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Assessment of Coal Permeability using Injection Falloff Test and Effect of Temperature and Skin Factor on It: A Case Study for Coal Seams of Jamalganj Coalfield, Bangladesh

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ABSTRACT

The Jamalganj coalfield with the coal deposits of the Permian Gondwana Group in the half-graben basin was discovered in Joypurhat District, Northwestern Bangladesh, sometime in 1962. Individual coalbed thickness ranges from 0.60 m to 42 m and seams were encountered between the depth ranges of 640 m and 1158 m. Since mining has not yet begun due to the greater depth of the coal seams, several researchers have proposed a Coalbed Methane (CBM) exploration in this region. This research focuses on the permeability of the Jamalganj coal derived from the in-situ Injection Falloff Test (IFT), which is an important reservoir parameter and one of the key factors in CBM exploration and Underground Coal Gasification (UCG). In addition to that, the relationship of temperature and skin factor with permeability is one of the key findings of this research, permeability obtained from the IFT ranges from 2.57 to 121.16 mD while the skin factor ranges from -6.11 to 50.85 and a higher temperature gradient as of about 4°C per 100 m depths was observed. The study shows that temperature has an inverse relationship with the permeability that decreases with depth and temperature increases, which is analogous with the other CBM producing reservoirs around the world. The negative skin factor denotes flow enhancement near the wellbore and a well-stimulated reservoir, and the positive skin factor indicates increased flow resistance near the wellbore, which reduces permeability. The permeability data suggest that the analyzed coal seams of the Jamalganj Coalfield are suitable for unconventional gas production by either CBM or UCG development.

Introduction

The coal deposits of the Permian Gondwana Group were reported back in the late fifties in Northern Bangladesh where the wells struck coals located in several graben structures in Joypurhat, Dinajpur, and Rangpur districts. The Jamalganj Coalfield was discovered by Bangladesh's coal research program sponsored by the United Nations in 1962, in which 10 wells (Figure 1) were drilled for exploration and mining feasibility in the Jamalganj and Paharpur areas of Joypurhat district and discovered coal seams in 9 wells out of 10 with a maximum gross coal thickness of about 99 m in a single well (Adhikari and Faruque, 2016; Badrul Imam, 2002).

The coalfield was the single largest coal reserve in the country, with over 1 billion tons of coal discovered over an 11 square-kilometer area in the early 1960s (Adhikari and Faruque, 2016). But, due to the greater depths (700 m-1100 m) of most of the coal seams, immediate coal mining has not been initiated. Based on the adsorption isotherm studies, Holloway and Baily (1995) observed that the coals of the Jamalganj area are mostly gassy over the year. Imam (2002, 2013), Adhikari and Faruque (2016)) have recommended the proper assessment of CBM in this coalfield. Coalbed Methane reservoir parameters, such as gas content, coal seam permeability, coal seam thickness, critical desorption pressure, and reservoir pressure generally

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affect the CBM production, among which the permeability is the key factor controlling the migration and flow of gas in CBM reservoir and thus control the CBM production (Wang et al., 2019; Zhou and Yao, 2014). It is noted that previous study estimated 4.99 BCM Gas-In-Place using the standard volumetric method over an area of 64.42 km^2 of the study area (Adhikari and Faruque, 2016). It was also stated by several authors (Cummins and Fredericks, 2006; Guo and Cheng, 2013) that coal permeability assessment is the basic parameter for the reservoir characteristics as well as CBM exploration, and extraction, which also provides the basis for the decision of an efficient channel linkage and process control for Underground Coal Gasification (UCG) (Liu et al., 2014).

In other words, permeability is one of the important features to assess CBM potentiality, but there is a deficiency of these types of data for the Jamalganj coalfield. Besides, only a few works have been done so far in this context. For example, Holloway and Baily (1995) examined a single coal sample from the Jamalganj and told about the cleat system and the permeable nature of the coal seams. Imam (2002) also presumed that the Jamalganj coal was permeable, as evidenced by mud losses during the drilling of the EDH-14 well, and was reported by the Geological Survey of Pakistan in 1966. Regarding the deficiency of data, Petrobangla, the national oil company of Bangladesh, took an initiative to conduct a feasibility study for the Extraction of Coalbed Methane at the Jamalganj coalfield in 2016. During the feasibility study, Injection Falloff Tests (IFT) were executed to evaluate the permeability of the coal seams. Since the permeability of the anisotropic coal seams obtained from IFT is the geometric mean of permeability (Zhou and Yao, 2014) and the value can be estimated using Horner semi-log plot for the falloff data (Zuber et al., 1990), the current study focuses attention on the determination of the coal permeability, skin factor, and initial reservoir pressure of four coal seams from three boreholes in the Jamalganj area using IFT data to characterize the reservoir, as well as the effect of temperature and skin factor on permeability, which may play an important role in the future CBM and UCG development and production in this coalfield, which can lead to the resolution of the energy crisis in Bangladesh.

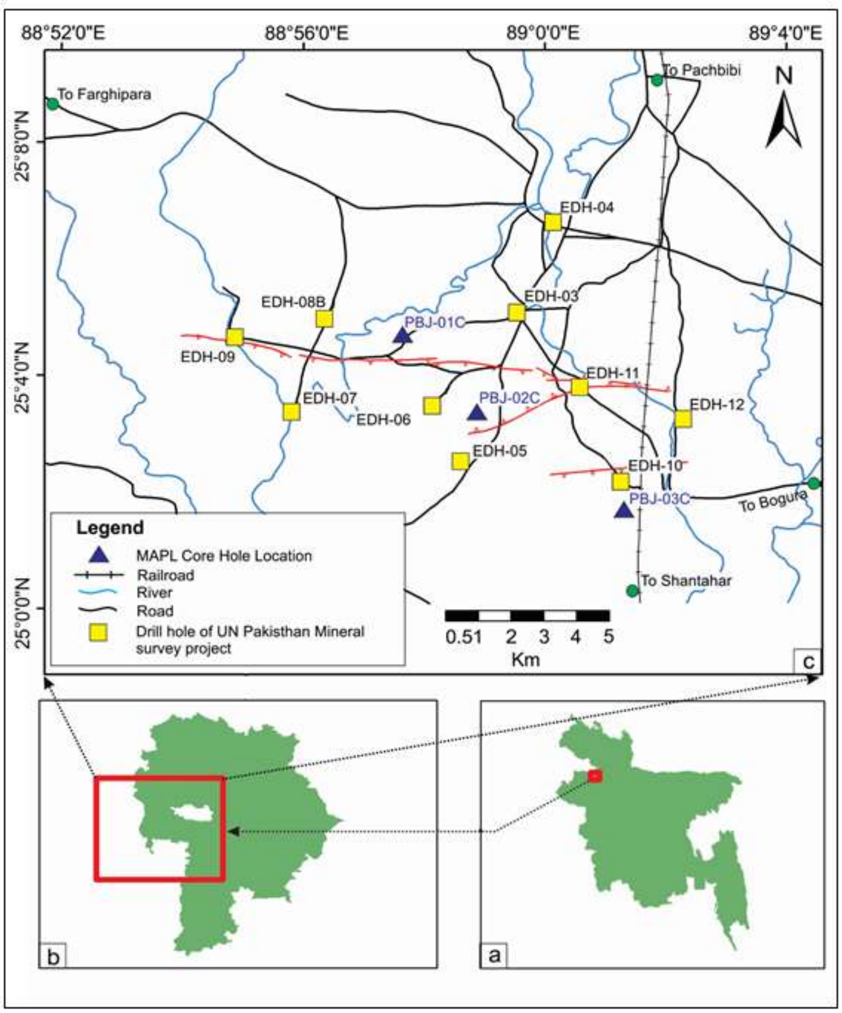

Figure 1: Core hole location map of the study area

Study Area

The Jamalganj Coalfield is located approximately 8 kilometers from the district town of Joypurhat and is well connected by the Bangladesh Railway's Dhaka-Ishwardi-Dinajpur Railway line, which runs along the eastern edge of it. The region is also well served by all-weather National Highways and a district road system, and all core holes in the field are easily approachable. Previously, in 1962, ten core holes were drilled in the research area for exploration and mining feasibility. Later, for the feasibility study for the Extraction of Coalbed Methane (CBM), three core holes were drilled and designated as PBJ01C, PBJ02C, and PBJ03C in 2016 (Figure 1), which were particularly selected to conduct the present research work.

The Jamalganj-Joypurhat physiography shows a flat alluvial terrain. The area is a relatively highland and termed as a Table Land under the physiographic divisions of Bangladesh (Zaher and Rahman, 1980). The area generally experiences a tropical humid climate. Winter is cold with mercury dipping as low as 9°C; summer is oppressive with temperature often soaring up to 42°C even. During the monsoon, there is usually heavy rainfall with annual rainfall varying between 150 cm and 170 cm (Adhikari and Faruque, 2016).

Materials and Methods

The Injection Falloff Test (IFT) is an effective way to obtain CBM reservoirs information and parameters, i.e., effective permeability, skin factor, etc. which can be conducted when the suitable coal seam has been drilled and recovered (Cummins and Fredericks, 2006). The Injection Falloff Test (IFT) involves injecting fluid into the reservoir to increase bottom hole pressure, and a thereafter shut-in period and pressure drop during the falloff period (Bourdet, 2002). This method is efficient for testing water-saturated coal seams and it is imperative that the test be performed without exceeding the fracture gradient of the formation in order to obtain accurate analysis result (Halliburton, 2011). In conventional IFT, shut-in time is laser than injection time, but injection time should be shorter as possible to minimize testing costs (Seidle et al., 1991). The obtained pressure data from IFT can be interpreted by using analytical method, e.g., Horner plot (Horner, 1951) and MDH plot (Miller, 1950) and type curve or history matching (Hopkins, 1998). In this study, IFTs were executed in four coal seams of three different core wells and Horner plot and type curve or history matching methods were applied (Figure 2). The interpretation of IFT data provides estimations in permeability, skin factor, and reservoir pressure for the object coal seams.

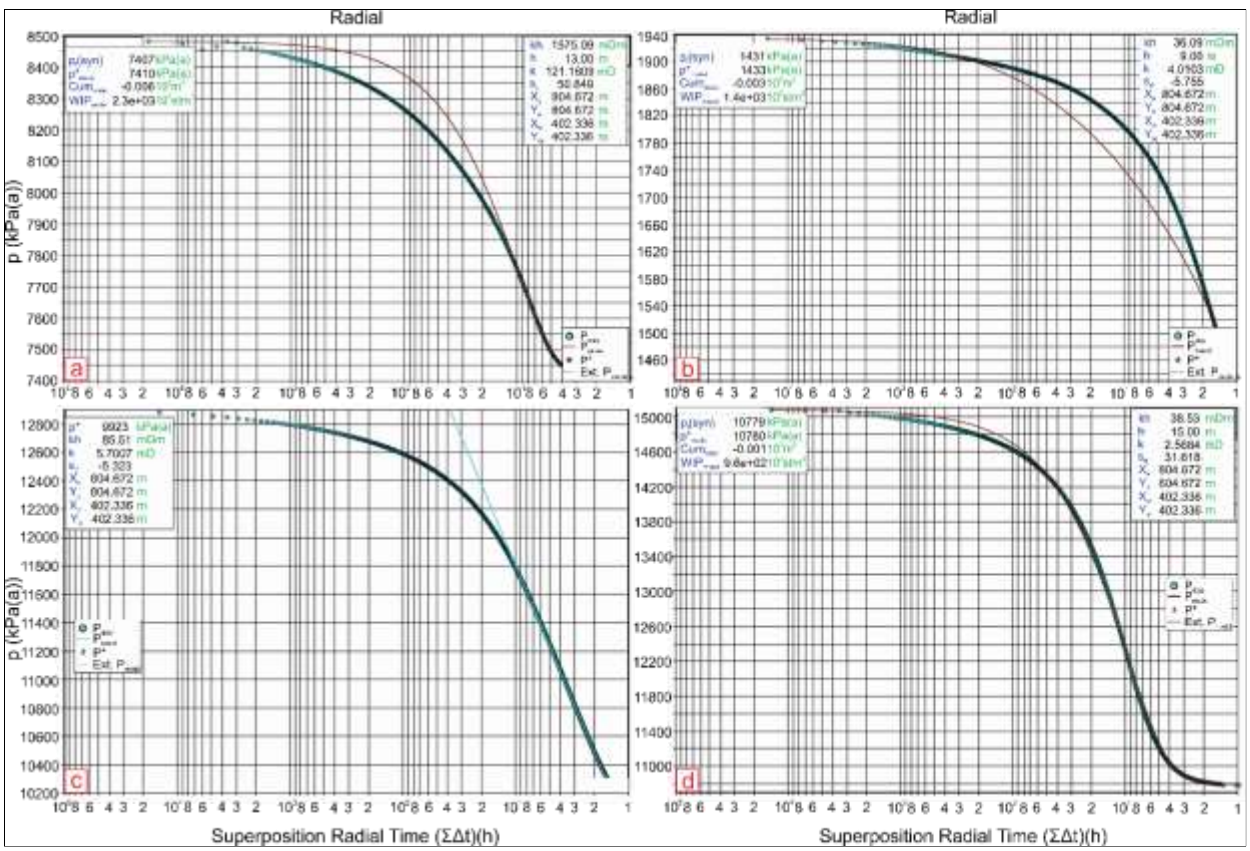

Figure 2: Permeability, skin factor and reservoir pressure values obtained from Horner plot and type curve or history matching. (a), (b) for coal seam-II, VI of core hole PBJ01C, (c) for coal seam-IV of core hole PBJ02C and (d) for coal seam-VII of core hole PBJ03C

For the testing procedure, the “NuFlo Scanner 2200 by Cameron” was used, and it helped monitor the flow rate and pressure variations during injection on real time display with ModWorX Pro interface software. Reservoir input value and fluid properties for the analysis (Adhikari and Faruque, 2016) are as follows:

- Well Bore radius: 0.048 m
- Porosity (ϕ_t): 25-30%
- Water saturation: 100%
- Gas saturation: 0%
- Water Specific Gravity (γ_w): 1.00
- Salinity: 0
- Water formation volume factor (B_w): 1.007
- Solution Gas Ratio (R_{sw}): 0.00

An overview of the results derived and analyzed by F.A.S.T. Well Test software package. The main features of this software include Pressure Volume Temperature (PVT) analysis, well testing analysis, simulation, etc. The input parameters for the determination of well test results include formation porosity, borehole radius, water formation volume factor, etc. At the interpretation phase, some assumptions were made, such as infinite acting reservoir, homogeneous reservoir/dual porosity (Figure 3) and single phase flow (Adhikari and Faruque, 2016). Temperature logging was carried out to know coal seam in-situ temperature using probe from Robertson Geologging Ltd., UK.

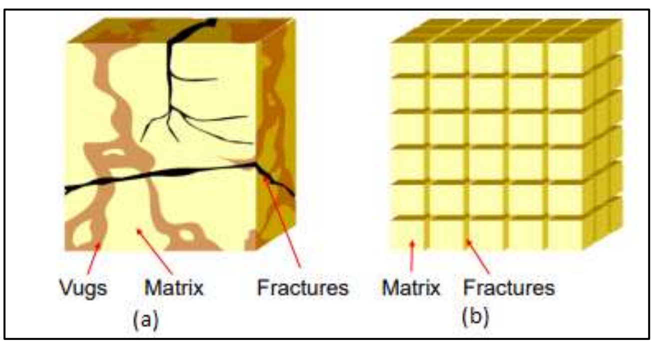

Figure 3: Duel porosity model for the coal seams: (a) for actual reservoir and (b) for model reservoir

Geological Settings

Geologic and Tectonic Features of Bangladesh

Almost three quarters of Bangladesh’s surface is covered by alluvial plains, thus covering the natural exposures including structural features of older rocks. During the last sixty years, exploration activities for hydrocarbon resources in the form of well drilling and geophysical surveys have revealed a lot of subsurface geology of the country. This alluvium covered area forms the largest tectonic region in Bangladesh and can be sub divided into three tectonic zones (Platformal Shelf or Stable Shelf, Hinge Zone, and Bengal Fore deep). The southern onshore part of the Bengal Basin forms an N-S alignment parallel to the structural setting of the fold belt to the east. Further to the north, the foredeep forms a sub-basin called Sylhet Trough or Surma Basin. It turns in the NE-SW direction (Figure 4).

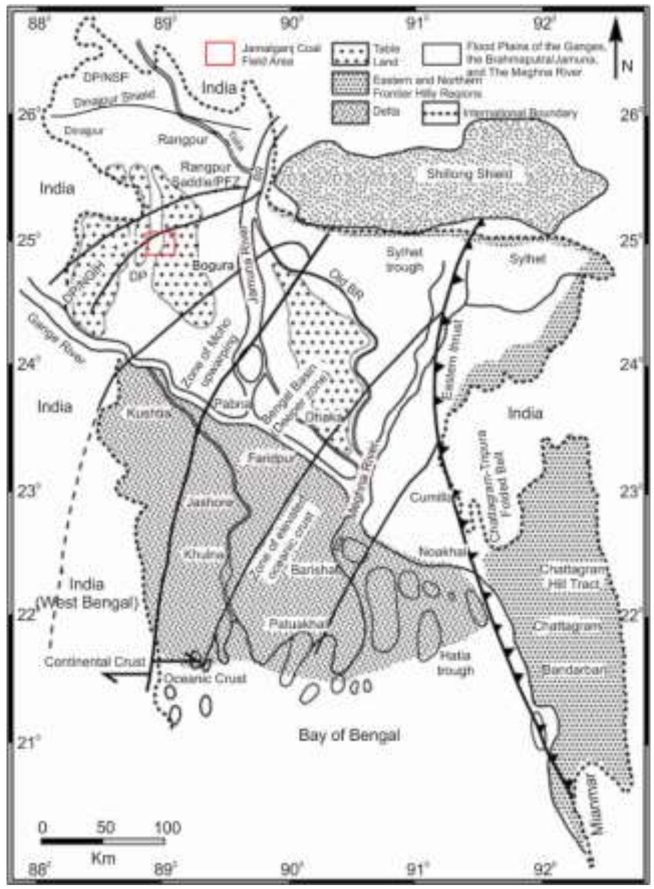

Figure 4: The tectonic map of Bangladesh and the location of the Jamalganj Coalfield within the physiographic and tectonic divisions of Bangladesh. Heavy bold lines indicate the boundary of the major tectonic divisions. Medium bold lines in the northwest part indicate the tectonic boundary of sub-zones within the Dinajpur Shield. BR: Brahmaputra River, DP: Dinajpur Platform, NGIH: Nawabganj–Gaibandha Intracratonic High, NSP: North Slope of the Platform (part of Sub-Himalayan Foredeep), PFZ: Platform Flank Zone (modified after Islam and Hayashi, 2008; Islam et al., 2009)

The western flank of the Bengal basin comprises of two tectonic elements—the shelf slope and the foreland slope. The former also is described as the Hinge Zone. The southern slope of the Rangpur Saddle forms the Western Foreland Shelf of the Bengal Basin. This structural unit plunges with an inclination of merely 1˚ to 3˚ towards the shelf edge in the south east. The Western Foreland Shelf is built up of the gently south-eastwards dipping Achaean Basement Complex and of the overlying deposits of the Gondwana System, Rajmahal Volcanics, late Cretaceous-Paleogene platform deposits and of Neogene progradational delta sequences. The width of the stable shelf between Continental slope and Rangpur Saddle ranges from 60–130 km. The regional dip of formations ranges from 1˚ to 3˚ (Guha, 1978; Reimann, K.-U. and Hiller, 1993).

Gondwana Rocks and Coal Deposits

The term "Gondwana" was introduced by H.B Medlicott in 1872 of the Geological Survey of India (Venkatachala, 1987), and includes rocks from Upper Carboniferous to Lower Cretaceous in age. The Gondwana Group of rocks are divided broadly into two (Lower and Upper Gondwana) or three (Lower, Middle and Upper Gondwana) divisions by different schools. In Bangladesh, the subcrops of Gondwana rocks, underlain by Tertiary and Holocene sediments, have been discovered in graben or half graben structures based on seismic and Corewell data (Holloway and Baily, 1995) on the Western Foreland Shelf and the sedimentation of Gondwana sequence was found apparently discontinuous there. The Gondwana coals are encountered at 152 m – 1150 m in small graben structures, like Jamalganj, Barapukuria, Dighipara, and other places in Dinajpur and Rangpur districts are High Volatile C to A coal. These coals are earlier considered as equivalent to Barakar Formation (Permian) based largely on the thickness of coal seams at Jamalganj Coalfield, which are much thicker than those of Raniganj Formation of Upper Permian age in India (Robertson Research International, 1976). In Jamalganj area the non-coal upper 150 m – 200 m of Gondwana was considered as Upper Gondwana (Triassic to Jurassic age). The Lower Gondwana and Upper Gondwana in this area are locally named as Kuchma and Paharpur Formation (Zaher and Rahman, 1980).

During the present studies, drilling of three core holes (PBJ01C, PBJ02C and PBJ03C), the continuous coring was done for the whole section of the Gondwana, examination of the core section fails to reveal any visible discontinuity between the coal bearing lower section and non-coal upper parts of Gondwana rocks. In Figure 5, the coal seam correlation among the studied core holes were established based on lithological logs and geophysical logs using "Petrel" software, which shows the relative conditions of each holes.

However, in the Indian Gondwana Type Areas, the boundary between Lower and Upper Gondwana (Permo-Triassic boundary) is prominent and widespread (Dutta, 2002), which is completely absent in Jamalganj cores. On the other hand, the upper non-coal part of Gondwana rocks in Jamalganj shows a very close similarity with the coarse sandstone with the minor ferruginous shale/siltstone sequence of Barren Measures in several Gondwana basins in India, such as Bokaro, Jharia, Sohagpur. From these observations, it is suggested that in Jamalganj, the Gondwana strata representing Lower Permian in age and may be divided into a Coal bearing lower part correlating with the Barakar Formation and the non-coal upper part as Barren Measures in conformity with Indian Gondwana basins.

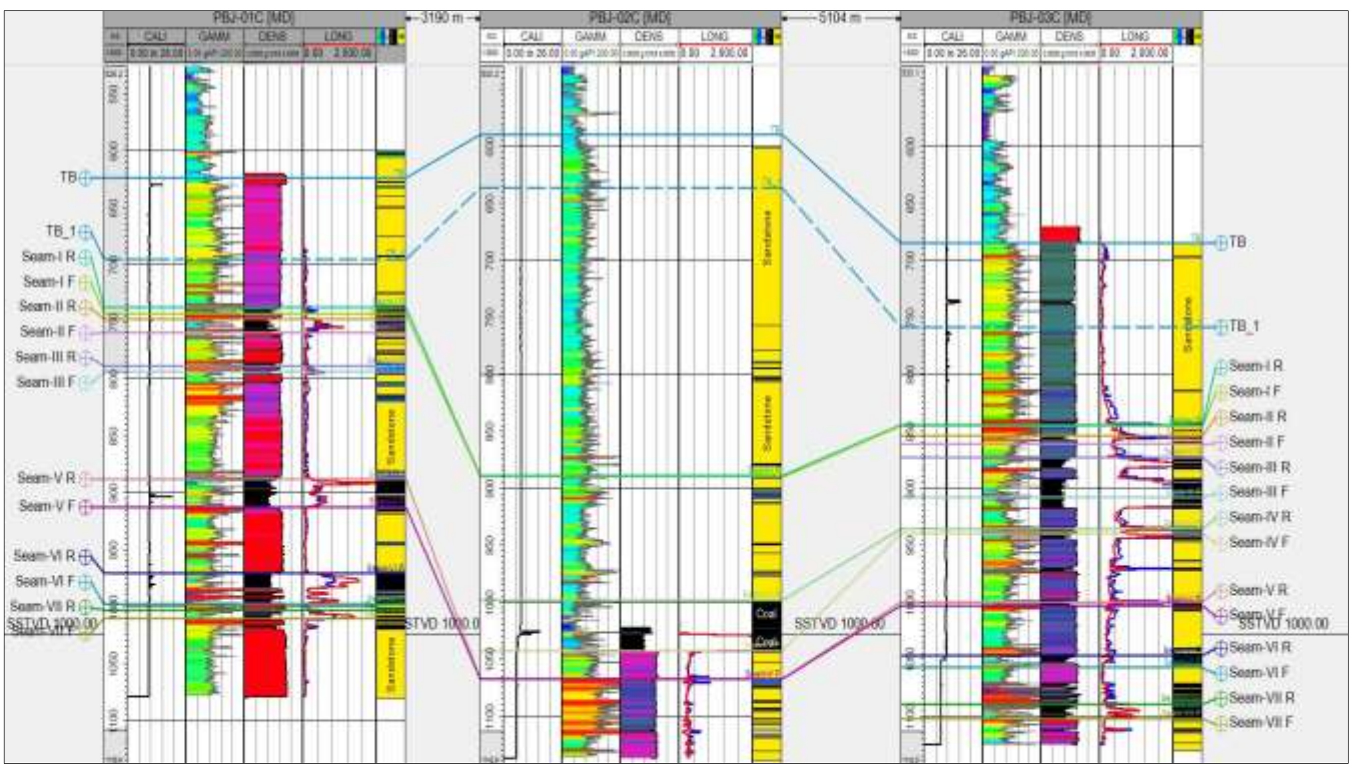

Figure 5: Coal seam correlation based on lithological logs and Geophysical logs core holes PBJ01C, PBJ02C and PBJ03C (from left to right)

Stratigraphy of Jamalganj Area

Jamalganj area has a half-graben structure with the northern faulted boundary (Bujrukh-Durgadoho fault) and the southern side dipping at shallow angle (3°-4°) towards the Continental slope (B. Imam, 2013). In the deeper exploration wells, the contacts of Gondwana (Barakar) with the basement granite was intersected, the total thickness of Gondwana (Damuda) was found to be about 494 m to 1200 m, while the thickness of Gondwana intersected in the three core holes in Jamalganj also have the similar thickness (over 450 m). The Gondwana rocks are overlain by the Jaintia Group of rock (Paleocene-Eocene) with Tura Formation at the base, followed successively upward by the Sylhet Limestone and Kopili Formations. Surma Group (Miocene), Dupi Tila (Pliocene-Pleistocene) and Alluvium (Holocene) (at top 20-30 m) are the upward trending younger groups and formations of the rock sequence of the study area. There is a huge gap in sedimentation between Lower Gondwana (Early to middle Permian) and Lowermost Tertiary (Early Paleocene). Often there occurs volcanic rock below the Tertiaries and is correlated with Rajmahal Trap of Eastern India (B. Imam, 2013). Generalized stratigraphy of the study area is given in Table 1.

Table 1: Stratigraphic succession of Jamalganj Coalfield area (after M.M. Rahman & M.A. Zaher, 1980)

Age		Group	Formation	Thickness [m]	Lithology
Holocene			ALLUVIAL SILT/BARIND CLAY	20-30	Clay, silt, coarse, medium and fine sand and gravel
Pleistocene			DUPITILA	12-70	Coarse to fine gravel and coarse sand
Pliocene	Late				
	Early				
		SURMA	Unconformity		
Miocene	Late		JAMALGANJ	250-380	Silt, fine sand, clay, quick sand, medium gravel, shaly clay, sandstone, shaly coal
	Middle				
	Early				
			Unconformity		
Oligocene	Late	BARAIL			
	Early				
Eocene	Late	JAINTIA	KOPILI	25-30	Shaly clay, sandstone
	Middle		SYLHET	15-45	Limestone, shaly clay
	Early		TURA	50-110	Sandstone, shaly clay, silt, shaly coal
Paleocene	Late				
	Early				
Cretaceous	Late				
	Early	UPPER GONDWANA	RAJMAHAL	-	Basalt trap & associated sill/dyke
			Unconformity		
Jurassic	Late				
	Middle				
	Early				
Triassic	Late				
	Middle				
	Early				
Permian	Late	LOWER GONDWANA			
	Middle		BAREN MEASURE	115-280	Medium to very coarse grained light greenish grey to greyish white chloritic sandstone; often interbedded with pebbles and conglomerate; matrix feldspathic; large cross bedded with minor siltstone/chloritic shale often ferruginous;
	Early		BARAKAR	300-400	Coarse to medium white feldspathic sandstone, very hard and compact with seven major coal seam zone; with grey shale and carb. shale. Garnet bearing cross bedded at the lower part and devoid of coal.
Precambrian					Granite and gneisses

Results

The present study deals with three core holes, i.e., PBJ01C, PBJ02C, and PBJ03Chaving target depth of1080m, 1137 m, and 1126 m to assess the feasibility for CBM (Adhikari and Faruque, 2016). The Permeability obtained from the IFT ranges from 2-121mD. IFTs were performed over four (4) coal seams of three (3) core holes as coal seam-II & VI for PBJ01C, seam-IV for PBJ02C and seam-VII for PBJ03C to determine the permeability of the coal seams in the field. The highest permeability value was found in the seam-II (121.16 mD) of core hole PBJ01C and lowest (2.57 mD) in seam-VII of PBJ03C. The Seam-IV of core hole PBJ02C shows the permeability value of 5.92 mD and seam-VI of PBJ01C shows value of 4.01 mD. The permeability to air conducted at laboratory ranges between 0.22 mD to 1.16 mD, which is much less than the in-situ permeability test. The Skin factor for the seam-II & VI of the core hole PBJ01C were 50.85 and -5.78, respectively. The skin factor for the seam-IV of core hole PBJ02C found -6.11 and that of seam-VII of core hole PBJ03C was 31. The initial reservoir pressure obtained 7047 kPa and 9717 kPa for the seam-II & VI of core hole PBJ01C, 10151 kPa for seam-IV for hole PBJ02C and 10772 kPa for seam-VII for PBJ03C well, which is shown in the Table 2. For the core holes PBJ01C, PBJ02C and PBJ03C the temperature ranges from 27.94 to 61.67 ° C, 30.15 to 55.62°C and 30.77 to 63.99°C, respectively, from the surface to the depth up to 1136 m. Overall, the area witnesses a higher temperature gradient as of about 4°C per 100 m depth. From the permeability and temperature data, it is very much clear that the permeability is decreasing accordingly with depth and temperature increment (Figure 6).

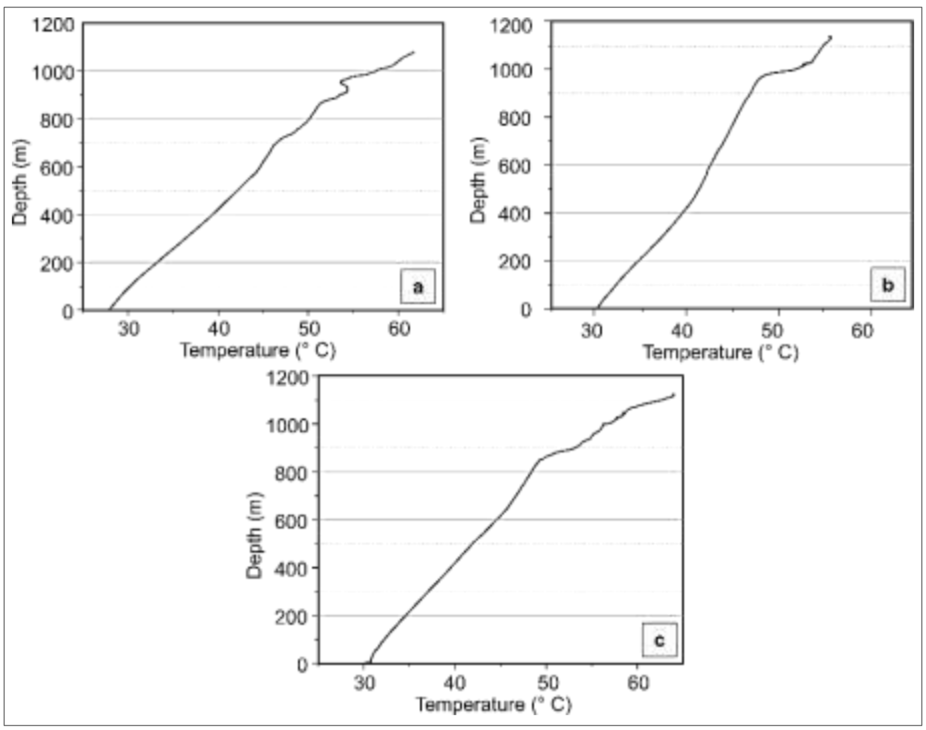

Figure 6: Depth vs Temperature relation in the study area: (a) for core hole PBJ01C, (b) for core hole PBJ02C and (c) for core hole PBJ03C

Table 2: Core hole specification and IFT data

Well ID	Coal Seam No.	Coal Seam Depth (m)	Coal Seam Thickness (m)	Formation Porosity, %	Well Bore Radius, r_w (m)	Formation Volume factor, B_w	Permeability, k (mD)	Skin Factor, s	Reservooir Pressure (kpa)	Injection Time (hrs)	Falloff Time (hrs)
PBJ01C	II	747-760	13	27	0.048	1.007	121.1609	50.849	7047	5	12
	VI	1003-1012	9	25	0.048	1.007	4.0103	-5.775	9717	4	12
PBJ02C	IV	1028-1043	15	25	0.03	1.006	5.9286	-6.106	10151	4	12
PBJ03C	VII	1088.5-1103.5	15	25	0.03	1.006	2.5684	31.618	10772	4	12

Discussions

The field permeability determination by Injection Falloff Tests (4 nos.) in three core holes indicates moderate to very high values (2.56–121.16 mD) even at a depth of over 900 m, whereas the permeability measured at Laboratory (0.22-1.16 mD), which is much less than the in-situ permeability test. In India, there are some CBM producing coalfield like the Jharia Coalfield and the Raniganj Coalfield where the coal permeability shows 0.32-1.08 mD and 0.6-12 mD, respectively (Chatterjee et al., 2019; Kumar et al., 2019). The CBM producing Qinshui Basin, China shows the permeability range from 0.02 to 0.6 mD (Liu et al., 2014; Zhu et al., 2018). Northern Bowen Basin, Queensland, Australia, San Juan Basin, USA, and Upper Silesian Coal Basin (USCB) in Poland show the permeability of 0.09-3.04 mD, 1.6-43.8mD and 0.4-1.5 mD, respectively (Shi and Durucan, 2010; Tan et al., 2018; van Bergen et al., 2009). In the Jamalganj Coalfield, the permeability shows the highest value for the seam-II of PBJ01C stated 121.16 mD, whereas seam-VI, IV and VII of PBJ01C and PBJ02C and PBJ03C are 4.01, 5.92 and 2.56 mD, respectively, which indicate that the coal is highly permeable and suitable for the CBM and UCG production. The higher value of permeability may be found in such a coal basin where the coal is highly cleated and fractured in nature and the low stress condition of sedimentary basin.

The temperature plays an important role on the permeability of the coal as well as the CBM production. Under the same stress condition, the increase of temperature cause decrease of permeability of the coal means they are negatively correlated because reduction of coal strength and increment of the plasticity are caused by the increment of coal temperature, which tends to heal the fractures and microcracks in coal (Chao et al., 2019). This phenomenon is similar to the other CBM producing coalfields around the globe; hence the CBM development in the Jamalganj Coalfield should be at shallow to intermediate depths where another parameters support.

The skin factor ranges from -6.106 to 50.849. The positive skin value found in the seam-II where the permeability found the very high and seam-VII of PBJ01C and PBJ03C, respectively. The negative skin values obtained from seam-VII and IV of the PBJ01C and PBJ02C, respectively, indicate these seams can produce more gas than other two seams tested. The positive skin values indicate extra flow resistance near the wellbore, whereas a negative skin value indicates flow enhancement near the wellbore and the reservoir is well stimulated. The positive skin value in a well shows that the well has formation damage. For CBM wells, formation damage is likely to happen during drilling operation when the drilling fluid induced to the formation are highly potential to plug or clog the cleats that act as pathway for the methane to be desorbed (Lee, 1982; Raja Bongsu, 2013). Similar events during drilling in the Jamalganj coalfield may occur which leads the positive skin value which will normally interrupt the CBM of UCG production if developed in the study area. The production well in San Juan Basin has -1.97 skin factor, which indicates that the reservoir is well stimulated. In the Jamalganj Coalfield, it shows the positive and negative skin factors as well from which it can be stated that the coal seams suitable for the CBM and UCG production where the value of skin found negative. From the above study, it is clear that the Jamalganj Coalfield has the potentials for unconventional gas production. Further detail research especially on the controlling parameter of the CBM and UCG production, like gas content, reservoir characterization, petrophysical and petrochemical analysis thus can lead to the development of the gas production which can help mitigate the energy demand of the country.

Conclusion

The Jamalganj Coalfield is the largest coal field in Bangladesh. The mining of coal here is more difficult and costlier than elsewhere as the coal seams are in deeper depth (700-1100 m) than other fields. The depth of coal seams, coal rank and geological condition support the Jamalganj Coalfield is suitable for the CBM and UCG development, but there was lacking of reservoir properties data. From the coal quality and gas content from adsorption isotherm studies, different authors over the years have considered the coals are gassy and had recommended for carrying out exploration for proper assessment of CBM in this coalfield. This research emphasizes the necessary reservoir data especially permeability, skin factor and initial reservoir pressure for the further initiative either CBM or UCG development. The permeability of the coal seams achieved from the study is suitable for reservoir characterization and unconventional gas production scheme. The data obtained from the study reflect the coal seams are highly cleated and permeable (2-121 mD) in comparison with other CBM producing coal fields around the world. The skin factor (-6.106 to 50.849) and temperature found in the study from 27.94 to 63.99 °C with the temperature gradient of 4°C per 100 meters, which is more likely to the global CBM or UCG producing coalfield. The effect of temperature on the permeability of the coal seams is similar to the other CBM producing reservoirs in the world as permeability is negatively correlated with temperature. The data obtained from the study suggest that the coal seams are highly fractured and permeable, which will enhance the gas production from the coal seams thus the Jamalganj Coalfield is suitable for unconventional gas production by either the CBM or UCG development.

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