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A numerical evaluation on the effects of impermeable faults on degasification efficiency and methane emissions during underground coal mining

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ABSTRACT

Impermeable geologic faults in the coal seam can cause intermittent production problems or can cause unexpected amounts of water or gas to issue from degasification boreholes. These faults also can impact methane emissions into the mine workings, especially if they hinder proper and effective degasification of the coal bed. They may also act as barriers for methane flow in the coal seam. Although this might seem beneficial for advancing mine workings, faulting may also cause gas pressure buildups and result in compartmentalization of the gassy regions from which large quantities of water and methane may rush into mine workings.

This study uses reservoir simulations to illustrate the effects of impermeable faults, with and without throws, on the production performance of vertical and horizontal degasification boreholes. These boreholes were drilled from the surface to intercept the coal layer and fault and were assumed to produce methane two years prior to mining of the coal seam. Longwall advances and face-position-related emissions and reservoir properties were characterized using sector definitions along the path of the panel grids. This work numerically evaluates water and gas productions of each borehole and presents the effects and the impacts of impermeable faults on methane emissions due to an advancing coal face. The results can be used to understand the effects of impermeable faults on borehole productions and face emissions due to these coal seam anomalies.

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1. Introduction

In underground coal mines, the required amount of ventilation air is based on estimates of gas release under normal conditions. Occasionally, unanticipated and unusually high emissions are encountered. These emissions, despite normal ventilation controls, may result in an explosive mixture at the face that may be ignited during mining. Investigations have shown that such emissions can often be associated with anomalous geologic features or conditions. While most operators are aware that certain geologic features may adversely affect productivity by increasing mining difficulties, few are aware of their potential as a gas emission hazard (Ulery, 2006).

Abnormal, unanticipated mine gas emissions in quantities sufficient to create hazardous conditions have often been attributed to various geologic features since the first recorded documentations of methane explosions in mines. For example, faults have long been recognized either as conduits for gas flow from strata adjacent to mined coal seams or as barriers for accumulation of large quantities of methane that could enter mine workings when intercepted.

Faults can be associated with many problems that threaten the safety of workers. For example, groundwater entering mine workings from fault zones can lead to a disaster for that operation. Fault zones are important since displacements can greatly reduce the strength of the seam bedrocks due to the creation of weakness zones and the presence of gauge materials that may be dissolved and become permeable to gas and water (Wu et al., 2004). McCulloch et al. (1975) noted that abnormal accumulations of water can be related to fracturing of the roof rock or to a fault zone.

Faults and the associated weakness zones may also be responsible for high gas concentrations encountered during mining (McCulloch et al., 1975). This is especially likely when there is stress redistribution as mining approaches a large-scale fault. In Germany, Thielemann et al. (2001) showed that in unmined regions, normal faults regularly act as gas conduits for surface emissions into the atmosphere from deep formations such as coal formations. They further demonstrated that distinctly higher rates of surface gas emissions occurred from normal faults in mined areas. This was presumably caused by the increased permeability of the fault and associated strata in response to mining. Therefore, it would seem likely that such faults could easily become pathways for gas emissions into mine workings from adjacent source beds. A shear zone in the coal seam, associated with faults, contains a large number of fractures and thus much gas, and may also be a major factor for a catastrophic failure or “outburst” of gas and coal during mining (Li et al., 2003).

One of the most effective approaches to alleviate the gas emissions from mined coal seams before mining starts is to drill stimulated

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vertical or horizontal boreholes to drain excessive gas from the coalbed (Diamond, 1994; Thakur, 1997; Noack, 1998). Vertical open-hole wells work best for high permeability coals by employing them in close spacing. These boreholes can be fractured particularly in medium permeability coals, thin beds and where multiple coal seams are penetrated. However, the problem is that most vertical wells are usually unsatisfactory due to low gas recovery rates, long term dewatering, the large number of wells needed to depressurize and limitations of surface access. Horizontal open-hole wells can be used for thick coal seams, low permeability coals, and in areas where good lateral continuity is present. Other alternatives are to use pinnate drainage pattern established by drilling multiple side laterals off a main horizontal lateral or a Z-pinnate drilling and completion system using one well site with pinnate development from four main horizontal laterals (PTTC, 2004). Horizontal wells and pinnate drilling systems have been successfully applied in several basins, including the Appalachian, San Juan and Arkoma basins. As drilling and completion strategies rapidly increase, complex horizontal drilling systems can become the most economically efficient way to produce coal seam methane.

These approaches have been proven to be very effective in various field applications to degasify fairly continuous and uniform coal seams (Perry et al., 1978; Prosser et al., 1981; Kelafant et al., 1988; Ertekin et al., 1988; Diamond et al., 1989; Aul and Ray, 1991; Young et al., 1993; Diamond, 1994; PTTC, 2004; Cameron et al., 2007). Numerous studies have demonstrated that under continuous and uniform coal seam circumstances, the performance of the boreholes and their effectiveness on reducing emissions can be predicted by modeling techniques (Sung and Ertekin, 1987; King and Ertekin, 1988; Karacan et al., 2007b). However, a uniform and continuous coal seam is seldom the case. The existence of various geologic anomalies and coal discontinuities, such as faults, can create serious problems in the drilling, completion, and production of degasification boreholes.

It is known that faults affect production characteristics of nearby coalbed methane boreholes. They create boundaries that can limit the drainage radius of the boreholes. This situation can be favorable or unfavorable in terms of gas production, depending on the size of the bounded reservoir. If the bounded volume is small, a limited amount of reservoir will be drained and thus the production potential of such a reservoir will be low. If the borehole is drilled into a large but bounded reservoir, this will potentially lead to a faster pressure drawdown when dewatering is initiated, causing higher gas saturations and production rates.

The effects of faults on coalbed gas productions have been experienced in various regions. For instance, in southeastern Deerlick Creek Field (Alabama), fault blocks have variable production characteristics. Exceptionally productive wells drilled near the eastern margin of the Strip Mine graben have penetrated a fault and are actually completed in the Holt Lake half graben (Sparks et al., 1993). Although production within the half-grabens is variable, large-scale production patterns in southeastern Deerlick Creek Field indicate that normal faults can compartmentalize coalbed methane reservoirs. Similarly, production patterns in the Cedar Cove Field of Alabama (Sparks et al., 1993) indicate that being adjacent to a major fault system has enhanced gas and water production. Pashin (1998) also reported major production experiences in complexly faulted regions in the coalbed methane fields of Alabama. Evidence suggests that faults in the Oak Grove field of the Black Warrior Basin affect gas and water production as well as the thicknesses of the seams, especially in the upthrown fault blocks. However, the significance of these structures in terms of coalbed methane exploration and production has yet to be fully appreciated.

Effective mapping of faults in coal mining is critical for productivity and safety of the workers. This is especially true where the coal seams are impacted by large displacements (Molinda and Ingram, 1989; Kecojevic et al., 2005). For instance, underground room and pillar mines in the Coalsburg seam north and south of the Warfield Fault in Mingo County, West Virginia, have been greatly impacted by faulting and related structures. Due to the combined effects of the folding and faulting, the northern mines are about 15 m (400 ft) higher in elevation than the southern ones. Overland conveyor belts connect mining blocks separated by the fault. The fault poses an extra challenge to mine development in this part of the Appalachian Basin (Coolen, 2003). The location of faults is important to Western Kentucky No. 4 seam mining also, since much of the mining occurs along the Pennyrile fault system and many mines are bordered with faults. In this region, these mines are sometimes forced to ramp up and down to reach a relatively flat reserve (Greb et al., 2001).

Site-specific considerations, through evaluations of in-place gas content and the minor and major geological faults that may affect the flow of gas during degasification and mining, are required for these challenging situations (Diamond, 1982). To help in these evaluations, numerical simulation techniques may be useful for understanding borehole production problems during degasification and emission problems during mining caused by geological faults. This study presents a numerical investigation of the effects of impermeable faults with and without throws on the pre-mining production performance of vertical and horizontal degasification boreholes and on the potential methane emissions during mining. Potential emissions due to coal seam discontinuities were modeled by assigning sequential regions in the grid. This work evaluated water and gas productions from each borehole and the impacts of coal seam discontinuities on methane emissions and water inflow into mine workings.

2. Methodology — reservoir modeling to simulate effects of impermeable faults in the coal seam on degasification and on emissions during mining

2.1. Coalbed methane reservoir and modeling parameters

A base coalbed methane reservoir model was developed to numerically evaluate the effects of various stratigraphic and geologic anomalies within the coal seam on production performance of vertical and horizontal boreholes and on gas emissions into a longwall operation. Computer Modeling Group's GEM (CMG, 2003) simulator was used in dual-porosity formulation. The base model was designed as a uniform and continuous coal seam reservoir. The grid block was designed in a multilayer (17-layers) 3-D structure which enabled spatial descriptions of the geometries and properties of the anomalies and discontinuities within the seam. A 2.6-m (8.5-ft) thick coal seam was modeled by assigning a 0.15-m (0.5-ft) grid thickness for each of the layers. Square grids were used with dimensions of 23 m×23 m (75 ft×75 ft) in the middle portion of the reservoir, gradually increasing up to 91.4 m (300 ft) at the boundaries. The modeled reservoir area for degasification and mining was approximately 4.9 km^2 (1200 acres).

In the base model, a 3:1 permeability anisotropy was created to include the effects of face and butt cleats on flow as observed in most coalbed methane reservoirs. Face and butt cleats were assumed to be perpendicular to each other, with face cleats oriented in the E–W direction and butt cleats in the N–S direction of the model. Mining direction and horizontal borehole drilling direction were modeled in the face-cleat direction, which is not uncommon for ground and methane control objectives in the southwestern Pennsylvania section of the Northern Appalachian Basin (Karacan et al., 2007a,b). Although, from only methane production point of view, the horizontal boreholes are preferred vertical to the face cleats, the ones drilled parallel to the mining direction (parallel to face cleats as in this study) are used both for degasification of the panel area in advance of mining and also for shielding the longwall entries against methane inflow during development mining and afterwards.

The base model also captured the porosity and permeability changes in the reservoir due to pressure depletion in the cleats and gas desorption from the coal matrix during primary gas production operations. During primary methane production, two distinct phenomena are associated with reservoir pressure depletion with opposing effects on coal porosity and permeability. The first is an increase in effective stress under uniaxial strain conditions. The second is methane desorption from the coal matrix resulting in matrix shrinkage and a decrease in effective stress (Harpalani and Chen, 1995; Palmer and Mansoori, 1996; Harpalani and Chen, 1997; Shi and Durucan, 2003).

The effects of matrix shrinkage and the accompanying increases in permeability and flow rate have been observed in field tests. A vertical degasification borehole with seven horizontal extensions from the bottom of a borehole in an 2.4-m (8-ft) thick section of the Pittsburgh seam produced from 2200 m^3/day (80 Mscfd) to 7300 m^3/day (260 Mscfd) per borehole. During the first 80 days of monitoring from each of the boreholes, gas production rates decreased for approximately the first 50 days before starting to increase (Fields et al., 1973). At another field production test in Mary Lee coal seam in Jefferson County, Alabama, the effectiveness of vertical boreholes on gas drainage was investigated by stimulating the well with foam and 420–840 μm size (20–40 mesh) sand. In the first 60 days of production, the flow rate decreased from 4000 m^3/day (140 Mscfd) to 1600 m^3/day (55 Mscfd). After this period, the flow rate gradually increased to 90 Mscfd at the end of seven months of monitoring (Lambert and Trevits, 1978). In this study, a model integrated into the GEM's code system by Palmer and Mansoori (1996) modeled flow rates and porosity and permeability changes in the reservoir. General reservoir properties and their average values used in building the base reservoir model are given in Table 1.

2.2. Methane drainage boreholes

Vertical and horizontal drainage boreholes were used to evaluate the effects of discontinuities on their degasification performance. In all of the models documented in this paper, boreholes were modeled as 15.2-cm (6-in.) diameter wells drilled from the surface into the coal seam. The total lengths of the simulated boreholes were 2.6 m (8.5 ft) and 1097 m (3600 ft) for vertical and horizontal boreholes, respectively. Thus, the vertical borehole completely penetrated into the coal seam. The horizontal borehole was modeled as a long-radius borehole with a 46-cm (1.5-ft) vertical section in the upper layers of the coal seam at the drill location. This short vertical leg was continued with a 91-m (300-ft) slanted interval (deviation angle is ~0.6°) before the borehole segment was completely horizontal. The horizontal section was modeled in face-cleat direction (E–W direction) in the middle layer of the coal seam, due to reasons explained in the previous section.

For the numerical simulations, the vertical-well skin factor was assumed to be −3, representing a well with a stimulation treatment, such as hydraulic fracturing, whereas the horizontal borehole was modeled as an undamaged and unstimulated well with a skin factor of 0. The roof and floor of the coal seams are very important because they facilitate hydrologic isolation of the coal, which ensures that water and gas will not be produced from adjacent permeable beds (Su et al., 2005). In the Powder River basin, it has been found that stimulation activities caused hydraulic fracturing of the coal and possibly the adjacent strata, resulting in excess water production and inefficient depressurization of coals (Colmenares and Zoback, 2007). All of the wells with exceptionally high water production are associated with vertical fracture growth. In these same wells, there are significant delays in gas production most likely due to inefficient depressurization of the coals. In all of the numerical simulations reported in this paper, floor and roof rocks are assumed to be undamaged in order to hydraulically confine the coal seam. In this study, both of the wells were operated with 0.136 MPa (20 psi) bottom hole pressure constraints for a total duration of two years prior to mining. During this period, both gas and water productions were modeled.

Table 1
Values of important reservoir parameters used in modeling the coal seam

Parameter	Value
Permeability-face cleat (md)	30
Permeability-butt cleat (md)	10
Effective porosity (%)	0.005
Effective fracture (cleat) spacing (m)/(ft)	0.03/0.1
Langmuir p. (MPa)/(psi)	2.25/326
Langmuir vol. (cm^3/g)/(scf/ton)	17.3/556
Desorption time constant (days)	50
Initial water saturation (%)	95
Coal density (g/cm^3)/(lb/ft^3)	1.35/84.7
Coal bed pressure (MPa)/(psi)	2.1/300
Poisson's ratio	0.3
Young's modulus (MPa/psi)	3740/550000
Strain at P∞ (infinite pressure)	0.01
Pore compressibility (1/kPa, 1/psi)	0.9/0.0006
P-M constant	3

2.3. Simulating face advance during longwall mining and associated emissions

This study modeled the advance of a 365.8-m (1200-ft) wide longwall panel whose start-up end was 1400 m (4500 ft) away from the borehole-drill locations (Fig. 1). Mining progressed from east to west (right to left) in Fig. 1 towards the borehole location. Every face advance was characterized by sequential “regions” of 69 m (225 ft), or three grids in the model, in length within the grid model. These regions represented the coal blocks to be mined during the mining process. Separate “regions” covering the same grid addresses were specified along the longwall advance direction for matrix and fracture elements of the dual-porosity grid model. This “proxy” approach to the moving boundary problem (Karacan et al., 2007a,b) enabled the separate determination of the “remaining adsorbed gas volume” in the coal matrix and the “free gas and water volumes” in the fractures (cleats). These volumes could be determined at any time after a certain operational period of the boreholes or they could be evaluated as a function of distance from either the start of the panel or from any of the modeled discontinuities. The gas and water quantities monitored and recorded by the simulator in each “region” were used to calculate potential emissions for a 9.1-m/day (30-ft/day) average face advance rate in the presence of stratigraphic discontinuities or geologic anomalies in the coal seam.

3. Results and discussion

An ideal coal seam from both a mining and a gas drainage point of view would possess a uniform thickness with no interruptions. However, this is rarely the case, as most coal seams exhibit geological features that disrupt this ideal design. Discontinuities, such as faults, can be structural in origin if they separate groups of rock. Discontinuities are an important consideration in evaluating the gas drainage potential of coal seams using vertical and horizontal gas drainage boreholes. Discontinuities and geologic anomalies can also be a serious problem for gas control in mining due to their potential effects on the flow of gas to the boreholes and into the working areas. This section discusses the effects of impermeable faults in coalbeds on degasification using vertical and horizontal boreholes, and their potential effects on methane emissions into mine developments using numerical reservoir simulation.

3.1. Primary recovery and emissions due to mining: simulation results of the “base case” using vertical and horizontal boreholes

Degasification simulations using the base coalbed methane model were performed to establish a comparison for the later simulations which evaluated the effects of impermeable faults. Vertical and

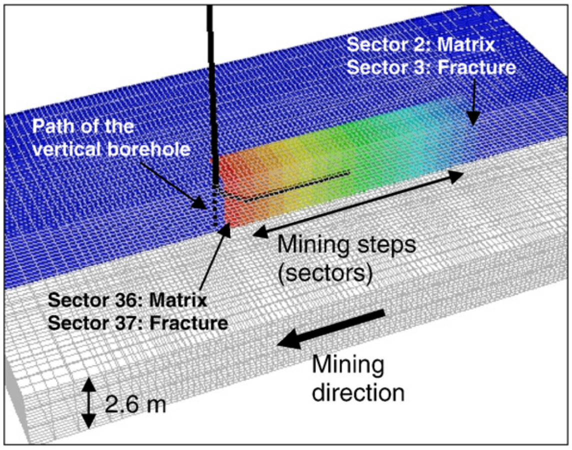

Fig. 1. Grid model of the coalbed that shows horizontal borehole and the sequential mining steps as described by different "sectors" for matrix and fracture elements.

horizontal boreholes configured as described in Section 2.2 produced for two years, which is considered as the pre-mining degasification duration for all the simulations in this study. After two years of degasification, the remaining gas in the coalbed was evaluated for potential emissions during a longwall mining operation. During these simulations, both methane and water flow rates were modeled.

Fig. 2 shows methane and water productions from single vertical and horizontal boreholes for a duration of two years. As expected, methane production from the horizontal boreholes is 2–3 times greater than from the vertical boreholes. At the beginning of the production period, this difference is even greater. This is due to the combination of differences in the lengths of the boreholes and the pressure depletion areas that they create during production. As noted by other researchers (Sung and Ertekin, 1987; King and Ertekin, 1988), the initial production (early time period) from the boreholes is mainly dominated by the depletion of fractures or cleats. Thus, during early times, the initial methane and water drainage rate is faster. This triggers a rapid water production rate and decreasing water saturation in the fractures while increasing gas saturation and its mobility through a quick shift in the gas relative permeability curve. After this initial period, a desorption- and diffusion-dominated region commences where saturation changes and production rates slowly decrease. In the vertical borehole production case shown in Fig. 2, the initial methane production rate was ~2500 m^3/day, which decreased to ~2000 m^3/day followed by an increasing trend as shown in a narrower scale in the inset plot. This behavior is due to the response of coal to pressure depletion during production as explained in Section 2.1. Water production rate was initially 4 m^3/day but subsequently decreased to 2–3 m^3/day.

In the horizontal borehole case, the initial methane production rate was ~9000 m^3/day and then decreased to ~5000 m^3/day at the end of two years. Similarly, initial water production was 12 m^3/day and then decreased to ~6 m^3/day. Since a long horizontal borehole is in direct communication with more fractures, its initial methane and water drainage rate is higher compared to a vertical well. This triggers a high water and gas production rate. After this initial period, a desorption- and diffusion-dominated phase starts characterized by a decreasing production rate. It is also interesting to note that the horizontal borehole either does not experience significant rate changes due to the coal's response to pressure depletion or its rate changes due to coal response are not as obvious as the vertical well in this study.

After two years of degasification, evaluation of possible methane emissions due to an advancing longwall in the "base model" was considered. This evaluation was based on the simulator-reported "free gas" and "adsorbed gas" still remaining in the coal fractures and matrix, respectively, in each of the sequential regions (Fig. 1) after borehole production. The emission rate analysis was based on a 9.1-m/day (30-ft/day) average face advance rate. The amount of gas available for emission was predicted from the remaining gas in the coal. According to this approach, 40% of the remaining adsorbed gas in the matrix after degasification and all of the remaining free gas in the fractures were assumed to be available for emission during the mining process. Similarly, water in the fracture system was calculated and was assumed to flow into the mine.

Fig. 3 shows calculated methane emission and water inflow rates into the mine as a function of longwall advance towards the borehole location. These data show that the horizontal borehole modeled in this study was more effective compared to a vertical borehole in reducing methane emissions due to its length along the mining horizon. The emission rate started decreasing notably as mining continued towards the horizontal borehole location and reduced to less than 20 m^3/min when the face location was 400 m away from the drilling location. A slight increase when the face was very close to the drill location was due to the vertical and slanted portion of the borehole, which was not as effective as the horizontal section. On the other hand, the vertical borehole did not affect the emission rates when mining first started. The emission rate decreased at a slow pace and reached a minimum (~22.5 m^3/min) when the face almost intercepted the borehole location. Water inflow to the mine showed a similar trend, decreasing to less than 0.025 m^3/min as mining advanced. In the vertical borehole case, water inflow was higher when compared to the horizontal borehole.

These simulations show that a horizontal borehole, when compared to a vertical borehole, produced more gas and water from the coalbed, thus reducing these inflows into the mine.

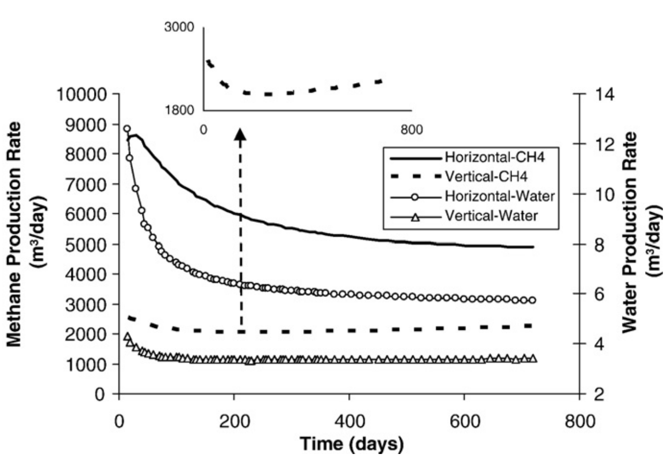

Fig. 2. Methane and water production curves for vertical and horizontal boreholes in the base model. Inset figure is the production rate from the vertical well at a smaller scale.

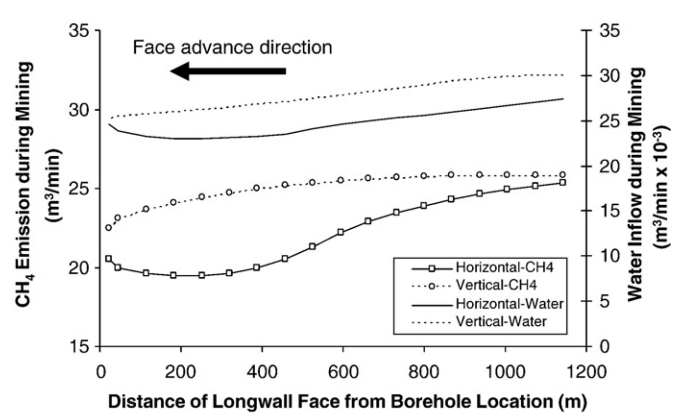

Fig. 3. Methane and water emissions into the mine in the base coal bed model after 2 years of degasification with vertical and horizontal boreholes.

3.2. Effect of "impermeable faults" on degasification efficiency and emissions during mining

3.2.1. Coalbed degasification efficiency using surface-drilled vertical and horizontal boreholes

In this study, the effects of impermeable faults on coalbed degasification efficiency using vertical and horizontal boreholes were investigated. A geological fault was located 340 m (1125 ft) east of the borehole-drill location in the base model. The fault direction was along the N–S (north–south) direction. A fault array was described in the model so that the flow interactions between the grids on either side of the fault blocks in a multilayer grid system would be in all directions in formulation. In order to make this fault an impermeable discontinuity in the model, the horizontal transmissibility along the fault block was set to zero.

The fault configurations simulated in this study included no throw, an upthrown block and a downthrown block. In all simulations, the block where the borehole was drilled was taken as stationary, and the block on the opposite side of the fault plane was moved according to the throw amount and direction. Thus, the fault block on the borehole drilling side was steady, whereas the vertical positions of the grids in the other fault block were moved by +/−1 m (+/−3 ft) up and down based on the throw direction. The geometry of the vertical borehole was not affected by these changes. However, in the case of the horizontal borehole, the borehole trajectory was adjusted after it penetrated the moving block, based on the throw amount and direction so that the borehole was always horizontal in both blocks.

It should be noted that, after this treatment, the distance between the borehole section and the top of the reservoir block had increased or decreased by 1 m (3 ft) based on the direction of throw. In a drilling operation or during shaped-charge jet penetration through fractures, possible rock damage around the tunnel may create a positive skin and impede fluid flow (Halleck and Dogulu, 1996). In this study, it was assumed that such damage was not present around the borehole along the fault line in the vertical flow direction. Fig. 4 shows cut-away pictures of the reservoir with a horizontal borehole and the three different fault structures.

It should also be mentioned that the fault geometries were idealized in this study by modeling them as vertical planes separating the two blocks. In nature, in most cases, fault planes have some kind of an angle depending on they are normal or reverse faults. The reason for modeling faults as vertical planes rather than oblique surfaces was to eliminate the possible effects of different fault angles on the results. The other reason was due to the necessity of creating extremely small grid dimensions in horizontal direction around the fault to create an angle approximately 60°. This would change the uniformity of grid sizes, increasing computational cost and also possibly would affect the results especially around the fault.

Fig. 5-A shows the methane production behavior of the vertical well in a faulted reservoir. It shows that the presence of an impermeable fault 343 m away from the borehole formed an effective boundary in the coal layer. Production data and a comparison with the base-case production curve show that at 175 days, pressure transients created by the vertical borehole reached the fault location. After this period, since the size of the reservoir was effectively limited, the reservoir pressure declined more rapidly and promoted more gas desorption and an increased production from the wellbore-side block. The pressure decline and associated desorption possibly accelerated the porosity and permeability changes in the reservoir due to compaction and matrix shrinkage processes in the coal. Thus, increased production after ~175 days was a combination of pressure transients in a bounded reservoir and the coal permeability change.

Fig. 5-B shows the methane production history of a horizontal well in a faulted reservoir. The data show that the horizontal wellbore was not affected by the presence of an impermeable fault as much as the vertical borehole. The productions in faulted reservoirs are close and a little lower compared to the base case and follow a similar decline trend. This may be because the horizontal borehole was in communication with both sides of the fault and the pressure continuity was almost maintained. However, the presence of an impermeable boundary may still be effective around the borehole and may affect the water drainage in the reservoir and saturation of phases. In the field, the preferred practice is to drill the horizontal boreholes in the coal bed in a slightly up-dip direction, in order for the water to drain and be removed more efficiently, which results in the gas rates to increase.

Since the performance of the vertical borehole was affected more by the presence of an impermeable fault in the reservoir, the effect of the proximity of the fault to the borehole location was also

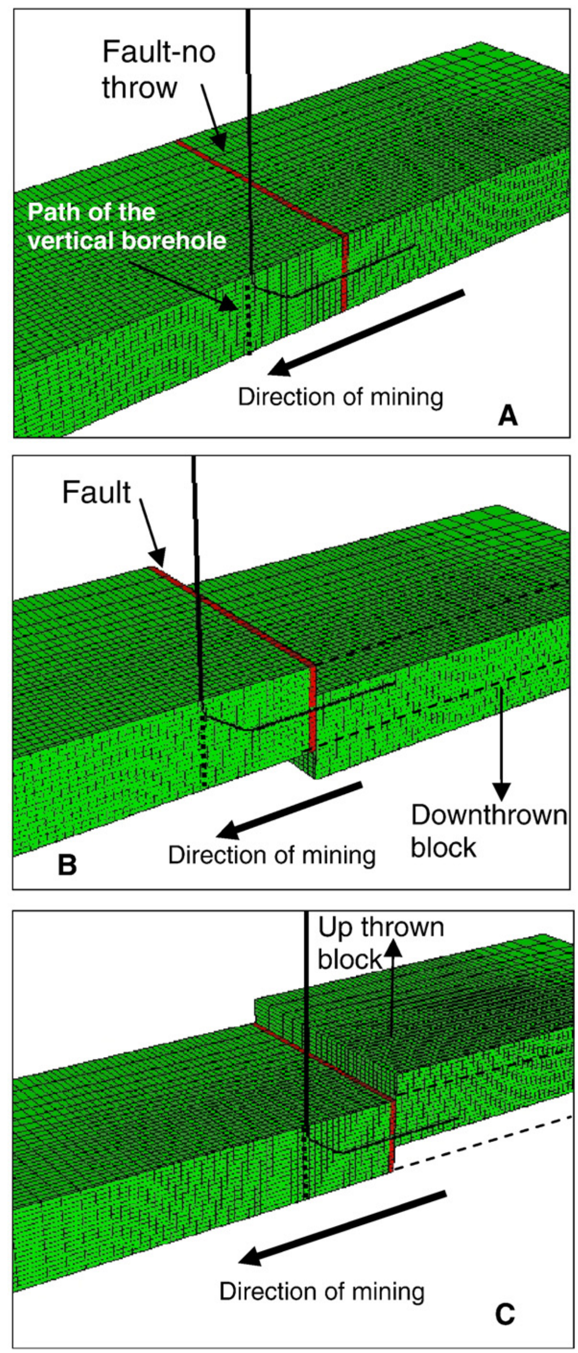

Fig. 4. Coal bed models that show the modeling of impermeable faults (A) with no throw, (B) with downward throw, and (C) with upward throw. The figures also show the relative positions of horizontal and vertical boreholes in each case.

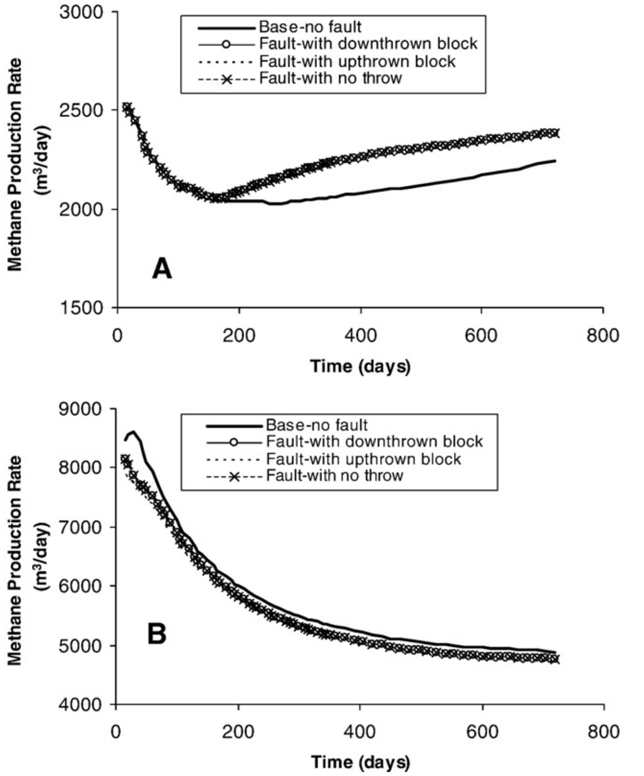

Fig. 5. Methane production curves with (A) a vertical borehole (B) a horizontal borehole in a coalbed with different fault geometries.

investigated. Impermeable faults 114 m and 572 m away from the borehole, in addition to the original fault location at 343 m, were simulated and compared. Fig. 6 shows that, based on the proximity of fault, the shape of the production rate curve changes. The reservoir with a fault which was far enough (572 m) from the borehole acted like the base case, which did not have any discontinuities. However, the boundary was still felt by the borehole at later times during the production period. If the borehole produced for one year, this effect probably would not have been felt, and the production curve would have been exactly the same as the base case. In this case, the production period for the vertical borehole dictates whether the coal seam behaves as a bounded reservoir or an infinite one. In the case of an impermeable fault at a very close proximity (114 m in this study) to the borehole, the interference due to the presence of the fault was felt almost instantly and manifested itself with a fast pressure decline and with a high gas rate that initially reached a peak production. Due to the instant interference of the boundary, the reservoir behaved like an infinite conductivity medium that produced gas at a high rate as in the case of hydraulic fractures with infinite conductivity (King and Ertekin, 1986, 1988). However, since the reservoir volume and gas content were low, the production rate declined as production continued (Fig. 6).

3.2.2. *Reservoir pressures prevailing in the longwall panel after degasification*

In order to evaluate the effects of impermeable faults on average reservoir pressure remaining after degasification of the panel area, the average pressures in the fracture sectors were calculated. Fig. 7 shows the change of the reservoir pressure in the panel area as a function of the distance to the borehole-drill location along the panel length, the fault characteristics, and the borehole type. The figure shows that the horizontal borehole was, as expected, capable of influencing reservoir pressure at larger distances from the drill location due to larger drainage area, and that it was possible to reduce reservoir pressure more than was achievable when employing a vertical borehole. With the horizontal borehole simulated in this study, reservoir pressures declined from 1.96 MPa (287 psi) at 1140 m (3750) from the borehole-drill location to 1.35 MPa (200 psi) at 23 m (75 ft) along the panel length towards the borehole-drill location. Although reservoir pressures appeared to be somewhat higher when the displacement was in the upward direction, especially towards the fault line, pressures were not greatly disturbed by the impervious zone at the fault line. Slightly higher pressures at the upthrown block were possibly due to the borehole being at a lower horizon in the reservoir and production being affected by water accumulation in this zone under gravity drainage. At the fault line, pressure decline curves crossed over and followed a reversed path towards the drill location.

In the case of a vertical borehole, the reservoir pressure distribution after two years of production was logarithmic from the start of the panel to the drill location in the base model (Fig. 7). However, when there was an impermeable fault present in the coal seam, the reservoir pressure of the changed abruptly between the two blocks on either side of the fault. This was because of the fact that pressure transients did not reach across the fault line during degasification. For the modeled case, the coal bed reservoir pressure difference between both sides of the fault was as much as 0.45 MPa (66 psi), which might also be associated with a significant methane content difference. Also, in the wellbore-block side of the reservoir, pressures were lower than the base case due to a smaller reservoir volume to drain. As these findings demonstrate, a significant pressure difference on both sides of a fault may be a problem during mining as the fault is mined through. This will be especially important if the longwall face approaches the fault from the borehole-side.

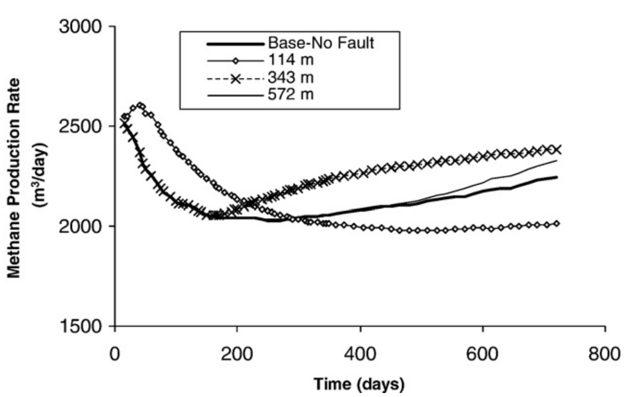

Fig. 6. Methane production curves with a vertical borehole that is located at different distances from an impermeable fault.

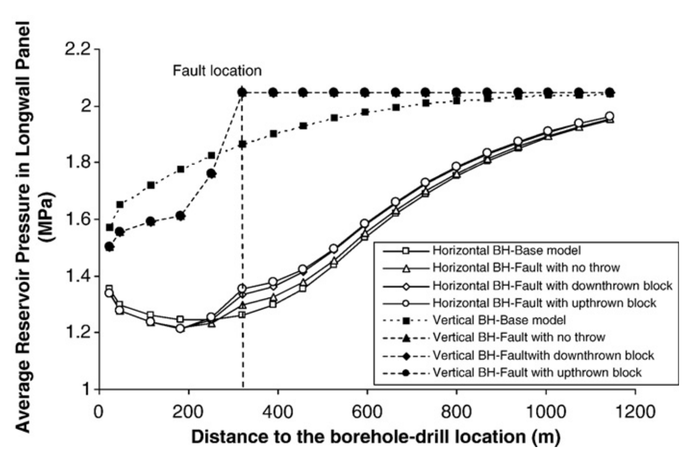

Fig. 7. The change of the coalbed pressure in the panel area as a function of distance to the borehole-drill location, fault characteristics, and the borehole type.

3.2.3. Methane emissions during longwall mining after degasification of the panel area

The effects of impermeable faults on methane and water inflows on an advancing face after degasification using vertical and horizontal boreholes were evaluated by using the technique described in Section 3.2.1. Fig. 8-A shows methane emissions and water inflow to an advancing face based on its distance from the horizontal borehole location. This figure compares the behavior of faults with different throws to the base case. The data show that, for a coal bed degasified using a horizontal borehole, the maximum changes in methane emission and water inflow to the mine occurred around the fault (343 m). Fig. 8-A also shows that the maximum methane emission into the mine occurred while the mining face passed through the upthrown fault block. This might be due to the fact that the bulk of the reservoir volume on the right side (upthrown block) of the fault line remained above the borehole trajectory. This might have caused the borehole segment in upthrown block be flooded by water entering the borehole by gravity drainage. Thus, the remaining gas that could not be produced effectively due to high water saturation was released into the mine. The next highest emission occurred when there was a right-hand fault block was downthrown along the fault line. In this case, the methane at the top of the reservoir was produced effectively by the borehole, while the remaining gas and water stayed in the coal seam underneath the borehole trajectory and was released into the mine during mining operations. Water inflow data shown in Fig. 8-A support these arguments for methane emissions.

In the water inflow case, mining through a fault from downthrown block direction releases more water into the mine since water cannot be removed effectively by a borehole located close to the top of the reservoir. The least amount of water in the mine was found when there was a throw in the upward direction. These data suggest that the presence of a fault and the direction of throw (if any) make a difference in methane and water emissions during mining. Gravity drainage plays a role in this process when there is a throw that creates a large difference in the relative height of the borehole in the coal seam. This situation may be improved by redirecting the borehole based on the throw direction after drilling through the fault line.

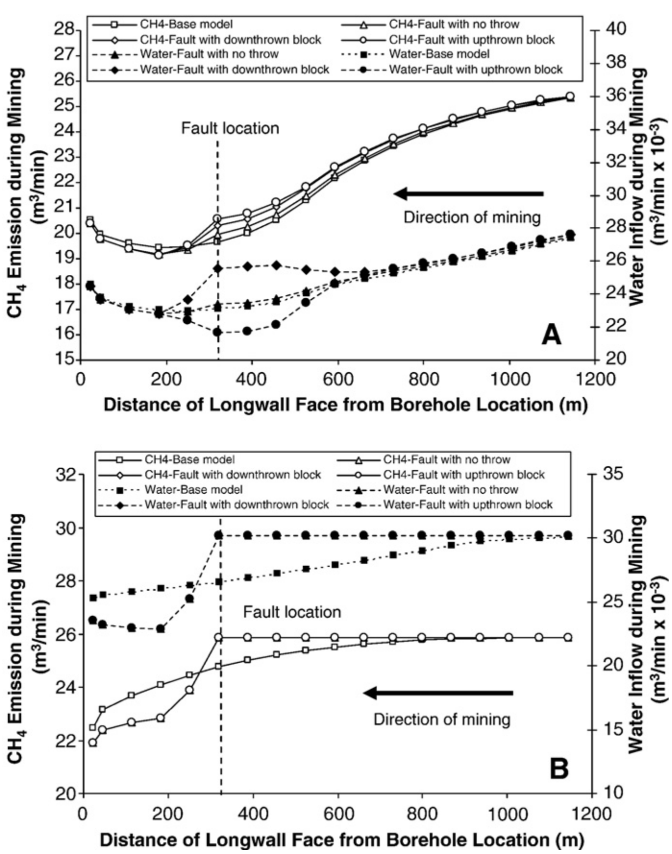

Fig. 8. Methane and water inflow into a mine advancing in a faulted coalbed. Figure (A) is after degasification with a horizontal borehole. Figure (B) is after degasification with a vertical borehole. In Figure B some of the data overlap.

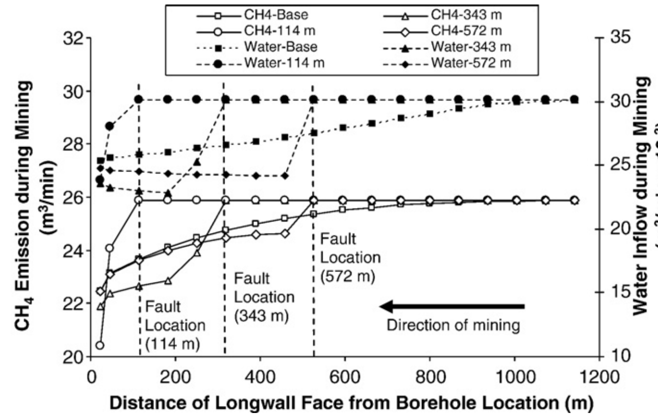

Fig. 9. Methane and water emissions into the longwall face after degasifying a coalbed with a vertical borehole located at various distances to an impermeable fault.

The effects of fault geometries on emissions after degasification with a vertical well are demonstrated in Fig. 8-B. In this case, one of the fault blocks was not drained at all and it did not make any difference whether there was a throw between two blocks across the fault line. The data show, however, that there would be a sharp decrease in methane emissions and water inflow after the mining face passed through the fault into the borehole block, which was degasified effectively. For the model used in this study, this difference in methane emission was as much as 4 m^3/min. The same argument would also be true if the mine approached from the other direction. In that case, there would be a jump in the methane and water emissions into the mine, which could create gas control difficulties. Therefore, it is important to locate the fault and determine the presence and extent of any throw in order to plan better borehole drilling and placement strategies.

3.3. Effect of proximity of vertical boreholes to impermeable faults on methane emissions during mining

Results in the previous sections show that vertical boreholes are not as effective as horizontal boreholes for draining methane from both sides of impermeable faults. In that case, the reservoir block that was not associated with the borehole was not drained. The data show, however, that there would be a sharp decrease (or increase, depending on the mining direction) in methane emissions and water inflow rates after the mine face passed through the fault. This raises the question of whether the proximity of the fault line to the vertical borehole location could change the degasification performance prior to mining and thus the methane emissions during mining. Thus, simulation runs were conducted with the vertical borehole drilled in a coal seam with an impermeable fault without any displacements. The models were constructed so that the borehole would be at different proximities to the fault and be operated two years prior to mining, as before.

Fig. 9 shows simulated methane and water emissions during mining after two years of degasification of the coal bed with a vertical borehole prior to its mining. The data show that as the borehole-drill location approached the fault during degasification, the methane and water inflow rates across the impermeable fault increased. For instance, when the fault was 572 m away from the borehole, methane emissions were constant until the face reached the fault location.

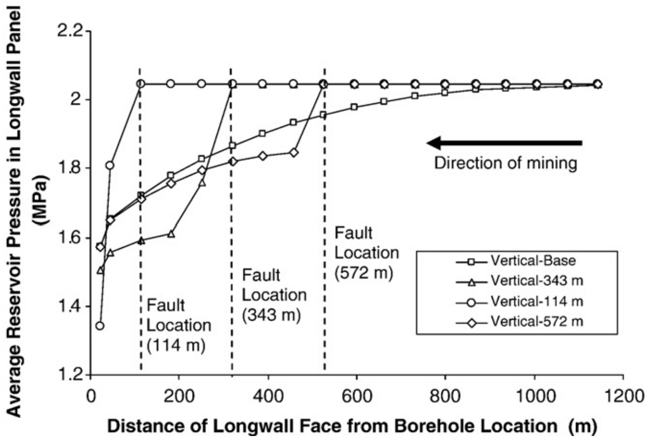

Fig. 10. Reservoir pressures prevailing after degasification of a longwall panel in a faulted coalbed reservoir using a vertical borehole drilled at three different proximities to the fault.

While mining through the fault line, methane emissions decreased by about 1.5 m^3/min and then continued with a gradual decline as mining approached the borehole location. On the other hand, when the fault was 114 m or 343 m away from the borehole, the decrease in emission rates was 4 and 6 m^3/min, respectively. Water inflows followed a similar trend based on the fault location. These results suggest that if there is an impermeable fault in close proximity to a vertical degasification borehole, abrupt changes in emissions during mining can be expected. This situation is probably more dangerous when the mining face approaches from the opposite direction (from left to right) as compared to the direction (from right to left) modeled in this study. In that case, a huge increase in emission and water inflow can occur and endanger miner safety. Thus, it is advisable to pay attention to the proximity of the faults to the vertical borehole locations in order to better degasify the coal beds and also to better control methane emissions and water inflows in the mines.

Fig. 10 shows coal reservoir pressure in the panel to be extracted as a function of proximity of the vertical borehole to the fault. The figure shows that as the distance of the borehole to the fault decreased, reservoir pressures decreased more quickly due to the pressure transients reaching the impermeable boundary earlier during the degasification period and draining a smaller reservoir volume. As a result, the reservoir pressure in the borehole block side was less and the differences in pressure between each side of the fault were greater, making gas pressure differentials higher during mine-through of the fault.

4. Conclusions

This study presented a numerical investigation using reservoir simulations of the effects of impermeable faults with and without throws on the production performances of vertical and horizontal degasification boreholes. Longwall advances, face-position-related emissions, and reservoir properties were also characterized using sector definitions along the path of the panel grids to evaluate the impacts of impermeable faults on methane emissions into mine workings.

Evaluations of a base coalbed methane model showed decreasing methane and water productivities with time for both vertical and horizontal boreholes. The effect of permeability changes in the coal seam was more pronounced with a vertical borehole compared to a horizontal borehole. The base-model simulations showed that, as expected, methane production from the horizontal borehole was 2 to 3 times greater than from the vertical borehole. At the beginning of production period, this difference was even greater. This was due to the differences in the lengths of the boreholes and the pressure depletion areas that they created during production. These simulations also showed that two years of degasification with a horizontal borehole reduced methane and water emissions into an approaching longwall face compared to a similar degasification period using a vertical borehole.

The methane production of a horizontal borehole was not significantly affected by the presence or displacement direction of a fault located 343 m distant. This was not the case with a vertical borehole, which showed, after 175 days of operation, increased methane production compared to the base model. This increased methane likely arose from the pressure transients from the vertical borehole reaching the impermeable fault boundary and causing increased production from the wellbore-side block. Further simulations showed that an impermeable fault in close proximity to the vertical borehole had greater impact on its production. A fault located farther from this borehole had much less impact.

Location of a vertical borehole is important to control the methane emissions into a mine in a faulted coal seam. Simulations were conducted of methane and water inflows in the presence of a fault located 343 m distant from a longwall face. These results showed dramatic reductions in gas and water inflows once the face passed through the fault into the borehole block. These data suggest that mining into the borehole block is preferable to mining in the other direction, which would lead to dramatic increases in methane and water inflows. Similar results were found when the impermeable fault was located 114 m and 572 m distant from a vertical borehole. Methane emissions and water inflows again decreased once the face passed through the fault. Average reservoir pressures also decreased at this point.

References

Aul, G.N., Ray, R., 1991. Optimizing methane drainage systems to reduce mine ventilation requirements. 5th US Mine Ventilation Symposium, Morgantown, WV, June 3–5.

Cameron, J.R., Palmer, I.D., Lukas, A., Moschovidis, Z.A., 2007. Effectiveness of horizontal wells in CBM. International Coalbed Methane Symposium, Paper 0716. The University of Alabama, Tuscaloosa, AL.

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

Computer Modeling Group Ltd, 2003. Generalized Equation of State Model-GEM. Computer Modeling Group, Calgary, Alberta, Canada.

Coolen, J.M., 2003. Coal mining along the Warfield Fault, Mingo County, West Virginia: a tale of ups and downs. International Journal of Coal Geology 54, 193–207.

Diamond, W.P., 1982. Site-specific and regional geologic considerations for coalbed gas drainage. Information Circular No. 8898. US Dept. of Interior, US Bureau of Mines, Pittsburgh, PA.

Diamond, W.P., 1994. Methane control for underground coal mines. Information Circular No. 9395. US Dept. of Interior, US Bureau of Mines, Pittsburgh, PA.

Diamond, W.P., Bodden, W.R., Zuber, M.D., Schraufnagel, R.A., 1989. Measuring the extent of coalbed gas drainage after 10 years of production at the Oak Grove Pattern, Alabama. Paper 8961, Proc., Coalbed Methane Symposium, Tuscaloosa, AL.

Ertekin, T., Sung, W., Schwerer, F.C., 1988. Production performance analysis of horizontal drainage wells for the degasification of coal seams. Journal of Petroleum Technology 625–632 May.

Fields, H.H., Krickovic, S., Sainato, A., Zabetakis, M.G., 1973. Degasification of virgin Pittsburgh Coalbed through a large borehole. Report of Investigations No. 7800. US Dept. of Interior, US Bureau of Mines, Pittsburgh, PA.

Greb, S.F., Eble, C.F., Williams, D.A., Nelson, W.J., 2001. Dips, ramps and rolls — evidence for paleotopographic and syn-depositional fault control on the Western Kentucky No. 4 Coalbed, Tradewater Formation (Bolsovian), Illinois Basin. International Journal of Coal Geology 45, 227–246.

Halleck, P.M., Dogulu, Y.S., 1996. Experiments and computer analysis show how perforators damage natural fractures. SPE Paper No. 37330. 1996 SPE Eastern Regional Meeting, Columbus, OH.

Harpalani, S., Chen, G., 1995. Estimation of changes in fracture porosity of coal with gas emission. Fuel 74, 1491–1498.

Harpalani, S., Chen, G., 1997. Influence of gas production induced volumetric strain on permeability of coal. Geotechnical and Geological Engineering 15, 303–325.

Karacan, C.O., Esterhuizen, G.S., Schatzel, S.J., Diamond, W.P., 2007a. Reservoir simulation-based modeling for characterizing longwall methane emissions and gob gas venthole production. International Journal of Coal Geology 71, 225–245.

Karacan, C.O., Diamond, W.P., Schatzel, S.J., 2007b. Numerical analysis of the influence of in-seam horizontal methane drainage boreholes on longwall face emission rates. International Journal of Coal Geology 72, 15–32.

Kecojevic, V., Willis, D., Wilkinson, W., Schissler, A., 2005. Computer mapping of faults in coal mining. International Journal of Coal Geology 64, 79–84.
Kelafant, J.R., Boyer, C.M., Zuber, M.D., 1988. Production potential and strategies in the Central Appalachian Basin. SPE Eastern Regional Meeting, Paper no. 18550, Charleston, WV, Nov. 1–4, pp. 305–312.
King, R.G., Ertekin, T., 1988. Comparative evaluation of vertical and horizontal drainage wells for the degasification of coal seams. SPE Reservoir Engineering 720–735 May.
King, R.G., Ertekin, T., 1986. Numerical simulation of the transient behavior of coal-seam degasification wells. SPE Formation Evaluation 165–183 April.
Lambert, S.W., Trevits, M.A., 1978. Effective placement of coalbed gas drainage wells. RI-PMOC-2(78). US Dept. of Energy, Pittsburgh, PA.
Li, H., Ogawa, Y., Shimida, S., 2003. Mechanism of methane flow through sheared coals and its role on methane recovery. Fuel 82, 1271–1279.
McCulloch, C.M., Diamond, W.P., Bench, B.M., Deul, M., 1975. Selected geologic factors affecting mining of the Pittsburgh Coalbed. Report of Investigations No. 8093. US Dept. of Interior, US Bureau of Mines, Pittsburgh, PA.
Molinda, G.M., Ingram, D.K., 1989. Effects of structural faults on ground control in selected coal mines in Southwestern Virginia. Report of Investigations No. 9289. US Dept. of Interior, US Bureau of Mines, Pittsburgh, PA.
Noack, K., 1998. Control of gas emissions in underground coal mines. International Journal of Coal Geology 35, 57–82.
Palmer, I., Mansoori, J., 1996. How permeability depends on stress and pore pressure in coalbeds. SPE Paper No. 36737. 1996 SPE Annual Technical Conference and Exhibition, Denver, CO.
Pashin, J.C., 1998. Stratigraphy and structure of coalbed methane reservoirs in the United States: an overview. International Journal of Coal Geology 35, 209–240.
Perry, H.H., Aul, G.N., Cervik, J., 1978. Methane drainage study in the Sunnyside Coalbed, UT. Report of Investigations No. 8323. US Dept. of Interior, US Bureau of Mines, Pittsburgh, PA.
Prosser, L.J., Finfinger, J., Cervik, J., 1981. Methane drainage study using an underground pipeline, Marianna Mine 58. Report of Investigations No. 8577. US Dept. of Interior, US Bureau of Mines, Pittsburgh, PA.
PTTC, 2004. Coalbed Methane Resources of the Southeast. http://www.pttc.org/workshop_summaries/sol_2004/537.htm.
Shi, J.Q., Durucan, S., 2003. Drawdown induced changes in permeability of coalbeds: a new interpretation of the reservoir response to primary recovery. Transport in Porous Media 1696, 1–16.
Sparks, D.P., Lambert, S.W., McLendon, T.H., 1993. Coalbed gas well flow performance controls, Cedar Cove Area, Warrior Basin, USA. Proc. 1993. International Coaled Methane Symposium, Tuscaloosa, AL, pp. 529–548.
Su, X., Lin, X., Liu, S., Zhao, M., Song, Y., 2005. Geology of coalbed methane reservoirs in the Southeast Qinshui Basin of China. International Journal of Coal Geology 62, 197–210.
Sung, W., Ertekin, T., 1987. Performance comparison of vertical and horizontal hydraulic fractures and horizontal boreholes in low permeability reservoir: a numerical study. Paper No: 16407. SPE/DOE Low Permeability Reservoirs Symposium.
Thakur, P.C., 1997. Methane drainage from gassy mines — a global review. Proc. 6th International Mine Ventilation Congress. Pittsburgh, PA, pp. 415–422.
Thielemann, T., Kroos, B.M., Littke, R., Welte, D.H., 2001. Does coal mining induce methane emissions through the lithosphere/atmosphere boundary in the Ruhr Basin, Germany. Journal of Geochemical Exploration 74, 219–231.
Ulery, J.P., 2006. Managing excess gas emissions associated with coal mine geologic features. In: Kissell, Fred (Ed.), Handbook for Methane Control in Mining. . NIOSH Information Circular 9486. US Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Pittsburgh, Pa.
Wu, Q., Wang, M., Wu, X., 2004. Investigations of groundwater bursting into coal mine seam floors from fault zones. International Journal of Rock Mechanics and Mining Sciences 41, 557–571.
Young, G.B.C., Paul, G.W., Saulsberry, J.L., Schraufnagel, R.A., 1993. A simulation-based analysis of multiseam coalbed well completions. Paper No 26628. 68th Society of Petroleum Engineers Annual Technical Conference and Exhibition.