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Western Resources Project Final Report—Produced Groundwater Associated with Coalbed Natural Gas Production in the Powder River Basin

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Editor

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CHAPTER 6

Geomechanics and the effectiveness of wellbore completion methods of coalbed natural gas (CBNG) wells in the Powder River Basin: Implications for water and gas production

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Abstract

The shallow depth and relatively low cost of coalbed natural gas (CBNG) wells in the Powder River Basin (PRB) have resulted in widespread use of open-hole/single horizon completion procedures. A common completion technique used by most operators in the PRB is to drill to the top of the coal seam, case and cement the wellbore, and then drill the coal section. After drilling, the coal section is under-reamed to enlarge the hole and to minimize the effects of any formation damage. In many cases, water is then pumped into the wellbore to "clean it out" and "enhance" production.

After analyzing pressure and flow rate data during these operations, it is clear that "water-enhancement" activities result in hydraulic fracturing of the coal. To determine whether vertical hydraulic fracture growth might extend into adjacent formations (and potentially result in both excess CBNG water production and inefficient depressurization of coals), water-enhancement test data from approximately 550 wells have been analyzed to obtain the magnitude of the least principal stress (S_3) in the coal seams. These data indicate that vertical fracture growth (S_3 corresponds to the minimum horizontal stress) does occur in many parts of the basin whereas the hydrofrac growth appears to be horizontal (S_3 corresponds to the overburden stress) in other areas. In addition, water production from wells with horizontal fractures is minimal and excessive water production is always associated to wells with vertical hydraulic fractures. In these wells with exceptionally high water production, the time at which gas production starts is significantly delayed relative to wells with vertical fractures and low water production, which are excellent gas producers. In general, wells with vertical fractures produced more gas than wells with horizontal fractures.

Wells with vertical fractures tend to be excellent gas producers, which implies that the face cleats in the coals must be efficiently connected by the induced vertical fracture. It has also been identified that horizontal hydraulic fracturing is typical toward the Sheridan area. This may be a significant finding, as water injection wells are perhaps needed in the near future in this region because the water has a high content of sodium and will need to be properly disposed. Thus, knowing that there is no vertical connection between the coal seam that is being produced and the sand layers where the water may be injected is particularly important for the operators of the area if water injection activities are undertaken here.

It appears that coal thickness affects the S_3 magnitudes. In general, in areas where a coal seam has a thickness greater than 60 feet S_3 is equivalent to the minimum horizontal stress, and therefore fractures propagate in the vertical direction. This implies that by identifying the areas where a coal seam is thicker than 60 feet, areas of vertical fracture propagation would also be identified. In order to minimize CBNG water production, recommendations for better well completion practices have been outlined here. In areas of known vertical fracture propagation it is necessary to limit the injection during the water enhancement tests in order to prevent propagation of induced fractures into the overlying water-bearing formations.

In areas where S_3 is unknown, a minifrac (approximately 2 bpm for about 2 min) should be done to determine the magnitude of S_3 and thus whether fracture propagation would be vertical or horizontal. If S_3 corresponds to the overburden, horizontal fracture propagation will occur and the water enhancement activities can proceed as usual. As many wells with horizontal fractures tend to be poor gas producers, it is also suggested that such wells are hydraulically fractured (and propped) to enhance gas production. If the shut-in pressure is significantly less than the overburden, vertical hydraulic fracture growth is implied and significantly reduced pumping is advised. This would be beneficial from the perspective of minimizing produced waters and decreasing the time for initial gas production.

Introduction

Most coalbed natural gas in the U.S. has been produced from the San Juan Basin of New Mexico and Black Warrior Basin of Alabama. In recent years, the Powder River Basin (PRB) has gained in importance as production and number of producing wells has increased tremendously.

The PRB of Wyoming and Montana is the site of the fastest growing domestic natural gas play, mostly from the development of coalbed natural gas (CBNG) from the Wyodak and Big George coal beds of the Fort Union Formation. Nearly 4 billion cubic feet (BCF) per day of CBNG are currently being produced in the U.S., with about 20% or 800 million cubic feet (MMCF) per day of it coming from the PRB. Within the next 10 years, as much as 75% of the growth in CBNG production in the U.S. is expected to occur in this region. Since 1996, the amount of producing wells has increased from around 30 to approximately 12,000 in the basin and it is anticipated that in the next decade the amount of producing wells will increase to between 20,000 and 50,000. Along with the growth in CBNG production has been the growth in produced water, as part of dewatering and depressurizing the coal formations, which enables the coals to release their adsorbed methane. CBNG water production has increased since 1996 from about 100 thousand barrels (MBBL) per day to 1.6 million barrels per day in 2003 (Wyoming Oil and Gas Conservation Commission, 2004). Coalbed natural gas wells in the PRB are generally pumped constantly, removing as much as 400 barrels per day per well (De Bruin and others, 2000). The production history of a typical CBNG well in the basin shows that even after gas production is initiated, large volumes of water are still being produced. Production from water-bearing coal seams can yield significant volumes of water, enough to make it difficult or infeasible to dewater the formation sufficiently to initiate CBNG flow (U.S. Environmental Protection Agency, 2002). Even though the water is generally of potable quality in the center of the basin, it becomes more saline toward the north and south. Therefore, the disposal of such great amounts of water produced by CBNG wells is a major environmental issue, especially in areas where the produced water has a high content of sodium.

At the moment production is concentrated along two main bands in the basin (**Figure 1**). Development toward the Sheridan area has started but it is not as developed as in Campbell and Johnson counties of Wyoming. Coalbed natural gas production has migrated toward the western part of the basin, compared to its initial times (1980s to early 1990s) when production was concentrated in Campbell County. Since about 12,500 wells have been drilled to date, with 50,000 wells total expected in the next decade, water disposal constitutes a major environmental challenge. At the present, 150 barrels of water are produced per well per day, with 50,000 wells in the basin, water production will rise to 7.5 million barrels per day. The goal of this study is to evaluate wellbore completion practices to determine if there are ways to produce less CBNG water and still achieve adequate coal depressurization for CBNG production. Minimizing water production would have appreciable beneficial consequences.

Geologic background

The PRB is bounded to the east by the Black Hills uplift, to the west by the Bighorn uplift and Casper arch, to the south by the Laramie and Hartville uplifts, and the Miles City arch and the Cedar Creek Anticline separate it from the Williston Basin to the north (**Figure 1**). The long axis of the basin is generally aligned NW-SE, and is 18,000 feet deep. Sediments range from Paleozoic at the bottom through Mesozoic to Tertiary at the top of the basin. The basin is a large asymmetrical syncline with its axis near the west side of the basin.

Several periods of deposition by marine and fluvial-deltaic processes have occurred within the basin during the Cretaceous and Tertiary periods. These Cretaceous and lower Tertiary rocks have a total thickness of up to 15,000 feet (Montgomery, 1999). Coal is found in the Paleocene Fort Union and Eocene Wasatch formations. Most of the coal beds in the Wasatch Formation are continuous and thin (6 feet or less) although, locally, thicker deposits have been found (De Bruin and others, 2000). The Fort Union Formation (Paleocene) extends over 22,000 square miles in the PRB. It is overlain by the Wasatch Formation (Eocene) and underlain by the Lance Formation (Upper Cretaceous) in the central part of the basin, and is more than 5200 feet thick along the basin axis.

In ascending stratigraphic order, the Fort Union Formation is divided into the Tullock, Lebo, and Tongue River Members. The Tullock Member is 740 feet thick, the Lebo Member 2600 feet thick, and the Tongue River Member 1860 feet thick. The Fort Union Formation outcrops on the eastern side of the basin, east of Gillette, and on the western side of the basin, north and south of Buffalo. Most of the coal beds in this formation are part of the upper Tongue River Member, which is typically 1500 to 1800 feet thick, and up to a composite total of 350 feet of coal can be found in various beds. The thickest of the individual coal beds is over 200 feet (Flores and Bader, 1999). Coal beds are interspersed with sandstone, conglomerate, siltstone, mudstone, and limestone.

Most CBNG wells in the Powder River Basin are in the Tongue River Member of the Fort Union Formation, in the Wyodak-Anderson coal zone, which contains up to 32 different coal beds according to some authors (Ayers, 1986), including the Big George in the central part of the basin (Flores and Bader, 1999). Most of the coal beds are found within 2500 feet of the ground surface. The Wyodak coal bed gets progressively deeper and thicker toward the west. The thickness of the Wyodak coal bed ranges from 42 to 184 feet. Most of the CBNG wells in the PRB are within the Wyodak coal zone near Gillette. The Big George coal bed is located in the central and western part of the PRB. Although the Big George is stratigraphically higher than the Wyodak, owing to the structure of the basin, the Big George, in the center part of the basin, is deeper than the Wyodak at the eastern margin of the basin.

The stratigraphic correlation of coal beds composing the Wyodak-Anderson coal zone is complex. Part of the problem originated from the use of the same names by various investigators for coal beds that are not stratigraphically correlative within the PRB. In addition, many local names were applied to coal beds in isolated areas, beds that were later physically correlated across the basin. Compounding these problems, no biostratigraphic studies were conducted to confirm or refute these physical correlations basin-wide. One solution to these stratigraphic correlation problems was

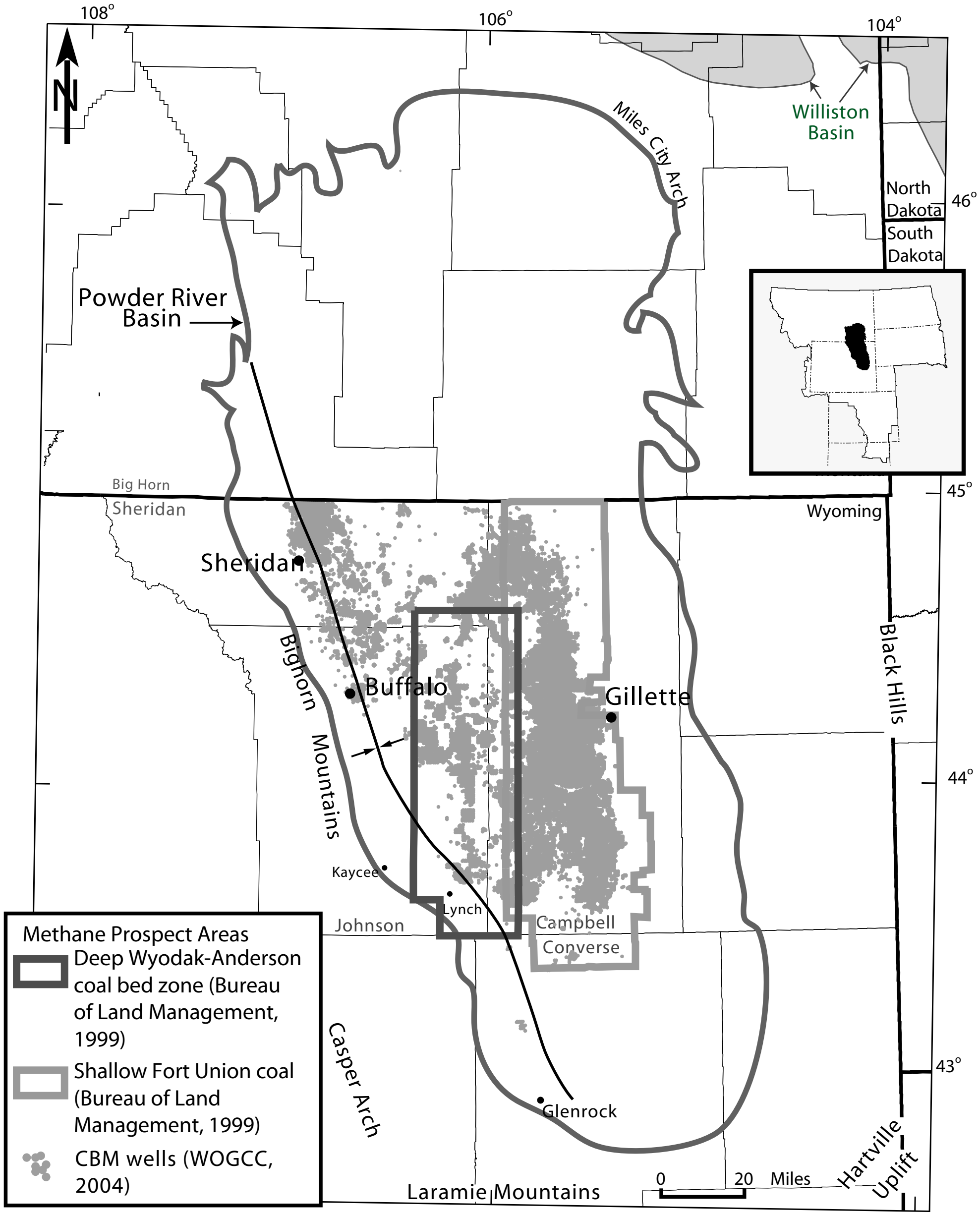

Figure 1. Location of the PRB showing counties, cities, CBNG wells and methane prospect areas (modified from Flores and Bader, 1999).

to lump all the coal beds and associated rocks into a single coal zone. This coal zone was named the Wyodak-Anderson coal zone by Averitt (1975) and was correlated basin-wide by Glass (1980). It has also been called the Wyodak coal, or the Anderson and Canyon coal beds coalesced (Flores and Bader, 1999).

The complexity of correlation is displayed by splitting and merging of the Wyodak-Anderson coal zone according to Flores and Bader (1999). Splitting of coal beds in the Wyodak-Anderson coal zone generates two beds (the lower Wyodak bed comprising the merged Canyon and Werner coals, and the upper Wyodak bed comprising the merged Smith, Swartz, and Anderson coal), three beds (Anderson or Dietz 1, Dietz 2, and Dietz 3), five beds (lower and upper Anderson and lower, middle, and upper Canyon beds), six beds (Smith, Swartz, Anderson, upper and lower Canyon, and Werner beds), or as many as eleven beds (Sussex beds). Overall, successive splitting and merging of beds in this coal zone basin-wide from overlapped, offset, zigzag, and shingled segments, results in older Wyodak-Anderson coal beds (for example, the Big George coal) in the west-central part of the basin than on the basin margins (for example, Smith, Anderson, Dietz, Canyon, School, and Badger coal) (Flores and Bader, 1999).

Most of the coal in the PRB is subbituminous in rank, which is indicative of a low maturity level. Some lignite, lower in rank, has also been identified. The thermal content of the coals found in the Powder River Basin is typically 8300 Btus per pound (U.S. Environmental Protection Agency, 2002). Coal in the PRB was formed at relatively shallow depths, at relatively low temperatures. Most of the methane generated under these conditions is biogenic, which means that it was formed by bacterial decomposition of organic matter. The coals from the Wasatch and Fort Union formations tend to be less thermally mature than the Tertiary coal beds located in the deeper parts of the Wind River, Bighorn, Hanna, and Green River coal fields of Wyoming (De Bruin and Lyman, 1999). Consequently, coal in the PRB contains less methane per unit volume than many other coal deposits in other parts of the country. The gas is typically more than 95% methane, the remainder being mostly nitrogen and carbon dioxide. This resource was overlooked for many years because it was thought to be too shallow for the production of significant amounts of methane. However, the relatively low gas contents of PRB coal is compensated by the thickness of the coal deposits. Because of the thickness of the deposits and their accessibility, commercial development of CBNG has been found to be economical. In the PRB, two different CBNG sources are commonly developed: (1) gas extraction from methane-charged dry sand layers overlying or interbedded with the coals, and (2) conventional methane extraction from the water saturated coal seams (U.S. Environmental Protection Agency, 2002).

Note about Big George Coal

The Big George coal, as defined and interpreted by Flores and Bader (1999), is the amalgamation of different coals, and is between 45 and 200 feet thick. The Big George, as so defined, exists only in the central part of the basin, that is, it directly indicates the location. According to what the operators of the basin have called Big George, this coal seam ranges from 5 feet to 200 feet in thickness, which does not coincide with the interpretation of Flores and Bader (1999). However, the interpretation of the operators and what they report to the Wyoming Oil and Gas Conservation Commission (WOGCC) has been adopted because making the reconciliation between the operators' interpretation and the interpretation of the U.S. Geological Survey is an extremely daunting, if not impossible, task and beyond the scope of this study.

It is very important to mention that the identification of coal seams in this study has been taken from what the operators report to the WOGCC website. Therefore, certain names may not coincide with Flores and Bader's (1999) interpretation of coals in the basin. However, a complete basin-wide reconciliation between all the different names for a certain coal bed does not exist yet so the WOGCC interpretation was chosen as a guide. Currently, efforts are taking place to reconcile the coal nomenclature (Jones, 2005), but, until these reconciliations are completed, some ambiguity remains regarding coal beds classified as Big George by different sources. In an attempt to reduce some of the uncertainty, Gamma Ray (GR) logs were analyzed, where available, to establish correlations across wells of the Big George and the Wyodak coals since they are thick and have a distinct GR response. Based on this analysis, we feel confident that the operators' definition and interpretation of these coal beds is consistent (see the section on Relationship between hydraulic fracture orientation and water and gas production for a more detailed description of the GR analysis). This GR-based distinction of coal beds is harder, if not impossible, for the thinner coals. Nevertheless, the possible confusion in definition of these coal beds should be kept in mind for future analyses.

Drilling and completion overview

The following is a standard drilling and completion procedure followed by the operators (**Figure 2**) in the PRB when under-reaming the coal seam.

The well is spudded with a 14 3/4" surface bit and drilled to 10% of the total well depth or a minimum of 95 feet (29 m). Then, a surface casing (10 3/4") is put in place and cemented. After cementing the surface casing, operators drill the next section down to the top of the coal. This section is drilled with water as a drilling fluid; sometimes gel is added to make the water more viscous, which improves the cleaning capacity of the drilling fluid. As a result, more debris can be transported out of the well. A 7-inch production casing is then put in place and cemented. The operators pay special attention to achieve a good high-quality cement job for this casing shoe, in order to prevent the CBNG from escaping the well, and also to prevent communication with overlying aquifers. Because of this, a cement bond log is run to ensure the quality of the cement job.

Initially, the coal section and an extra 10 feet (3 m) below the coal are drilled with a 6 1/4-inch bit. The drill fluid used is identical to the previous section (water with gel). After finishing the 6 1/4-inch hole through the coal, a GR log is run in order to accurately locate the extent of the coal seam. After logging, the diameter of the coal section is enlarged with an under-reamer to a final diameter of 14 inches. When there is more than one economical coal seam, operators under-ream the bottom coal bed and perforate the upper ones. Afterwards, the coal is water-enhanced. This procedure implies the pumping of 2500 gpm or 60

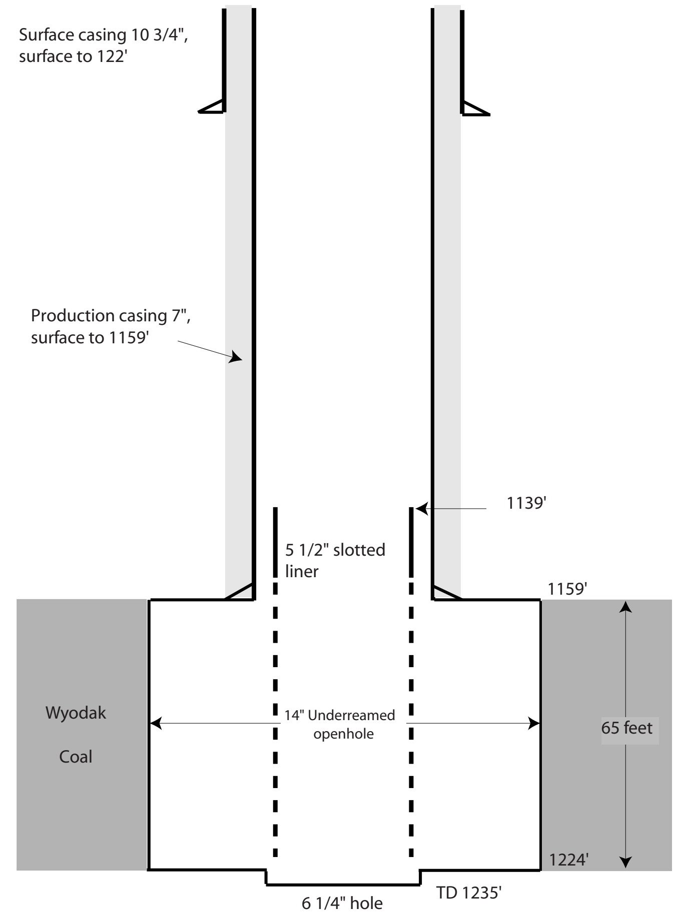

Figure 2. Standard completion method in the CBNG wells in the Powder River Basin using under-reaming. Some operators prefer not to use the slotted liner.

bpm of water into the coal for approximately 15 minutes. It is possible that during this process the coal is hydraulically fractured. Some operators use a 5 1/2-inch slotted liner in the open hole section of the well, as shown in **Figure 2**. This slotted liner is used to prevent debris migrating up the hole and blocking the flow. To finalize the completion of the well, a submersible water pump and the wellhead are installed. The tubing, with a submersible electric water pump, is inserted to allow the water to flow from the bottom of the hole. CBNG exits the well through the annulus formed by the casing and the tubing. The well is capped to control the flow of methane gas. Wells are often dewatered for several months before producing significant quantities of methane gas.

Hydraulic fracturing

During the early years of CBNG development in the PRB (1980s to early 1990s), gas exploration and development companies completed wells with and without hydraulic fracture techniques. Early wells were completed without fracturing treatments, particularly wells targeting gas reserves in coals interspersed between sandstone layers. However, the Quarterly Review (U.S. Environmental Protection Agency, 2002) reported that in one well, Rawhide 15-17, located north of Gillette, Wyoming, an "open frac" hydraulic fracturing was performed using 13,000 lbs of 12/20-mesh sand in 3500 gallons of gelled water. Several wells installed in the early 1990s by Betop, Inc. were fractured using 4000 to 15,000 gallons of a solution with 2% potassium chloride (KCl) in water. Sand was used to prop the fractures open in five of these wells (U.S. Environmental Protection Agency, 2002). However, hydraulic fracturing experienced little success in this basin. It was argued that fractured wells produced poorly because the permeable, shallow sub-bituminous coals collapsed under the pressure of the overburden after they were dewatered.

The PRB contains coals of high permeability. Consequently, drilling fluid (typically water) is lost when drilling the coal beds. Many times drilling mud is used to prevent loss of circulation. Because of this high permeability, most coal bed wells in the Fort Union Formation can be drilled and completed without the use of hydraulic fracturing. In the past, water or sand/water mixtures have been used to fracture the coal (U.S. Environmental Protection Agency, 2002).

The operators in the PRB routinely perform a procedure called "water-enhancement" and it is intended to create pathways in the coal for easier flow of water and gas into the well. This procedure results in the fracturing of the coal. In **Figure 3a** a water-enhancement test plot from the PRB is shown. The upper and lower panels show the flow rate in gallons per minute (gpm) and barrels per min (bpm) respectively. The middle panel shows the pressure-time history while the water was being pumped into the well. When a fracture is produced during the water-enhancement procedure, the pressure-time history from the water-enhancement test (middle panel in **Figure 3a**) is similar to the pressure-time history of an extended Leak-off Test (**Figure 3b**). The water-enhancement test data show that large volumes of water are pumped into the coal while the pressure remains constant. This indicates the formation of a hydraulic fracture and its propagation. The extent of a hydraulic fracture is controlled by the pumping pressure and the variation of the least principal stress with depth. We have also confirmed that such "enhancement" activities result in hydraulic fracturing of the coal through direct interviews with the different operators in the PRB.

Even though hydraulically fracturing the coal might be intended to render good results for CBNG production, if such a fracture is vertical and extends up into adjacent strata through a confining unit, it could result in both excess CBNG water production, as migration of groundwater

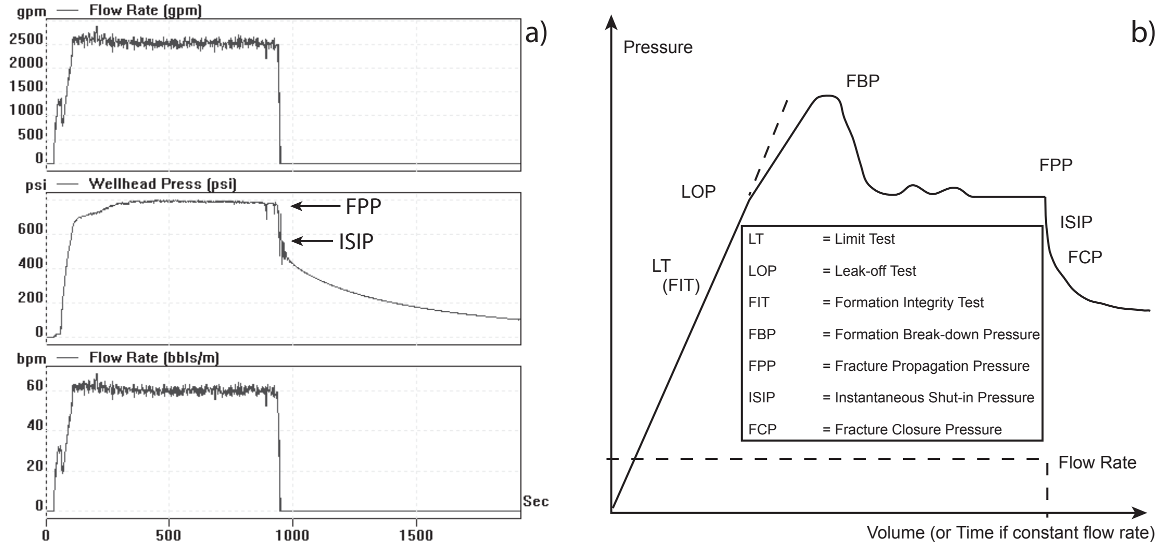

Figure 3. (a) Water-enhancement test from a CBNG well in the PRB. (b) Schematic illustration of an extended Leak-off Test (after Zoback and others, 2003).

toward the producing well occurs, and inefficient depressurization of coals. Avoiding this can result in great benefits for the operators and the environment.

To determine the direction of propagation of a hydraulic fracture it is necessary to know the magnitude of the least principal stress (S_3) since a hydraulic fracture will always propagate perpendicular to the orientation of S_3 (**Figure 4**). Therefore, if S_3 corresponds to the minimum horizontal stress, this indicates that the hydraulic fracture propagates in a vertical plane and if S_3 corresponds to the overburden stress, this indicates that the hydraulic fracture will propagate in the horizontal plane. Even though the water enhancement tests in the PRB are not made with the intention of determining the magnitude of S_3, they are a useful resource since it is possible to determine such magnitude from these tests.

It has been suggested that after a relatively short period of production (several months), an appreciable amount of the water produced from CBNG wells may come from the formations adjacent to the coal seams (personal communication with several operators, 2002 through 2003). It seems that one factor possibly exacerbating this is the vertical growth of hydraulic fractures during the drilling and completion of CBNG wells. We will test this by analyzing the relationship between hydraulic fracture orientation and water and gas production.

Least principal stress

Data analysis per area

As mentioned earlier, the magnitude of the least principal stress can be obtained from the water-enhancement tests. Figure 3a shows that at the surface the Fracture Propagation Pressure (FPP) is 750 psi and the Instant Shut-in Pressure (ISIP) is 600 psi. To determine the magnitude of the least principal stress at the depth of this test, it is neces-

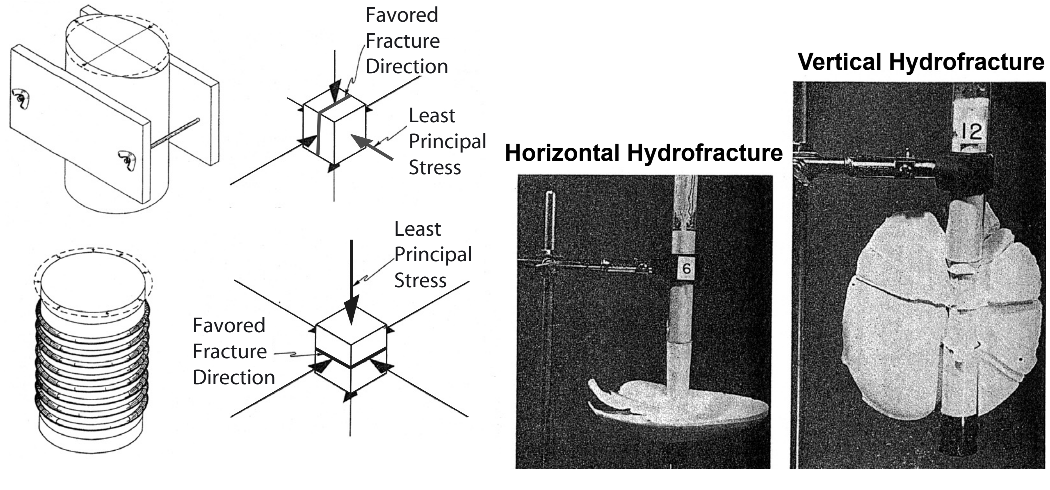

Figure 4. Hydraulic fractures always propagate perpendicular to the orientation of the least principal stress.

sary to add the pressure in the wellbore due to the column of wellbore fluid.

To date, we have analyzed water-enhancement tests from 550 wells, and obtained the magnitude of the least principal stress (S_3) for 372 of these wells. The well locations are shown in **Figure 5**. **Figures 6** to **8** show the analyzed data, which have been grouped by location (areas A, B, B1, B2, C, and D shown in **Figure 5**). The colors represent the producer coal interval in the respective wells, the black line is the overburden stress or S_v, and the gray line corresponds to the hydrostatic pressure or P_{hyd} (0.44 psi/ft).

The magnitude of S_v can be calculated by integration of rock densities from the surface to the depth of interest, z, that is

$$S_v = \int \rho(z) g dz \approx \bar{\rho} gz$$

where $\rho(z)$ is the density as a function of depth, g is the gravitational acceleration constant and $\bar{\rho}$ is mean overburden density. Since density logs were not available, a mean overburden density was assumed equal to 2.3 g/cc, which reflects the different lithologies that can be found above the coal (i.e. mudstones, shales, sandstones).

It is important to note that in some of the figures that follow, the ISIP's fall above the line denoting the overburden stress, which indicates that the magnitude of S_3 is greater than the magnitude of the overburden. Possible causes are the shallow depth of the measurements or the large volumes of water used in the water-enhancement test. At shallow depths the overburden might not be one of the principal stresses and therefore the ISIP's could be larger than the overburden. With respect to the other possible cause, since water enhancement tests are not originally intended to determine the magnitude of S_3, the large flow rate used in the tests could create friction effects that might disguise the actual magnitude of S_3. To reduce the uncertainty in determining the magnitude of S_3, water-enhancement tests made at lower flow rates (1 to 4 bpm instead of 60 bpm) would be more suitable for the determination of the least principal stress.

Area A

All the data from the 12 wells in Area A (**Figure 5**) come from the Roland coal, which is at a depth between 600 and 800 feet (**Figure 6a**). The magnitude of the least principal stress is approximately equal to the overburden. Therefore, since the overburden corresponds to the least principal stress, the hydraulic fractures produced in this area propagate in a horizontal plane. This may be a significant finding, as water injection wells are perhaps needed in the near future in this region because the water has a high sodium content and will need to be properly disposed. Thus, knowing that there is no vertical connection between the coal seam that is being produced and the sand layers where the water may be injected is particularly important for area operators if water injection activities are undertaken here.

Area B

The data in Area B (**Figure 5**) are from 50 wells that are producing from either the Anderson, Cook, Canyon, Smith, Stray, or Wall coals (**Figure 6b**). Down to a depth of 850 feet (Anderson, Cook, Canyon, Smith, and Stray coals), the magnitude of the least principal stress appears to correspond to the overburden, which indicates horizontal propagation of the hydraulic fractures. This implies that the coals just mentioned are not connected to adjacent formations, an important aspect to know if injection is needed in this area. In the Wall coal, between 850 and 1200 feet, the magnitude of the least principal stress is generally below the overburden. Therefore, for the Wall coal, most hydraulic fractures would appear to propagate in the vertical direction.

Areas B1, B2, and C (not shown)

Area B1 (**Figure 5**) is just to the west of Area B and all nine wells are in the Anderson coal. Water enhancement tests from these wells indicate that the least principal stress is clearly the minimum horizontal stress as it is well below the vertical stress. Therefore, the fractures propagate vertically. It is important to note that for these wells the Anderson coal is about 200 feet deeper than in Area B.

West of area B1, stress data from the Anderson coal in Area B2 (**Figure 5**) show that the least principal stress can either be the overburden (five wells) or the minimum horizontal stress (13 wells). This indicates that both types of hydraulic fractures are produced in this area. At this location, the Anderson coal spans from a depth of 500 to 1000 feet deep.

South of Area B, the magnitude of the least principal stress from 13 wells in the Anderson and Canyon coals in Area C (**Figure 5**) corresponds to the minimum horizontal stress. Thus, vertical hydraulic fracturing is expected in this region. In Area C the Anderson coal spans between 600 and 1000 feet, similar to Area B2.

Area D

In Area D (**Figure 5**) the data come from 61 wells in the Big George and Wyodak coals. For the Big George coal, all the wells located in T47N, R75W and most of the wells in T46N, R74W (**Figure 7a**) have water enhancement tests that indicate that the least principal stress corresponds to the minimum horizontal stress, i.e. the fractures would be expected to propagate vertically (**Figure 7b**). All the wells

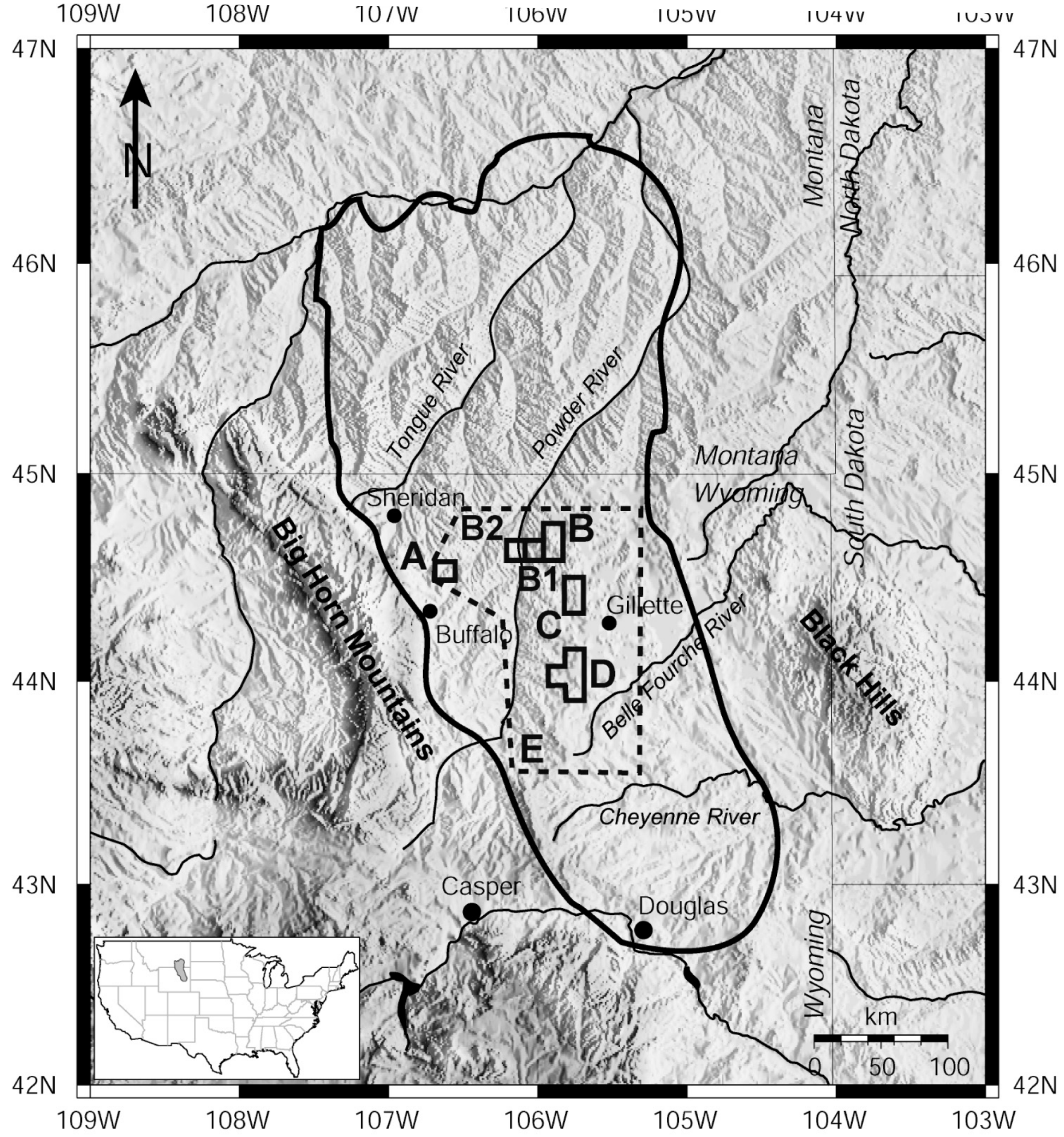

Figure 5. Water-enhancement test data from 550 wells were obtained from the locations delineated by thick lines. The letters identify the grouping of the fields in the areas we analyzed. The data from Figures 6 to 8 all come from areas A to D. The dashed line encompasses the total area (E), from where all the data were obtained.

located in T47N R74W and some of the wells located in T46N R74W (**Figure 7a**) show that the magnitude of the least principal stress corresponds to the overburden, i.e. the fractures propagate horizontally (**Figure 7c**). For the Wyodak coal a geographic differentiation is also seen. As can be observed in **Figure 8a**, in the wells located in sections 1, 2, 11, 12, 13, 14, 23, 24, 26 and 36 of T48N R74W (**Figure 8b**), the fractures propagate vertically. In sections 15 and 21, of the same township (**Figure 8b**), the fractures are expected to propagate horizontally (**Figure 8c**).

Variation of the least principal stress (S_3) across the basin

As mentioned earlier, the magnitude of the least principal stress has been determined from water-enhancement tests for wells targeting different coal seams in the basin. Maps of the occurrence of vertical and/or horizontal fractures in the central part of the basin have been made for each coal. However, water-enhancement test data have come only from about 550 wells, representing 4% of the total amount of wells in the PRB. Therefore, more data are needed to make the maps more complete.

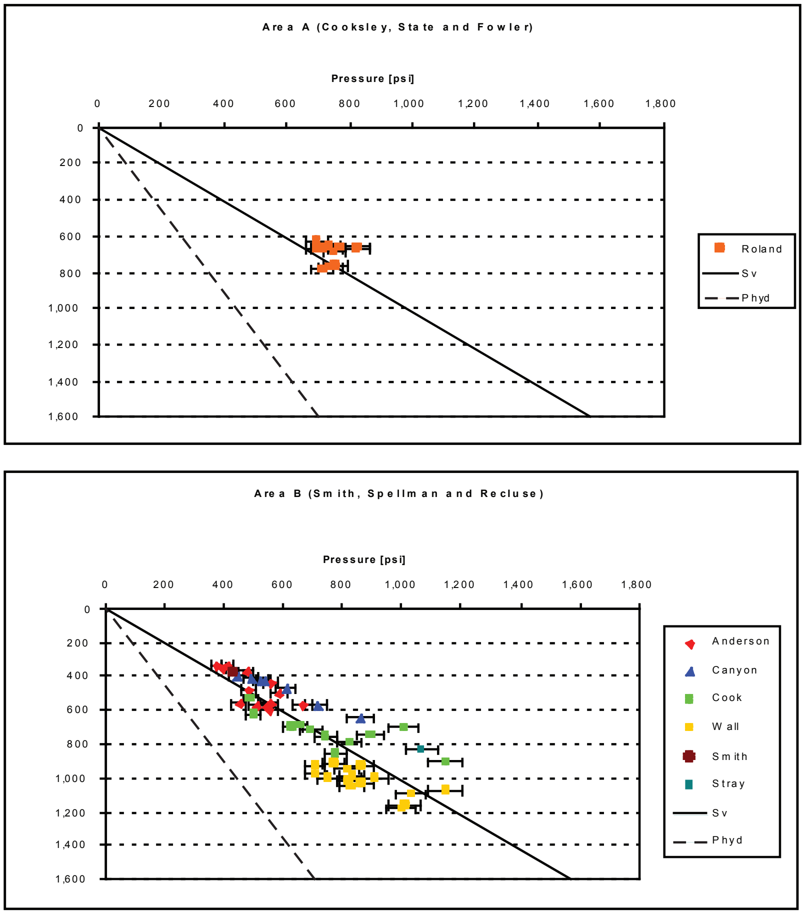

Figure 6. Magnitude of S_3 in the Powder River Basin versus depth for Area A and Area B. The data has been plotted per geographic location and the color denotes the coal seam where the test was performed. The location of areas A and B can be seen in Figure 5.

In **Figures 9** and **10**, the blue color represents areas where the fractures are horizontal, that is $S_3 = S_V$ ($S_3/S_V = 1$). The red shades represent areas where the fractures are vertical, that is $S_3 = S_{hmin}$, ($S_3/S_V < 1$). These maps were made using the interpolation tool from GMT (the Generic Mapping Tool; Wessel and Smith, 1995). The areas that do not have any points are areas where there is no control over the interpolation and should be interpreted carefully, hence, the question marks. The interpolation for each coal was made with the numbers of points outlined in **Table 1**. Many of the wells (data points) are situated very close to each other, so the symbols for some wells overlap or plot on top of each other.

In **Figures 9** and **10** it can be seen that vertical and horizontal fractures occur in many areas of the basin. However, it seems that north of Gillette and Buffalo, horizontal fracturing is more common than vertical fracturing. It appears that for places where the coal is thinner, there is more possibility of horizontal fracturing. For instance, in Big George (**Figure 9**) and Wyodak (**Figure 10**), which are thick coals, areas with vertical fractures are more common than areas with horizontal fractures. Conversely, for Anderson, Canyon, Cook, Werner, and Wall (the last three not shown in here), which are thinner coals, areas with horizontal fractures seem to be more common.

The reliability of the maps could be improved if more least-principal stress data are acquired and also if a consensus on the naming of coals could be reached to ensure a consistent classification.

These maps are potentially very useful for future developments in the basin. The operators could use the maps as tools to easily identify areas where potential fractures could propagate in the vertical or horizontal plane. If the operators know in advance that they would cause vertical fracture growth with their enhancement techniques, they could then limit the amount of water they use in the tests to hopefully limit the extent of vertical fracture propagation.

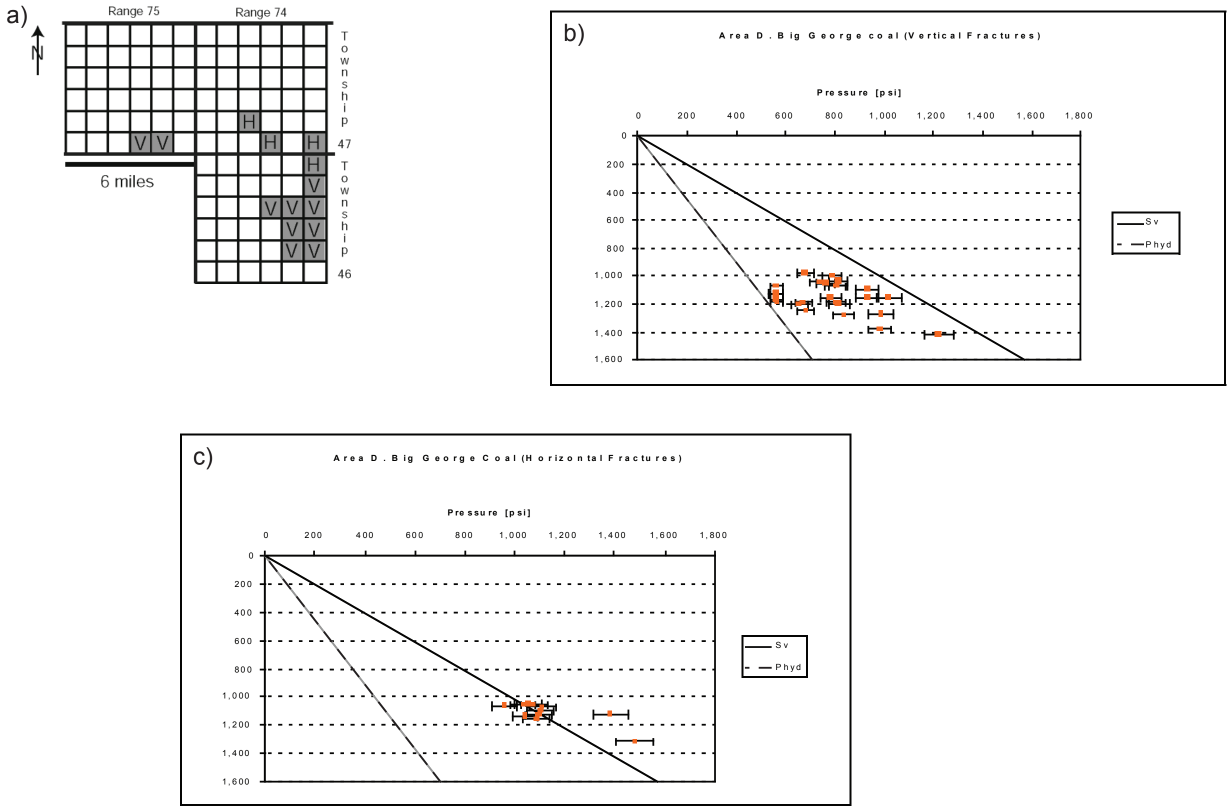

Figure 7. Magnitude of S_3 in the Powder River Basin versus depth for the Big George coal in Area D. (a) Occurrence of horizontal (H) and vertical (V) hydraulic fractures in Area D. The location of this area can be seen in **Figure 5**. (b) S_3 corresponds to the minimum horizontal stress. (c) S_3 corresponds to the vertical stress.

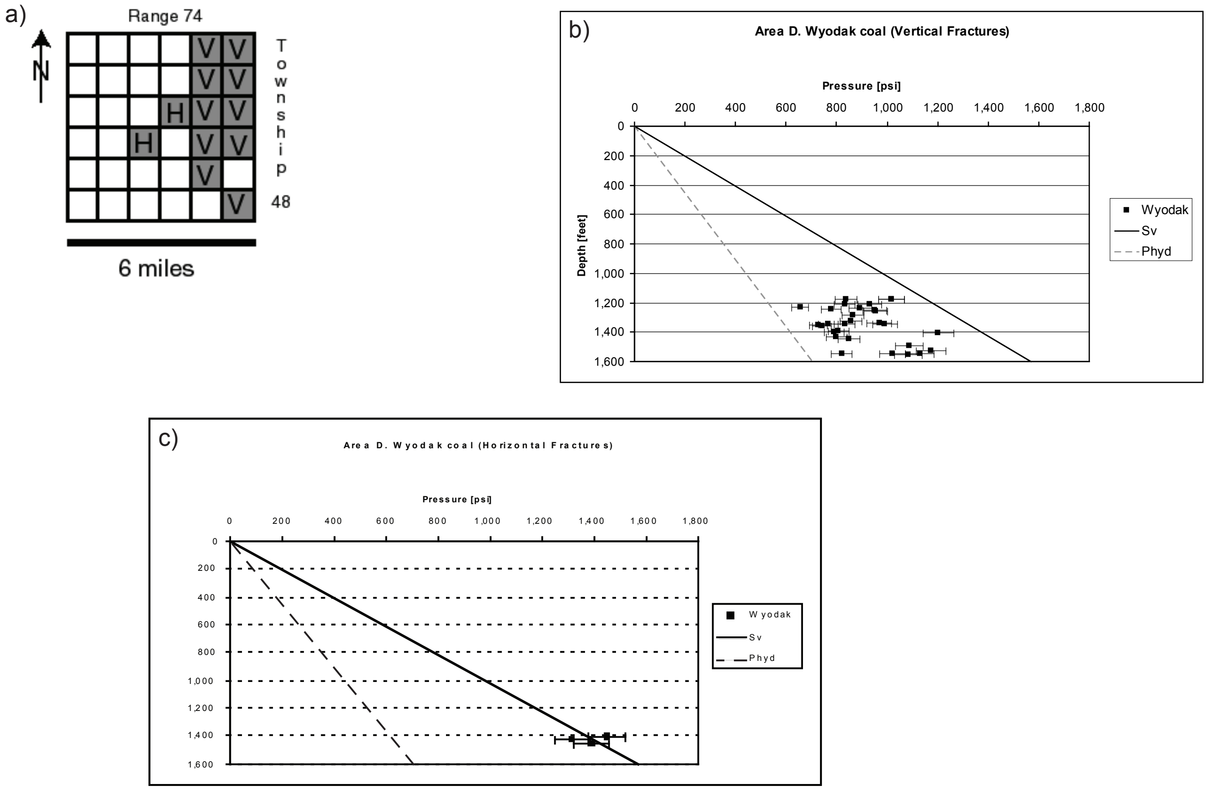

Figure 8. Magnitude of S_3 in the Powder River Basin vs. depth for the Wyodak coal in Area D. (a) Occurrence of horizontal (H) and vertical (V) hydraulic fractures in Area D. The location of this area can be seen in **Figure 5**. (b) S_3 corresponds to the least horizontal stress. (c) S_3 corresponds to the vertical stress.

Table 1. Number of data points used to make the interpolation of S_3/S_V for each coal seam.

Coal seam	# of data points
Anderson	79
Big George	76
Canyon	44
Cook	14
Wall	38
Werner	9
Wyodak	91

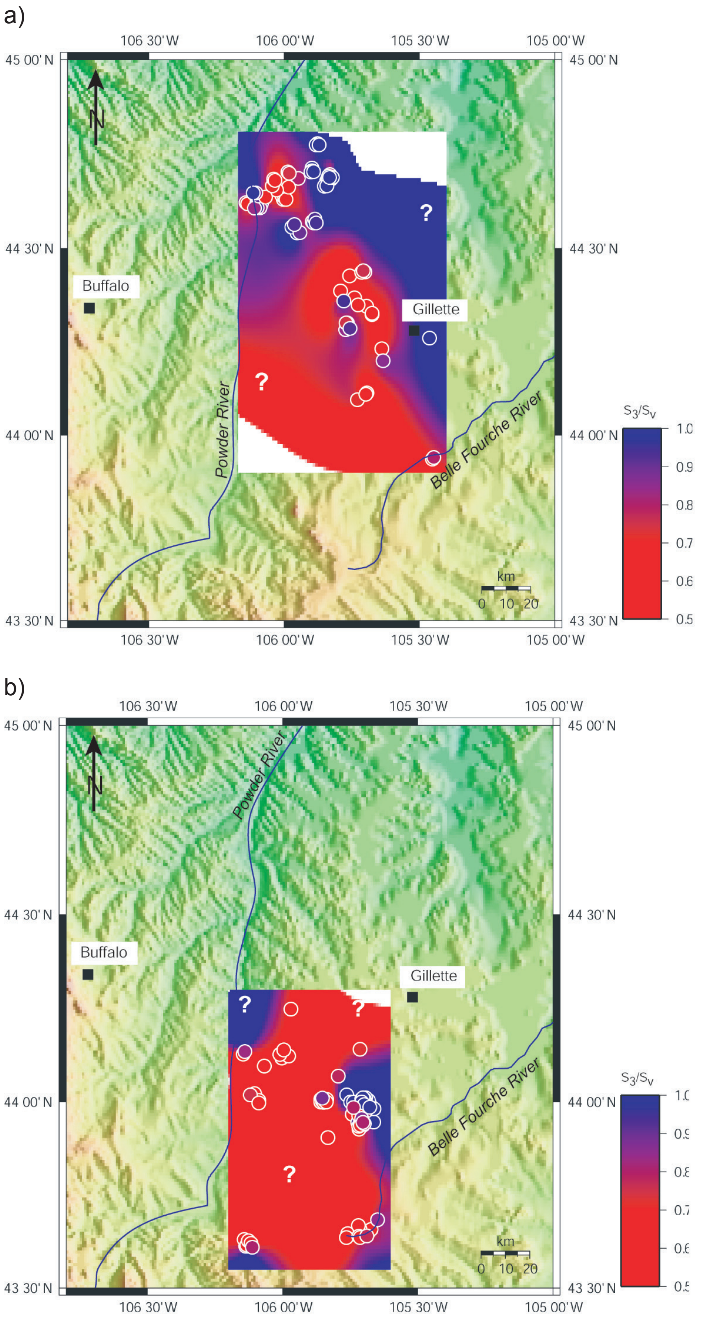

Figure 9. Map showing variation of S_3/S_v for (a) Anderson coal and (b) Big George coal. The circles are actual data points. If $S_3/S_v = 1$, horizontal fractures are expected. If $S_3/S_v < 1$, vertical fractures are expected.

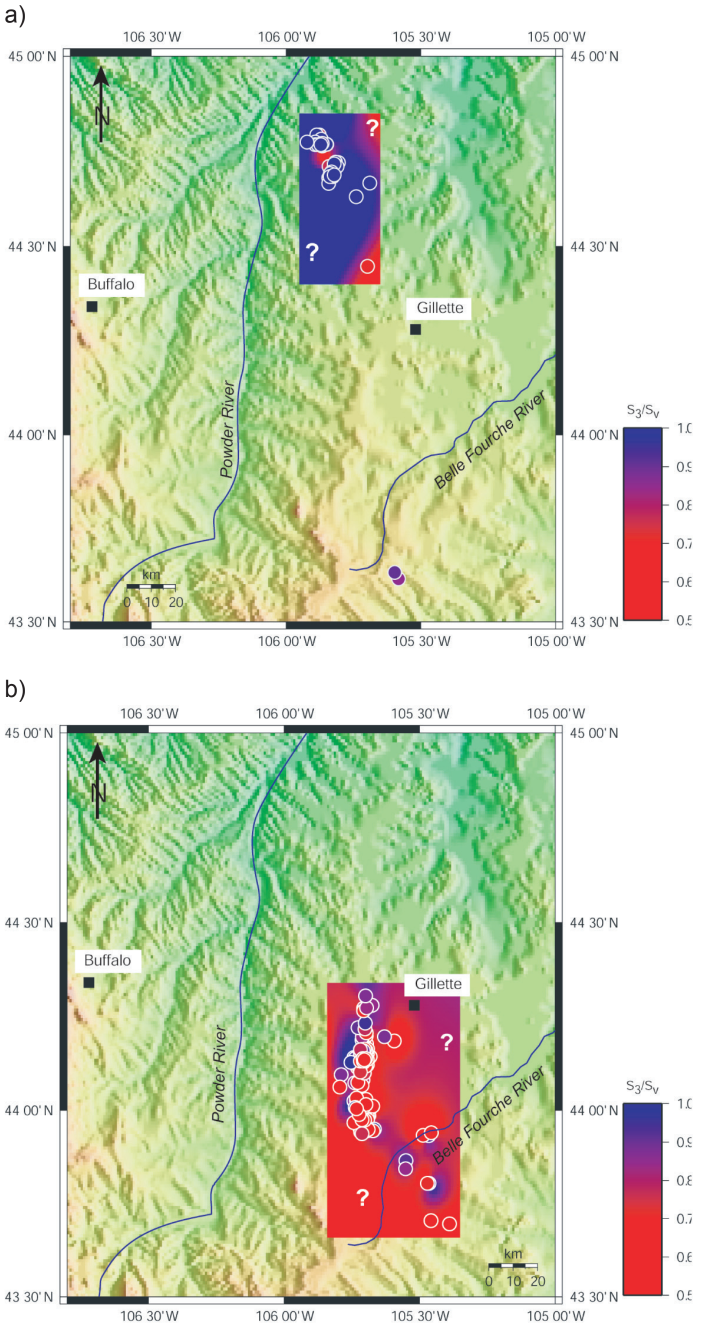

Figure 10. Map showing variation of S_3/S_v for (a) Canyon coal and (b) Wyodak coal. The circles are actual data points. If $S_3/S_v = 1$, horizontal fractures are expected. If $S_3/S_v < 1$, vertical fractures are expected.

Possible causes for the variation of S_3 in the basin

Thickness

The differential stress appears to be larger in thicker coals than in thinner coal beds (**Figures 11a** and **12**). This means that in thicker coals the difference between the overburden and the least principal stress is large and the propagation of fractures occurs in the vertical direction. For thinner coals, the difference between S_V and S_3 is smaller and S_V is often the least principal stress, in which case fractures propagate in the horizontal direction.

For thinner coals it is possible to obtain magnitudes of S_3 equivalent to S_V and also equivalent to the minimum horizontal stress. However, the difference between S_V and the minimum horizontal stress is not large, i.e. assuming that S_V is S_1, the differential stress is small. For thicker coals the magnitude of the least principal stress is equivalent to the minimum horizontal stress and the difference between S_3 and S_V is large, which indicates that the differential stress is also large.

For the Big George coal there seems to be a direct relationship between thickness and the magnitude of S_3 (**Figure 11**). In fact, when the Big George coal is thicker than 47 feet, only vertical fractures occur in this coal. Mapping the thickness of the Big George coal (**Figure 11b**) and comparing it with the map of S_3/S_V (**Figure 9**) it can be seen that the region in the central part of the map is most probably a vertical-fracture-prone area because the thickness of the Big George coal at this location is much greater than 47 feet.

For the other coals (Anderson, Canyon, Wall, and Wyodak), the magnitude of S_3/S_V is less than 0.9 at thickness greater than 60 feet, which implies that only fractures propagating in the vertical plane will occur at thickness greater than 60 feet in these coals. There is not enough data available to make any interpretations about thickness and fracturing in the Werner coal.

Pore pressure changes

Even though changes in pore pressure might not necessarily imply large changes in the magnitude of S_3, it was necessary to investigate this hypothesis. **Figure 13** shows maps with interpolated values of P_{obs}/P_{hyd} (observed pressure over hydrostatic pressure) for the Big George and Wyodak coals respectively. The magnitude of S_3/S_V is also shown. If $P_{obs} = P_{hyd}$ then $P_{obs}/P_{hyd} = 1$ but if $P_{obs} < P_{hyd}$ then $P_{obs}/P_{hyd} < 1$ indicating subhydrostatic conditions.

As well numbers have increased in the basin, depressurization of the Wyodak-Anderson coal bed has also increased (Meyer, 1999). This explains why the Big George coal is almost entirely in subhydrostatic conditions, with the exception of small areas in the central part of the region. It can also be seen that the Big George coal becomes more subhydrostatic toward the east, where CBNG operations

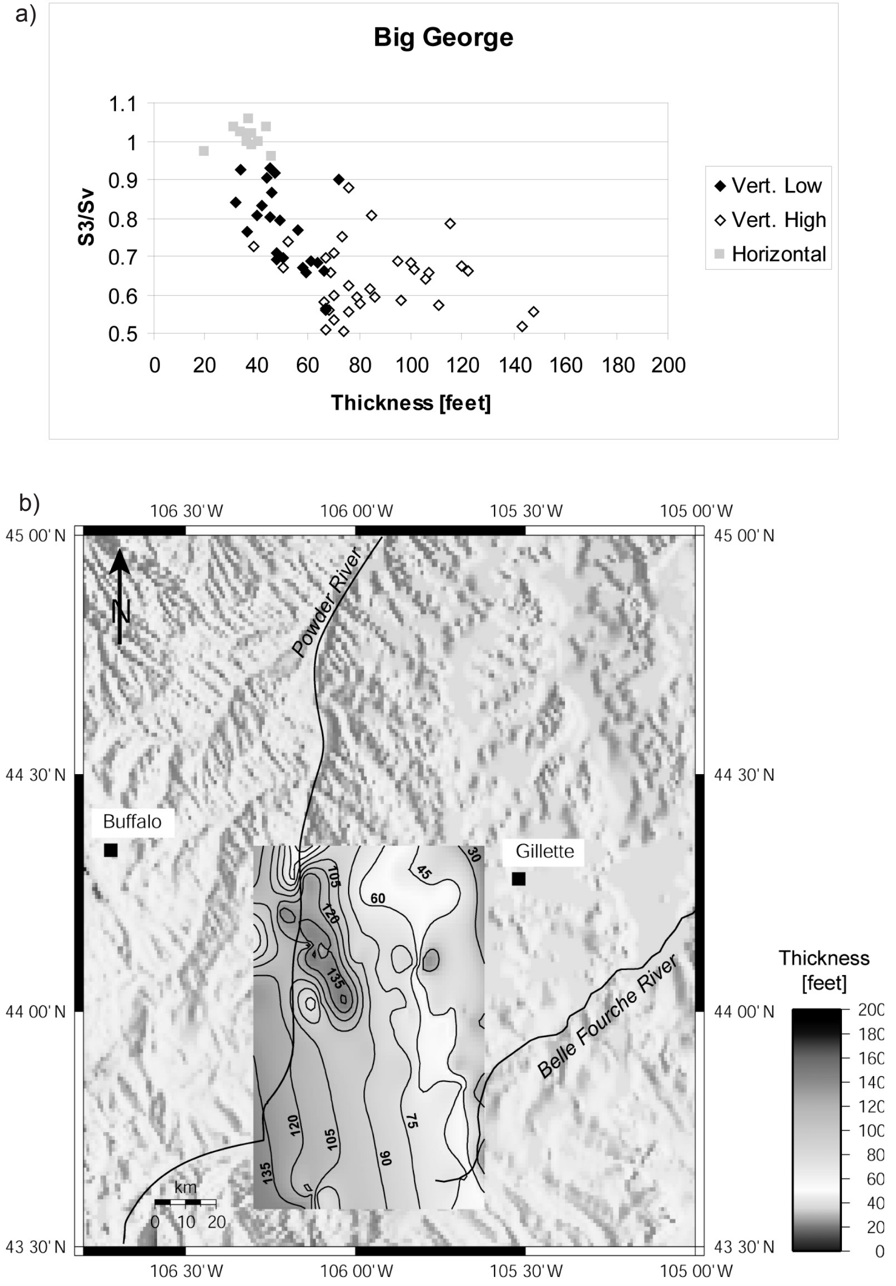

Figure 11. (a) S_3/S_V versus thickness for Big George coal. (b) Thickness of Big George. Note that towards the center of the map, Big George is thicker.

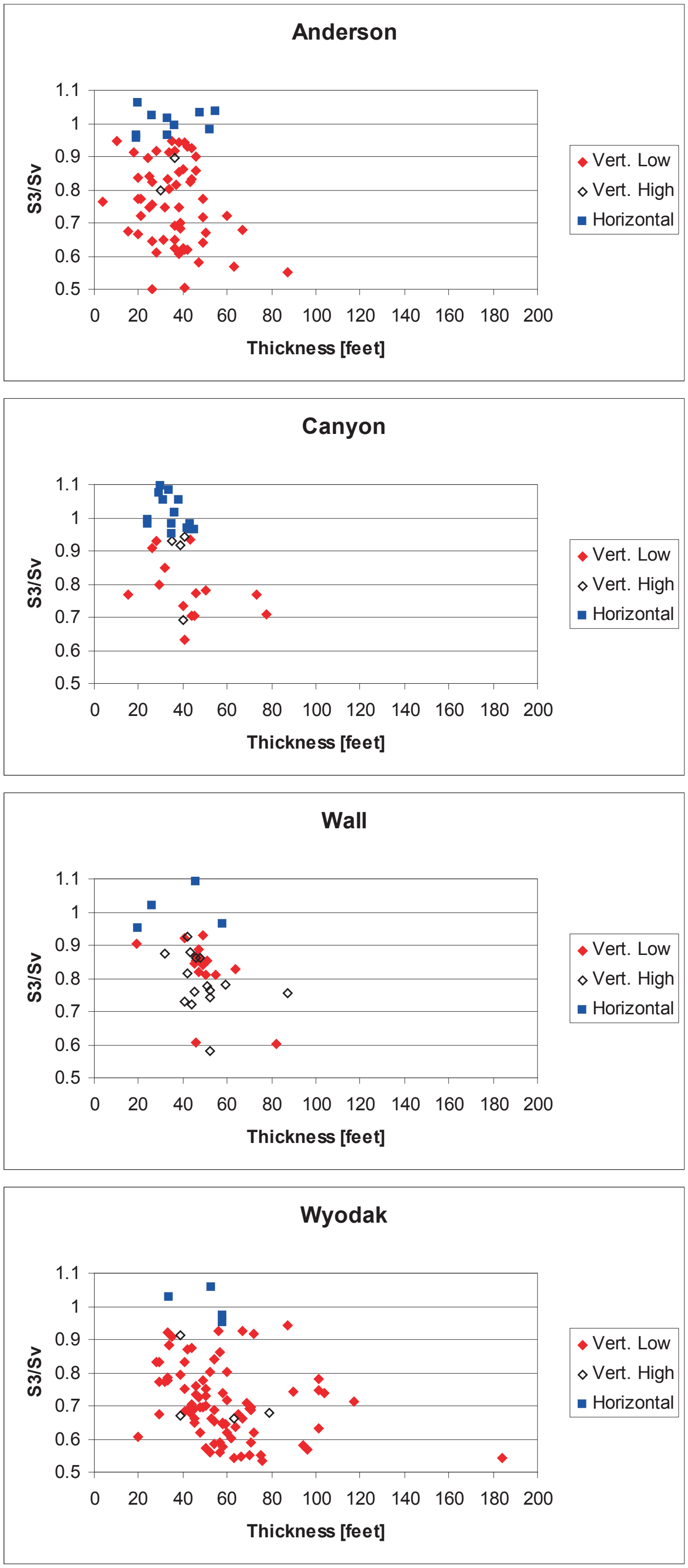

Figure 12. S_3/S_V versus thickness for Anderson, Canyon, Wall, and Wyodak coals. Low and high corresponds to low water production and high water production respectively.

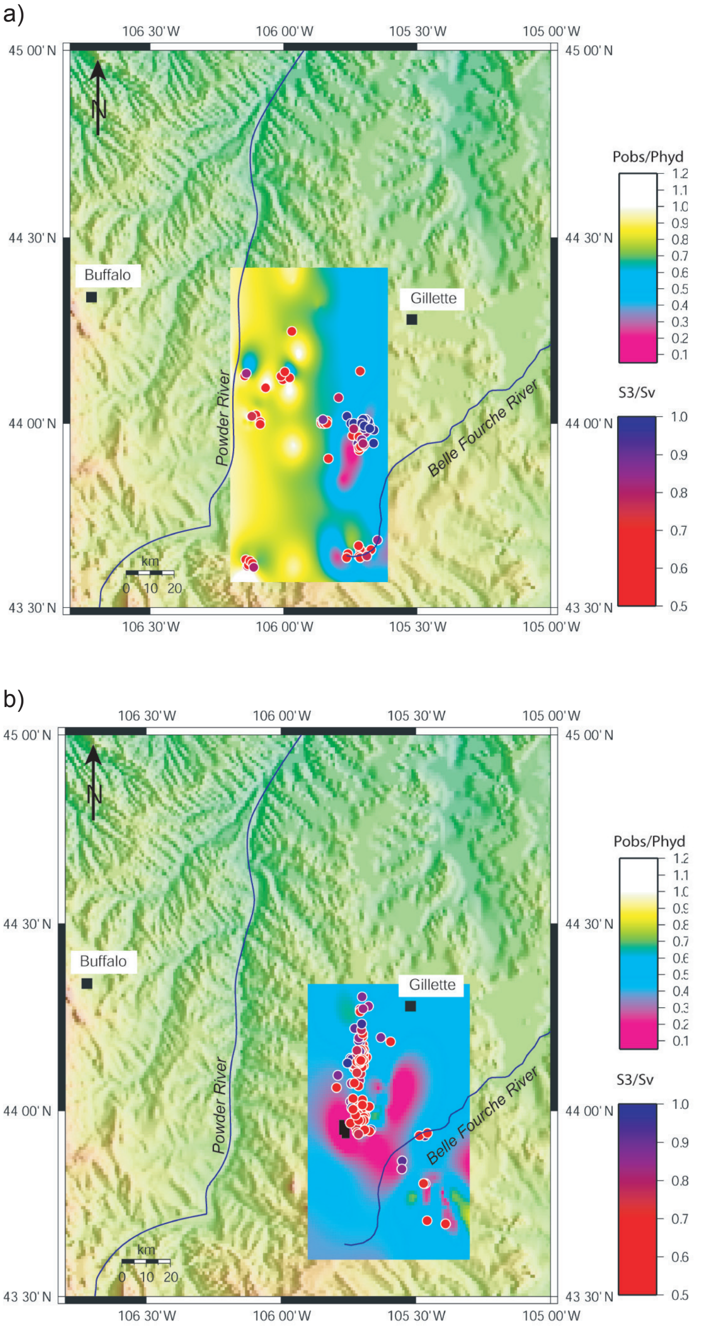

Figure 13. Pore pressure interpolation for (a) Big George and (b) Wyodak coals. Data points denote value of S_3/S_v.

started a decade ago. However, vertical fractures and horizontal fractures occur under no specific pore pressure condition. Vertical fractures occur in places under subhydrostatic, as well as hydrostatic conditions. For the Wyodak coal, the ratio of P_{obs}/P_{hyd} does not exceed 0.7, which means that the entire coal in this area is under subhydrostatic conditions. However, it is possible to have both vertical and horizontal fractures.

From the above analysis it is apparent that there is no correlation between the magnitude of S_3 and pore pressure.

Further analysis is required on a more comprehensive data set in order to confirm this conclusion.

Relationship between hydraulic fracture orientation and water and gas production

As shown in the previous section, the magnitude of the least principal stress and therefore the type of hydraulic fracture varies across the basin. If the vertical hydraulic fractures propagate into an aquifer layer (and if these fractures remain open through time), a hydraulic connection between the coal and the aquifer layer would be established. As a result, a large water production and either a delay in gas production or a lower gas production rate in wells with vertical fractures are expected, compared to wells with horizontal fractures. The operators report water and gas production data for each well to the WOGCC once the well has been put into production. The analysis was made depending on the availability of these data. Thus, there are more wells with least principal stress data than with water and gas production data.

The plots in this section show average gas production in thousand cubic feet (MCF) per month versus average water production in barrels per month (**Figure 14**). Each symbol represents a well, and the color indicates the orientation of the hydraulic fracture, i.e., red is for vertical fractures and blue is for horizontal ones. **Figure 12** shows that within each coal seam there seems to be more wells with vertical fractures than with horizontal fractures. It can also be seen that wells with horizontal fractures always produce low water volumes (less than 7000 barrels per month). In addition, large water production is always associated to wells with vertical fractures. It is important to note that wells with vertical fractures can produce low water volumes and/or large water volumes. However, wells with vertical fractures producing large volumes of water are poor gas producers, while wells with vertical fractures producing small volumes of water tend to be excellent gas producers (i.e., a well producing more than 3000 MCF per month). It is important to keep in mind that the presented data come only from a subset of wells in the basin. Nevertheless, the fact that the relationships are consistent among the different coals seams increases the confidence in these findings.

When looking at **Figure 14**, it is interesting to note that wells with horizontal fractures, even if they are good gas producers, never get to produce as much gas as wells with vertical fractures. The only exception to this is the Werner coal. However, the data for this coal come from only nine wells, which is not sufficient to make any comparisons.

In the following paragraphs, we will discuss the regional trends of water and gas production for the individual coals. As can be seen in **Figure 14**, the Anderson coal in general is not a big water producer. Only three wells produce more than 7000 barrels per month. From the 71 wells we analyzed in the Anderson coal, 27% have horizontal fractures and 73% have vertical fractures. 79% of the water production and 78% of the gas production is produced by wells with vertical fractures, which means that fracture geometry has hardly any impact on water and gas production in this coal. Only about 15% of the wells with vertical fractures in the Anderson coal actually produce large amounts of water.

For the Canyon coal, 34 wells were analyzed, of which 47% have vertical fractures. It is interesting to note that the water production for this coal is almost identical for wells with vertical fractures and wells with horizontal fractures. However, 69% of the gas production comes from wells with vertical fractures, which suggests that wells with vertical fractures are better gas producers than wells with horizontal fractures.

For the Wall coal, 36 wells were analyzed; 81% of these wells have vertical fractures and produce 91% of the water and 86% of the gas. Wells with vertical fractures that produce large amounts of water represent 39% of all the wells and they produce 60% of the water and 44% of the gas from this coal.

For the Big George coal, 74 wells were analyzed, of which 82% have vertical fractures. In total, wells with vertical fractures produce 95% of the water and 99% of the gas. It is important to point out that only half of the wells with vertical fractures are responsible for the bulk of water production (85% of the total amount of produced water) but these large water producers still only account for 45% of the total amount of gas produced from the Big George coal. The remaining 54% of gas production by wells with vertical fractures is from wells with low water production.

There were 85 wells analyzed from the Wyodak coal and 91% had vertical fractures. From this 91%, 5% had high water production. It is curious to note that even though the Big George coal and the Wyodak coal are similar in thickness, their gas and water production differ greatly. For the wells in the Wyodak coal, those with vertical fractures and large water production are only responsible for 13% of the total amount of water produced from this coal. This means that 78% of the water is produced by wells with vertical fractures and low water production, and these same wells produce 92% of the gas from the coal. This seems to imply that the high water production from wells in the Big George coal is not just related to thickness, since the Wyodak coal has a similar thickness and yet, does not produce as much

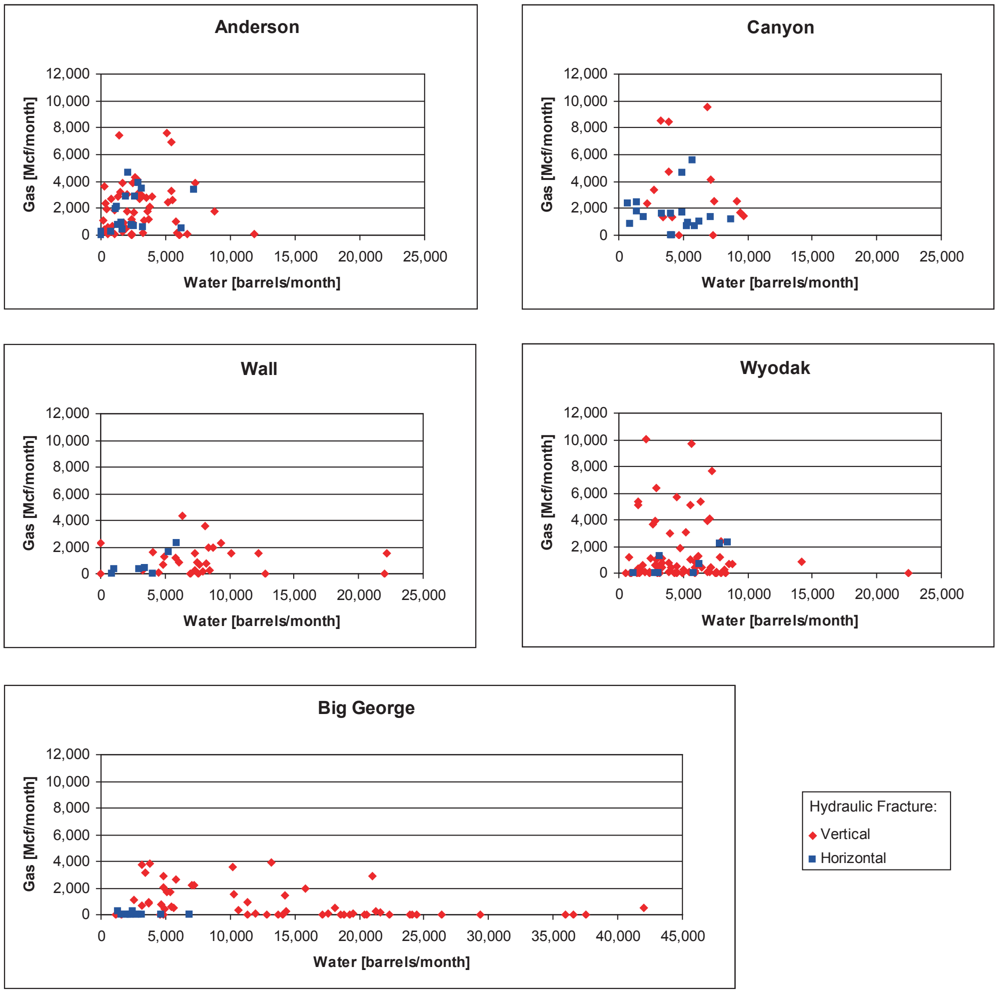

Figure 14. Average gas production versus average water production for Anderson, Canyon, Wall, Wyodak, and Big George coals. The gas production scale for all the plots is the same. The water production scale is the same for all the coals except for Big George coal and it is from 0 to 25,000 and from 0 to 45,000 barrels per month, respectively.

water. At the same time, the Wyodak coal is a better gas producer, perhaps because the depressurization of the coal is more efficient, or because its gas content may be much higher than the Big George coal.

As can be seen in **Figure 14**, wells in the Big George coal produce a maximum of 4000 MCF per month while the wells in the Wyodak coal can produce 10,000 MCF per month. Even the large water producers in the Wyodak coal do not produce as much water as those in the Big George coal (23,000 barrels per month compared to 43,000 barrels per month respectively). A possible explanation for the high water production by Big George wells can be given by comparing Gamma Ray logs between the Big George and Wyodak coals. The GR log in the Big George coal has a blocky signal that is easily identifiable in all the wells analyzed. Conversely, in the Wyodak coal, the GR signal shows more variations, suggesting that interbedded shale stringers lie within this coal (**Figure 15**).

The shales might be acting as flow barriers impeding the flow of water toward the well. If the water cannot flow to the well, then depressurization does not occur. This process is expected to reduce gas production unless the shale stringers also contain gas thereby contributing to the overall gas production from the Wyodak coals. Thus, the presence of shale may explain why the Wyodak coal is not a big water producer and at the same time produces large amounts of gas. The shale stringers in the Wyodak coal can also be acting as barriers for fracture propagation and since the Big George does not have such barriers, the fractures might be propagating into adjacent formations allowing for a hydraulic connection.

The Big George coal is an amalgamation of the Anderson and Canyon coals, however, it does not produce as much gas as the individual Anderson and Canyon coal beds (**Figure 14**). Possibly, the free gas that used to be present in the various coals has escaped out of the coal toward overlying formations (sands, shales). It is known that some sands across the basin contain gas, which are economically extractable (U.S. Environmental Protection Agency, 2002). Therefore, the idea of the Big George coal being under-saturated of methane is a plausible one. This could be another possible factor responsible for the Big George coal producing less gas than the Wyodak coal. In addition, if the Big George coal is hydraulically connected to overlying forma-

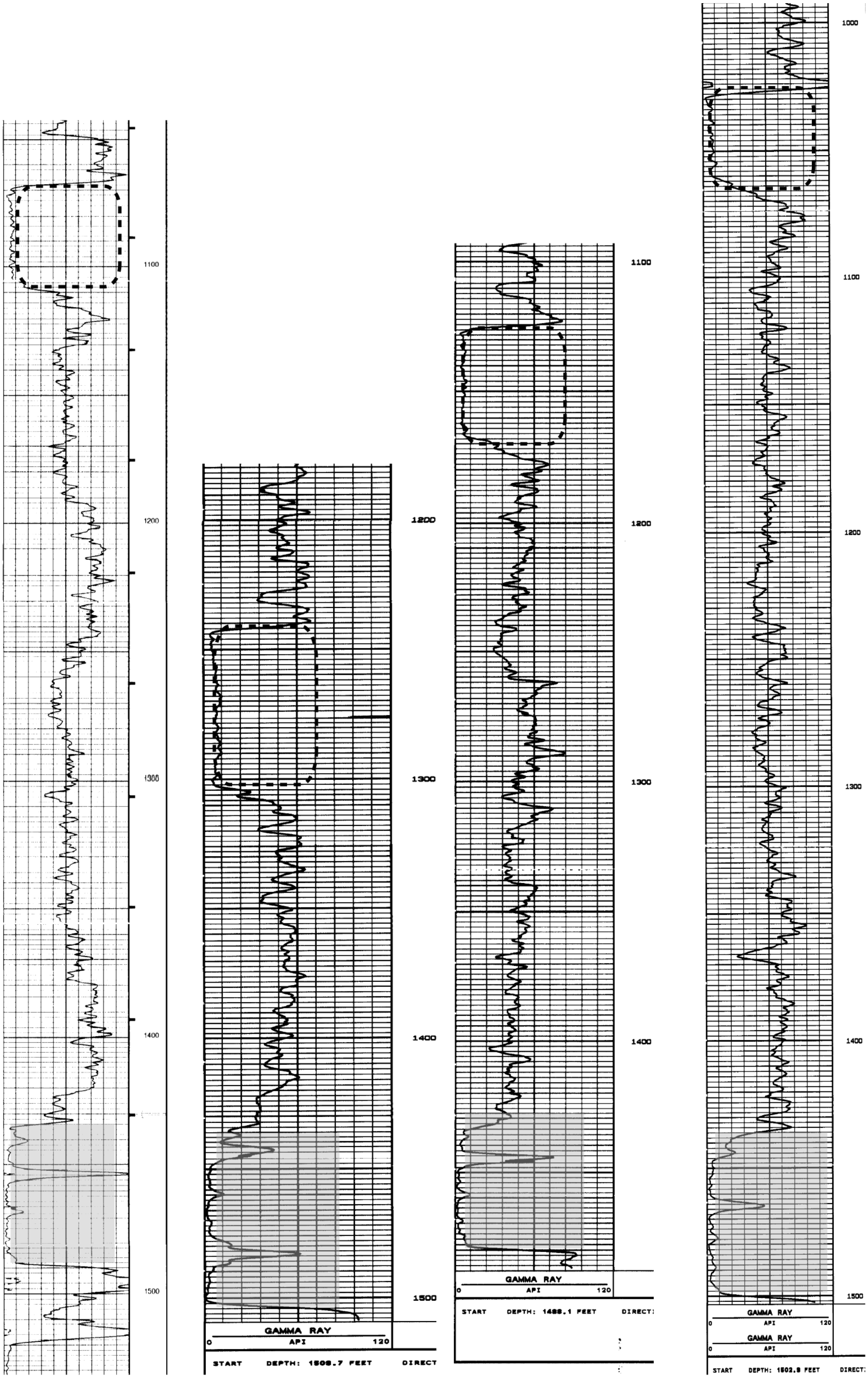

Figure 15. Gamma Ray logs showing Big George (dashed line) and Wyodak (gray) for wells: 534670, 539081, 539123, 545693, respectively. Source: WOGCC Web site.

tions it is being dewatered inefficiently and this could also account for the lower gas production.

Water and gas production in specific areas of the basin

In this section, the wells for a given coal are analyzed in an area-specific manner to determine if the relationships seen in the previous section are not only regional but can also apply to smaller areas. **Figures 16** through **24** show plots of water and gas production (barrels and MCF respectively) for each area that has been analyzed. The plots also indicate whether the data come from wells with vertical or horizontal hydraulic fractures. All the wells show water and gas production since the time production started; in this way it is easier to establish comparisons among wells. The water and gas production data for all the wells were obtained from the WOGCC website.

Area D (Big George coal)

There is a marked contrast in water production depending on the type of hydraulic fracture produced in the Big George coal as can be seen in **Figures 16** and **17** (data for wells with horizontal and vertical fractures, respectively). Wells with vertical fractures produce more water than wells with horizontal fractures. In fact, 71% of the CBNG water from the Big George coal is produced by only 32% of the wells (those enclosed in the blue dashed box in **Figure 17**), all of which are characterized by vertically propagating hydraulic fractures. The same wells that produce 71% of the CBNG water in this area have been in production for at least 16 months and still show no gas production. Actually, gas production seems to only occur in wells (with horizontal or vertical fractures) that produce less than 10,000 barrels of water in a given month. Wells with vertical fractures that produce low water volumes are excellent gas producers. Even though for some of these wells gas production is delayed between 4 to 14 months, it can also be seen that these wells produce 12 times more gas than wells with horizontal fractures. Therefore, wells with vertical fractures that produce low water volumes are better gas producers than wells with horizontal fractures.

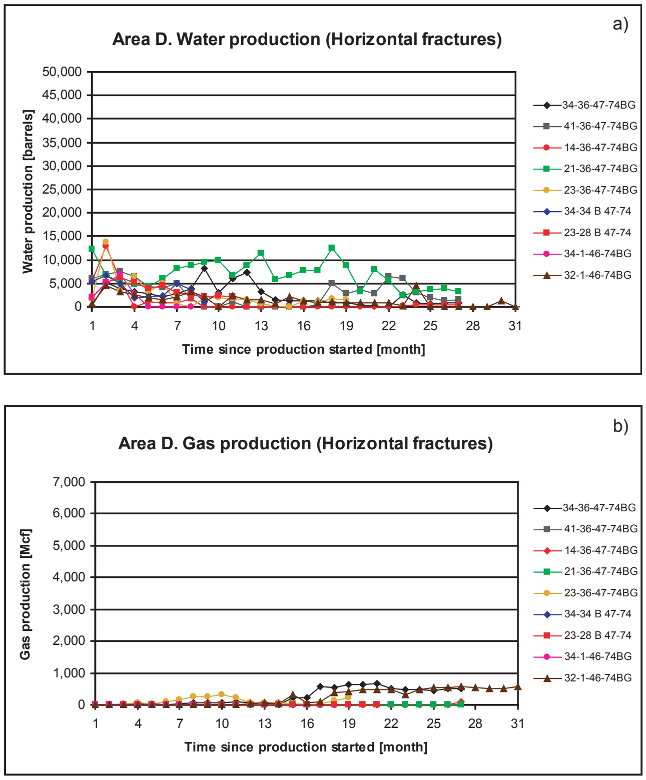

Figure 16. Water and gas production from the Big George coal for wells with horizontal fractures in Area D. (a) Water production and (b) gas production. Water production is low and gas production is immediate but low (compare to gas production from wells with vertical fractures in Figure 17b).

Area D (Wyodak Coal)

For the Wyodak coal (**Figures 18** and **19**), the difference in water production between wells is not as large as

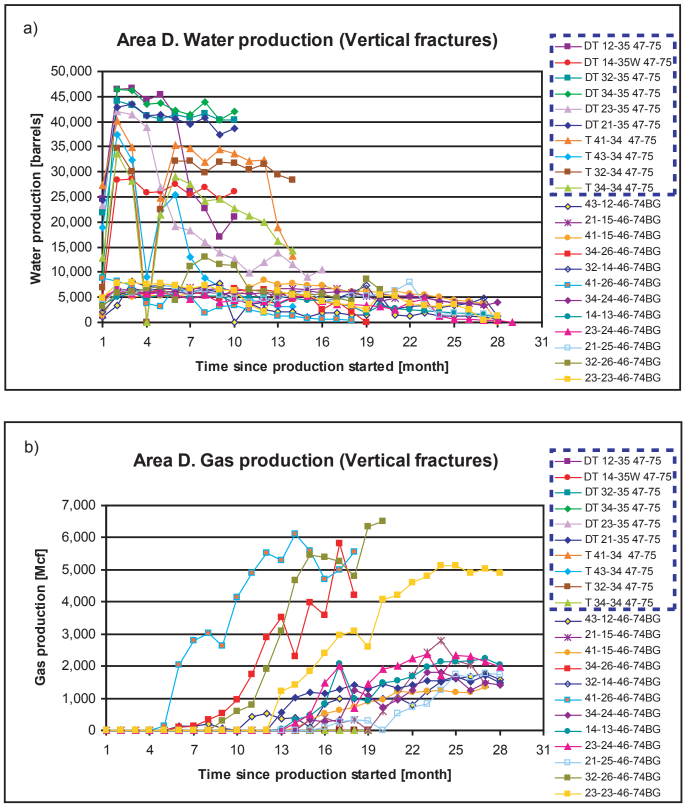

Figure 17. Water and gas production from the Big George coal for wells with vertical fractures in Area D. (a) Water production and (b) gas production The water production in wells with vertical fractures is about 7 to 10 times larger than that of the wells with horizontal fractures (Figure 16). All the wells enclosed by the dashed black box produce more than 10,000 barrels in a month and have not produced any gas. For wells producing less than 10,000 barrels in a month of water gas production is large but delayed by at least 5 months.

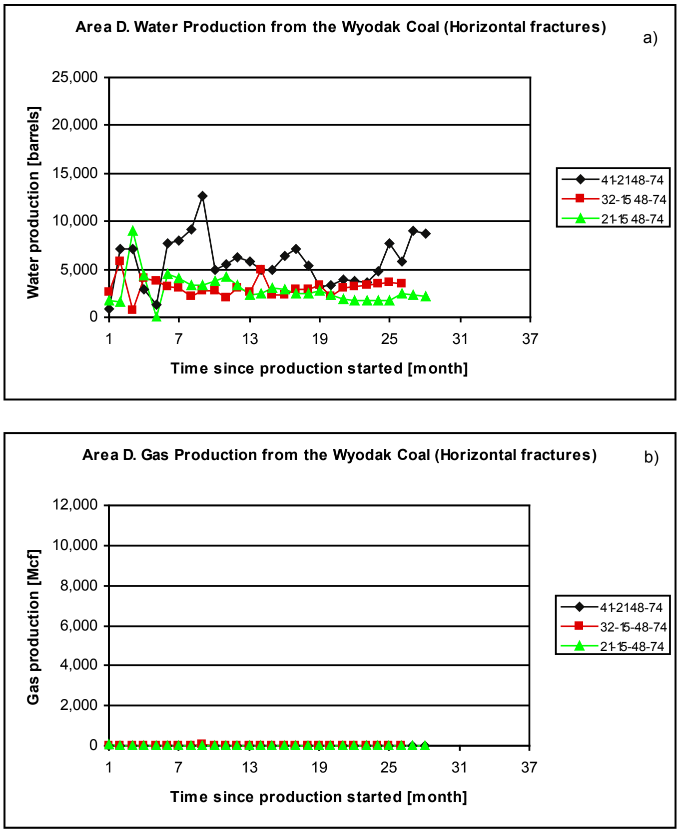

Figure 18. Water and gas production from the Wyodak coal for wells with horizontal fractures in Area D. (a) Water production and (b) gas production. Note that even though water production is low, gas production is nearly zero.

in the Big George coal. However, the average water rate in wells with horizontal fractures is at least 2000 barrels per month lower than for the wells with vertical fractures. In this area, few wells with vertical fractures are producing gas, but they produce more gas than wells with horizontal fractures (e.g. 7 MCF, 173 MCF, and 68 MCF by the 19th month). These wells might not be depressurized enough for methane to desorb but it will be interesting to compare gas production between the wells with horizontal fractures and wells with vertical fractures in the future. Already four of the wells with vertical fractures are producing more gas than wells with horizontal fractures.

Area B2 (Anderson coal)

In Area B2, the water production of wells with horizontal fracturing (**Figure 20**) ranges from 0 to 6000 barrels, with only one well having an anomalous water production rate of 12,000 barrels after nine months of being in production (3-34-54-77). In general, the gas production of these wells increases with time, as can be seen in **Figure 20**, and the maximum gas production was about 9000 MCF in well 1-35-54-77.

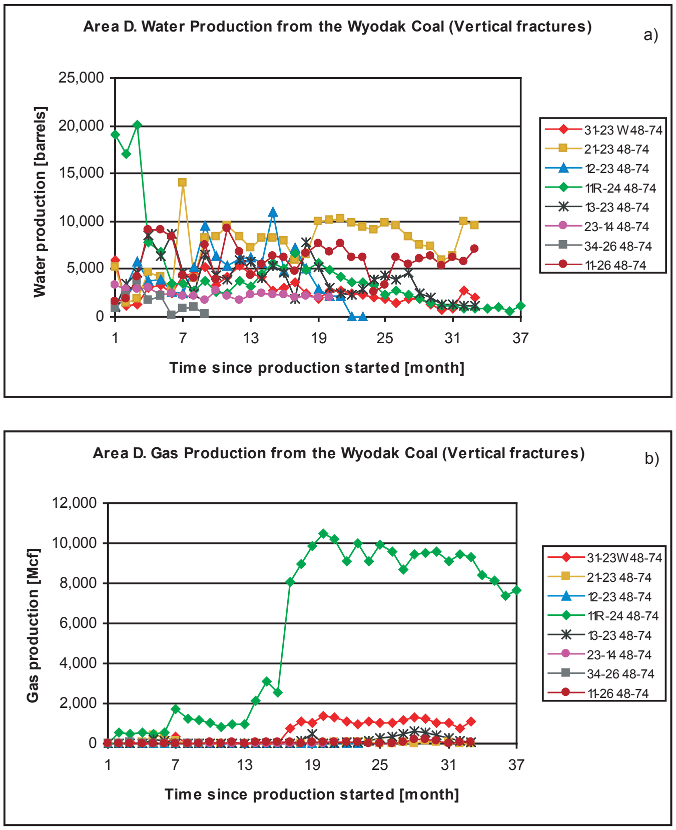

Figure 19. Water and gas production from the Wyodak coal for wells with vertical fractures in Area D. (a) Water production and (b) gas production.

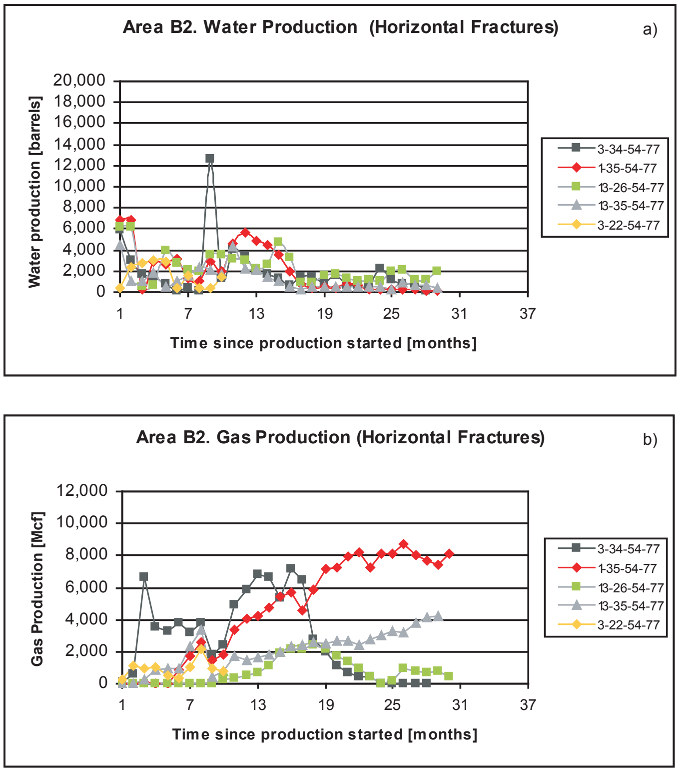

Figure 20. Water and gas production from the Anderson coal for wells with horizontal fractures in Area B2. (a) Water production and (b) gas production.

Wells with vertical fractures (**Figure 21**) that reached a water production rate of more than 6000 barrels per month in the first 12 months, either have delays in gas production of about 12 months (e.g. 5-35-54-77, 3-35-54-77, 11-26-54-77, and 15-35-54-77) or show no gas production at all (e.g. 13-28-54-77 and 3-33-54-77). Interestingly, wells with vertical fractures that have water production rates less than 6000 barrels per month produce gas immediately, reaching a gas production of 6000 MCF in the first 12 months of production (15-34-54-77, 15-24-54-77, and 1-22-54-77).

Area B1 and B (Anderson coal)

Water production of more than 8000 barrels per month in the first seven months is more common in wells with vertical fractures than in wells with horizontal fractures (**Figure 22**). Even though water production is greater in wells with vertical fractures in Area B1 than in wells with horizontal fractures in Area B, gas production is immediate and in general, they all have similar trends in gas production, which increases up to the 13th month of production and then declines over time. However, wells with vertical fractures produce at least 3000 MCF per month but they also reach 4000 and even 11,000 MCF per month compared to the steady and lower gas production from the wells with horizontal fractures (between 1000 and 4000 MCF per month). Since gas production in the wells with vertical fractures was not affected by water production, that is, production of large water volumes did not imply a delay in gas production, the large water volumes produced here in the first seven months might just have been part of a normal dewatering process. After all, these wells do not produce as much water as the wells with vertical fractures in Area B2 (**Figure 21**). It is interesting to note that wells with vertical fractures are better gas producers than wells with horizontal fractures as has also been found for the Big George coal.

Area B (Wall Coal)

As can be seen in **Figures 23** and **24**, there is a marked difference in water production between wells with horizontal fracturing and some of the wells with vertical fracturing. The wells Smith 5-1W, 5-18W, 11-1W, 14-1W, and 6-1W (**Figure 24**) produce almost four times more water than the two wells with horizontal fractures (**Figure 23**). These wells with high water production also produce the least amount of gas among all the wells with vertical fractures, e.g. Smith 14-1 (**Figure 24**). In some cases, gas production is delayed by at least 15 months and water production can be as high as 15,000 barrels. Interestingly, Smith 3-1 W (**Figure 24**), which has vertical fractures, has an average water production of only 5000 barrels per month, similar to the wells with horizontal fractures (**Figure 23**), and its gas production is high (approximately 10,000 MCF). A possible expla-

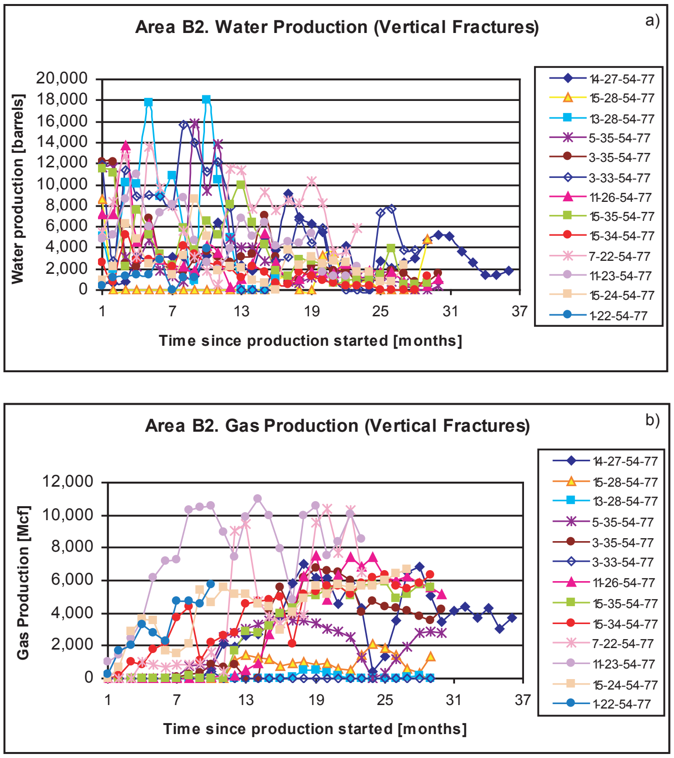

Figure 21. Water and gas production from the Anderson coal for wells with vertical fractures in Area B2. (a) Water production and (b) gas production.

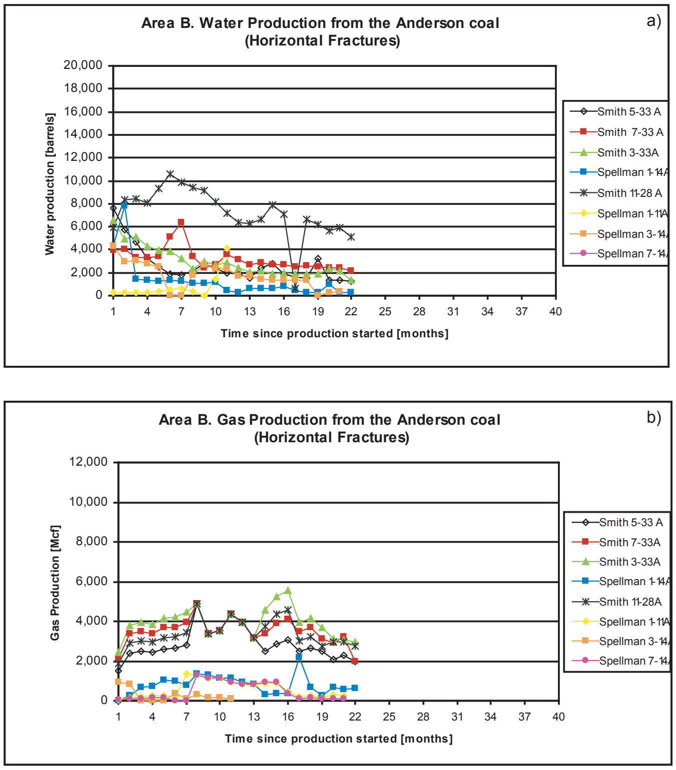

Figure 22. Water and gas production from the Anderson coal for wells with horizontal fractures in Area B. (a) Water production and (b) gas production.

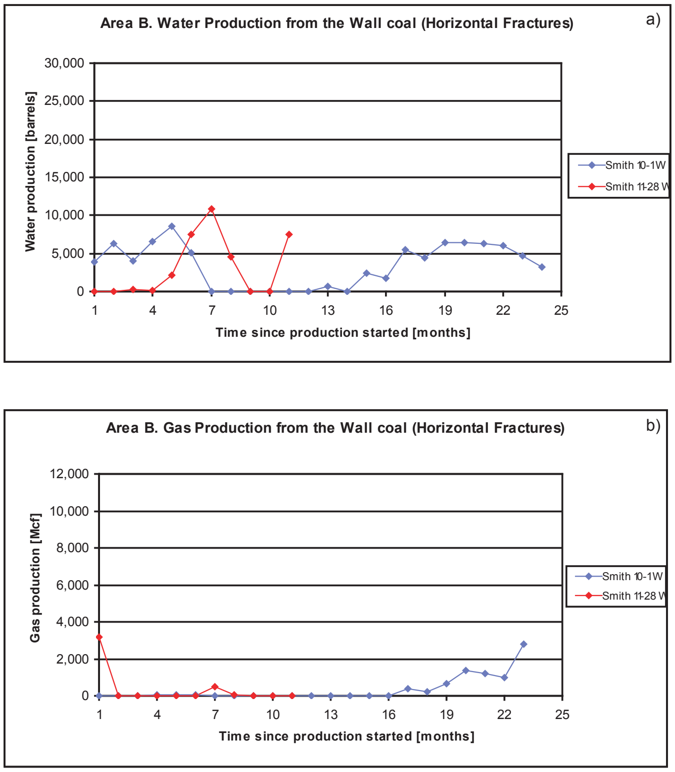

Figure 23. Water and gas production from the Wall coal for wells with horizontal fractures in Area B. (a) Water production and (b) gas production.

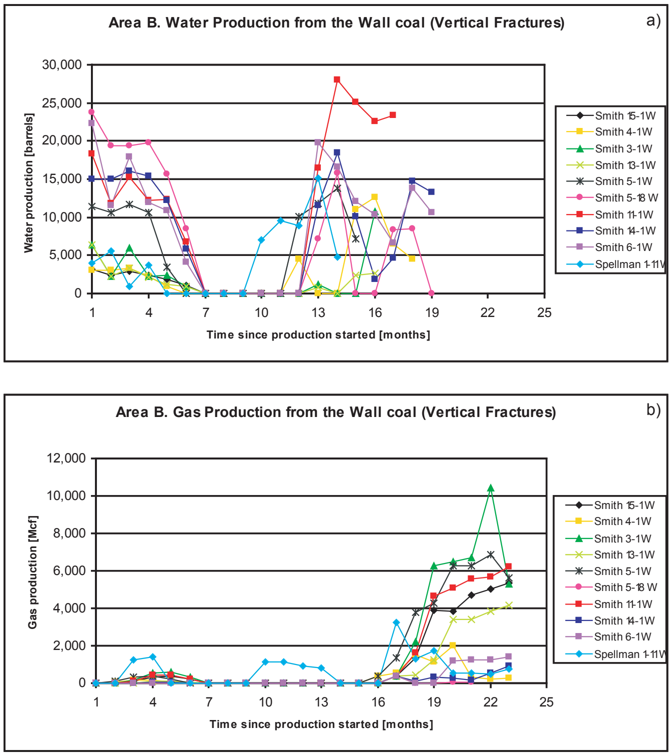

Figure 24. Water and gas production from the Wall coal for wells with vertical fractures in Area B. (a) Water production and (b) gas production.

nation for what is observed in Smith 3-1W is that the vertical fracture may not be extending into the aquifer layer, so water production from the aquifer layer is not being tapped, preventing high water production.

Area C (Anderson Coal)

Even though water production rates are not too high in these wells, in wells with lower water production, more gas is produced. However, the maximum gas production reached in this area (4500 MCF for well 9-27-51-74) is about half of what is being produced in area B2 (**Figure 21**) for the same coal (the Anderson coal). In addition, most of the wells in Area C are only producing an average of 1000 MCF per month, which is relatively low compared to the gas production in areas B1 and B2 (**Figure 21**). This could be due to inefficient depressurization of the coal, or the Anderson coal could be under-saturated of methane in this area.

Area A (Roland Coal)

Water production from the Roland coal in Area A started at about 1000 barrels per month and increased to between 2500 and 6000 barrels per month for the different wells, with some periods of zero production interspersed. These wells show no gas production. We are unable to compare this water production with other wells because none of the other wells we have analyzed are producing from the Roland coal.

How does the relation between hydraulic fracture orientation and cleat system affect the water and gas production?

Fluid flow in coal beds occurs through the natural fractures, or cleats. Cleats are systematic, orthogonal fracture systems that commonly are perpendicular to bedding. They commonly form during coalification and the face (dominant) cleat orientation reflects the far-field stress present during their formation. Tectonic postcoalification fractures also may be present. The face cleat is more continuous than the subordinate butt cleat and in general, cleat density is greatest in thin, bright, low-ash coals (Ayers, 2002). Cleats are perpendicular to the bedding of the coal seam.

Wells with induced vertical hydraulic fractures are, in general, better gas producers than wells with induced horizontal hydraulic fractures. Therefore, the vertical fractures must have a strike nearly perpendicular to the strike of the face cleats, which would imply an efficient connection of several face cleats through the vertical hydraulic fracture. Wells with horizontal hydraulic fractures that produce relatively good amounts of gas (more than 3000 MCF per month), must be producing free gas and gas from the cleats, which get connected by the horizontal hydraulic fracture. However, horizontal fractures do not seem to be the most efficient pathway for flow of methane from the coal into the well.

There are wells with horizontal hydraulic fractures in the Anderson and Canyon coals that produce more gas than wells with horizontal fractures in the Big George and Wyodak coals. Interestingly, the Anderson and Canyon coals are thinner and shallower than the Big George and Wyodak coals. The cleat density may be larger in the thinner coals than in the thicker coals and the amount of free gas is generally higher in shallower coals than in deeper coal. These could explain why horizontal fractures in thinner coals are better conduits than in thicker coals and therefore, this could also explain why wells with horizontal fractures in thinner coals are better gas producers than wells with horizontal fractures in thicker coals.

In areas of vertical hydraulic fracturing: why do some wells have large water production and others low water production?

One of the goals of this study is to understand why some wells with vertical fractures have excessive water production, while water production is low in adjacent wells. We have identified three different factors that may be responsible for this observation: stratigraphy, thickness, and depth.

Stratigraphy

Excess CBNG water production could result from the propagation of the vertical fractures into overlying strata, creating a hydraulic connection between the formations. GR logs from a number of wells with vertical fractures in Area D have been analyzed. It was expected that wells with vertical fractures and excessive water production would be overlain by sand bodies, which behave as aquifers, and would therefore yield a large amount of water once the coals began to be dewatered. With respect to the wells with vertical fractures and low water production, it was expected that the coals in these wells were overlain by shales, which have low permeability, and therefore yield less water than sands.

Some of the wells with vertical fractures and large water production rates have sand bodies overlying the coal. However, other wells with vertical fractures and large water production rates have shales overlying the coal. Furthermore, wells with vertical fractures and low water production rates were either overlain by shales or sands. Thus, no obvious relationship between stratigraphy and water production can be established. In the future, the availability and analysis of a more extensive GR log dataset may yet reveal whether a relationship does exist between vertical fracture growth and stratigraphy.

Thickness

As can be seen in **Figure 25a**, there is a general trend that the thicker the Big George coal, the greater the water production. However, at a given thickness, say 70 feet, the average water production for different wells ranges from 0 to 40,000 barrels per month. For the Wyodak coal (**Figure 25b**), water production is generally low, despite the large thickness of the coal seam. Even where the coal is thicker than 100 feet, the average water production is less than 8000 barrels per month. This implies that coal seam thickness is not an obvious indicator for the amount of water a coal will end up producing.

Depth

Figure 26 shows a plot of water production versus depth for the Big George coal seam. The plot shows that wells with vertical fractures and high water production rates occur at any depth between 750 and 1500 feet. Therefore, there appears to be no direct correlation between high water production and depth.

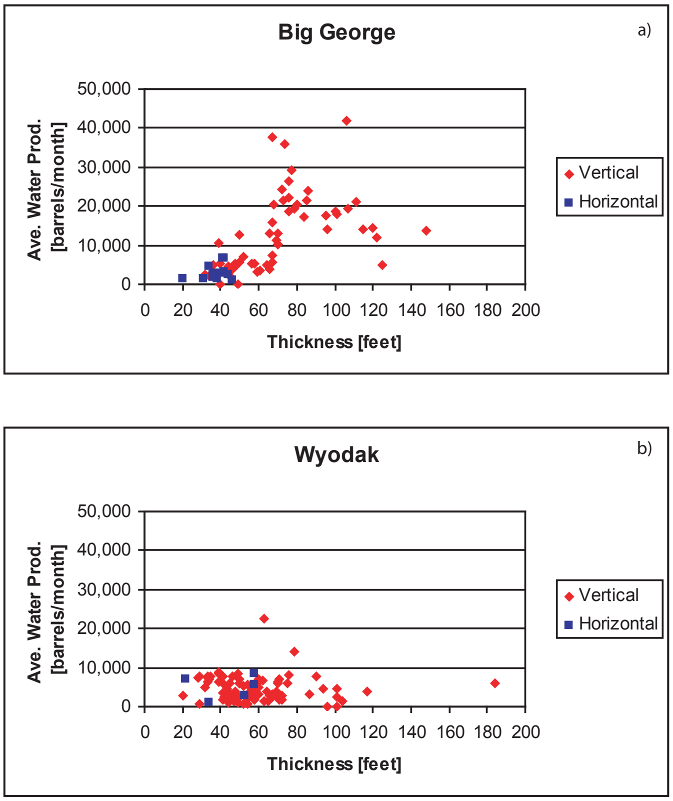

Figure 25. Average water production versus thickness for the (a) Big George and (b) Wyodak coals.

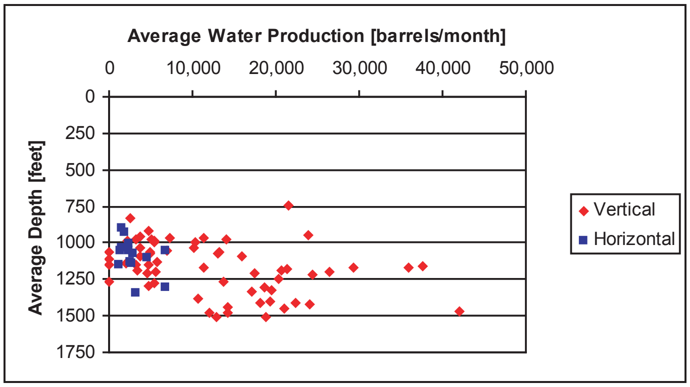

Figure 26. Average water production versus depth for the Big George coal.

None of the investigated factors (stratigraphy, coal thickness, depth) appear to affect the amount of water that is produced in wells with vertical fractures. At this time and considering the factors just mentioned, the prediction of water production in these wells is still not viable.

Pore pressure and gas production

It is known that methane desorbs from the coal once the pressure in the coal decreases. The aim of this section is to investigate the amount of depressurization required for methane desorption to occur. The data presented in this section come from the Big George coal. Figure 27 shows the water and gas production data for each well and also the changes in delta pressure with time. Delta pressure is equivalent to hydrostatic pressure minus observed pressure, which indicates that with time, the observed pressure should be lower due to the dewatering (and depressurizing) of the coal and therefore the delta pressure should increase.

Well SRU2 (**Figure 27a**) shows a change of about 200 psi in delta pressure with ongoing depletion, due to water production, but even after three years it is still not producing any gas. Even though depressurization is implied, the large water production rate (about 35,000 barrels per month) indicates that depressurization might not be taking place effectively. The coal at this site may be in connection with overlying strata.

For well Roush (**Figure 27b**), a change in delta pressure of approximately 30 psi was not enough for the methane to desorb from the coal. The change in 30 psi occurred during the first year of production and gas production started a year after that. Dewatering for 18 months was necessary for this well to start producing gas.

Well Oh (**Figure 27c**) has horizontal fractures and is located in T46N, R73W, adjacent to Area D. In the first six months of production, the delta pressure changed by 25 psi. However, this well has been in production for four years and gas production has still not begun. This indicates that the initial change in pore pressure was not large enough for the methane to be desorbed. In addition, delta pressure might still not be increasing sufficiently for the methane to desorb at all. This well confirms the previous findings, that is, wells with horizontal fractures in the Big George coal produce low water volumes and gas production is low or absent.

For some wells, a 25 psi change in pressure is enough for the gas to desorb, while for others it is not large enough. In fact, even a large change like 200 psi in the case of SRU2 was not large enough for the methane to desorb. It appears that something more complicated might be taking place in this well. The coal at this site may be in hydraulic connection

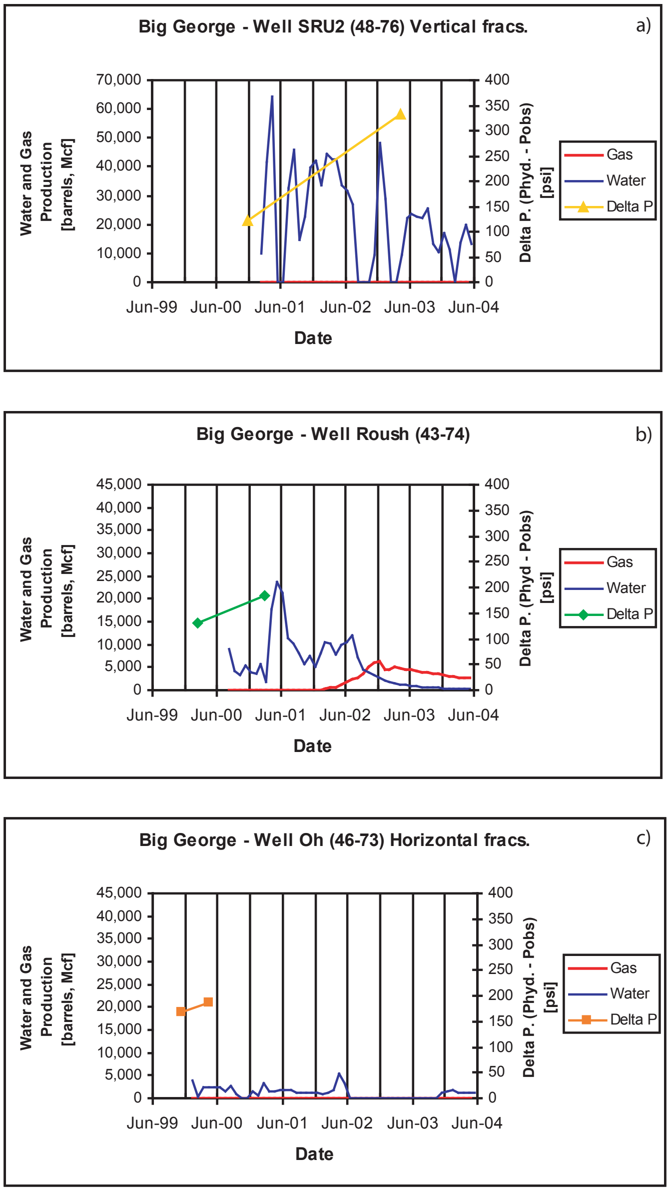

Figure 27. Plots of water and gas production versus time and delta pressure (hydrostatic pressure minus observed pressure) for different wells in the Big George coal.

with adjacent strata, which would explain the large volumes of water produced and the absence of gas production.

Temporal and spatial variations in pore pressure

Figure 28a is a crossplot of P_{obs}/P_{hyd} versus time when the measurement was made and shows no correlation between changes in pore pressure and time for the Big George coal. **Figure 28b** shows a map of interpolated P_{obs}/P_{hyd} with data points over the top. Each symbol represents the year in which the pore pressure (P_p) measurement was taken. There seems to be more of a spatial trend than a temporal trend. The darker areas ($P_{obs}/P_{hyd} < 1$) are defined not only by data points from 1999 but also from 2004, whereas the lighter ($P_{obs}/P_{hyd} \geq 1$) areas are not only defined by data points from 2004, but also from 1998 to 2002. This may indicate that P_p not only depends on time (when dewatering began) but also on the area (there may be interaction with other formations).

Figure 29a shows elevation with respect to delta pressure for Big George coal. In general, if a fluid level remains at constant elevation while the topography increases, the pore pressure at the depth of the water table will be more subhydrostatic at the location of highest elevation, compared to the pore pressure at depth in the location of lower topography. This means that if elevation increases, delta pressure should also increase, i.e. the pore pressure should become more subhydrostatic. The data presented in this figure do not show this trend when considered as a whole. However, according to the trends observed in **Figure 29a**, it is possible to establish four different groups of these data (**Figure 29b**). For Group 1 there seems to exist a correlation between elevation and pore pressure since pore pressure tends to become more subhydrostatic with the increase in elevation. However, for Groups 2, 3, and 4, pore pressure becomes more subhydrostatic at constant elevation. In **Figure 29c**, fluid elevation is plotted against delta pressure and what can be seen here is that for Group 1 fluid elevation remains constant while delta pressure increases (i.e., pore pressure becomes more subhydrostatic).

For Groups 2, 3, and 4 fluid elevation decreases at the same time that pore pressure becomes more subhydrostatic. These findings are summarized in **Figure 30a**, where the brown line corresponds to elevation and the blue line corresponds to the fluid elevation. By determining the location of these wells in the basin we were able to identify that the wells belonging to Group 1 are all located on slopes of hills, the wells from Group 2 are located on a plateau, the ones from Group 3 are in the Powder River valley and the wells from Group 4 are located on a ridge (**Figure 30b**). In summary, wells located on the slopes become more subhydrostatic with elevation because the fluid level remains constant. In addition, wells located in plateaus, river valleys and ridges become more subhydrostatic at constant elevation because the fluid level decreases. Usually, the water table reflects the topography in a more subdued way. However, these data allow one to real-

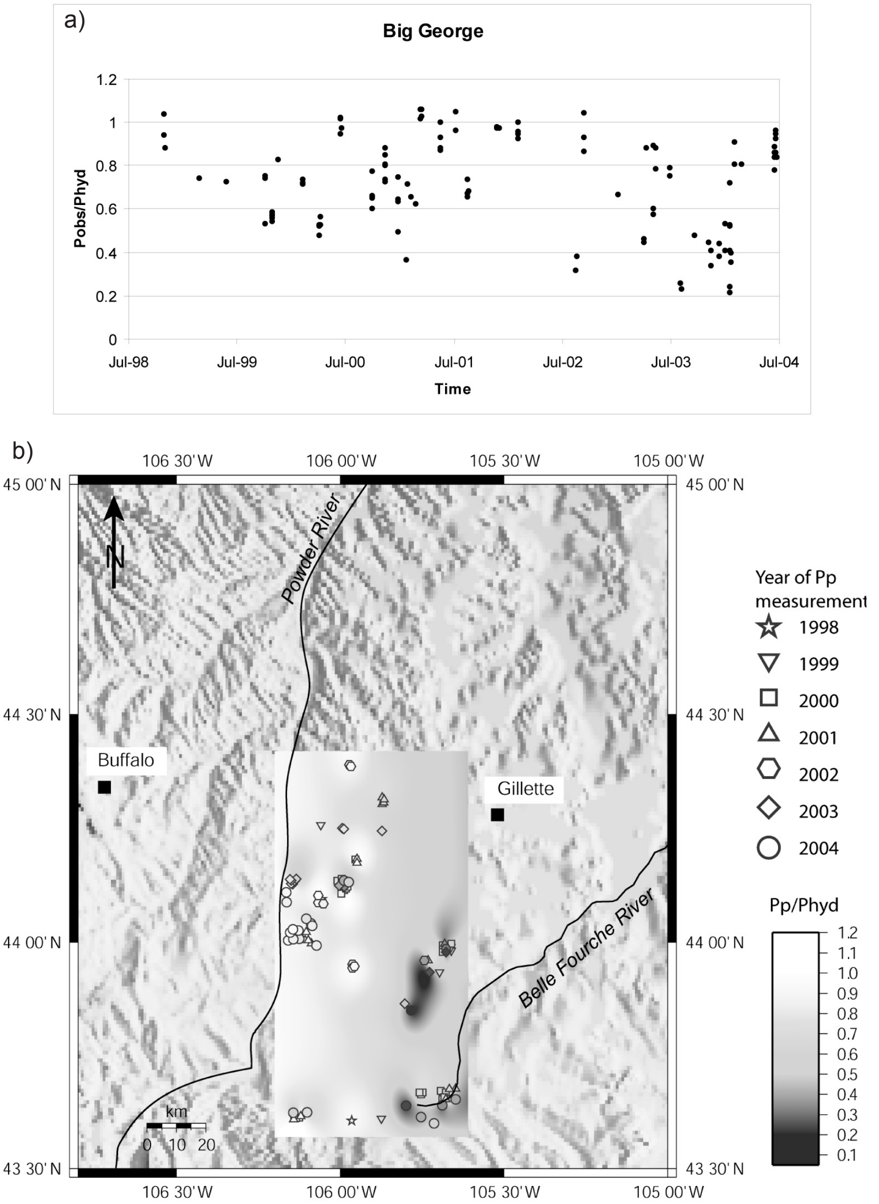

Figure 28. (a) Cross-plot of P_{obs}/P_{hyd} versus time. (b) Map of P_{obs}/P_{hyd} for Big George coal; symbols represent the year at which the pore pressure measurement was done.

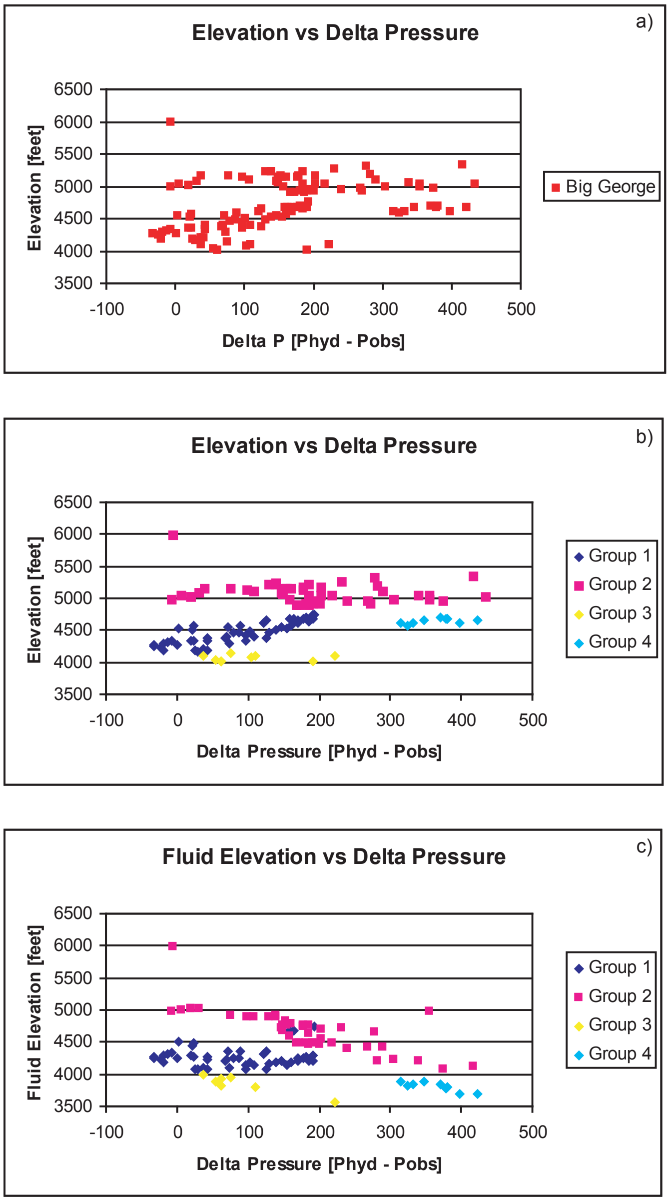

Figure 29. Elevation versus delta pressure for Big George coal. (a) Ungrouped data. (b) Same data grouped in four different groups. (c) Fluid level versus delta pressure for the four groups.

ize that the water table does not follow the topography in the studied region, which might be indicating the impact of anthropogenic activities (e.g. domestic water wells, mining, CBNG operations) in the groundwater system.

With the limited amount of P_p data obtained, it has not been possible to find a clear correlation between P_p and depth, thickness or elevation. A possible explanation for this lack in trend in pore pressure is that the coal may not be a hydraulically isolated formation. The coals may be in communication with other formations resulting in a masked magnitude of the "coal" pore pressure. Since there may be a hydraulic connection between the coals and adjacent formations, the pore pressure magnitude obtained in the coal may be the pore pressure that results from the hydraulic interplay of all the formations hydraulically connected at a certain location in the basin.

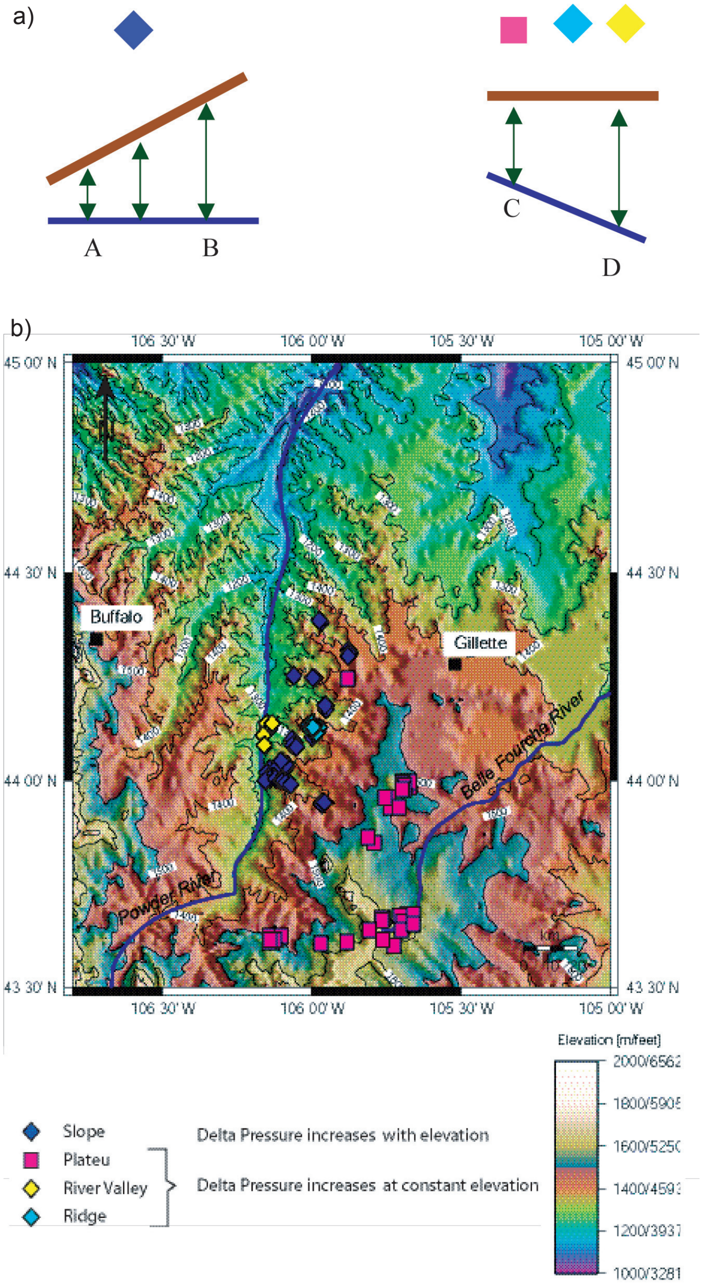

Figure 30. (a) Variations of fluid elevation and topography for Group 1 (on the left) and Groups 2, 3, and 4 (on the right). For Group 1 the pore pressure at point B is more subhydrostatic than at point A; for Groups 2, 3, and 4 the pore pressure at point D is more subhydrostatic than at point C. (b) Location of the wells that conform the different groups. The elevation contours are in meters.

Figure 31 shows an example in which the delta pressure has varied by 150 psi even though production has not started. This well is located in T46N, R74W (in Area D). An important observation about this well is that gas production starts before water production, which may originate from desorbed gas due to depressurization. The average water

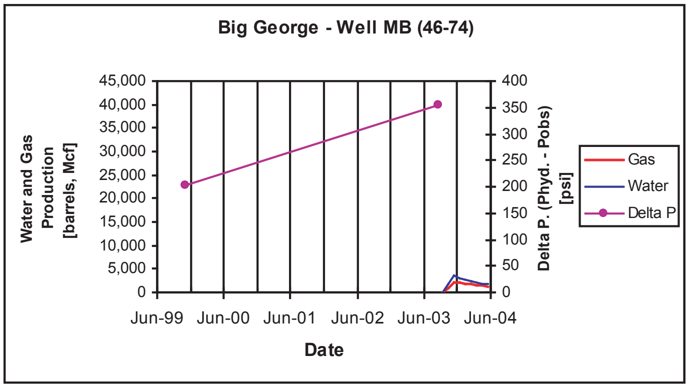

Figure 31. Logically, changes of pressure occur after dewatering starts. However, in this well the pore pressure changes before production starts.

production is 2082 barrels per month and the average gas production is 1416 MCF per month. S_3 data are not available for this specific well but the S_3 data from wells in this same field and in the same section (and adjacent sections) indicate that $S_3 = S_{hmin}$, corresponding to vertical fracture propagation. Thus, this well reinforces what has been observed before, that is, wells with vertical fractures that produce low water volumes produce gas immediately.

However, the reason why the pore pressure varies before the dewatering phase starts is unknown and deserves attention. Production-induced pore pressure changes may perhaps affect the magnitude of S_3 as well. However, further analysis is needed to understand how the reservoir works, its connection and correlation with adjacent formations and how the drawdown from one well affects the pore pressure in other wells and whether this inflicts a change in S_3.

Recommendations to achieve best well completion practices

In this study, we have demonstrated that water-enhancement activities during wellbore completion result in hydraulic fracturing of the coal. All of the wells with exceptionally high water production are associated with vertical fracture propagation. In these same wells, there are very significant delays in gas production, apparently due to inefficient depressurization of the coals. Approximately half of the wells characterized by vertical hydraulic fracturing are also characterized by excessive water production.

In areas of known vertical fracture propagation it is necessary to limit the injection during the water enhancement tests in order to prevent propagation of induced fractures into the overlying water-bearing formations. In areas of unknown least principal stress an alternative to the "standard" wellbore completion methods is suggested to limit the number of wells characterized by excessive water production and delayed gas. Water-enhancement procedures should be done in two steps. In the first step, a minifrac (about 2 bpm for about 2 min) should be done to determine the magnitude of the least principal stress and thus whether fracture propagation would be vertical or horizontal. If the least horizontal stress corresponds to the overburden (approximately 1 psi per foot), it is safe to assume that horizontal fracture propagation will occur and the water enhancement activities can proceed at whatever rate and duration the operator chooses. Because many wells with horizontal fractures tend to be poor gas producers, such wells could be hydraulically fractured (and propped) to enhance gas production without risk of significantly affecting the rate of water production. If the shut-in pressure is significantly less than the overburden (about 0.6 to 0.9 psi per foot), vertical hydraulic fracture growth is implied and significantly reduced pumping is advised. This would be beneficial from the perspective of minimizing produced waters and decreasing the time for initial gas production.

Mapping the thickness of a coal seam could also be used to predict the direction in which a fracture will propagate. As was shown in **Figures 11** and **12**, hydraulic fractures propagate in the vertical plane in coals as thick or thicker than 60 feet. Therefore, if the thickness of the coal is greater than 60 feet, the water enhancement test should be done with a reduced amount of water to prevent vertical hydraulic fracture propagation.

Summary and conclusions

Through analysis of water-enhancement tests performed in CBNG wells of the PRB, it is clear that the water-enhancement activities result in hydraulic fracturing of the coal and possibly the adjacent strata, resulting in perhaps both excess CBNG water production and inefficient depressurization of coals.

The magnitude of the least principal stress has been compiled for 372 wells, and this has demonstrated that both vertical and horizontal hydraulic fracture propagation occurs within the basin. Where the least principal stress is vertical, hydraulic fracture growth is horizontal and water production is minimal. Where the least principal stress is horizontal, fracture growth is vertical and water production is significantly greater for some wells. It is important to note that all of the wells with exceptionally high water production are always associated with vertical fracture growth. In these same wells, there are significant delays in gas production, perhaps due to inefficient depressurization of the coals. However, wells with vertical fractures that produce low water volumes are excellent gas producers (they produce more than 3000 MCF per month) and are better gas producers than wells with horizontal fractures. Since wells with vertical fractures are, in general, excellent gas producers, it is inferred that the face cleats in the coals must be efficiently connected by the induced vertical fracture.

It has been identified that horizontal hydraulic fracturing is typical toward the Sheridan area. This may be a significant finding, as water injection wells are perhaps needed in the near future in this region because the water has a high content of sodium and will need to be properly disposed. Thus, knowing that there is no vertical connection between the coal seam that is being produced and the sand layers where the water may be injected is particularly important for the operators of the area if water injection activities are undertaken here.

While the reason for the variation in the magnitude of S_3 has not been determined it does appear that coal thickness affects the S_3 magnitudes. In general, in areas where a coal seam has a thickness greater than 60 feet S_3 is equivalent to the minimum horizontal stress, and therefore fractures propagate in the vertical direction. By knowing the areas where a coal seam is thicker than 60 feet, propagation of a vertical fracture into adjacent formations could be avoided by scaling down the water-enhancement procedure.

In order to minimize produced CBNG waters, recommendations for better well completion practices have been outlined. In areas of known vertical fracture propagation it is necessary to limit the injection during the water enhancement tests in order to prevent propagation of induced fractures into the overlying water-bearing formations. In areas of unknown least principal stress an alternative to the "standard" wellbore completion methods has been suggested to limit the number of wells characterized by excessive water production and delayed gas. A minifrac should be done to determine the magnitude of the least principal stress and thus whether fracture propagation would be vertical or horizontal. If the least horizontal stress corresponds to the overburden, horizontal fracture propagation will occur and the water enhancement activities can proceed at whatever rate and duration the operator chooses. As many wells with horizontal fractures tend to be poor gas producers, it is also suggested that such wells are hydraulically fractured (and propped) to enhance gas production. If the shut-in pressure is significantly less than the overburden, vertical hydraulic fracture growth is implied and significantly reduced pumping is advised. This would be beneficial from the perspective of minimizing produced waters and decreasing the time for initial gas production.

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