Strontium isotopes as indicators of aquifer communication in an area of coal bed natural gas production, Powder River Basin, Wyoming and Montana

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ABSTRACT

Development of the coal-bed natural gas resource of the Powder River Basin of Wyoming and Montana has proceeded rapidly, from fewer than 200 wells in 1995 to more than 22,000 wells in 2007. Continued development of this resource will depend on minimization of water production during gas recovery as well as responsible use of the produced water. Ideally, water should be withdrawn only from isolated coal aquifers to prevent any unnecessary water withdrawal from overlying or underlying aquifers. This study uses the ratio of $^{87}Sr/^{86}Sr$ of ground water to identify hydraulically isolated coal seams. The ratio of $^{87}Sr/^{86}Sr$ of ground water represents a time-integrated record of water–rock interaction, such that water from aquifers composed of different rocks may acquire different Sr isotopic ratios.

Sr isotopic data are presented for 145 samples of ground water co-produced with coal-bed natural gas and 14 water samples from wells completed in sandstone aquifers in the Powder River Basin. The coal zone from which each sample was collected was determined by analysis of gamma logs and correlation with the Wyoming State Geological Survey database.

The Sr isotopic ratios and geochemical compositions of ground waters from coal in the Powder River Basin of Wyoming are influenced by a number of factors, including the coal zone from which ground waters are produced, their residence time, the degree to which coal aquifers are confined, and geographic location. The data indicate that the Upper Wyodak coal-zone aquifer in the Gillette and Schoonover areas in the eastern Powder River Basin appears to be a well-confined, combined sand and coal aquifer unit. In contrast, the Wyodak Rider coal zone aquifer may be only partially confined, allowing interactions between sandstone and possibly other coal aquifers. Wells in this area exhibit highly variable Sr isotope ratios and total dissolved solids, and they also are characterized by greater than average water/gas production ratios, consistent with incomplete isolation of the Wyodak Rider coal zone. Faults in the northeastern part of the Powder River Basin may affect aquifer connectivity, either by acting as seals or conduits. Higher gas production correlates with lower Sr isotopic ratios in this part of the basin. Although a correlation between Sr isotopic ratios of produced water with fracture pattern developed during the well enhancement process might be expected, no strong relationship was observed. Evidently there are many factors in addition to fracture pattern that control interactions between aquifers.

KEY WORDS: aquifer communication, coal-bed natural gas, Powder River Basin, produced water, sodium-adsorption ratio, strontium isotopes, water quality.

INTRODUCTION

The Powder River Basin of northeastern Wyoming and southeastern Montana is one of the most significant energy-producing regions of the United States. Powder River Basin coal provides approximately 40 percent of all the coal consumed in the nation annually (473 million short tons in 2006; Bureau of Land Management-Wyoming; Energy Information Administration Coal Report for 2006).

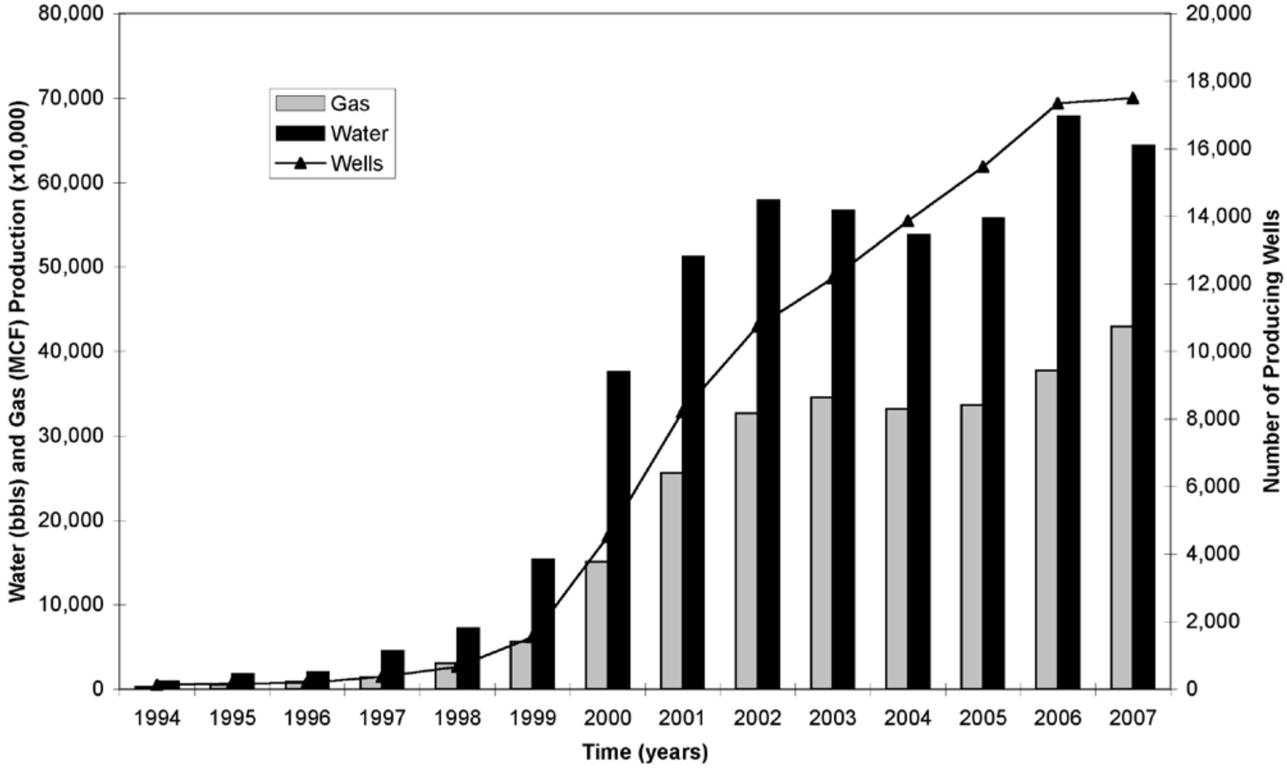

Figure 1. Water and gas production in Powder River Basin, 1994–2006. Although the number of producing wells continues to increase, water and gas production has remained fairly constant since 2002. Data from Wyoming Oil and Gas Conservation Commission.

These Tertiary-age, nonmarine subbituminous coals are valued for their low sulfur (~0.5% S) and ash (6–7%) contents (Ellis, 1999; Lyman and Hallberg, 2000).

Powder River Basin coals also host an important natural gas resource. Economically recoverable reserves in the Wyoming parts of the Powder River Basin are estimated at 25.2 trillion cubic feet (Bank and Kuuskraa, 2006), approximately 10–15 percent of the United States' natural gas reserve. Production of this resource requires drilling a well to the target coal seam, typically less than 2000 feet, under-reaming the coal to create a large void, installation of a submersible pump, and removing water from the coal seam to reduce hydrostatic pressure, allowing the methane to desorb and rise up the annular space of the cased well (DeBruin and Lyman, 1999). After an initial period of water production, a typical well produces 60,000 cubic feet (60 Mcf, 1700 cubic meters) of methane per day and 4,500 gallons (17,000 liters) of water per day (based on January, 2007 data from the Wyoming Oil and Gas Conservation Commission, 2007). Total production in the Powder River Basin as of January, 2007 is approximately 1,033,000 Mcf (29,250,000 cubic meters) of methane per day and 78.2 million gallons (296 million liters) of water per day (Wyoming Oil and Gas Conservation Commission, 2007).

The natural-gas resource developed rapidly. In Wyoming, the number of coal-bed natural gas (CBNG) wells has increased from 152 wells in 1995 to more than 22,000 wells in 2007 (Fig. 1; Surdam et al., 2007; Wyoming State Geological Survey Coal Section, 2007). However, more recently the pace of development has slowed due to concerns about beneficial use and proper disposal of co-produced water (Bank and Kuustraa, 2006). Water is a valuable commodity in this semi-arid region, and production of ground water from coal seams may decrease water availability for agricultural and domestic use in areas adjacent to CBNG activity. In 2003 (and amended in 2006), the State of Montana issued standards for water quality in the Powder, Little Powder, Tongue River, and Rosebud Creek watersheds

(Administrative Rule of Montana 17.30.1670, 2007). Because CBNG co-produced water discharged into surface drainages could impact water quality downstream in Montana, these concerns have led to a shift in water-disposal methods from untreated surface discharge, either into impoundments (ponds) excavated within existing channels or impoundments off existing channels, to treatment prior to surface disposal, dispersal by means of atomization sprayers, or use of produced water for surface and sub-surface irrigation (Wheaton and Donato, 2004).

Responsible development of the CBNG resource requires minimization of water production during gas recovery. Ideally, water should be withdrawn only from isolated coal aquifers to prevent wasteful and unnecessary water withdrawal from any overlying or underlying sandstone aquifers. The objective of this study is to identify locations in the Powder River Basin where coal seams are hydraulically isolated from adjacent aquifers and hence water production will be limited to the coal. Communication between coals and adjacent aquifers can be the result of depositional setting or vertical fracturing during well development. This study uses the ratio of $^{87}Sr/^{86}Sr$ of ground water to evaluate aquifer communication. The ratio of $^{87}Sr/^{86}Sr$ of ground water represents a time-integrated record of water–rock interaction, such that water from aquifers composed of different rocks may acquire different Sr isotopic ratios. This present work builds upon the preliminary Sr isotopic data from CBNG and monitoring wells presented by Frost et al. (2002). That work showed that coal- and sandstone-aquifer systems may have distinct Sr isotopic compositions, and intermediate ratios may indicate incomplete aquifer isolation or improper well completion and therefore wasteful excess water production. The initial work focused on a limited data set from the eastern area of the Powder River Basin in the vicinity of Gillette and Wright, Wyoming, and it did not differentiate individual coal zones. Hence the goals of this study are to address the following questions:

1. Do coal-aquifer and sandstone-aquifer waters have distinctive Sr isotopic compositions basin-wide?
2. Can different coal zones be identified by distinctive Sr isotopic compositions?
3. What are the geologic or geographic variables that control coal-aquifer isolation?
4. Do Sr isotopic compositions correlate to fracture patterns introduced during completion of individual wells?

HYDROGEOLOGIC SETTING

The Powder River Basin is a 60,000 km^2 (23,000 mi^2) asymmetric structural and sedimentary basin in northeastern Wyoming and southeastern Montana that formed during Late Cretaceous to early Tertiary time as a Laramide foreland basin (Ayers, 1986; Flores and Ethridge, 1985; Hinaman, 2005). The basin's axis trends north–northwest and is proximal to the western margin (Fig. 2). The basin is bounded to the east by the Black Hills, to the west by the Big Horn Mountains and the Casper Arch, and to the south by the Laramie Mountains and the Hartville Uplift. The northern part of the basin in Montana is bounded by the Miles City Arch and the Cedar Creek Anticline (Montgomery, 1999). Coal seams are found in both the Paleocene Fort Union Formation, which crops out on the basin margins, and the overlying Eocene Wasatch Formation. The uppermost member of the Fort Union Formation, the Tongue River Member, transitions into the Wasatch Formation without obvious lithologic change at the contact (Hinaman, 2005; Glass, 1976). Both formations are composed of sandstone, siltstone, mudstone, conglomerate, limestone, carbonaceous shale, and coal. In areas where the coal beds split, fluvial channel sandstones or mudstones are the interbedding strata (Flores and Bader, 1999).

Coal correlations across the basin are complicated by the merging and splitting of coal seams and by the use of local names in different parts of the basin. In this study we adopt the nomenclature of the Wyoming State Geological Survey (Wyoming State Geological Survey Coal Section, 2007), which divides the late Paleocene and Eocene coals into eight coal zones. From stratigraphically lowest to highest, the six coal zones within the Tongue River Member of the Paleocene Fort Union Formation are the Basal Tongue River, Sawyer, Knobloch, Lower Wyodak, Upper Wyodak, and Wyodak Rider. The Eocene Wasatch Formation includes the Felix and the overlying Lake DeSmet coal zones (Fig. 3).

Davis (1976) described four major aquifers in the Powder River Basin: (1) continuous coals with widely variable transmissivity from 100 gal/day/ft to 10,000 gal/day/ft based on fracture concentration and conti-

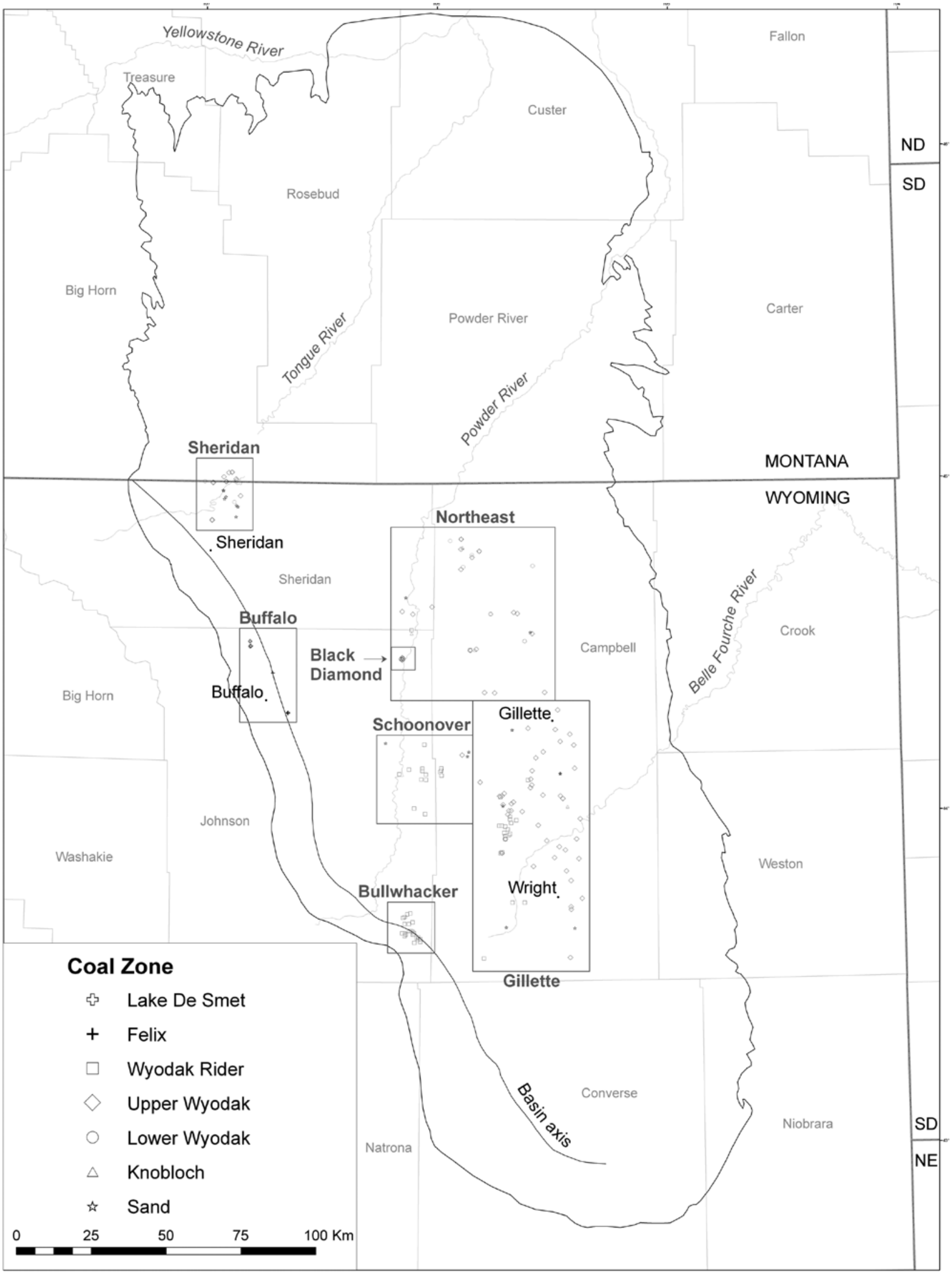
Yellowstone River
Treasure
Fallon
Custer
ND
SD
Rosebud
Big Horn
Carter
Powder River
Tongue River
Powder River
Sheridan
MONTANA
WYOMING
Northeast
Sheridan
Sheridan
Belle Fourche River
Buffalo
Crook
Campbell
Black Diamond
Buffalo
Big Horn
Gillette
Schoonover
Johnson
Weston
Washakie
Bullwhacker
Wright
Gillette
Coal Zone
Lake De Smet
Felix
Wyodak Rider
Upper Wyodak
Lower Wyodak
Knobloch
Sand
Basin axis
Converse
Niobrara
Natrona
SD
NE
0
25
50
75
100 Km

Figure 2, facing page. Generalized map of asymmetric Powder River Basin, showing basin axis along its western margin as identified by Wyoming State Geological Survey Coal Section (2007); McLellan et al. (1990) suggested the axis passes through Sheridan area and continues into Montana. Most coal production is from open-pit mines along eastern margin of basin in Wyoming. Coal bed methane production started west of these mines in area near Gillette and Wright, Wyoming and has since spread westward and northward. Locations of samples analyzed in this study are shown by symbols that are keyed to coal zone or sandstone aquifer from which water samples were collected. Boxes outline groups of wells discussed in text.

nuity; (2) clastic overburden and underburden adjacent to the coals including paleochannel sands, siltstone, and shale deposits, all with low permeability and a high degree of isolation from one another; (3) clinker, produced by baking and melting overburden during combustion of coal beds, which has porosities up to 35 percent and variable transmissivity from 150 gal/day/ft to 3,000,000 gal/day/ft; and (4) alluvial aquifers noted for transmissivities of 200–500 gal/day/ft. The regional topographic gradient drives the basin-wide flow system from the southwestern side of the basin to the lower northeastern section of the basin (McPherson and Chapman, 1996). A potentiometric surface map of the Upper Wyodak coal seam produced by Daddow (1986) suggests that recharge and flow in the coal mimics the recharge patterns inferred from the topographic geometry of the basin. Recharge that occurs near the coal outcrop on the eastern margin is driven by topographic gradient westward toward the basin axis and from the southern margin to the north (Rankl and Lowry, 1985; Daddow, 1986).

Ground-water residence times are poorly known for Powder River Basin aquifers. Pearson (2002) suggested times of 7,000–70,000 years for ground water to flow from the eastern recharge to the central part of the basin based on limited tritium data and Darcy's Law calculations. Residence-time ages between the recharge area and the most easterly wells in the Sheridan area (Fig. 2) were estimated between 1,200 and 12,000 years based on the proximity of these wells to the recharge and the hydraulic gradient (Pearson, 2002). These estimates are in general agreement with a maximum mean ^{14}C date of 21,000 years as reported by Frost and Brinck (2005) from an artesian well discharging from a sandstone aquifer in the center of the basin immediately west of the Powder River (sec. 19, T. 52 N., R. 77 W.).

METHODS

Water samples were obtained from producing CBNG wells and

Figure 3. Coal zones of Powder River Basin. Eocene coal zones of Wasatch Formation include Felix and overlying Lake DeSmet. Paleocene coal zones from are, from Fort Union Formation are (stratigraphically lowest to highest) basal Tongue River, Sawyer, Knobloch, Lower Wyodak, Upper Wyodak, and Wyodak Rider. Most coal-bed natural gas is recovered from Lower Wyodak, Upper Wyodak, and Wyodak Rider coal zones. Coal-zone nomenclature is from Wyoming State Geological Survey Coal Section (2007).

Formation	Coal Zone	Central Coal	West Coal
Wasatch	Lake De Smet		Buffalo Cameron Murray Ucross
	Felix	Felix	Bull Creek
Fort Union (Tongue River Member)	Wyodak Rider	Roland Smith	Baker Taft Smith
	Upper Wyodak	Anderson Lower Anderson Canyon	Dietz 1 Dietz 2 Dietz 3
	Lower Wyodak	Cook Gates Wall B Wall C Wall Wall D Pawnee Lower Pawnee	Monarch Carney
	Knobloch	Moyer	Lower Moyer
	Sawyer	Zed Dannar	
	Basal Tongue River	Terret Burly Broadus	

from monitoring wells. Two well-casing volumes of water were removed from monitoring wells prior to sample collection; water from continuously pumping CBNG wells was collected via bypass valves after a 5 second flushing period. Temperature and pH were measured in the field. Samples were filtered through a 0.45 micron filter and kept cool and dark prior to analysis. One aliquot of each sample was acidified to pH 2 for cation analysis.

Strontium was isolated from a 3 ml aliquot of each un-acidified water sample using Teflon columns filled with Eichrom® Sr-Spec resin and the strontium isotopic composition determined by thermal ionization mass spectrometry at the University of Wyoming. The internal precision of $^{87}Sr/^{86}Sr$ isotope ratio measurements is ± 0.00001. Seventy-six analyses of NBS 987 strontium standard measured during the course of this study gave an average value of $^{87}Sr/^{86}Sr = 0.71026 \pm 0.00002$ (2 standard deviations). All analyses were normalized to an $^{86}Sr/^{88}Sr$ ratio value of 0.1194. Analytical blanks were less than 0.2 ng, negligible compared to sample sizes of at least 0.1 microgram strontium. Sr concentrations were determined by ICP-MS or by isotope dilution.

Major cations and trace elements were measured for the CBNG production wells by ICP-MS, sodium (Na) by flame atomic absorption, anions by ion chromatography, and alkalinity by potentiometric titration at the University of Wyoming. TDS was calculated by summing the major ionic constituents and converting bicarbonate into equivalent carbonate (Drever, 1997).

SAMPLES

159 ground-water samples were analyzed for this study and are interpreted along with 30 additional analyses reported in Frost et al. (2002). The water samples were obtained with the assistance of the U.S. Geological Survey (USGS), Coal Bed Methane Associates of Laramie (CBMA), Inc., the Casper office of the Bureau of Land Management (BLM), Welldog Inc. with the cooperation of RMT Williams Production Company, and Black Diamond Production Company. These include 14 water samples from wells completed in sandstone aquifers. The 145 coal-aquifer samples include water produced from the Eocene Wasatch Formation Lake DeSmet and Felix coal zones and from the upper Paleocene Fort Union Formation Wyodak Rider, Upper Wyodak, Lower Wyodak, and Knobloch coal zones. Sr isotopic data and selected water quality data for each sample are reported in Table 1. Complete geochemical analyses for 69 samples that were obtained by the authors are available in Campbell (2007); water-quality data for the remaining 90 samples were obtained from the BLM, USGS, and CBMA, Inc.

The coal zone from which each CBNG-produced water sample was collected was determined by analysis of gamma logs for each well, which are available from the Wyoming Oil and Gas Conservation Commission and Montana Board of Oil and Gas websites. The lithologic interpretations of these logs were combined with the database used by the Wyoming State Geological Survey to construct cross sections and identify the coal zone from which the water was withdrawn. The coal zones, along with the coal-seam names filed by the producer with the Wyoming Oil and Gas Conservation Commission and Montana Board of Oil and Gas, are listed in Table 1.

RESULTS

Water-quality Results

Lee (1981) showed that deep ground waters in the Powder River Basin are uniformly of sodium-bicarbonate signature, but that shallow ground waters are more variable in composition. His observations reflect the geochemical evolution of water-recharging coal aquifers, which Brinck et al. (*in press*) summarized as composed of five steps. First, soluble salts that have accumulated in the semi-arid soils of the basin redissolve. Next, the water dissolves gypsum and salts in the aquifer and incorporates products of pyrite oxidation. These processes result in calcium-sulfate-dominated ground waters. Third, sulfate reduction consumes sulfate and generates bicarbonate. This increase in bicarbonate causes precipitation of calcite. Accompanying these steps is cation exchange between water and aquifer materials, which removes calcium and magnesium from the water and replaces them with sodium. In addition, bacterially mediated methanogenesis takes place in Powder River Basin coals.

The major ion chemistry of water samples in this study illustrates the geochemical evolution described above. Waters from shallow wells in the Gillette area

Table 1. Sr isotopic and selected water quality data for CBNG co-produced water samples, Powder River Basin, Wyoming. (continued on pages 156–159).

Sample Name	API Number	Well Name	Coal Name	Coal Zone	Depth (ft)	E recharge (km)	Longitude	Latitude	$^{87}Sr/^{86}Sr$	TDS	SO_4	SAR	Data Source
B1LD	1921166	Texaco 13U 31-32	Ucross	Lake De Smet	205		-106.788	44.520	0.71414	-	-	-	Pearson, 2002
B2LD	1921198	Texaco 43HE-123	Ucross	Lake De Smet	223		-106.784	44.506	0.71376	1,586	-	-	Pearson, 2002
B3F	1921269	LDEC 21BC1-212	Bull Creek	Felix	763		-106.691	44.425	0.71239	595	83.6	-	Pearson, 2002
B4F	1921270	LDEC 21BC2-212	Felix	Felix	905		-106.691	44.425	0.71149	535	7.46	-	Pearson, 2002
B5F	1921436	CrossH 32UF-1701	Upper Felix	Felix	945		-106.627	44.305	0.71193	547	18.1	-	Pearson, 2002
B6LD	1921437	Cross H 32U-1701	Ucross	Lake De Smet	397		-106.626	44.305	0.71256	1,071	8.2	-	Pearson, 2002
B7LD	1921505	Texaco 33BC-123	Bull Creek	Lake De Smet	695		-106.787	44.505	0.71275	1,138	68	-	Pearson, 2002
BD1BL	1926349	Landrey 22-20-5277C	Cook	Lower Wyodak	1,577	50.4	-106.153	44.469	0.71547	1,757	1.9	18.3	Campbell, 2007
BD2BU	1926350	Landrey 22-20-5277D	Anderson	Upper Wyodak	1,202	50.4	-106.153	44.469	0.71404	3,046	2.3	35.4	Campbell, 2007
BD3BU	1926351	Landrey 42-20-5277D	Anderson	Upper Wyodak	1,075	50.7	-106.145	44.470	0.71333	2,343	1.8	36.3	Campbell, 2007
BD4BL	1926357	Landrey 31-20-5277C	Cook	Lower Wyodak	1,515	50.7	-106.148	44.473	0.71483	2,714	0.3	37.6	Campbell, 2007
BD5BU	1926353	Landrey 31-20-5277D	Anderson	Upper Wyodak	1,200	50.7	-106.148	44.473	0.71249	2,609	0.4	33.1	Campbell, 2007
BD7BL	1926358	Landrey 33-20-5277C	Cook	Lower Wyodak	1,451	50.7	-106.148	44.466	0.71517	1,841	0.5	19.1	Campbell, 2007
BD8AU	1926352	Landrey 33-20-5277D	Anderson	Upper Wyodak	1,060	50.7	-106.148	44.466	0.71364	2,362	0	52.5	Campbell, 2007
BD9AL	1926354	Landrey 42-20-5277B	Wall	Lower Wyodak	1,649	50.4	-106.146	44.469	0.71475	1,123	14.1	16	Campbell, 2007
BD10BL	1926359	Landrey 42-20-5277C	Cook	Lower Wyodak	1,442	50.4	-106.146	44.470	0.71506	2,544	1.1	26.8	Campbell, 2007
BW1W	1923370	Moore Land Federal 41-14-4277	Big George	Wyodak Rider	1,235		-106.071	43.617	0.71218	1,193	0	6.01	Campbell, 2007
BW2W	1923392	Moore Land Federal 12-11-4277	Big George	Wyodak Rider	1,330		-106.086	43.628	0.71536	1,351	0	8.15	Campbell, 2007
BW3W	1923393	Moore Land Federal 21-11-4277	Big George	Wyodak Rider	1,462		-106.080	43.631	0.71213	1,348	0	5.71	Campbell, 2007
BW4W	1923394	Moore Land Federal 23-11-4277	Big George	Wyodak Rider	1,332		-106.081	43.624	0.71211	1,662	0.2	7.07	Campbell, 2007
BW5W	1923400	Moore Land Federal 43-11-4277	Big George	Wyodak Rider	1,322		-106.071	43.625	0.71221	1,266	0	6.43	Campbell, 2007
BW6W	1924199	BCU Dry Fork 21-27-4377	Big George	Wyodak Rider	1,583		-106.103	43.676	0.71806	2,010	0	8.16	Campbell, 2007
BW7W	1924888	BCU Dry Fork 34-17-4377	Big George	Wyodak Rider	1,489		-106.136	43.692	0.71203	3,033	0.1	12.1	Campbell, 2007
BW8W	1924891	BCU State 41-16-4377	Big George	Wyodak Rider	1,443		-106.112	43.703	0.71314	4,467	0.1	21.2	Campbell, 2007
BW9W	1924897	BCU State 12-16-4377	Big George	Wyodak Rider	1,604		-106.125	43.700	0.71222	1,844	0.1	9.37	Campbell, 2007
BW10W	1924914	BCU Dry Fork 21-20-4377	Big George	Wyodak Rider	1,536		-106.142	43.689	0.71210	1,419	0.1	8.69	Campbell, 2007
BW11W	1925029	BCU 32-28-4377	Big George	Wyodak Rider	1,607		-106.117	43.671	0.71260	1,144	0	6.23	Campbell, 2007
BW12W	1925038	BCU 32-15-4277	Big George	Wyodak Rider	1,438		-106.096	43.614	0.71200	1,690	0	9.57	Campbell, 2007
BW13W	1925050	BCU 34-33-4377	Big George	Wyodak Rider	1,450		-106.116	43.650	0.71300	2,263	0	12.1	Campbell, 2007
BW14W	1925054	BCU 14-34-4377	Big George	Wyodak Rider	1,604		-106.108	43.650	0.71259	912	0	6.4	Campbell, 2007
BW15W	1925061	BCU 34-5-4277	Big George	Wyodak Rider	1,434		-106.136	43.635	0.71143	2,334	0	10.4	Campbell, 2007
BW16W	1925073	BCU 32-5-4277	Big George	Wyodak Rider	1,485		-106.136	43.643	0.71175	3,170	0	14.9	Campbell, 2007
BW17W	1925080	BCU 43-5-4277	Big George	Wyodak Rider	1,490		-106.131	43.639	0.71217	4,020	0	30.9	Campbell, 2007
BW18W	1925086	Bullwhacker Creek UN 32-3-4277	Big George	Wyodak Rider	1,479		-106.097	43.643	0.71283	1,364	0	7.38	Campbell, 2007
BW19W	1925087	Bullwhacker Creek UN 23-3-4277	Big George	Wyodak Rider	1,493		-106.101	43.639	0.71239	1,012	0	8.42	Campbell, 2007
BW20W	1925088	Bullwhacker Creek UN 21-3-4277	Big George	Wyodak Rider	1,517		-106.101	43.647	0.71438	2,160	0.1	9.7	Campbell, 2007
BW21W	1925099	BCU 12-5-4277	Big George	Wyodak Rider	1,484		-106.146	43.643	0.71055	3,161	0	12.6	Campbell, 2007
BW22W	1926313	BCU 32-29-4377	Big George	Wyodak Rider	1,553		-106.136	43.671	0.71266	1175	0	7.21	Campbell, 2007
G1U	530473	Lynde Trust 15-34	Wyodak	Upper Wyodak	482	12.5	-105.487	44.056	0.71294	382	0.1	6	Frost et al., 2002
G2U	530802	Thrush 5-44	Wyodak	Upper Wyodak	275	5.8	-105.405	43.987	0.71287	644	0.1	8	Frost et al., 2002
G3U	530949	Mankin 14-23	Wyodak	Upper Wyodak	612	10.3	-105.477	44.048	0.71319	530	0	7	Pearson, 2002
G4U	530994	Leo CG 41-30	Wyodak	Upper Wyodak	399	6.7	-105.477	44.048	0.71315	625	0.1	7	Frost et al., 2002
G5U	531229	John Miller 5-32-15	Wyodak	Upper Wyodak	270	10.1	-105.496	44.315	0.71268	720	0.08	8.4	Frost et al., 2002

Table 1. Sample locations, selected water quality, and Sr isotopic data for water samples analyzed for this study (continued).

Sample Name	API Number	Well Name	Coal Name	Coal Zone	Depth (ft)	from east recharge zone (km)	Longitude	Latitude	$^{87}Sr/^{86}Sr$	TDS	SO_4	SAR	Data Source
G6U	531234	Durham Ranch 3-31-20-4571	Wyodak	Upper Wyodak	457	13.8	-105.412	43.867	0.71339	660	0	6.3	Frost et al., 2002
G7U	531384	Durham Ranch 5-33-3	Anderson	Upper Wyodak	661	14.6	-105.493	43.903	0.71333	571	0.1	7	Frost et al., 2002
G8U	531494	Durham Ranch 8-42-11	Anderson	Upper Wyodak	570	14	-105.468	43.893	0.71305	-	0.01	6.9	Frost et al., 2002
G9U	531760	Durham State 34-16	Anderson	Upper Wyodak	715	20.9	-105.513	43.870	0.71419	510	0.03	7.3	Frost et al., 2002
G10U	531900	MM 24-7	Fort Union	Upper Wyodak	853	16.3	-105.560	44.059	0.71380	620	0.73	6.9	Pearson, 2002
G11U	531934	Tripp 41-2	Wyodak	Upper Wyodak	842	20.7	-105.589	44.171	0.71354	888	0.1	8	Pearson, 2002
G12K	532105	Haight 22-25	Pawnee/Cache	Knobloch	1,411	8.2	-105.457	44.023	0.71242	270	0.04	10.28	Pearson, 2002
G13U	532860	W. Fork Flocchini 43-12	Wyodak	Upper Wyodak	879	16.3	-105.445	43.801	0.71396	480	0.75	6.1	Pearson, 2002
G14U	532910	Lange 14-14	Fort Union	Upper Wyodak	901	20.5	-105.605	44.132	0.71379	840	0	8.1	Pearson, 2002
G15U	531711	Bog State 2-36	Wyodak	Upper Wyodak	765	10.9	-105.450	43.569	0.71370	395	0.1	6	Frost et al., 2002
G16U	533031	Swanson 13-14-49-72	Anderson	Upper Wyodak	531	10.9	-105.487	44.220	0.71244	-	-	-	Pearson, 2002
G17U	533115	Durham Ranch 13-36	Wyodak	Upper Wyodak	746	5.9	-105.464	43.830	0.71393	390	0.82	6.1	Frost et al., 2002
G18U	533307	Bluebird CS State #1	Big George	Upper Wyodak	1,094	38.1	-105.822	44.098	0.71420	900	4.34	-	Pearson, 2002
G19U	533964	Laney 9-19-49-71A	Anderson	Upper Wyodak	450	6.7	-105.430	44.209	0.71276	620	4	7.1	Frost et al., 2002
G20U	533975	Moser 14-35	Wyodak	Upper Wyodak	1,014	21.4	-105.606	44.089	0.71417	660	0	7.3	Pearson, 2002
G21U	533977	Moser 43-27	Wyodak	Upper Wyodak	1,066	24.1	-105.611	44.107	0.71355	697	0.9	7	Frost et al., 2002
G22U	534071	Wagensen 11-32-4671	Wyodak	Upper Wyodak	397	8.4	-105.421	43.926	0.71358	509	0.25	-	Frost et al., 2002
G23U	534083	Heiland 42-3-4773	Wyodak	Upper Wyodak	992	22.5	-105.612	44.081	0.71386	710	1.9	7	Frost et al., 2002
G24U	534118	Persson 12-33	Wyodak	Upper Wyodak	1,315	24.3	-105.647	44.009	0.71429	700	0.89	7.8	Pearson, 2002
G25U	534171	Schlautmann 16-10-45-74WY	Canyon	Upper Wyodak	1,432	38.2	-105.731	43.884	0.71414	900	12	9.3	Frost et al., 2002
G26W	534174	Schlautmann 9-10-45-74BG	Anderson	Wyodak Rider	1,225	38	-105.731	43.887	0.71320	970	5.1	11	Pearson, 2002
G27W	534176	Schlautmann 15-10-45-74BG	Anderson	Wyodak Rider	1,146	39	-105.736	43.884	0.71367	1120	1.5	12	Pearson, 2002
G28W	534249	Heiland 24-27-4873	Wyodak	Wyodak Rider	775	22	-105.621	44.104	0.71338	680	0.1	6	Frost et al., 2002
G29U	534735	Rourke 8-18-48-71A	Anderson	Upper Wyodak	490	6.5	-105.427	44.139	0.71304	-	-	-	Pearson, 2002
G30U	535359	Lindsey 21-13-4673	Wyodak	Upper Wyodak	1,044	20.2	-105.580	43.968	0.71403	777	0.03	-	Frost et al., 2002
G31U	535985	Steinhoefel 5-7-49-71	Anderson	Upper Wyodak	326	8.3	-105.446	44.242	0.71261	-	-	-	Pearson, 2002
G32U	536125	Meserve 5-3-49-72A	Anderson	Upper Wyodak	498	12.7	-105.507	44.256	0.71287	770	0.07	7.6	Pearson, 2002
G33W	536791	McBeth 41-7-4673BG	Big George	Wyodak Rider	1,008	26.8	-105.671	43.983	0.71372	772	0.039	-	Frost et al., 2002
G34U	537482	Milne 15-30-49-72A	Anderson	Upper Wyodak	911	17.7	-105.558	44.189	0.71327	800	0.06	8	Pearson, 2002
G35U	538804	Bluebird CS State #19	Wyodak	Upper Wyodak	1,375	38	-105.822	44.098	0.71597	897	3.32	-	Pearson, 2002
G36U	539087	Throne 14-23-4774	Wyodak	Upper Wyodak	1,514	29.1	-105.727	44.030	0.71473	907	0	-	Pearson, 2002
G37U	539139	Geer 43-24-4774	Wyodak	Upper Wyodak	1,368	28.8	-105.692	44.033	0.71430	1,195	0.25	-	Campbell, 2007
G38U	539435	Durham Ranch 23-26-4573	Wyodak	Upper Wyodak	1,040	27.6	-105.601	43.844	0.71510	810	1.8	7.1	Frost et al., 2002
G39U	540399	Hayden 23-11-4774	Wyodak	Upper Wyodak	1,510	26.5	-105.722	44.064	0.71435	1,578	1.94	8.39	Campbell, 2007
G40U	540415	Geer 21-15-4774	Wyodak	Upper Wyodak	1,590	28.2	-105.741	44.056	0.71509	1,214	0.07	8.58	Campbell, 2007
G41W	540416	Geer 32-15-4774BG	Big George	Wyodak Rider	1,286	27.1	-105.737	44.053	0.71372	-	0.15	-	Campbell, 2007
G42U	540418	Hayden 41-15-4774	Wyodak	Upper Wyodak	1,584	27.1	-105.731	44.057	0.71460	1,266	1.65	8.26	Campbell, 2007
G43W	541776	Persson 43-12-4674 BG	Big George	Wyodak Rider	1,175	29.3	-105.692	43.975	0.71343	1,349	2	11.5	Campbell, 2007
G44U	541784	State 41-36-4774 BG	Big George	Upper Wyodak	1,091	28.1	-105.693	44.012	0.71376	1,109	0	10.4	Campbell, 2007
G45U	541788	State 21-36-4774 BG	Big George	Upper Wyodak	1,077	28.1	-105.702	44.012	0.71452	1,343	2.45	9.48	Campbell, 2007
G46U	541789	State 14-36-4774 BG	Big George	Upper Wyodak	1,180	28.9	-105.707	44.001	0.71444	1,262	1.43	7.85	Campbell, 2007
G47W	541935	Geer 34-1-4674BG	Big George	Wyodak Rider	1,164	30.1	-105.697	43.986	0.71351	1,402	6.91	11	Campbell, 2007
G48W	541938	Geer 32-1-4674BG	Big George	Wyodak Rider	1,080	32	-105.697	43.994	0.71355	1,284	0.08	11.3	Campbell, 2007

Table 1. Sample locations, selected water quality, and Sr isotopic data for water samples analyzed for this study (continued).

Sample Name	API Number	Well Name	Coal Name	Coal Zone	Depth (ft)	from east recharge zone (km)	Longitude	Latitude	$^{87}Sr/^{86}Sr$	TDS	SO_4	SAR	Data Source
G49U	542226	Geer 22-19-4773	Wyodak	Upper Wyodak	1,356	26.5	-105.683	44.038	0.71423	883	0.54	8.05	Campbell, 2007
G50W	543933	Persson 41-15-4674BG	Big George	Wyodak Rider	1,230	34.4	-105.732	43.967	0.71357	1,378	1.19	11.7	Campbell, 2007
G51W	543939	Persson 21-15-4674BG	Big George	Wyodak Rider	1,308	36.6	-105.742	43.967	0.71278	1,407	1.64	12.3	Campbell, 2007
G52W	543943	Mcbeth 21-25-4674BG	Big George	Wyodak Rider	1,070	33.1	-105.702	43.938	0.71403	1,192	9.82	11.9	Campbell, 2007
G53W	543944	Mcbeth 34-26-4674BG	Big George	Wyodak Rider	1,010	32.4	-105.717	43.927	0.71372	1,201	0.06	11.9	Campbell, 2007
G54U	543946	Mcbeth 34-26-4674	Wyodak	Upper Wyodak	1,365	32.7	-105.717	43.927	0.71464	1,046	2.88	10.6	Campbell, 2007
G55W	543952	Mcbeth 23-23-4674BG	Big George	Wyodak Rider	1,085	35.6	-105.721	43.945	0.71358	1,186	2.33	12	Campbell, 2007
G56W	543957	Ruby 32-14-4674BG	Big George	Wyodak Rider	1,225	35.7	-105.717	43.964	0.71392	1,361	1.96	11	Campbell, 2007
G57W	543959	Mcbeth32-26-4674BG	Big George	Wyodak Rider	1,080	32.7	-105.717	43.935	0.71376	1,215	0.27	11.7	Campbell, 2007
G58W	543981	Mcbeth 14-13-4674BG	Big George	Wyodak Rider	1,122	34.1	-105.707	43.956	0.71397	1,330	0.07	10.4	Campbell, 2007
G59U	547297	Flying T 12-32-4672	Canyon	Upper Wyodak	1,028	18.9	-105.545	43.921	0.71332	997	0.81	7.82	Campbell, 2007
G60W	543969	Mcbeth 34-24-4674BG	Big George	Wyodak Rider	975	35.7	-105.697	43.942	0.71407	1,306	0	10.3	Campbell, 2007
G61U	532140	Little Thunder Edwardds 43-124372	Wyodak	Upper Wyodak	675	14	-105.445	43.714	0.71366	396	1.8	6	Frost et al., 2002
G62U	533187	Thunder Edwards 21-7	Wyodak	Upper Wyodak	606	12.3	-105.446	43.722	0.71333	470	17	5.7	Pearson, 2002
G63W	534517	Pine Tree Draw CS State #1	Big George	Wyodak Rider	1,075	27.6	-105.807	43.567	0.71378	649	2.95	-	Pearson, 2002
G64U	534524	Stuart 12-33	Wyodak	Upper Wyodak	620	9.3	-105.399	43.747	0.71363	494	-	-	Frost et al., 2002
G65W	535476	Moore CS #60	Big George	Wyodak Rider	925	32.8	-105.688	43.735	0.71387	671	0.05	-	Pearson, 2002
G66W	543698	Groves CS #21	Big George	Wyodak Rider	980	28.8	-105.637	43.735	0.71457	571	0.29	-	Pearson, 2002
G67S		Martens and Peck Sec. 22 CBM VS Sand Monitoring	Sand	Sand	80	10.6	-105.487	44.123	0.71263	4290	2410	-	Frost et al., 2002
G68S		Martens and Peck Sec. 22 CBM Sand Monitoring	Sand	Sand	400	10.6	-105.486	44.123	0.71265	587	99.7	-	Frost et al., 2002
G69S		Monitoring	Sand	Sand	185	10.6	-105.487	44.123	0.71271	3650	2140	-	Frost et al., 2002
G70S		Barlow BWQ Glenn Barlow #4 Permit 166	Sand	Sand	400	42.5	-105.869	44.189	0.71214	588	296	-	Pearson, 2002
G75S		Barlow BWQ Glenn Barlow #2 Permit 164	Sand	Sand		43	-105.874	44.176	0.71179		-	-	Pearson, 2002
G71S		Throne 11-26-4774 MS	Sand	Sand	1,450	29.3	-105.727	44.027	0.71389	322	-	-	Pearson, 2002
G72S		BRC FED 33-31A	Sand	Sand	300	10.6	-105.430	43.657	0.71304	1580	983	-	Pearson, 2002
G73S		All Night Creek Sand Barrett State 13-36-4374 MS	Sand	Sand	860	25.9	-105.714	43.660	0.71228	281	1.1	-	Pearson, 2002
G74S		CBM-MON-1W	Sand	Sand	860	29.6	-105.687	44.255	0.71258	1010	10	13	Frost et al., 2002
G54C		CBM-MON-2	Wyodak-upper	Upper Wyodak	905	22.8	-105.621	44.260	0.71349	1030	1	9	Frost et al., 2002
N1U	529839	Walls Fee 74-7	Wyodak	Upper Wyodak	480	6.3	-105.551	44.368	0.71308	990	0.81	7.7	Pearson, 2002
N2U	531001	Hall 33-2633	Canyon	Upper Wyodak	299	0	-105.602	44.545	0.71335	1,040	0.7	8	Frost et al., 2002
N3L	532869	Soukup Draw State #1	Lower Canyon	Lower Wyodak	528	3.4	-105.633	44.522	0.71366	894	0.17	-	Pearson, 2002
N4L	534205	Parks Longhorn 6-14-55-73W	Pawnee	Lower Wyodak	545	0	-105.598	44.749	0.71393	800	3	11	Pearson, 2002
N5L	534424	L-X Bar LXFee 14-35A	Anderson	Upper Wyodak	543	21.8	-105.854	44.775	0.71314	1,320	1.2	23	Pearson, 2002
N6L	534425	LXFee 3-2C	Canyon	Lower Wyodak	805	21.8	-105.854	44.782	0.71175	1,600	1.6	23	Pearson, 2002
N7U	534475	West 12-28CA	Canyon	Upper Wyodak	645	25.8	-105.901	44.800	0.71238	1,550	0.92	22	Pearson, 2002
N8L	534690	LX-State-1-36C	Canyon	Lower Wyodak	687	19.4	-105.824	44.793	0.71404	1,050	0.16	22	Pearson, 2002
N9U	535333	LX-State 1-36ALC	Anderson	Upper Wyodak	390	19.4	-105.824	44.794	0.71362	1,390	1.9	18	Pearson, 2002
N10L	535352	West 16-13CO	Cook	Lower Wyodak	1,020	30.9	-105.946	44.825	0.71463	2,000	0.16	32	Pearson, 2002
N11U	535416	Floyd 10-28-51-74A	Anderson	Upper Wyodak	812	22.4	-105.760	44.367	0.71449	540	0.78	13	Frost et al., 2002
N12U	535851	Floyd 10-30-51-74A	Anderson	Upper Wyodak	963	26.3	-105.803	44.368	0.71399	1,306	1.2	-	Frost et al., 2002
N13K	536006	WEST 6-28-56-75CO	Wall/Pawnee	Knobloch	1,150	25.2	-105.894	44.804	0.71256	1,550	0.07	32	Pearson, 2002
N14U	538294	Spotted Horse CS State #13	Upper Canyon	Upper Wyodak	603	25.2	-105.901	44.739	0.71332	1,331	0.83	-	Pearson, 2002
N15L	538300	Spotted Horse CS State #6	Wall	Lower Wyodak	775	24	-105.891	44.746	0.71414	1,350	1.22	-	Pearson, 2002

Table 1. Sample locations, selected water quality, and Sr isotopic data for water samples analyzed for this study (continued).

Sample Name	API Number	Well Name	Coal Name	Coal Zone	Depth (ft)	from east recharge zone (km)	Longitude	Latitude	$^{87}Sr/^{86}Sr$	TDS	SO_4	SAR	Data Source
N16L	539040	Stevens 5-4-53-74 A	Anderson	Lower Wyodak	1,085	12.3	-105.776	44.605	0.71418	-	-	-	Pearson, 2002
N17L	540220	Soukup Draw CS State #7	Wall	Lower Wyodak	811	3.4	-105.633	44.522	0.71343	593	0.04	-	Pearson, 2002
N18U	540502	Kline Draw CS State #12	Upper Canyon	Upper Wyodak	360	28	-105.900	44.830	0.71213	1,443	0.46	-	Pearson, 2002
N19L	540518	Kline Draw CS State #28	Cook	Lower Wyodak	615	28	-105.900	44.830	0.71218	1,362	0.58	-	Pearson, 2002
N20L	540534	Kline Draw CS State #44	Wall	Lower Wyodak	701	28	-105.900	44.830	0.71486	1,624	1.07	-	Pearson, 2002
N21L	541229	Stevens 5-4-53-74CO-R	Cook	Lower Wyodak	1,120	12.3	-105.775	44.604	0.71481	1,004	0.27	-	Pearson, 2002
N22U	541695	BC 07CK-05-53-73	Cook	Upper Wyodak	661	3.4	-105.664	44.606	0.71427	-	9.52	-	Pearson, 2002
N23U	542974	BC 01CN-06-53-73	Canyon	Upper Wyodak	492	4	-105.679	44.609	0.71456	715	6.32	-	Pearson, 2002
N24U	3321346	Kuhn Ranch 1-3-53-77A	Anderson	Upper Wyodak	904	38.4	-106.104	44.604	0.71065	1,741	0.92	-	Pearson, 2002
N25U	554969	Laramore 5275-10-43CA	Canyon	Upper Wyodak	720	25.2	-105.862	44.495	0.71322	1,029	1.9	11.9	Campbell, 2007
N26K	554972	Laramore 5275-11-43WA	Cook	Knobloch	1,725	23.4	-105.841	44.496	0.71468	1,617	3.9	12.6	Campbell, 2007
N27L	554973	Laramore 5275-10-43MO	Wall	Lower Wyodak	1,460	25.2	-105.862	44.495	0.71336	1,489	0.9	15.3	Campbell, 2007
N28U	554976	Laramore 5275-11-41LA	Anderson Lower	Upper Wyodak	589	22.1	-105.837	44.499	0.71321	1,642	5.8	16.4	Campbell, 2007
N29W	554978	Laramore 5275-10-43LA	Anderson Lower	Wyodak Rider	508	22.1	-105.862	44.496	0.71357	1,445	0.6	18.6	Campbell, 2007
N30K	1921558	Kuhn Ranch 7-27-53-77W	Wall	Knobloch	1,667	40	-106.108	44.545	0.71495	1,549	0.04	-	Pearson, 2002
N31W	1921910	Kuhn Ranch 7-22-53-77A	Anderson	Wyodak Rider	978	38.7	-106.108	44.556	0.71293	1,698	1.63	-	Pearson, 2002
N32U	3320335	Floyd 9-29A	Anderson	Upper Wyodak	656	32.3	-106.023	44.626	0.71312	1,240	0.12	24	Pearson, 2002
N33U	3321101	Tietjen 15-29-5477A	Anderson	Upper Wyodak	917	42.1	-106.149	44.612	0.71166	1,446	1.6	-	Pearson, 2002
N34S		Arvada BWQ Gallimore #1	Sand	Sand	200	44.3	-106.133	44.654	0.71154	968	13	21.4	Pearson, 2002
NE2S		Redstone Sand	Sand	Sand	140	0.5	-105.608	44.549	0.71271	1660	740	5	Pearson, 2002
S1U	529688	BTP 4975 8-32	Wall	Upper Wyodak	1,795	45.6	-105.897	44.180	0.71479	624	1.2	8	Frost et al., 2002
S2W	536103	SRU 23-22-4876	Big George	Wyodak Rider	1,450	53.5	-105.982	44.118	0.71496	-	-	17.7	Campbell, 2007
S3W	536109	SRU Iberlin 14-15-4876	Big George	Wyodak Rider	1,520	52.4	-105.988	44.129	0.71540	1,990	54.6	15.4	Campbell, 2007
S4W	541364	Schoonover Road CMB 21-15-4876	Big George	Wyodak Rider	1,688	51.7	-105.983	44.140	0.71402	1,308	2.34	-	Pearson, 2002
S5W	550056	Schoonover Road CBM 23-15-4876	Big George	Wyodak Rider	1,609	50.7	-105.984	44.133	0.71126	1,504	-	7.78	Campbell, 2007
S6W	1921071	Pilot State 16-32	Big George	Wyodak Rider	1,224	62.6	-106.118	44.136	0.71280	2,720	0.3	26	Frost et al., 2002
S7W	1921141	Lantern CS State 1	Big George	Wyodak Rider	1,241	56.5	-106.051	44.002	0.71307	1,717	-	-	Pearson, 2002
S8W	1921469	Jones 11-1996	Big George	Wyodak Rider	1,043	57.4	-106.054	44.211	0.71386	1,418	17.8	-	Pearson, 2002
S9W	1922921	KU Herriet L&L 32-27-4777	Big George	Wyodak Rider	1,561	60.7	-106.097	44.019	0.71100	3,631	-	31.7	Campbell, 2007
S10W	1924064	Harriet L&L Fed 32-19-4877	Big George	Wyodak Rider	1,451	66.3	-106.159	44.122	0.71113	3,823	-	27.7	Campbell, 2007
S11W	1925501	SRU 12-30-4876	Big George	Wyodak Rider	1,205	56.9	-106.047	44.105	0.71288	2,699	0.2	21.8	Campbell, 2007
S12W	1925517	SRU 12-19-4876	Big George	Wyodak Rider	1,268	58.7	-106.048	44.121	0.71388	3,195	0.1	31	Campbell, 2007
S13W	1925557	SRU 12-25-4877	Big George	Wyodak Rider	1,179	58.9	-106.067	44.106	0.71460	3,795	-	29.6	Campbell, 2007
S14W	1925566	SRU 23-13-4877	Big George	Wyodak Rider	1,327	57.2	-106.063	44.132	0.71340	3,416	0.2	25.6	Campbell, 2007
S15W	1925568	SRU 21-13-4877	Big George	Wyodak Rider	1,539	57.2	-106.063	44.139	0.71348	3,270	0.1	24.8	Campbell, 2007
S16S	141663	Stranahan Federal 14 MG-1498 Sand	Sand	Sand	1,130	69.6	-106.217	44.215	0.71185	91.5	13.8	-	Pearson, 2002
SH1U	3320292	Rice and sons 33C-2674	Carney	Upper Wyodak	646		-106.954	44.885	0.71164	954	0.11	-	Pearson, 2002
SH2U	3320317	Rice and sons 33M-2674	Monarch	Upper Wyodak	561		-106.954	44.884	0.71216	1,070	1.31	-	Pearson, 2002
SH3U	3320688	Pilch 11A-35-58-83	Anderson	Upper Wyodak	442		-106.835	44.958	0.70808	1,289	0.72	-	Pearson, 2002
SH4L	3320827	LPD 13M-3 57-83	Monarch	Lower Wyodak	660		-106.860	44.939	0.71121	1,284	0.04	-	Pearson, 2002
DS4C	2500321243	Consol 43EC-1990	Carney	Lower Wyodak	630		-106.872	45.029	0.71034	1199	-	-	Pearson, 2002
DS5C	2500321390	State/Consol 33C-3699	Carney	Lower Wyodak	705		-106.986	45.000	0.71000	1600	-	-	Pearson, 2002
DS6C	2500321390	Consol 33C-3699	Carney	Lower Wyodak	705		-106.896	45.000	0.70991	1536	-	-	Pearson, 2002

Table 1. Sample locations, selected water quality, and Sr isotopic data for water samples analyzed for this study (continued).

Sample Name	API Number	Well Name	Coal Name	Coal Zone	Depth (ft)	from east recharge zone (km)	Longitude	Latitude	$^{87}Sr/^{86}Sr$	TDS	SO_4	SAR	Data Source
DS7C	2500321378	Consol 31C-3290	Carney	Lower Wyodak	650		-106.854	45.000	0.71060	1327	-	-	Pearson, 2002
DS8C	2500321512	Shell 44D-3399	Dietz	Upper Wyodak	318		-106.951	44.997	0.70937	1337	-	-	Pearson, 2002
DS9C	2500321400	Consol 43D-1990	Dietz	Upper Wyodak	321		-106.872	45.029	0.70903	1092	0.125	-	Pearson, 2002
DS10C	2500321313	State/Consol 33D1-3699	Dietz 1	Upper Wyodak	249		-106.896	45.000	0.70791	1899	0.23	-	Pearson, 2002
DS11C	2500321332	Consol 31D1-3290	Dietz 1	Upper Wyodak	297		-106.854	45.009	0.70850	1067	16.5	-	Pearson, 2002
DS12C	2500321299	Consol 33D2/3-3699	Dietz 2/3	Upper Wyodak	379		-106.896	45.000	0.70980	1074	0.15	-	Pearson, 2002
DS14C	2500321513	Shell 44M-3399	Monarch	Upper Wyodak	421		-106.951	44.997	0.71168	1,717	-	-	Pearson, 2002
DS16C	2500321396	Consol 14M-1990	Monarch	Upper Wyodak	354		-106.885	45.027	0.71051	932	-	-	Pearson, 2002
DS17C	2500321298	State/Consol 33M-3699	Monarch	Upper Wyodak	482		-106.896	45.000	0.71048	1250	-	-	Pearson, 2002
DS18C	2500321325	Consol 13M-2599	Monarch	Upper Wyodak	418		-106.906	45.015	0.71073	1219	0.03	-	Pearson, 2002
DS19C	2500321361	Consol 42M-3290	Monarch	Upper Wyodak	468		-106.852	45.005	0.71120	1216	0.074	-	Pearson, 2002
B8S		JM Huber Gutz #1	Sand	Sand	190		-106.845	44.925	0.71005	703	14	27.18	Pearson, 2002
DS2S		JM Huber Beatty Gulch Pasture #1	Sand	Sand	4		-106.896	44.954	0.70829	1900	23	26.06	Pearson, 2002
B9S		JM Huber Paterson Well #2	Sand	Sand	40		-106.852	44.894	0.70960	-	-	-	Pearson, 2002
B10S		Dunning #3 JM Huber LPD BWQ [SPRING?]	Sand	Sand	300		-106.902	44.948	0.70884	-	-	-	Pearson, 2002
B11S		JM Huber S and J Paterson #1	Sand	Sand	140		-106.851	44.928	0.71044	706	12	26.67	Pearson, 2002
B12S		JM Huber LPD BWQ Dunning Home #2	Sand	Sand			-106.908	44.973	0.71008	-	-	-	Pearson, 2002
B13S		JM Huber Dunning Barn #1	Sand	Sand	40		-106.906	44.973	0.71080	-	-	-	Pearson, 2002

are mainly sulfate and calcium dominated. The same is true in water samples from the Jacobs Ranch Mine east of Wright, Wyoming, completed in both coal and shale or sandstone aquifers (Frost et al., 2001); there is considerable variation. Deeper sandstone wells and coal wells are sodium-bicarbonate type (Fig. 4). Although water from all coal zones is sodium-bicarbonate type (and thus major ion compositions do not differentiate waters from different coal zones), there are some spatial patterns in water quality.

Total dissolved solids (TDS) are lowest along the eastern margin of the Powder River Basin, typically under 1000 mg/L. They are highest along the Johnson–Campbell county line at approximately 106° W longitude (exceeding 3.000 mg/L in some wells) and intermediate in the area of Sheridan (Fig. 5). Our data are consistent with those of Rice et al. (2000), whose smaller dataset was restricted mainly to water samples from wells in Campbell County near the eastern edge of the Powder River Basin. They described the variation in TDS in the Powder River Basin as increasing from southeast to northwest but did not have access to the more recently completed, deeper wells farther west into the basin that exhibit the highest TDS. Neither did they analyze the relatively dilute produced water from wells in the Sheridan area.

Sodium-adsorption ratio (SAR), defined as:

$$SAR\left(\frac{\sqrt{mmol}}{\sqrt{L}}\right)=\frac{\left[Na^{+}\right]}{\sqrt{\left[Ca^{2+}+Mg^{2+}\right]}}$$

(Essington, 2004) also is highest along 106° W longitude (Fig. 6). Most water samples with SAR greater than 20 are found in this area of the basin.

Most of the samples in this study are from wells located in Wyoming on the eastern side of the basin axis, where the CBNG development began. The recharge area for these samples is along the eastern margin of the basin. A major recharge zone for coal aquifers is the clinker outcrops adjacent to the surface coal mines that extend from southeast of Wright to northeast of Gillette. Ground water recharged on the eastern side of the basin is driven westward by the topographic gradient toward the Powder River and the basin's axis. The distance of the well from the eastern clinker outcrops is a proxy for relative ground-water residence time, such that wells closer to the clinker outcrop yield water with shorter resi-

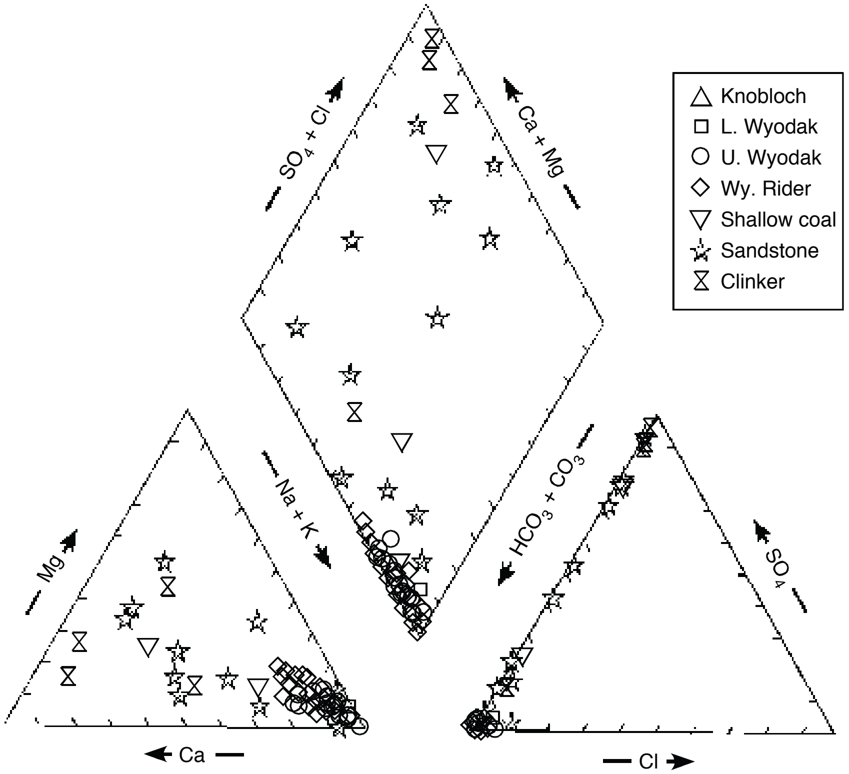

Figure 4. Trilinear diagram showing major ion composition of water from coal, clinker, and sandstone aquifers in Powder River Basin. Although water samples from shallow clinker, sandstone, and coal aquifers have variable composition, all waters from deeper wells (>40 m or 125 ft) are of sodium-carbonate type. Data from this study and Frost et al. (2001).

dence time than wells located farther west. Plotted as a function of distance from recharge, TDS of coal-aquifer waters increases with increasing distance into the basin, and values of TDS higher than 2,000 mg/L occur for samples collected more than 45 km from recharge (Fig. 7). Some shallow wells, ranging in depth from 80 to 300 feet (25–92 m), in sandstone aquifers near the recharge area also have high TDS (Fig. 7). Water from these shallow wells is also high in sulfate. High concentrations of sulfur in wells suggest that they have not yet undergone bacterial reduction of sulfate. That process reduces the concentration of sulfate and increases the concentration of bicarbonate, causing Ca and Mg to precipitate as carbonates and decreasing TDS (Brinck et al., *in press*). Disregarding these samples and considering only those that have undergone sulfate reduction, residence time appears to be more important than depth of coal seam. There is no strong correlation of TDS with well depth, although all CBNG well waters with high TDS are from wells more than 1,000 ft deep. SAR also increases with increasing distance from recharge zone (Fig. 8), although there is considerable variation.

Strontium Isotope Results

^{87}Sr/^{86}Sr ratios for the ground waters in this study vary from less than 0.711 to more than 0.715 (analytical uncertainty is ± 0.00002). The ^{87}Sr/^{86}Sr ratios are lowest in the Sheridan area along the Montana–Wyoming border, and the highest are along 106° W longitude (Fig. 9). Water from sandstone aquifers are generally among the lowest ratios; most are between 0.7083 and 0.7127, although two samples have ^{87}Sr/^{86}Sr ratios > 0.713.

In most areas of the Powder River Basin, ^{87}Sr/^{86}Sr ratios for ground water from different coal zones are overlapping (Fig. 10). However, in the Buffalo area, water from the Lake DeSmet coal zone is more radiogenic than water from the Felix coal zone. Also, in the Black Diamond development area of the northeastern part of the basin, water sampled from the Lower Wyodak coal zone is more radiogenic than water from the Upper Wyodak coal zone.

DISCUSSION

Trends in Water Quality and Sr Isotopic Composition in Gillette–Schoonover Area

Because this part of the basin was the first to be developed for the CBNG resource, the preliminary studies by Frost et al. (2001, 2002) were focused on wells located between Gillette and Wright (here referred to as the Gillette area; see area outlined on Fig. 2). Most of these wells were completed in the Upper Wyodak coal zone. Our new analyses include a number of samples further westward into the basin, here referred to as the Schoonover area (Fig. 2). Many of these wells are completed within the Wyodak Rider coal zone, in a thick seam informally called "Big George." The TDS, SAR, and

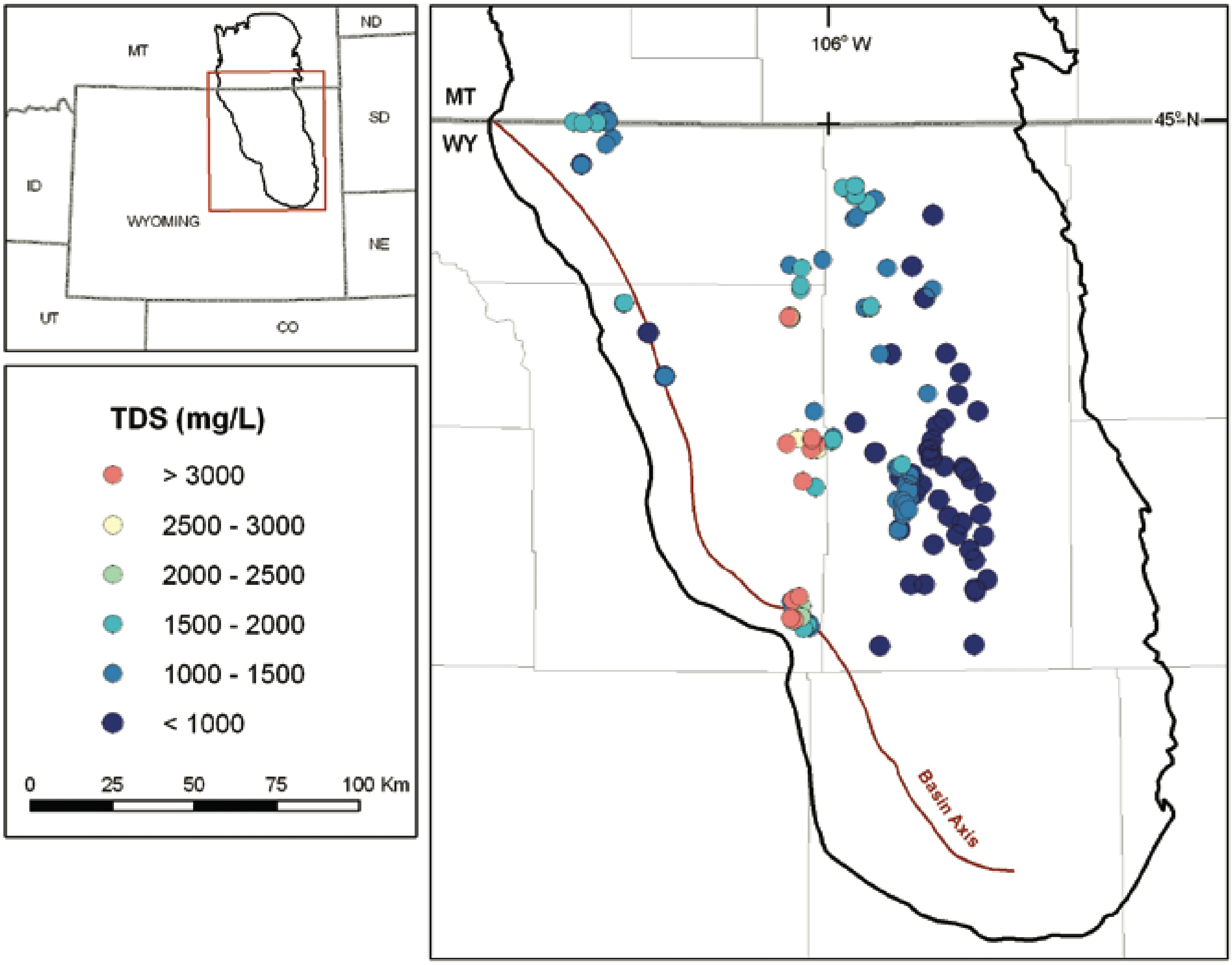

Figure 5. Total dissolved solids (TDS) in ground water co-produced with coal-bed natural gas. TDS are lowest in eastern parts of basin, and highest values occur along 106° W longitude. Water-quality data from Table 1.

^{87}Sr/^{86}Sr ratios for waters from these wells are plotted in Figures 7, 8, and 11 as functions of distance from the recharge area along the eastern margin of the basin.

Water from the Upper Wyodak coal zone is low in SAR (<10) and TDS (<1,000 mg/L), and TDS increases slightly with increasing distance from the recharge zone (Figs. 7 and 8). Water from the Wyodak Rider coal zone extends the trend to higher TDS and SAR, particularly for samples more than 50 km from the recharge zone. The ^{87}Sr/^{86}Sr ratios in waters of the Upper Wyodak coal zone in the Gillette-Schoonover area show an increasing ratio with increasing distance from the recharge zone, as described by Frost et al. (2002; Fig. 11). However, waters from the Wyodak Rider coal zone fall below this trend and extend to very low ratios. The sandstone-aquifer waters in the Schoonover area are similarly low in ^{87}Sr/^{86}Sr.

The trend in results for TDS from CBNG co-produced waters implies an increase in dissolved solids with increased water-residence time. The correlation of ^{87}Sr/^{86}Sr ratios in waters of the Upper Wyodak coal zone with distance into the basin from the recharge zone suggests that the ^{87}Sr/^{86}Sr ratio increases with increased water–rock interaction along the flow path.

Water from shallow-sandstone aquifers in the Gillette and Schoonover areas has relatively unradiogenic ^{87}Sr/^{86}Sr isotopic ratios, irrespective of distance from the recharge area (Frost et al., 2002; Brinck and Frost, 2007). As a result, the distinction between Upper Wyodak coal zone waters and water from shallow-sandstone aquifers becomes pronounced for

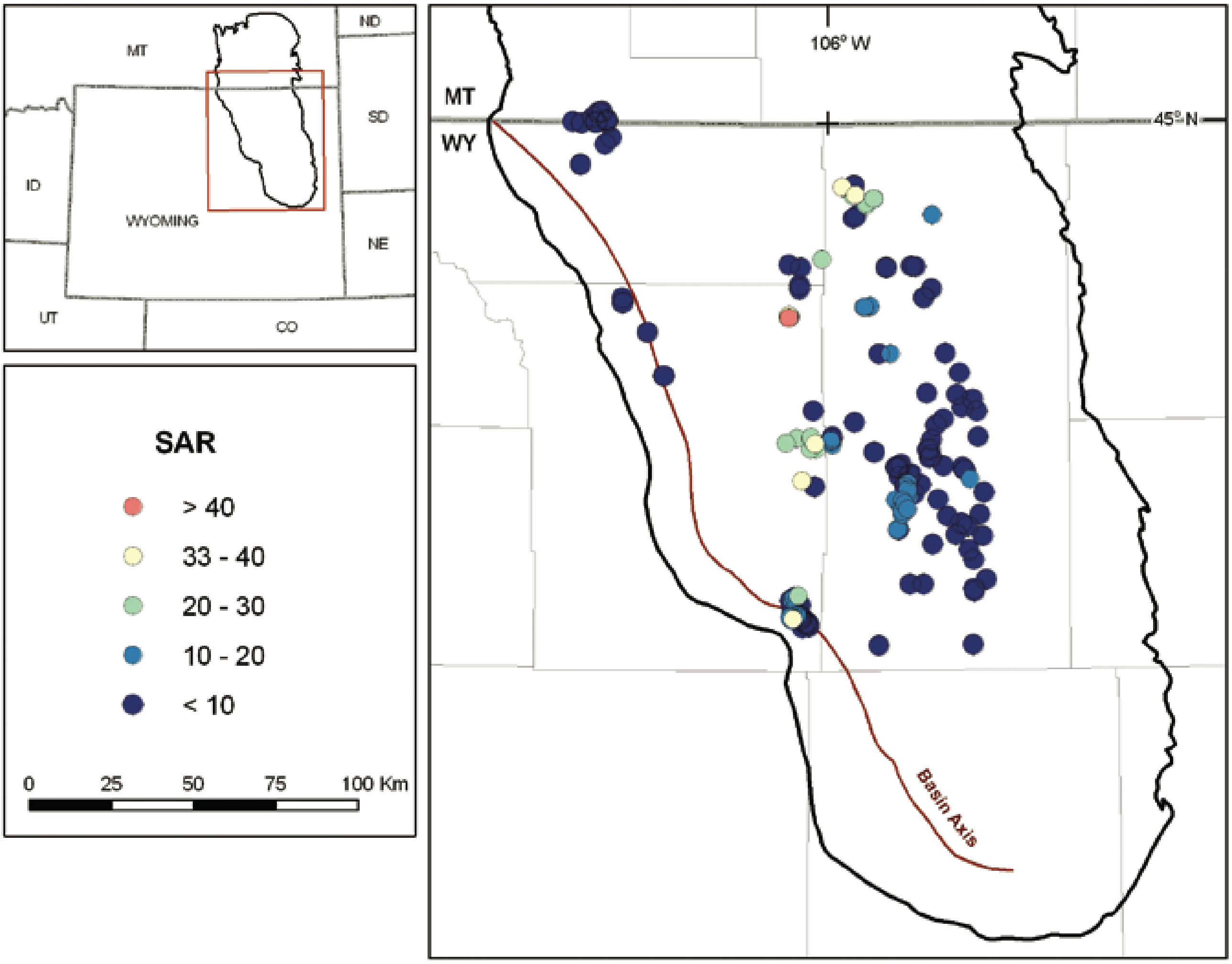

Figure 6. Sodium adsorption ratio (SAR) in ground water co-produced with coal bed natural gas. SAR is low along margins of basin and highest in center at around 106° W longitude. SAR data from Table 1.

wells located more than 5 km into the basin. That suggests the Upper Wyodak aquifer system is isolated from other, shallower-sandstone aquifers.

In contrast, one ground-water sample collected from a deep sandstone, G71S (1,450 ft), has a Sr isotopic ratio and TDS indistinguishable from a neighboring Upper Wyodak well (1,448 ft deep). Moreover, where Upper Wyodak coals are in direct contact with overlying sandstones as determined from gamma-log analysis (e.g., samples G13U, G14U, and G20U), the water samples do not have the higher TDS and lower $^{87}Sr/^{86}Sr$ that might be expected if these wells produced ground water from both coal and a chemically and isotopically distinctive sandstone aquifer. These results suggest that the Upper Wyodak aquifer is composite, composed of both coal and sandstone.

The chemical and isotopic characteristics of ground-water samples from the Wyodak Rider coal zone contrast with those from the Upper Wyodak coal zone. A large range in TDS and $^{87}Sr/^{86}Sr$ ratios is observed in the Wyodak Rider coal zone waters, particularly at 50 to 70 km into the basin from the eastern recharge zone. In some cases this may reflect well completion. Two of the wells, S6W and S7W are perforated to draw water from the coal and overlying sands. Hence elevated TDS and lower $^{87}Sr/^{86}Sr$ ratios reflect the introduction of water from both aquifers into these wells. For other wells that are open only to coal, the variability may indicate incomplete aquifer isolation and resulting interaction of ground waters between coal and sandstone aquifers. This hypothesis is supported by a seismic survey conducted in the

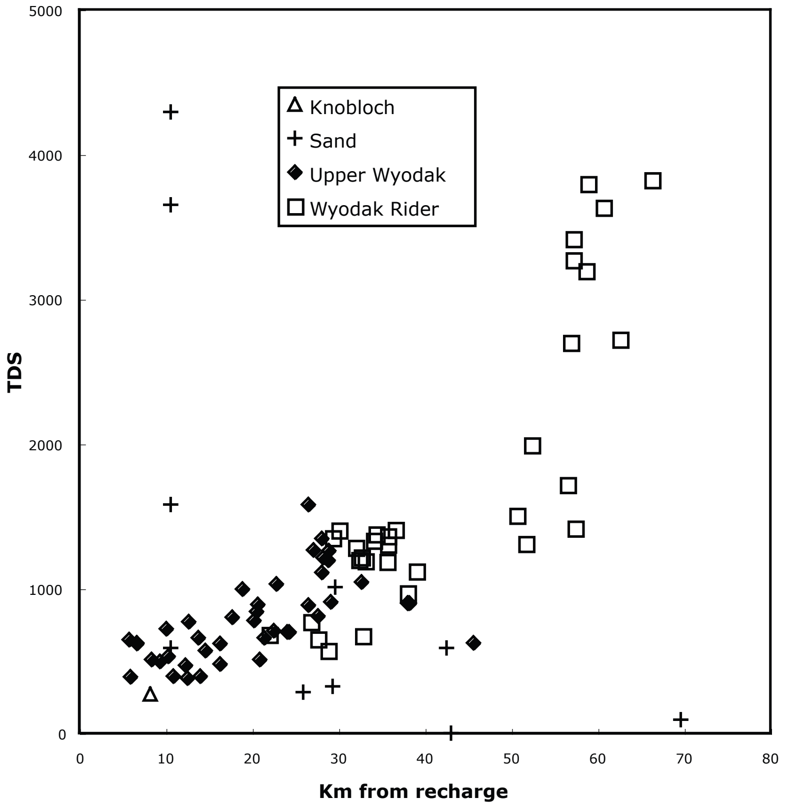

Figure 7. Total dissolved solids (TDS) as a function of distance from recharge zone for samples located in Gillette and Schoonover areas. Some ground water from sandstone aquifers have high TDS. TDS for ground water from coal seams generally increases with increasing distance from recharge; Wyodak Rider ground water samples in the Schoonover area are particularly high. Data from Table 1.

vicinity of 106° W longitude at Burger Draw by Morozov (2002) that imaged the Big George coal (part of the Wyodak Rider coal zone) and identified complex faulting with offsets of approximately 10 meters (30 feet) within the Big George coal and underlying strata. This faulting could cause hydraulic connections between coal and other aquifers.

Many Wyodak Rider wells produce higher water-to-gas ratios than average for the Powder River Basin. The average water/gas ratio for 19,158 coalbed natural gas wells that have produced for more than two years is 1.8 bbls/mcf (Surdam et al., 2007), Although 30 percent of the wells studied here that are completed in the Big George seam of the Wyodak Rider coal zone have average or below average water/gas ratios, an equal number have water/gas ratios greater than 20, and 15 percent exceed 100 (Fig. 12; Table 2; Wyoming Oil and Gas Conservation Commission, 2007). By contrast, water/gas ratios for other coal seams include few to no ratios exceeding 20 (Fig. 4; Table 2; Wyoming Oil and Gas Conservation Commission, 2007). The intermediate Sr isotope ratios and elevated TDS compared to other coal aquifer waters, coupled with evidence of faults in the subsurface, long dewatering periods and minimal gas production, all suggest that the Wydoak Rider coal zone is not well isolated from adjacent aquifers, particularly in the vicinity of 106° W longitude.

We conclude that in the Gillette-Schoonover area, the Upper Wyodak coal zone appears to be isolated, and thus CBNG development likely removes water only from a composite Upper Wyodak aquifer system. On the other hand, the TDS, SAR and Sr isotopic characteristics of some of the waters from Wyodak Rider wells suggest that there may be leakage from adjacent aquifers when these wells are depressurized, particularly in the center of the basin.

Possible Influence of Faulting on Sr Isotopic Composition of Ground Water

Northeastern Area

The Sr isotopic data from the northeastern part of the Powder River Basin are more scattered than those from the Gillette and Schoonover areas (Fig. 13). Some of the northeast samples plot above the "Gillette trend" as defined by the Upper Wyodak water samples from the Gillette area (Fig. 13); others plot below.

One distinction between the northeastern area and the Gillette–Schoonover areas is the presence of mapped faults in the northeast. These faults could act either as seals or conduits for water and gas flow. The group of samples lying above the Gillette Sr isotopic trend is located in the eastern part of the Northeast area. These samples have comparatively low TDS (<1,000 mg/L). The high $^{87}Sr/^{86}Sr$ ratios and low TDS suggest that

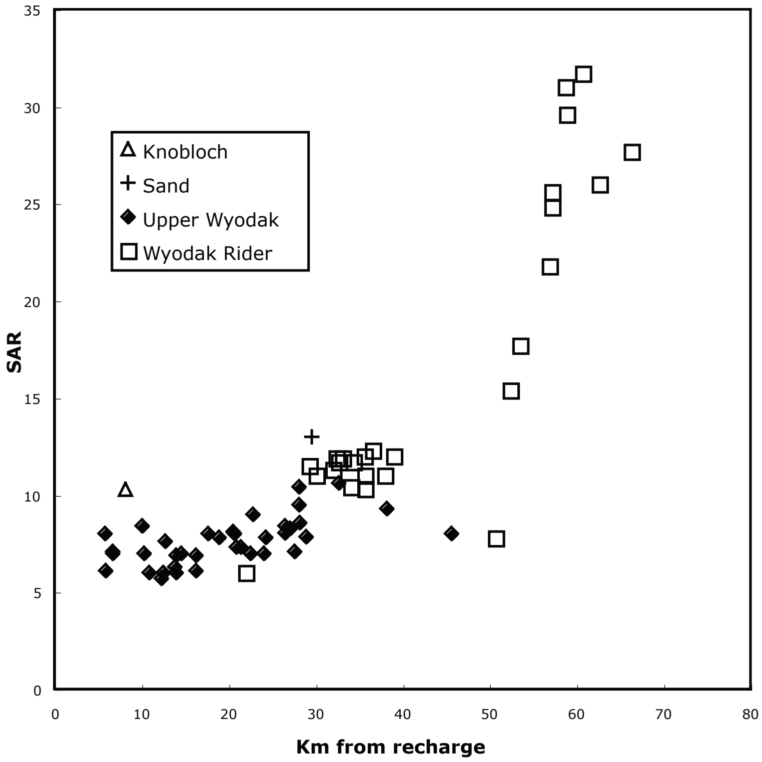

Figure 8. Sodium-adsorption ratio (SAR) as a function of distance from recharge area for samples in Gillette and Schoonover areas. As for TDS, SAR values are highest for water samples from Wyodak Rider coal zone, particularly in Schoonover area. Data from Table 1.

these coals are well isolated from sandstone aquifers and that if faults influence the hydrology of this area, they are acting as seals. It is noteworthy that none of these wells has produced more than 500 MCF gas/month (Wyoming Oil and Gas Conservation Commission, 2007).

The group of samples lying below the Gillette trend is located northwest of the high $^{87}Sr/^{86}Sr$ ratio group. These water samples also have higher TDS (1,300–1,800 mg/L). The combination of low $^{87}Sr/^{86}Sr$ ratios and high TDS suggests that in this area the coals are not completely isolated, possibly because the faults in this area act as conduits to ground-water flow. Wells in this area are associated with relatively high gas production (typically >1.000MCF/month; Wyoming Oil and Gas Conservation Commission, 2007).

Sheridan Area

The Sheridan sample subset also illustrates the possible role of faults in increasing recharge rates, decreasing residence time of ground water in coal and sandstone aquifers, and allowing co-mingling of waters from different aquifer types. This area is marked by a number of steeply dipping, east–northeast-trending normal faults (Van Voast et al., 1977; Kanizay, 1978; Love and Christiansen, 1985). Coal-aquifer waters of the Sheridan area display lower Sr isotopic ratios than those from the Gillette area (Figs. 9 and 10) and no correlation between isotopic ratio and production depth. Like the group of samples from northeastern coal-aquifer water with low $^{87}Sr/^{86}Sr$ ratios, the TDS of these coal-aquifer waters is elevated (700–1,900 mg/L) relative to the TDS of the Upper Wyodak samples near Gillette. The relatively high TDS of both the northeastern subset and Sheridan area samples suggests that the waters are in the initial phase of ground-water evolution expected for ground waters with short residence times. It is possible that local faults may serve as recharge zones for the coal and sand aquifers. Fault displacements in the Sheridan area of 200–300 ft (Culbertson and Mapel, 1976; Van Voast and Hedges, 1975) could place lithologies with different isotopic and geochemical qualities in direct contact, thus providing an intermediate isotope signature between coal and sandstone.

Little to no gas has been produced from any of these wells. The low Sr isotope ratios and lack of gas production suggest: (1) these samples are composed of water from both coal and sandstone aquifers; (2) faults in this region served as conduits for ground-water recharge and flow, complicating the depressurization process; and/or (3) proximity to recharge area is not favorable for coalbed natural-gas production on the western side of the basin. A combination of these processes appears to limit gas production and retard development of distinct isotopic and chemical characteristics in produced water between coal and sand aquifers.

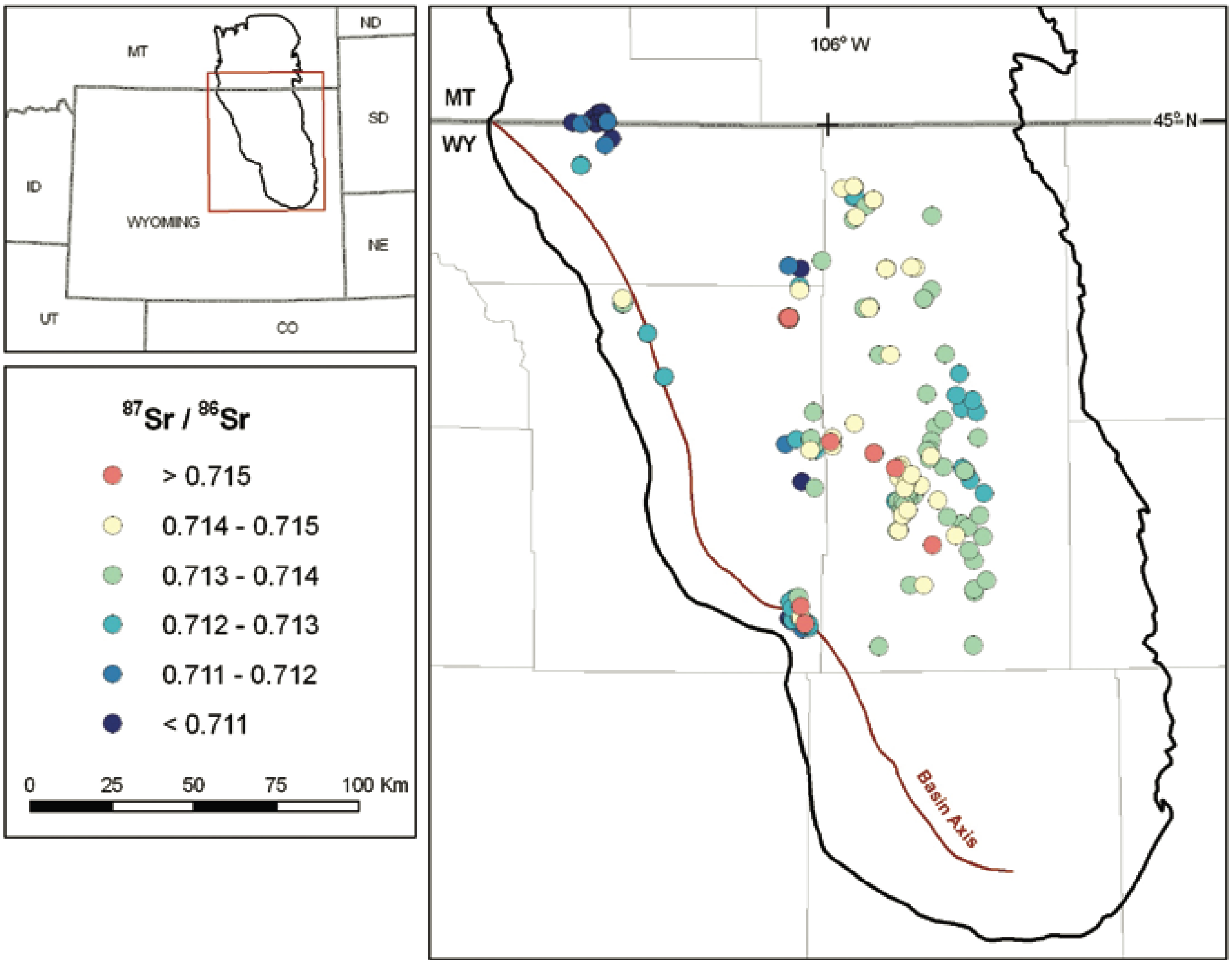

Figure 9. $^{87}Sr/^{86}Sr$ ratios for water co-produced with coal-bed natural gas. Ratios increase from east to west, with highest ratios occurring for samples from wells located at approximately 106° W longitude. Lowest ratios are from Sheridan area near Wyoming–Montana border. Data from Table 1.

Geographic and Temporal Variability Due to Depositional Systems and Sediment Provenance

Although the details are debated, there is general agreement that the Paleocene and Eocene strata of the Powder River basin were deposited in a fluvial/lacustrine environment. Ayers and Kaiser (1984) envisioned a system of deltas supplying Lake Lebo. Each delta had a different source area, and therefore may have transported clastic material with different $^{87}Sr/^{86}Sr$ ratios. Seeland (1992) suggested a north-flowing fluvial system fed by various uplifts around the basin. Cross bedding in the sandstone aquifers of the Tongue River Member of the Fort Union Formation and of the Wasatch Formation led Flores (1986) to conclude that sediment was variously sourced from the Big Horn Mountains, Casper Arch, Laramie Mountains, Hartville Uplift, and Black Hills. Some of the variations in $^{87}Sr/^{86}Sr$ ratio of water produced from coals in different parts of the Powder River Basin may reflect these differences in sediment sources. For example, the samples from the Sheridan area, which have the lowest $^{87}Sr/^{86}Sr$ ratios, may reflect the dominance of non-radiogenic strontium from Paleozoic and Mesozoic limestone exposed in the northern Big Horn Mountains.

Other variations in $^{87}Sr/^{86}Sr$ ratio may reflect temporal changes in depositional systems. For example, CBNG is being developed in the Buffalo area from the Eocene Lake DeSmet and Felix coals. The Lake DeSmet coals have higher $^{87}Sr/^{86}Sr$ ratios than

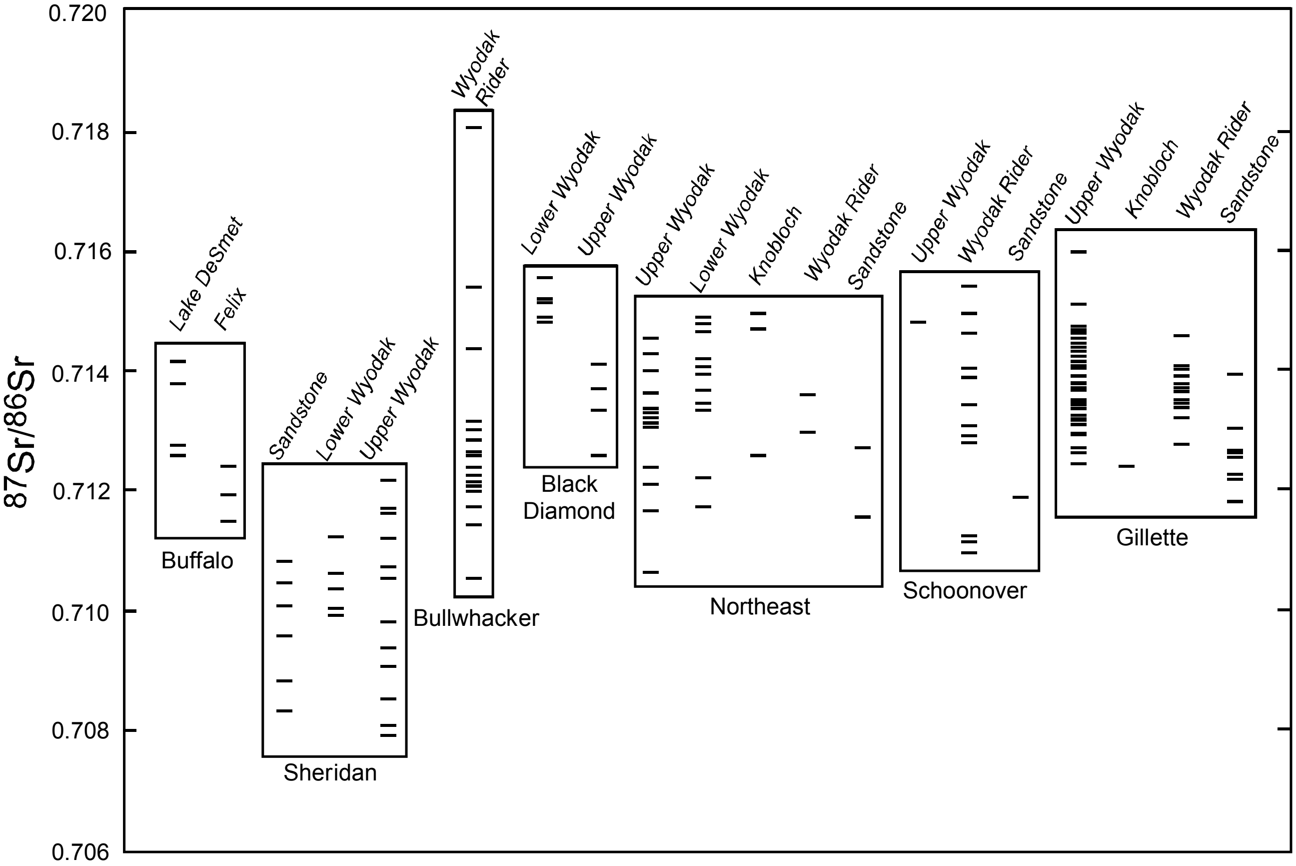

Figure 10. $^{87}Sr/^{86}Sr$ ratios by coal zone and location in Powder River Basin. In most areas of Powder River Basin, $^{87}Sr/^{86}Sr$ ratios do not distinguish different coal zones. But in Buffalo area, water from Lake DeSmet coal zone is more radiogenic than water from Felix coal zone. In Black Diamond development area of northeastern part of basin, water from Lower Wyodak coal zone is more radiogenic than water from the Upper Wyodak coal zone. Data from Table 1.

underlying Felix coals, possibly reflecting an increase in the amount of radiogenic (high $^{87}Sr/^{86}Sr$ ratio) Precambrian detritus being eroded from the Big Horn Mountains as these were uplifted in Eocene time (Whipkey et al., 1991).

Aeolian dust may be an important source of the Sr preserved in coal. A number of studies have determined that the majority of Sr in plant material originates from dry or wet deposition of atmospheric dust (Graustein and Armstrong, 1983; Négrel et al., 1993). The dense, woody vegetation of peat swamps may have trapped airborne dust, and the low-energy environment of the swamps may have allowed dust to settle and be preserved during the coalification process. Some sources of aeolian detritus may be local, but fine atmospheric dust may have been derived from great distances (e.g., Dymond et al., 1974). As for fluvially transported clastic material, the $^{87}Sr/^{86}Sr$ ratio of aeolian dust deposited in the Powder River Basin may vary spatially and temporally.

Correlation of Sr Isotopic Compositions to Water Enhancement and Resulting Fracture Patterns

The water-enhancement process used to complete CBNG wells in the Powder River Basin hydraulically fractures the coal. Water is pumped into the coal seam at a rate of 2,500 gallons per minute for approximately 15 minutes, cleaning out the coal fines and inducing fractures that may create pathways for gas and water to flow to the wellbore. The orientation of these hydraulic fractures can be determined from the wells' completion records (Colmenares and Zoback, 2007). Colmenares and Zoback (2007) found that wells with horizontal fractures typically produce less gas than wells with vertical fractures. Some wells with vertical fractures are high water producers (more than 10,000 barrels/month); a large fraction of these produce no gas or have delays in gas production of about 12 months.

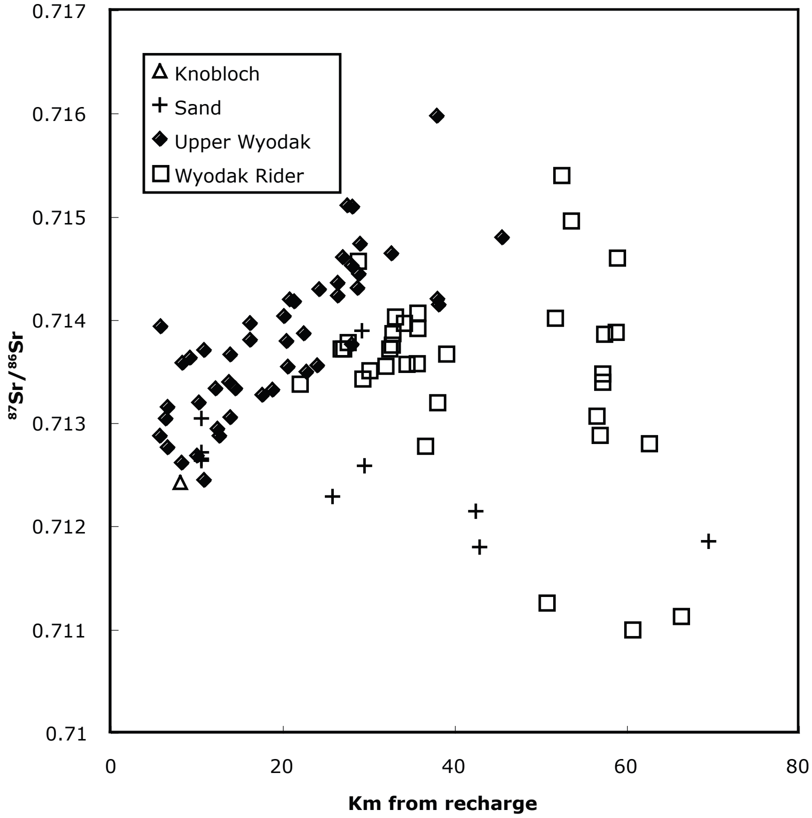

Figure 11. ^{87}Sr/^{86}Sr ratios as a function of distance from recharge area for water samples in Gillette and Schoonover areas. Note the regular increase in Sr-isotope ratio for samples from Upper Wyodak coal zone; this is suggested to reflect water–rock interaction along flow path in a well-confined aquifer. The Wyodak Rider samples depart from this trend, particularly in the Schoonover area, and may reflect incomplete isolation of this coal aquifer from deep sandstone aquifers containing less radiogenic (lower) ^{87}Sr/^{86}Sr ratios. Data from Table 1.

We have obtained water samples and Sr isotopic compositions for 50 of the wells for which Colmenares and Zoback (2007) identified fracture patterns to determine whether fracture pattern and/or water and gas production correlates with ^{87}Sr/^{86}Sr ratio. Of these, 47 are vertically fractured, and 3 are horizontally fractured. The vertically fractured wells were subdivided into two groups: those wells that are high water producers (more than 6,000 bbls/month or 1,000 cubic meters/month) and those that are low water producers. Overall, there appears to be little correlation among Sr isotopic composition, fracture pattern, or water/gas ratio. The average ^{87}Sr/^{86}Sr ratio is only slightly lower for water from vertically fractured, low water producers compared to vertically fractured high water producers (Fig. 14). However, in the southeastern corner of Johnson County, in the small, 10 km by 10 km Bullwhacker area (Fig. 2), where wells have been drilled into the Wyodak Rider coal zone, the different fracture patterns are associated with different ^{87}Sr/^{86}Sr ratios. In this area, the vertically fractured, high water producing wells have ^{87}Sr/^{86}Sr = 0.71055–0.71271; vertically fractured, low water producing wells have higher ^{87}Sr/^{86}Sr = 0.71200–0.71536; and the one horizontally fractured well has the highest ^{87}Sr/^{86}Sr = 0.71806.

The lack of a strong correlation between ^{87}Sr/^{86}Sr ratio and fracture pattern is not surprising. A correlation would not be expected unless the fractures produce hydraulic connections that allow water to be introduced into the coal seam from another, isotopically distinct aquifer. If the fractures do not propagate vertically into another aquifer because no sand horizons are within the thickness affected by fracturing (typically 30 meters or 100 feet), then no excess water production or perturbation of Sr isotopic ratio is expected. Moreover, even if another aquifer were intersected by the induced fractures, this aquifer must contain water with a different ^{87}Sr/^{86}Sr ratio in order to affect the Sr isotopic ratio of the CBNG produced water.

CONCLUSIONS

The Sr isotopic ratios of ground waters from coal in the Powder River Basin of Wyoming are influenced by a number of factors including the coal zone from which ground waters are withdrawn, ground water residence time in a particular aquifer, the degree to which coal aquifers are confined, and geographic location. These factors and their effects on Sr isotopic ratios are summarized below.

1. The Upper Wyodak coal zone aquifer in the Gillette and Schoonover areas appears to be composed of a combined sand- and coal-aquifer unit. The ground

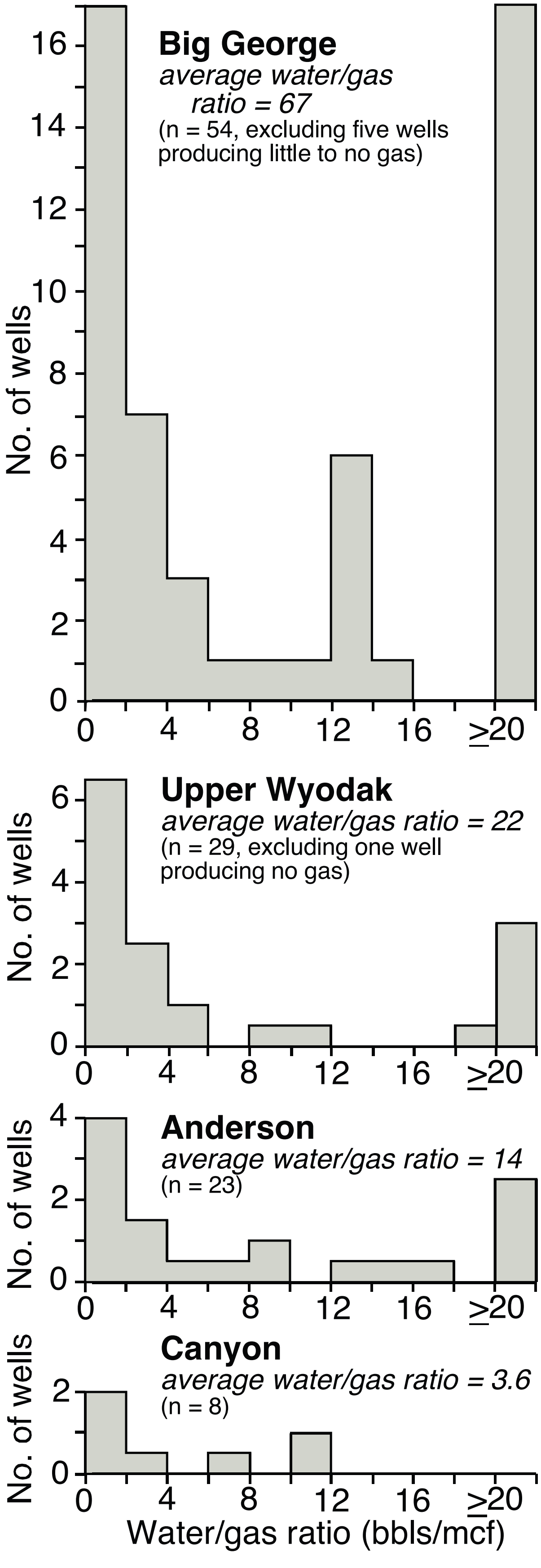

Figure 12. Histograms of water/gas production ratios (bbls/mcf) for wells completed in Big George, Upper Wyodak, Anderson, and Canyon coal seams. A greater proportion of wells completed in Big George coal seam have high water/gas ratios compared to wells in other coal seams. Data from Table 2.

water of the Upper Wyodak coal zone in these areas shows a trend of increasing distance from recharge resulting in more radiogenic ground water due to the continued dissolution of radiogenic Sr-bearing components of the coal. The TDS value of these wells also increases with increasing distance from recharge due to water–rock interactions along the flow path.

2. The Wyodak Rider coal zone aquifers in the Gillette and Schoonover regions are only partially confined, allowing interactions between sandstone and possibly other coal aquifers with the Wyodak Rider aquifer. This interaction results in a departure from the Upper Wyodak trend with the Wyodak Rider samples showing increased variability with increased distance from the recharge. Wells in the Schoonover area, where the ^{87}Sr/^{86}Sr and TDS variability are more pronounced, also produce, on average, more water than wells from the Gillette Wyodak Rider. Likewise, wells in the Schoonover area may not be completely confined.

3. The ^{87}Sr/^{86}Sr ratios of the coal-aquifer ground water from the Northeast area are more variable than in the Gillette area and may be influenced by the presence of faults. Produced water with low ^{87}Sr/^{86}Sr ratios may be influenced by faults apparently acting as conduits for water flow enabling mixing of water from different aquifers. Some samples from the Sheridan area also exhibit low Sr isotopic ratios, and faults in this area also may enhance recharge and flow rates. The low ^{87}Sr/^{86}Sr ratio produced water in the Northeast area is associated with higher gas production than the high ^{87}Sr/^{86}Sr ratio produced water, suggesting the possibility that the Sr isotopic ratio of water samples from newly drilled wells may help predict the future gas production from the well.

4. Depositional environment may play an important role in the Sr isotope ratio of ground water throughout the basin. Previous research has identified multiple sources in the surrounding Laramide uplifts for the sediments that compose the Fort Union and Wasatch Formations of the basin. These sources have highly variable ratios of ^{87}Sr/^{86}Sr, which may be imparted to the ground waters from each of these areas. In the western part of the basin, in vicinities of

Table 2. Water and gas production for wells analyzed in this study (continued on pages 170–171).

Sample Name	Coal Name	Coal Zone	Well Completion Date[1]	Water Production (Bblsmo)[1]	Gas Production (Mcf/mo)[1]	Water/Gas Ratio (Bbls/mcf)[2]	Hydraulic Fracture Pattern[3]
BD2BU	Anderson	Upper Wyodak	4/13/06	0	0		
N24U	Anderson	Upper Wyodak	10/3/00	31,301	176,287	0.2	
G34U	Anderson	Upper Wyodak	11/18/99	109,946	175,972	0.6	
N32U	Anderson	Upper Wyodak	8/13/99	159,266	245,232	0.6	
N5L	Anderson	Upper Wyodak	5/26/99	80,840	105,990	0.8	
N9U	Anderson	Upper Wyodak	6/12/03	271,517	304,034	0.9	
SH3U	Anderson	Upper Wyodak	12/4/99	145,994	112,883	1.3	
G19U	Anderson	Upper Wyodak	2/9/99	116,349	78,148	1.5	
N31W	Anderson	Wyodak Rider	1/17/01	89,064	46,341	1.9	
G31U	Anderson	Upper Wyodak	8/23/99	240,314	108,736	2.2	
G16U	Anderson	Upper Wyodak	12/16/98	178,509	73,549	2.4	
G32U	Anderson	Upper Wyodak	9/7/99	543,279	156,808	3.5	
G29U	Anderson	Upper Wyodak	5/11/99	308,452	67,223	4.6	
N12U	Anderson	Upper Wyodak	1/3/00	166,618	21,140	7.9	
G9U	Anderson	Upper Wyodak	5/31/98	968,824	121,805	8.0	
N11U	Anderson	Upper Wyodak	8/10/99	594,698	60,797	9.8	
N33U	Anderson	Upper Wyodak	8/25/00	122,656	9,321	13.2	
G7U	Anderson	Upper Wyodak	12/6/96	1,017,185	69,006	14.7	
N29W	Anderson Lower	Wyodak Rider	5/23/05	59,186	3,479	17.0	
N16L	Anderson	Lower Wyodak	3/21/00	11,058	462	23.9	
G8U	Anderson	Upper Wyodak	7/18/97	1,774,782	69,434	25.6	
G27W	Anderson	Wyodak Rider	6/1/99	186,907	5,645	33.1	
N28U	Anderson Lower	Upper Wyodak	6/3/05	70,009	1,861	37.6	
G26W	Anderson	Wyodak Rider	6/28/99	680,020	9,615	70.7	
BD3BU	Anderson	Upper Wyodak	3/30/06	3,789	0		
BD5BU	Anderson	Upper Wyodak	3/26/06	4,435	0		
BD8AU	Anderson	Upper Wyodak	3/20/06	0	0		
BW17W	Big George	Wyodak Rider	2/11/05	25,348	125,838	0.2	V-L
S9W	Big George	Wyodak Rider	9/26/03	247,186	1,212,450	0.2	V-L
S14W	Big George	Wyodak Rider	6/15/05	47,102	132,770	0.4	V-L
BW16W	Big George	Wyodak Rider	2/10/05	91,601	231,960	0.4	V-L
BW21W	Big George	Wyodak Rider	2/7/05	67,249	125,554	0.5	V-L
BW15W	Big George	Wyodak Rider	2/14/05	94,605	161,042	0.6	V-L
G65W	Big George	Wyodak Rider	11/30/99	175,859	173,191	1.0	
G53W	Big George	Wyodak Rider	8/3/01	179,334	170,797	1.0	V-L
G57W	Big George	Wyodak Rider	7/26/01	198,495	183,931	1.1	V-L
G51W	Big George	Wyodak Rider	7/10/01	205,444	159,121	1.3	V-L
G43W	Big George	Wyodak Rider	3/13/01	113,115	86,406	1.3	V-L
G55W	Big George	Wyodak Rider	4/30/01	198,331	142,405	1.4	V-L
G58W	Big George	Wyodak Rider	5/30/01	124,942	77,122	1.6	V-L
S6W	Big George	Wyodak Rider	3/17/99	78,057	46,399	1.7	
S5W	Big George	Wyodak Rider	12/5/03	64,803	37,848	1.7	V-L
G47W	Big George	Wyodak Rider	2/27/01	33,607	17,993	1.9	H-L
BW18W	Big George	Wyodak Rider	1/24/05	193,959	102,829	1.9	V-H
BW12W	Big George	Wyodak Rider	1/31/05	158,976	66,911	2.4	V-H
G56W	Big George	Wyodak Rider	6/11/01	169,790	71,022	2.4	V-L
G48W	Big George	Wyodak Rider	3/12/01	76,012	30,891	2.5	H-L
G52W	Big George	Wyodak Rider	5/22/01	157,409	56,594	2.8	V-L
S15W	Big George	Wyodak Rider	6/20/05	94,197	31,969	2.9	V-L
S13W	Big George	Wyodak Rider	8/16/05	27,966	8,351	3.3	V-L
G50W	Big George	Wyodak Rider	7/20/01	222,043	66,262	3.4	V-L
G60W	Big George	Wyodak Rider	5/14/01	209,259	52,521	4.0	V-L
BW4W	Big George	Wyodak Rider	1/18/05	226,831	53,860	4.2	V-H

Table 2. Water and gas production for wells analyzed in this study (continued).

Sample Name	Coal Name	Coal Zone	Well Completion Date[1]	Water Production (Bblsmo)[1]	Gas Production (Mcf/mo)[1]	Water/Gas Ratio (Bbls/mcf)[2]	Hydraulic Fracture Pattern[3]
G63W	Big George	Wyodak Rider	8/18/99	704,401	142,119	5.0	
S11W	Big George	Wyodak Rider	5/25/05	67,889	8,790	7.7	V-L
S3W	Big George	Wyodak Rider	8/24/00	699,414	72,258	9.7	V-H
G46U	Big George	Upper Wyodak	4/23/01	43,105	3,683	11.7	
BW11W	Big George	Wyodak Rider	7/15/05	249,760	17,769	14.1	V-H
S2W	Big George	Wyodak Rider	8/21/00	602,820	41,235	14.6	V-H
BW5W	Big George	Wyodak Rider	1/20/05	268,360	18,331	14.6	V-H
BW9W	Big George	Wyodak Rider	3/29/05	276,075	18,366	15.0	V-H
BW19W	Big George	Wyodak Rider	1/12/05	256,541	16,977	15.1	V-H
BW3W	Big George	Wyodak Rider	1/25/05	260,618	17,217	15.1	V-H
S4W	Big George	Wyodak Rider	10/4/00	469,688	29,216	16.1	
BW14W	Big George	Wyodak Rider	2/24/05	236,336	11,783	20.1	V-H
S10W	Big George	Wyodak Rider	3/16/05	449,245	20,420	22.0	V-H
BW7W	Big George	Wyodak Rider	4/6/05	163,870	7,265	22.6	V-H
BW22W	Big George	Wyodak Rider	8/10/05	226,108	7,971	28.4	
BW10W	Big George	Wyodak Rider	4/7/05	185,207	5,424	34.1	V-H
S12W	Big George	Wyodak Rider	7/5/05	25,847	700	36.9	V-L
BW20W	Big George	Wyodak Rider	1/18/05	179,012	3,843	46.6	V-H
BW1W	Big George	Wyodak Rider	1/12/05	310,776	4,208	73.9	V-H
S7W	Big George	Wyodak Rider	7/5/00	1,774,190	21,393	82.9	
BW13W	Big George	Wyodak Rider	2/21/05	197,063	1,178	167.3	V-H
G44U	Big George	Upper Wyodak	4/16/01	145,396	684	212.6	
BW6W	Big George	Wyodak Rider	4/26/05	220,471	633	348.3	H-H
G33W	Big George	Wyodak Rider	11/3/99	223,105	583	382.7	
BW2W	Big George	Wyodak Rider	2/7/05	170,360	407	418.6	V-H
BW8W	Big George	Wyodak Rider	4/5/05	189,931	266	714.0	V-H
G45U	Big George	Upper Wyodak	4/9/01	210,740	259	813.7	
G18U	Big George	Upper Wyodak	11/2/98	438,107	25	little gas	
G41W	Big George	Wyodak Rider	5/4/00	1,083,991	0	no gas	
G66W	Big George	Wyodak Rider	3/22/01	59,363	0	no gas	
S8W	Big George	Wyodak Rider	6/29/01	182,915	0	no gas	
B3F	Bull Creek	Felix	12/3/99	58,471	0	no gas	
B7LD	Bull Creek	Lake De Smit	12/7/00	2,405	15	160.3	
G59U	Canyon	Upper Wyodak	5/28/03	72,843	196,464	0.4	V-L
N6L	Canyon	Lower Wyodak	3/29/99	190,086	219,243	0.9	
N7U	Canyon	Upper Wyodak	6/21/99	138,656	125,610	1.1	
N25U	Canyon	Upper Wyodak	5/18/05	119,114	69,019	1.7	
N8L	Canyon	Lower Wyodak	5/20/03	349,685	129,604	2.7	
N23U	Canyon	Upper Wyodak	1/5/01	79,708	10,733	7.4	
G25U	Canyon	Upper Wyodak	5/11/99	141,868	12,562	11.3	
SH1U	Carney	Upper Wyodak	3/17/99	410,725	35,670	11.5	
BD1AL	Cook	Lower Wyodak	4/6/06	0	0		
BD1BL	Cook	Lower Wyodak	4/7/06	0	0		
BD4AL	Cook	Lower Wyodak	3/24/06	2,483	0		
BD4BL	Cook	Lower Wyodak	3/25/06	2,483	0		
BD7AL	Cook	Lower Wyodak	3/29/06	0	0		
BD7BL	Cook	Lower Wyodak	3/30/06	0	0		
BD10AL	Cook	Lower Wyodak	3/22/06	3,262	0		
BD10BL	Cook	Lower Wyodak	3/22/06	3,262	0		
N10L	Cook	Lower Wyodak	10/19/99	308,219	296,916	1.0	
N19L	Cook	Lower Wyodak	12/19/00	222,890	105,917	2.1	
N21L	Cook	Lower Wyodak	9/14/00	503,291	8,253	61.0	
N22U	Cook	Upper Wyodak	11/7/00	59,655	211,876	0.3	
N26K	Cook	Knobloch	5/23/05	243,665	339	718.8	
B4F	Felix	Felix	11/15/99	49,768	0	no gas	
G10U	Fort Union	Upper Wyodak	12/18/97	639,031	277,089	2.3	

Table 2. Water and gas production for wells analyzed in this study (continued).

Sample Name	Coal Name	Coal Zone	Well Completion Date[1]	Water Production (Bblsmo)[1]	Gas Production (Mcf/mo)[1]	Water/Gas Ratio (Bbls/mcf)[2]	Hydraulic Fracture Pattern[3]
G14U	Fort Union	Upper Wyodak	6/15/98	403,374	445,701	0.9	
N3L	Lower Canyon	Lower Wyodak	5/30/98	262,714	38,879	6.8	
SH2U	Monarch	Upper Wyodak	3/23/99	368,481	11,062	33.3	
SH4L	Monarch	Lower Wyodak	2/17/00	471,213	330,768	1.4	
N4L	Pawnee	Lower Wyodak	2/10/99	104,683	44,537	2.4	
G12K	Pawnee/Cache	Knobloch	8/9/99	225,683	0	no gas	
B1LD	Ucross	Lake De Smit	1/17/00	36,862	0	no gas	
B2LD	Ucross	Lake De Smit	9/7/99	108,971	129	844.7	
B6LD	Ucross	Lake De Smit	3/27/01	287	0	no gas	
N14U	Upper Canyon	Upper Wyodak	2/16/00	93,530	300,176	0.3	
N18U	Upper Canyon	Upper Wyodak	1/4/01	117,648	170,351	0.7	
B5F	Upper Felix	Felix	3/12/01	27,496	0	no gas	
BD6AL	Wall	Lower Wyodak	3/8/06	0	0		
BD9AL	Wall	Lower Wyodak	3/9/06	0	0		
N15L	Wall	Lower Wyodak	1/13/00	129,731	107,168	1.2	
N17L	Wall	Lower Wyodak	8/16/00	1,417,653	11,059	128.2	
N20L	Wall	Lower Wyodak	12/19/00	135,922	61,558	2.2	
N27L	Wall	Lower Wyodak	5/3/05	197,061	0	no gas	
N30K	Wall	Knobloch	7/19/00	355,376	0	no gas	
S1U	Wall	Upper Wyodak	9/21/89	322,501	333	968.5	
N13K	Wall/Pawnee	Knobloch	11/4/99	212,441	36,464	5.8	
G62U	Wyodak	Upper Wyodak	8/6/98	178,596	534,643	0.3	
G24U	Wyodak	Upper Wyodak	6/28/99	133,624	192,863	0.7	
G4U	Wyodak	Upper Wyodak	6/14/96	185,393	258,313	0.7	
G21U	Wyodak	Upper Wyodak	2/11/99	302,648	420,034	0.7	
G20U	Wyodak	Upper Wyodak	2/1/99	316,751	439,084	0.7	
G28W	Wyodak	Wyodak Rider	3/4/99	438,787	570,071	0.8	
G30U	Wyodak	Upper Wyodak	8/6/99	522,576	505,167	1.0	
G11U	Wyodak	Upper Wyodak	1/21/98	289,224	264,160	1.1	
G54U	Wyodak	Upper Wyodak	5/10/01	141,861	124,152	1.1	V-L
G23U	Wyodak	Upper Wyodak	1/29/99	424,118	276,469	1.5	
G2U	Wyodak	Upper Wyodak	4/11/95	401,219	249,271	1.6	
G17U	Wyodak	Upper Wyodak	11/2/98	1,269,443	780,749	1.6	
G37U	Wyodak	Upper Wyodak	4/12/00	177,898	100,597	1.8	V-L
G6U	Wyodak	Upper Wyodak	11/23/96	388,341	180,140	2.2	
G49U	Wyodak	Upper Wyodak	10/26/00	206,900	95,596	2.2	V-L
G3U	Wyodak	Upper Wyodak	4/5/96	477,164	211,107	2.3	
G39U	Wyodak	Upper Wyodak	7/18/00	217,490	68,309	3.2	V-L
G1U	Wyodak	Upper Wyodak	2/10/93	1,273,509	387,359	3.3	
G22U	Wyodak	Upper Wyodak	1/27/99	709,555	150,555	4.7	
G64U	Wyodak	Upper Wyodak	5/26/99	912,817	191,734	4.8	
G61U	Wyodak	Upper Wyodak	5/20/98	742,141	85,480	8.7	
G5U	Wyodak	Upper Wyodak	10/15/96	790,452	67,914	11.6	
G13U	Wyodak	Upper Wyodak	6/22/98	824,389	45,816	18.0	
G36U	Wyodak	Upper Wyodak	4/5/00	399,984	13,602	29.4	
N1U	Wyodak	Upper Wyodak	1/30/90	2,512,405	57,071	44.0	
G15U	Wyodak	Upper Wyodak	6/10/97	1,379,519	26,330	52.4	
G38U	Wyodak	Upper Wyodak	4/7/00	138,415	1,503	92.1	
G42U	Wyodak	Upper Wyodak	5/25/00	284,509	879	323.7	V-L
G35U	Wyodak	Upper Wyodak	9/15/00	154,770	6	little gas	
G40U	Wyodak	Upper Wyodak	4/27/00	154,251	0	no gas	V-L

[1] Production data from the Wyoming Oil and Gas Conservation Commission (2007).

[2] Water/gas ratios indicated only for wells more than 2 years old.

[3] Hydraulic fracture pattern as identified by Colmenares and Zoback (2007).

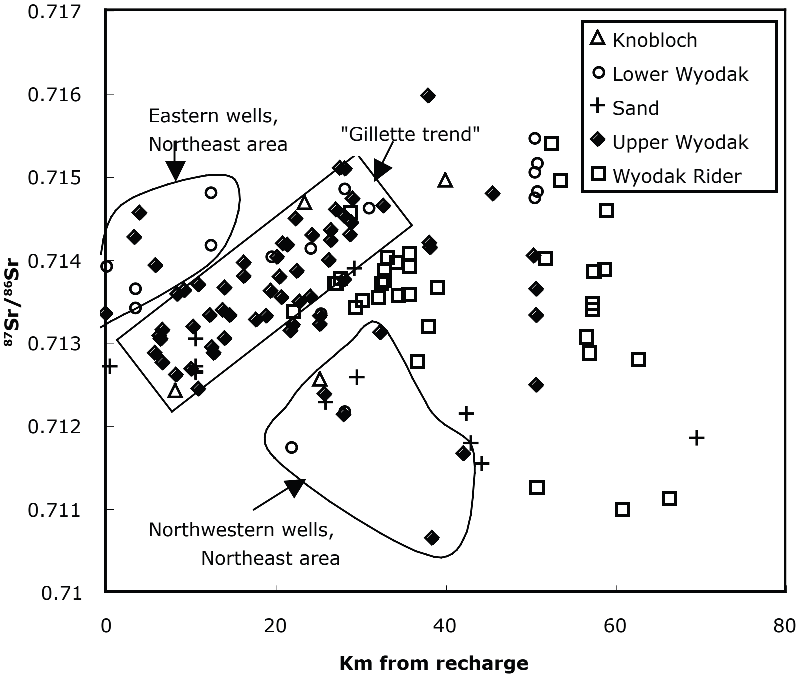

Figure 13. $^{87}Sr/^{86}Sr$ ratios as a function of distance from recharge area for water samples in northeast area. These data form two groups that correspond to distinct geographic areas; one plots above Gillette trend and the other below. The group of samples lying above Gillette Sr-isotopic trend have comparatively low TDS, whereas samples lying below Gillette trend have higher TDS and lower $^{87}Sr/^{86}Sr$ ratios. Coals yielding latter group of water samples may be affected by faults that act as conduits to ground-water flow. Data from Table 1.

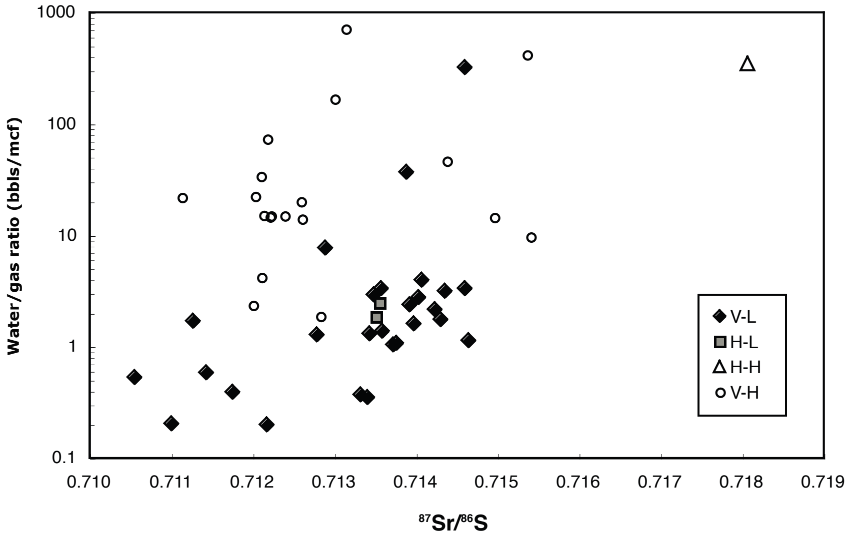

Figure 14. Water/gas production ratios for wells with known fracture patterns as a function of $^{87}Sr/^{86}Sr$ ratios. V-H = vertical high-water producing wells; V-L = vertically fractured low water-producing wells; H-L = horizontally fractured, low-water producing wells; and H-H = horizontally fractured, high water-producing wells. Data from Tables 1, 2, and Wyoming Oil and Gas Commission (2007).

Buffalo and Sheridan, CBNG produced waters tend to have lower $^{87}Sr/^{86}Sr$ ratios than those in the central and eastern margin of the basin, the Northeast, Schoonover, and Gillette areas. Temporal changes in depositional environment may explain the higher Sr isotopic ratios of water withdrawn from the Lake DeSmet coal zone compared to the underlying Felix coal zone in the vicinity of Buffalo. We also note that the water and gas production from the Eocene coals appears to be significantly lower than that of the Paleocene coals. That conclusion is based on a limited number of samples, however, and additional evaluation is warranted.

5. Evaluating the direction of fractures propagated during the water-enhancement process, coupled with the $^{87}Sr/^{86}Sr$ of the produced water, may be useful in evaluating wells with minimal gas production and high water production. Vertically fractured coal seams where sandstone is present within 30 meters (100 feet) above or below the coal are most likely to be in hydraulic communication with sandstone aquifers. However, water from two aquifers must have distinctive Sr isotope ratios in order for the direction of fracture propagation to be correlated with the Sr isotopic ratio of the produced water.

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REFERENCES CITED

Administrative Rule of Montana 17.30.1670. http://161.7.8.61/17/17-2757.htm (accessed December, 2007).

Ayers, W. B., Jr., 1986, Lacustrine and fluvial deltaic depositional systems, Fort Union Formation (Paleocene), Powder River Basin, Wyoming and Montana: American Association of Petroleum Geologists Bulletin, v. 70, p. 1651–1673.

Ayers, W. B., Jr., and Kaiser, W. R., 1984, Lacustrine–interdeltaic coal in the Fort Union Formation (Paleocene), Powder River Basin, Wyoming and Montana, *in* Rahmani, R. A., and Flores, R. M., eds., Sedimentology of coal and coal bearing sequences: International Association of Sedimentologists, Special Publication 7, p. 61–84.

Bank, G. C. and Kuuskraa, V. A., 2006, The economics of Powder River Basin coalbed methane development, Department of Energy: http://www.fossil.energy.gov/programs/oilgas/publications/coalbed_methane/06_prb_study.pdf (accessed December, 2007).

Bureau of Land Management—Wyoming: http://www.blm.gov/wy/st/en/programs/energy/Coal_Resources/PRB_Coal/production.html (accessed December, 2007).

Brinck, E., and Frost, C. D., 2007, Detecting infiltration and impacts of introduced water using strontium isotopes: Ground Water, v. 45, p. 554–569.

Brinck, E. L., Drever, J. I., and Frost, C. D., *in press*, The geochemical evolution of water co-produced with coal bed natural gas in the Powder River Basin, Wyoming: Environmental Geosciences.

Campbell, C. E., 2007, Strontium isotopes as tracers of water co-produced with coal bed natural gas in the Powder River Basin, Wyoming [M.S. thesis]: Laramie, University of Wyoming, 124 p.

Colmenares, L. B., and Zoback, M. D., 2007, Hydraulic fracturing and wellbore completion of coalbed methane wells in the Powder River Basin, Wyoming: Implications for water and gas production: American Association of Petroleum Geologists Bulletin, v. 91, p. 51–67.

Culbertson, W. C., and Mapel, W. J., 1976, Coal in the Wasatch Formation, northwest part of the Powder River Basin near Sheridan, Sheridan County, Wyoming, *in* Geology and Energy Resources of the Powder River, Wyoming Geological Association 28th Annual Field Conference Guidebook, p. 193–201.

Daddow, P. B., 1986, Potentiometric surface map of the Wyodak–Anderson coal bed, Powder River structural basin, Wyoming, 1973–1984: U.S. Geological Survey Water Resources Investigations Report 85-4305, scale 1:250,000, 1 sheet.

Davis, R. W., 1976, Hydrologic factors related to coal development in the eastern Powder River Basin, *in* Geology and energy resources of the Powder River: Wyoming Geological Association 28th Annual Field Conference Guidebook, p. 203–207.

DeBruin, R. H., and Lyman, R. M., 1999, Coalbed methane in Wyoming, *in* Miller, W. R. ed., Coalbed methane and the Tertiary geology of the Powder River Basin Wyoming and Montana: Wyoming Geological Association 50th Annual Field Conference Guidebook, p. 61–72.

Drever, J. I., 1997, The geochemistry of natural waters: Upper Saddle River, NJ, Prentice Hall, 436 p.

Dymond, J., Biscaye, P. E., and Rex, R. W., 1974, Eolian origin of mica in Hawaiian soils: Geological Society of America Bulletin, v. 85, 37–40.

Ellis, M. S., 1999, U.S. Geological Survey 1999 assessment of Wyodak–Anderson coal resources in the Powder River Basin, Wyoming and Montana, *in* Miller, W. R. ed., Coalbed methane and the Tertiary geology of the Powder River Basin Wyoming and Montana: Wyoming Geological Association 50th Annual Field Conference Guidebook, p. 43–60.

Energy Information Administration Annual Coal Report for 2006: http://www.eia.doe.gov/cneaf/coal/page/acr/acr_sum.html (accessed December, 2007).

Essington, M. E., 2004, Soil and water chemistry: An integrative approach: Boca Raton, Florida, CRC Press, 552 p.

Flores, R. M., 1986, Styles of coal deposition in Tertiary alluvial deposits, Powder River Basin, Montana and Wyoming, *in* Lyons, P. C., and Rice, C. L., eds., Paleoenvironmental and tectonic controls in coal-forming basins of the United States: Geological Society of America Special Paper 210, p. 79–104.

Flores, R. M., and Bader, L. R., 1999, Fort Union coal in the Powder River Basin, Wyoming and Montana: A synthesis: U.S. Geological Survey Professional Paper1625-A, Chapter PS, 75 p.

Flores, R. M., and Ethridge, F. G., 1985, Evolution of intermontane fluvial systems of Tertiary Powder River Basin, Montana and Wyoming, *in* Flores, R. M., and Kaplan, S. S., eds., Cenozoic paleogeography of west-central United States: Rocky Mountain Paleogeography Symposium 3, Denver, Colorado: The Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, p. 107–126.

Frost, C. D., and Brinck, E., 2005, Strontium isotopic tracing of the effects of coal bed natural gas (CBNG) development on shallow and deep groundwater systems in the Powder River Basin, Wyoming: Wyoming State Geological Survey Report of Investigations 55, p. 93–107.

Frost, C. D., Pearson, B. N., Ogle, K. M., Heffern, E. L., and Lyman, R. M., 2002, Sr isotopic tracing of aquifer interactions in an area of coal and methane production, Powder River Basin, Wyoming: Geology, v. 30, p. 923–926.

Frost, C. D., Viergets, J. E., Pearson, B. N., Heffern, E. L., Lyman, R. M., and Ogle, K. M., 2001, Sr isotopic identification of coal and sandstone aquifers and monitoring of aquifer interactions in an area of active coalbed-methane production, Powder River Basin, Wyoming, *in* Stilwell, D. P., ed., Wyoming gas resources and technology: Wyoming Geological Association 52nd Annual Field Conference Guidebook, p. 107–122.

Glass, G. B., 1976, Update on the Powder River coal basin, *in* Geology and energy resources of the Powder River: Wyoming Geological Association 28th Annual Field Conference Guidebook, p. 209–220.

Graustein, W. C., and Armstrong, R. L., 1983, The use of strontium-87/strontium-86 ratios to measure atmospheric transport into forested watersheds: Science, v. 219, p. 289–292.

Hinaman, K., 2005, Hydrogeologic framework and estimates of ground-water volumes in Tertiary and Upper Cretaceous hydrogeologic units in the Powder River Basin, Wyoming: U.S. Geological Survey Scientific Investigations Report 2005–5008, 18 p.

Kanizay, S. P., 1978, Preliminary geologic map of the Sheridan area, northwestern Powder River Basin, Wyoming: U.S. Geological Survey Miscellaneous Field Studies Map MF-1043, scale 1:50,000, 1 sheet.

Lee, R. W., 1981, Geochemistry of water in the Fort Union Formation of the northern Powder River Basin, southeastern Montana: U.S. Geological Survey Water-Supply Paper 2076, 17 p.

Love, J. D., and Christiansen, A. C., 1985, Geologic map of Wyoming: U.S. Geological Survey, State Geologic Map, scale 1:500,000, 3 sheets.

Lyman, R. M., and Hallberg, L. L., 2000, Wyoming coal mines and markets: Wyoming State Geological Survey Coal Report CR 00-1, 11 p.

McLellan, M. W., Biewick, L. R. H., Molnia, C. L., and Pierce, F. W., 1990, Cross sections showing the reconstructed stratigraphic framework of Paleocene rocks and coal beds in the northern and central Powder River Basin, Wyoming and Montana: U.S. Geological Survey Map I-1959-A, scale 1:500,000, 2 sheets.

McPherson, B. J. O. L., and Chapman, D. S., 1996, Thermal analysis of the southern Powder River Basin, Wyoming: Geophysical Research Letters, v. 61, p. 1689–1701.

Montgomery, S. L., 1999, Powder River Basin, Wyoming: An expanding coalbed methane (CBM) play: American Association of Petroleum Geologists Bulletin, v. 83, 1207–1222.

Morozov, I., 2002, County line CDP seismic survey, *in* Institute for Energy Research/Anadarko Coal Bed Methane Project Phase 1 (June 2001–February 2002) Final Report, 11 p.

Négrel, P., Allegre, C. J., Dupre, B., and Lewin, E., 1993, Erosion sources determined by inversion of major and trace element ratios and strontium isotopic ratios in river water: The Congo Basin case: Earth and Planetary Science Letters, v. 120, p. 59–76.

Pearson, B. N., 2002, Sr isotope ratio as a monitor of recharge and aquifer communication, Paleocene Fort Union Formation and Eocene Wasatch Formation, Powder River Basin, Wyoming and Montana [M.S. thesis]: Laramie, University of Wyoming, 151 p.

Rankl, J. G., and Lowry, M. E., 1985, Ground-water-flow systems in the Powder River structural basin, Wyoming and Montana: U.S. Geological Survey Water Resources Investigations Report 85-4229, 39 p.

Rice, C. A., Ellis, M. S., and Bullock, J. H., Jr., 2000, Water co-produced with coalbed methane in the Powder River Basin, Wyoming: Preliminary compositional data: U.S. Geological Survey Open-File Report 00-372, 18 p.

Seeland, D., 1992, Depositional systems of a synorogenic continental deposit: The upper Paleocene and lower Eocene Wasatch Formation of the Powder River Basin, northeast, Wyoming: U.S. Geological Survey Bulletin 1917-H, 20 p.

Surdam, R. C., Jiao, Z., Clarey, K., DeBruin, R. H., Bentley, R., Stafford, J., Deiss, A., Ewald, M., 2007, An evaluation of coalbed methane production trends in Wyoming's Powder River Basin: A tool for resource management: Wyoming State Geological Survey Challenges in Geologic Resource Development No. 3, 42 p.

Van Voast, W. A., and Hedges, R. B., 1975, Hydrogeologic aspects of existing and proposed strip coal mines near Decker, southeastern Montana: Montana Bureau of Mines and Geology Bulletin 97, 31 p.

Van Voast, W. A., Hedges, R. B., and McDermott, J. J., 1977, Hydrogeologic conditions and projections related to mining near Colstrip, southeastern Montana: Montana Bureau of Mines and Geology Bulletin 102, 43 p.

Wheaton, J., and Donato, T., 2004, Coalbed-methane basics: Powder River Basin, Montana: Montana Bureau of Mines and Geology Information Pamphlet 5, 25 p.

Whipkey, C. E., Cavaroc, V. V., and Flores, R. M., 1991, Uplift of the Bighorn [sic] Mountains, Wyoming and Montana—A sandstone provenance study: U.S. Geological Survey Bulletin 1917-D, 20 p.

Wyoming Oil and Gas Conservation Commission: http://www.wogcc.state.wy.us/ (accessed December, 2007).

Wyoming State Geological Survey Coal Section: http://www.wsgs.uwyo.edu/Coal/CBM_Info.aspx (accessed December, 2007)

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