J. Bangladesh Acad. Sci., Vol. 39, No. 2, 177-194, 2015

QUALITY ASSESSMENT OF THE PERMIAN COALS FROM DIGHIPARA BASIN, BANGLADESH BASED ON PROXIMATE, ULTIMATE AND MICROSCOPIC ANALYSES

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ABSTRACT

Assessment of coal quality based on proximate (volatile matter, fixed carbon, ash, moisture), ultimate (C, H, N, S, O) and microscopic (macerals, microlithotypes, coal facies) analyses of the Permian coals from the Dighipara basin, Bangladesh was carried out. A total of 11 coal core samples collected from two bore holes of Dighipara basin were analyzed. ASTM standards were followed for proximate and ultimate analyses. ICCP systems were used for the microscopic study. Thermal maturity, physical characteristics of the coal seams, gross calorific value and atomic ratios of H/C and O/C were also considered.

Key words: Proximate, Ultimate, Microscopic analysis, Quality, Dighipara coal

INTRODUCTION

The study area is located in the north-western part of Bangladesh between longitudes 89º02'E-89º07'E and latitudes 25º23'N-25º30'N. The area consists of a number of Gondwana basins at shallow depths of the sedimentary succession. Among these Gondwana basins, five basins are discovered with commercially important Permian coal resource or deposit namely, Jamalganj (1962), Barapukuria (1985), Khalaspir (1989), Dighipara (1995) and Phulbari (1997). Approximately three billion tons of Permian Gondwana coal resources (70 TCF gas equivalents) have been estimated in these five coal basins discovered so far in Bangladesh. All of the recognized coal basins have been identified in the Platform unit of the Bengal basin, north-west of Bangladesh (Fig. 1). The estimated coal resources include 1053 million tons (Mt) in Jamalganj, 390 Mt in Barapukuria, 685 Mt in Khalaspir, 600 Mt in Dighipara, and 572 Mt in Phulbari coal basin (Imam 2013, Farhaduzzaman 2013).

The overall primary energy is based mostly (91.41%) on local natural gas and imported oil in Bangladesh (BPDB 2014). Nonetheless, the proved natural gas is not

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sufficient to meet up the national demand and in fact, the authority (Petrobangla) is struggling to provide the required gas supply. Coal fuels more than 40% for electricity generation and 70% for steel production in the current world (World Coal Association 2014) whereby only 2.45% power is generated from the coal in Bangladesh. At present, realizing the importance, the policy makers and relevant experts of Bangladesh are emphasizing more on the usage of coals in order to meet up the tremendous demand of the energy-starved country.

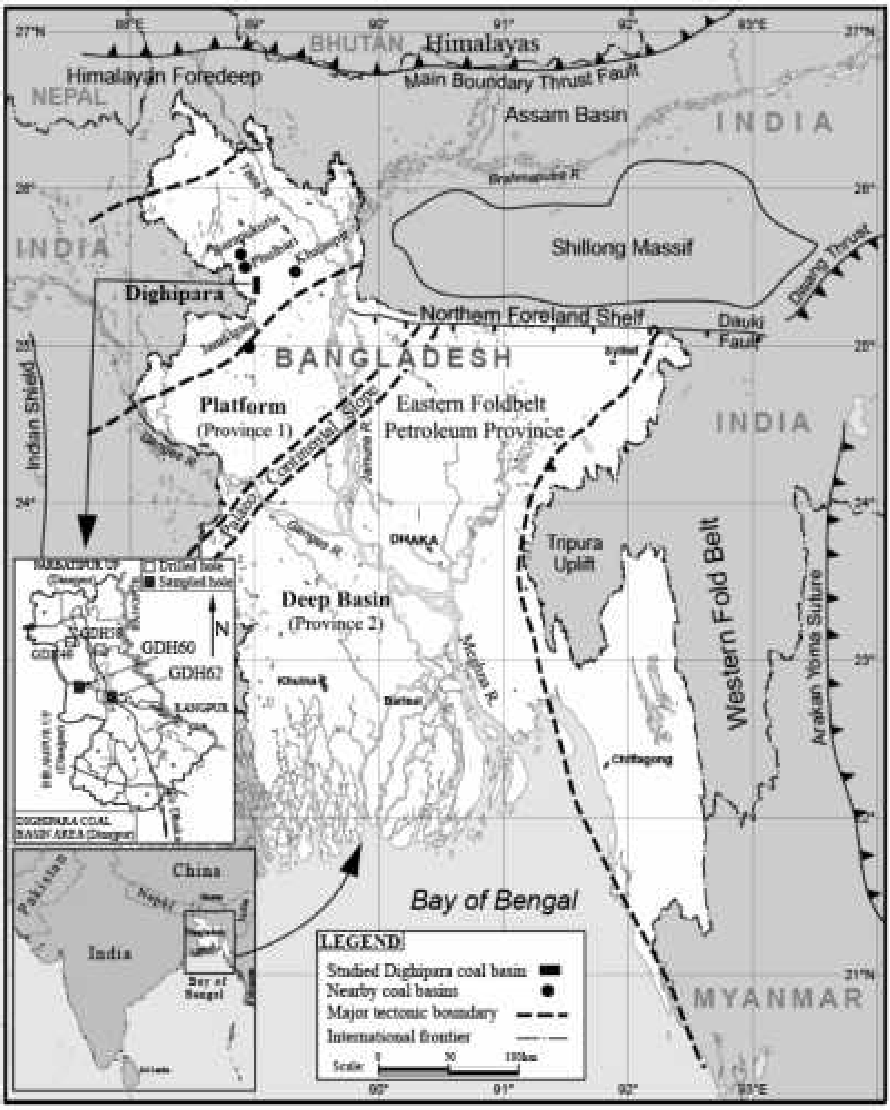

Fig. 1. The study area, drill hole location and major tectonic elements of the Bengal basin, Bangladesh (modified after Khan 2006, Farhaduzzaman *et al*. 2012a, b and 2013b).

There are very few coal-quality based research (considering Permian coals) available in the scientific community. Podder and Hossain (1996) published an article on carbonization of coking coals of Barapukuria and Khalaspir basins, Bangladesh. Podder and Majumder (2001) worked on thermal and electrical characterization of Barapukuria coal, Bangladesh. Imam *et al*. (2002) published a paper on coal bed methane (CBM) prospect of the Permian coal of the Jamalganj basin. Islam and Hayashi (2008) discussed on geology and CBM resource potential of the Barapukuria coal basin. The proximate and ultimate analyses are the first criteria to be considered for evaluating the quality of any kind of coals (ASTM 1990). But there is no work published on the coal quality assessment of the Dighipara half-graben coal basin, Bangladesh. Therefore, the principal objective of the current research was to assess the overall quality of Permian coals of the Dighipara basin, Bangladesh based on standard proximate analysis, ultimate analysis and microscopic observation. Furthermore, this study helps us to understand its best usage of the Permian coals of the Dighipara, Bangladesh.

Table 1. Stratigraphic succession of the Dighipara coal basin (Modified after Hasan and Islam 2003, Farhaduzzaman *et al.* 2013a).

Age	Group	Formation	Simplified lithology	Max. thickness (m)	Depositional environment
Holocene		Alluvium	Silt, clay, sand, soft and rootlets	1	Fluvial-alluvial and rapidly prograding delta
Plio-pleistocene		Barind clay	Reddish brown silty sticky clay	8	
			Unconformity		
Late pliocene	Dupity tila	Yellowish brown fine to coarse poorly consoliadted sands and pebbles with occasional claystone bands		320	Fluvial and prograding delta-shelf
Early pliocene to late miocene	Lower dupi tila	Grey to bluish gery plastic clayey sand Bottom part soft and white kaolimitic clays			
			Unconformity		
Permian	Gondwana	Gondwana	Feldspathic sandstone, carbonaceous sandstone and shale, conglomerate with coal beds	289	Fluvial to delta plain, coal swamps
			Unconformity		
Archaean	Pre-cambrian	Basement complex	Gneissic and schistose metamorphic and metaigneous rocks with weathered top	41	Stable Gondwana continent

Stratigraphy of the Dighipara coal basin has not been well established and it is still under exploration. The Geological Survey of Bangladesh (GSB) have drilled four holes (as of December 2011) in the Dighipara and found coal in all holes. On the basis of lithological logging and data collection while sampling and during drilling, the following description has been prepared. Dighipara coal basin is located within the southern slope of the Platform unit (Fig. 1). The Dighipara basin is a north-south elongated oval-shaped and fault bounded basin. The eastern side of the basin might be fault bounded, as evidenced from the Bouger gravity anomaly map.

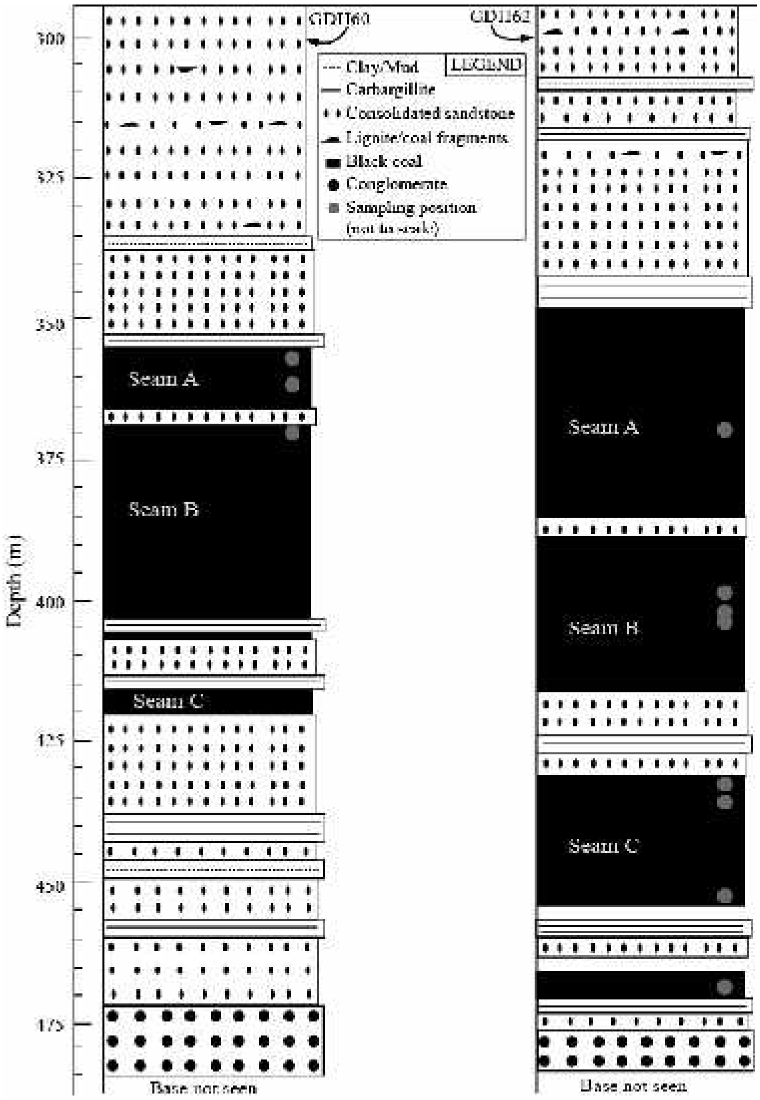

Fig. 2. Lithostratigraphic columns (partly) of the studied drill hole GDH60 and GDH62 of the Dighipara coal basin, Bangladesh. The sampling positions are also shown.

The northeast-southwest trending fault may be the northern limit of the basin. The basin might have formed by faulting in the crystalline basement during Permo-Carboniferous time. Later on, these basins were reshaped and basin marginal adjustments took place from time to time due to the Himalayan upheavals. Subsequently the Tertiary and Quaternary sediments were deposited over the crystalline basement within the half-graben basin.

Table 2. Thickness and depth (in meter) of coal seams found in four defferent drill holes of Dighipara basin (after Hasan and Islam 2003, Alam 2010, Farhaduzzaman 2013).

Seam no.	GDH49		GDH58		GDH60		GDH60	
	Depth (m)	Thickness	Depth (m)	Thickness	Depth (m)	Thickness	Depth (m)	Thickness
Seam A	327.96-34503	17.07	383.53-400.51	16.98	355.09-365.00	9.91	323.09-342.90	19.81
Seam B	348.39-382.22	33.83	403.62-438.91	35.29	368.81-402.71	33.90	348.08-384.66	36.58
Seam C	384.66-391.67	7.01	441.35-442.57	1.22	707.52-408.04	0.52	388.32-395.02	6.70
Seam D	395.94-398.37	2.43	44.79-455.07	10.28	416.36-419.25	2.89	397.31-400.66	3.35
Seam E	400.43	402.03	1.60	-	-	-	407.97-408.89	0.92
Seam G	-	-	-	-	-	-	414.83-417.73	2.90
Cumulative thickness			62.25		63.77	47.22	71.07	

The probable basin area is about 15 km^2 and the estimated resource is 600 million tons at Dighipara (Farhaduzzaman 2013). The lithological descriptions and their corresponding stratigraphic positions of the geological formations are similar in comparison to those of the nearby Barapukuria basin (Hasan and Islam 2003). The geological formations of the Dighipara basin include (from bottom upward) Basement Complex, Gondwana Group, Dupi Tila, Barind Clay and Alluvium. The simplified lithostratigraphic description of the Dighipara basin is stated in Table 1 (Fig. 2).

MATERIALS AND METHODS

A total of 11 coal core samples were collected from GSB's core laboratory at Bogra, Bangladesh. Eight samples were chosen from bore hole GDH62 and three samples from GDH60. All the samples were taken from top seams namely, Seam A, Seam B and Seam C of two bore holes at Dighipara. The study area, borehole location, sampling position and a simplified lithostratigraphic succession of the representative bore holes GDH60 and GDH62 (in part) of the Dighipara are shown in Figs 1 and 2. Standard classification of coals by rank prescribed by The American Society for Testing and Materials (ASTM 1990) has been used to assess the quality of the Permian coals from the Dighipara basin, Bangladesh. Proximate analysis, ultimate analysis and gross calorific value (GCV) measurements are carried out at the accredited coal quality testing laboratory of the Minerals and Geoscience Department (JMG) Malaysia.

The proximate analysis of coal can be reported on the basis of four ways such as: (a) as received (ar)- includes total moisture, (b) air dried (ad)- includes inherent moisture only, (c) dry basis (db)- excludes all moisture and (d) dry ash free (daf) or dry and mineral matter free (dmmf)- excludes all moisture and ash. The proximate analysis comprised of the measurements of moisture content, volatile matter and ash using in-house test methods followed by ASTM standards and the fixed carbon is determined by the difference.

Ultimate analysis in the studied coal comprised of the determination of carbon and hydrogen in the material as found in the gaseous products of its complete combustion, the determination of sulfur, nitrogen and ash in the material as a whole, and the calculation of oxygen by difference (ASTM 1989). Gross calorific value (GCV) is also determined using the ASTM standard test methods for the ASTM coal rank classification system.

All the samples are microscopically examined at the Geology Department, University of Malaya. The procedure, description and analysis published by ICCP (1963) and ICCP System 1994 (1998 and 2001) have been followed for the purpose of microscopic study. The samples are prepared by mounting whole rock fragments in resin blocks and polished to a highly reflecting surface using progressively finer alumina suspension (1, 0.3 and 0.05 µm). Microscopic observation is carried out under oil immersion in plane polarised reflected white light, using a LEICA DM6000M microscope and CTR6000 photometry system equipped with fluorescence illuminators. Random vitrinite reflectance (% R_o) measurements in oil immersion are made in reflected white light using Diskus Fossil software equipped with a Basler digital camera.

RESULTS AND DISCUSSION

The number of coal seams varied from three to seven whereby the top seams, namely Seam A, Seam B and Seam C constitute the lion's share of the resource at the Dighipara coal basin. The coal was found at depths of 323 - 455 m, which indicates the resource identified here is comparatively deeper than the Barapukuria basin which is located north to the basin. The cumulative thickness of coal seams at Dighipara ranges from 47.22 to 71.07 m, whilst the average thickness is 61 meters (Hasan and Islam 2003, Alam 2010, Farhaduzzaman 2013). The thickness and depth of coal seams found in four different drill holes of the basin can be showed in Table 2.

The Permian coals of Dighipara are mainly banded dull to dull in nature as followed by the JORC Code (2004). The banded bright and bright banded coals are not uncommon in the studied coal seams of the Dighipara basin. The coal is highly cleated. The cleats are generally irregular to planar and pyritic infill is common along the joint planes and cleats.

Proximate analysis was used to establish the rank of coals and show the ratio of combustible to incombustible constituents. It provides the basis for buying and selling and evaluate for beneficiation or for other purposes (ASTM 1989). The parameters obtained from the proximate analysis of the Permian coals from the Dighipara basin are shown in Table 3.

Table 3

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Moisture is an important property of coal since all coals are mined wet. Physically and chemically bound water can contribute to total moisture. Groundwater and other extraneous moisture is known as adventitious moisture and is readily evaporated. Moisture held within the coal itself is known as inherent moisture (IM) and is analyzed quantitatively. The moisture content decreases with maturity and ranking of coal due to the decrease of porosity (Stach *et al.* 1982). The moisture percent (air-dry basis) of the analyzed Dighipara coals ranges from 2% to 4.6% while the arithmetic mean is 3% (Table 3) and it is fairly low because of its high rank.

Volatile matters in coal refer to gaseous products in coal (except for moisture vapor) which are liberated at high temperature in the absence of air. This is usually a mixture of short and long chain hydrocarbons, aromatic hydrocarbons and some sulfur. Along with ranks, volatile matter is frequently used to assess the coke yield on carbonization and burning characteristics. Measured volatile matter (ad-basis) in the studied Permian coals varies from 22.40 to 33.50% (Table 3). It is fairly high in the investigated coals which indicate high volatile bituminous coal (Stach *et al*. 1982).

Ash is the non-combustible residue remaining after burning the coal. Ash obtained differs from in composition from the inorganic constituents present in the original coal. Incineration causes an expulsion of all water, the loss of carbon dioxide from carbonates, the conversion of iron pyrites into ferric oxide and other chemical reactions (ASTM 1989). The ash content (ad-basis) determined from the studied Dighipara coals is 5.70 - 28.80% and its arithmetic mean is 15%. There are a few processes involved with the presence of ash. It actually corresponds to the minerals in coal which might have washed or blown into the accumulating peat resource by epiclastic or pyroclastic processes. However the minerals can also be formed by the accumulation of skeletal fragments and biogenic components into the coal deposit. The syngenetic and epigenetic precipitation of biogenic minerals through crystallization processes in peat system can also contribute to the development of minerals in coal (Farhaduzzaman 2013). The ash content found in the studied coals is fairly low. Ash yield in seam A was low compared to Seam B and Seam C. Hence a few different options could be considered for the contribution of mineral formation in the studied coals: (a) doming process of accumulated peat deposit, (b) leaching of minerals from previously deposited peat resource and (c) deposition of peat on an exposed condition while there was no active inorganic sedimentation. The coalification process itself might contribute for the formation of minerals in coal, but this is unlikely to have occurred for the current case. In addition, the doming of accumulated peat resource can restrict the introduction of detrital minerals and sulfur-rich waters into the resource as previously reported by Cohen and Stack (1996).

The fixed carbon in coal is the solid residue (other than ash) which is obtained by destructive distillation (e.g. after volatiles are driven off). It is made up principally of carbon, but may contain appreciable amounts of sulfur, hydrogen and oxygen (ASTM 1989). This differs from the ultimate carbon content of the coal because some carbon is lost in hydrocarbons with the volatiles. Fixed carbon is used as an estimate of the amount of coke that will be yielded from a sample of coal. The high content of fixed carbon 47.70-60.58% found in the presently analyzed coals indicates that these coals can partly be used to produce coke. This byproduct (coke) is an important fuel for the steel industries. Based on Permian coals from the Phulbari basin (which is close to the current studied basin) Farhaduzzaman (2008) discusses that the Permian coals can provide 25% as coke for the steel industry. This study supports that the analyzed coals from Dighipara can contribute in metallurgy after proper processing for coke preparation. Following the coal rank interpretation made by Stach et al. (1982), the observed fixed carbon percentages correspond to mainly ‘high volatile A bituminous coal’ together with some ‘medium volatile bituminous coal’.

The information obtained by the ultimate analysis (i.e., S, N, H, O) is intended for the general utilization by applicable industries to provide the basis for evaluation, beneficiation or for other purposes. The ultimate analysis of the examined Dighipara coals also helps us to summarize the ash content and the content of organic constituents in a specific format which ultimately permits cursory valuation of coals for use as a fuel or in other carbonaceous processes and of cokes (if possible) for metallurgical purposes.

As stated by ASTM standards (1989, 1990), the total sulfur content obtained by this ultimate analysis is used to serve a number of interests such as: (a) evaluation of coal preparation, (b) evaluation of potential sulfur emissions from coal combustion or conversion processes, (c) evaluation of coal quality in relation to contract specification and (d) other purposes of commercial or scientific interests. The high presence of sulfur in coal can cause acid rain which is very harmful for the environment and human being. The most commonly found forms are sulfate sulfur and pyritic sulfur along with minor presence of organic sulfur. Except for one sample (DPCL35), the sulfur percentage in the studied Permian coals of the Dighipara basin is very low and it is less than 1, and therefore points to a freshwater depositional environment. Lower inputs of sulfur containing minerals to the peat depositional system and the concomitant limited presence of sulfur-reducing organisms are considered for this low amount of sulfur content in the examined Dighipara coals of Permian age (Farhaduzzaman 2013). The main source of sulfur minerals is considered the marine water. Low sulfur content generally indicates the fresh water inputs as consistent with the present case. The minor presence of syngenetic pyrite (sulfur-bearing mineral) in the examined Permian coals observed under microscope indicates, however, the influence of marine contribution although this marine influence is not supported much by other evidence. But the common presence of epigenetic pyrite found in the cleats of the studied Dighipara coals corresponds to fresh-brackish water environment (Hower and Bland 1989). This kind of epigenetic sulfur-bearing minerals (pyrite) is also frequently observed physically during the field examination of the studied Permian coals. The cleat-filling epigenetic pyrites are believed to have precipitated post-depositionally from solutions percolating through fresh-brackish water formation underlying and/or overlying the coal seams (Cohen and Stack 1996). Both pyritic sulfur (as iron sulfide/pyrite) and sulfate sulfur (as carbonates) are observed in the examined coal samples.

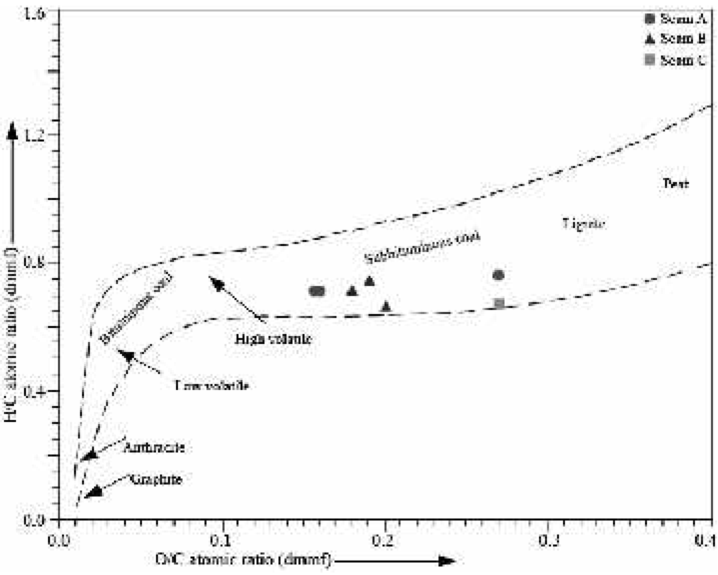

Fig. 3. van Krevelen's diagram based on atomic ratios of H/C and O/C analyzed for the Permian coals of the Dighipara basin, Bangladesh (modified after Tissot and Welte 1984). It shows the examined Dighipara coals are of subbituminous rank.

The total carbon comprises not only the organic carbon (as kerogen or bitumen) but also the inorganic carbon (as mineral carbonates). The total hydrogen includes the hydrogen present in the free moisture accompanying the samples as well as hydrogen present as water of hydration of silicates. The per cent of carbon and hydrogen is used to calculate the amount of oxygen (air) required in combustion processes and in the calculations of efficiency of combustion processes. Carbon and hydrogen determinations are considered in material balances on coal conversion processes. It is also significant in correlations of chemical and physical properties such as yields of products in liquefaction, reactivity in gasification and the density and porosity of coal (ASTM 1989). The contents of total carbon and total hydrogen found in the studied Permian coals of the Dighipara basin are 49.80 - 77.00% and 3.1 - 4.6%, respectively (Table 3). The high content of total carbon and the favorable content of hydrogen indicate that the studied coals are potential for coal liquefaction (coal to liquids: CTL) either by direct or indirect methods (World Coal Institute 2007). However, it requires further study for detail interpretation aligned with the clean coal technology aspects CCT or CTL which is the topmost research arena in the current world.

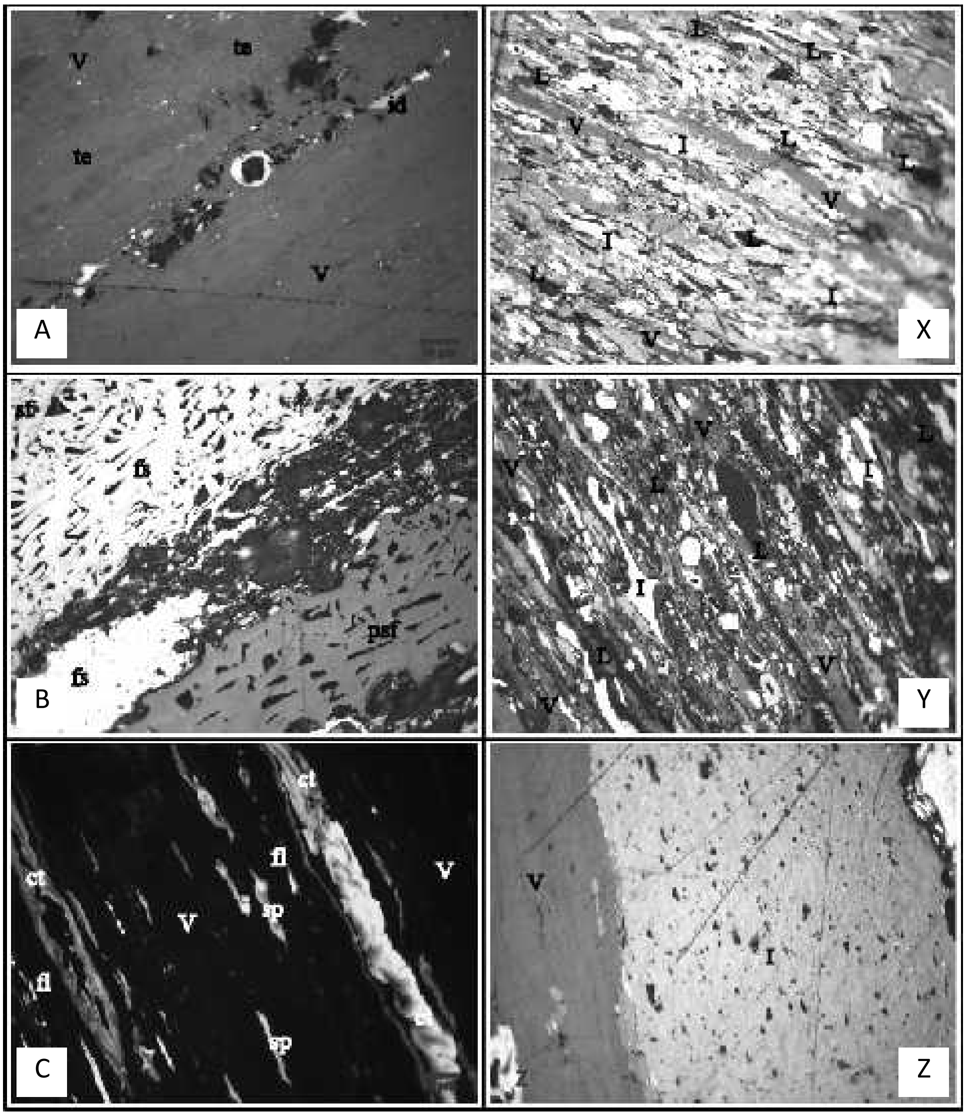

Fig. 4. Photomicrographs for the studied coal samples of the Dighipara basin. (A) Grey color vitrinite maceral [V] with structured telinite [te] and white inertodetrinite [id] in reflected white light. (B) White color inertinite maceral fusinite [fs] with dull white color semifusinite [sf] or structured pyrosemifusinite [psf] in reflected white light. (C) Bright yellow to dull yellow fluorescent liptinite maceral cutinite [ct] together with lamellar shaped sporinite [sp] and fluorinite [fl] under ultraviolet light. (X) The dominant microlithotype trimacerite: clarodurite includes mainly inertinite [I] and liptinite [L] along with vitrinite [V] as minor constituent. (Y) The second largest group of microlithotype duroclarite: includes mainly vitrinite and liptinite with inertinite as minor constituent. (Z) Bimacerite microlithotype vitrinertinite which comprises vitrinite and inertinite only.

The determination of total nitrogen is required for evaluating the potential formation of nitrous oxides which is considered as one of the important pollutants in the atmosphere. It is also used for the oxygen estimation by difference. The measured total nitrogen and total oxygen in the studied coals is very low and it varies from 0.91 to 1.83% and from 16.30 to 45.72%, respectively and this is not considered as a hazardous constituent for the environmental concern.

The atomic ratios of H/C and O/C can be used in van Krevelen's diagram for the purpose of coal-quality analysis. This diagram provides the information on kerogen type as well as the evolutionary paths of the organic matter from different sources (Tissot and Welte 1984). The kind of hydrocarbon to be generated from the organic matter can also be determined using the compositional study of the kerogens. The atomic ratios of H/C and O/C of the analyzed Permian coals of the Dighipara basin range from 0.66 to 0.78 and 0.16 to 0.69, respectively. All the studied coal samples of Dighipara plotted in van Krevelen's diagram indicate the subbituminous rank (Fig. 3). However, a few samples (DPCL37, DPCL38, DPCL40 and DPCL44) are not revealed in the diagram and it occurred due to their increased atomic O/C ratios influenced probably by the increased ash contents compared to all other samples. The presence of different minerals might also affect the oxygen increase which requires further study.

Calorific value is significantly used to compute the total calorific content of the quantity of coal represented by the sample for payment purposes, provided the buyer and seller mutually agree upon this. GCV is also important for computing the calorific value versus sulfur content to determine if the coal meets regulatory requirements for industry fuels (ASTM 1985). The measured GCV of the Permian coals from the Dighipara basin varies from 12128 to 13725 Btu/lb (moist and mineral matter free, mmmf-basis). It corresponds mainly to 'high volatile B bituminous coal' ranges up to 'high volatile C bituminous coal' in rank (Stack *et al*. 1982, ASTM 1990). Seam A and Seam B are comparatively better in rank considering Seam C. The GCV is supposed to be increased with depth. But the measured gross calorific value and fixed carbon of Seam C are slightly lower in amount although it is located at the bottom position compared to Seam A and Seam B. It is possibly caused due to inferior quality (including higher ash) of Seam C comparing with Seam A and Seam B.

MICROSCOPIC ANALYSIS

The quantitative and qualitative analyses of macerals and associated minerals (vol.%) are carried out in the present study. The details of different macerals and mineral matter of the Dighipara coal basin are summarized in Table 4. The analyzed Permian coal is rich in inertinite group macerals (32.2 - 55.0 vol.%) followed by vitrinite (18.5 - 38.7 vol.%) and liptinite group (14.0 - 24.4 vol.%).

Table-4-5++++++++++++

Semifusinite, fusinite and inertodetrinite are the main constituents of the inertinite group. Collotelinite and collodetrinite are the dominant components of vitrinite group. Sporinite, cutinite and resinite are common macerals of the liptinite group. A few representative macerals observed under microscope are shown in Figs 4A, B and C.

All the different microlithotypes in the analyzed Permian coal samples from Dighipara are identified in detail concentration. Trimaceral group members such as clarodurite (22%) and duroclarite (18%) are found to be the most dominant maceral associations in the studied Dighipara samples. Durite (14%) is the most dominant bimaceral group: durite I is present in higher amounts than durite E. Other bimaceral groups i.e., clarite and vitrinertite are also common in the samples. Figs 4X, Y and Z exhibit a few of the different microlithotypes found in the studied coal samples under microscope.

Vitrinite reflectance plays a large role in defining the quality assessment of whole coal. The physical and chemical properties of vitrinite change with the course of coalification. Thus the determination of vitrinite reflectance is a fundamental tool in coal petrology. Random vitrinite reflectance (%R_o) measurements carried out for the analyzed Permian coals of Dighipara ranges from 0.7 to 0.8. It corresponds to 'high volatile B bituminous coal' and 'high volatile C bituminous coal' followed by the rank classification adopted by Stach *et al*. (1982) and subsequently used by different others.

QUALITY OF THE DIGHIPARA COALS

The purpose of any classification is to provide a convenient means for the primary evaluation of a coal product with appropriate internally accepted criteria. The cross-plot of volatile matter versus fixed carbon (modified after Stach *et al*. 1982, ASTM 1990) indicates that the analyzed coals fall into the rank of 'high volatile bituminous coal' together with minor presence of 'medium volatile bituminous coal'. The mostly used van Krevelen's diagram, however, shows the subbituminous rank of the studied Permian coals (Fig. 3). Another cross-plot presented by gross calorific value and vitrinite reflectance (modified after Stach *et al*. 1982, ASTM 1990) shows that the examined Dighipara coals are 'high volatile B bituminous coal' and 'high volatile C bituminous coal' in rank. Seam A and Seam B are slightly better in quality and rank compared to Seam C.

Quality of the Dighipara coals is compared with the Permian coals of the Jamalganj, Barapukuria, Phulbari and Khalaspir half-graben coal basins, Bangladesh (Table 5). The proximate and ultimate analysis results of the Permian coals obtained from the discovered coal deposits show that all the coals are of, in general, similar quality and it is bituminous rank. The value of the gross calorific value (air dried: ad-basis) is the highest (12100 Btu/lb) for Jamalganj deposit while it is the lowest (11264 Btu/lb) for Khalaspir deposit. The fixed carbon content ranges from 45 wt.% (the lowest in Jamalganj) to 54 wt.% (the highest in Dighipara). The content of sulfur is very low (less than 1 wt.%) in all the Permian coals studied.

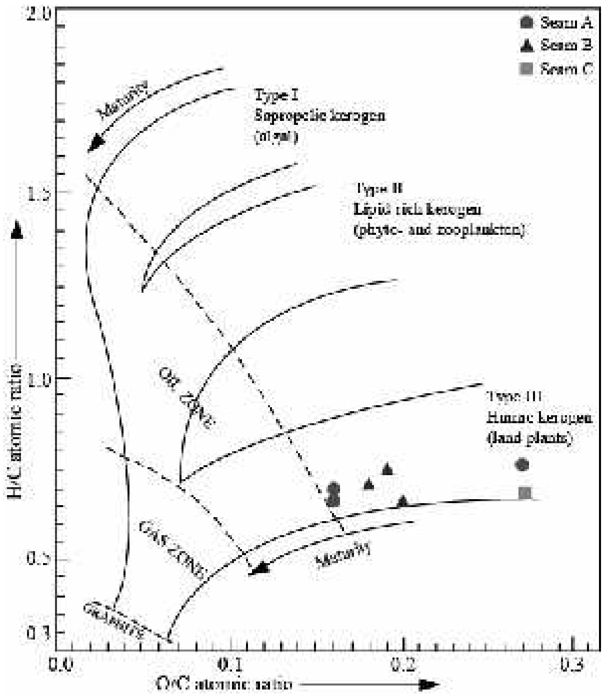

Fig. 5. Modified van Krevelen's diagram shows the coalification path or kerogen evolutionary path based on atomic ratios of H/C versus O/C of the studied Dighipara coals (modified after Tissot and Welte 1984). The analyzed coals are of humic origin sourced from Type III organic matter (land plants).

Based on the atomic ratios of H/C and O/C, the modified van Krevelen's diagram shows that the organic matter of the analyzed Permian coals is of Type III kerogen (Fig. 5). It is also supported by the abundance of Type III representing vitrinite macerals observed under microscope. Although now it is accepted that coal is capable of generating hydrocarbon generation and expulsion, but for the last couple of decades there was a long debate on it. Vitrinite reflectance value is the most reliable tool for assessing the thermal maturation of the organic matter in sediments. The random vitrinite reflectance (%R_o) of 0.7 - 0.8 indicates that the organic matter in the studied Dighipara coals is in peak maturity stage for hydrocarbon generation (Peters and Cassa 1994). Erik (2011) reported the atomic ratio of H/C less than 0.9 is considered necessary for hydrocarbon generation and expulsion from subbituminous coals. The measured H/C value 0.66 to 0.78 of the investigated Permian coals from Dighipara indicates that the organic matter in the coals is capable of generating hydrocarbons which also have expelled to the related petroleum system.

The liptinite macerals with perhydrous vitrinite in the coals are considered as the most important constituents for hydrocarbon generation. The exsudatinite within crack network appears to have developed in these samples and shows the liptinitic materials have already expelled their liquid hydrocarbon constituents to the carrier bed. The indigenous solid bitumen and fluorinite found in the analyzed samples also suggests the generation and expulsion of hydrocarbon from these samples have occurred (Farhaduzzaman *et al.* 2013b). Micrinite is considered to be the residue of hydrocarbon generation. The significant presence of micrinite in the analyzed samples suggests the organic matter has already expelled liquid hydrocarbons in the associated Gondwana Petroleum System. This interpretation is also agreed with the study reported early by Frielingsdorf *et al.* (2008) and Farhaduzzaman *et al.* (2012a, 2013b) who have used different methods including organic geochemistry, biomarkers, petrography, basin modeling etc.

CONCLUSIONS

- Based on the proximate analysis, the studied Permian coals of the Dighipara coal basin is categorized by high volatile, low ash and low sulfur in contents. The heat value (GCV) is fairly high (12128-13725 Btu/lb). It seems that as a part of the clean coal technology (CCT), the examined Permian coal has the potential for coal liquefaction (coal to liquids: CTL) which is evidenced by the high contents of total carbon and favorable amount of hydrogen. Nevertheless it requires additional study on CTL.

- Cross-plots of volatile matter versus fixed carbon and vitrinite reflectance versus gross calorific value indicate the analyzed coals are of mainly ‘high volatile B bituminous coal’ ranging up to ‘medium volatile bituminous coal’ as the highest rank and ‘high volatile C bituminous coal’ as the lowest rank. However, van Krevelen’s diagram based on the atomic ratios of H/C and O/C corresponds to ‘subbituminous coal’ in rank. Seam A and Seam B are comparatively better in quality considering Seam A.

- Inertinite is the most dominant maceral group of the analyzed Gondwana coals of the Dighipara basin followed by vitrinite and liptinite group macerals. Trimacerite is identified as the dominant microlithotype of the investigated coal samples. The second largest microlithotypes is bimacerite and then monomacerite with considerable carbominerites.

- The vitrinite reflectance value (greater than 0.7 $\%R_o$) and some diagnostic macerals (e.g., exsudatinite, solid bitumen, fluorinite) suggests the analyzed Permian coal is mature enough for hydrocarbon generation and expulsion. The studied coals containing dominantly Type III kerogen representing vitrinite macerals and some Type II representing liptinite macerals suggest that the coals are predominantly gas-prone showing some oil generating potential.

ACKNOWLEDGEMENTS

The authors are grateful to former DG of GSB for permitting the usage of the samples and data. They would also like to thank JMG Malaysia for providing the laboratory facilities. The first author cordially appreciated the cooperation and motivation provided by Prof. Dr. Khalil R. Chowdhury and his colleagues of JU. The management and colleagues of Sylhet Gas Fields Ltd., Petrobangla deserves the thanks for the official support to this Ph.D. research (M.F.). The authors also acknowledge the Bright Sparks Fellowship BSP-APP-1080-2012 and grants PV100-2011A and RG145-11AFR of University Malaya for financial supports.

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(Revised manuscript received on 28 June, 2015)