ICMERE2015-PI-027

LOG BASED PETROPHYSICAL ANALYSIS OF MIO-PLIOCENE SANDSTONE RESERVOIR AT WELL RASHIDPUR-4 IN BANGLADESH

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Abstract*- Gamma-ray, spontaneous potential, density, neutron, resistivity, caliper, temperature and sonic logs are used to analyze petrophysical parameters of the well Rashidpur-4 in Bangladesh. Quantitative measurements of different factors such as shale volume, porosity, permeability, water saturation, hydrocarbon saturation and bulk volume of water are carried out using well logs. Petrographic and X-ray Diffraction (XRD) results based on several core samples are also compared with log-derived parameters. Measured shale volume ranges from 11% to 38% and porosity is 19% - 28%. However, log-derived porosity is slightly higher than the thin section porosity. Water saturation of the interested zones varies from 14-38% 13-39% and 16-41% measured from Schlumberger, Fertl and Simandoux formulas respectively. Conversely hydrocarbon saturation ranges from 62-86%, 61-83% and 59-84% respectively. In the analyzed zones, the permeability values are calculated as 28-305 mD. Good to very good quality hydrocarbon reservoir is appraised for the studied four zones based on the present study.*

Keywords: Petrophysics, Saturation, Porosity, Reservoir, Rashidpur-4.

1. INTRODUCTION

Bangladesh lies in the northeastern corner of Indian subcontinent at the head of the Bay of Bengal (Fig. 1). The Bengal Basin occupies entire Bangladesh (two-third of the basin) surrounding India and Myanmar [1-3]. During Eocene, the Bengal Basin evolved from the collision between northward drifting Indian plate and relatively passive Asian plate [1]. The generalized stratigraphy of the well RP4 can be shown in Table 1. Estimated gas reserve in Bangladesh is 26.84 TCF with 42 TCF undiscovered [4-5]. Petrobangla re-estimated the total recoverable oil reserve of 137 million barrels STOIP [6]. Crude oil production took place here from 1987 to 1997. Currently, out of 26 gas fields (including one minor oil filed) so far discovered, only 22 are producing. The gas production started in 1959. Now the daily production of gas and condensate is approximately 2550 MMCFD (million cubic feet per day) and 10219 BBLD (barrels per day) respectively (accessed Petrobangla website on 27 Apr 2015 [29]). The majority of gasfields in Bangladesh produce dry gas with a significant proportion of condensate.

Petrophysical log interpretation is one of the most useful and important tools to characterize the reservoir property [8]. Well log data helps to identify permeable zones and productive zones for hydrocarbon with depth and thickness. It distinguishes the interfaces of oil, gas or water of a particular reservoir. Permeable zones may contain either hydrocarbon or water or both. Petrophysical study involves the analysis of different parameters of reservoirs including lithology, volume of shale, porosity, water saturation, hydrocarbon saturation, permeability, hydrocarbon moveability and pore geometry by using appropriate well log data.

Table 1: Generalized stratigraphic succession of well Rashidpur-4, the Bengal Basin (modified after Alam et al., 2003; Imam, 2005).

Age	Group	Formation	Simplified lithology	Formation base (m)	Depositional environment
Holocene		Alluvium	Silt, clay, sand and gravels.	2	Fluvial system.
Plio-Pleistocene		Madhupur Clay	Yellowish brown silty clay.	12	Fluvial system.
Late Pliocene	Dupi Tila	Dupi Tila	Fine to medium grained poorly consolidated sandstones, silty, with lignite fragments and fossil woods, intercalations of mottled clay horizons.	562	Fluvial system.
Middle Pliocene	Tipam	Girujan Clay	Mottled clay.	662	Lacustrine & fluvial overbank.
	Tipam	Tipam Sandstone	Coarse grained sandstone with wood fragments and coal interbeds.	1126	Braided fluvial systems.
Early Pliocene	Surma	Boka Bil	Alternating shale and sandstone with minor siltstone.	2505	Subaerial to brackish with marine influence.
Miocene	Surma	Bhuban	Alternating and repetetive sandstones and shales with minor conglomerate and siltstone.	3069	Pro-delta and delta front of mud rich delta system.

It provides the unique opportunity to observe the relationship between porosity and saturation. Reliable evaluation of hydrocarbon resources in shaly clastic reservoir rocks is an important task. The determination of reservoir quality and formation evaluation processes largely depends on quantitative evaluation of petrophysical properties. In Bangladesh, the petrophysical evaluation concerning shaly sandstone has been performed in limited extent [9-10]. It requires further study on petrophysical analysis of the Bengal Basin. In this regard, present study attempts to analyze the petrophysical properties of shaly sand gas reservoir encountered in the well Rashidpur-4 (RP4), the Bengal Basin, Bangladesh. The study also makes sense regarding the reservoir potential of the Mio-Pliocene sandstones in the studied well.

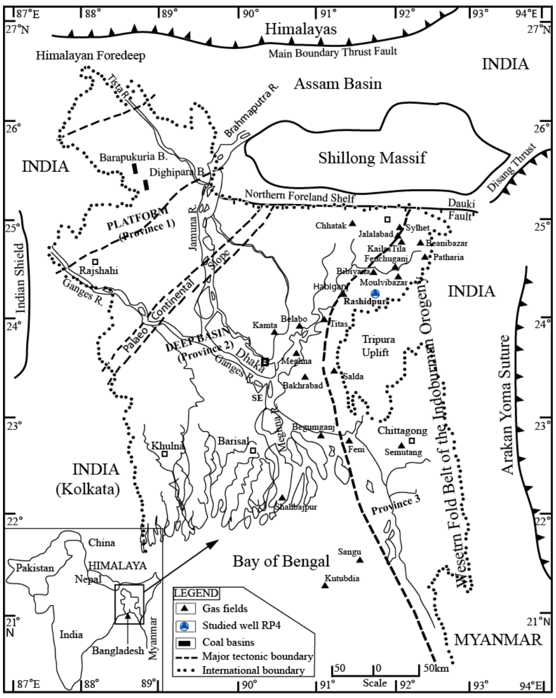

Fig. 1: Location map of the study area showing the major tectonic elements of the Bengal Basin, Bangladesh [modified after 11-13].

2. MATERIALS AND METHODS

The scanned images (TIFF format) of gamma (GR), resistivity (deep and shallow), sonic, SP, neutron, density, temperature and caliper logs of the well Rashidpur-4 (RP4) were collected from BAPEX, Petrobangla for the present study. These TIFF images have been converted to digital data (LAS format) using Didger®4 software. Subsequently, the digitized LAS files have been transferred to Excel software which is used for current analysis. It covers a total gross thickness of 1463 m (depth 1310 – 2774 m) of the well RP4.

2.1 Shale volume: Calculating gamma ray index (IGR) is the first step needed to determine the volume of shale (Vsh) from a gamma ray log [14].

$$I_{GR} = \frac{GR_{\log} - GR_{\min}}{GR_{\max} - GR_{\min}} \text{------------------------} (1)$$

For Tertiary rocks, the shale volume is:

$$V_{sh} = 0.083\left[2^{(3.7 \times I_{GR})} - 1.0\right] \text{--------------------} (2)$$

2.2 Porosity: Dresser Atlas [14] proposed the following equation to calculate porosity from density log:

$$\phi_{Den} = \left(\frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}\right) - V_{sh}\left(\frac{\rho_{ma} - \rho_{sh}}{\rho_{ma} - \rho_f}\right) \text{-------------} (3)$$

The combined neutron and density log is used for getting the corrected porosity [15]:

$$\phi_{Ncorr} = \phi_N - \left[\left(\frac{\phi_{Nclay}}{0.45}\right) \times 0.30 \times V_{sh}\right] \text{---------------} (4)$$

$$\phi_{Dcorr} = \phi_D - \left[\left(\frac{\phi_{Nclay}}{0.45}\right) \times 0.13 \times V_{sh}\right] \text{---------------} (5)$$

$$\phi_{N-D} = \sqrt{\frac{\phi_{Ncorr^2} + \phi_{Dcorr^2}}{2.0}} \text{----------------------} (6)$$

Thickness weighted average porosity [16] is also measured as below:

$$\phi_{av} = \frac{\sum_{i=1}^{n} \phi_i h_i}{\sum_{i=1}^{n} h_i} \text{----------} (7)$$

2.3 Water saturation: Three more commonly used shaly-sand formulas for calculating water saturation (S_w) can be shown as:

$$S_w = \left(\frac{0.4 \times R_w}{\phi^2}\right) \times \left[-\frac{V_{sh}}{R_{sh}} + \sqrt{\left(\frac{V_{sh}}{R_{sh}}\right)^2 + \frac{5\phi^2}{R_t \times R_w}}\right] \text{-----------} (8)$$

$$S_w = \frac{1}{\phi} \times \left[\sqrt{\frac{R_w}{R_t} + \left(\frac{a \times V_{sh}}{2}\right)^2} - \frac{a \times V_{sh}}{2}\right] \text{-------------} (9)$$

$$S_w = \frac{-\frac{V_{sh}}{R_{sh}} + \frac{\phi^2}{0.2 \times R_w \times (1.0 - V_{sh}) \times R_t}}{\frac{\phi^2}{0.4 \times R_w \times (1.0 - V_{sh})}} \text{--------------------} (10)$$

Equation (8), (9) and (10) were introduced by Simandoux [17], Fertl [18] and Schlumberger [15] respectively. Thickness weighted average water saturation is calculated using the following formula given by Bradley [16].

$$S_{wav} = \frac{\sum_{i=1}^{n} Sw_i \phi_i h_i}{\sum_{i=1}^{n} \phi_i h_i} \text{----------} (11)$$

2.4 Formation water resistivity: Formation water resistivity (R_w) of the hydrocarbon bearing zone has been calculated from the formula given by Bateman and Konen [19].

$$R_w = 10^{\left\{\frac{SSP}{K} + \log R_{mf}\right\}} \text{------------------------} (12)$$

2.5 Permeability: The formula by Coates and Dumanoir [20] is used for permeability (K).

$$K = \left(\frac{C \times \phi^{2w}}{w^4 \times (R_w/R_{tirr})}\right)^2 \text{--------------------------------} (13)$$

Permeability has also been calculated using Wyllie and Rose's formula [21]:

$$K = \left(79 \times \phi^3 / S_{wirr}\right)^2 \text{(dry gas)} \text{-----------------------------} (14)$$

Thickness weighted average permeability is measured as stated below [16].

$$K_{av} = \frac{\sum_{i=1}^{n} k_i h_i}{\sum_{i=1}^{n} h_i} \quad \text{-----} (15)$$

2.6 Hydrocarbon moveability: Movability of hydrocarbon is measured as follows:

$$\frac{S_w}{S_{xo}} = \left(\frac{R_{xo} / R_t}{R_{mf} / R_w} \right)^{1/2} \quad \text{-----} (16)$$

2.7 Bulk volume of water: The bulk volume of water (BVW) has been calculated using Morris and Biggs [22] formula:

$$BVW = S_w \times \phi \quad \text{-----} (17)$$

3. RESULTS AND ANALYSIS

3.1 Identification of hydrocarbon bearing zones

Hydrocarbon bearing zones can be identified with the combined use of GR, SP, resistivity (RILD and RSFL), neutron, density and sonic log responses. In the identified hydrocarbon bearing zones, gamma ray log shows low response and SP log shows high value and it deflects from the shale base line (Fig. 2). For this purpose, resistivity logs are the best option to detect hydrocarbon bearing zones. The resistivity log response in the hydrocarbon bearing zones is very high (Asquith and Gibson, 1982). Normally in hydrocarbon bearing zones deep resistivity log (RILD) value is higher than the shallow resistivity log (MSFL). Very low bulk density and neutron porosity compared to water bearing sandstone and a negative separation between density and neutron responses are also the indicators of hydrocarbon bearing zones [18]. High deflection of neutron and density log with sharp decrease of porosity and density indicate gaseous hydrocarbon. In all of the identified 4 hydrocarbon bearing zones, some shales are interbedded with the reservoir sandstone which affects the reservoir properties. In this study, 20 permeable zones have been identified from the composite log analysis of 1464 m thickness (1310-2774 m) of the well RP4. Among these permeable zones, four zones (cumulative thickness 168 m) have been identified as hydrocarbon bearing and the remaining is water bearing.

3.2 Shale distribution

Generally shale evaluation includes the determination of shale parameters as well as its volume and types. The determination of shale parameters often depends on the experience of log analyst since these parameters vary with different geological factors. Volume of shale in the hydrocarbon bearing zones of the reservoir sandstones of the studied well has been calculated using Schlumberger [15] and Dresser Atlas [14] formulas. The cutoff value of shale volume of shaly sandstone reservoir is about 20-30% [10]. The average shale volume of the identified hydrocarbon bearing zones of the well RP4 is 20% (Table 2). Zone 3 contains the lowest and Zone 1 contains the highest volume of shale. Waxman and Smits [23] suggested that CEC value > 0.2 indicate smectite or illite type of clay, whereas CEC value < 0.2 indicates kaolinite or chlorite. In the present study, CEC values are found ≈ 0.2 which indicates mixed types of clay (i.e., chlorite, illite and kaolinite) throughout the Mio-Pliocene reservoir intervals of the Bengal Basin, Bangladesh [24].

Table 2: Log based petrophysical analysis results of 4 hydrocarbon (HC) bearing zones identified in well Rashidpur-4 of Bengal Basin, Bangladesh [Vsh = shale volume; phi = porosity; Sw= water saturation (%) whereas Sc- Schlumberger (1975), Ft= Fertl (1975), Sd= Simandoux (1963); Sh= hydrocarbon saturation (%); Sw/Sxo= moveability; BVW= bulk volume of water; K= permeability (mD) whereas Wy- Wyllie and Rose (1950), Ct- Coates and Dumanoir (1973)].

Gas Zone [depth, m]	Thick (m)	Vsh (%) [ϕ (%)]	Sw (Sc) [Sw (Ft)]	Sw (Sd) [Sw (avrg)]	Sh (Sc) [Sh (Ft)]	Sh (Sd) [Sh (avrg)]	Sw/Sxo [range]	BVW [range]	K (Wy) [K (Ct)]	K (avrg) [range]
Zone 1 [1447-1522]	75	36 [19]	19 [15]	26 [20]	81 [85]	74 [80]	0.1 [0.1-0.4]	0.04 [0.02-0.05]	22 [87]	54 [1-306]
Zone 2 [2337-2350]	13	14 [19]	33 [35]	36 [35]	67 [65]	64 [65]	0.2 [0.1-0.2]	0.07 [0.05-0.07]	3 [62]	33 [4-63]
Zone 3 [2466-2483]	17	11 [19]	38 [39]	41 [39]	62 [61]	59 [61]	0.1 [0.1-0.2]	0.07 [0.05-0.08]	4 [51]	28 [1-84]
Zone 4 [2668-2731]	63	18 [28]	14 [13]	16 [14]	86 [87]	84 [86]	0.2 [0.1-0.4]	0.04 [0.02-0.06]	253 [357]	305 [1-735]
Gross value	168	20 [21]	26 [26]	30 [27]	74 [75]	70 [73]	0.2 -	0.06 -	71 [139]	105 -

3.3 Porosity (φ) distribution

Porosity of rock is a fraction of void space compared to its total volume. The determination of porosity is a very important step for calculating fluid saturation in reservoir evaluation. Neutron and density logs have been used to calculate porosity distribution for the current study. The cutoff porosity for sandstone reservoir is considered as 8% [8]. The estimated porosity of the hydrocarbon zones of the Mio-Pliocene succession ranges from 7% to 36% having the thickness weighted average porosity of 22% (Table 2). Based on porosity values, Bradley [16] classified sandstone reservoirs as poor (5-10%), fair (10-15%), good (15-20%), very good (20-25%) and excellent (higher than 25%) categories. Here, the studied sandstone reservoir is considered as very good category. The calculated porosity data is independent without having any control by any other means.

3.4 Water saturation (Sw) distribution

Water saturation of the currently examined hydrocarbon bearing zones in the studied well has not been used for Archie's (1942) formula. Because this formula is valid for clean sandstone and the values are much affected by incursion of shale and porosity. Therefore, three most popular formula have been used which were proposed by Simandoux [17], Fertl [18] and Schlumberger [15]. Finally, the average value of the water saturation calculated from these three different formulas have been considered for further calculation. The calculated average water saturation values of the four hydrocarbon bearing zones 1-4 in the well RP4 are 20%, 35%, 39% and 14% respectively (Table 2). Thickness weighted average water saturation of the examined reservoir sandstones is 20%.

3.5 Hydrocarbon saturation (Sh) distribution

Hydrocarbon saturation of a reservoir is determined by subtracting water saturation from the value of total saturation which is 1 (one). The permeable zone having more than 60% hydrocarbon saturation (Sh) value is commonly treated as hydrocarbon bearing zone (Asquith and Gibson, 1982). Following all three commonly used formulas, Sh values of all hydrocarbon bearing zones are greater than 60% (Fig. 3). Sometimes the presence of shale in the studied reservoir sandstones decreases the content of Sh. In case of water saturation calculation, Schlumberger's formula [15] has been found better suited among these three formulas [10]. The calculated average values of hydrocarbon saturation of the zones 1-4 of the studied well RP4 are 80%, 65%, 61% and 86% respectively. 80% is the thickness weighted average hydrocarbon saturation of the studied sandstones. Based on hydrocarbon saturation, the zones can be ranked as Zone 4 > Zone 1> Zone 2> Zone 3.

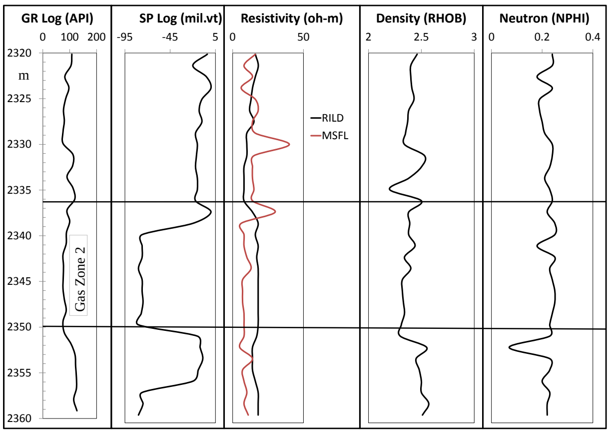

Fig.2: Composite log responses of the hydrocarbon bearing Zone 2 (2337-2350 m) identified in Mio-Pliocene sandstones of the well Rashidpur-4, Bangladesh [25].

3.6 Permeability (K) distribution

Permeability is the property of a rock that has to transmit fluids. The results of permeability measurement are shown in the Table 2. The average permeability values of the gas zones 1-4 of the investigated reservoir sandstones are 54, 33, 28 and 305 mD respectively. Measured thickness weighted average permeability of the Mio-Pliocene reservoir is 144 mD. Considering its average permeability, Zone 4 is the most potential zone. All values calculated here indicate the identified hydrocarbon bearing zones are commonly good to very good reservoirs according to the generalized observation made by Asquith and Gibson [8].

3.7 Hydrocarbon moveability index (Sw/Sxo)

Hydrocarbon moveability index is the ratio between water saturation of uninvaded zone (Sw) to the water saturation of flushed zone (Sxo). If the ratio of Sw and Sxo is ≥1, then the hydrocarbon would not move toward the well bore. If this ratio is less than 0.7 (for sandstone), the hydrocarbon is considered as moveable [15]. From the calculated results (Table 2), it can be inferred that the hydrocarbon of the selected zones in the studied well RP4 is moveable. Because all movability index values are less than 0.7.

3.8 Bulk volume of water (BVW)

Bulk volume of water is the product of formation's water saturation and its porosity. It is important to know BVW whether the formation is at irreducible water saturation or not. When the value of BVW is constant or close to constant with some minor scattering, it indicates the homogenous formation having close to irreducible water saturation. If the BVW ranges from 0.035 to 0.07, the grain size of the rock succession is fine to very fine grained sandstone [18]. The BVW values of the hydrocarbon bearing zones in the studied well have been calculated using Morris and Biggs [22] formula. The calculated bulk volume of water is nearly constant with some minor scattering in the hydrocarbon bearing zones which indicate that the reservoir rock consists mainly of fine to medium grained sandstone.

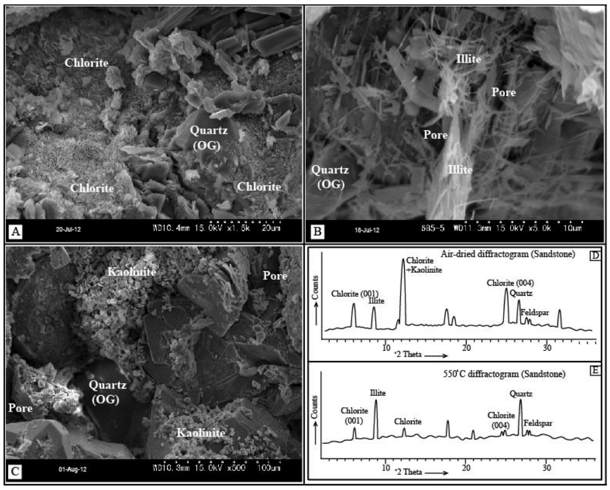

Fig.3: Clay minerals observed in sandstones of RP4 using scanning electron microscopic and XRD. (A) Clusters of pore-filling euhedral and pseudohexagonal chlorite crystals, depth 2683 m. (B) The filamentous illite coating the detrital grain surfaces associated with quartz overgrowth, depth 2757 m. (C) Kaolinite books, face-to-face stacks of pseudohexagonal plates, partly occluded the pore throats, depth 2670 m. (D) Non-treated air-dried x-ray diffractogram of sandstones. Here chlorite, illite and kaolinite clay minerals are identified. (E) 550 °C heated x-ray diffractogram of sandstone and hence the kaolinite peak is disappeared remained a small peak for chlorite [24-25].

4. DISCUSSION

Porosity and permeability are the two most important parameters which can be determined from well log analysis directly or indirectly [8]. These characteristics of rock are affected by many ways during logging measurements. There are many variables and techniques to minimize the adverse down hole effects and drawbacks of some computation procedures. However, none of them is unique. For example, a, m and n are three parameters (constants) termed as tortuosity, cementation and saturation exponent. These parameters differ from rock to rock and basin to basin. In the Bengal Basin, there are no prescribed values of these parameters. In this study, the values of these parameters have been used in a generalized fashion and considered as 0.62, 2.15 and 2 respectively. These values might also affect the overall calculations. Neutron, density and sonic log readings have been used to determine the porosity. Porosity measurements from density logs require matrix density. Most postulated matrix density for sandstone is 2.7 cc/gm [15]. Core derived density values from this study range from 2.1 to 2.6 gm/cc. The constant value of matrix density might also affect the porosity calculation from density log. The computation processes needs some correction due to shale effect on the log data because the studied reservoirs consist of more than 10% shale. If the effects of shale on the porosity measurement are not duly minimized, then the measurement might lead to deviation from the correct values. There is no known tool that can measure permeability without any error. Core derived permeability is often calculated based on empirical rather than measured studies. Well logs can predict relative indications of permeability, which are usually termed "permeability index" and are qualitative rather than quantitative. The quality of the index hinges on the quality of the data [15]. The hardest parameter to pin-point is that the irreducible water saturation (Swirr).

Log derived permeability formulas are only valid for estimating permeability in formation with irreducible water saturation [15]. The product of water saturation (Sw) and porosity (ø) is known as bulk volume of water (BVW). If values for BVW across the reservoir interval are constant or very close to constant, then the hydrocarbon production from the reservoir should be water free. Hence, the saturated water in the uninvaded zone will not move due to capillary pressure existing between the sediment grains [22]. Nevertheless, it is always difficult to find a reservoir at irreducible water saturation state due to heterogeneities in the reservoir properties. The present study also suffers from this difficulty. In shaly sand calculation, the shale parameters within the reservoir translated from the neighboring shale zone which may not be the same in all cases.

In this study, petrography (thin section) based average porosity ranges from 17% to 23% having the average value of 19%. The log derived average porosity value is 7-36% (average 22%). There is a slight increase of porosity values in case of log analysis. Only five selected sandstone samples of RP4 are chosen for petrographic (thin section) analysis. Here comparatively shale free sandy samples are considered for measurement. This is obvious that relatively clean sandstone provides high permeability and comparatively high porosity. It is because of the fact that due to larger pore radius core samples exhibit high permeability and porosity. Because of shale effect, the log measurements exhibit significant increase in porosity and a decrease in permeability. Four gas zones from the well RP4 consist of 168 m thick gas sands. So, huge data points even from thinly laminated shaly horizon are accompanied by comparatively less shaly sandy horizon increase the log porosity and decrease the log permeability. The heterogeneity of the studied reservoirs might be responsible for down grading the log permeability values.

There are many examples from petroleum basins around the world that the permeability of petroleum reservoir rocks may range from 0.1 to 1000 or more millidarcies (mD). The quality of a reservoir as determined by permeability (in mD) may be ranked as poor if K<1, fair if 1<K<10, moderate if 10<K<50, good if 50<K<250 and very good if K>250 [26]. The average permeability measured for the gas zones ranges from 28 to 306 mD. In this regard, permeability values of all reservoir intervals of the well Rashidpur-4 indicate good to very good quality reservoirs (Table 2). Porosity, hydrocarbon saturation and movability index values of the selected hydrocarbon zones also advocate in favor of good to very good reservoir condition in the Bengal Basin. This interpretation is also supported by Islam [9, 10], Rahman and McCann [27] and Imam [7]. The identified zone 4 (2668-2731 m) is the most potential hydrocarbon bearing zone based on its porosity. This is also supported by other parameters like hydrocarbon saturation and permeability. The studied clays within the reservoir sandstone samples are mixed types (i.e., chlorite, illite and kaolinite) throughout the Mio-Pliocene Surma Group. This is consistent with the interpretation made with the help of XRD and microscopic study (Fig.3). It is also reported by Imam and Shaw [28], Islam [9-10] and Rahman and McCann [27]. Anomaly in log based measurements may be because of the inherent problems of different formulas, e.g., selection of saturation and permeability formulas and constraints related to values of different constants.

5. CONCLUSION

Among twenty permeable zones of the well RP4, four potential gas zones are identified. Their gross cumulative thickness is 168 m. The study measures the log derived petrophysical parameters including shale volume, porosity, water saturation, hydrocarbon saturation, permeability, moveability index and bulk volume of water. These are (average) 20%, 22%, 20%, 80%, 144mD, 0.2, 0.06 respectively. Hydrocarbons of these zones are moveable since Sw/Sxo is found less than 0.7. Schlumberger equation is found more suitable for water saturation calculation comparing with Fertl and Simandoux equations. The log derived porosity slightly exceeds thin section porosity. Bulk volume of water of the hydrocarbon zones indicates fine to medium grained sandstones. Petrographic evidences and XRD results confirms the dominance of mixed type of clays including chlorite, illite and kaolinite in the examined sandstones. The study reveals that all of the four gas zones possess good to very good quality reservoirs in the well Rashidpur-4 of the Bengal Basin, Bangladesh. This good to very good quality reservoir quality is also supported by the interpretation based on petrography. Nonetheless, zone 4 is considered the best potential for hydrocarbon generation and production of the well Rashidpur-4.

6. ACKNOWLEDGEMENT

The authors are grateful to chairman of Petrobangla for supplying data/sample. Sylhet Gas Fields Ltd, Petrobangla deserves appreciation for official support (M.F.) to carry out this research. Prof. Khalil R. Chowdhury and his colleagues at Jahangirnagar University have encouraged much for the present research (PhD). The authors also acknowledge the financial support grants PV100-2011A and

RG145-11AFR and Bright Sparks Fellowship BSP-APP-1080-2012 of UM.

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