GEOHORIZONS

Hydraulic fracturing and wellbore completion of coalbed methane wells in the Powder River Basin, Wyoming: Implications for water and gas production

Lourdes B. Colmenares and Mark D. Zoback

ABSTRACT

Excessive water production (more than 7000 bbl/month per well) from many coalbed methane (CBM) wells in the Powder River Basin of Wyoming is also associated with significant delays in the time it takes for gas production to begin. Analysis of about 550 water-enhancement activities carried out during well completion demonstrates that such activities result in hydraulic fracturing of the coal. Water-enhancement activities, as the operators in the basin call this procedure, consists of pumping 60 bbl of water/min into the coal seam during approximately 15 min. This is done to clean the wellbore and to enhance CBM production. Hydraulic fracturing is of concern because vertical hydraulic fracture growth could extend into adjacent formations and potentially result in excess CBM water production and inefficient depressurization of coals. Analysis of the pressure-time records of the water-enhancement tests enabled us to determine the magnitude of the least principal stress (S_3) in the coal seams of 372 wells. These data reveal that because S_3 switches between the minimum horizontal stress and the overburden at different locations, both vertical and horizontal hydraulic fracture growth is inferred to occur in the basin, depending on the exact location and coal layer. Relatively low water production is observed for wells with inferred horizontal fractures, whereas all of the wells associated with excessive water production are characterized

Manuscript received October 3, 2005; provisional acceptance February 9, 2006; revised manuscript received June 16, 2006; final acceptance July 18, 2006.
DOI:10.1306/07180605154

AUTHORS

Lourdes B. Colmenares ~ *Department of Geophysics, Stanford University, Stanford, California 94305; present address: Kalchbuehlstrasse 20, Zurich 8038, Switzerland; lbcf@pangea.stanford.edu*

Lourdes Colmenares got her undergraduate degree as a geophysics engineer at the Universidad Simón Bolívar in Caracas, Venezuela. She worked as an instructor in the Department of Earth Sciences of this university for one year before joining the Stress and Crustal Mechanics Group at Stanford University, from which she received her Ph.D. in geophysics in January 2005.

Mark D. Zoback ~ *Department of Geophysics, Stanford University, Stanford, California 94305*

Mark Zoback is the Benjamin M. Page Professor of Earth Sciences and professor of geophysics at Stanford University. His principal research interests are in the fields of crustal stress and reservoir geomechanics. He is currently one of the principal investigators of the SAFOD Project (San Andreas Fault Observatory at Depth) and chair of the Science Advisory Group of the International Continental Drilling Program.

ACKNOWLEDGEMENTS

We thank Apache Corporation, Conoco-Phillips, and Marathon-Pennaco Energy (sponsors of the Western Resources Project Foundation) for initiating and supporting this study. Special thanks to Britt Dearman, Chris Hogle, and Gabriel D'Arthenay for their help and to Conoco-Phillips, Marathon Oil-Pennaco, Williams, and Wolverine Energy for providing the data used in this study. The Stanford Rock and Borehole Geophysics Program also provided financial support.

by inferred vertical hydraulic fractures. The reason wells with exceptionally high water production show delays in gas production appears to be inefficient depressurization of the coal caused by water production from the formations outside the coal. To minimize CBM water production, we recommend that in areas of known vertical fracture propagation, the injection rate during the water-enhancement tests should be reduced to prevent the propagation of induced fractures into adjacent water-bearing formations. In areas where S_3 is unknown, a minifrac should be done to determine the magnitude of S_3 (to know whether fracture propagation will be vertical or horizontal), so the water-enhancement activities at the time of well completion are done to minimize water production and optimize gas production.

INTRODUCTION

In recent years, coalbed methane (CBM) production in the Powder River Basin of Wyoming has gained importance in production, and the number of producing wells has increased markedly. Gas storage in coal beds is more complex than in most conventional carbonate and sandstone reservoirs. According to Yee, Seidle, and Hanson (in De Bruin and Lyman, 1999), CBM is stored in four ways: (1) as free gas within the micropores and fractures (cleats); (2) as dissolved gas in water within the coal; (3) as adsorbed gas held by molecular attraction on maceral, micropore, and cleat surfaces; and (4) as absorbed gas within the molecular structure of the coal. The percentage of adsorbed methane generally increases with increasing pressure and coal rank, whereas coals at shallower depths with good cleat development contain significant amounts of free and dissolved gas.

Along with the growth in CBM 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 (e.g., Rice et al., 2000; Crockett and Meyer, 2001). Coalbed-methane water production has increased since 1996 from about 100,000 bbl/day to approximately 1.6 million bbl/day in 2003 (WOGCC, 2004). 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 CBM flow (USEPA, 2002). Although the water is generally of potable quality in the center of the basin, it becomes more saline toward the north, west, and south of it (Flores and Bader, 1999; Rice et al., 2000; Bartos and Muller Ogle, 2002; Wheaton and Metesh, 2002).

Coalbed methane production is concentrated along two main bands in the basin, and although development toward the Sheridan area has started, it is not as developed as in the Campbell and Johnson counties of Wyoming (Figure 1). Coalbed methane production has migrated toward the western part of the basin, compared to its initial times (1980s to early 1990s) when production was concentrated in the Campbell County (De Bruin and Lyman, 1999). As about 12,500 wells have been drilled to date, with 50,000 more wells expected in the next decade (Environmental News Network, 2001), water disposal constitutes a major environmental challenge. At present, an average of about 150 bbl of water is produced per well per day. When there are about 50,000 producing wells in the basin, water production would be expected to rise to approximately 7.5 million bbl per day. Therefore, the disposal of such great amounts of water produced by CBM wells is a major environmental issue, especially in areas where the produced water has poor water quality.

The goal of this study is to evaluate wellbore completion practices to determine if there are ways to produce less CBM water and still achieve adequate coal depressurization for CBM production. We show below that about one-third of the wells characterized by excessive water production (wells producing more than 7000 bbl/month) also show significant delays in the time it takes for gas production to begin. Hence, minimizing the number of wells producing excess water would have appreciable beneficial consequences for optimal operations and minimal environmental impact.

GEOLOGY AND COALBED METHANE IN THE POWDER RIVER BASIN

The Powder River Basin is bounded to the east by the Black Hills uplift, to the west by the Bighorn uplift and Casper arch, and to the south by the Laramie and Hartville uplifts, and to the north, it is separated from the Williston Basin by the Miles City arch and the Cedar Creek anticline (Figure 1). The long axis of the basin is generally aligned northwest-southeast and is 18,000 ft (5486 m) deep (USEPA, 2002). Rock formations range from Paleozoic at the bottom through Mesozoic to Tertiary at the top of the basin (De Bruin et al., 2001).

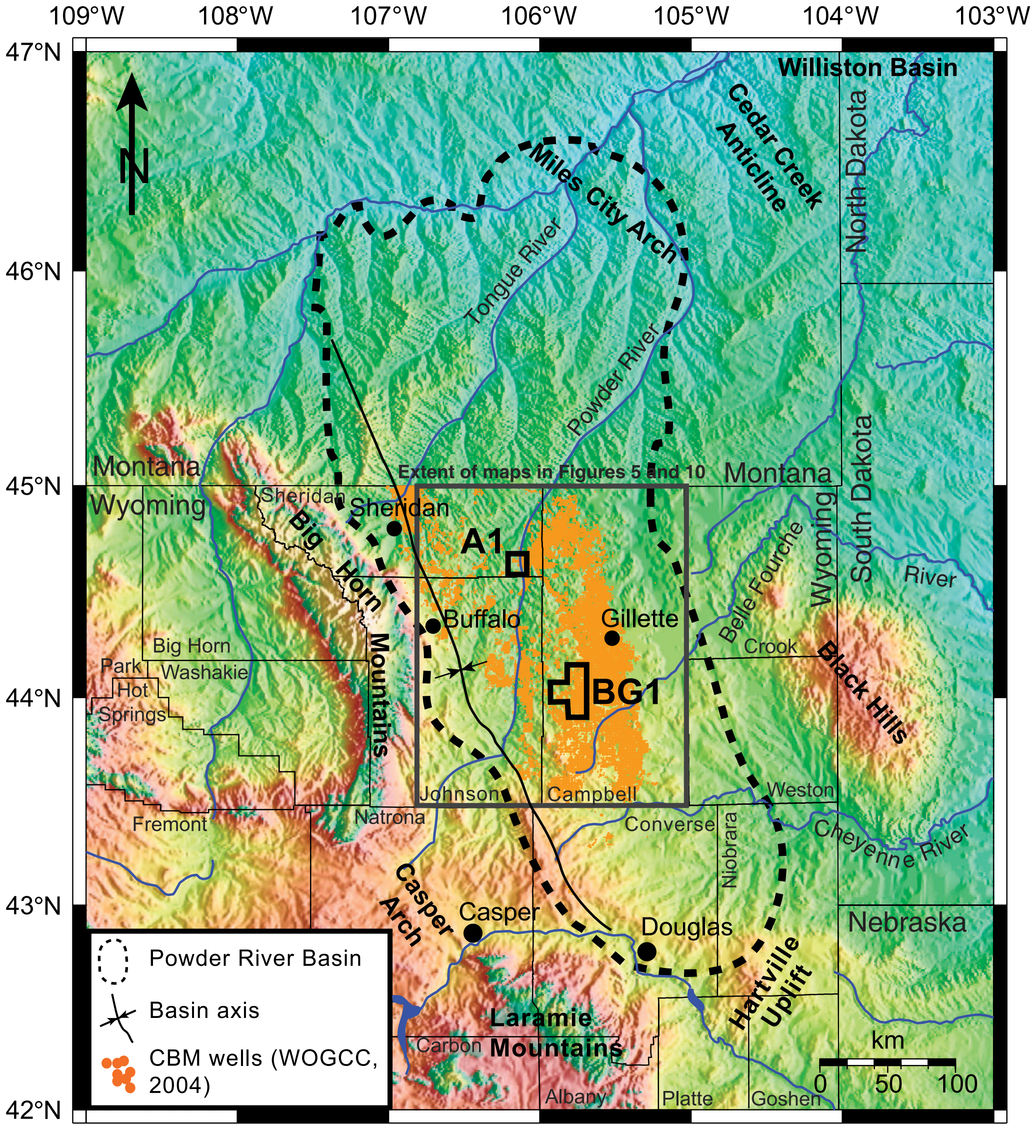


Figure 1. Map of the Powder River Basin in Wyoming and Montana (modified from Flores and Bader, 1999; USEPA, 2002). Also shown are the locations of areas BG1 and A1, from which the well's data in Figures 6 and 7 came from. The area enclosed by the gray line denotes the extent of maps shown in Figures 5 and 10.

The basin is a large asymmetrical syncline with its axis near its west side (Flores and Bader, 1999). Coal is found in the Paleocene Fort Union and Eocene Wasatch formations (Figure 2). Most of the coal beds in the Wasatch Formation are continuous and thin (6 ft [1.8 m] or less), although locally, thicker deposits have been found (De Bruin and Lyman, 1999). The Fort Union Formation extends more than 22,000 mi^2 (56,979,736 m^2) in the Powder River Basin in Wyoming and Montana. It is overlain by the Wasatch Formation and underlain by the Lance Formation in the central part of the basin and is more than 5200 ft (1585 m) thick along the basin axis (Flores and Bader, 1999).

Most of the coal in the Powder River Basin is subbituminous in rank. Some lignite has also been identified. The thermal content of the coals found in the Powder River Basin is typically 8300 Btu/lb (Randall in USEPA, 2002). Coal in the Powder River Basin was formed at relatively shallow depths at relatively low temperatures. Most of the methane generated under these conditions is biogenic. 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 Powder River Basin 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 content of the Powder River Basin coal is compensated

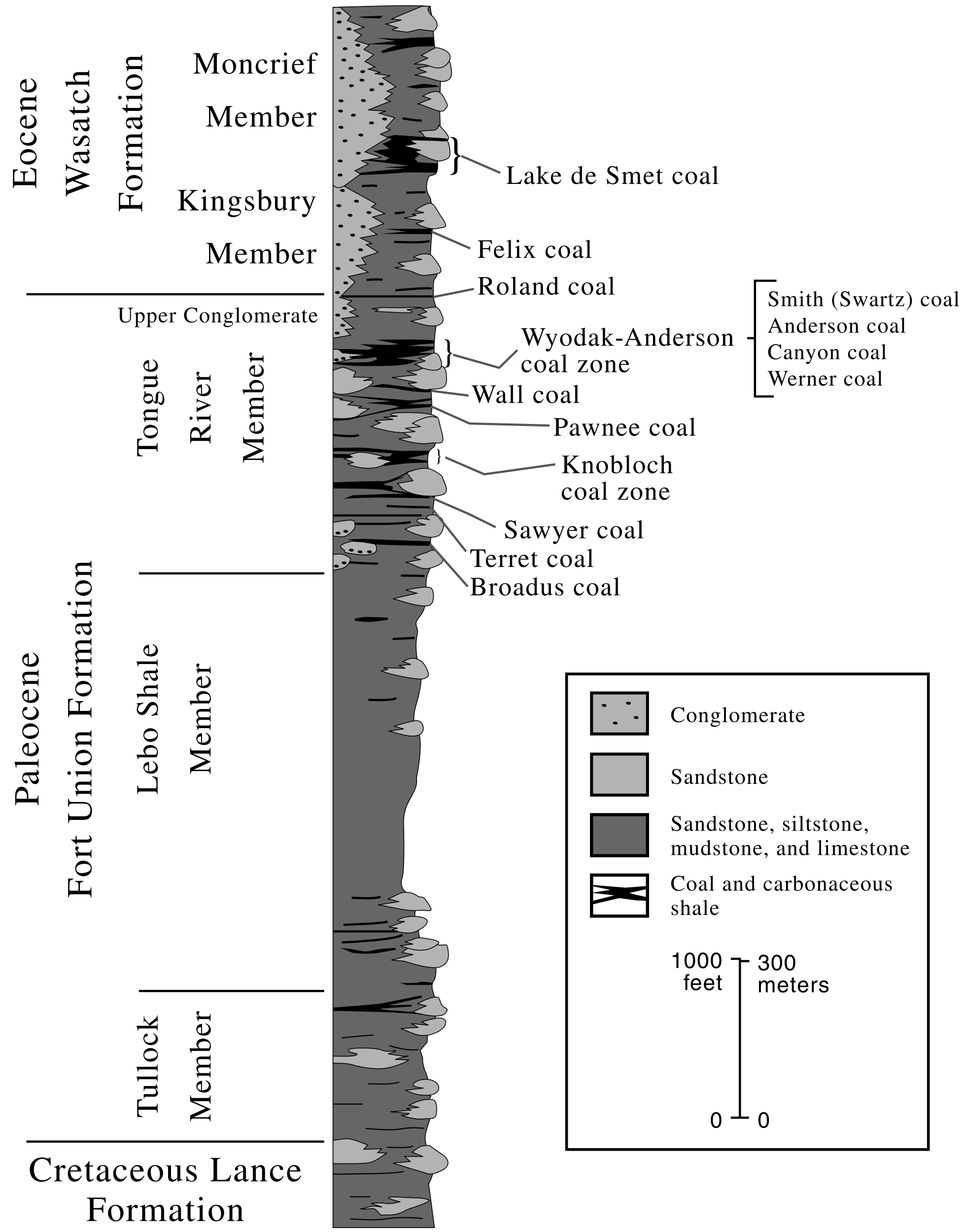


Figure 2. Composite stratigraphic column showing subdivisions of the Upper Cretaceous rocks, the Paleocene Fort Union Formation, and the Eocene Wasatch Formation in the Powder River Basin, Wyoming and Montana. The Wyodak-Anderson coal zone is synonymous to the Big George coal in the central part of the basin (modified from Flores and Bader, 1999).

by the thickness of the coal deposits. Because of the thickness of the deposits and their accessibility, commercial development of the CBM has been found to be economical (USEPA, 2002).

DRILLING AND COMPLETION OVERVIEW

A common completion technique used by many operators in the Powder River Basin is to drill to the top of the coal seam, case and cement the wellbore, and then drill the coal section with a relatively small diameter bit (frequently 6.25 in. [15.8 cm]). This section of the well is then under-reamed to enlarge the hole diameter (to ~14 in. [~35.5 cm]) and to minimize formation damage in the coal section. In most cases, water is then pumped into the wellbore to clean it out and enhance CBM production by creating pathways in the coal for easier flow of water and gas into the well. This procedure is called water enhancement and commonly consists of pumping water at a rate of approximately 2500 gal/min (~60 bbl/min) into the coal for approximately 15 min. To finalize well completion, tubing with a submersible electric water pump is inserted to allow both water and gas to separately flow from the bottom of the well. Methane exits the well through the annulus formed

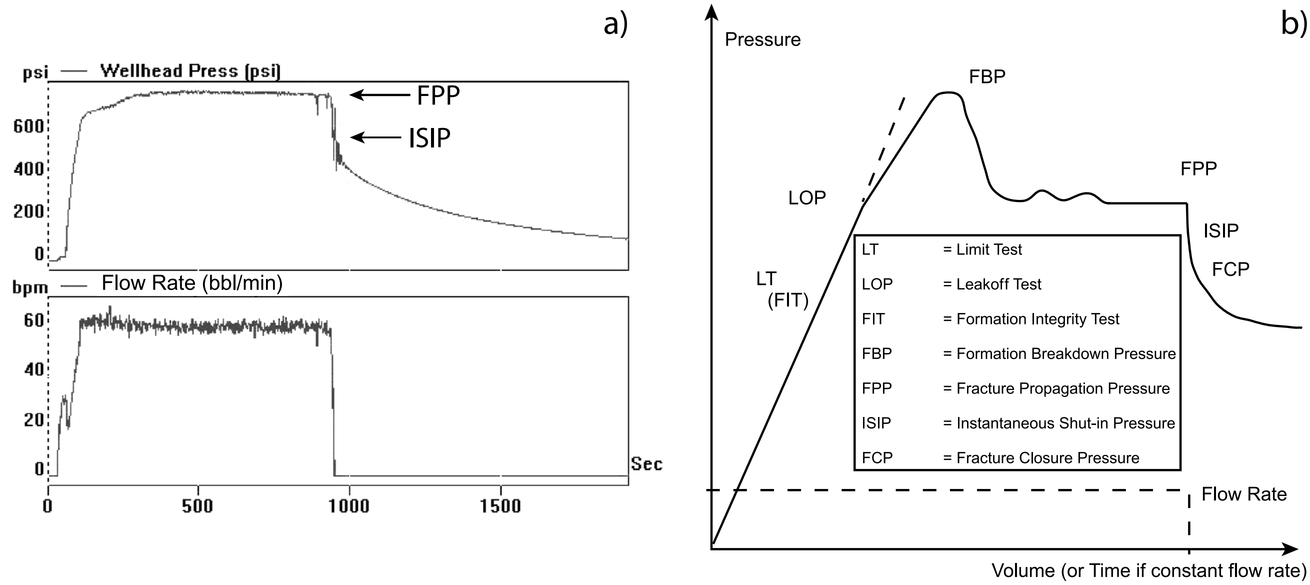


Figure 3. (a) Water-enhancement test from a coalbed methane well in the Powder River Basin. (b) Schematic illustration of an extended leakoff test (Zoback et al., 2003). The dashed line diverging from the curve corresponds to the case when no fracture is opened.

by the casing and the tubing. Wells are commonly dewatered for several months before producing significant quantities of methane gas (De Bruin et al., 2001).

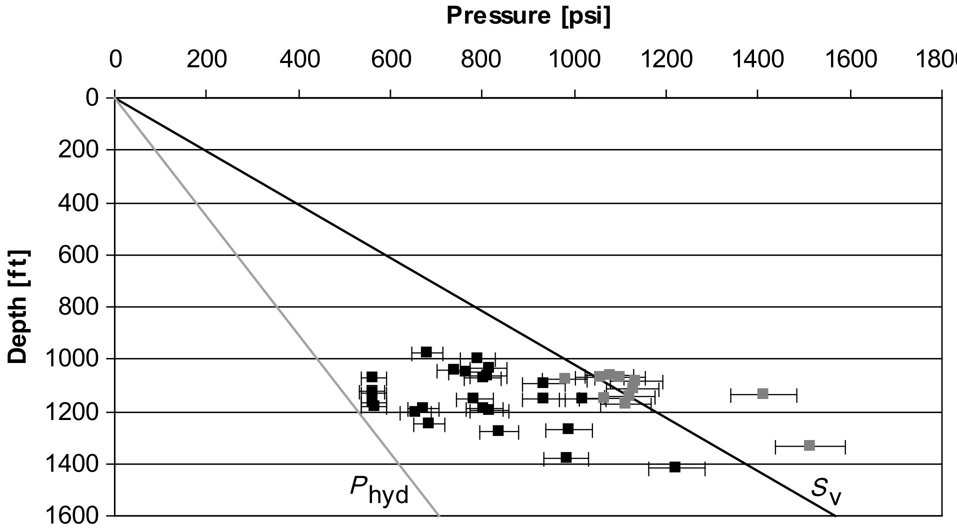
Hydraulic Fracturing in the Powder River Basin

During the initial years of CBM development in the Powder River Basin, gas exploration and development companies completed wells with and without hydraulic fracturing to test whether it would be possible to stimulate production. However, conventional hydraulic fracturing (using viscous gels and proppants) was relatively expensive and seemed to result in limited benefit. Hydraulic fracturing of the coal also became associated with the potential for increased groundwater flow into the CBM wells and collapse of openhole wells in the coal upon dewatering (USEPA, 2002).

Although conventional hydraulic fracturing is not done currently, water-enhancement procedures commonly result in hydraulic fracturing of the coal. In Figure 3a, a water-enhancement test plot from the Powder River Basin is shown. The upper panel on the left shows the pressure-time history while the water was being pumped into the well. The lower panel on the left shows the flow rate in barrels per minute. The pressure-time history from the water-enhancement test is similar to the pressure-time history of a minifrac or extended leakoff tests (Figure 3b) in that as large volumes of water are pumped into the coal at constant rate, the pressure remains constant. This characteristic of the tests is clear evidence of hydraulic fracture propagation into the formation. A reliable measurement of the least principal stress is obtained from the instantaneous shut-in pressure after abruptly stopping flow into the well because any pressure gradient caused by viscous pressure losses disappears when pumping stops (Haimson and Fairhurst, 1970).

To determine whether a hydraulic fracture will propagate in a vertical or horizontal plane, it is necessary to know the magnitude of the least principal stress (S_3) because a hydraulic fracture will always propagate perpendicular to the orientation of S_3, that is, in the direction that offers the least resistance (Hubbert and Willis, 1957). If S_3 corresponds to the minimum horizontal stress, the hydraulic fracture will propagate in a vertical plane. If S_3 corresponds to the overburden stress, hydraulic fractures will propagate in a horizontal plane. In the case when a hydraulic fracture propagates in a vertical plane, the extent of vertical propagation is controlled by the variation of the least principal stress with depth as related to the pumping pressure. If the hydraulic fracture extends up into the adjacent strata through a confining unit, it could result in both excess CBM water production (from groundwater in adjacent strata) and inefficient depressurization of coals. It has been suspected that in some cases, even after a relatively short period of production (several months), an appreciable

Figure 4. Magnitude of the least principal stress (S_3) in the Powder River Basin vs. depth for the Big George coal in Area BG1 (shown in Figure 1). S_v is the overburden stress, and P_{hyd} is hydrostatic pore pressure. In some parts of area BG1, the least principal stress is clearly less than the vertical stress (black symbols) such that $S_3 \equiv S_{hmin}$ and hydraulic fractures would be expected to propagate in a vertical plane. In other areas (gray symbols), $S_3 \sim S_v$ and horizontal hydraulic fracture propagation would be expected. 1 psi = 0.006895 MPa; 1 ft = 0.3048 m.



amount of the water produced from CBM wells may come from the formations adjacent to the coal seams (personal communication with several operators). A similar conclusion can be reached on the basis of a simple mass balance in cases where the volume of the water produced exceeds that available from the pore space of the coal. It seems, therefore, that one factor possibly exacerbating the water production problem in some wells is the vertical growth of hydraulic fractures during water-enhancement activities associated with the completion of CBM wells. We will test this hypothesis by analyzing the relationship between hydraulic fracture orientation and water and gas production.

LEAST PRINCIPAL STRESS IN THE POWDER RIVER BASIN

As mentioned above, 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 is 750 psi (5.7 MPa) and the instantaneous shut-in pressure is 600 psi (4.1 MPa). To determine the magnitude of the least principal stress at the depth of this test, it is necessary to add the pressure in the wellbore because of 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 the wells. The well data we present in this study are concentrated in two areas of the basin (termed A1 and BG1), which are shown in Figure 1. Once the magnitude of the least principal stress has been determined for a well at a specific coal interval, the overburden stress or S_v is also calculated. The magnitude of S_v can be obtained by integration of rock densities from the surface to the depth of interest, z, that is

$$S_v = \int \rho(z) g dz \approx \bar{\rho} g z \qquad (1)$$

where $\rho(z)$ is the density as a function of depth, g is the gravitational acceleration constant, and $\bar{\rho}$ is the mean overburden density (Jaeger and Cook, 1971). Because density logs were not available, a mean overburden density was assumed equal to 2.3 g/cm^3, which reflects a reasonable average value for the different lithologies found above the coal (i.e., mudstones, shales, and sandstones).

The method by which we identify whether the least principal stress corresponds to the overburden is to compare the S_3 value determined from the instantaneous shut-in pressure with the expected value of S_v. Figure 4 shows the least-principal-stress data we obtained for the Big George coal from different parts of area BG1. We show two reference lines in Figure 4, one corresponding to the overburden stress (S_v) and one corresponding to hydrostatic pore pressure, P_{hyd} (0.44 psi/ft). In some parts of area BG1, the data points clearly fall below the overburden (black symbols), such that the least principal stress corresponds to the minimum horizontal stress (or $S_3 \equiv S_{hmin}$). In such areas, vertical hydraulic fracture propagation is expected.

Conversely, in other parts of area BG1, S_3 values fall along the overburden line (gray symbols), meaning that the least principal stress corresponds to the overburden or S_v (or $S_3 \equiv S_v$). In such areas, horizontal fracture propagation is expected. The two data points indicating $S_3 > S_v$ are inexplicable (and perhaps spurious) as one would always expect $S_3 \leq S_v$.

We have mapped the occurrence of inferred vertical and/or horizontal hydraulic fractures for several coals in the central part of the basin. In Figure 5, the blue shades represent areas where the fractures are inferred to be horizontal ($S_3/S_v \geq 0.95$), and the red shades represent areas where the fractures are inferred to be vertical ($S_3/S_v < 0.95$). These maps were made using the interpolation tool from GMT (the generic mapping tool; Wessel and Smith, 1995). The areas where there is no control over the interpolation should be interpreted with caution and, hence, are labeled with question marks. Many of the wells (data points) are situated very close to each other, so that in some places, the symbols for some wells overlap. Figure 5 presents maps for the Anderson (79 points), Big George (76 points), Canyon (44 points), and Wyodak (91 points) coals.

Figure 5 indicates that inferred vertical and horizontal fractures occur in many areas of the basin. However, north of the cities of Gillette and Buffalo (where the coal is thinner), horizontal fracturing is more common than vertical fracturing. For instance, the Big George coal (Figure 5b) and Wyodak coal (Figure 5d) are thick coals, and inferred vertical fractures are more common than inferred horizontal fractures. The effect of coal thickness on the magnitude of the least principal stress will be revisited below.

RELATIONSHIP OF HYDRAULIC FRACTURE ORIENTATION TO WATER AND GAS PRODUCTION

As shown in the section above, the magnitude of the least principal stress with respect to S_v (and, therefore, whether the hydraulic fracture is inferred to be horizontal or vertical) varies across the basin. If vertical hydraulic fractures propagate into an aquifer, a hydraulic connection between the coal and the aquifer could be established if these fractures stay open through time. As a result, large water production (along with either a delay in gas production or a lower gas production rate) might be observed in some wells with vertical fractures. The water and gas production data for each well are reported by the operators to the Wyoming Oil and Gas Conservation Commission (WOGCC) once the well has been put in production. Based on the availability of data at the time of this study, there are more wells with least-principal-stress data than with water and gas production data.

Figures 6 and 7 show water and gas production for the Big George and Anderson coals in areas BG1 and A1, respectively. The figures separate the data into groups corresponding to wells with inferred 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 (2004) Web site.

Area BG1 (Big George Coal)

A marked contrast in water production is observed, depending on the inferred orientation of hydraulic fracture produced in the Big George coal, as can be seen in Figure 6. Thirty-one wells were studied in the area. Vertical hydraulic fracturing occurred in approximately two-thirds of the wells (22 of 31), and horizontal hydraulic fracturing occurred in approximately one-third of the wells. Overall, wells with vertical fractures produced much more water than wells with horizontal fractures. Importantly, 71% of the water from the Big George coal is produced by only one-third of the total number of wells (those enclosed in the blue dashed box in Figure 6a, b), all of which are characterized by inferred vertically propagating hydraulic fractures. Thus, half of the wells with vertical fractures produce excessive water. Also note that the same wells that produce 71% of the CBM water show no gas production, even after being in production for more than 16 months. In fact, for the period shown, gas production seems to occur only in wells (with inferred horizontal or vertical fractures) that produce less than 10,000 bbl of water/month. Wells with vertical fractures that produce low water volumes (less than 7000 bbl/month) are excellent gas producers (more than 3000 mcf/month). Although for some of these wells, gas production is delayed between 4 and 14 months, these wells produce 12 times more gas than wells with inferred horizontal fractures. Therefore, wells with vertical fractures that produce low water volumes are better gas producers than wells with horizontal fractures. This suggests that the most desirable outcome would be to produce from wells with vertical fractures,

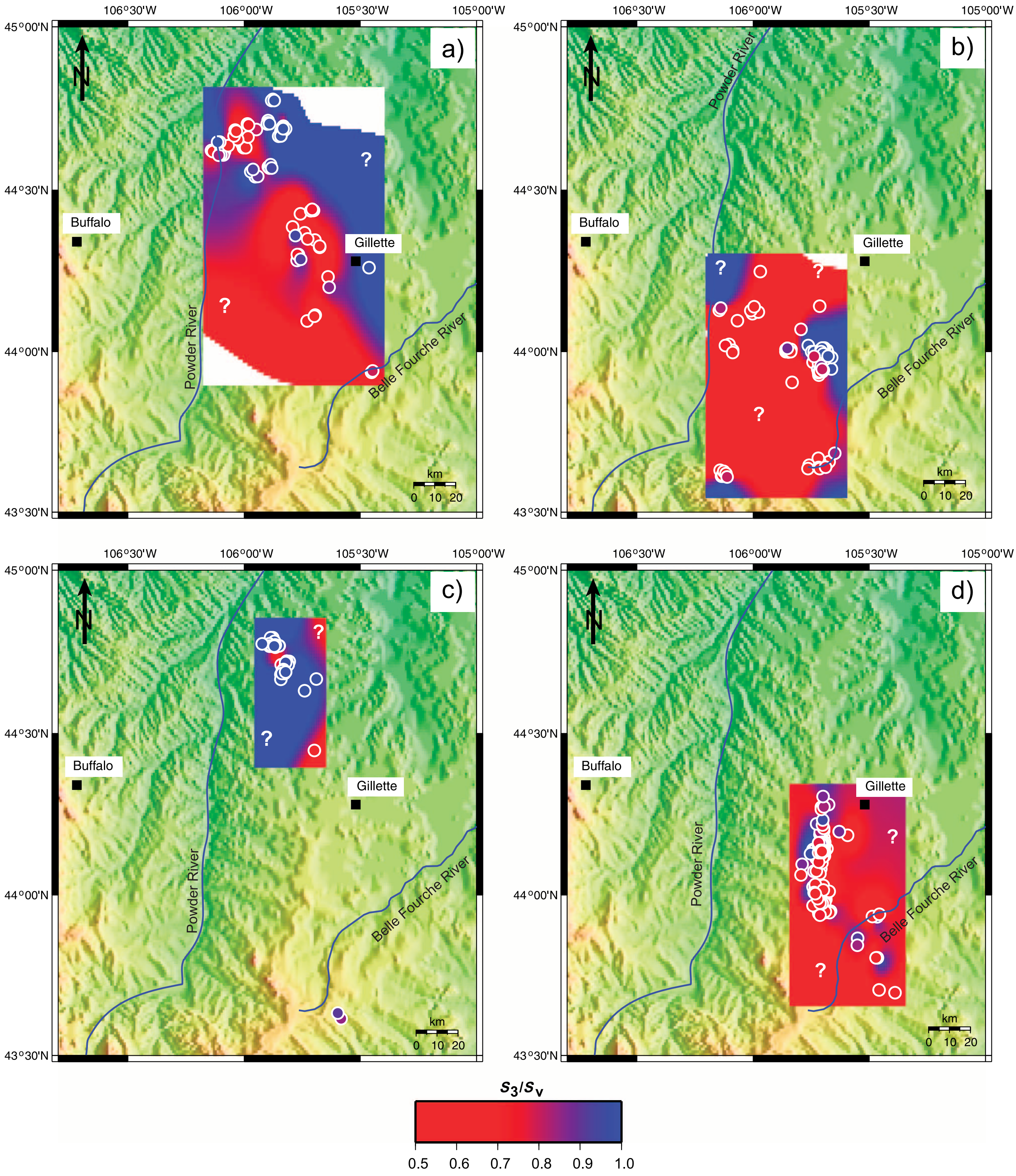


Figure 5. Map showing variation of S_3/S_v in the central part of the basin for the (a) Anderson, (b) Big George, (c) Canyon, and (d) Wyodak coals. The circles are actual data points. If $S_3/S_v \geq 0.95$, inferred horizontal fractures are expected. If $S_3/S_v < 0.95$, inferred vertical fractures are expected.

but to avoid drilling wells with excessive water production. However, the operators do not have control over whether a vertical or a horizontal fracture will be induced during the water-enhancement procedure. Therefore, knowing in advance whether an area is vertical fracture prone could help the operators to

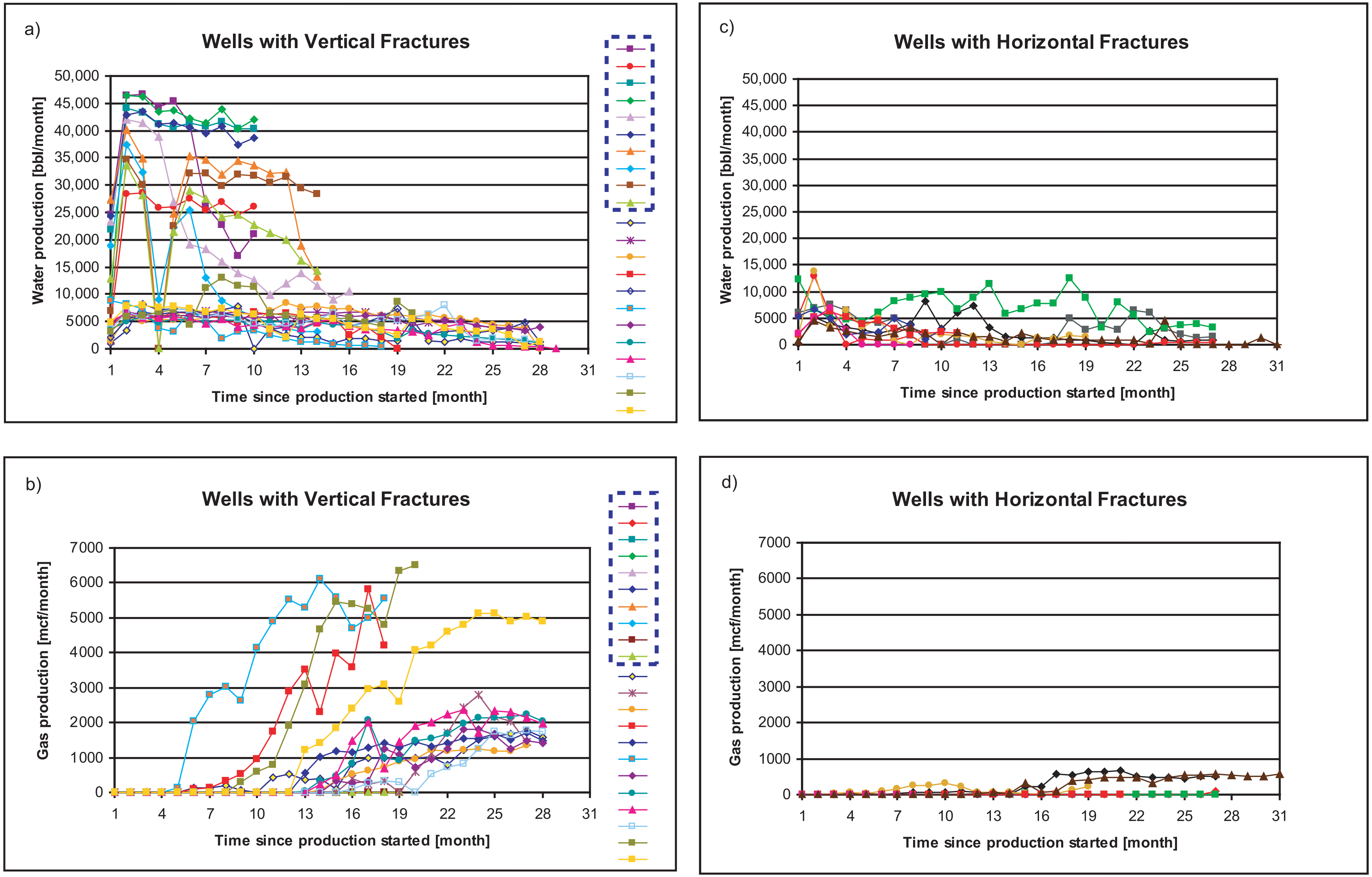


Figure 6. Water and gas production from the Big George coal for wells with inferred vertical fractures (a and b) and horizontal fractures (c and d) in area BG1. The water production in wells with vertical fractures is about 7–10 times larger than that of the wells with horizontal fractures. All the wells enclosed by the dashed blue box (a and b) produce more than 10,000 bbl in a month and have not produced any gas. For wells with horizontal fractures (c and d), water production is low, and gas production is immediate but also low (compare to gas production from wells with vertical fractures in [b]).

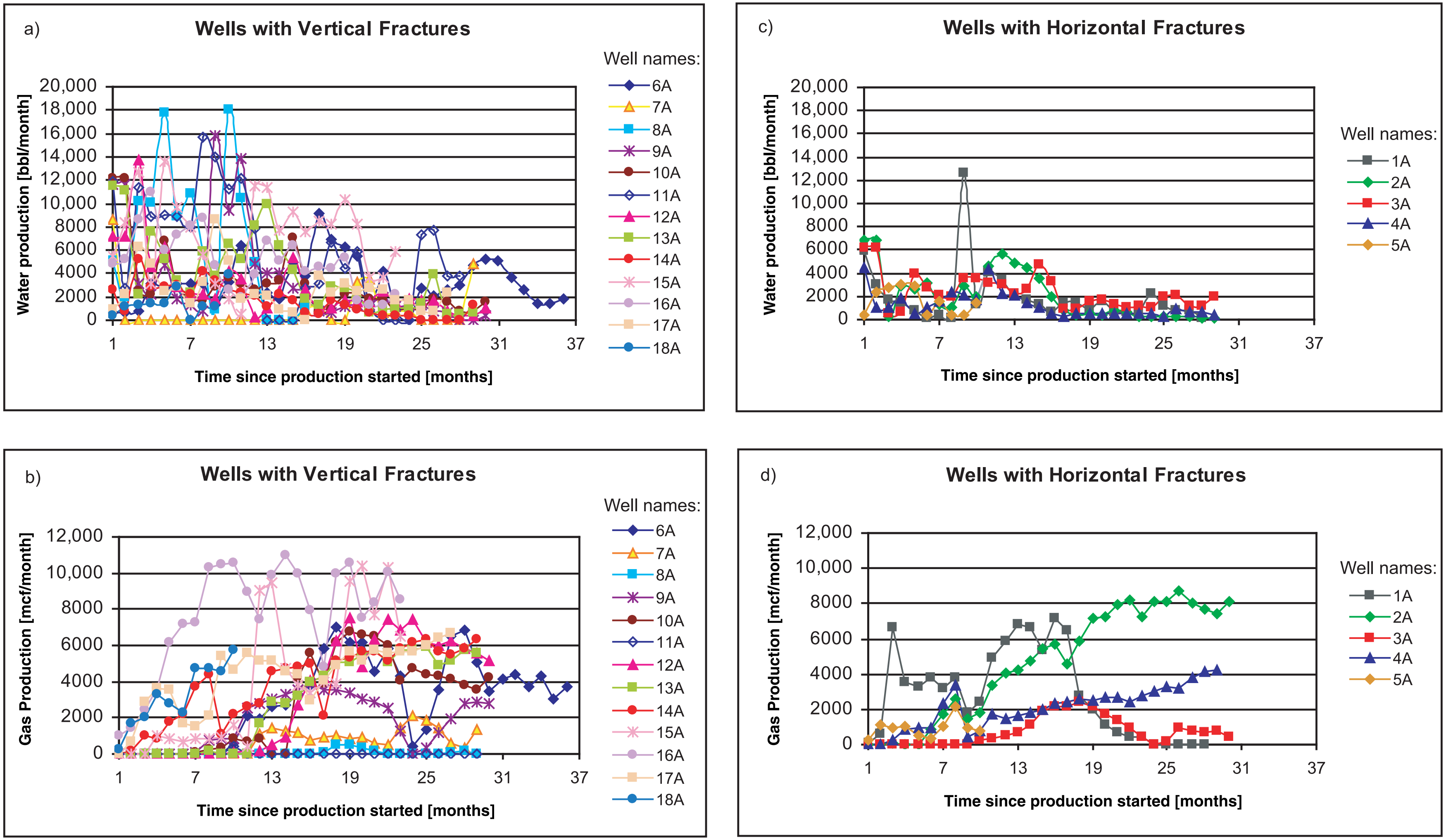


Figure 7. Water and gas production from the Anderson coal for wells with vertical fractures (a and b) and wells with horizontal fractures (c and d) in area A1. Wells with vertical fractures produce more water than wells with horizontal fractures.

Table 1. Water and Gas Production (in Percentage) per Coal Seam and According to the Type of Inferred Fracture*

	Percentage of wells with Inferred Horizontal Fractures	Percentage of Wells with Inferred Vertical Fractures	Percentage of All Wells with Inferred Vertical Fractures that Are Large Water Producers
Anderson coal (71 wells)	27	73	4
Water production (%)	21	79	14
Gas production (%)	22	78	4
Canyon coal (34 wells)	53	47	12
Water production (%)	50	50	22
Gas production (%)	31	69	24
Wall coal (36 wells)	19	81	39
Water production (%)	9	91	61
Gas production (%)	14	86	44
Big George coal (74 wells)	18	82	50
Water production (%)	5	95	84
Gas production (%)	1	99	45
Wyodak coal (85 wells)	9	91	5
Water production (%)	9	91	13
Gas production (%)	6	94	2

*Large water production is defined to be greater than 7000 bbl/month.

regulate the propagation of a vertical fracture. This would optimize overall gas production while minimizing water production.

Area A1 (Anderson Coal)

In area A1, wells with vertical fractures (Figure 7a, b) also produce more water than wells with horizontal fractures (Figure 7c, d). Water production of wells with horizontal fracturing (Figure 7c) ranges from about 0 to 6000 bbl, with only one well having an anomalous water production rate of 12,000 bbl in 1 month after 9 months of being in production (well 1A). Overall, the gas production of these wells increases with time, as can be seen in Figure 7d, and the maximum gas production was about 9000 mcf/month in well 2A. Wells with vertical fractures (Figure 7a, b) that reached a water production rate of more than 6000 bbl/month in the first 12 months either have delays in gas production of about 12 months (e.g., wells 9A, 10A, 12A, 13A) or show no gas production at all (e.g., wells 8A and 11A). Interestingly, wells with vertical fractures that have water production rates less than 6000 bbl/month produce gas immediately, reaching a gas production of 6000 mcf/month in the first 12 months of production (wells 14A, 17A and 18A).

REGIONAL SUMMARY

In Table 1, we summarize water and gas production (in percentage) per coal seam and according to the type of inferred fracture. In general, we observe that within each coal seam, there are more wells with inferred vertical fractures than horizontal fractures. Although about half of the wells (and half of the water produced) from the Canyon coal comes from wells with horizontal fractures, the corresponding amounts are quite low for the other coals. In the Anderson, Wall, and Wyodak coals, a smaller percentage of the wells are characterized by horizontal fracture propagation (27, 19, and 9%, respectively), with roughly proportionate amounts of water being produced (21, 9, and 9%, respectively). In contrast, 18% of the wells in the Big George coal are characterized by horizontal hydraulic fracture propagation, but only 5% of the water is produced from these wells.

All wells that produce large volumes of water (more than 7000 bbl/month) are associated with vertical fractures. Proportionately, there are relatively few large water producers in the Anderson, Canyon, and Wyodak coals. In contrast, a large percentage of the wells in the Wall and Big George coals are large water producers. In the Wall coal, for example, 81% of all wells have vertical hydraulic fractures, and 39% of all wells are large water producers. In the Big George coal, 82% of all wells have vertical hydraulic fractures, and 50% of all wells are large water producers. It is important to remember that in addition to the cost associated with water disposal, we showed in Figures 6a, b, and 7a, b that wells with vertical hydraulic fractures that are producing large volumes of water show significant delays (and commonly reduced quantities) of gas production.

DISCUSSION

To understand why some wells with vertical fractures have excessive water production, whereas water production is low in adjacent wells, we have briefly investigated three different factors that may be responsible for this observation: stratigraphy, thickness, and depth.

Excess CBM water production could result from the propagation of the vertical fractures into overlying strata, creating a hydraulic connection between the formations. Gamma-ray logs from several wells with vertical fractures in area BG1 were analyzed. One might expect that wells with vertical fractures and excessive water production would be overlain by sand bodies capable of yielding a large amount of water where the coals are dewatered. Correspondingly, one might expect that the wells with vertical fractures and low water production might be overlain by shales, which would yield less water than sands.

In fact, some of the wells with inferred vertical fractures and high water-production rates do have sand bodies overlying the coal. However, other wells with inferred vertical fractures and high water-production rates have shales overlying the coal. Furthermore, wells with inferred vertical fractures and low water-production rates were overlain by either shales or sands. Thus, no obvious relationship between stratigraphy and water production could be established so far. In the future, the availability and analysis of a more extensive gamma-ray-log data set may yet reveal a relationship between the extent of vertical fracture growth and stratigraphy.

As shown in Figure 8a, there is a general trend for more water production with larger thickness in the Big George coal. However, at a given thickness, for example, 70 ft (21 m), the average water production for different wells ranges from 2000 to 40,000 bbl/month. For the Wyodak coal (Figure 8b), water production is generally low, despite the relatively similar thickness of the coal seam. Even where the coal is thicker than 100 ft (30.4 m), the average water production is less than 8000 bbl/month for the Wyodak coal. This implies that coal-seam thickness is not a unique indicator of the amount of water a given coal will end up producing.

Finally, we found that wells with inferred vertical fractures and high water-production rates occur at any depth between 750 and 1500 ft (228.6 and 457.2 m). Therefore, there appears to be no direct correlation between high water production and depth.

None of the investigated factors (stratigraphy, coal thickness, and depth) seem to directly predict the amount of water that will be produced in wells in which there will be vertical hydraulic fractures formed during the water-enhancement procedure.

Possible Causes for the Variation of the Least Principal Stress in the Basin

The ratio of S_3 to S_v appears to be smaller in thicker coals than in thinner coal beds (Figure 9). This means that in thicker coals, the difference between the overburden and the least principal stress is large, and the tendency for the propagation of fractures in the vertical direction is greater. For thinner coals, the difference between S_v and S_3 is smaller, and S_v is sometimes the least principal stress, in which case, fractures propagate in the horizontal direction.

For the Big George coal, there is a direct relationship between thickness and the magnitude of S_3 (Figure 9). In fact, when the Big George coal is thicker than 47 ft (14 m), only vertical fractures occur. Mapping the thickness of the Big George coal (Figure 10a) and comparing it with the map of S_3/S_v (Figure 10b) shows 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 ft (14 m). For the other coals (Anderson, Canyon, Wall, and Wyodak), the magnitude of S_3/S_v is less than 0.95 at thicknesses greater than 60 ft (18 m), which implies that only fractures propagating in the vertical plane will occur at thicknesses greater than 60 ft (18 m) in these coals.

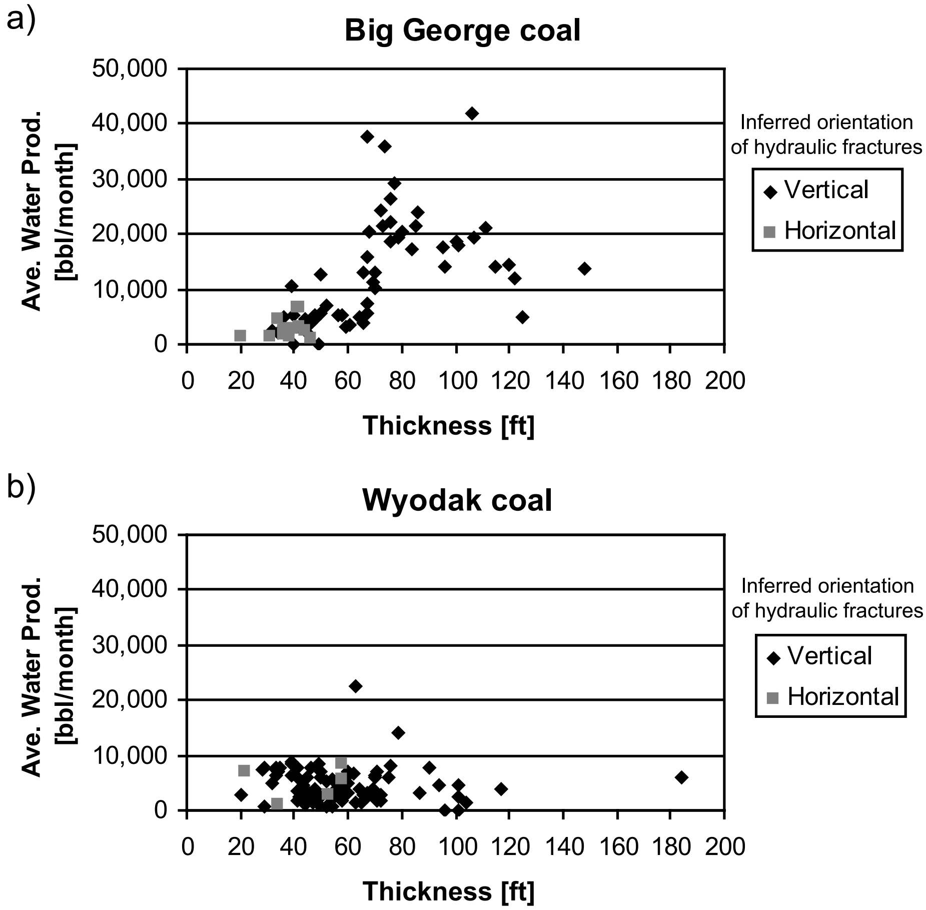


Figure 8. Average water production vs. thickness for the (a) Big George and (b) Wyodak coals.

In Figure 11a and b, we investigate whether inferred fracture geometry (horizontal vs. vertical) correlates with reservoir depth. Knowledge of such a correlation could potentially aide in designing more efficient exploration strategies. However, Figure 11 shows that the S_3/S_v ratio, and therefore, the inferred fracture geometry, is not related to depth in a systematic manner. Although the data from Big George coal indicate a tendency for high S_3/S_v and, hence, inferred horizontal fracturing at shallow depth, the opposite is true in the Wyodak coal. The source for the S_3/S_v variations within the coals in the Powder River Basin remains unknown.

Nevertheless, Figure 11 (as well as Figure 4) illustrates that the coals can sustain an appreciable amount of differential stress at all investigated depth ranges, as evidenced by the appreciable deviations of S_3/S_v from a value of 1. The capability of the coals in the Powder River Basin to sustain appreciable stress differences might be caused by the rank of these coals (subbituminous, lignite). According to Jones et al. (1988), coals with carbon contents between about 50 and 65% can have appreciable compressive strengths and may therefore be able to retain differential stress for long periods of time.

Recommendations for Best Well-Completion Practices

Note that the 550 wells we have analyzed only represent 4% of the total amount of wells in the Powder River Basin. The reliability of maps such as those presented in Figure 5 would obviously be substantially improved if more widespread least-principal-stress data were available. However, such maps are still potentially very useful for future CBM development in the basin. Operators can use such maps as tools to identify areas where hydraulic fractures would propagate either vertically or horizontally. If operators know in advance that water enhancement could lead to vertical fracture growth, they could reduce the water-injection rate to minimize the extent of vertical fracture propagation. In areas where the least principal stress is unknown, water-enhancement procedures should be done in two steps. In the first step, a minifrac (~2 bbl/min for

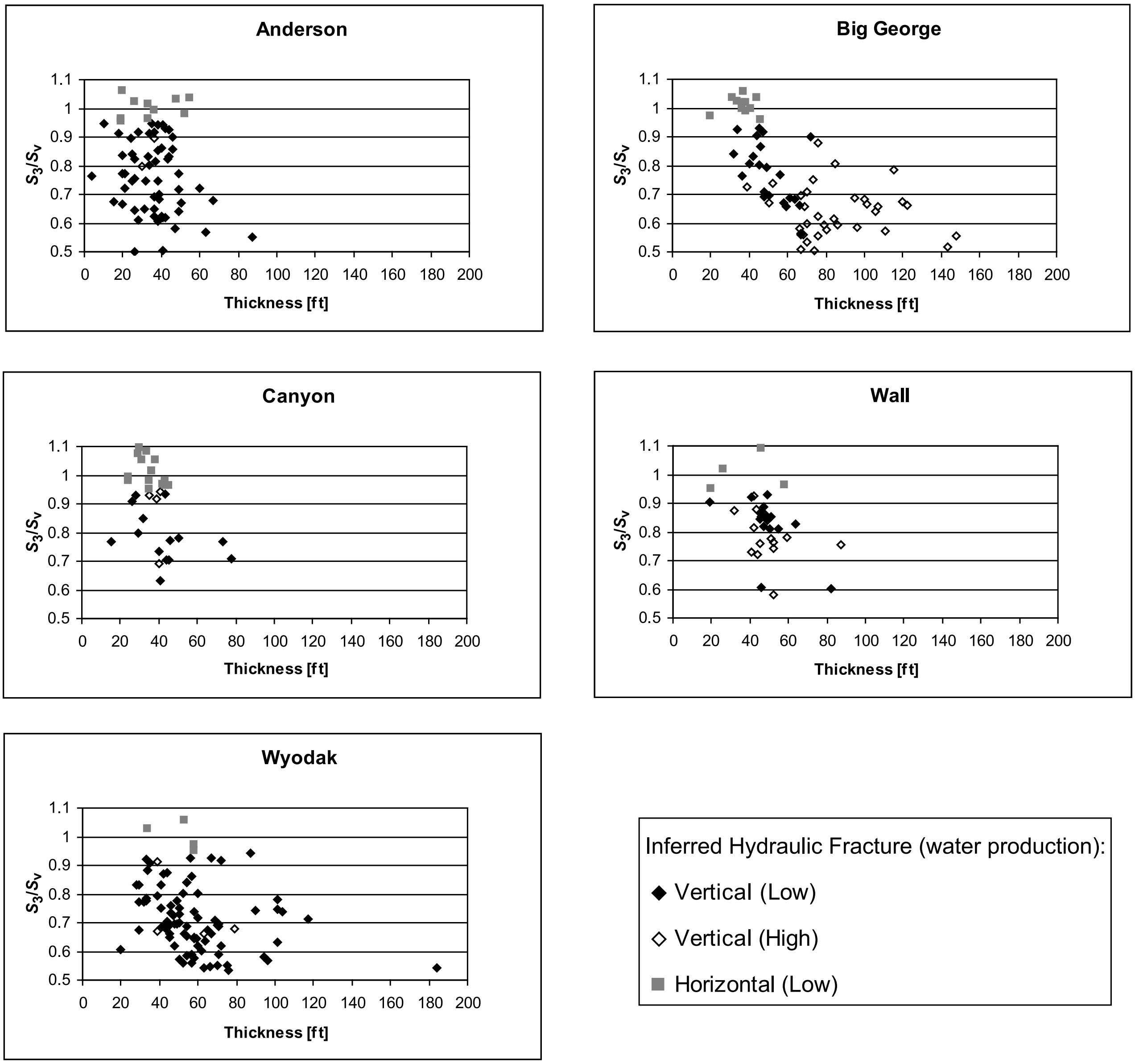


Figure 9. S_3/S_v vs. thickness for the Anderson, Big George, Canyon, Wall, and Wyodak coals. Low and high corresponds to low water production (less than 7000 bbl/month per well) and high water production (more than 7000 bbl/month per well), respectively.

~2 min) should be done to determine the magnitude of the least principal stress and, thus, whether fracture propagation will be vertical or horizontal. If the least horizontal stress corresponds to the overburden (approximately 1 psi/ft), it is safe to assume that the horizontal fracture propagation will occur, and the water-enhancement activities can proceed at whatever rate and duration the operator chooses. Because many wells with inferred horizontal fractures tend to be poor gas producers, especially those targeting deeper coals, such wells might be considered as candidates for conventional hydraulic fracturing to enhance gas production without the risk of significantly affecting the rate of water production. If the shut-in pressure is significantly less than the overburden (~0.6–0.95 psi/ft; ~13.7–21.8 kPa/m), vertical hydraulic fracture growth is implied, and pumping with reduced rates during the water-enhancement procedure is advised. This would be beneficial from the perspective of minimizing produced waters and decreasing the time for initial gas production. If the thickness of the coal is greater than 60 ft (18 m), the water-enhancement test should be done with a reduced pumping

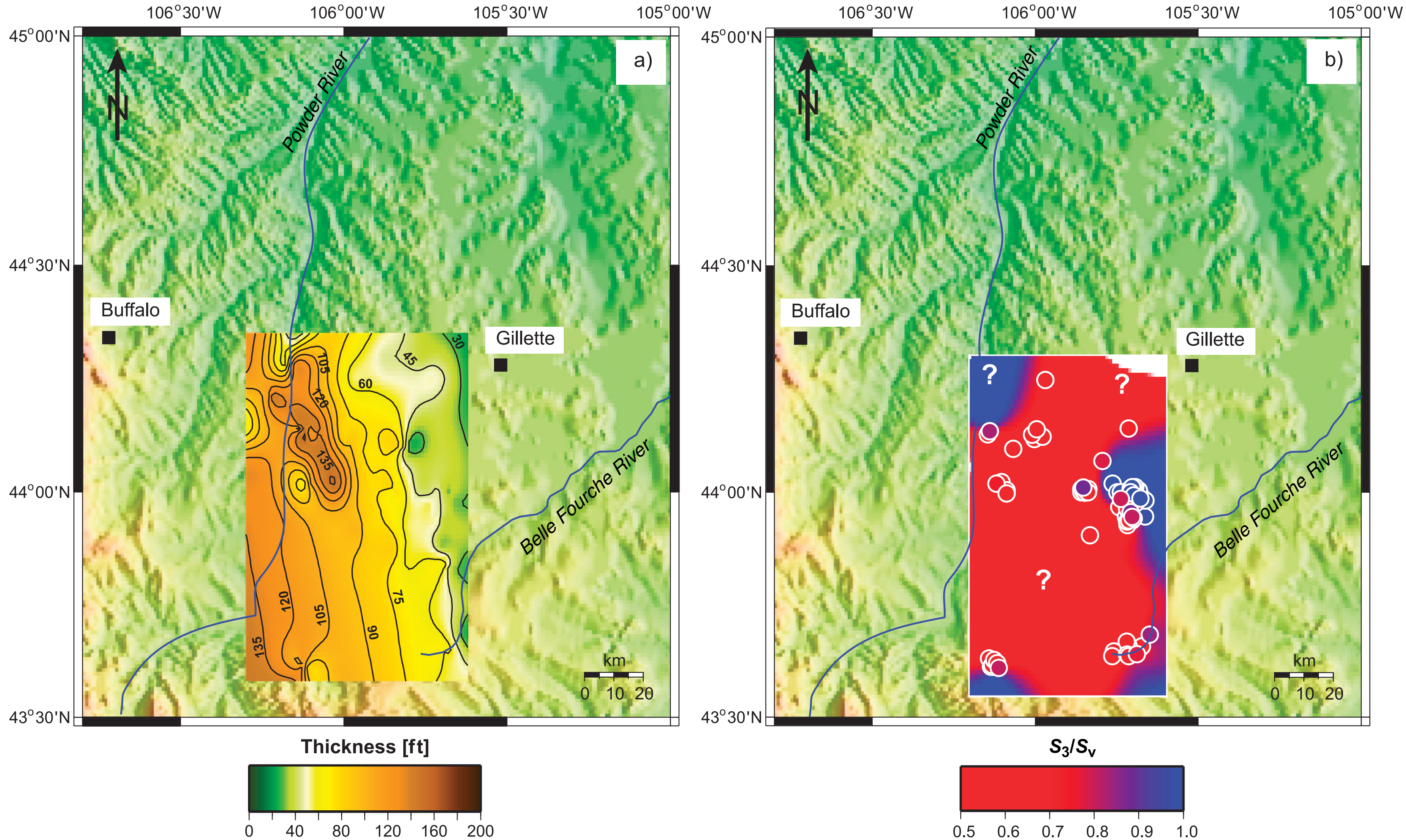
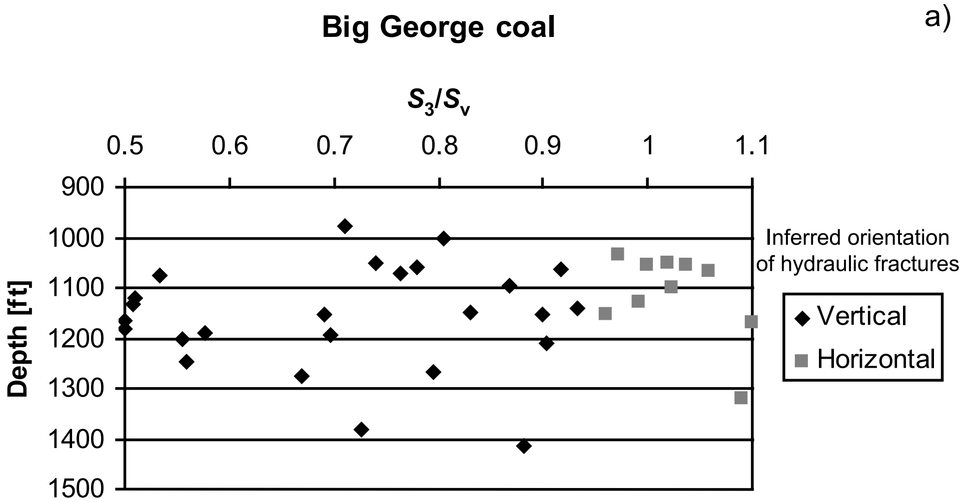
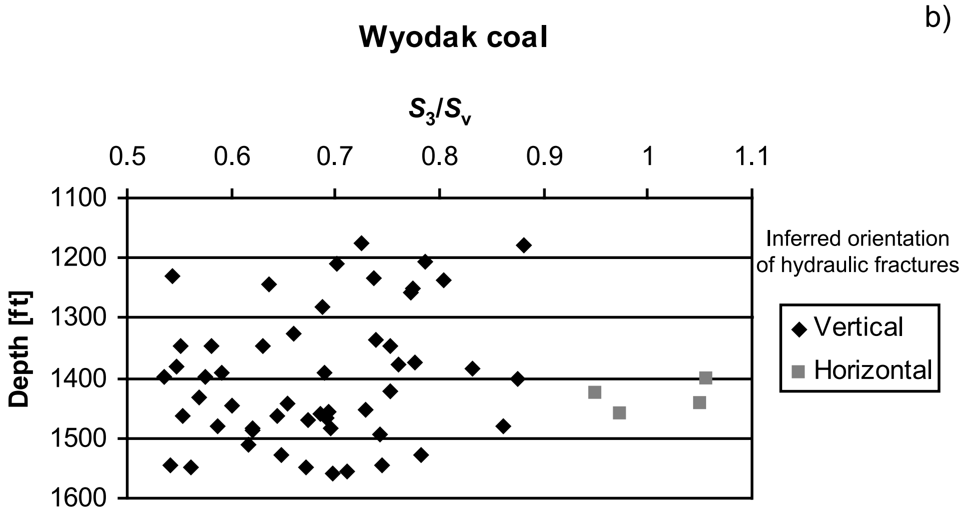


Figure 10. (a) Thickness map of the Big George coal. (b) Map showing variation of S_3/S_v for the Big George coal.

Figure 11. S_3/S_v vs. coal seam depth for the (a) Big George and (b) Wyodak coals.





rate to prevent vertical hydraulic fracture propagation because we have observed that coals with thicknesses greater than 60 ft (18 m) have $S_3 = S_{hmin}$.

CONCLUSIONS

Through analysis of water-enhancement tests performed in CBM wells of the Powder River Basin, we have found that the water-enhancement activities result in hydraulic fracturing of the coal and possibly the adjacent strata, resulting in excess CBM 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 inferred vertical and horizontal hydraulic fracture propagation occurs within the basin. Where the least principal stress is vertical, hydraulic fracture growth is inferred to be horizontal, and water production is minimal. Where the least principal stress is horizontal, fracture growth is inferred to be vertical, and water production is significantly greater for some wells. 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, most likely because of inefficient depressurization of the coals. However, wells with vertical fractures that produce low water volumes are excellent gas producers and are better gas producers than wells with horizontal fractures in the same coal.

Although the reasons for the variation in the magnitude of S_3 have not been determined, we showed that one of the factors affecting it is coal thickness. In general, in areas where a coal seam has a thickness greater than 60 ft (18 m), S_3 is equivalent to the minimum horizontal stress, and therefore, fractures propagate in the vertical direction. Therefore, knowing the location where the coal seams are thicker than 60 ft (18 m) can help to avoid the propagation of vertical fractures caused by water-enhancement procedures.

Finally, for better well-completion practices in areas of known vertical fracture propagation, it is necessary to reduce the water-injection rate during the water-enhancement tests to prevent the propagation of induced fractures into the overlying water-bearing formations. In areas of unknown least principal stress, a minifrac should be done to determine the magnitude of the least principal stress and, thus, whether fracture propagation would be vertical or horizontal to proceed accordingly with the water-enhancement procedure.

REFERENCES CITED

Bartos, T. T., and K. Muller Ogle, 2002, Water quality and environmental isotopic analyses of ground-water samples collected from the Wasatch and Fort Union formations in areas of coalbed methane development— Implications to recharge and ground-water flow, eastern Powder River Basin, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 02-4045, 89 p.

Crockett, F., and J. Meyer, 2001, Update and revision of interim drainage report on coalbed methane development and drainage of federal land in the south Gillette area, Campbell and Converse counties, Wyoming. T40–50N, R70–75W: Bureau of Land Management, Wyoming, 16 p.

De Bruin, R., and R. Lyman, 1999, Coalbed methane in Wyoming, *in* W. R. Miller, ed., Coalbed methane and the Tertiary geology of the Powder River Basin, Wyoming and Montana: Wyoming Geological Association Guidebook 50, p. 61–72.

De Bruin, R. H., R. M. Lyman, R. W. Jones, and L. W. Cook, 2001, Coalbed methane in Wyoming: Wyoming State Geological Survey, Information Pamphlet 7, revised ed., 19 p.

Environmental News Network, 2001, Coalbed methane boom in Wyoming's Powder River Basin: http://www.climateark.org/articles/2001/4th/comeboom.htm (accessed November 2001).

Flores, R. M., and L. R. Bader, 1999, Fort Union coal in the Powder River Basin, Wyoming and Montana: A synthesis, *in* U.S. Geological Survey Professional Paper 1625-A, Resource assessment of selected Tertiary coal beds and zones in the Northern Rocky Mountains and Great Plains region: http://geology.cr.usgs.gov/energy/coal/PP1625A/Chapters/PS.pdf (accessed February 2003).

Haimson, B., and C. Fairhurst, 1970, In situ stress determination at great depth by means of hydraulic fracturing, *in* W. Somerton, ed., 11th Symposium on Rock Mechanics: Society of Mining Engineers of the American Institute of Mining Metallurgical and Petroleum Engineers, p. 559–584.

Hubbert, M. K., and D. G. Willis, 1957, Mechanics of hydraulic fracturing: Petroleum Transactions of the American Institute of Mining Metallurgical and Petroleum Engineers, v. 210, p. 153–163.

Jaeger, J. C., and N. G. W. Cook, 1971, Fundamentals of rock mechanics: London, Chapman and Hall, 515 p.

Jones, A., G. Bell, and R. Schraufnagel, 1988, A review of the physical and mechanical properties of coal with implications for coal-bed methane well completion and production, *in* J. E. Fassett, ed., Geology and coal-bed methane resources of the northern San Juan Basin, Colorado and New Mexico: Rocky Mountain Association of Geologists Guidebook, p. 169–181.

Rice, C. A., M. S. Ellis, and J. H. Bullock, 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.

USEPA (U.S. Environmental Protection Agency), 2002, DRAFT evaluation of impacts to underground sources of drinking water by hydraulic fracturing of coalbed methane reservoirs (EPA 816-D-02-006): http://www.epa.gov/safewater/uic/cbmstudy/docs.html (accessed April 2003).

Wessel, P., and W. H. F. Smith, 1995, New version of the generic mapping tools released: EOS Transactions of the American Geophysical Union, v. 76, p. 329.

Wheaton, J., and J. Metesh, 2002, Potential ground-water drawdown and recovery from coalbed methane development in the Powder River Basin, Montana: Montana Bureau of Mines and Geology Open-File Report 458, 53 p.

WOGCC (Wyoming Oil and Gas Conservation Commission), 2004: http://wogcc.state.wy.us (accessed between 2001 and August 2004).

Zoback, M. D., C. A. Barton, M. Brudy, D. A. Castillo, T. Finkbeiner, B. Grollimund, D. B. Moos, P. Peska, C. D. Ward, and D. J. Wiprut, 2003, Determination of stress orientation and magnitude in deep wells: International Journal of Rock Mechanics and Mining Sciences, v. 40, p. 1049–1076.