# Coal Bed Discontinuity Effects on the Production of Degasification Boreholes and on Emissions during Longwall Mining

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## Abstract

Geological discontinues in the coalbed, such as faults, sandstone channels, permeability facies, lithotype changes, and large scale partings in the coal seam, can cause intermittent production problems or produce unexpected amounts of water or gas from degasification boreholes. These discontinuities not only can impact methane emissions into the mine workings, especially if they hinder proper and effective degasification of the coalbed but may act as conduits for methane flow from gassy strata into advancing mine workings. The effects of these discontinuities are still under debate by mining and gas production experts. This study presents a numerical investigation using reservoir simulations of the effects of partings and permeability facies and lithotype changes on the production performances of vertical and horizontal degasification boreholes, as well as the emissions during longwall operations.

In this work, the grid block was designed in a multi-layer 3-D structure which enabled spatial descriptions of the geometries and properties of the discontinuities within the coal seam. The studied coal seam discontinuities and their properties were distributed arbitrarily within the model. Production was simulated by vertical and horizontal boreholes. Degasification boreholes operated two years prior to start of the mining.

The results of this numerical study show that in coal seams with major heterogeneities and discontinuties, the geometry and location of the boreholes are important for improved gas production. These considerations are also important for controlling methane and water inflow into the working environment during longwall mining.


## Introduction

Occasionally, unanticipated and unusually high emissions, despite normal ventilation controls in coal mines, may result in an explosive mixture at the working face that can be easily ignited during mining. Abnormal, unanticipated mine gas emissions in quantities sufficient to create hazardous conditions have often been attributed to various geologic features. During burial and diagenesis of the organic matter that ultimately forms mineable coal beds, dispersed organic matter many occur also in adjacent strata that is not being directly exposed by the mining process. This material can produce methane in quantities far exceeding the storage capacity of the coal and surrounding rock (Juntgen and Klein, 1975). The flow of this gas at high rates into the mine workings may be either facilitated or temporarily impeded by the presence of geologic structures or anomalies during mining of the nearby coal seams.

One of the most effective approaches to alleviate the gas emissions from mined coal seams before mining starts is to drill stimulated vertical or horizontal boreholes to drain excessive gas from the coalbed (Noack, 1998; Diamond, 1994; Thakur, 1997). This approach has 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; Diamond, 1994; Aul and Ray, 1991; Zuber, 1998; Kelafant et al., 1988; Ertekin et al., 1988; Young et al., 1993; Cameron et al., 2007; Diamond et al., 1989; Young et al., 1991).

Under continuous and uniform coalbed circumstances, the performance of the boreholes and their effectiveness on reducing emissions can be predicted by modeling techniques (Karacan, 2007a, 2007b; King and Ertekin, 1988; Sung and Ertekin, 1987). However, a uniform and continuous coalbed is seldom the case in nature. The existence of various geologic anomalies and discontinuities within and surrounding the coalbed, such as partings, faults, sand channels, and changes in coal bed permeability and lithotypes, can create serious problems in the drilling, completion, and production of degasification boreholes. Thus, site-specific considerations are required for these challenging situations (Diamond, 1982). The emission of methane into the mine via geologic discontinuities are often distinctly associated with features of varying scale are occasionally immediate and catastrophic; but, more often, these emissions are subtler and not easily detected without field reconnaissance and instrumentation. Such emissions may also lead to hazardous accumulations of methane if not recognized and remedied. Thus, special site-specific considerations should include the evaluation of the gas emission potential of the coal seam and the associated geological factors by assessing the in-place gas content and the reservoir properties of the surrounding rock. These assessments can then be integrated into a predictive model of the gas emission into a working mine using numerical simulation techniques.

This study presents a numerical investigation on the effects of a number of geological features, namely lithotype changes, permeability facies and partings, on the pre-mining production performance of vertical and horizontal degasification boreholes and on the potential methane emissions during mining. Potential emissions due to coalbed discontinuities were modeled by assigning sequential regions in the grid. This work evaluated water and gas productions from each borehole and the impacts of geological discontinuities on methane emissions and water inflows into mine workings.

## Methodology - Reservoir Modeling to Simulate Effects of Coal Bed Discontinuities

**Coal Bed Reservoir and Modeling Parameters.** A base coalbed reservoir model was developed to numerically evaluate the effects of various discontinuities within the coalbed on the production performance of vertical and horizontal boreholes and on gas emissions into a longwall operation. The base model was designed as a uniform and continuous coalbed reservoir, using Computer Modeling Group's GEM (CMG, 2003) simulator in the dual-porosity formulation.

The grid block was designed in a multi-layer (17-layers) 3-D structure which enabled spatial descriptions of the geometries and properties of the discontinuities within the coal seam. A 2.6 m (8.5-ft) thick coalbed 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, but 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 reservoirs. Face and butt cleats were assumed perpendicular to each other and face cleats were oriented in the E-W direction and butt cleats in the N-S direction of the model. Mining direction and horizontal borehole drilling direction was modeled in the face-cleat direction, which is not uncommon for ground and methane control objectives (Karacan et al., 2007a; Karacan et al., 2007b).

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 of effective stress (Harpalani and Chen, 1995; Palmer and Mansoori, 1996; 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 8-ft thick section of the Pittsburgh Coalbed 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. Then, they started to increase (Fields et al., 1973). At another field production test in the Mary Lee Coalbed in Jefferson County, Alabama, the effectiveness of vertical boreholes on gas drainage was investigated by stimulating the well with foam and 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, Palmer and Mansoori (1996) model built into the GEM's code system to simulate porosity and permeability changes in the reservoir was used and associated effects on flow rate were modeled. General reservoir properties and their average values used in building the base coalbed model is given in Table 1.

**Methane Drainage Boreholes.** In this study, the effects of discontinuities on degasification performances of vertical and horizontal drainage boreholes were evaluated. In all of the models documented in this paper, boreholes were modeled as a 15.2 cm (6-inch) 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. The horizontal borehole was modeled as a long-radius borehole with 46 cm (1.5-ft) vertical section in the upper layers of the coalbed at the drill location. This short vertical leg was continued with a 91 m (300 ft) slanted interval (deviation angle is ~ $0.6^o$) before the borehole trajectory was horizontal. The horizontal section was modeled in the face cleat direction (E-W direction) in the middle layer of the coalbed.

For the numerical simulations, the vertical well skin factor was assumed to be -3, representing that of 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 coalbed, if they are impermeable, 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 the stimulation activities resulted in 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 always 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 undamaged to hydraulically confine the coalbed. In this study, both of the wells were operated with 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.

**Simulating Face Advance During Longwall Mining and Associated Emissions.** This study modeled the advance of a 1200-ft wide, flat longwall panel whose start-up end was 1400 m (4500 ft) away from the borehole drill locations **(Fig. 1)**. In this figure, colors represent different sector numbers, and thus sequential mining steps. Mining progressed and from east to west (right to left) in **Fig. 1** towards the borehole location. Every face advance was characterized by sequential "sectors" of 69 m (225 ft or 3 grids in the model) in length within the grid model. These sectors represented the coal blocks to be mined during mining process. Separate "sectors" 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 implementation of moving boundary problem (Karacan et al., 2006a; 2007b) 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 "sector" were used to calculate potential emissions for a 9.1 m/day (30 ft/day) average face advance rate in the presence of discontinuities in the coal bed.

## Results and Discussions

Discontinuities are an important consideration in evaluating the gas drainage potential of the coal seams using vertical and horizontal gas drainage boreholes. Discontinuities 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 types and origins of geological discontinuities in the coal beds, their effects on coal seam degasification using vertical and horizontal boreholes, and their potential effects on methane emissions into an operating longwall using numerical reservoir simulation.

**Primary Recovery and Emissions due to Mining in the Absence of Coal bed Discontinuities: Simulation Results of the "Base Case".** Degasification simulations using the base coalbed-methane model were performed to establish a comparison for the later simulations which evaluated the effects of formulated discontinuities. Pre-mining degasification duration for all the simulations in this study was simulated as two years. After two years of degasification, remaining gas in the coal was evaluated for potential emissions during a longwall mining operation. During these simulations, both methane and water flow rates were reported.

**Fig. 2** shows methane and water productions of the boreholes for two-year duration. As expected, methane production from the horizontal borehole is 2-3 times more than the vertical borehole. At the beginning of production period, this difference is even more. This is due to the combination of difference in the lengths of the boreholes and the pressure depletion areas that they create during production. As noted by other researchers (King and Ertekin, 1988; Sung and Ertekin, 1987), 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, 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, 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 the coal to pressure depletion during production as explained in section 2.1. Water production rate initially was 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 decreased to ~5000 $m^3$/day at the end of two years. Similarly, initial water production was 12 $m^3$/day but 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, desorption and diffusion-dominated phase starts and the production rate and its variability decreases. It is also interesting to note that the horizontal borehole does not experience, or it is not as obvious as the vertical well in this study, the rate changes due to the coal's response to pressure depletion.

After two years of degasification, evaluation of possible methane emissions into the "base model" was made. 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 degasification. The 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 and all of the remaining free gas in the fractures were assumed available for emission during 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 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 direction. 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 vertical and slanted portion of the borehole, which was not as effective as the horizontal section. Water inflow to the mine showed a similar trend, decreasing to less than 0.025 $m^3$/min as mining advanced. 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 minimum (~22.5 $m^3$/min) when the face almost intercepted the borehole location. In the vertical borehole case, water inflow was higher when compared to the horizontal borehole.

These simulations show that in the base model with no discontinuities, a horizontal borehole produced more gas and water from the coalbed and reduced methane emission and water inflow rates into the mine when compared to a vertical borehole.

**Effects of Partings and Parting Layers in the Coal Bed.** Coalbeds can include various non-coal materials deposited during peat accumulation.Such non-coal material may be referred as partings in the coalbed. These non-organic rich horizons are composed on mineral mater that is commonly argillaceous (clay), siliciclastic (quartz dominated) and occasionally carbonate rocks. Most are the result of changes in the depositional environment within the peat swamp in which the coal was forming. Influxes of non-organic material that entered the system disrupted the sequence of terrestrial plant growth, death and burial and resulted in these rapid and irregular changes in lithofacies. A special form of parting are composed of altered volcanic ash layers (tornstein), which represent volcanic events of short duration and therefore are nearly isochronous horizons, such as in Ferron group, may also be found within coal seams (Lamarre, 2003). Rock partings or parting layers creates density variations in the coal, which is a function of mineral material, or ash, within the coal seam (Beaton et al., 2005; Manchioni, 2003). Most importantly in terms of fluid and gas flow, these partings create strong discontinuities in the petrophysical fabric (porosity and permeability) within the coalbed methane reservoir. These may also be related to gas concentration within the coalbed.

During coalbed degasification, boreholes drilled in an area of extensive partings could encounter irregular flows of gas. A horizontal borehole drilled completely above or below an extensive parting, or a collection of partings, that effectively separates a coalbed into separate reservoirs may drain methane only from that portion of the coalbed. The other portion of the coalbed would remain undrained and the gas still would represent a potential hazard to the future mining or would be unavailable for commercial production (Diamond, 1982). In the case of vertical boreholes, encountering partings can also be problematic to the flow of gas. Since the length of a vertical borehole is much less then a horizontal borehole, drilling into a thick parting interval may render the borehole useless. Also, if the fracturing treatment does not penetrate effectively above and below the parting, the flow could be reduced. Parting layers that compartmentalize the coalbed hydraulically are also important from a mine ventilation standpoint since they can isolate large volume of gas that can suddenly be liberated when penetrated by a mine entry.

***Numerical Evaluation of the Effect of Partings on Degasification and Methane Emissions during Mining.*** In order to investigate potential effects of partings and parting layers in the coalbed on borehole production and mining emissions, grids that represented the properties of parting layers were randomly distributed in the middle part of the grid model of the coalbed around the borehole location. These blocks or cells within the model were represented with values of 0.05 md and 2% fracture for permeability and porosity, respectively. Matrix properties of partings were assigned “null” values so they were effectively non-porous and non-permeable, they did not have gas storage capacity, and they did not add to fluid flow. A fracture spacing of 6 m (20 ft) was assigned to the partings and initialized with the same water saturation and pressures in the fractures. **Figs 4-A and 4-B** show the distribution of grids representing parting layers in the cut-away picture of the coalbed along the horizontal borehole and their sizes and extensions, respectively.

**Fig. 5** compares borehole methane productions in the presence of parting layers with those results of the base coalbed. The methane production curves show that the region in the coalbed with partings **(Fig. 4)** resulted in a decrease in methane productions with both vertical and horizontal boreholes. In both cases, the production rates were almost half of that of a continuous coalbed. The difference may be due to the decrease in methane content in coalbed in the presence of parting layers as well as changes in the coalbed permeability around the boreholes. Since both boreholes were drilled through the low permeability parting layers on their trajectory or they were surrounded by those layers, the effective permeability of the coalbed that the boreholes intersected was lower than the base coalbed case. The changes in the methane rates are similar to observed differences reported in King and Ertekin (1988) that reflected the changes between high hydraulic fracture permeabilities versus low ones around the boreholes.

**Figs. 6 and 7** shows how potential methane emissions and water inflows change, respectively, during mining after degasification using vertical and horizontal boreholes. In these figures, emission and inflow data are compared with the base case. **Fig. 6** shows that after mining started following degasification using a vertical borehole, methane emissions calculated in each sector started to decrease in the parting-rich section of the coalbed at about 229 m (750 ft) from the borehole location. This decrease compared to base case was probably due to the decrease in methane content in parting-rich section of the coal seam compared to the rest of the coal bed. **Fig. 6** shows a similar methane emission potential after degasification with a horizontal borehole. By using a horizontal borehole, potential methane emissions into the mine were reduced by about ~3-4 $m^3$/min compared to using a vertical degasification borehole.

On the other hand, a sharp increase in the water inflow into the mine was observed due to water stored in the fracture volume of the parting layers compared to base coal seam case **(Fig. 7)**. For degasification with either the vertical or the horizontal borehole, water inflows were calculated to increase from an average rate of 0.025 $m^3$/min to 0.06 $m^3$/min, when there are parting layers in the coal seam. There were also increases and decreases in water inflows based on the position of mine face relative to the intensity of partings in the coal seam. Thus, it can be argued that the intensity and the distribution of partings are important in mining the areas of high parting concentrations. The distribution of partings relative to face advance direction might also be something to consider for controlling unexpected emissions.

**Effects of Spatial Changes in Coal Types and Coal Microlithotypes.** One of the common features of coalbeds is variation of coal types. These variations manifest themselves as changes in petrographic characteristics of the coal on a various scales, from megascopically recognizable units – lithotypes to microlithotypes and macerals, as well as changes in geomechanical properties of the coal seam. The origin of coal type variations can be due to groundwater level fluctuations in the ancient peat-forming environments, due to different peat accumulation rates (Silva et al. 2007) or changes in the type of primary vegetation that contributed to the peat (Kulczynski, 1949; Moore, 1989; Calder, 1993; Diessel et al., 2000). From duller to the brighter lithotypes, there is a significant decrease of inertinite contents and an increase in vitrinite. Local variations in inertinite contents can be linked to an incomplete burning of the organic matter by local fires or aerobic biodegradation due to bacterial attack when water level dropped (Silva et al., 2007).

Different coal components have different capacities for gas generation and storage capacity (Lamberson and Bustin, 1993; Gurdal and Yalcin, 2000; Karacan and Mitchell, 2003; Beaton et al., 2005). Most researchers agree that vitrinite-rich, bright coals have a greater methane adsorption capacity than inertinite-rich, rank-equivalent coals. However, in some cases, inertinite-rich coals have been found to have the greatest methane adsorption capacity (Ettinger et al., 1966; Clarkson and Bustin, 1996; Mastalerz et al., 2004) mostly due to the volume created by the fusinites with open-cell lumina.

Different coal types also have different desorption rates, which can impact gas emissions and borehole productions. Studies on coal samples showed that dull coals desorb more rapidly than bright coals (Karacan and Mitchell, 2003; Karacan and Okandan, 2001). Both rank and coal type were found to influence effective diffusivity. Dull coals have faster desorption rates (2-3 times) than their bright equivalents in most cases (Laxminarayana and Crosdale, 1999) due to predominance of large, open cell lumina (Karacan and Mitchell, 2003; Karacan and Okandan, 2001; Crosdale et al., 1998). Bright, vitrinite rich coals usually have the slowest desorption rates which is associated with their highly microporous structure.

The importance of different coal lithotypes and microlithotypes for underground coal mining were summarized in different studies. For instance, variable gas desorption rates for different coal types were speculated to impact outbursts in mines (Beamish and Crosdale, 1998). Effectively, in the mine-face environment as pressure is removed from the coal, different desorption rates of the coal lithotypes create a large gas content gradient, namely: (1) vitrinite-rich or inertodetrinite-rich coal bands do not desorb rapidly, retaining their gas and thus producing a steep gas content gradient and (2) fusinite-rich or semi-fusinite-rich coal bands lose their gas more rapidly and thus have a shallow gas content gradient. In addition, when the coal strength information is combined with the sorption behavior of coal macerals, it is suggested that outburst proneness of coals rich in vitrinite and inertodetrinite is greatly increased (Beamish and Crosdale, 1998).

***Numerical Analysis of the Effects of Coal Type Variations in Coalbed Degasification and Methane Emissions during Mining.*** In this analysis, the properties of the coalbed given in Table 1 are considered as the continuous coal type in the coalbed. In order to model the discontinuous coal type, the gas storage (adsorption properties), volume change parameters due to primary recovery (Palmer-Mansoori model parameters) and diffusion properties (desorption time constant) of the coalbed were changed to values representative of an inertinite-rich coal. For this purpose, the grids representing partings in **Fig. 4** were assigned the properties of inertinite-rich coals reported in the literature.

The properties of the inertinite-rich coals were gathered from different studies. For geomechanical properties of coals, Gentzis et al. (2007) reported that the values of Young's modulus ranged from 1119 MPa to 5070 MPa and Poisson's ratio ranged from 0.26 to 0.48 within the seams but reported generally higher Young's modulus and lower Poisson's ratio for inertinite-rich seams. These measurements were based on static and dynamic tests performed on six large blocks of bituminous coal from active mines in the Foothills and Mountain regions of Western Canada. Gas transport and storage properties of dull, inertinite-rich coals were also based on different studies stating dull coals have faster desorption rates (2-3 times) than their bright equivalents (Laxminarayana and Crosdale, 1999) and documenting data on their gas adsorption capacities. The properties used in this study to represent an inertinite-rich coal are given in Table 2.

**Fig. 8** shows the production behavior of vertical and horizontal boreholes in a coal seam that had randomly distributed inertinite-rich patches along the borehole trajectories and in the way of mining. The graph shows that the presence of coal-type discontinuities did not change the production performance of vertical and horizontal boreholes dramatically. Production values are somewhat better than in the base case, probably due to this type of coal having more gas content and greater volumetric changes during pressure depletion. However, this situation may change if the borehole is either partially or completely in inertinite. For instance, **Fig. 9** shows two different cases where inertinite was not randomly distributed within the coal seam, but was in the form of blocks and layers. In these cases, vertical and horizontal boreholes are drilled partially and completely into the inertinite-rich coal.

**Fig. 10** shows the comparison of base-case methane production from a vertical borehole with the cases shown in **Fig. 9.** This figure shows that base-case production is better than the other two coal seam scenarios. The base case production is followed by the layered and blocky discontinuity situations: a vertical borehole drilled completely into a block of inertinite-rich coal has a steeper methane-rate decrease compared to base case. This may be due to a fast decrease in pore pressure, less gas content in the coal and a lower Langmuir pressure that affects the shape of the isotherm during desorption. The decrease of production rate has almost stopped after 100 days and followed by a relatively stable trend and a production increase due to permeability rebound.

The effects of randomly distributed coal type variations, such as in **Fig. 4**, on emissions during mining were investigated in advancing sectors as before. **Fig. 11** shows that mining in the base coal seam that was degasified by a horizontal borehole resulted in less methane emission into the mine as compared to degasification with a vertical borehole due to producing more gas with this type of borehole. When there are random channels of inertinite as a discontinuity in the base case, the potential emissions after using both of the borehole patterns are higher due to slightly less amount of gas produced during degasification **(Fig 8)**.

**Effects of Permeability Facies and Their Changes in the Coal Bed.** Permeability is a critical factor controlling methane and water production from coal seam reservoirs and determining the efficiency of a degasification project. However, reservoir permeability usually is not constant and not uniform throughout the reservoir. Coal cleats, their spacing and permeability are known factors creating preferential flow direction and magnitude in the coal seam. Coal deformation is another factor affecting the permeability in coal. For instance, in Qinshui Basin of China, the coalbed is severely deformed and contains mylonitic structures where the primary permeability is obscured. Thus permeability of the coalbed methane reservoir is controlled by shear fractures creating a significant reservoir heterogeneity making it difficult to describe permeability distribution (Su et al., 2005) for degasification studies.

In the Black Warrior Basin, a strong structural control is present on gas and water production and the relationship of production to structure is different in each field analyzed. Variable well performance in all areas suggests that hidden interwell heterogeneity related to fractures, high permeability pathways and shear structures influences production (Pashin, 1998). Thus, the regional permeability and the gas content generalities cannot be applied uniformly across the basin or coal seam.

Generally, high permeability areas in the coalbed are more productive and better suited for methane production compared to low permeability zones. For example, the highly productive “fairway zone” of the Fruitland formation in the San Juan Basin of Colorado and New Mexico contains individual wells that can produce $28\text{-}170\times10^3$ $m^3$/day (1-6 MMscf/day). Permeability within San Juan Basin ranges from 15-60 md in the high productive fairway zones, and tapers to less than 5 md in the least productive areas of the basin (Ayers, 2002). This and similar studies suggest that the highest permeability coals have the best reservoir characteristics. However, Bustin and Clarkson (1998) showed that such reservoirs consequently may have the lowest gas saturation, due to leakage, and thus may have poorer coalbed methane resource potential. On the other hand, if the coalbed is non-permeable, it may have a higher gas content, which may be released only during the crushing process as mining progresses. This condition may lead to lower gas production potentials during degasification but high methane emissions during mining that may create an unsafe atmosphere.

***Numerical Investigation of the Effects of Permeability Facies in the Coal Bed on Degasification and Mining Emissions.*** The effects of changes in coal seam permeability on degasification and consequently on methane emissions during mining were investigated using the same model geometries shown in **Fig. 4** (random patches of low permeability-Case I) and in **Figs. 9A and B** (Case II and III). For these analyses, the base permeabilities of coal (30 md in E-W direction, 10 md in N-S direction) in those regions were changed to low and high permeabilities (5 times) representing myolitic factures and calcite filled cleats, and large permeable deformation fractures, respectively. In assignment of the permeabilities, 3:1 anisotropy was kept constant. **Fig. 12** schematically shows the assigned permeabilities in different regions for the three cases examined.

**Fig. 13** shows methane productions from simulated vertical and horizontal boreholes. Results show that existence of randomly distributed low-permeability patches along the trajectory of the boreholes result in decreased methane production compared to the base case.

**Fig. 14** shows the performances for boreholes drilled in the coalbed but intercepting various permeability zones shown as Case II (blocky) and Case III (layered) in **Fig. 12**. The figure shows that the worst performing borehole was the vertical borehole drilled in a low permeability zone in the coalbed. Although this is an expected result, it emphasizes the importance of finding sweet spots or “fairways” in the coalbed for a successful degasification operation. A vertical borehole drilled in a layered-permeability coalbed performed close to the base situation with uniform permeability at later times in the production. However, its initial methane production rate was higher due to the high-permeability zone at the bottom. The rate started to decline as water accumulated in that zone due to gravity drainage. Thus, the borehole lost its advantage of being drilled into a high permeability zone at the bottom. Although water was either produced or drained from the low-permeability top layer, which might have been a production-enhancing factor for coal seams, this advantage was outweighed by the low permeability of this layer. The high production would have been longer lasting if the high permeability zone was located at the top.

The production of the horizontal borehole was also affected by the location and geometry of the permeability facies. Results show that a horizontal borehole drilled in a coal seam such as in Case II, produced as well as the base case, may be even better in the long run. However, when the borehole was drilled between a low- and a high-permeability layer, it entered a declining trend very quickly due to small amount of production from the low-permeability top layer. Again, having the high permeability layer at the top might have improved production behavior.

**Fig. 15** shows the impacts of random permeability variations on methane emissions after degasification of the coal seam shown in Case I with vertical and horizontal boreholes. This figure shows that the emissions after degassing with a vertical well are very close those of the base case. This is due to the limited number of low-permeability zones intercepted by the borehole. However, the emissions that might be measured after degassing with a horizontal borehole were higher since the horizontal borehole intercepted more low permeability zones.

**Fig. 16-A** shows the methane emissions and water inflow into an operation for Cases II and III after degassing with a vertical borehole. This figure shows that the highest methane emissions into the mine occur after the heterogeneous coal bed of Case II was degasified with a vertical borehole which was drilled in a low-permeability zone. Since the borehole was not as effective in producing gas from the coal bed, most of the gas remained in the seam and entered the mine. A similar explanation could be valid for the water inflow as well for this situation.

The methane emissions after degasification of a layered reservoir (Case III) with a vertical borehole were similar to the base case **(Fig. 16-A)**. However, it made a difference in the case of water inflow, where the water inflow rate was lower than the base case. This may be due to removing a high amount of water from the reservoir from the lower perforations, which were in the highest permeable zone of the borehole.

**Fig. 16-B** shows the methane emissions and water inflow into a longwall mine operating in a coal seam of cases II and III type after degassing with a horizontal borehole. This figure shows that after degassing the coal seam with a horizontal borehole, both water and methane emissions into a mine are less compared to a situation where a vertical borehole is used. Also, both water and methane inflow rates do not differ much between cases with different heterogeneities. This may be due to the fact that horizontal borehole production influences an extensive area and the effect of local heterogeneities are less pronounced on emissions afterwards during mining.

## Conclusions

This work presents the impacts of geologic discontinuities such as the presence of partings within the seam and tabular variations in coal type, microlithotypes, and permeability facies on the performances of horizontal and vertical boreholes and the inflow rates of water and methane into an active longwall operation. Compared to a continuous coalbed, the presence of partings resulted in a reduced methane production from both horizontal and vertical degasification boreholes. This was likely due to the lower methane content in the presence of these partings and changes in permeability around the boreholes. Methane inflows to the longwall face were generally lower in the presence of a parting. Water inflow rates were higher in the presence of a coal seam parting due to the amount of water stored in the fracture volume of the parting. These inflows increased in intensity as the longwall face approached either the horizontal or vertical borehole.

Lithotype variations modeled as randomly distributed inertinite-rich regions along horizontal and vertical borehole trajectories did not change the degasification performances of the horizontal or vertical boreholes. With the inertinite then modeled as blocks and layers, methane production from the vertical borehole showed a significant decrease followed by a relatively stable increase.

Subsequent analyses assuming random permeability variations revealed that methane productions from horizontal and vertical boreholes were less than those obtained from the original continuous coalbed model. Zones of increased permeability were then modeled as either blocky or layered regions. A horizontal degasification borehole drilled into a blocky zone could produce as good as the continuous model. When drilled between low and high permeability layers, methane output quickly decreased due to limited production from the low-permeability top layer. This work also showed that a vertical degasification borehole drilled into a blocky zone had the worst performance and permitted increased methane and water inflows to the mining face. Borehole production improved when drilled into a layered zone which produced lower methane and water inflows. Methane emissions and water inflow into a longwall mine operating in a coal seam with blocky and layered permeability facies show that after degassing the coal seam with a horizontal borehole, both water and methane emissions into a mine are less compared to a situation where a vertical borehole is used. Also, both water and methane inflow rates do not differ much between cases with different heterogeneities. This may be due to the fact that horizontal borehole production influences an extensive area and the effect of local heterogeneities are less pronounced on emissions afterwards during mining.

The results of this numerical study show that in coal seams with major heterogeneities and discontinuties, the type and location of the boreholes are important for improved gas production. These considerations are also important for controlling methane and water inflow into the working environment during longwall mining.

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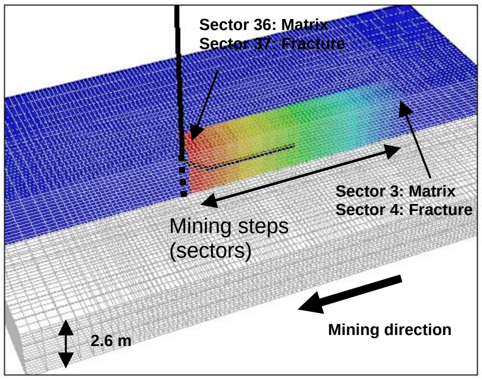
Table 1. Values of some of the reservoir parameters of used in modeling the coalbed.

| **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. (cc/g) / (scf/ton) | 17.3/556 |
| Desorption time constant (days) | 50 |
| Initial water saturation (%) | 95 |
| Coal density (g/cc) / (lb/ft$^3$) | 1.35/84.7 |
| Coalbed pressure (MPa) / (psi) | 2.1/300 |
| Poisson's ratio | 0.3 |
| Young's modulus (MPa/psi) | 3740/5.5×10$^5$ |
| Strain at P∞ (infinite pressure) | 0.01 |
| Pore compressibility (1/KPa, 1/psi) | 0.9 / 6.0×10$^{-4}$ |
| P-M constant | 3 |

Table 2. Parameters used to represent an inertinite-rich coal material for geomechanical changes, adsorption and gas emission properties.

| **Parameter** | **Value** |
|---|---|
| Langmuir p. (MPa) / (psi) | 1.25/182 |
| Langmuir vol. (cc/g) / (scf/ton) | 12.4/400 |
| Desorption time constant (days) | 15 |
| Coal density (g/cc) / (lb/ft$^3$) | 1.44/90.2 |
| Poisson's ratio | 0.2 |
| Young's modulus (MPa/psi) | 4830/7.1×10$^5$ |
| Strain at P∞ (infinite pressure) | 0.005 |
| Pore compressibility (1/KPa, 1/psi) | 0.03 / 2.0×10$^{-5}$ |
| P-M constant | 3 |



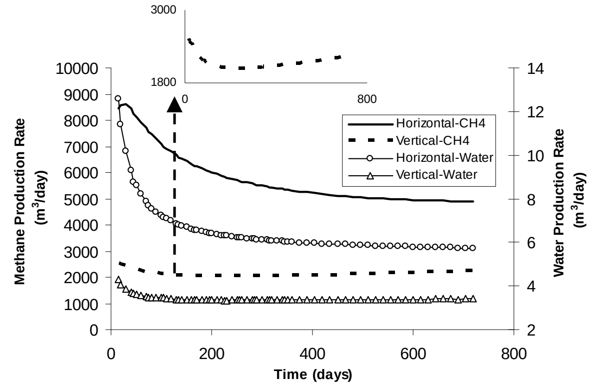




**Figure 1. Grid model of the coalbed that shows horizontal borehole and the sequential mining steps as described by different "sectors" for matrix and fracture elements.**

**Figure 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 maller scale.**

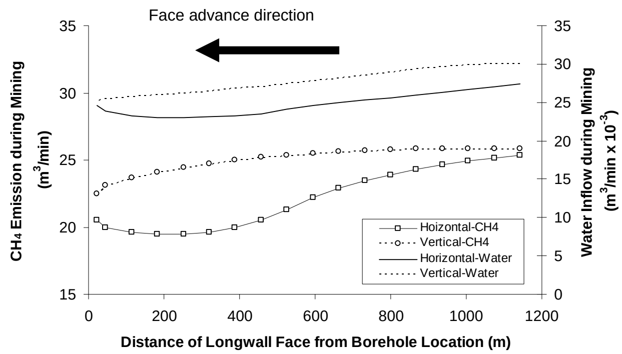



**Figure 3. Methane emission and water inflow into a mine advancing towards the borehole (Figure 1) in the base coalbed model after degasification with vertical and horizontal boreholes.**

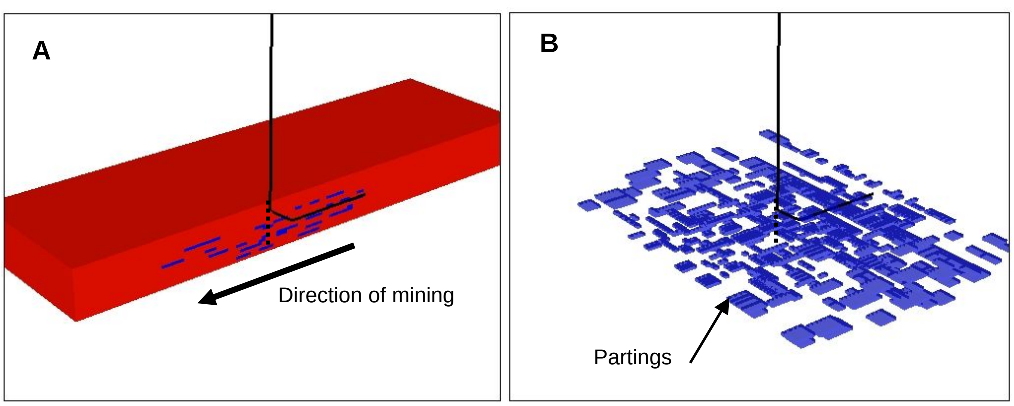



**Figure 4. A cut-away of the coalbed reservoir along the horizontal borehole location. Figure (A) shows the distribution of partings in the coalbed. Figure (B) shows the rendered 3-D image of the modeled partings to show their population and distribution.**

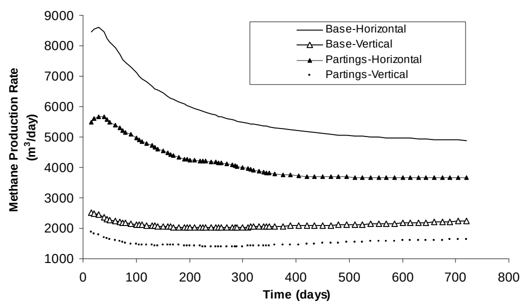



**Figure 5. Methane productions from the boreholes drilled in a coalbed with parting layers (shown in Figure 4)**

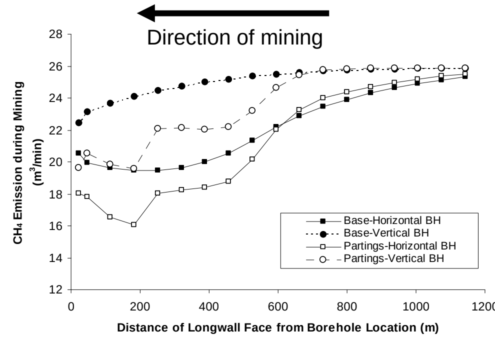



**Figure 6. Methane emissions into the advancing mine in a coalbed with parting layers.**

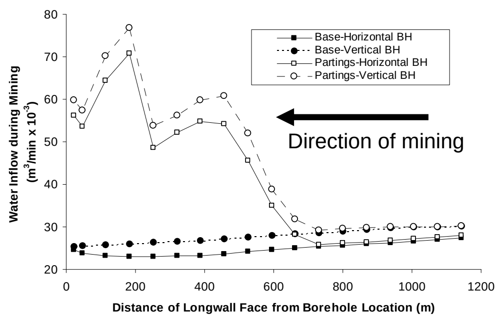



**Figure 7. Water inflows into the advancing longwall in a coalbed with parting layers compared to the base case.**

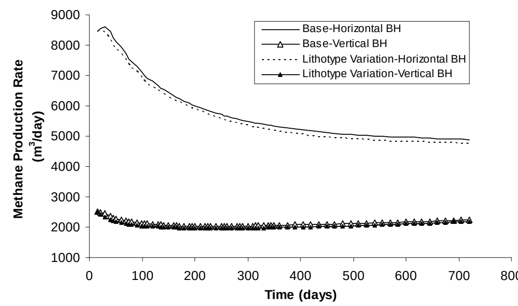



**Figure 8. Methane productions from the vertical and horizontal boreholes that were drilled into a coalbed with microlithotype variations.**

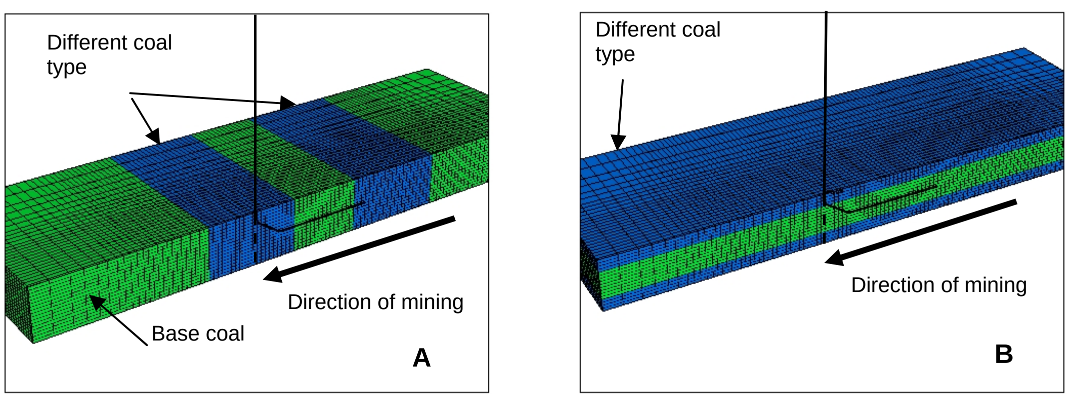
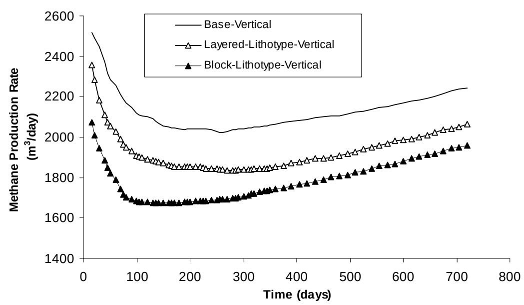



**Figure 9. Cut-aways of the coal seam reservoir along the horizontal borehole location to show the effect of blocky (A), and layered (B) coal-type variations in the reservoir on methane production.**



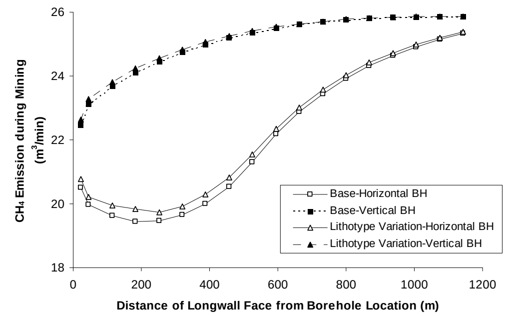




**Figure 10. Methane productions from a vertical borehole drilled into a coalbed with coal type (microlithotype) variations.**

**Figure 11. Methane emissions into the advancing mine in a coalbed with random (shown in Figure 4) coal-type variations after degasification with vertical and horizontal boreholes.**

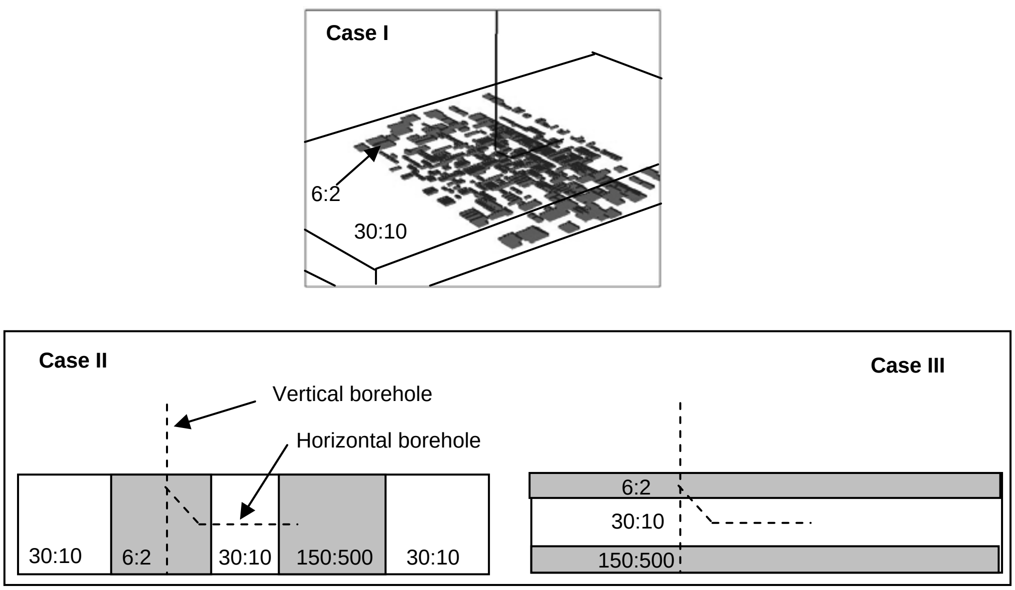
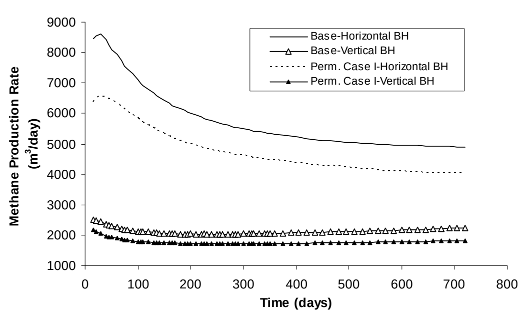



**Figure 12. A schematic representation of the permeability cases that were modeled in the coal seam and the assigned permeability values.**



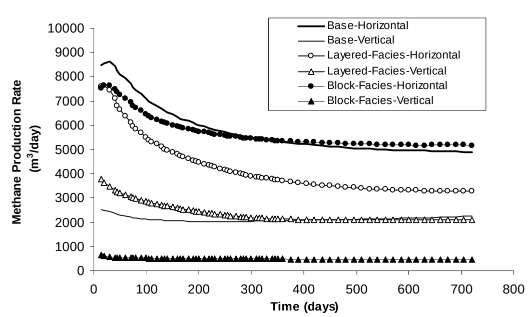




**Figure 13. Methane productions from the vertical and horizontal boreholes that were drilled into a coalbed with random permeability variations (Case I).**

**Figure 14. Methane productions vertical and horizontal boreholes drilled into a coalbed with various permeability facies schematically shown in Figure 12.**

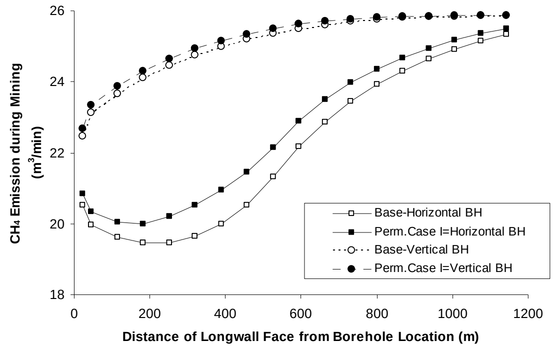



**Figure 15. Methane emissions in a coal bed with random permeability variations after degasification with vertical and horizontal boreholes.**

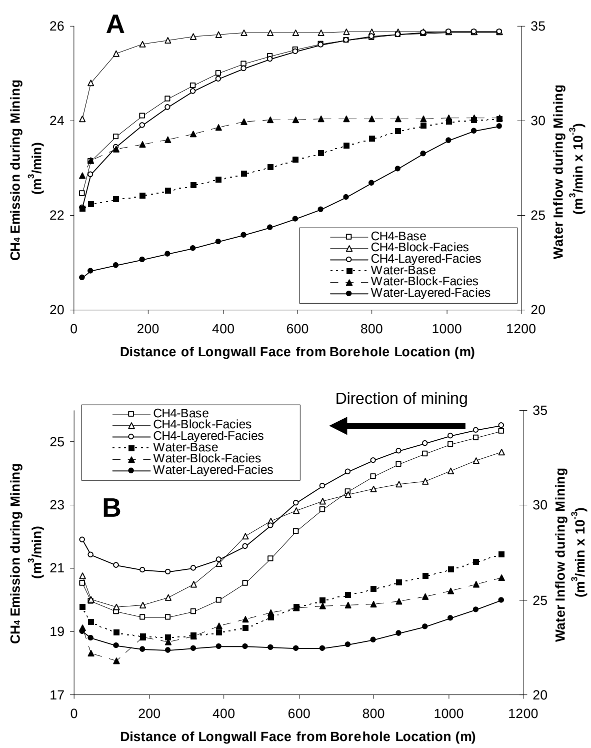



**Figure 16. Methane and water emissions into a mine operating in a coal bed with permeability variations (Case II and Case III) after degasification with a vertical borehole (A) and a horizontal borehole (B).**