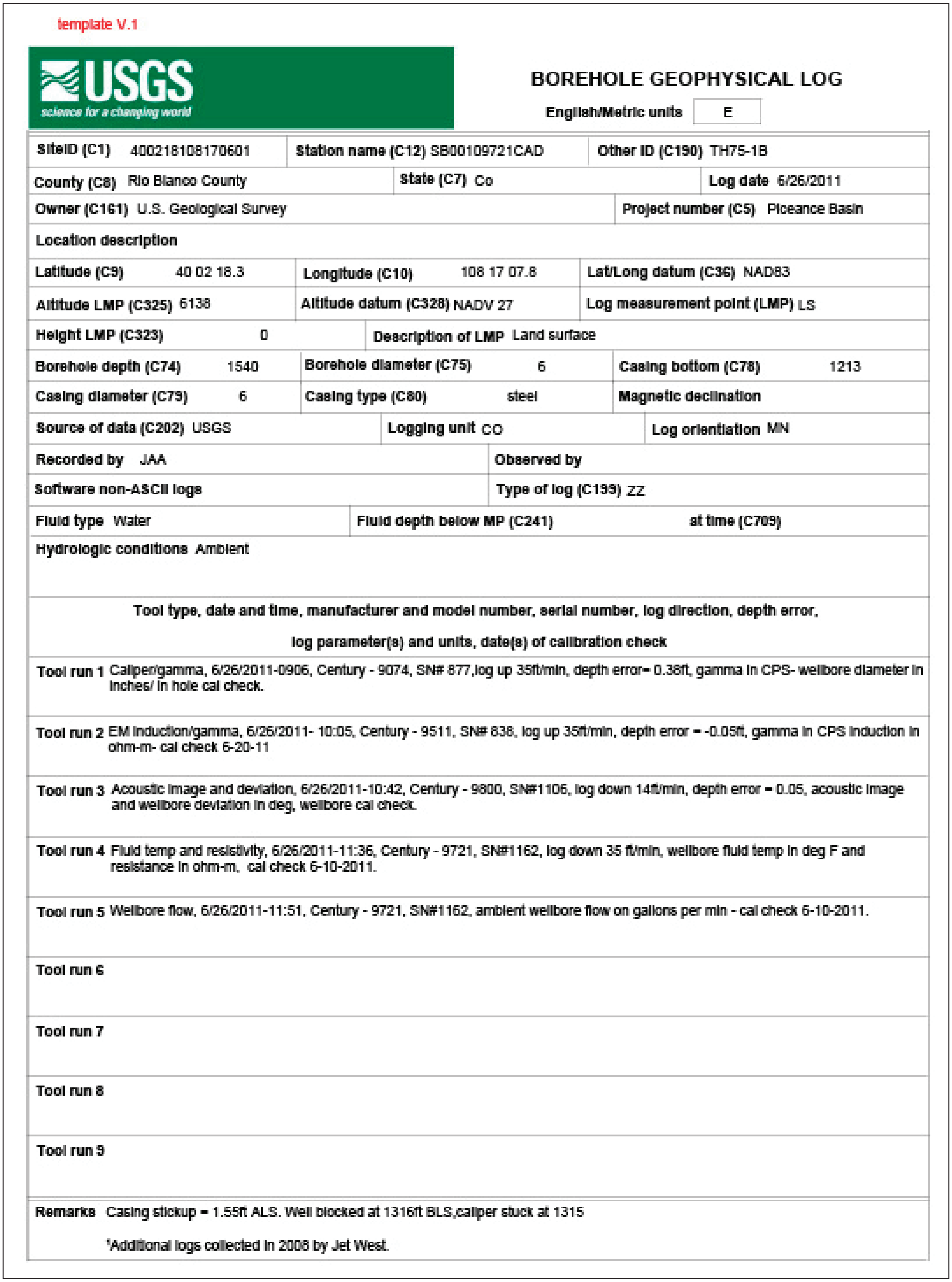


Figure 1–4. Geophysical logs for monitoring well 1A.—Continued



template V.1

USGS
science for a changing world

BOREHOLE GEOPHYSICAL LOG

English/Metric units E

SiteID (C1) 400218108170601	**Station name (C12)** SB00109721CAD	**Other ID (C190)** TH75-1B
County (C8) Rio Blanco County	**State (C7)** Co	**Log date** 6/26/2011
Owner (C161) U.S. Geological Survey		**Project number (C5)** Piceance Basin
Location description		
Latitude (C9) 40 02 18.3	**Longitude (C10)** 108 17 07.8	**Lat/Long datum (C36)** NAD83
Altitude LMP (C325) 6138	**Altitude datum (C328)** NADV 27	**Log measurement point (LMP)** LS
Height LMP (C323) 0	**Description of LMP** Land surface	
Borehole depth (C74) 1540	**Borehole diameter (C75)** 6	**Casing bottom (C78)** 1213
Casing diameter (C79) 6	**Casing type (C80)** steel	**Magnetic declination**
Source of data (C202) USGS	**Logging unit** CO	**Log orientation** MN
Recorded by JAA	**Observed by**	
Software non-ASCII logs	**Type of log (C199)** ZZ	
Fluid type Water	**Fluid depth below MP (C241)**	**at time (C709)**
Hydrologic conditions Ambient		

Tool type, date and time, manufacturer and model number, serial number, log direction, depth error, log parameter(s) and units, date(s) of calibration check

Tool run 1	Caliper/gamma, 6/26/2011-0906, Century - 9074, SN# 877,log up 35ft/min, depth error= 0.36ft, gamma in CPS- wellbore diameter in inches/ in hole cal check.
Tool run 2	EM induction/gamma, 6/26/2011- 10:05, Century - 9511, SN# 838, log up 35ft/min, depth error = -0.05ft, gamma in CPS induction in ohm-m- cal check 6-20-11
Tool run 3	Acoustic image and deviation, 6/26/2011-10:42, Century - 9800, SN#1106, log down 14ft/min, depth error = 0.05, acoustic image and wellbore deviation in deg, wellbore cal check.
Tool run 4	Fluid temp and resistivity, 6/26/2011-11:36, Century - 9721, SN#1162, log down 35 ft/min, wellbore fluid temp in deg F and resistance in ohm-m, cal check 6-10-2011.
Tool run 5	Wellbore flow, 6/26/2011-11:51, Century - 9721, SN#1162, ambient wellbore flow on gallons per min - cal check 6-10-2011.
Tool run 6	
Tool run 7	
Tool run 8	
Tool run 9	

Remarks Casing stickup = 1.55ft ALS. Well blocked at 1316ft BLS,caliper stuck at 1315

[1]Additional logs collected in 2008 by Jet West.

Figure 1–5. Geophysical logs for monitoring well 1B.

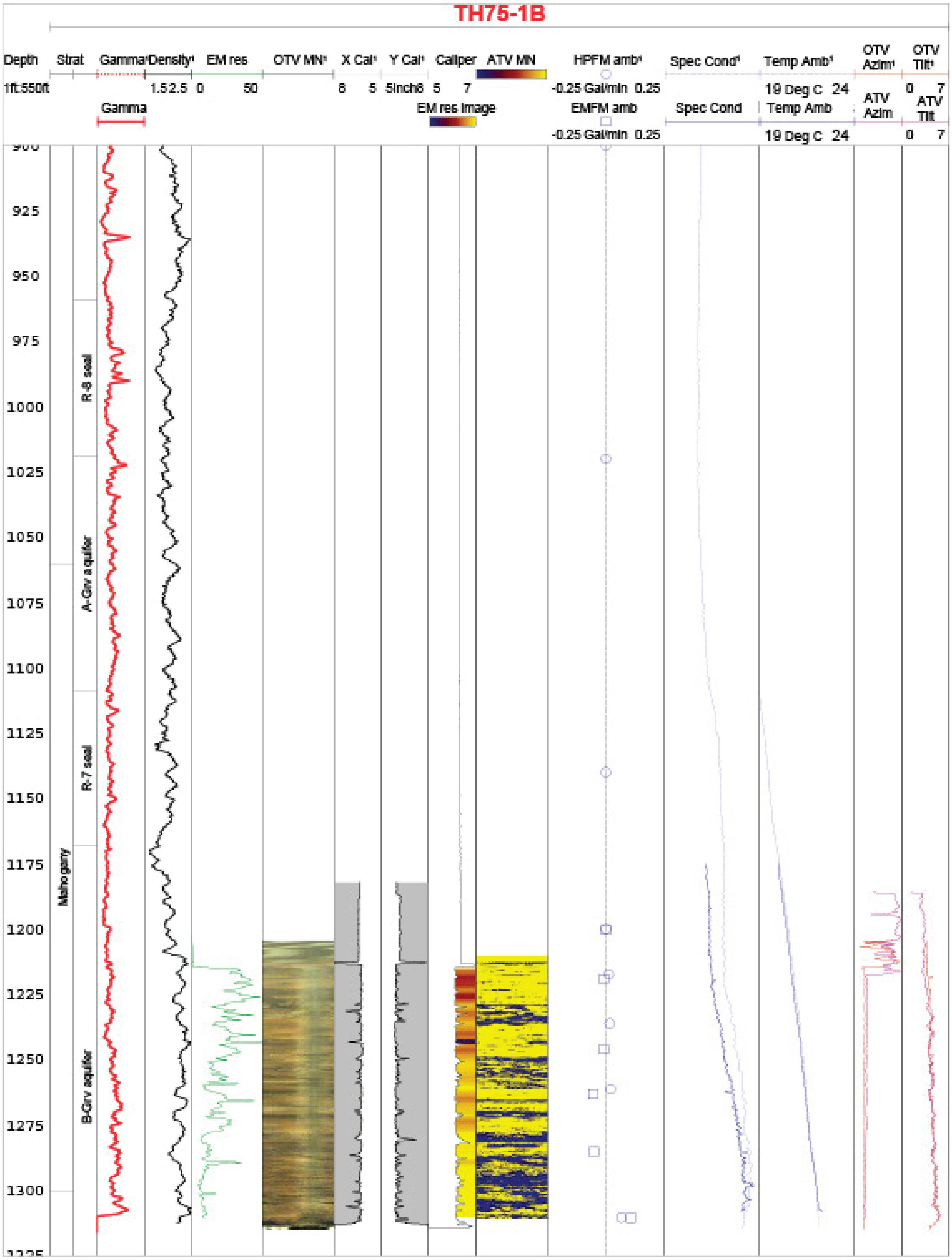
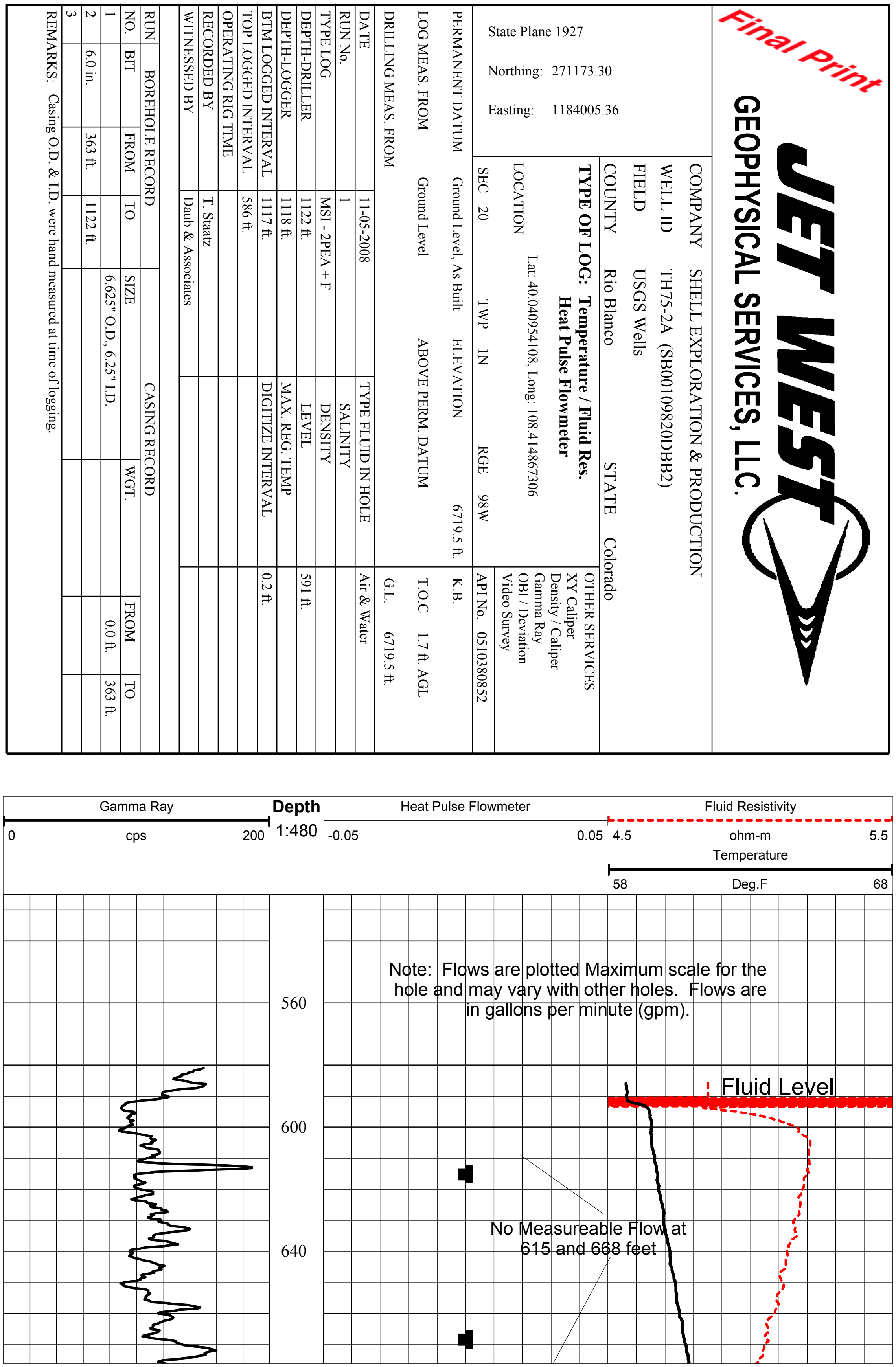


Figure 1–5. Geophysical logs for monitoring well 1B.—Continued



Final Print

JET WEST GEOPHYSICAL SERVICES, LLC.

State Plane 1927
Northing: 271173.30
Easting: 1184005.36

COMPANY	SHELL EXPLORATION & PRODUCTION
WELL ID	TH75-2A (SB00109820DBB2)
FIELD	USGS Wells
COUNTY	Rio Blanco STATE Colorado

TYPE OF LOG: Temperature / Fluid Res.
Heat Pulse Flowmeter

LOCATION
Lat: 40.040954108, Long: 108.414867306
SEC 20 TWP 1N RGE 98W

OTHER SERVICES
XY Caliper
Density / Caliper
Gamma Ray
OBI / Deviation
Video Survey

API No. 0510308852

PERMANENT DATUM	Ground Level, As Built	ELEVATION	6719.5 ft.	K.B.
LOG MEAS. FROM	Ground Level	ABOVE PERM. DATUM		T.O.C 1.7 ft. AGL
DRILLING MEAS. FROM				G.L. 6719.5 ft.

DATE	11-05-2008	TYPE FLUID IN HOLE	Air & Water
RUN No.	1	SALINITY	
TYPE LOG	MSI - 2PEA + F	DENSITY	
DEPTH-DRILLER	1122 ft.	LEVEL	591 ft.
DEPTH-LOGGER	1118 ft.	MAX. REG. TEMP	
BTM LOGGED INTERVAL	1117 ft.	DIGITIZE INTERVAL	0.2 ft.
TOP LOGGED INTERVAL	586 ft.		
OPERATING RIG TIME			
RECORDED BY	T. Staatz		
WITNESSED BY	Daub & Associates		

RUN	BOREHOLE RECORD			CASING RECORD			
NO.	BIT	FROM	TO	SIZE	WGT.	FROM	TO
1				6.625" O.D., 6.25" I.D.		0.0 ft.	363 ft.
2	6.0 in.	363 ft.	1122 ft.				
3							

REMARKS: Casing O.D. & I.D. were hand measured at time of logging.

Note: Flows are plotted Maximum scale for the hole and may vary with other holes. Flows are in gallons per minute (gpm).

No Measureable Flow at 615 and 668 feet

Figure 1–6. Geophysical logs for monitoring well 2A.

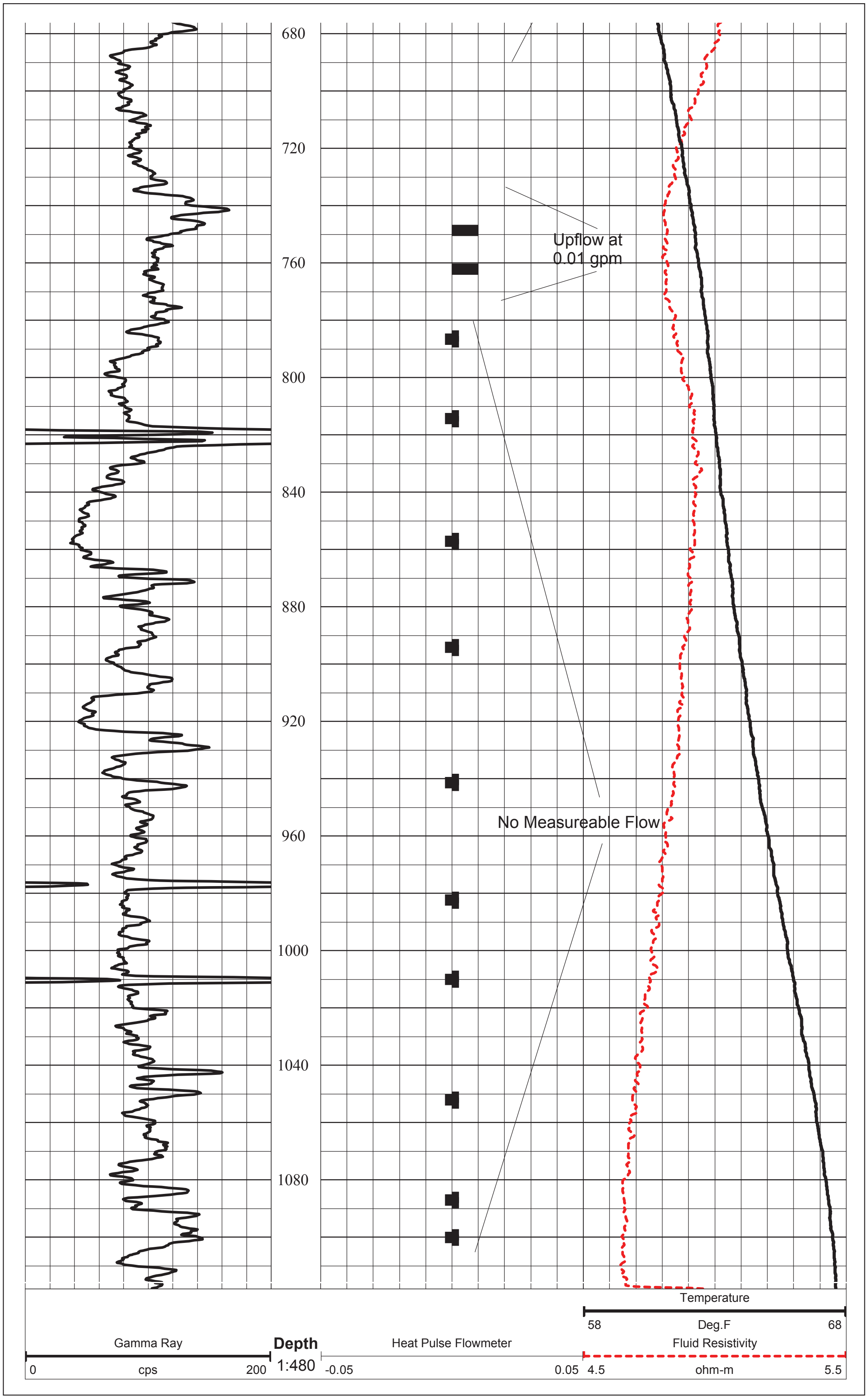
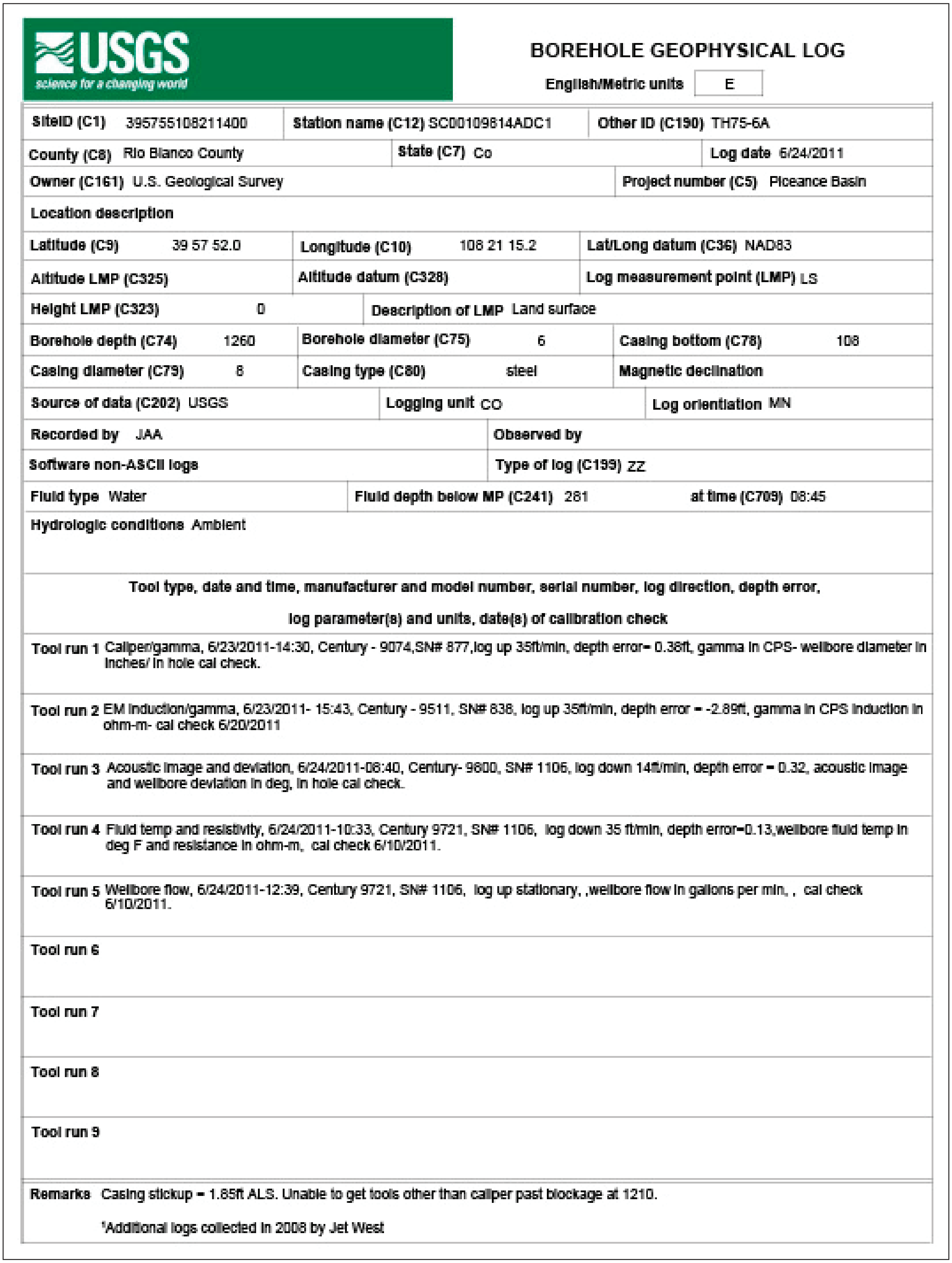


Figure 1–6. Geophysical logs for monitoring well 2A.—Continued



USGS science for a changing world

BOREHOLE GEOPHYSICAL LOG

English/Metric units E

SiteID (C1) 395755108211400
Station name (C12) SC00109814ADC1
Other ID (C190) TH75-6A
County (C8) Rio Blanco County
State (C7) Co
Log date 6/24/2011
Owner (C161) U.S. Geological Survey
Project number (C5) Piceance Basin
Location description
Latitude (C9) 39 57 52.0
Longitude (C10) 108 21 15.2
Lat/Long datum (C36) NAD83
Altitude LMP (C325)
Altitude datum (C328)
Log measurement point (LMP) LS
Height LMP (C323) 0
Description of LMP Land surface
Borehole depth (C74) 1260
Borehole diameter (C75) 6
Casing bottom (C78) 108
Casing diameter (C79) 8
Casing type (C80) steel
Magnetic declination
Source of data (C202) USGS
Logging unit CO
Log orientation MN
Recorded by JAA
Observed by
Software non-ASCII logs
Type of log (C199) ZZ
Fluid type Water
Fluid depth below MP (C241) 281
at time (C709) 08:45
Hydrologic conditions Ambient

Tool type, date and time, manufacturer and model number, serial number, log direction, depth error, log parameter(s) and units, date(s) of calibration check

Tool run 1 Caliper/gamma, 6/23/2011-14:30, Century - 9074,SN# 877,log up 35ft/min, depth error= 0.38ft, gamma in CPS- wellbore diameter in inches/ in hole cal check.

Tool run 2 EM induction/gamma, 6/23/2011- 15:43, Century - 9511, SN# 838, log up 35ft/min, depth error = -2.89ft, gamma in CPS induction in ohm-m- cal check 6/20/2011

Tool run 3 Acoustic image and deviation, 6/24/2011-08:40, Century- 9800, SN# 1106, log down 14ft/min, depth error = 0.32, acoustic image and wellbore deviation in deg, in hole cal check.

Tool run 4 Fluid temp and resistivity, 6/24/2011-10:33, Century 9721, SN# 1106, log down 35 ft/min, depth error=0.13,wellbore fluid temp in deg F and resistance in ohm-m, cal check 6/10/2011.

Tool run 5 Wellbore flow, 6/24/2011-12:39, Century 9721, SN# 1106, log up stationary, ,wellbore flow in gallons per min, , cal check 6/10/2011.

Tool run 6

Tool run 7

Tool run 8

Tool run 9

Remarks Casing stickup = 1.85ft ALS. Unable to get tools other than caliper past blockage at 1210.

[1]Additional logs collected in 2008 by Jet West

Figure 1–7. Geophysical logs for monitoring well 6A.

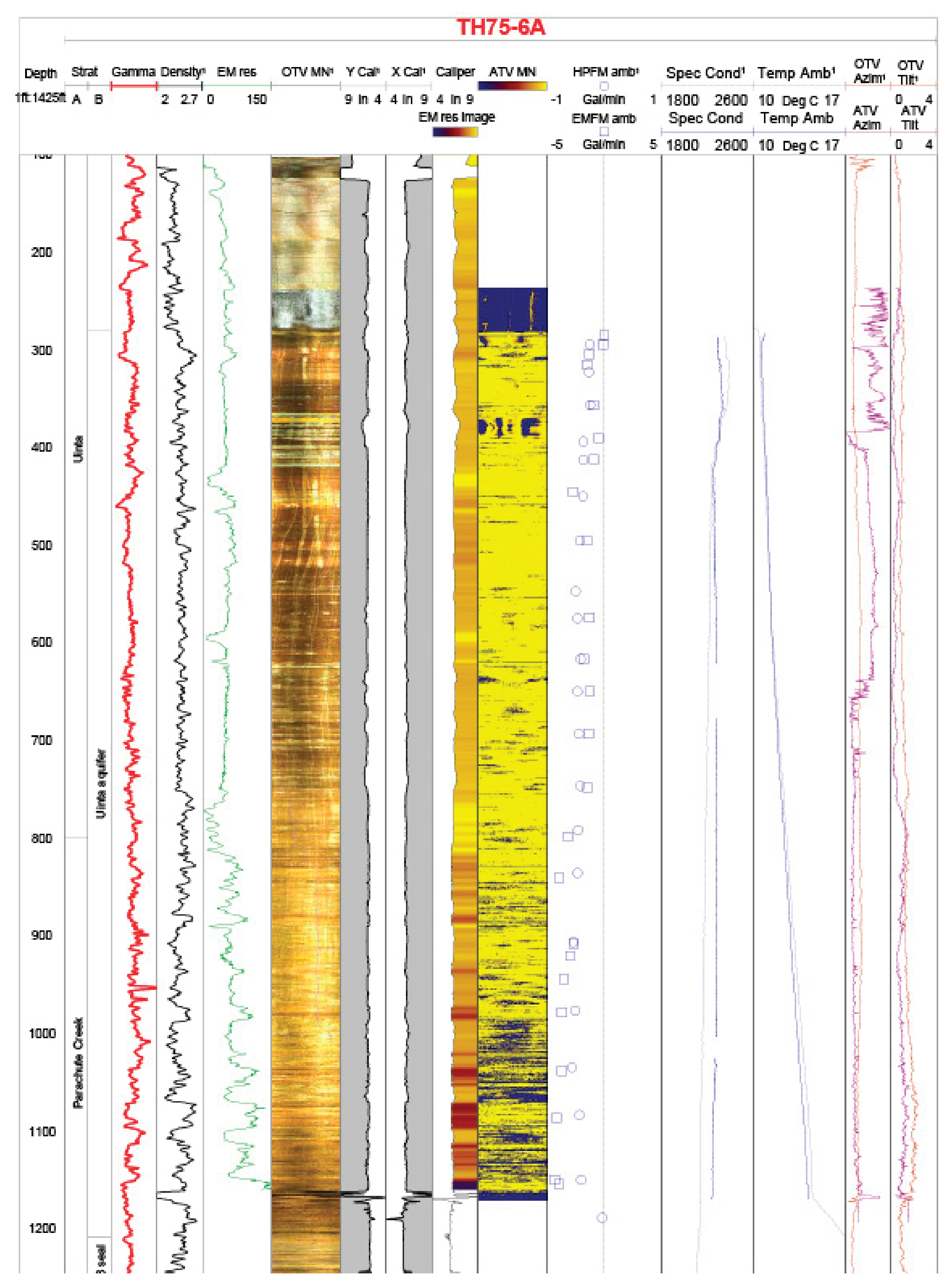
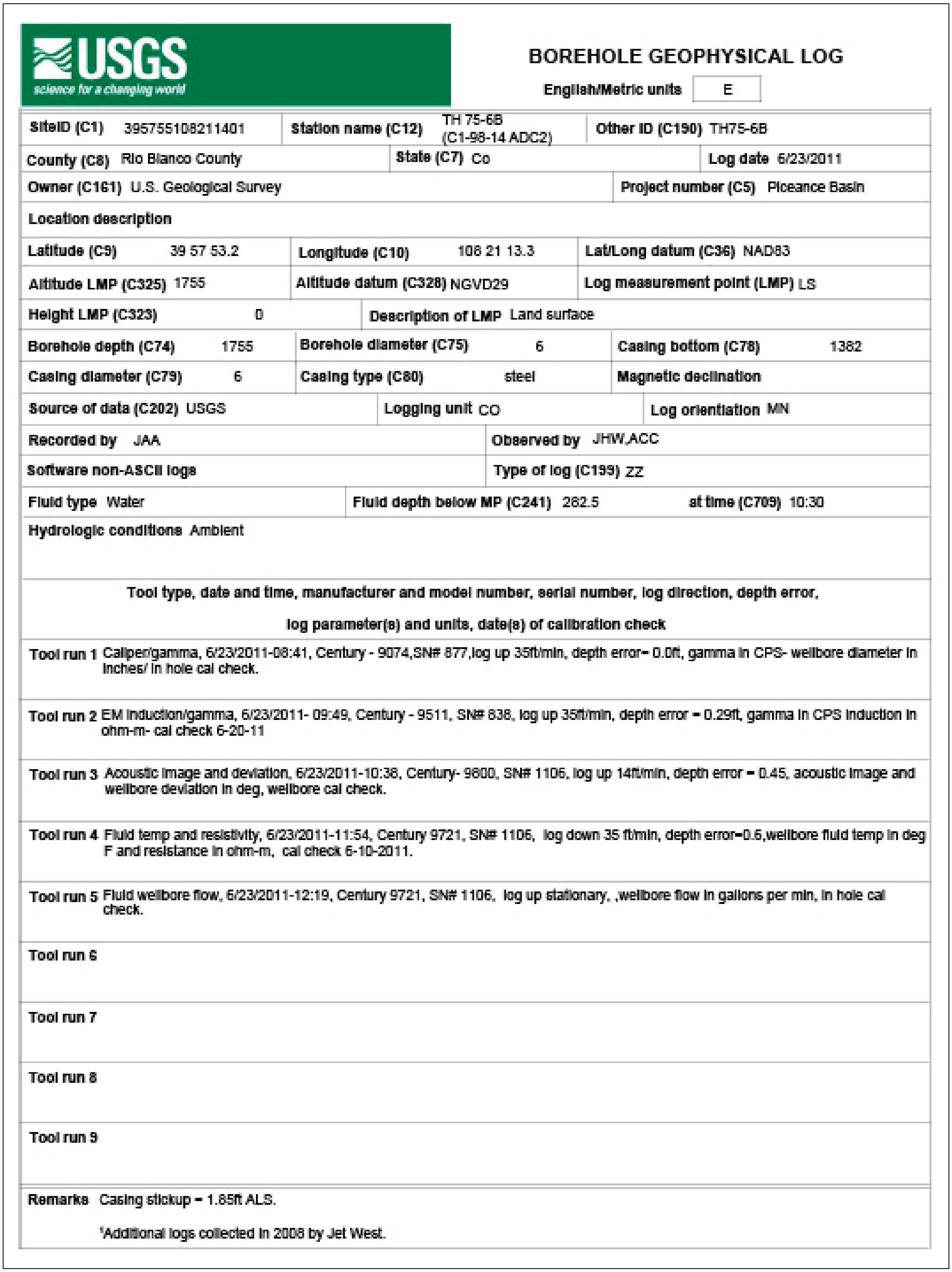


Figure 1–7. Geophysical logs for monitoring well 6A.—Continued



USGS
science for a changing world

BOREHOLE GEOPHYSICAL LOG

English/Metric units E

SiteID (C1) 395755108211401 **Station name (C12)** TH 75-6B (C1-98-14 ADC2) **Other ID (C190)** TH75-6B

County (C8) Rio Blanco County **State (C7)** Co **Log date** 6/23/2011

Owner (C161) U.S. Geological Survey **Project number (C5)** Piceance Basin

Location description

Latitude (C9) 39 57 53.2 **Longitude (C10)** 108 21 13.3 **Lat/Long datum (C36)** NAD83

Altitude LMP (C325) 1755 **Altitude datum (C328)** NGVD29 **Log measurement point (LMP)** LS

Height LMP (C323) 0 **Description of LMP** Land surface

Borehole depth (C74) 1755 **Borehole diameter (C75)** 6 **Casing bottom (C78)** 1382

Casing diameter (C79) 6 **Casing type (C80)** steel **Magnetic declination**

Source of data (C202) USGS **Logging unit** CO **Log orientation** MN

Recorded by JAA **Observed by** JHW,ACC

Software non-ASCII logs **Type of log (C199)** ZZ

Fluid type Water **Fluid depth below MP (C241)** 282.5 **at time (C709)** 10:30

Hydrologic conditions Ambient

Tool type, date and time, manufacturer and model number, serial number, log direction, depth error, log parameter(s) and units, date(s) of calibration check

Tool run 1 Caliper/gamma, 6/23/2011-08:41, Century - 9074,SN# 877,log up 35ft/min, depth error= 0.0ft, gamma in CPS- wellbore diameter in inches/ in hole cal check.

Tool run 2 EM induction/gamma, 6/23/2011- 09:49, Century - 9511, SN# 838, log up 35ft/min, depth error = 0.29ft, gamma in CPS induction in ohm-m- cal check 6-20-11

Tool run 3 Acoustic image and deviation, 6/23/2011-10:38, Century- 9800, SN# 1106, log up 14ft/min, depth error = 0.45, acoustic image and wellbore deviation in deg, wellbore cal check.

Tool run 4 Fluid temp and resistivity, 6/23/2011-11:54, Century 9721, SN# 1106, log down 35 ft/min, depth error=0.6,wellbore fluid temp in deg F and resistance in ohm-m, cal check 6-10-2011.

Tool run 5 Fluid wellbore flow, 6/23/2011-12:19, Century 9721, SN# 1106, log up stationary, ,wellbore flow in gallons per min, in hole cal check.

Tool run 6

Tool run 7

Tool run 8

Tool run 9

Remarks Casing stickup = 1.85ft ALS.

[1] Additional logs collected in 2008 by Jet West.

Figure 1–8. Geophysical logs for monitoring well 6B.

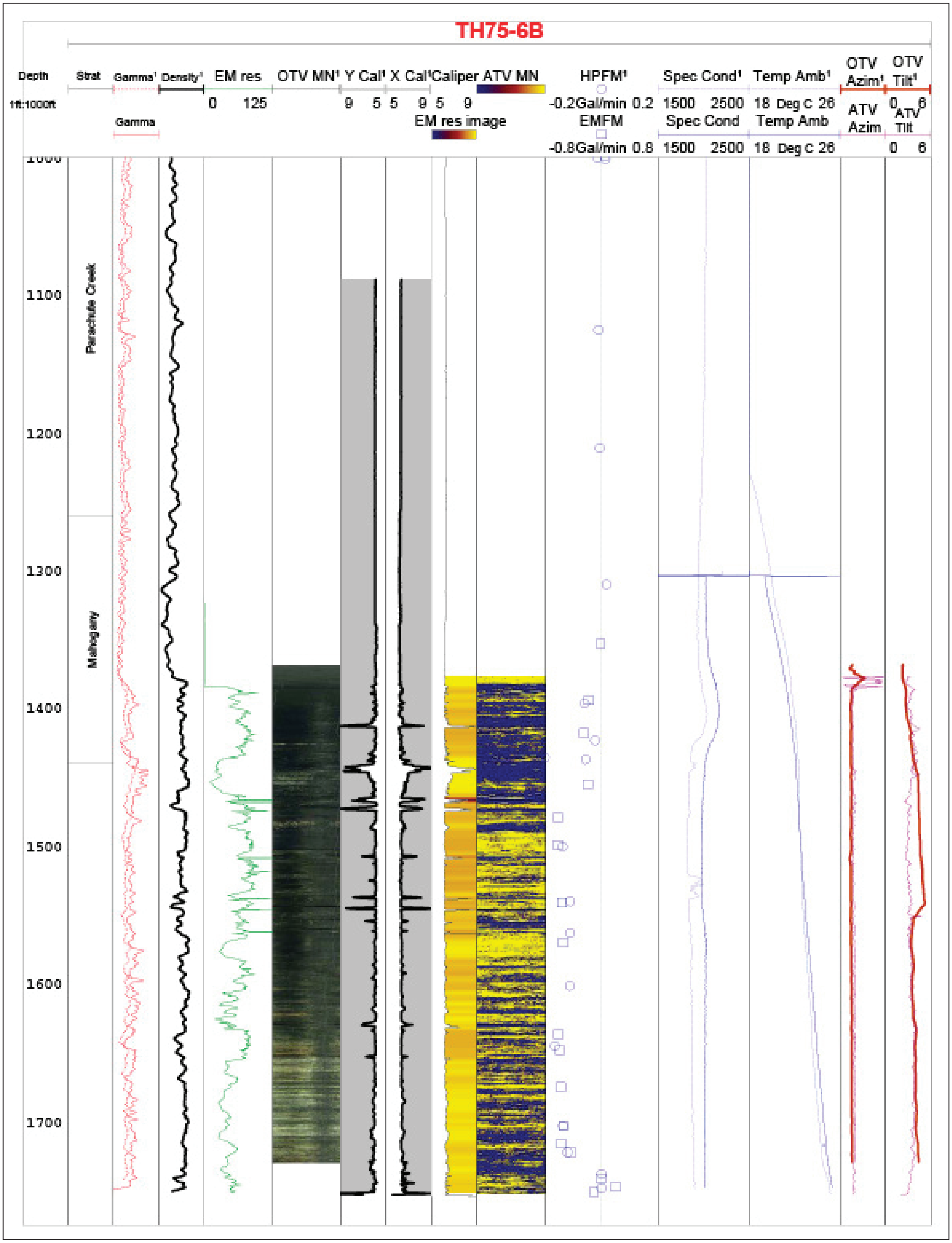
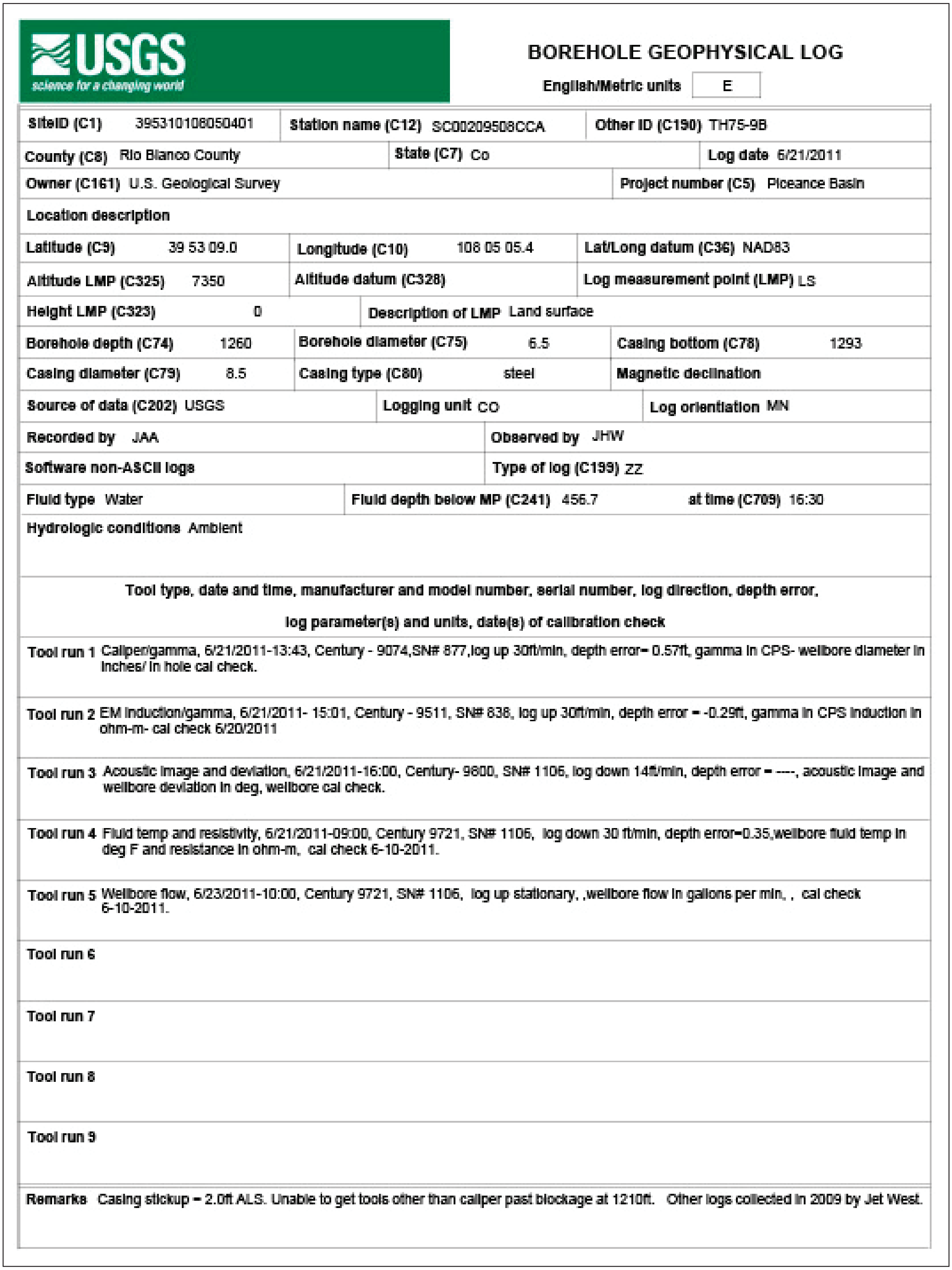


Figure 1–8. Geophysical logs for monitoring well 6B.—Continued



USGS
science for a changing world

BOREHOLE GEOPHYSICAL LOG

English/Metric units E

SiteID (C1) 395310108050401 **Station name (C12)** SC00209508CCA **Other ID (C190)** TH75-9B

County (C8) Rio Blanco County **State (C7)** Co **Log date** 6/21/2011

Owner (C161) U.S. Geological Survey **Project number (C5)** Piceance Basin

Location description

Latitude (C9) 39 53 09.0 **Longitude (C10)** 108 05 05.4 **Lat/Long datum (C36)** NAD83

Altitude LMP (C325) 7350 **Altitude datum (C328)** **Log measurement point (LMP)** LS

Height LMP (C323) 0 **Description of LMP** Land surface

Borehole depth (C74) 1260 **Borehole diameter (C75)** 6.5 **Casing bottom (C78)** 1293

Casing diameter (C79) 8.5 **Casing type (C80)** steel **Magnetic declination**

Source of data (C202) USGS **Logging unit** CO **Log orientation** MN

Recorded by JAA **Observed by** JHW

Software non-ASCII logs **Type of log (C199)** ZZ

Fluid type Water **Fluid depth below MP (C241)** 456.7 **at time (C709)** 16:30

Hydrologic conditions Ambient

Tool type, date and time, manufacturer and model number, serial number, log direction, depth error, log parameter(s) and units, date(s) of calibration check

Tool run 1 Caliper/gamma, 6/21/2011-13:43, Century - 9074,SN# 877,log up 30ft/min, depth error= 0.57ft, gamma in CPS- wellbore diameter in inches/ in hole cal check.

Tool run 2 EM induction/gamma, 6/21/2011- 15:01, Century - 9511, SN# 838, log up 30ft/min, depth error = -0.29ft, gamma in CPS induction in ohm-m- cal check 6/20/2011

Tool run 3 Acoustic image and deviation, 6/21/2011-16:00, Century- 9800, SN# 1106, log down 14ft/min, depth error = ----, acoustic image and wellbore deviation in deg, wellbore cal check.

Tool run 4 Fluid temp and resistivity, 6/21/2011-09:00, Century 9721, SN# 1106, log down 30 ft/min, depth error=0.35,wellbore fluid temp in deg F and resistance in ohm-m, cal check 6-10-2011.

Tool run 5 Wellbore flow, 6/23/2011-10:00, Century 9721, SN# 1106, log up stationary, ,wellbore flow in gallons per min, , cal check 6-10-2011.

Tool run 6

Tool run 7

Tool run 8

Tool run 9

Remarks Casing stickup = 2.0ft ALS. Unable to get tools other than caliper past blockage at 1210ft. Other logs collected in 2009 by Jet West.

Figure 1–9. Geophysical logs for monitoring well 9B.

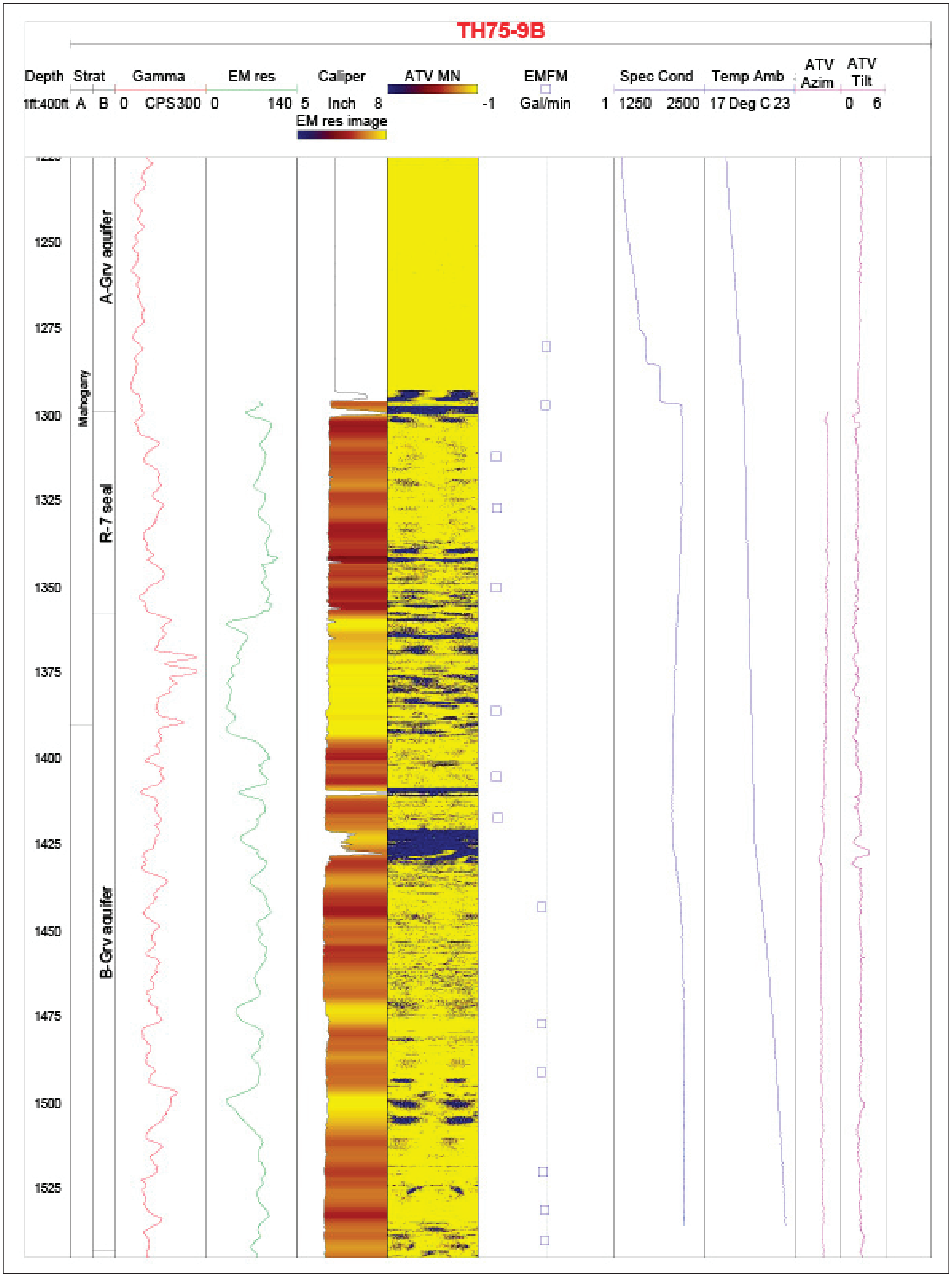
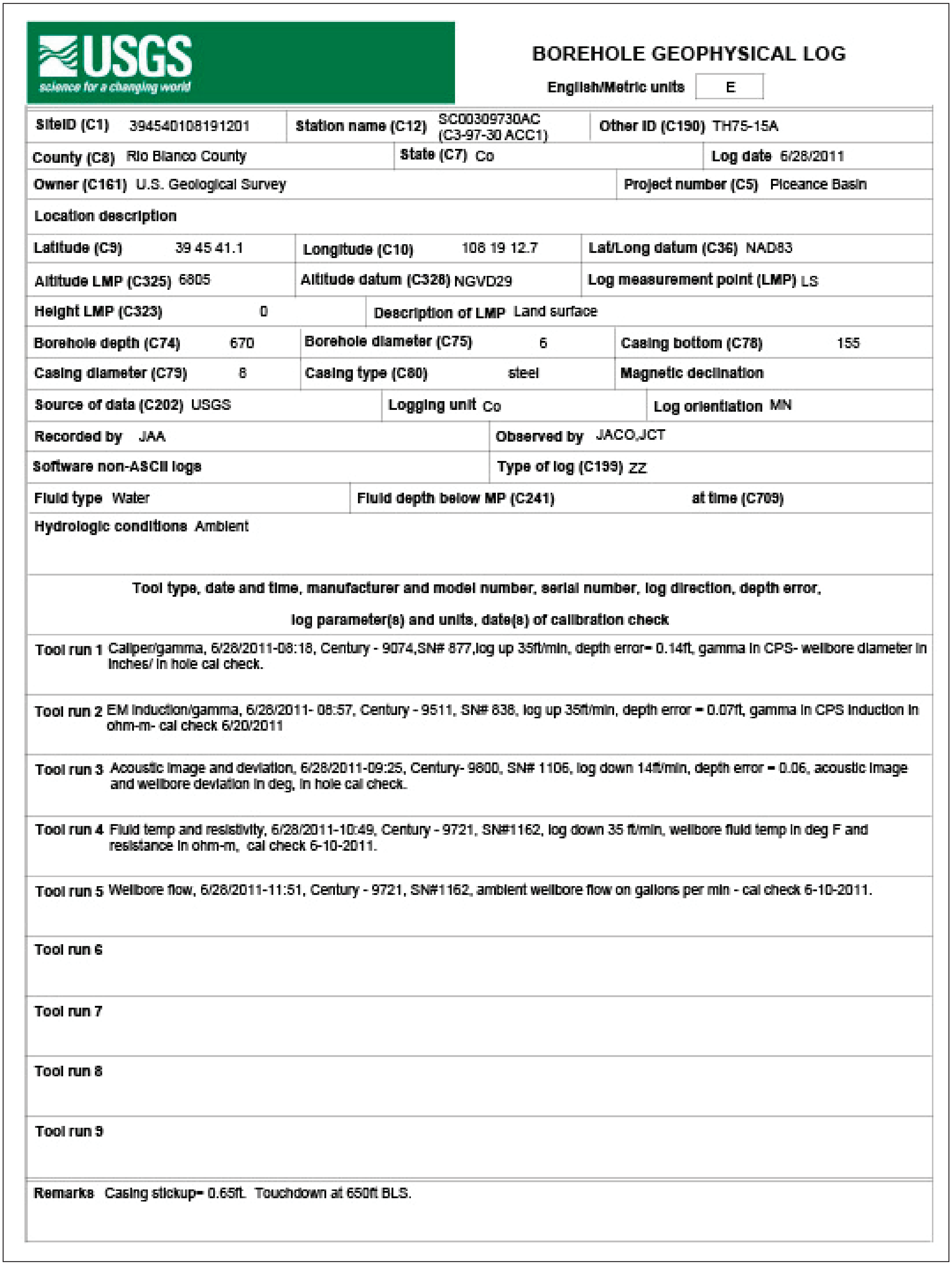


Figure 1–9. Geophysical logs for monitoring well 9B.—Continued



USGS
science for a changing world

BOREHOLE GEOPHYSICAL LOG

English/Metric units E

SiteID (C1) 394540108191201	**Station name (C12)** SC00309730AC (C3-97-30 ACC1)	**Other ID (C190)** TH75-15A
County (C8) Rio Blanco County	**State (C7)** Co	**Log date** 6/28/2011
Owner (C161) U.S. Geological Survey		**Project number (C5)** Piceance Basin
Location description		
Latitude (C9) 39 45 41.1	**Longitude (C10)** 108 19 12.7	**Lat/Long datum (C36)** NAD83
Altitude LMP (C325) 6805	**Altitude datum (C328)** NGVD29	**Log measurement point (LMP)** LS
Height LMP (C323) 0	**Description of LMP** Land surface	
Borehole depth (C74) 670	**Borehole diameter (C75)** 6	**Casing bottom (C78)** 155
Casing diameter (C79) 8	**Casing type (C80)** steel	**Magnetic declination**
Source of data (C202) USGS	**Logging unit** Co	**Log orientation** MN
Recorded by JAA	**Observed by** JACO,JCT	
Software non-ASCII logs	**Type of log (C199)** ZZ	
Fluid type Water	**Fluid depth below MP (C241)**	**at time (C709)**
Hydrologic conditions Ambient		

Tool type, date and time, manufacturer and model number, serial number, log direction, depth error, log parameter(s) and units, date(s) of calibration check

Tool run 1 Caliper/gamma, 6/28/2011-08:18, Century - 9074,SN# 877,log up 35ft/min, depth error= 0.14ft, gamma in CPS- wellbore diameter in inches/ in hole cal check.

Tool run 2 EM induction/gamma, 6/28/2011- 08:57, Century - 9511, SN# 838, log up 35ft/min, depth error = 0.07ft, gamma in CPS induction in ohm-m- cal check 6/20/2011

Tool run 3 Acoustic image and deviation, 6/28/2011-09:25, Century- 9800, SN# 1106, log down 14ft/min, depth error = 0.06, acoustic image and wellbore deviation in deg, in hole cal check.

Tool run 4 Fluid temp and resistivity, 6/28/2011-10:49, Century - 9721, SN#1162, log down 35 ft/min, wellbore fluid temp in deg F and resistance in ohm-m, cal check 6-10-2011.

Tool run 5 Wellbore flow, 6/28/2011-11:51, Century - 9721, SN#1162, ambient wellbore flow on gallons per min - cal check 6-10-2011.

Tool run 6

Tool run 7

Tool run 8

Tool run 9

Remarks Casing stickup= 0.65ft. Touchdown at 650ft BLS.

Figure 1–10. Geophysical logs for monitoring well 15A.

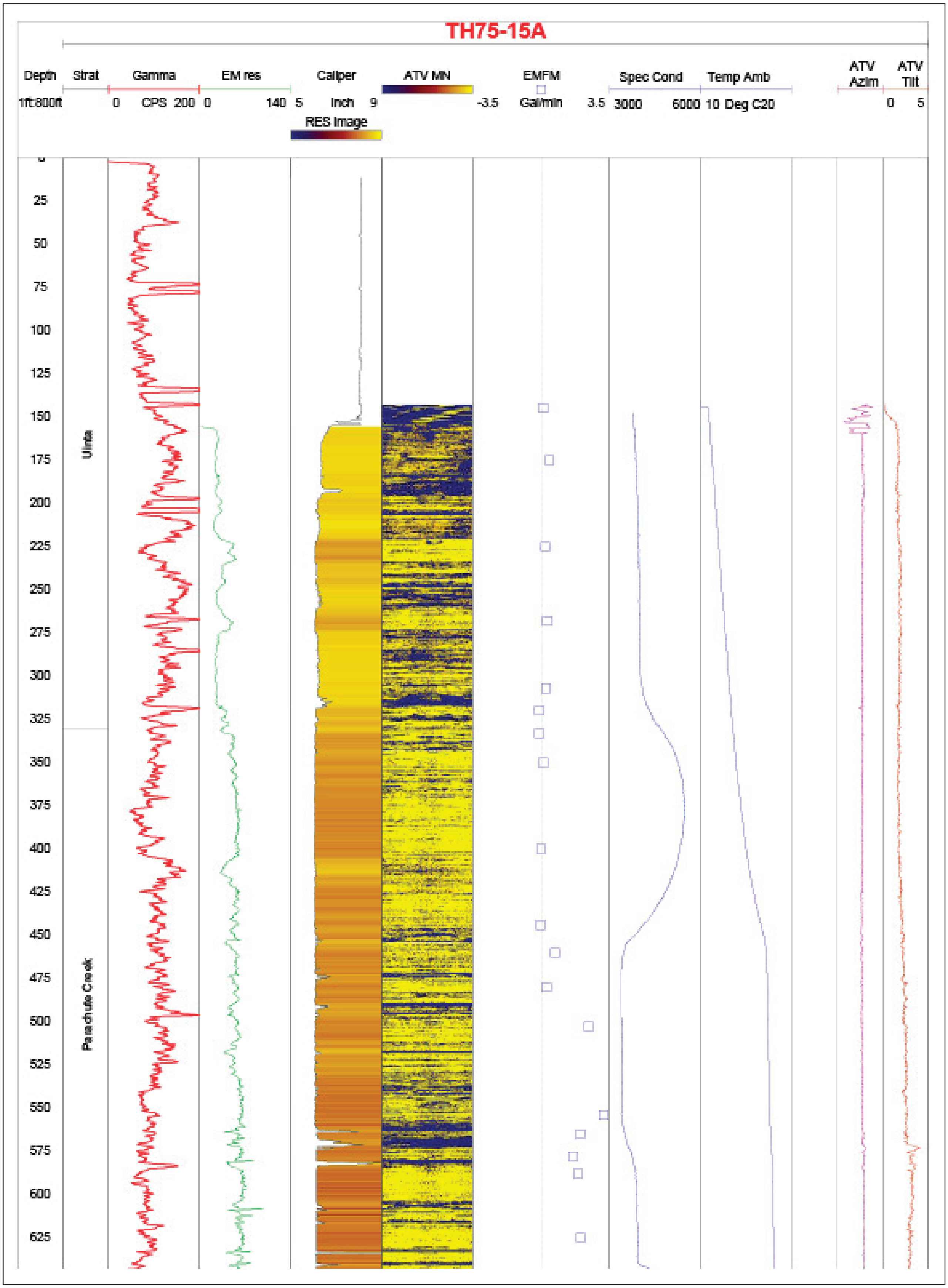


Figure 1–10. Geophysical logs for monitoring well 15A.—Continued

USGS science for a changing world

BOREHOLE GEOPHYSICAL LOG

English/Metric units E

SiteID (C1) 394540108191202	**Station name (C12)** SC00309730ACC2	**Other ID (C190)** TH75-15B
County (C8) Rio Blanco County	**State (C7)** Co	**Log date** 6/28/2011
Owner (C161)		**Project number (C5)** Piceance Basin
Location description		
Latitude (C9) 39 45 40.2	**Longitude (C10)** 108 19 13.3	**Lat/Long datum (C36)** NAD83
Altitude LMP (C325) 6805	**Altitude datum (C328)** NGVD29	**Log measurement point (LMP)** LS
Height LMP (C323) 0	**Description of LMP** Land surface	
Borehole depth (C74) 1040	**Borehole diameter (C75)** 6	**Casing bottom (C78)** 740
Casing diameter (C79) 6	**Casing type (C80)** steel	**Magnetic declination**
Source of data (C202) USGS	**Logging unit** CO	**Log orientation** MN
Recorded by JAA	**Observed by** JT,JC	
Software non-ASCII logs	**Type of log (C199)** ZZ	
Fluid type Water	**Fluid depth below MP (C241)**	**at time (C709)**
Hydrologic conditions Ambient		

Tool type, date and time, manufacturer and model number, serial number, log direction, depth error, log parameter(s) and units, date(s) of calibration check

Tool run 1 Caliper/gamma, 6/28/2011-0906, Century - 12:59, SN# 877,log up 35ft/min, depth error= -1.91ft, gamma in CPS- wellbore diameter in inches/ in hole cal check.

Tool run 2 EM induction/gamma, 6/28/2011- 13:40, Century - 9511, SN# 838, log up 35ft/min, depth error = 0.07ft, gamma in CPS induction in ohm-m- cal check 6-20-11

Tool run 3 Acoustic image and deviation, 6/28/2011-14:08, Century - 9800, SN#1106, log up14ft/min, depth error = 0.45, acoustic image and wellbore deviation in deg, wellbore cal check.

Tool run 4 Fluid temp and resistivity, 6/28/2011-14:08, Century 9721, SN# 1106, log up 35 ft/min, depth error=0.32,wellbore fluid temp in deg F and resistance in ohm-m, cal check 6/10/2011.

Tool run 5 Wellbore flow, 6/28/2011-15:36, Century 9721, SN# 1106, log up stationary, wellbore flow in gallons per min, cal check 6/10/2011.

Tool run 6

Tool run 7

Tool run 8

Tool run 9

Remarks Casing stickup= 1.40. Well bridged at 880 ft BLS.

Figure 1–11. Geophysical logs for monitoring well 15B.

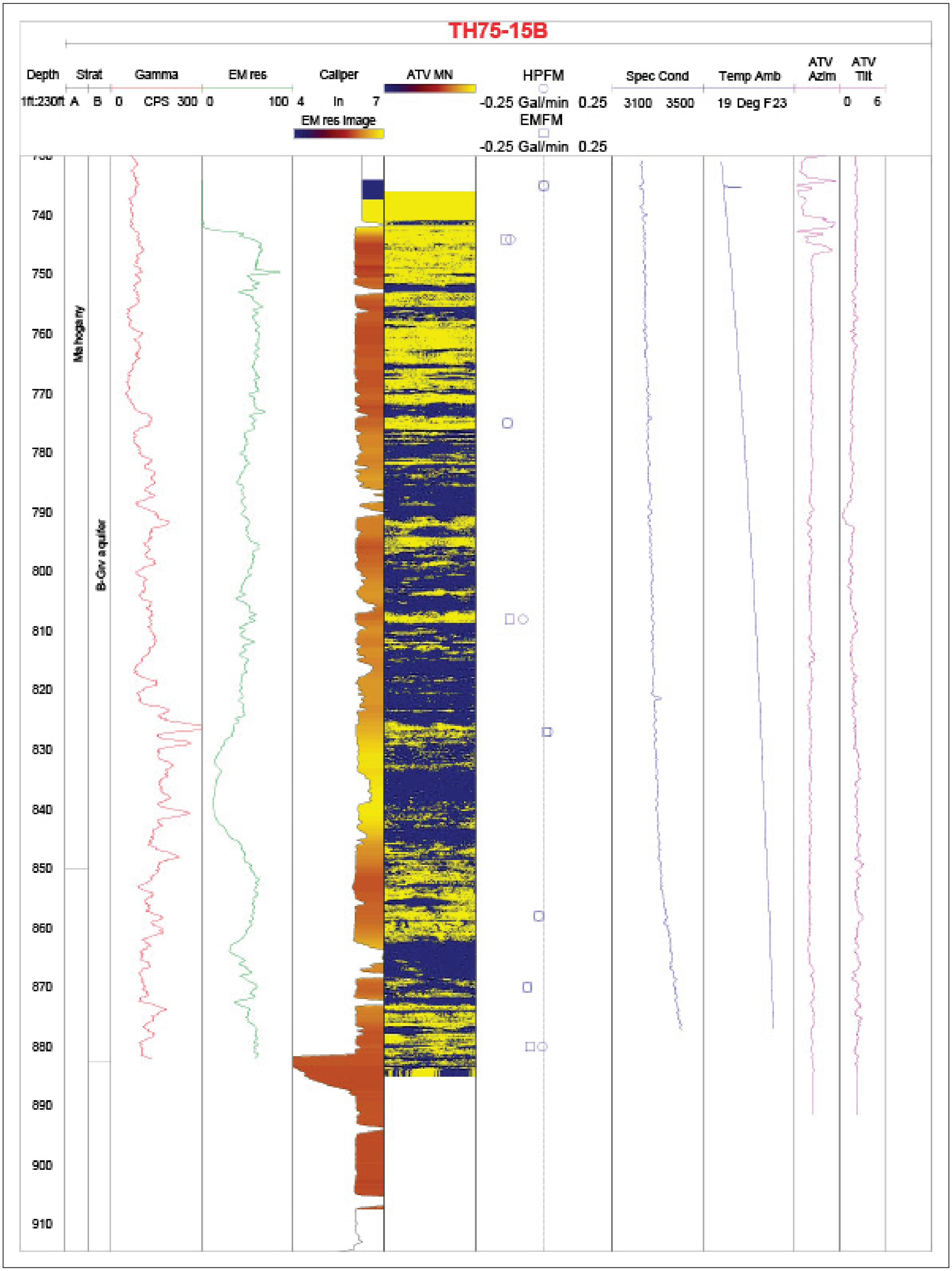
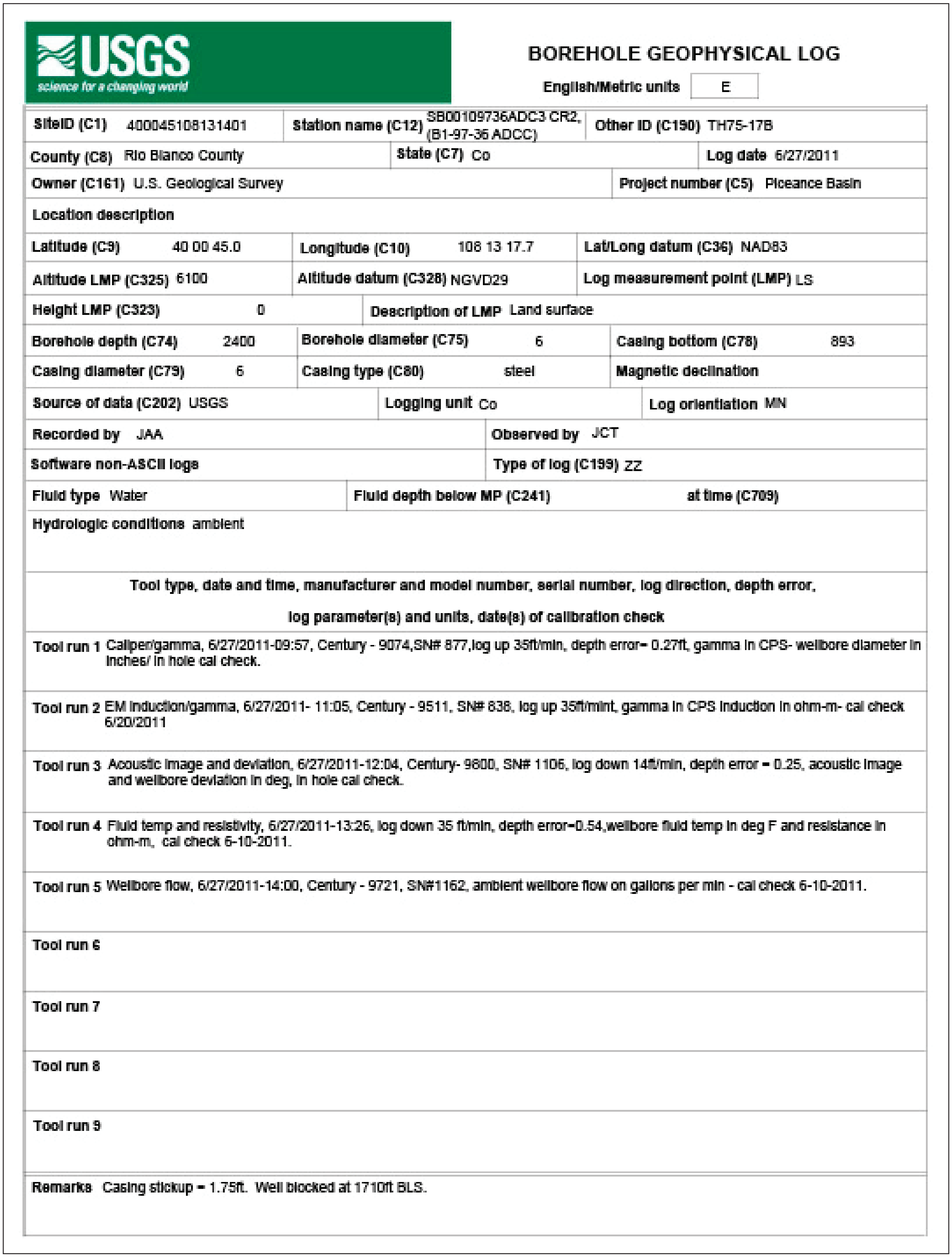


Figure 1–11. Geophysical logs for monitoring well 15B.—Continued



USGS
science for a changing world

BOREHOLE GEOPHYSICAL LOG

English/Metric units E

SiteID (C1) 400045108131401	**Station name (C12)** SB00109736ADC3 CR2, (B1-97-36 ADCC)	**Other ID (C190)** TH75-17B
County (C8) Rio Blanco County	**State (C7)** Co	**Log date** 6/27/2011
Owner (C161) U.S. Geological Survey		**Project number (C5)** Piceance Basin
Location description		
Latitude (C9) 40 00 45.0	**Longitude (C10)** 108 13 17.7	**Lat/Long datum (C36)** NAD83
Altitude LMP (C325) 6100	**Altitude datum (C328)** NGVD29	**Log measurement point (LMP)** LS
Height LMP (C323) 0	**Description of LMP** Land surface	
Borehole depth (C74) 2400	**Borehole diameter (C75)** 6	**Casing bottom (C78)** 893
Casing diameter (C79) 6	**Casing type (C80)** steel	**Magnetic declination**
Source of data (C202) USGS	**Logging unit** Co	**Log orientation** MN
Recorded by JAA	**Observed by** JCT	
Software non-ASCII logs	**Type of log (C199)** ZZ	
Fluid type Water	**Fluid depth below MP (C241)**	**at time (C709)**
Hydrologic conditions ambient		

Tool type, date and time, manufacturer and model number, serial number, log direction, depth error, log parameter(s) and units, date(s) of calibration check

Tool run 1 Caliper/gamma, 6/27/2011-09:57, Century - 9074,SN# 877,log up 35ft/min, depth error= 0.27ft, gamma in CPS- wellbore diameter in inches/ in hole cal check.

Tool run 2 EM induction/gamma, 6/27/2011- 11:05, Century - 9511, SN# 838, log up 35ft/mint, gamma in CPS induction in ohm-m- cal check 6/20/2011

Tool run 3 Acoustic image and deviation, 6/27/2011-12:04, Century- 9800, SN# 1106, log down 14ft/min, depth error = 0.25, acoustic image and wellbore deviation in deg, in hole cal check.

Tool run 4 Fluid temp and resistivity, 6/27/2011-13:26, log down 35 ft/min, depth error=0.54,wellbore fluid temp in deg F and resistance in ohm-m, cal check 6-10-2011.

Tool run 5 Wellbore flow, 6/27/2011-14:00, Century - 9721, SN#1162, ambient wellbore flow on gallons per min - cal check 6-10-2011.

Tool run 6

Tool run 7

Tool run 8

Tool run 9

Remarks Casing stickup = 1.75ft. Well blocked at 1710ft BLS.

Figure 1–12. Geophysical logs for monitoring well 17B.

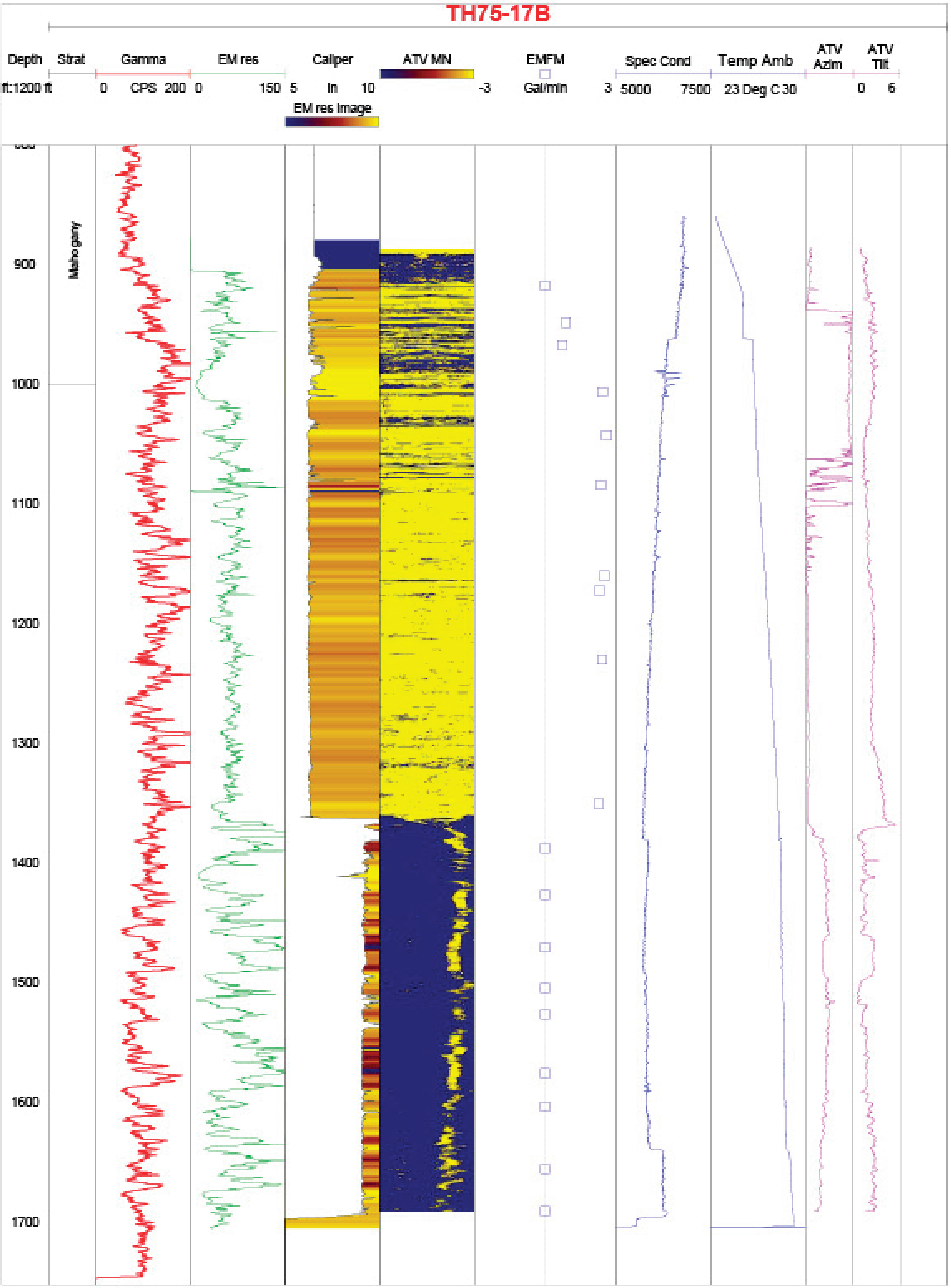
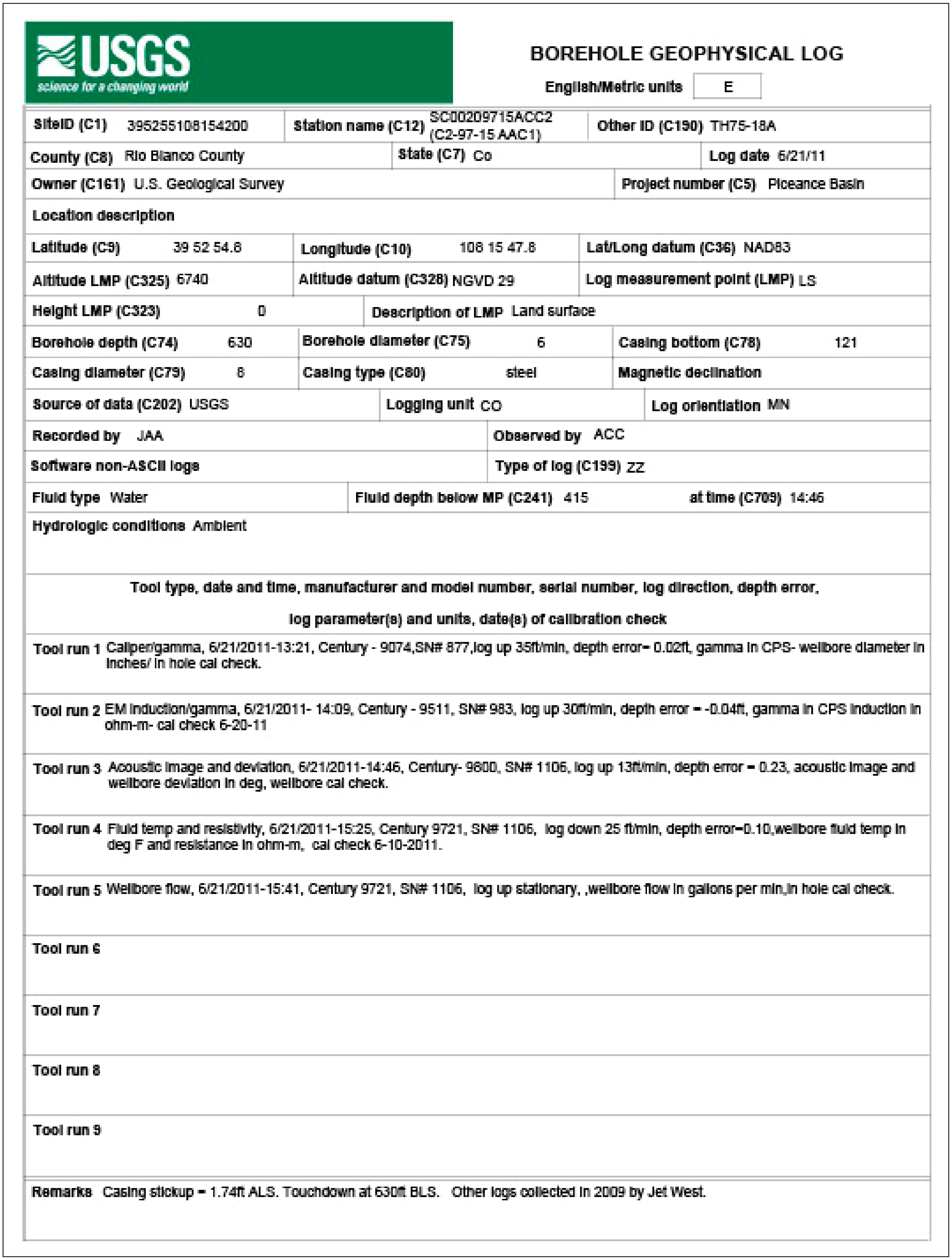


Figure 1–12. Geophysical logs for monitoring well 17B.—Continued



USGS
science for a changing world

BOREHOLE GEOPHYSICAL LOG

English/Metric units E

SiteID (C1) 395255108154200 | **Station name (C12)** SC00209715ACC2 (C2-97-15 AAC1) | **Other ID (C190)** TH75-18A

County (C8) Rio Blanco County | **State (C7)** Co | **Log date** 6/21/11

Owner (C161) U.S. Geological Survey | **Project number (C5)** Piceance Basin

Location description

Latitude (C9) 39 52 54.8 | **Longitude (C10)** 108 15 47.8 | **Lat/Long datum (C36)** NAD83

Altitude LMP (C325) 6740 | **Altitude datum (C328)** NGVD 29 | **Log measurement point (LMP)** LS

Height LMP (C323) 0 | **Description of LMP** Land surface

Borehole depth (C74) 630 | **Borehole diameter (C75)** 6 | **Casing bottom (C78)** 121

Casing diameter (C79) 6 | **Casing type (C80)** steel | **Magnetic declination**

Source of data (C202) USGS | **Logging unit** CO | **Log orientation** MN

Recorded by JAA | **Observed by** ACC

Software non-ASCII logs | **Type of log (C199)** ZZ

Fluid type Water | **Fluid depth below MP (C241)** 415 | **at time (C709)** 14:46

Hydrologic conditions Ambient

Tool type, date and time, manufacturer and model number, serial number, log direction, depth error, log parameter(s) and units, date(s) of calibration check

Tool run 1 Caliper/gamma, 6/21/2011-13:21, Century - 9074,SN# 877,log up 35ft/min, depth error= 0.02ft, gamma in CPS- wellbore diameter in inches/ in hole cal check.

Tool run 2 EM induction/gamma, 6/21/2011- 14:09, Century - 9511, SN# 983, log up 30ft/min, depth error = -0.04ft, gamma in CPS induction in ohm-m- cal check 6-20-11

Tool run 3 Acoustic image and deviation, 6/21/2011-14:46, Century- 9800, SN# 1106, log up 13ft/min, depth error = 0.23, acoustic image and wellbore deviation in deg, wellbore cal check.

Tool run 4 Fluid temp and resistivity, 6/21/2011-15:25, Century 9721, SN# 1106, log down 25 ft/min, depth error=0.10,wellbore fluid temp in deg F and resistance in ohm-m, cal check 6-10-2011.

Tool run 5 Wellbore flow, 6/21/2011-15:41, Century 9721, SN# 1106, log up stationary, ,wellbore flow in gallons per min,in hole cal check.

Tool run 6

Tool run 7

Tool run 8

Tool run 9

Remarks Casing stickup = 1.74ft ALS. Touchdown at 630ft BLS. Other logs collected in 2009 by Jet West.

Figure 1–13. Geophysical logs for monitoring well 18A.

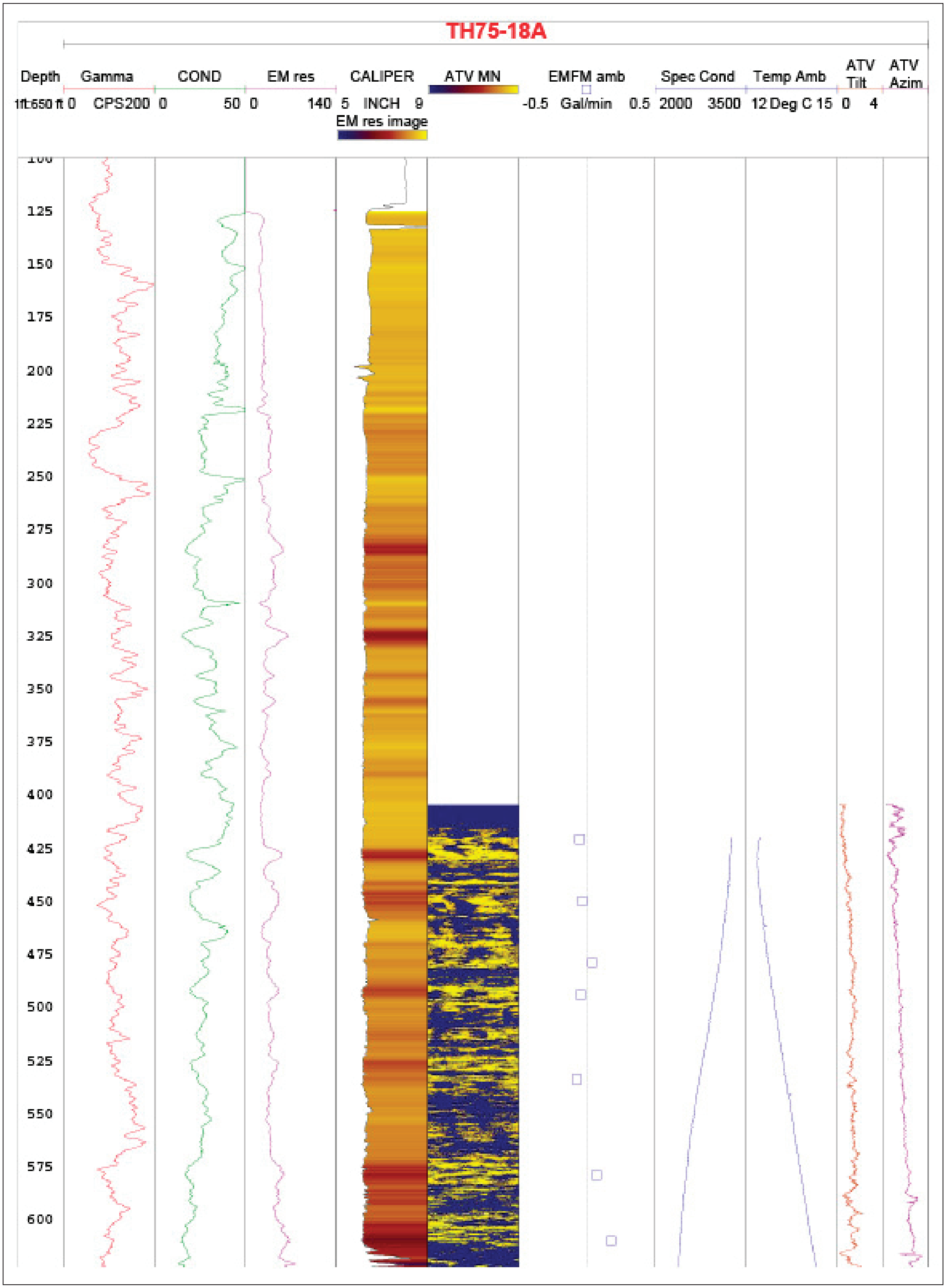


Figure 1–13. Geophysical logs for monitoring well 18A.—Continued

Appendix Table 2–1. Quality control data for blanks.

[U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; °C, degrees Celsius; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, nitrogen; P, phosphorus; µg/L, micrograms per liter; <, less than; >, greater than; --, no data]

Well name	Sample type	Geologic interval in which sample interval is located	Collection date	Collection time	Specific conductance (µS/cm at 25 °C)	Residue on evaporation at 180 °C (mg/L)	Calcium, filtered (mg/L)
1A	Equipment blank	U-PCM	6/4/2012	1300	--	--	--
1A	Source solution blank	U-PCM	6/4/2012	1301	--	--	--
1B	Equipment blank	PCMB	6/4/2012	1330	--	--	--
6B	Environmental	PCMB	8/25/2010	1300	1,340	854	3.25
6B	Source solution blank	PCMB	8/26/2010	1340	--	--	--
6B	Field blank	PCMB	8/26/2010	1400	<5	<10	<0.044
9B	Environmental	MZ	8/18/2012	1100	1,590	984	7.77
9B	Field blank	MZ	8/19/2012	830	<5	<20	<0.022
13A	Environmental	PCMA	11/2/2010	1310	1,390	932	25.7
13A	Field blank	PCMA	11/2/2010	1500	--	--	--
13A	Equipment blank	PCMA	6/4/2012	1430	--	--	--
13U	Equipment blank	U-PCM	6/4/2012	1400	--	--	--
15A	Environmental	PCMA	8/19/2011	1300	2,170	1,390	6.59
15A	Field blank	PCMA	8/19/2011	1500	<5	<12	<0.022

Well name	Sample type	Collection date	Magnesium, filtered (mg/L)	Sodium, filtered (mg/L)	Potassium, filtered (mg/L)	Chloride, filtered (mg/L)	Bromide, filtered (mg/L)	Sulfate, filtered (mg/L)	Fluoride, filtered (mg/L)
1A	Equipment blank	6/4/2012	--	--	--	--	--	--	--
1A	Source solution blank	6/4/2012	--	--	--	--	--	--	--
1B	Equipment blank	6/4/2012	--	--	--	--	--	--	--
6B	Environmental	8/25/2010	2.34	301	0.617	11.3	0.083	32	18.2
6B	Source solution blank	8/26/2010	--	--	--	--	--	--	--
6B	Field blank	8/26/2010	<0.016	<0.1	<0.064	<0.12	<0.02	<0.18	<0.08
9B	Environmental	8/18/2012	4.00	378	0.747	14.7	0.0581	0.644	17.4
9B	Field blank	8/19/2012	<0.011	<0.06	<0.03	<0.06	<0.01	<0.09	<0.04
13A	Environmental	11/2/2010	53.1	213	0.264	6.67	0.0613	312	2.41
13A	Field blank	11/2/2010	--	--	--	--	--	--	--
13A	Equipment blank	6/4/2012	--	--	--	--	--	--	--
13U	Equipment blank	6/4/2012	--	--	--	--	--	--	--
15A	Environmental	8/19/2011	4.85	509	1.76	116	0.317	29.4	19.1
15A	Field blank	8/19/2011	<0.008	<0.06	<0.022	<0.06	<0.01	<0.09	<0.04

Well name	Sample type	Collection date	Silica, filtered (mg/L)	Nitrogen, total, filtered (mg/L)	Ammonia, filtered (mg N/L)	Nitrite, filtered (mg N/L)	Nitrite + nitrate, filtered (mg N/L)	Orthophosphate, filtered (mg P/L)
1A	Equipment blank	6/4/2012	--	--	--	--	--	--
1A	Source solution blank	6/4/2012	--	--	--	--	--	--
1B	Equipment blank	6/4/2012	--	--	--	--	--	--
6B	Environmental	8/25/2010	12.7	--	--	--	--	--
6B	Source solution blank	8/26/2010	--	--	--	--	--	--
6B	Field blank	8/26/2010	<0.058	--	--	--	--	--
9B	Environmental	8/18/2012	11.4	--	--	--	--	--
9B	Field blank	8/19/2012	<0.018	--	--	--	--	--
13A	Environmental	11/2/2010	24	--	--	--	--	--
13A	Field blank	11/2/2010	--	--	--	--	--	--
13A	Equipment blank	6/4/2012	--	--	--	--	--	--
13U	Equipment blank	6/4/2012	--	--	--	--	--	--
15A	Environmental	8/19/2011	10.5	2.54	2.16	<0.001	<0.02	0.04
15A	Field blank	8/19/2011	<0.029	<0.05	0.0118	<0.001	<0.02	<0.004

Appendix Table 2–1. Quality control data for blanks.—Continued

[U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; °C, degrees Celsius; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, nitrogen; P, phosphorus; µg/L, micrograms per liter; <, less than; >, greater than; --, no data]

Well name	Sample type	Collection date	Organic carbon, filtered (mg/L)	Aluminum, filtered (µg/L)	Antimony, filtered (µg/L)	Arsenic, filtered (µg/L)	Barium, filtered (µg/L)	Beryllium, filtered (µg/L)
1A	Equipment blank	6/4/2012	0.1	--	--	--	--	--
1A	Source solution blank	6/4/2012	0.1	--	--	--	--	--
1B	Equipment blank	6/4/2012	0.1	--	--	--	--	--
6B	Environmental	8/25/2010	--	--	--	--	--	--
6B	Source solution blank	8/26/2010	--	--	--	--	--	--
6B	Field blank	8/26/2010	--	--	--	--	--	--
9B	Environmental	8/18/2012	1.6	--	--	--	--	--
9B	Field blank	8/19/2012	--	--	--	--	--	--
13A	Environmental	11/2/2010	--	--	--	--	--	--
13A	Field blank	11/2/2010	--	--	--	--	--	--
13A	Equipment blank	6/4/2012	0.5	--	--	--	--	--
13U	Equipment blank	6/4/2012	--	--	--	--	--	--
15A	Environmental	8/19/2011	2.9	5.73	<0.027	0.155	220	0.133
15A	Field blank	8/19/2011	0.2	<1.7	<0.027	<0.022	<0.07	<0.006

Well name	Sample type	Collection date	Boron, filtered (µg/L)	Cadmium, filtered (µg/L)	Chromium, filtered (µg/L)	Cobalt, filtered (µg/L)	Copper, filtered (µg/L)	Iron, filtered (µg/L)
1A	Equipment blank	6/4/2012	--	--	--	--	--	--
1A	Source solution blank	6/4/2012	--	--	--	--	--	--
1B	Equipment blank	6/4/2012	--	--	--	--	--	--
6B	Environmental	8/25/2010	--	--	--	--	--	80.8
6B	Source solution blank	8/26/2010	--	--	--	--	--	--
6B	Field blank	8/26/2010	--	--	--	--	--	<6
9B	Environmental	8/18/2012	--	--	--	--	--	108
9B	Field blank	8/19/2012	--	--	--	--	--	5.87
13A	Environmental	11/2/2010	--	--	--	--	--	8
13A	Field blank	11/2/2010	--	--	--	--	--	--
13A	Equipment blank	6/4/2012	--	--	--	--	--	--
13U	Equipment blank	6/4/2012	--	--	--	--	--	--
15A	Environmental	8/19/2011	4,020	0.026	1.16	<0.02	<0.5	17
15A	Field blank	8/19/2011	<3	<0.016	<0.06	<0.02	<0.5	<3.2

Well name	Sample type	Collection date	Lead, filtered (µg/L)	Lithium, filtered (µg/L)	Manganese, filtered (µg/L)	Molybdenum, filtered (µg/L)	Nickel, filtered (µg/L)	Selenium, filtered (µg/L)
1A	Equipment blank	6/4/2012	--	--	--	--	--	--
1A	Source solution blank	6/4/2012	--	--	--	--	--	--
1B	Equipment blank	6/4/2012	--	--	--	--	--	--
6B	Environmental	8/25/2010	--	--	7.94	--	--	--
6B	Source solution blank	8/26/2010	--	--	--	--	--	--
6B	Field blank	8/26/2010	--	--	0.64	--	--	--
9B	Environmental	8/18/2012	--	--	3.47	--	--	--
9B	Field blank	8/19/2012	--	--	0.332	--	--	--
13A	Environmental	11/2/2010	--	--	1.34	--	--	--
13A	Field blank	11/2/2010	--	--	--	--	--	--
13A	Equipment blank	6/4/2012	--	--	--	--	--	--
13U	Equipment blank	6/4/2012	--	--	--	--	--	--
15A	Environmental	8/19/2011	<0.015	673	6.94	0.0792	0.226	0.036
15A	Field blank	8/19/2011	<0.015	<0.22	<0.16	<0.014	<0.09	<0.03

Appendix Table 2–1. Quality control data for blanks.—Continued

[U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; °C, degrees Celsius; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, nitrogen; P, phosphorus; µg/L, micrograms per liter; <, less than; >, greater than; --, no data]

Well name	Sample type	Collection date	Silver, filtered (µg/L)	Strontium, filtered (µg/L)	Thallium, filtered (µg/L)	Uranium, filtered (µg/L)	Vanadium, filtered (µg/L)	Zinc, filtered (µg/L)	Toluene (µg/L)
1A	Equipment blank	6/4/2012	--	--	--	--	--	--	<0.1
1A	Source solution blank	6/4/2012	--	--	--	--	--	--	<0.1
1B	Equipment blank	6/4/2012	--	--	--	--	--	--	<0.1
6B	Environmental	8/25/2010	--	--	--	--	--	--	<0.1
6B	Source solution blank	8/26/2010	--	--	--	--	--	--	<0.1
6B	Field blank	8/26/2010	--	--	--	--	--	--	<0.1
9B	Environmental	8/18/2012	--	--	--	--	--	--	<0.1
9B	Field blank	8/19/2012	--	--	--	--	--	--	<0.1
13A	Environmental	11/2/2010	--	--	--	--	--	--	3.1
13A	Field blank	11/2/2010	--	--	--	--	--	--	<0.1
13A	Equipment blank	6/4/2012	--	--	--	--	--	--	<0.1
13U	Equipment blank	6/4/2012	--	--	--	--	--	--	<0.1
15A	Environmental	8/19/2011	0.0206	1,260	<0.01	0.0051	0.105	<1.4	<0.1
15A	Field blank	8/19/2011	<0.005	<0.2	<0.01	<0.004	<0.08	<1.4	<0.1

Well name	Sample type	Collection date	Benzene (µg/L)	Ethylbenzene (µg/L)	o-xylene (µg/L)	Tert-butyl methyl ether (µg/L)	Xylene, total (µg/L)	m- and p-xylene (µg/L
1A	Equipment blank	6/4/2012	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2
1A	Source solution blank	6/4/2012	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2
1B	Equipment blank	6/4/2012	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2
6B	Environmental	8/25/2010	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2
6B	Source solution blank	8/26/2010	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2
6B	Field blank	8/26/2010	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2
9B	Environmental	8/18/2012	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2
9B	Field blank	8/19/2012	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2
13A	Environmental	11/2/2010	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2
13A	Field blank	11/2/2010	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2
13A	Equipment blank	6/4/2012	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2
13U	Equipment blank	6/4/2012	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2
15A	Environmental	8/19/2011	0.6	<0.1	<0.1	<0.2	<0.2	<0.2
15A	Field blank	8/19/2011	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2

Appendix Table 2–2. Quality control data for replicates.

[U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; °C, degrees Celsius; mg/L, milligrams per liter; N, nitrogen; P, phosphorus; µg/L, micrograms per liter; ng/L, nanograms per liter; cm^{3}STP/g, cubic centimeters at standard temperature and pressure per gram of water; R/R$_a$, (helium-3/helium-4)$_{sample}$/(helium-3/helium-4)$_{air}$; ‰, per mil; VSMOW, Vienna Standard Mean Ocean Water; pmc, percent modern carbon; DIC, dissolved inorganic carbon; VPDB, Vienna Peedee Belemnite; <, less than; >, greater than; --, no data; RPD, relative percent difference]

Well name	Sample type	Geologic interval in which sample interval is located	Collection date	Collection time	Alkalinity (mg/L as CaCO	Residue on evaporation at 180 °C (mg/L)	Calcium, filtered (mg/L)	Magnesium, filtered (mg/L)
13A	Environmental	PCMA	8/14/2012	1100	459	938	25.8	54.8
13A	Replicate	PCMA	8/14/2012	1101	445	935	25.8	54.8
13A	RPD	--	--	--	3.1	0.3	0.0	0.0
13B	Environmental	PCMB	8/17/2011	1400	731	876	15.2	18.2
13B	Replicate	PCMB	8/17/2011	1401	--	843	15.0	17.9
13B	RPD	--	--	--	--	3.8	1.3	1.7
13U	Environmental	PCMA	8/14/2012	1400	--	--	--	--
13U	Replicate	PCMA	8/14/2012	1401	--	--	--	--
13U	RPD	--	--	--	--	--	--	--

Well name	Sample type	Collection date	Sodium, filtered (mg/L)	Potassium, filtered (mg/L)	Chloride, filtered (mg/L)	Bromide, filtered (mg/L)	Sulfate, filtered (mg/L)	Fluoride, filtered (mg/L)	Silica, filtered (mg/L)
13A	Environmental	8/14/2012	233	0.294	6.49	0.0620	314	2.32	22.6
13A	Replicate	8/14/2012	235	0.275	6.50	0.0719	316	2.18	22.5
13A	RPD	--	0.9	6.7	0.2	14.8	0.6	6.2	0.4
13B	Environmental	8/17/2011	293	0.555	9.45	0.0694	38.5	4.56	14.7
13B	Replicate	8/17/2011	285	0.551	9.42	<0.01	71.6	4.43	14.7
13B	RPD	--	2.8	0.7	0.3	--	60.1	2.9	0.0
13U	Environmental	8/14/2012	--	--	--	--	--	--	--
13U	Replicate	8/14/2012	--	--	--	--	--	--	--
13U	RPD	--	--	--	--	--	--	--	--

Well name	Sample type	Collection date	Nitrogen, total, filtered (mg/L)	Ammonia, filtered (mg N/L)	Nitrite, filtered (mg N/L)	Nitrite + nitrate, filtered (mg N/L)	Ortho-phosphate, filtered (mg P/L)	Organic carbon, filtered (mg/L)	Aluminum, filtered (µg/L)
13A	Environmental	8/14/2012	--	--	--	--	--	1.9	--
13A	Replicate	8/14/2012	--	--	--	--	--	1.2	--
13A	RPD	--	--	--	--	--	--	46.6	--
13B	Environmental	8/17/2011	0.670	0.480	0.00123	<0.02	0.012	1.6	1.99
13B	Replicate	8/17/2011	0.673	0.569	<0.001	<0.02	0.0098	1.6	1.99
13B	RPD	--	0.4	17.0	--	--	20.2	1.2	0.0
13U	Environmental	8/14/2012	--	--	--	--	--	--	--
13U	Replicate	8/14/2012	--	--	--	--	--	--	--
13U	RPD	--	--	--	--	--	--	--	--

Well name	Sample type	Collection date	Antimony, filtered (µg/L)	Arsenic, filtered (µg/L)	Barium, filtered (µg/L)	Beryllium, filtered (µg/L)	Boron, filtered (µg/L)	Cadmium, filtered (µg/L)	Chromium, filtered (µg/L)
13A	Environmental	8/14/2012	--	--	--	--	--	--	--
13A	Replicate	8/14/2012	--	--	--	--	--	--	--
13A	RPD	--	--	--	--	--	--	--	--
13B	Environmental	8/17/2011	<0.027	0.037	3,280	0.0398	246	<0.016	0.066
13B	Replicate	8/17/2011	<0.027	0.058	3,220	0.0403	241	<0.016	<0.06
13B	RPD	--	--	44.2	1.8	1.2	2.1	--	--
13U	Environmental	8/14/2012	--	--	--	--	--	--	--
13U	Replicate	8/14/2012	--	--	--	--	--	--	--
13U	RPD	--	--	--	--	--	--	--	--

Appendix Table 2–2. Quality control data for replicates.—Continued

[U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; °C, degrees Celsius; mg/L, milligrams per liter; N, nitrogen; P, phosphorus; µg/L, micrograms per liter; ng/L, nanograms per liter; cm^{3}STP/g, cubic centimeters at standard temperature and pressure per gram of water; R/R$_a$, (helium-3/helium-4)$_{sample}$/(helium-3/helium-4)$_{air}$; ‰, per mil; VSMOW, Vienna Standard Mean Ocean Water; pmc, percent modern carbon; DIC, dissolved inorganic carbon; VPDB, Vienna Peedee Belemnite; <, less than; >, greater than; --, no data; RPD, relative percent difference]

Well name	Sample type	Collection date	Cobalt, filtered (µg/L)	Copper, filtered (µg/L)	Iron, filtered (µg/L)	Lead, filtered (µg/L)	Lithium, filtered (µg/L)	Manganese, filtered (µg/L)	Mercury, unfiltered (ng/L)
13A	Environmental	8/14/2012	--	--	12.5	--	--	1.18	--
13A	Replicate	8/14/2012	--	--	8.17	--	--	1.13	--
13A	RPD	--	--	--	41.9	--	--	4.33	--
13B	Environmental	8/17/2011	<0.02	<0.5	<3.2	<0.015	123	4.12	0.75
13B	Replicate	8/17/2011	<0.02	<0.5	<3.2	<0.015	121	3.54	0.71
13B	RPD	--	--	--	--	--	1.6	15.1	5.5
13U	Environmental	8/14/2012	--	--	--	--	--	--	--
13U	Replicate	8/14/2012	--	--	--	--	--	--	--
13U	RPD	--	--	--	--	--	--	--	--

Well name	Sample type	Collection date	Methyl mercury, unfiltered (ng/L)	Molybdenum, filtered (µg/L)	Nickel, filtered (µg/L)	Selenium, filtered (µg/L)	Silver, filtered (µg/L)	Strontium, filtered (µg/L)	Thallium, filtered (µg/L)
13A	Environmental	8/14/2012	--	--	--	--	--	--	--
13A	Replicate	8/14/2012	--	--	--	--	--	--	--
13A	RPD	--	--	--	--	--	--	--	--
13B	Environmental	8/17/2011	<0.04	<0.014	0.168	0.064	0.0078	4,640	<0.01
13B	Replicate	8/17/2011	0.05	<0.014	<0.09	<0.03	0.0072	4,600	<0.01
13B	RPD	--	--	--	--	--	8.0	0.9	--
13U	Environmental	8/14/2012	--	--	--	--	--	--	--
13U	Replicate	8/14/2012	--	--	--	--	--	--	--
13U	RPD	--	--	--	--	--	--	--	--

Well name	Sample type	Collection date	Uranium, filtered (µg/L)	Vanadium, filtered (µg/L)	Zinc, filtered (µg/L)	Nitrogen (mg/L)[1]	Argon (mg/L)[1]	Carbon dioxide (mg/L)[1]	Methane (mg/L)[1]
13A	Environmental	8/14/2012	--	--	--	22.5	0.7669	16.85	0.2132
13A	Replicate	8/14/2012	--	--	--	22.1	0.7574	16.85	0.2057
13A	RPD	--	--	--	--	1.9	1.2	0.0	3.6
13B	Environmental	8/17/2011	0.007	<0.08	1.52	1.70	0.1010	29.3300	60.0182
13B	Replicate	8/17/2011	0.007	<0.08	1.47	1.59	0.0931	30.17	51.9705
13B	RPD	--	0.0	--	3.3	6.6	8.1	2.8	14.4
13U	Environmental	8/14/2012	--	--	--	--	--	--	--
13U	Replicate	8/14/2012	--	--	--	--	--	--	--
13U	RPD	--	--	--	--	--	--	--	--

Well name	Sample type	Collection date	Carbon dioxide (mole percent)	Methane (mole percent)	Ethane (mole percent)	Ethylene (mole percent)	Propane (mole percent)	Iso-butane (mole percent)
13A	Environmental	8/14/2012	3.53	0.878	0.0066	<0.0001	<0.0001	<0.0001
13A	Replicate	8/14/2012	--	--	--	--	--	--
13A	RPD	--	--	--	--	--	--	--
13B	Environmental	8/17/2011	1.32	95.11	0.1120	<0.0001	0.0297	0.0051
13B	Replicate	8/17/2011	1.64	95.12	0.1000	<0.0001	0.0248	0.0042
13B	RPD	--	21.6	0.0	11.3	--	18.0	19.4
13U	Environmental	8/14/2012	--	--	--	--	--	--
13U	Replicate	8/14/2012	--	--	--	--	--	--
13U	RPD	--	--	--	--	--	--	--

Appendix Table 2–2. Quality control data for replicates.—Continued

[U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; °C, degrees Celsius; mg/L, milligrams per liter; N, nitrogen; P, phosphorus; µg/L, micrograms per liter; ng/L, nanograms per liter; cm^{3}STP/g, cubic centimeters at standard temperature and pressure per gram of water; R/R$_a$, (helium-3/helium-4)$_{sample}$/(helium-3/helium-4)$_{air}$; ‰, per mil; VSMOW, Vienna Standard Mean Ocean Water; pmc, percent modern carbon; DIC, dissolved inorganic carbon; VPDB, Vienna Peedee Belemnite; <, less than; >, greater than; --, no data; RPD, relative percent difference]

Well name	Sample type	Collection date	N-butane (mole percent)	Iso-pentane (mole percent)	N-pentane (mole percent)	Hexanes + (mole percent)	Helium (10^{-8} cm^{3}STP/g)	Neon (10^{-7} cm^{3}STP/g)
13A	Environmental	8/14/2012	<0.0001	<0.0001	<0.0001	<0.0001	18.71	2.469
13A	Replicate	8/14/2012	--	--	--	--	--	--
13A	RPD	--	--	--	--	--	--	--
13B	Environmental	8/17/2011	0.0032	0.0009	<0.0001	<0.0001	--	--
13B	Replicate	8/17/2011	0.0028	0.0008	<0.0001	<0.0001	--	--
13B	RPD	--	13.3	11.8	--	--	--	--
13U	Environmental	8/14/2012	--	--	--	--	73.80	1.39
13U	Replicate	8/14/2012	--	--	--	--	49.30	0.946
13U	RPD	--	--	--	--	--	39.8	38.0

Well name	Sample type	Collection date	Argon (10^{-4} cm^{3}STP/g)[2]	Krypton (10^{-4} cm^{3}STP/g)[2]	Xenon (10^{-4} cm^{3}STP/g)[2]	Nitrogen (10^{-4} cm^{3}STP/g)[2]	R/Ra	Toluene (µg/L)
13A	Environmental	8/14/2012	4.14	9.546	1.376	2.130	0.292	2.9
13A	Replicate	8/14/2012	--	--	--	--	--	0.9
13A	RPD	--	--	--	--	--	--	105
13B	Environmental	8/17/2011	--	--	--	--	--	3.1
13B	Replicate	8/17/2011	--	--	--	--	--	3.4
13B	RPD	--	--	--	--	--	--	9.2
13U	Environmental	8/14/2012	3.45	9.035	1.501	1.44	0.065	--
13U	Replicate	8/14/2012	2.99	8.177	1.432	0.66	0.068	--
13U	RPD	--	14.3	10.0	4.7	74.3	4.5	--

Well name	Sample type	Collection date	Benzene (µg/L)	Ethylbenzene (µg/L)	o-xylene (µg/L)	Tert-butyl methyl ether (µg/L)	Xylene, total (µg/L)	m- and p-xylene (µg/L)
13A	Environmental	8/14/2012	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2
13A	Replicate	8/14/2012	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2
13A	RPD	--	--	--	--	--	--	--
13B	Environmental	8/17/2011	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2
13B	Replicate	8/17/2011	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2
13B	RPD	--	--	--	--	--	--	--
13U	Environmental	8/14/2012	--	--	--	--	--	--
13U	Replicate	8/14/2012	--	--	--	--	--	--
13U	RPD	--	--	--	--	--	--	--

Well name	Sample type	Collection date	δ^{2}H, water (‰, VSMOW)	δ^{18}O, water (‰, VSMOW)	Carbon-14, DIC (pmc)	δ^{13}C, DIC (‰, VPDB)	δ^{2}H, methane (‰, VSMOW)	δ^{13}C, methane (‰, VPDB)	^{36}Cl/Cl (10^{-15})
13A	Environmental	8/14/2012	--	--	--	--	--	--	--
13A	Replicate	8/14/2012	--	--	--	--	--	--	--
13A	RPD	--	--	--	--	--	--	--	--
13B	Environmental	8/17/2011	–150	–19.51	0.32	–9.31	–275.0	–62.51	--
13B	Replicate	8/17/2011	–151	–19.58	0.79	–5.79	–272.7	–63.27	--
13B	RPD	--	0.6	0.4	84.7	46.6	0.8	1.2	--
13U	Environmental	8/14/2012	--	--	--	--	--	--	868
13U	Replicate	8/14/2012	--	--	--	--	--	--	668
13U	RPD	--	--	--	--	--	--	--	26.0

[1] Analysis done using gas chromatography.

[2] Analysis done using mass spectrometry.

Appendix Table 2–3. Quality control data for matrix spikes.

[U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; µg/L, micrograms per liter; <, less than; --, no data; %, percent]

Well name	Sample type	Geologic interval in which sample interval is located	Collection date	Collection time	Toluene (µg/L)	Benzene (µg/L)	Ethyl-benzene (µg/L)	o-xylene (µg/L)	Tert-butyl methyl ether (µg/L)	Xylene, total (µg/L)	m- and p-xylene (µg/L)
13U	Environmental	U-PCM	8/14/2012	1300	<0.1	0.7	<0.1	<0.1	<0.2	<0.2	<0.2
13U	Environmental-spiked	U-PCM	8/14/2012	1301	0.2275	0.9118	0.2292	0.2322	0.5882	--	0.5174
13U	Amount spike added	--	--	--	0.233	0.233	0.28	0.28	0.652	--	0.652
13U	Spike recovery (%)	--	--	--	97.64	90.90	81.86	82.93	90.21	--	79.36

Appendix Table 2–4. Data for halogenated volatile organic compounds (hVOCs) in water collected from the monitoring wells.

[--, no data; U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; pg/kg H_2O, picograms per kilogram of water; <, less than; values in gray type are not considered to be detections, values in black, bold type are considered to be detections and those shaded in gray are greater than the estimated concentration in air-saturated water]

Well name	Sample type	Collection date	Geologic interval in which sample interval is located	Concentration (pg/kg H_2O)					
				Chemical formula:	CCl_3F	CCl_2F_2	$C_2Cl_3F_3$	CH_3Cl	CF_2ClBr
				Common name:	CFC-11	CFC-12	CFC-113	Methyl chloride	Halon 1211
				Estimated concentration in air-saturated water[1]	800	500	100	7,000	10
				Drinking-water standard[4]	--	--	--	--	--
--	Source solution blank	6/4/2012	--		18	33	7	<59	<2
--	Pump equipment blank[6]	6/4/2012	--		--	--	--	<59	<2
9B	Kemmerer field blank[6]	8/19/2012	--		692	142	29	672	<2
B12B	Environmental	8/15/2012	PCMB		**93**	**121**	**30**	<59	<2
1A	Environmental	8/16/2012	U-PCM		47	17	24	612	<2
1B	Environmental	8/16/2012	PCMB		<1	<6	<9	<59	<2
2A	Environmental	8/21/2012	U-PCM		96	25	10	<59	<2
6A	Environmental	8/17/2012	U-PCM		52	30	10	<59	<2
6B	Environmental	8/17/2012	PCMB		22	8	<9	**5,650**	<2
9B	Environmental	8/18/2012	MZ		32	10	<9	1,050	<2
13A	Environmental	8/14/2012	PCMA		**25**	<6	<9	<59	<2
13A	Replicate	8/14/2012	PCMA		**11**	<6	<9	<59	<2
13B	Environmental	8/14/2012	PCMB		**19**	**24**	**10**	<59	<2
13U	Environmental	8/14/2012	U-PCM		**22**	<6	<9	<59	<2
15A	Environmental	8/20/2012	PCMA		84	<6	<9	<59	<2
15B	Environmental	8/20/2012	MZ		2	9	<9	985	<2
17B	Environmental	8/19/2012	PCMB		44	<6	<9	<59	<2
18A	Environmental	8/18/2012	U-PCM		24	12	<9	<59	<2
Number of detections[2,7]					**4**	**2**	**2**	**1**	0
Number of detections with concentrations greater than air-saturated water[2,7]					0	0	0	0	0

Well name	Sample type	Collection date	Geologic interval in which sample interval is located	Concentration (pg/kg H_2O)					
				Chemical formula:	CH_3Br	C_2H_5Cl	$C_2H_2Cl_2$	CH_3I	CH_2Cl_2
				Common name:	Methyl bromide	Chloroethane (CA)	1,1-Dichloroethene (1,1-DCE)	Methyl iodide	Methylene chloride
				Estimated concentration[1] in air-saturated water	400	30	7	200	700
				Drinking-water standard[4]	--	--	7,000,000	--	5,000,000
--	Source solution blank	6/4/2012	--		<2	<110	<58	<1	<271
--	Pump equipment blank[6]	6/4/2012	--		<2	<110	<58	8	9,530
9B	Kemmerer field blank[6]	8/19/2012	--		<2	<110	<58	3	23,900
B12B	Environmental	8/15/2012	PCMB		<2	<110	<58	12	2,120
1A	Environmental	8/16/2012	U-PCM		<2	**1,790**	**6,360**	**97**	3,810
1B	Environmental	8/16/2012	PCMB		<2	**31,500**	**216,000**	**723**	<271
2A	Environmental	8/21/2012	U-PCM		<2	<110	<58	<1	38,200
6A	Environmental	8/17/2012	U-PCM		<2	**167**	<58	**75**	3,560
6B	Environmental	8/17/2012	PCMB		<2	<110	<58	**16**	53,700
9B	Environmental	8/18/2012	MZ		<2	<110	<58	<1	56,800
13A	Environmental	8/14/2012	PCMA		<2	<110	<58	<1	19,300
13A	Replicate	8/14/2012	PCMA		<2	<110	<58	<1	8,710
13B	Environmental	8/14/2012	PCMB		<2	<110	<58	<1	39,000
13U	Environmental	8/14/2012	U-PCM		<2	<110	<58	<1	44,500
15A	Environmental	8/20/2012	PCMA		<2	<110	<58	<1	47,900
15B	Environmental	8/20/2012	MZ		<2	<110	<58	**150**	10,100
17B	Environmental	8/19/2012	PCMB		<2	**890**	<58	**18**	28,100
18A	Environmental	8/18/2012	U-PCM		<2	<110	<58	<1	184,000
Number of detections[2,7]					0	**4**	**2**	**6**	0
Number of detections with concentrations greater than air-saturated water[2,7]					0	**4**	**2**	**1**	0

Appendix Table 2–4. Data for halogenated volatile organic compounds (hVOCs) in water collected from the monitoring wells.—Continued

[--, no data; U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; pg/kg H_2O, picograms per kilogram of water; <, less than; values in gray type are not considered to be detections, values in black, bold type are considered to be detections and those shaded in gray are greater than the estimated concentration in air-saturated water]

Well name	Sample type		Concentration (pg/kg H_2O)					
		Chemical formula:	$C_2H_2Cl_2$	$C_2H_4Cl_2$	$C_2H_2Cl_2$	$CHCl_3$	CH_2ClBr	$C_2H_3CL_3$
		Common name:	Trans-1,2-Dichloroethene	1,1-Dichloroethane	Cis-1,2-Dichloroethene	Chloroform	Bromochloromethane	1,1,1-Trichloroethane
		Estimated concentration in air-saturated water[1]	1	50	--	700	40	300
		Drinking-water standard[4]	100,000,000	--	70,000,000	[5]80,000,000	--	--
--	Source solution blank		<3	<343	<1,940	517	<6	<5
--	Pump equipment blank[6]		<3	<343	<1,940	1,380	4	7
9B	Kemmerer field blank[6]		<3	<343	<1,940	23,500	52	37
B12B	Environmental		<3	<343	<1,940	405	<6	<5
1A	Environmental		<3	<343	<1,940	**264,000**	<6	<5
1B	Environmental		<3	<343	<1,940	**282,000**	<6	<5
2A	Environmental		<3	<343	<1,940	2,360	14	12
6A	Environmental		<3	<343	<1,940	50,200	235	32
6B	Environmental		<3	<343	<1,940	7,790	44	7
9B	Environmental		<3	<343	<1,940	47,700	243	<5
13A	Environmental		<3	<343	<1,940	338	<6	<5
13A	Replicate		<3	<343	<1,940	596	<6	<5
13B	Environmental		<3	<343	<1,940	595	<6	<5
13U	Environmental		<3	<343	<1,940	88	<6	<5
15A	Environmental		<3	<343	<1,940	7,670	145	<5
15B	Environmental		<3	<343	<1,940	9,900	200	<5
17B	Environmental		<3	<343	<1,940	21,300	113	14
18A	Environmental		<3	<343	<1,940	44,900	<6	<5
Number of detections[2,7]			0	0	0	**2**	0	0
Number of detections with concentrations greater than air-saturated water[2,7]			0	0	0	**2**	0	0

Well name	Sample type		Concentration (pg/kg H_2O)					
		Chemical formula:	CCl_4	$C_2H_4Cl_2$	C_2HCl_3	CH_2Br_2	$C_2H_3Cl_3$	C_2Cl_4
		Common name:	Carbon tetrachloride	1,2-Dichloroethane (1,2-DCA)	Trichloroethene (TCE)	Dibromomethane	1,1,2-Trichloroethane (1,1,2-TCA)	Tetrachloroethene (PCE)
		Estimated concentration in air-saturated water[1]	2,000	20	800	--	60	1,000
		Drinking-water standard[4]	5,000,000	5,000,000	5,000,000	--	5,000,000	5,000,000
--	Source solution blank		25	<107	<12	<3	<187	22
--	Pump equipment blank[6]		36	<107	20	<3	<187	18
9B	Kemmerer field blank[6]		102	<107	28	<3	<187	58
B12B	Environmental		13	<107	33	<3	<187	63
1A	Environmental		222	**17,200**	77	<3	**7,360**	**796**
1B	Environmental		52	**110,000**	**1,010**	<3	**4,640**	**1,710**
2A	Environmental		10	<107	39	<3	<187	42
6A	Environmental		26	<107	42	<3	**5,300**	52
6B	Environmental		2	<107	43	<3	<187	29
9B	Environmental		3	<107	91	<3	**2,620**	74
13A	Environmental		<1	<107	**3,020**	<3	**9,880**	**2,020**
13A	Replicate		4	<107	**3,000**	<3	<187	**1,990**
13B	Environmental		14	<107	**526**	<3	<187	**482**
13U	Environmental		<1	<107	<12	<3	<187	51
15A	Environmental		3	<107	**263**	<3	<187	37
15B	Environmental		20	<107	**631**	<3	**2,770**	48
17B	Environmental		3	<107	61	<3	<187	82
18A	Environmental		<1	<107	<12	<3	<187	41
Number of detections[2,7]			0	**2**	**5**	0	**6**	**4**
Number of detections with concentrations greater than air-saturated water[2,7]			0	**2**	**2**	0	**6**	**2**

Appendix Table 2–4. Data for halogenated volatile organic compounds (hVOCs) in water collected from the monitoring wells.—Continued

[--, no data; U-PCM, Uinta Formation or Uinta-Parachute Creek Member transition zone; PCMA, Parachute Creek Member above the Mahogany zone; MZ, Mahogany zone; PCMB, Parachute Creek Member below the Mahogany zone; pg/kg H_2O, picograms per kilogram of water; <, less than; values in gray type are not considered to be detections, values in black, bold type are considered to be detections and those shaded in gray are greater than the estimated concentration in air-saturated water]

Well name	Sample type	Concentration (pg/kg H_2O)				Number of detections[2,3]	Number of detections with concentrations greater than air-saturated water[2,3]	Total concentration of detected compounds[2,3] (pg/kg)
		Chemical formula:	$C_2H_4Br_2$	$C_2H_2Cl_4$	$C_2H_2Cl_4$			
		Common name:	1,2-Dibromoethane	1,1,1,2-Tetrachloroethane	1,1,2,2-Tetrachloroethane (1,1,2,2-PCA)			
		Estimated concentration in air-saturated water[1]	--	60	1,000			
		Drinking-water standard[4]	--	--	--			
--	Source solution blank		<17	<15	<2,110	--	--	--
--	Pump equipment blank[6]		<17	<15	<2,110	--	--	--
9B	Kemmerer field blank[6]		<17	<15	<2,110	--	--	--
B12B	Environmental		<17	<15	<2,110	3	0	244
1A	Environmental		<17	<15	**2,830**	6	5	36,336
1B	Environmental		<17	<15	**12,700**	7	7	377,560
2A	Environmental		<17	<15	<2,110	0	0	0
6A	Environmental		<17	<15	**5,280**	3	3	10,747
6B	Environmental		<17	<15	<2,110	0	0	0
9B	Environmental		<17	<15	<2,110	1	1	2,620
13A	Environmental		<17	<15	<2,110	4	3	14,945
13A	Replicate		<17	<15	<2,110	3	2	5,001
13B	Environmental		<17	<15	<2,110	5	0	1,061
13U	Environmental		<17	<15	<2,110	1	0	22
15A	Environmental		<17	<15	<2,110	1	0	263
15B	Environmental		<17	<15	<2,110	2	1	3,401
17B	Environmental		<17	<15	**10,700**	2	2	11,590
18A	Environmental		<17	<15	<2,110	0	0	0
Number of detections[2,7]			0	0	**4**	--	--	--
Number of detections with concentrations greater than air-saturated water[2,7]			0	0	**4**	--	--	--

[1] From Deeds and others (2012). Included here for general comparison purposes only.

[2] If a compound was detected in the equipment or field blank, it was not considered a detection in an environmental sample unless the concentration was five times greater than the concentration in the blank, with the exception of methylene chloride where a factor of 10 times was used (U.S. Environmental Protection Agency, 1989).

[3] Excluding methyl chloride, methyl iodide, and chloroform.

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

[5] Standard is for the sum of concentrations for chloroform, bromoform, bromodichloromethane, and dibromochloromethane (U.S. Environmental Protection Agency (2012).

[6] Pump blank applies to B12B, 13A, 13B, and 13U. Kemmerer blank applies to all other samples.

[7] Excluding replicate sample from well 13A.

Publishing support provided by:
Denver Publishing Service Center, Denver, Colorado

For more information concerning this publication, contact:
Director, USGS Colorado Water Science Center
Box 25046, Mail Stop 415
Denver, CO 80225
(303) 236-4882

Or visit the Colorado Water Science Center Web site at:
http://co.water.usgs.gov/

This publication is available online at:
http://pubs.usgs.gov/sir/2013/5132/

McMahon and others—**Chemistry and Age of Groundwater in Bedrock Aquifers of the Piceance and Yellow Creek Watersheds**—Scientific Investigations Report 2013–5132