Coal Bed Methane (CBM) Resources of Lower Indus Basin, Sindh-Pakistan

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Abstract – Pakistan is energy deficient and underdeveloped country but it processes huge resources of lignite coal. The contemporaneous models for Coal Bed Methane (CBM) in low-rank coals have changed dramatically in recent years due to the growth of commercial CBM activity in the Powder River Basin (PRB). The CBM models are still evolving because the CBM evaluation concepts are on steep learning curve based on proven and tested commercial activities. Coal is an unusual lithology in that it is both an excellent source and reservoir rock (Levine, 1993). CBM resource has also been found in commercial quantities in the Cambay Basin of India. The CBM resource of Cambay Basin and Powder River Basin (PRB) are similar in age and rank to most of Pakistan's coal. The success in the above mentioned basins provoked geoscientists in Pakistan to re-look into Sindh's CBM resource. Thar coal is considered as the largest reserves of low ranking coal in Pakistan. Preliminary geological investigation was carried out; results show that low ranked coal seams of class Lignite B to High Volatile B sub bituminous coal exist in Sindh. The rank specified above is better in quality than Powder River Basin Coal Deposits, so it warrants further evaluation to firm up further exploration and subsequent exploitation. Interactive wireline correlations between several wells have been carried out explicitly. Results show that isolated coal seams of Bara Member (Paleocene) and Sohnari Member of Laki Formation (Eocene) exists a few kilometers in sub-surface. The thickness of coal seams is thickest in Thar area with better prospect for gas adsorption capacity. The dedicated CBM studies also reveal that the bituminous coal exists in Badin, Sonda, Thatta and Jherruck areas. Depositional Model of Thar coal deposit has been prepared using plate reconstruction.

Keywords – CBM, Lower Indus Basin, Sindh, Pakistan.

INTRODUCTION

CBM is found as trapped and adsorbed on the surface of pores and cleats in coal seams. It is used as fuel gas and is mainly composed of methane (CH\textsubscript{4}) as its name suggests. Coalbed methane (CBM) is also known as coal seam gas (CSG) in Australia suggesting that there is no unequivocal terminology for gas extracted from coals. Porosity and permeability in coals exist due to the presence of matrix porosity (micropores) and natural fractures known as cleats (Siddiqui et.al, 2010). According to Ahmad et.al (2010), 10% of the world's coal deposits are present in Sindh, Pakistan, it may be considered promising for CBM potential of the country.

Coal is located in the southern, mid-western and northern parts of Pakistan (Fig.1). Based on geological mapping, coal resources in the south (Sindh) are approximately 185 Billion Tonnes and are mostly Lignitic to sub-bituminous, while the estimated resources in the north (Potwar Plateau and Salt Range) are 235 MM Tonnes and are Lignitic to Bituminous. Analogy for the coals in the south is Powder River basin (Wyoming and Montana) in USA where extensive CBM operations and production has been taking place.

This study is taken a solid step forward initiating evaluation of CBM Resources on the basis of available Coal properties. This study shows that coals in the North are much more favorable for CBM due to their maturity and sub-bituminous to bituminous nature. Most of Previous Work

A) Previous Work

Pakistan is endowed with large reserves of coal deposits ranging from lignite to high volatile bituminous. The 7th largest lignitic coal reserves (Fig.3); need to be exploited for provincial as well as national development. Coal assessment was first initiated by US Geological Survey with the financial help of US Aid. The largest part of measured deposits is associated with Southern Sindh Monocline (Malkani 2012). Figures 1 & 2 are explicitly depicting coal deposits of Sindh monocline. Ahmad et.al (2010) presented Badin and Thar Coal as potential candidates for CBM and compared coal composition, seam thickness and confined aquifer within and below coal zone with its analog on Indian side. Ahmad et.al (2010) proposed strong cooperation among industry and research and development (R & D) organizations / universities in sharing technical information and experience and recommend government support. Siddiqui et.al (2010) and Siddiqui et.al (2011) presented the results of detailed Scanning Electron Microscopic (SEM) study carried out on coal samples from various locations of Thar and Lakhra coalfields of Sindh to evaluate the porosity and permeability patterns. The study suggested that the Thar and Lakhra coals may have best permeability for the storage of CBM provided other geological factors required for the CBM generation are favorable. Coal deposits in Sindh is present nearby gas pipeline infrastructure (Fig.2). Biggest Challenge is to appraise and produce gas at economic rates.

B) Coal Reserves of Pakistan

Malkani (2012) presented the details of coal reserves of Pakistan along with coal properties based on various projects carried out by Geological Survey of Pakistan (GSP). CBM potential is evaluated on the basis of data used by Malkani (2012). Operational coal mines aren’t depicting the true coal potential of the country. However, coal reserves measured on the basis of geological mapping adds valuable addition in
total reserves. Therefore total reserves of coal is 186 billion tones in Pakistan, out of which most coal is associated with Sindh Monocline. This paper also emphasizes on assessment of CBM resource based on various properties of coal. The coal resources of the major administrative units of Pakistan (Malkani 2012) are as under,

- Tertiary coal is being exploited from Early Paleocene, Hangu Formation (in Makerwal and Surghar areas) and Late Paleocene, Patala Formation (Central and Eastern Salt Range) in Punjab province. Total reserves of Punjab Coal are about 235 million tons (Malkani 2012).
- Working coal mines in Sindh are Lakhra and Meting-Jhimpir coalfields whilst non-developed coalfields are Sonda-Thatta, Jherruck, Ongar, Indus East, Badin and Thar coalfields with total reserves of about 185,457 million tones (Malkani 2012). Coal seams are associated with Paleogene rocks of Sindh Monocline.
- Working coal mines in KPK are Hangu/Orakzai, Cherat, Dara Adamkhel and Gulakhel coalfields. Non-developed coal field in the same region is the Shirani coalfield with total reserves of about 122.99 million tones (Malkani 2012).
- The coal deposits of Baluchistan are situated between, Quetta-Duki, it is comprised of commercial deposits over a large area, roughly coincident with the eastern flank of the Sanjawi Arch, and a narrow elongate area between Quetta and Johan. Coal bearing host rock in Baluchistan province is Toi Formation (Eocene). The Eocene coal fields are, Khost-Shahrig-Harnai,
**Fig. 3**  Coal characteristic of Pakistan (Based on data published by Malkani, S.A., 2012)
Johan, Ghazoe, Ghar, Dewan, Narwel-Dab and Kingri. In the Sor Range near Quetta, the Toi Formation consists of calcareous sandstone, conglomerate, calcareous claystone and carbonaceous shale with commercially exploitable coal seams. Cretaceous or Cretaceous-Tertiary (K-T) coal is present in Maastrichtian age. Total reserves of Baluchistan Coal are about 458.5 million tonnes.

- Total reserves of Azad Kashmir and Kotli coalfields are about 8.72 million tonnes.

C) Coal Bearing Facies in Lower Indus Basin (Sindh)

<table>
<thead>
<tr>
<th>COAL BEARING FACIES IN PALEOGENE OF LOWER INDUS BASIN (SINDH) PAKISTAN</th>
<th>Laki Limestone</th>
<th>Meeting Shale</th>
<th>Meeting Limestone</th>
<th>Sohrni Formation</th>
<th>Lakhra Formation</th>
<th>Bara Formation</th>
<th>Khadro Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early Eocene</td>
<td>Laki Group</td>
<td>Dominantly limestone</td>
<td>Claystone, Sand with bed of Limestone and sand</td>
<td>Dominantly limestone</td>
<td>Varicoloured lateritic clay and shale with locally coal seams</td>
<td>Limestone, Sandstone, shale interbeds</td>
<td>Claystone, shale, Early Eocene siltstone, sandstone, coal, carbonaceous</td>
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<tr>
<td>Lakhra Formation</td>
<td>Limestone</td>
<td>Sandstone, shale interbeds</td>
<td>Limestone, Sandstone, shale interbeds</td>
<td>Claystone, shale, Early Eocene siltstone, sandstone, coal, carbonaceous</td>
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<tr>
<td>Bara Formation</td>
<td>Claystone, shale, Early Eocene siltstone, sandstone, coal, carbonaceous</td>
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<tr>
<td>Khadro Formation</td>
<td>Sandstone, shale</td>
<td></td>
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</tbody>
</table>

Fig. 4 Cleat Characteristic in coal deposits of LIB (Sindh), modify after Siddiqui et.al 2012.

D) Cleats in coal deposits of Lower Indus Basin (LIB)

Coal contains dual porosity; it contains micropores (matrix) and network of natural fractures, also known as cleats (Siddiqui et.al, 2012). Fig.4. is showing Cleat Characteristic in coal deposits of Sindh Monocline.

E) Analogy of coal fields in Lower Indus Basin (Pakistan) and Powder River Basin (USA)

The Powder River Basin (PRB) is located in northeastern Wyoming and southern Montana in USA. It covers an area of approximately 66,822 square miles with majority of the potentially productive coal zones ranging from about 137m to over 1981 m below ground surface. Gas Reserves range from 7 to 12 TCF (PPL in-house evaluation). In 2002, wells in the Powder River Basin produced about 823 million cubic feet (Mcf) per day of coalbed methane (DOE, 2002). Most of the coal in the Powder River Basin is subbituminous in rank, which is indicative of a low level of maturity. Some lignite, lower in rank, has also been identified. The thermal content of the coals found in the Powder River Basin is typically 8,300 British thermal units per pound. Coal is found in the Paleocene, Fort Union Formation and Eocene, Wasatch Formation of Powder River Basin. Most of the Coalbeds in the Wasatch Formation are continuous and thin (six feet or less) although, some localized thicker deposits have also been found.

In Sindh, coal was first discovered from Lakhra in 1853. Most of Sindh’s coal fields are associated with Bara Member of Ranikot Group (Paleocene). However, in some parts, Sohnari Member of Laki Group (Eocene) hosts coal. The thickest coal beds are present in Thar coal field, where maximum seam thickness is 40m. The average thickness of coal seams range from 0.3 to 2.5m.

Table 1 Analogy between Lower Indus Basin, Sindh, Pakistan and Powder River Basin (PRB), USA (Internal reports of PPL)

<table>
<thead>
<tr>
<th>Composition</th>
<th>Powder River Basin</th>
<th>Lower Indus Basin (Sindh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating value (Btu/lb)</td>
<td>12,770</td>
<td>8,683</td>
</tr>
<tr>
<td>Ash (% dry)</td>
<td>17.4</td>
<td>6.6</td>
</tr>
<tr>
<td>Moisture (%)</td>
<td>3.1</td>
<td>23.8</td>
</tr>
<tr>
<td>Sulfur (% dry)</td>
<td>4.2</td>
<td>0.4</td>
</tr>
<tr>
<td>CaO (%)</td>
<td>2.7</td>
<td>28.3</td>
</tr>
<tr>
<td>MgO (%)</td>
<td>1</td>
<td>4.5</td>
</tr>
</tbody>
</table>

The previous Geological & Geophysical (G&G) work is very limited and the true thickness of the seam can’t be concluded from these studies. Preliminary evaluation shows that coal seams distribution is in the form of isolated bodies with chances of thick coal seams in areas other than Thar Coal Field. A 6m thick coal seam is reported in Jheruck coal field and heating value of the seam is 8,800-12,846 BTU/lb which is also higher than Powder River Basin (PRB) coal. A brief comparison between coal fields (characteristic) of...
Fig. 5  Generalized analogy between coal characteristic of Lower Indus Basin, Sindh, Pakistan and Powder River Basin (PRB), USA. (Based on data published by Malkani, S.A., 2012 and Flores, R.M., 2004)
Lower Indus Basin (LIB), Sindh, Pakistan and Powder River Basin, USA is given in Table 1 and discussed rank wise in Fig. 5.

F) CBM Resources in Barmer Basin (India)

The Western Rajasthan Shelf which forms an integral part of Indus Basin, and is composed of three main sub basins which are separated from each other by basement ridges/faults. These Sub-basins are:
1. Jaisalmer Sub-basin
2. Bikaner-Nagaur Sub-basin
3. Barmer-Sanchor Sub-basin

Barmer Basin (Ayaz, et al., 2014) was considered as having extension of coal of Sindh and CBM has been exploited North Gujrat, nearby Pakistan Border (Fig.6). CBM Exploration in the acreage falling in Barmer-Sanchor Basin, covering an area of about 790 sq. km in Banaskantha district of North Gujarat was taken up by ONGC as operator (Chakraborty, A. et.al, 2011). In this area, coal seams are confined to the Middle Tharad Formation of Middle Eocene age (Fig.7). The coal ranks as Lignite and is similar to lignite of Sindh. The Thard Formation (Lower to Middle Eocene) is correlatable with Laki Group on the basis of overall lithology and its lower part may be considered as extension of Sohnari Member with coal bearing facies in Pakistan but thorough research is needed to firm it up. The initial syn-rift basin fill sediment is of Paleocene age and is equivalent to Syn-rift basin fill sediment of Paleogene in Sindh Monocline.

![Barmer Basin](image)

According to Rao et.al (2014), lab analysis data showed that Barmer Basin coals are high in moisture (9-23%), very low ash (2-9%), content with high volatile matter (30-55%) with low calorific value and were assigned to Lignite rank. Low Vitrinite reflectance (0.28 to 0.4) values were observed, indicating very low thermal maturity. The test wells in the study area did not produce coalbed gas, even after dewatering for one year, showing little accumulation of gas in the drilled wells. This is due to the low rank and low thermal maturity, lack of cleat and fracture, high degree of under saturation, great difference between reservoir pressures and critical desorption pressures. Whereas, Sindh coal is older than Barmer coal, which suggests that it got more time for maturation from Lignite to Bituminous, at places. Interestingly, cleats are present in Sindh Coal contrary to Barmer Coal, which was the main reason of deterioration of reservoir quality in Barmer Coal.

![Coal bearing facies of Barmer Sanchor Basin](image)

![Thickness of Eocene coal](image)

G) Coal Bearing Facies in wells drilled in Sindh Monocline

Subsurface data of multiple wells shows that the coal bearing facies are mostly associated with Paleocene (Bara Formation) and Eocene (Sohnari Member of Laki Formation) in the surrounding of the Meting-Jhimpir and Sonda-Thatta-Jherruck-Ongar areas. Fig.8 is showing thickness of Paleocene coal seams drilled in the petroleum wells situated in the surrounding of Paleocene coal fields of Sindh. Similarly Fig.9 is showing thickness of Eocene coal seams drilled in the wells present in the surrounding of Eocene coal fields (Sindh). Average thickness of Eocene coal is 3-1 m.

![Coal bearing facies of Sindh](image)

H) Quality of Sindh Coal

Qualitative analysis of coal bearing facies in Sindh province has been done on the basis of heating values of coal. The data used to arrive on the conclusions was published report of Malkani, S. A., (2012) of Geological Survey of Pakistan (GSP). Lakhra, Meting-Jhimpir and Sonda East are low quality coals, because their rank is restricted to Lignite to subbituminous C only. Best quality of coal is situated in
Sonda-Thatta-Jherruck–Ongar areas. Eocene Coal is also present in the surrounding of Sonda-Thatta-Jherruck–Ongar areas. Figure-10 is showing quality of coal seams of Paleocene/Eocene coal fields of Sindh, on the basis of heating values. This heating value is directly proportional to methane in coal.

Lakhra and Sodha East contain low ranks of coal, of varying quality. The coal is not lignite throughout, but also matures at places up to Sub Bituminous C, which increases the tendency for adsorption of gas. Similarly, Thar Coal is not only limited to lignite rank throughout, it is also mature up to Subbituminous A rank. Results show that the Thar Coal is the best candidate for the exploration of CBM project as pilot project because (i) Heating value is higher than Powder River Basin and Barmer Basin Coal. (ii) Thickest Coal Seam is present in Thar. (iii) Thar Coal should be extended to deep in basin as deepest is considered, as the best part for exploitation of CBM gas. (iv) Micropores or intrinsic pore spaces within the coal matrix stores the methane gas in Thar Coal (Siddiqui et.al, 2012).

Ash quality of coal of various regions of Pakistan is also analyzed in this paper. Sonda-Thatta-Jherruck – Ongar coals produce highest proportion of ash as compared to other region’s coals. Fig.11 is showing distribution of ash in coal seams of Paleocene/Eocene coal fields (Sindh). Additionally, distribution of sulphur and moisture was also considered and the figures,12 and 13 are showing distribution of sulfur and moisture in coal seams of Paleocene/Eocene coal fields (Sindh) respectively. Results show that moisture content is comparatively less in Sonda.

I) Facies Study on wireline logs

The depositional model shows that Bara Formation consists of sediments of deltaic environment. The predominant lithology is sand with intercalations of clay and shale. The formation can be divided into two parts,

- Interbeds of sand and shale
- Mostly shaly part with sand at the base

Fig.15 is showing coal bearing facies on the mud log as well as wireline of Meting-01 well. The average thickness of coal is 1 m, it can be clearly seen on the mud log and wireline logs. The Coal seams as interpreted on wireline logs showing that the coals are well isolated seams. Whereas Figure.14 is showing Stratigraphic Section of Coal bearing facies of Laki Group (Sohnari Member).

Eocene coal is present in the SSW of Meting-Sonda-Thatta-Jherruck Fields. Meting X-1 is only well in this project which contains both Paleocene and Eocene Coals. Fig.17 is showing Wireline logs correlation of Coal Facies in Bara Formation (Paleocene), Lower Indus Basin, Sindh, Pakistan. Three types of facies are identified in wireline logs correlation. Fig.16 is showing wireline logs correlation of Coal facies in Sonhari Formation (Eocene), Lower Indus Basin, Sindh, Pakistan. Correlations show that isolated coal seams are present and probably deposited along the fringes of river dominant deltaic deposits.

J) Depositional Model

According to Malkani(2004),Thar coalfield rests on Pre-Cambrian shield rocks and is covered by sand dunes. The coal thickness varies from 0.20-40m. There are maximum 20 coal seams in the area. The most common depth for coal seams is 150-203m. The thickness of overburden varies from 114-245m above the top coal seam. Malkani (2004) considered Reed as origin of Thar Coal which is commonly used for grass like plant in wetland. The thick coal seam with low ash and sulphur indicate stable upper delta environments (Ghaznavi, 2002). Kumar (2012) presented origin of organic matter as mixture of pollens, spores, algae, cuticles, fungi and wood. Kumar’s (2012) work suggests that palynological assemblages recommend a warm and exceptionally humid climate.

According to Hakko (2015) , Bara Formation (Middle Paleocene) consists of fine-grained sandstone and subordinate amount of shale, carbonaceous shale, siltstone and coal beds of variable thicknesses in boreholes of Thar coal field investigation of major elements (Si, Ti, Al, Na, Ca, K, Mn, Mg, Fe+3). Elemental ratios and their correlation coefficient ($R^2$) show that the origin of its constituting silica content is detrital, which is further confirmed by differences in the source of silica and alumina. Therefore, the studied sediments have potentially deposited along the fringes of basin in deltaic to near shore depositional environment. They assumed that sedimentation took place under humid climatic conditions, with relatively fast rate of sedimentation, showing better conditions for the growth, accumulation and preservation of organic source material of its coal. They proposed that sediments were potentially derived from igneous and metamorphic rock.

In this paper, Plate Reconstruction was carried out using GPlate software, results show that the greater Indian peninsula was approaching towards line of tropical humid environment (Fig.18) at the time of Paleogene. At that time, Indian Shield element was probably exposed and eroded due to rise and fall of sea and humid climatic conditions, as suggested by previous workers. As a result sediments were deposited along Indian Shield Element. As plate moved toward north, mangroves as discussed by Kumar (2012) and thick vegetation had been developing in area of Thar Coal Field. Presence of carbonaceous shales show the presence of marshy area, which existed for some time. However, whole area was under influence of humid tidal environment. As a result, thick vegetation grew in Thar Coal field area. Probably, Thar Coal area was relatively high as compared to its surrounding and a possible reason for origin of thick vegetation in limited aerial extension. Fig.19 is showing gross depositional model based on wireline log modeling and prevailing literature. Author believes that coal seams are not continuous in wire line logs showing isolated seams in subsurface along monocline slope of Sindh Monocline. In Lakhra, Sonda-Thatta, Ongar, Jherruck, and Sondha East, deposition of coal took place along margins of fluvio-deltaic tributaries. Vegetation was not thick as compare to Thar in these areas.
Fig. 8  Thickness of Paleocene coal seams drilled in the wells present in the surrounding of Paleocene coal fields (Sindh)

Fig. 9  Thickness of Eocene coal seams drilled in the wells present in the surrounding of Eocene coal fields (Sindh)
Fig. 10  Quality of coal seams of Paleocene/Eocene coal fields (Sindh)

Fig. 11  Distribution of ash in coal seams of Paleocene/Eocene coal fields (Sindh)
Fig. 12  Distribution of sulfur in coal seams of Paleocene/Eocene coal fields (Sindh)

Fig. 13  Distribution of Moisture in coal seams of Paleocene/Eocene coal fields (Sindh)
Fig. 14  Coal bearing facies encountered in Sonhari Formation (Eocene) in Mehran-1

Fig. 15  Coal bearing facies encountered in Bara Formation (Paleocene) in Meting-1
Fig. 16  Stratigraphic Correlation of Coal Facies in Sonhari Formation (Eocene), Lower Indus Basin, Sindh, Pakistan using Mud Logs of wells

Fig. 17  Wireline Correlation of Coal Facies in Bara Formation (Paleocene), Lower Indus Basin, Sindh, Pakistan
Fig. 18 Plate reconstruction shows that Greater India is approaching line of tropical humid environment

Fig. 20 Gross Depositional Model of Bara Coal at the time of Coalification in Lower Indus Basin
K) Pore Diameter of Thar Coal

Siddiqui (2012) recently studied the characteristics of pores and its effect on probable occurrence of coalbed methane in Thar coal field Pakistan. He found that Thar coalfield has dual porosity. Some coal seams have nearly micropores or meso-pores, while other seams possess meso pores. He further reported that pore volume vary between 0.06 and 2.36 cc/g for seams of Thar coalfield. This study shows that the Thar Coal contains pores to have free as well as adsorbed gas.

CONCLUSIONS

- Coal is associated with Bara Formation (Middle Paleocene) and Sohnari Member (Early Eocene) in Lower Indus Basin.
- Mixed quality of coal is present in all over Lower Indus Basin, Sindh, Pakistan
- Sonda-Thatta-Jherruck have good quality of coal (Sub-bituminous C- bituminous HV B.
- Ongar, Badin and Thar coal quality belongs to Lignite to subbituminous A
- Lakhra-Meting –Jhampir coal rank is Lignite class B to Sub-bituminous C
- Coal seams are present in number of wells and could not be correlated to each other;showing isolated seams of coal.
- Quality of coal will increase with depth along slope of Sindh Monocline. The reason for enhanced coal quality is attributed to overburden and maturation.
- Thar Coal is considered as the biggest lignite deposits of Pakistan and overall study shows that Thar coal also extends into subsurface along monoclonal slope. Further investigations are also recommended
- Presence of cleats in Badin and Thar increases prospectively of coal.
- Powder River Basin (USA) is considered as analogy of Sindh Coal Fields.

RECOMMENDATIONS

Authors strongly recommend Government of Pakistan, Sindh Coal Authority, National and International Donor Agencies and E&P companies to carry out Pilot project to exploit CBM resources in Lower Indus Basin, Sindh. Gas Pipe Line is already available nearby by prospect area. Seismic Mapping is helpful to mark prospect area for experimental drilling in subsurface. Gas adsorption properties will be established for CBM reserves on the basis of core studies taken during pilot project.

Authors also recommend for development of legal frame work for the exploitation of CBM resources of Pakistan which may include incentive for exploitation through pilot projects and gas sales agreement as national policy.

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