

Article

Diagenetic Clay Minerals and Their Controls on Reservoir Properties of the Shahbazpur Gas Field (Bengal Basin, Bangladesh)

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Received: 9 April 2020; Accepted: 29 June 2020; Published: 30 June 2020



Abstract: Clay mineralogy and diagenesis affect the reservoir quality of the Neogene Surma Group in the Hatiya trough of Bengal Basin, Bangladesh. X-ray diffraction and scanning electron microscopic analyses of diagenetic clay minerals from Shahbazpur#2 well reveal that on average illite is the dominant clay mineral (50%), followed by chlorite (24%), kaolinite (23%) and smectite (2.50%). The absence of smectite at Core-2 (3259.80 m to 3269 m) results from the total transformation of smectite to illite owing to burial depth and high K-feldspar. The diagenetic changes are a result of chemical processes such as cementation, chlorite authigenesis, dissolution, alteration and replacement that have significantly affected the reservoir properties. Cementation plays an important role in reducing reservoir properties with pore and fracture filling cement. The relative percentage of illite and smectite minerals (>90% illite in I/S mixed layer) and Kübler index value (0.34° to 0.76° $\Delta 2\theta$) indicate a diagenetic zone with subsurface temperatures of 120–180 °C in the studied samples. The temperature range determined using clay percentages and the Kübler index as a geothermometer is supported by observed diagenetic features such as quartz overgrowths, smectite to illite transformations and chlorite coatings. The diagenetic features cause variable reservoir porosity and permeability that are critical in planning exploration and development programs of this field or analog fields across the Bengal Basin.

Keywords: clay minerals; reservoir heterogeneity; diagenesis; geothermometer; Kübler index

1. Introduction

The Bengal Basin is located on the northeastern part of the Indian subcontinent and is bound to the north by the Shillong Plateau, to the east by the Indo–Burman Range and to the west by the Indian shield (Figure 1). The basin is open to the south and merges with the Bengal Fan. It contains a very thick Lower Cretaceous to Holocene sedimentary succession (~22 km) with several hydrocarbon-bearing horizons, mostly in the Miocene sandstones [1–5]. The basin-fill history of the Bengal Basin shows that deltaic deposits progressively filled the basin during and after Miocene; the time when the basin became a remnant ocean basin [6,7]. For the past few decades, the Bengal Basin has been the subject of much investigation owing to its petroleum potential.

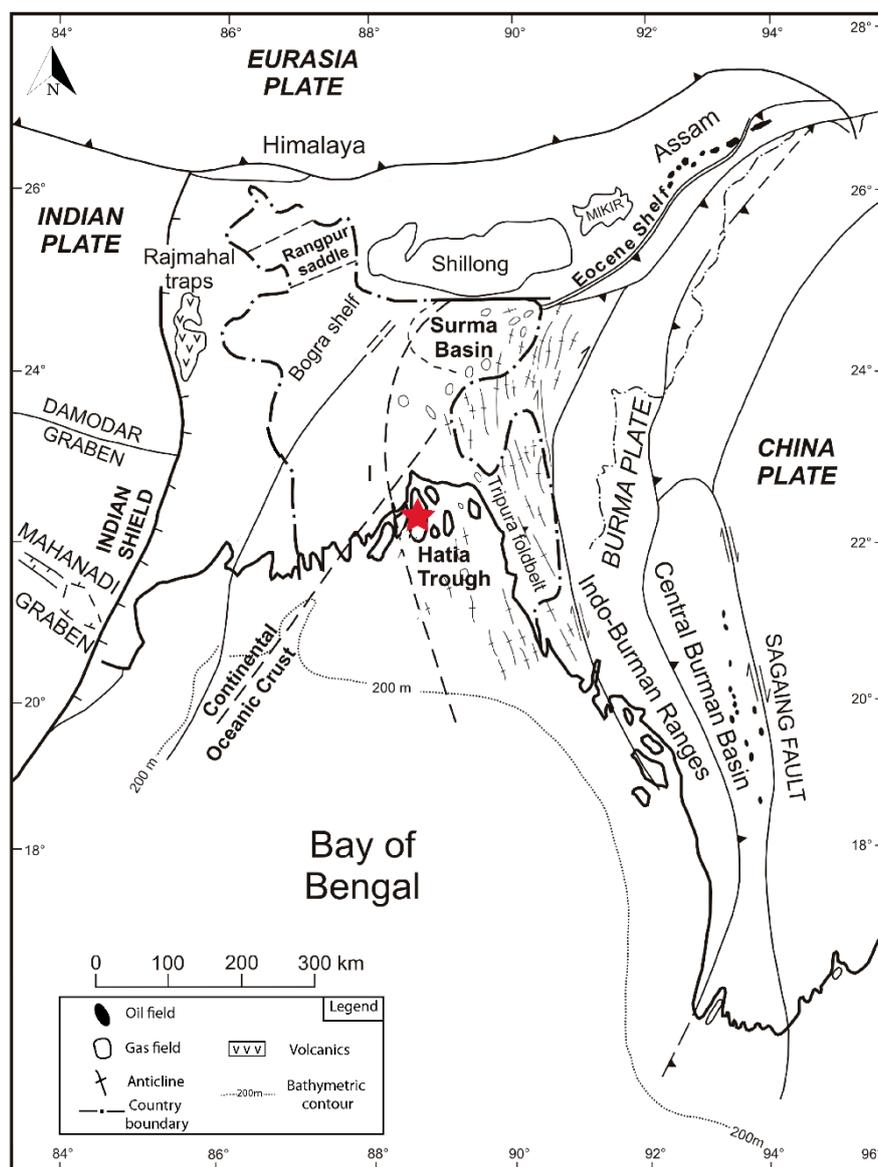


Figure 1. Regional map of the Bengal Basin showing major structural elements (after Curiale et al. 2002). Red asterisk shows the approximate location of the Shahbazpur structure within the Bengal Basin.

Few studies have focused on the clay mineralogy of the reservoir rocks and its implications for reservoir quality [8–10]. In this study, we present an investigation of diagenetic clay minerals of the reservoir rocks of Shahbazpur#2 well using X-ray diffraction (XRD) and scanning electron microscopy (SEM). The aim of this study is to present a detailed diagenetic analysis of the Surma Group sandstones to understand the various diagenetic controls and their effects on reservoir properties.

2. Regional Geology

2.1. Geologic Setting

The Shahbazpur gas field is situated within the Hatia trough of the Bengal foredeep (Figure 1) and is characterized by a large NNW–SSE-trending anticline that hosts the field’s gas accumulations [8]. Although the structure has no surface expression, it represents the western extension of the Chittagong-Tripura Fold Belt (CTFB) [8]. The CTFB and its correlative structures formed in the Miocene as a result of collision of the Indian plate with the Burma and Tibetan plates. The formation of

the structure probably began not before Late Miocene, and its acme of development took place during Mio-Pliocene sedimentation and ended in Plio-Pleistocene [11]. The eastern flank of the structure is relatively gentler in dip than the western flank, and no major fault are expressed at the surface; however, blind thrusts are possibly present [11]. The probable source rocks in the Bengal Basin are Upper Eocene and Lower Miocene shallow marine deposits. The generated hydrocarbons are likely to be migrated through the blind thrusts formed contemporaneously with the formation of CTFB [7].

2.2. Stratigraphy

The fluvial-deltaic Surma Group of the Bengal Basin (Figure 2) are generally considered the reservoir rocks of the Shahbazpur structure [8]. The age of these reservoir rocks probably extends from Late Miocene to Early Pliocene [8]. However, some authors suggest rocks drilled in Shahbazpur#2 well which consist of predominantly of shale with occasional interbedded sandstone and calcareous siltstone were deposited in Plio-Pleistocene [7,12].

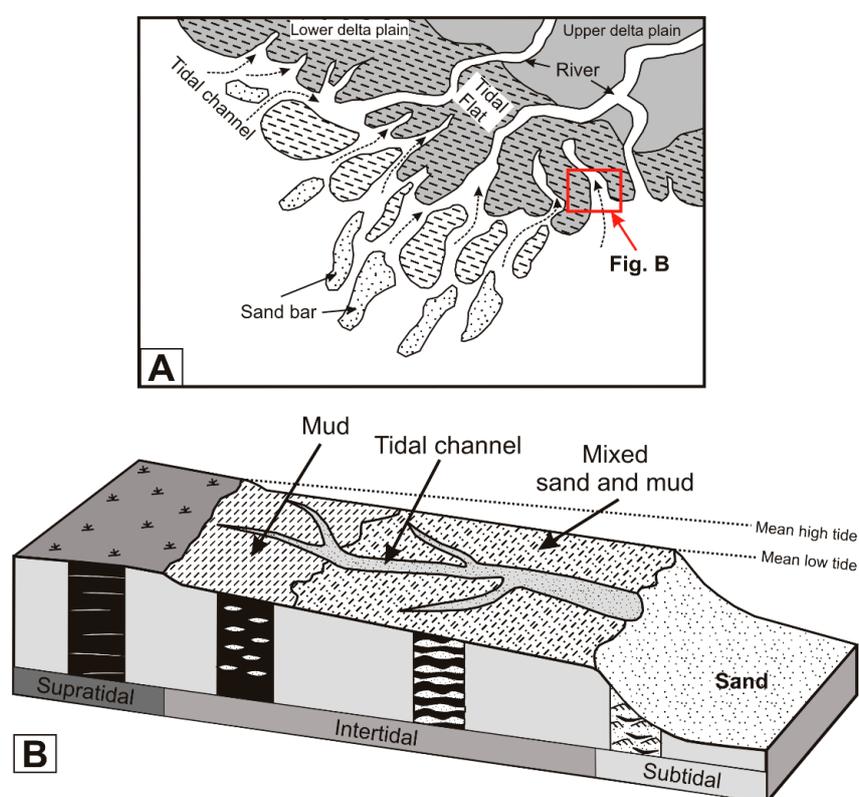


Figure 2. Schematic depositional models for the Miocene reservoir sediments deposited in the Hatia trough. (A) Aerial view of a tide dominated delta system and (B) schematic diagram showing different sub-environments in a tidal flat setting. Diagrams are not drawn to scale.

The sedimentary succession of the Shahbazpur #2 well can be subdivided into two units: an upper mud dominant (Unit A) and a lower sand dominant (Unit B). Unit A consists of mostly shale and mudstone with some sandy/silty shale beds and rare laminated sandstone layers. Whereas sand dominated Unit B comprises mainly fine- to medium-grained sandstones with flaser-bedding, cross-lamination and parallel lamination. These sandstones are interbedded with shale, sandy/silty shale and sometimes mudstone (Table 1). Some massive-bedded sandstone layers are also present in the lower part of this unit. This sandy sequence is also interbedded with shale, sandy/silty shale and sometimes mudstone (Table 1).

Table 1. Reservoir succession of Shahbazpur#2 well.

Age (approx.)	Traditional Nomenclature	Unit	Lithology
Miocene	Surma Group	Unit A (mud dominant sequence)	Shale, mudstone and sandy/silty shale, with some laminated sandstone layers.
		Unit B (sand dominant sequence)	Fine- to medium-grained sandstones with some shale and sandy/silty shale.

3. Materials and Methods

X-ray diffraction (XRD) of five representative samples was carried out using a Rigaku: Ultima-IV (185 mm) Goniometer (Cu/ 40KV/ 40 mA) with a scanning speed of $2^\circ 2\Theta/\text{min}$. Samples (four shale and one sandstone) from the depth of 2591.83 m, 2593.3 m, 3261.93 m, 3263.49 m and 3266.37 m were selected for clay mineral identification. The samples were run between 3° – $70^\circ 2\Theta$. Clay mineral fractions $\leq 2 \mu\text{m}$ were obtained by the sedimentation method [9]. The samples were run as air-dried, ethylene glycolated and DMSO (dimethyl sulfoxide) treated. The samples were swelled with ethylene glycol to identify smectite and DMSO to differentiate kaolinite from chlorite. Semiquantitative estimation of clay minerals was made after Biscaye (1965) [13]. The quantification of clay minerals was made by considering peak area above the background for each diagnostic reflection multiplied by a correction factor. The Kübler index, which is the full width at half-maximum height (FWHM) of the 10 \AA peak of interstratified I/S minerals is measured on the $<2 \mu\text{m}$ fraction of air-dried samples using CuK α radiation. The Kübler index reflects the metamorphic conditions of a rock interval; hence this helps to determine the present-day temperature [14]. Core plug porosities and permeabilities were determined in the laboratory of Bangladesh Petroleum Exploration Company Limited. The porosity and permeability were measured using the modified pressure transient method. Helium gas was used as a permeating medium [15].

Pearson's correlation co-efficient was determined to measure how strong a relationship exists between two variables (e.g., porosity vs depth, porosity vs permeability). Then bootstrapping was performed which uses a random sampling of the variables to determine n-number ($n = 100$) of correlation co-efficient between two variables. The inherent idea of bootstrapping is to infer about a population from sample data by random resampling [16].

Samples were prepared for scanning electron microscope (SEM) analysis using samples less than 1-cm diameter. Illite–smectite was identified by wavy platy morphology with short honeycomb like crystals/ or lath-like form. The characteristic “booklet” appearance of stacked hexagonal plates was diagnostic to identify kaolinite as described in Rahman and Worden, 2016 [17].

4. Results

The analysis of all the X-ray diffractograms results in four major groups of clay minerals: illite (average—50%), chlorite (average—24%), kaolinite (average—23%) and smectite (average—2.5%) sequentially by abundance (Figure 3). A number of mixed layer clays are also present in the samples in a minor amount. The samples show 3% and 2% of smectite at 2591.83 m and 2593.3 m, respectively, and smectite is absent at >3000 m depth (Table 2).

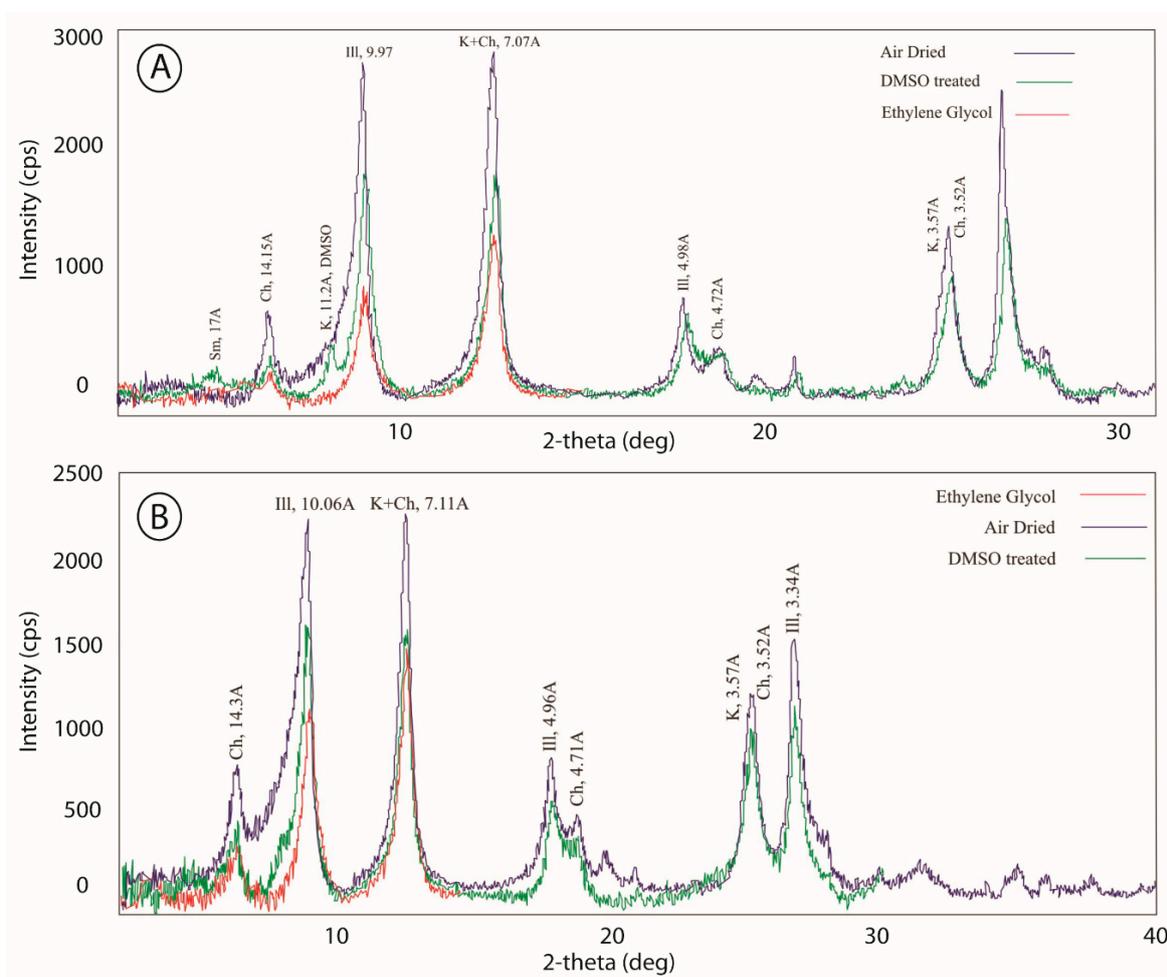


Figure 3. X-ray of clay fraction (2 μ m) showing the presence of major clay mineral type at the depth of about (A) 2591.83 m of the Core-1 of Shahbazpur#2 well and (B) 3263.49 m of the Core-2 of Shahbazpur#2 well. Sm = smectite, Ch = chlorite, Ill = Illite and K = kaolinite.

Table 2. The relative percentage of clay minerals of some selective samples of the Shahbazpur#2 well.

Well	Sample No.	Strat. Unit	Depth (m)	Illite (%)	Chlorite (%)	Kaolinite (%)	Smectite (%)	Measured FWHM ($^{\circ}\Delta 2\theta$)
Shahbazpur#2	SNT-1	Unit A	2591.83	48	24	23	3	0.43
	SNT-3	Unit A	2593.3	54	22	21	2	0.48
	SNT-7	Unit B	3261.93	54	23	22	0	0.52
	SNT-9	Unit B	3263.49	55	23	21	0	0.76
	SNT-11	Unit B	3266.37	42	29	28	0	0.34

The percentage of authigenic chlorite ranges from 3.61% to 5.23% and occurs mainly as pore-filling [18]. Kaolinite is present in primary pore space as well as in secondary pores where feldspar grains are degraded. Authigenic quartz is present in minor amounts. Petrophysical properties determined from core samples are shown in Table 3 [18]. The average core porosity is 13.42% and permeability is 44.6mD. Major observations between the petrophysical parameters include a moderate positive correlation between porosity and permeability ($r = 0.4-0.6$) and a negative correlation of porosity and depth ($r = -0.6$ to -0.8). However, the histogram of bootstrapped Pearson correlation coefficient (r) in the cross plots, the r values show a wide range (Figures 4 and 5). The Kübler index from the $10A^{\circ}$ peak of interstratified I/S minerals ranges between $0.34^{\circ}\Delta 2\theta$ and $0.76^{\circ}\Delta 2\theta$ with $I/S \geq 3$ ordering.

Table 3. Core petrophysical parameters of Shahbazpur#2 well at different depths.

Well No	Core No.	Depth (m)	Porosity (%)	Permeability (mD)	
				Horizontal Permeability	Vertical Permeability
Shahbazpur#2	1	2591.50	8.27	24.41	-
		2591.70	6.76	-	-
		2592.30	1.89	-	-
		2592.70	12.95	-	-
		2593.10	7.00	-	-
	2	3265.70	19.31	50.01	-
		3265.90	16.38	45.85	-
		3266.10	18.56	95.23	-
		3266.20	14.86	-	37.32
		3266.30	17.39	54.90	-
		3266.50	16.11	-	35.40
		3266.80	19.32	60.54	-
		3266.90	9.93	-	11.91
		3267.10	15.99	44.15	-
		3267.50	13.71	-	-
		3267.70	15.98	20.09	-
		3267.90	13.68	55.39	-

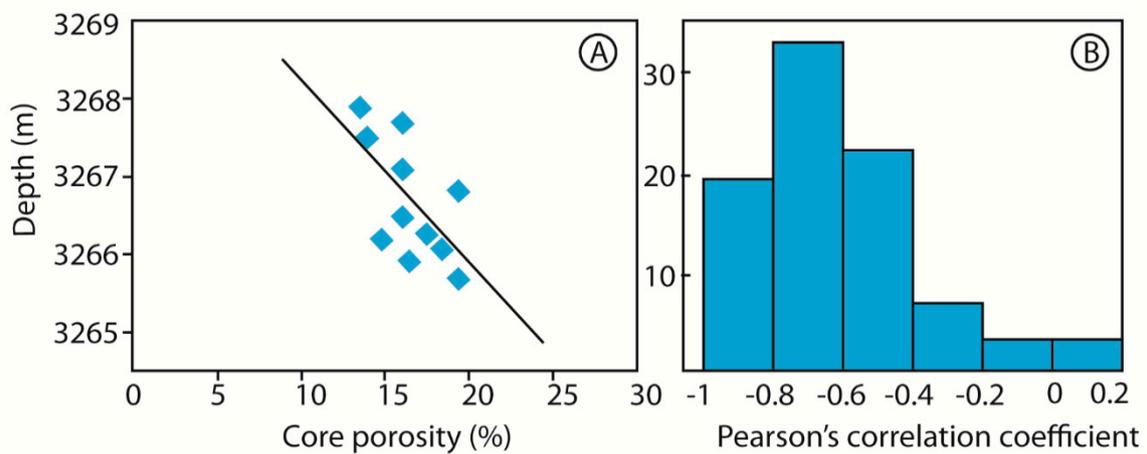


Figure 4. (A) Change of core porosity in relation to depth of Shahbazpur#2 sandstone samples; (B) histogram of bootstrapped Pearson's correlation coefficient.

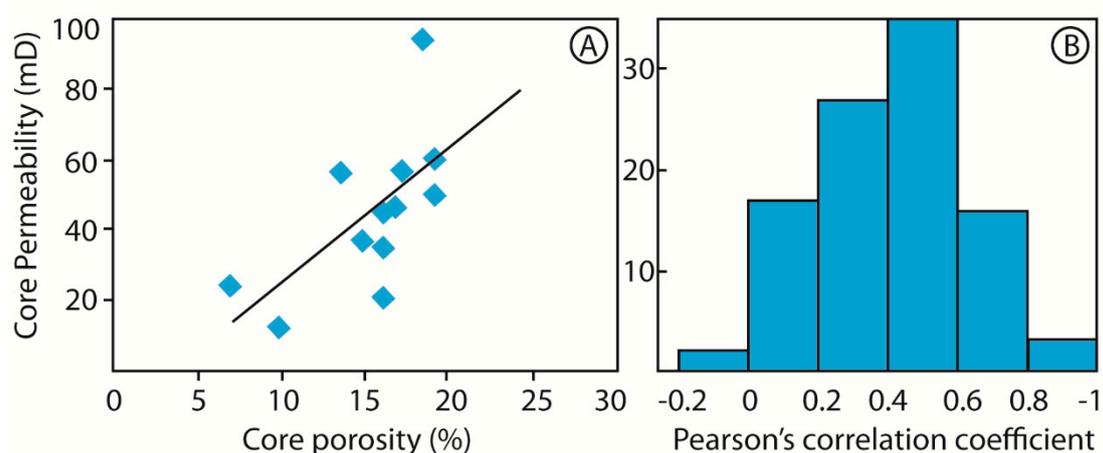


Figure 5. (A) Change of core permeability in relation to depth of Shahbazpur#2 sandstone samples; (B) histogram of bootstrapped Pearson's correlation coefficient.

5. Discussion

The principal cements in the Surma Group sandstones are authigenic chlorite, clay cement, calcite cement and quartz. Most of the authigenic chlorite is thought to be associated with and may have been formed from altered biotite [8]. This mixed layer clay mineral results from the interstratification of different mineral layers in a single structure [19]. In SEM view, the presence of chlorite was observed as pore-lining and discontinuous rims in the studied samples. The authigenic chlorites in the Surma Group are Fe-rich as suggested by Imam and Shaw, 1987 [10]. Authigenic chlorite cement has a significant role in preserving porosity and permeability [20,21]. The porosity preservation results from hindering quartz overgrowths by the presence of pore-lining chlorite along quartz grains. This process explains the scarcity of quartz overgrowth observed in Surma Group sandstones of the study area. Authigenic chlorite seems to be forming from early to late phases, evidenced from textural (size and shape) relationships of this cement with other framework minerals [18].

Presence of smectite and its diagenetic effect in the Upper Surma Group is reported in previous literature [8–10]. However, smectite is absent in sand-dominated Unit B. Throughout the Bengal Basin, significant variation in the content of K-feldspar with depth in the Neogene Surma Group has been observed [22]. This lack of smectite may be explained by either the lack of K-feldspar in Unit B or the conversion of smectite to illite through the intermediate mixed layer clays of illite–smectite—or some combination of these two causes [23]. It is likely that the kaolinite cements originated from the diagenetic alteration of detrital feldspars because some of the studied samples are subarkosic and there is abundant secondary porosity formed as a result of k-feldspar dissolution [18]. The pressure solution and transformation of smectite to illite in the adjacent shales is not a significant source of silica due to small percentage of smectite presence. We argue such a low amount of smectite results in very minor quartz overgrowth. The authors understand that the derived percentages after Biscaye (1965) are not rigid numbers. However, the relative percentages align with the clay percentages of the Surma Group throughout the Bengal Basin in Rahman et al. 2016 [17].

Kübler index values range between $0.34^\circ \Delta 2\theta$ and $0.76^\circ \Delta 2\theta$ and indicate a deep diagenetic zone with subsurface temperatures ranging between 120–180 °C [14]. The changes in the proportion of illite, smectite (I/S) interpreted from XRD can also be helpful to make a semiquantitative estimation of temperature due to burial depth. An empirical relationship between these changes in I/S and subsurface temperature was first demonstrated by Hoffman and Hower (1979) [24]. Three interstratification forms of illite and smectite (I/S) using the “Reichweite” (R) notion were developed using XRD profiles of natural materials with calculated profiles [25]. According to these models, the temperatures for $R \geq 3$ ordering (90% illite) is >170–180 °C in the studied samples. However, some authors indicate that interstratified I/S with about 90% of illite can already be formed above 120–130 °C [26]. Based

on Kübler index values, I/S mixed layer percentages and diagenetic features, the authors suggest a prevailing subsurface temperature of 120–180 °C in the studied Neogene Surma Group sandstones.

Based on the diagenetic features observed in this study and previous works on Surma Group sandstones (using petrography and SEM analysis) across Bengal Basin, a sequence of diagenetic processes is presented in Figure 6.

Stages	Relative timing of the processes	
	Early	Late
Infiltration of clay coatings	_____	
Mechanical compaction	_____	_____
Authigenic chlorite	_____	_____
Carbonate cement	_____	_____
Dissolution of feldspar and carbonates	_____	_____
Quartz overgrowths		_____
Authigenic illite		_____

Figure 6. Relative succession of the diagenetic processes in the sandstones of the Surma Group from this study and previous studies across Bengal Basin [8–10].

Mechanical compaction during burial and authigenesis control the reservoir quality of the Surma Group sandstones [8]. Pore-filling, pore-lining chlorite and clay cements are responsible for porosity reduction in the sandstones. However, Fe-rich chlorite also inhibits quartz overgrowth, hence preserving primary porosity. However, sandstones of the Surma Group show good porosities (~20%) and high permeabilities (~30–90 mD), it is likely that the reservoir intervals show compartmentalization by intervening low-moderate quality sandstones resulting from diagenetic processes.

6. Conclusions

(1) X-ray diffraction analysis of the clay minerals reveals that illite is the dominant clay mineral followed by chlorite, kaolinite and smectite. The absence of smectite at core-2 indicates total transformation of smectite to illite due to increasing burial temperature and high K-feldspar.

(2) The illite–smectite ratio and Kübler index indicate burial temperatures of 120–180 °C. The diagenetic features such as chlorite authigenesis and absence of smectite with depth support this temperature range.

(3) Sandstones with good porosities (average 13.42%) and high permeabilities (average 44.6 mD) were observed in the reservoir rocks of the Shahbazpur field. No definitive relations can be determined between porosity and permeability with depth. The variability of petrophysical properties and observed diagenetic features results in heterogeneity within the reservoir rock. The heterogeneity within the reservoir rock should be taken into consideration while planning the development strategy of this field or analog fields.

(4) The histogram of bootstrapped ($n = 100$) Pearson's correlation co-efficient between porosity and permeability shows a value of 0.4 to 0.6 which means weakly positive correlation exists between these two variables. Whereas, porosity shows strong negative correlation (−0.6 to −0.8) with depth, probably caused by increasing compaction and diagenesis.

Author Contributions: Conceptualization, M.N.H. and R.Y.; methodology, M.N.H. and R.Y.; software, M.N.H.; validation, M.N.H., R.Y. and M.J.J.R.; formal analysis, M.N.H.; investigation, M.N.H.; writing—original draft

preparation, M.N.H.; writing—review and editing, R.Y., S.P.-M.; visualization, M.N.H.; supervision, R.Y., M.J.J.R., S.P.-M.; project administration, R.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors are grateful to the Bangladesh Atomic Energy Commission, Geological Survey of Bangladesh and the Bangladesh Petroleum Exploration Company, Ltd. for allowing to use their laboratories. The authors would also like to thank three anonymous reviewers and the academic editor for their thorough and critical reviews which improved the clarity and quality of this article.

Conflicts of Interest: The authors declare no conflicts of interest.

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