

# Petrography and Diagenesis of the Tertiary Surma Group Reservoir Sandstones, Bengal Basin, Bangladesh

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**Abstract** The aim of this research was to evaluate petrographic characteristics of the Tertiary Surma Group sandstone reservoirs. The diagenetic constituents, processes and their impacts on reservoir quality were evaluated. A total of 33 core samples collected from 8 different wells located in 7 different gas fields of Bangladesh were used for the current study. The standard petrographic microscope, scanning electron microscope (SEM/FESEM) and XRD were used in the current study. The framework grains, mineralogy, matrix, pore properties and cements were identified and counted properly. The framework grains were in accordance to dominance quartz (76-91%), rock fragments (5-16%) and feldspar (3-14%). The identified important diagenetic components were quartz cements, authigenic clays, carbonate cements and dissolution. The early to intermediate stage of the diagnostic realm was estimated in the studied samples, e.g., mechanical compaction, chloritization, carbonate precipitation, dissolution, quartz overgrowth and authigenesis of clays. The reservoir quality was not much affected by the effects of diagenesis. However, it seems to be controlled mostly by the mechanical compaction including its grain size, sorting and fabric. In addition the authigenic cements slightly modified its porosity and permeability status during diagenesis. The measured average thin section porosity and its permeability suggested good to excellent reservoir quality for hydrocarbons.

**Keywords** Petrography, Diagenesis, Surma Group, Sandstone, Reservoir porosity, Permeability

## 1. Introduction

Reservoir quality in sandstone is controlled by several interrelated factors such as mineral composition, depositional facies, diagenetic events and circulating basinal fluids [1,2]. Diagenesis is by far the most significant issue among these factors impact on the reservoir property [3,4]. It includes a variety of postdepositional processes and

reactions modifying the original state of the rock [4, 5, 6]. Numerous workers have already tried to understand these processes and reactions as diagenesis can result in both positive and negative deviations from a simple trend of declining porosity and permeability with increasing depth [7, 8].

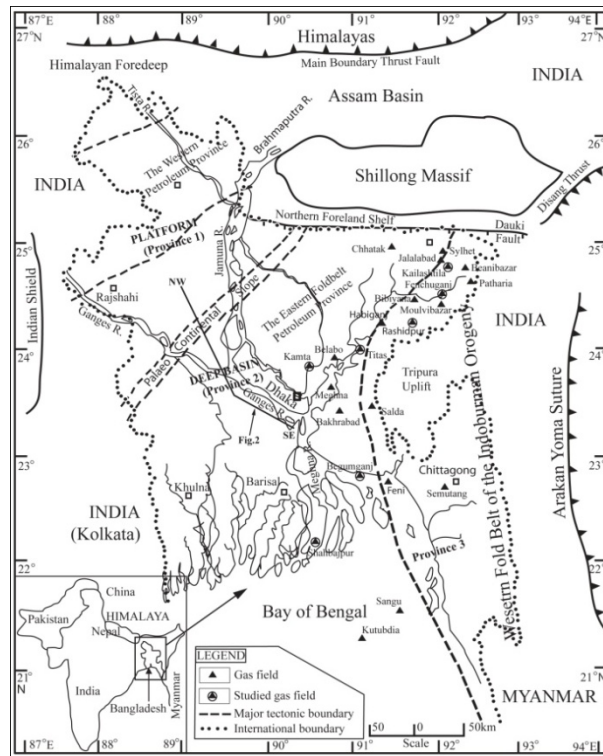
The reservoir rock of the Bengal Basin is the Surma Group of Tertiary sandstone (litharenites) comprising quartz (predominant, ~ 60-70%) with lesser amount of feldspars [9,10,11,12]. The sandstones are deposited at the continental margin under the quartzose sedimentary provenance to [12,13]. These sandstones are good quality reservoir rock with ~20% porosity [14, 15, 16] and permeability of 200-400 milli darcy [18]. A significant works [9,10,11,12,13,17, 18,19,20,21] have been conducted on petrography, geochemistry and isotopic analysis. However, there are limited publications on the sandstone diagenesis of Bengal Basin, although they are mostly based on a particular area of the basin [15,16,17]. Therefore the Surma Group sandstones deserve more research for additional clarification and understanding. In this paper, the detail description of the rock was carried out using the standard petrographic microscope and scanning electron microscope (SEM and FESEM) along with the XRD analysis. It provides valuable information on the texture, composition, microstructure and classification focusing on the diagenetic properties of the Surma Group sandstone reservoir of Bengal Basin, Bangladesh. Almost the whole area of the Deep Basin unit of the Bengal Basin, Bangladesh is covered by the current research (Fig.1). Emphasis is given to those diagenetic factors (e.g., cements and dissolution) that affected the reservoir porosity and permeability of Surma Group siliciclastic sandstone reservoir, Bangladesh.

## 2. Overview of the Study Area

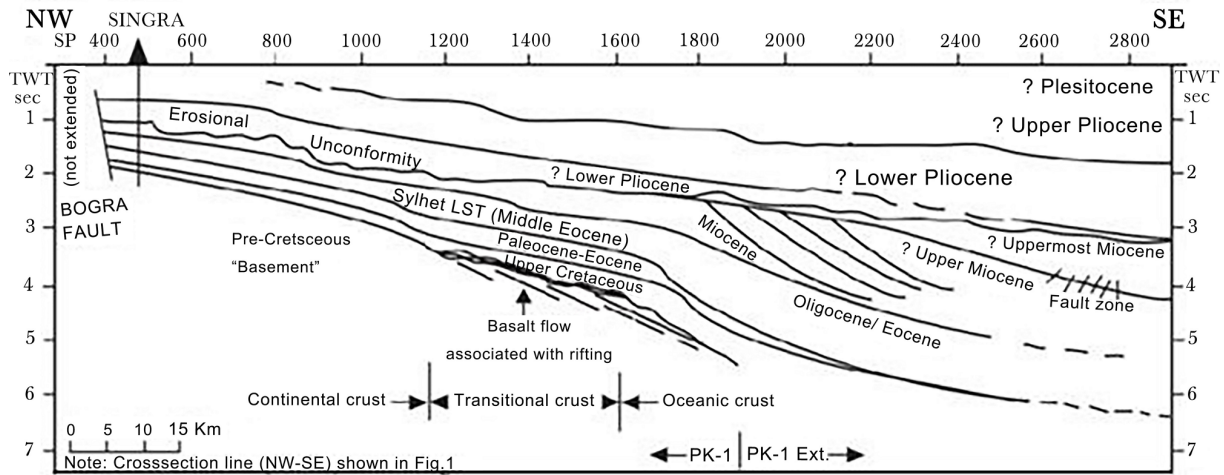
The Bengal Basin of Bangladesh comprises two major petroleum provinces, namely (a) The Western Petroleum Province and (b) The Eastern Foldbelt Petroleum Province (Fig.1). The Eastern Foldbelt Petroleum Province, is the only

known proved petroleum system. At present, all gas and condensate are producing from this petroleum system in Bangladesh [25]. The Eastern Foldbelt Petroleum System is a northeastern Oligocene-Miocene system which is characterized by anticlinal traps with channel cuts created within Middle- to Late Miocene reservoir sandstones capped by the upper marine shale, the top part of Surma Group[25]. In addition, there are lots of potential stratigraphic traps that are yet to be drilled. The hydrocarbon source of the system is most likely the Middle Oligocene Jenum shales and Miocene Surma Group shales. The estimated gas reserve Gas Initial In Place (GIIP) at 2P (proved+probable) is 26.84 Trillion Cubic

Feet (TCF) in Bangladesh [26]. Additional 41.60 TCF undiscovered gas resource (GIIP) has also been estimated by the Hydrocarbon Unit and National Petroleum Development (HCU-NPD) [16]. Recently Hossain [27] published the re-estimated recoverable oil reserve of 137 million barrels stock tank oil-initially-in-place (STOIIP). Crude oil production started in 1987 and stopped in 1997. Currently, out of 25 gas fields (including one minor oil field) so far discovered, only 20 are producing. The gas production started in 1959 and now the daily production of gas and condensate is approximately 2279 million cubic feet per day and 7076 barrels per day respectively as of 07 Feb 2014[28].



**Figure 1.** The Bengal Basin and its adjoining area show the studied gas fields whereby the major tectonic elements are also shown; The NW-SE geological cross-section shows in Fig.2 (modified after Farhaduzzaman et al. [21,22]; Khan [23]; Reimann [24]).



**Figure 2.** Geological cross-section of the Bengal Basin

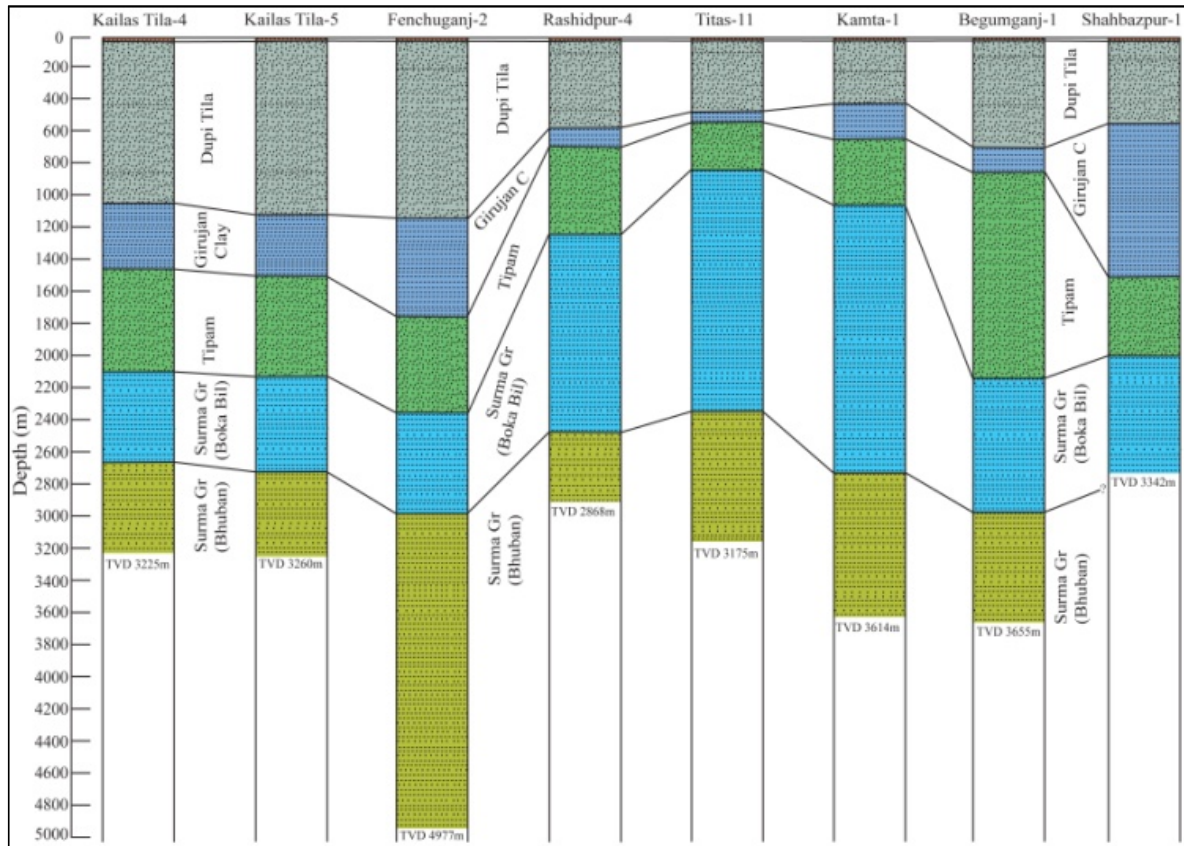


Figure 3. Well correlations among the studied well of the Bengal Basin

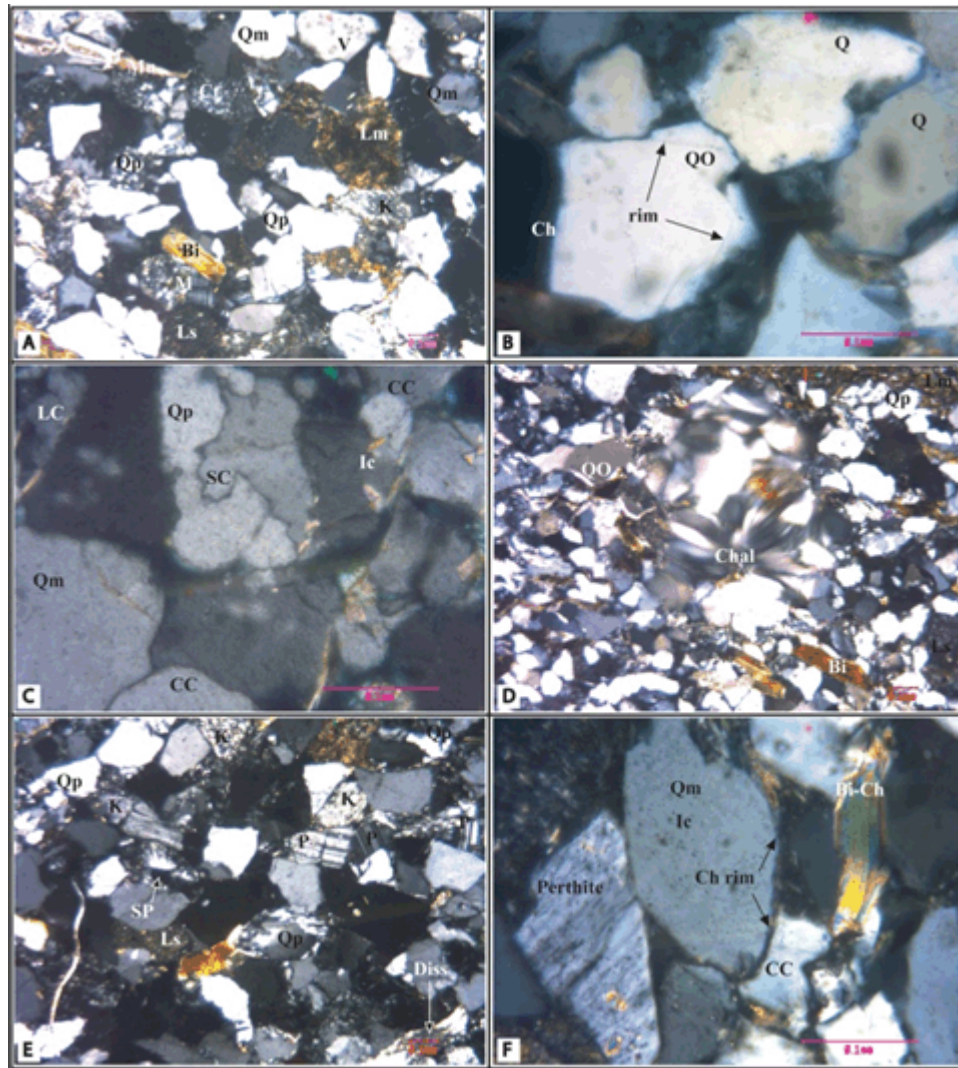
### 3. Materials and Methods

A total of thirty three reservoir sandstone core samples were collected from eight wells of seven gas fields, including Kailash Tila, Rashidpur, Fenchuganj, Titas, Kamta, Begumganj and Shahbazpur. The studied gas fields are located in the Deep Basin unit, the Bengal Basin, Bangladesh. The analyzed reservoir sandstone samples of the Surma Group, which is the most significant geological unit of the Bengal Basin (Figs.1,2,3) due to huge petroleum reserve. The investigated core samples were cleaned properly at the time of drilling and subsequently stored in the Core Laboratory of state-owned company BAPEX. Prior to this study, the core samples were collected from the storehouse of Bangladesh Petroleum Exploration and Production

Company (BAPEX). The collected samples were cleaned again (if required) at the University of Malaya (UM) laboratory before starting the experiment. The procedure specified by Adams et al. [29] was followed for thin section preparation. A slab of rock was thoroughly cleaned and vacuum impregnated with low viscosity epoxy to fill the pores and mechanically support the specimen material. After grinding (up to 3F grade) and washing, the rock sample was polished using cerium oxide (0.8 micron size). The smooth surface of the rock sample was glued to a microscope slide using the epoxy resin. These thin sections were analyzed with a Leica DMLP microscope for polarization techniques in transmitted and incident light.

**Table 1.** Petrographic results (%) of Surma Group sandstones, Bengal Basin. (Q= quartz, Qm= monocrystalline quartz, Qp= polycrystalline quartz, F= feldspar, K= potash feldspar, P= plagioclase feldspar, H= heavy minerals, C= detrital carbonate, L= labile lithic grains, Ls= sedimentary lithics, Lm= metamorphic lithics, Lv= volcanic lithics, Qc= quartz cement, Cc= carbonate cement, Clc= chlorite cement; Gr= grain, F= fine, VF= very fine, M= medium, TSP = thin section porosity).

Gas Filed	Well	Sample	Depth (m)	Gr size	Q			F		Mica		Chlo rite	H	L			C	Matrix	Cement			TSP (%)
					Qm	Qp	Chert	P	K	Musco vite	Bio tite			Ls	Lm	Lv			Qc	Cc	Clc	
Kamta	1	KM1ST1	2839	VF-F	45.5	22	5.8	1.8	4.5	3.4	3.3	0.7	0.2	0.2	6.5	0.2	0.1	2.2	0.5	2.5	0.6	22
Kamta	1	KM1ST2	2840	VF-F	38.8	24.5	4.6	1.2	3.6	5.5	3.2	1.2	0	0.4	8.2	0.1	0	1.8	2.2	3.1	1.6	15
Kamta	1	KM1ST3	2842	VF-F	39.9	15.8	3.4	1.7	3.1	4.5	3.8	0.2	0	0.8	8.5	0.4	0.7	5.8	4.1	4.9	2.4	17
Kamta	1	KM1ST4	2958	VF-M	42.4	11.8	10.2	5.9	6.2	3.3	3.1	0	0	0.5	6.7	0.2	1.6	4.2	2.5	0.8	0.6	18
Kamta	1	KM1ST5	2961	VF-M	50.2	9.5	5.8	3.6	5.2	6.1	5.4	1	0.4	0	4.1	0.2	2.1	5.2	0.3	0.9	0	21
Kamta	1	KM1ST6	2962	VF-M	47.5	16.8	4.9	3.1	5	3.6	2.3	0.8	0.1	0.2	5.8	0.2	4.1	3.1	0.5	0.8	1.2	20
Kamta	1	KM1ST7	3021	VF-F	58.7	19.2	8.6	0.9	1.6	1.1	0.4	0.5	0	0.2	6.1	0	0	2.2	0.2	0	0.3	18
Kamta	1	KM1ST8	3022	VF-F	56.2	17.9	11	1.7	2.1	2.1	0.3	1.3	0	0	4.2	0.3	0.2	0.5	0.7	1.5	0	22
Kamta	1	KM1ST9	3025	VF-M	47.9	11.8	8.8	4.9	6.1	1.9	1.5	0.5	0	0	5.2	0.2	0	6.1	1.2	2.8	1.1	17
Kamta	1	KM1ST10	3377	VF-M	54.8	6.6	11.7	2.1	4.9	0.8	0.4	0.2	0	1.2	4.3	0.1	5.9	5.7	0.7	0.4	0.2	23
Kamta	1	KM1ST11	3379	VF-M	49.9	9.7	7.8	0.4	2.2	5.6	4.6	0.9	0.3	3.1	6.2	0.7	0	0.4	2.3	5.2	0.7	18
Kamta	1	KM1ST12	3380	VF-M	44.7	11.9	6.6	2.7	4.4	8.7	6.2	0.5	0	0.3	3.4	0.1	0.4	8.3	0.6	1.1	0.1	12
Kailas Tila	4	KT4ST1	3117	F-M	40.7	18.8	8.3	4.1	6.2	3.9	1.1	0.8	0	0.4	5.6	0.4	0	5.6	0.9	3.2	0	11
Kailas Tila	4	KT4ST2	3118	F-M	45.4	13.6	9.1	2.5	2.7	4.1	0.2	0.5	0	2.4	8.2	0.8	1.3	6.1	1.7	0.9	0.5	19
Kailas Tila	4	KT4ST3	3119	F-M	54.2	7.9	4.3	0.8	3.1	7.2	3.1	1.5	0	0	5.7	0.5	0.8	4.9	3.1	1.5	1.4	15
Kailas Tila	4	KT4ST4	3121	VF-M	56.2	5.5	3.8	0.5	5.1	6.9	5	0.8	0.1	0.1	6.2	0	0	5.2	2.2	1.6	0.8	18
Kailas Tila	4	KT4ST5	3262	F-M	37.8	11.9	7.2	3.2	5.4	7.2	4	0.7	0.4	2.1	5.9	0.3	0	8.4	4.1	0.5	0.9	10
Kailas Tila	5	KT5ST6	2399	VF-M	33.7	19.2	4.3	1.9	4.1	5.7	4.9	0.5	0	1.4	10.1	0.1	0.5	6.2	2.5	4.8	0.1	21
Kailas Tila	5	KT5ST7	2402	F-M	41.4	6.3	11.1	0.8	2.1	6.8	3.7	1.1	0	0	8.3	0.2	4.2	5.8	1.6	6.6	0	22
Rashidpur	4	RP4ST8	2670	F-M	34.9	18.8	5.9	1.6	4.6	8.2	4.1	0.9	0	0.5	6.9	0	3.4	6.2	0.8	3.2	0	23
Rashidpur	4	RP4ST9	2683	F-M	51.5	4.7	6.4	2.8	4.8	4.5	4.9	0	0	0.2	10.4	0.6	1.5	4.4	2.4	0.6	0.3	17
Rashidpur	4	RP4ST10	2715	F-M	55.4	13.6	4.9	0.5	1.9	2.9	1.6	0.2	0	2.8	8.8	0.2	0	2.7	3.7	0.8	0	20
Rashidpur	4	RP4ST11	2752	F-M	39.7	11.9	8.2	4.2	5.1	6.7	0.5	0.8	0.4	0	7.2	0.4	0	5.1	4.5	5.3	0	19
Rashidpur	4	RP4ST12	2757	VF-M	35.8	12.6	7.8	5.1	3.2	4.9	5.1	1.2	0	0.6	5.7	0	0	6.2	1.6	9.8	0.4	18
Begumganj	1	BG1ST17	3571	VF-M	56.2	5.7	4.2	2.5	2.8	6	2.5	0.2	0.2	0	9.2	0.1	3.7	2.7	0.8	3.2	0	10
Begumganj	1	BG1ST18	3577	F-M	48.9	19.7	5.1	0.9	5.2	1.5	1.5	0	0	0	8.8	0	1.5	5.3	0.9	0.7	0	14
Begumganj	1	BG1ST19	3578	VF-F	37.3	20.1	6.8	3.8	5.9	1.8	0.6	0.2	0	0.4	5.2	0.2	6.2	6.9	1.2	3.2	0.2	17
Fenchuganj	2	FN2ST20	3265	VF-M	51.2	6.8	4.9	0.5	3.2	7.6	1.2	0.8	0.3	4.2	6.1	0.2	0	5.1	2.6	0	5.3	17
Fenchuganj	2	FN2ST21	3620	F-M	44.4	11.9	5.2	4.1	5.9	6.8	5.9	0.6	0	1.5	4.8	0	1.8	4.6	0.4	0.9	1.2	13
Shahbazpur	1	SB1ST19	3404	F-M	38.9	20.2	7.7	2.6	6.1	1.9	1.5	0	0.2	0.2	7.2	0.3	0	5.8	1.9	5.5	0	20
Shahbazpur	1	SB1ST22	3409	F-M	54.7	7.5	5.9	1.7	3.8	4.9	0.5	0.4	0	3.2	8.3	0.2	0.2	6.2	0.4	2	0.1	16
Titans	11	T11ST23	2699	F-M	51.4	10	7.1	4.1	4.8	1.5	0.4	0.2	0	0.4	10.5	0	0	4.5	3.2	1.7	0.2	19
Titans	11	T11ST27	2784	F-M	49.8	19.6	8.3	1.4	4.3	3.1	1.1	0.7	0.1	0	7.7	0.3	0.1	2.1	0.9	0	0.5	20
Range (8 wells in 7 fields)			2398-3620	VF-M	33.7-58.7	4.7-24.5	3.4-11.7	0.4-5.9	1.6-6.3	0.8-8.7	0.2-6.2	0.0-1.5	0-0.4	0.0-4.2	3.4-10.5	0.0-0.8	0.0-6.2	0.2-8.4	0.2-4.5	0.0-9.8	0.0-5.3	10-23



Note: Thin sections under crossed nicols.

**Figure 4.** Photomicrographs: (A) The most abundant both kinds of quartz (Qm and Qp) show grey interference color in association with chert (Ct) consisting of numerous microquartz grains; Several quartz grains (dark grey) show undulatory extinction and few show vacuoles (V); Microcline (M) shows cross-hatched twinning attached with brownish mica (Bi); Other commonly found sedimentary rock fragment (Ls) and metamorphic rock fragments (Lm); depth 3025m at Kamta well-1 (KM1ST9). (B) Rounded quartz grain shows overgrowth separated by its thin clay rim 'dust line'; Dark green chlorite cement (Ch) also observed between grains; depth 3379m at Kamta well-1 (KM1ST11). (C) Different kinds of grain contacts between quartz grains- long contact (LC) correspond relatively to the early stage of diagenesis whereby concavo-convex (CC) and suture contacts (SC) represent intermediate stage of diagenesis; Mica inclusions (Ic) also shown; depth 3578m at Begunganj well-1 (BG1ST19). (D) Fibrous variety of quartz, chalcedony (Chal), rarely found; Quartz overgrowth (QO) also showed; depth 2670m at Rashidpur well-4 (RP4ST8). (E) Plagioclase feldspar (P) identified by its albite twinning; Altered alkali feldspar (K) and its dissolution (Diss) also shown; Mold as secondary porosity (SP) also found; depth 2401.5m at Kailas Tila well-5 (KT5ST7). (F) Perthitic texture distinguished by the patchy intergrowth of albite into the orthoclase; Dark green chlorite (Ch) cement rimming the quartz grain; Brownish biotite is altering to greenish chlorite (Bi-Ch); depth 2699m at Titas well-11 (T11ST23) [31].

The PixeLINK digital camera attached to the Leica DMLP microscope chosen for capturing the images of the pores samples studied. The SWIFT (Model F) was used for point counting while the modal composition was achieved based on 600-point modal analysis per thin section. Few selected sandstone samples were analyzed with JEOL JSM-7600F field emission scanning electron microscope (FESM) operated at the Physics Department of the University of Malaya. Hence the secondary electron detector mode was used for capturing the images for the current analysis. Few images were taken from HITACHI 3000S scanning electron microscope (SEM) fitted with backscattered electron

detector operated at the University of Tsukuba, Japan. The high resolution examinations, including clay minerals, pore geometry, permeability, dissolution effect, cements, quartz overgrowth, texture and other related diagenetic imprints were investigated using SEM.

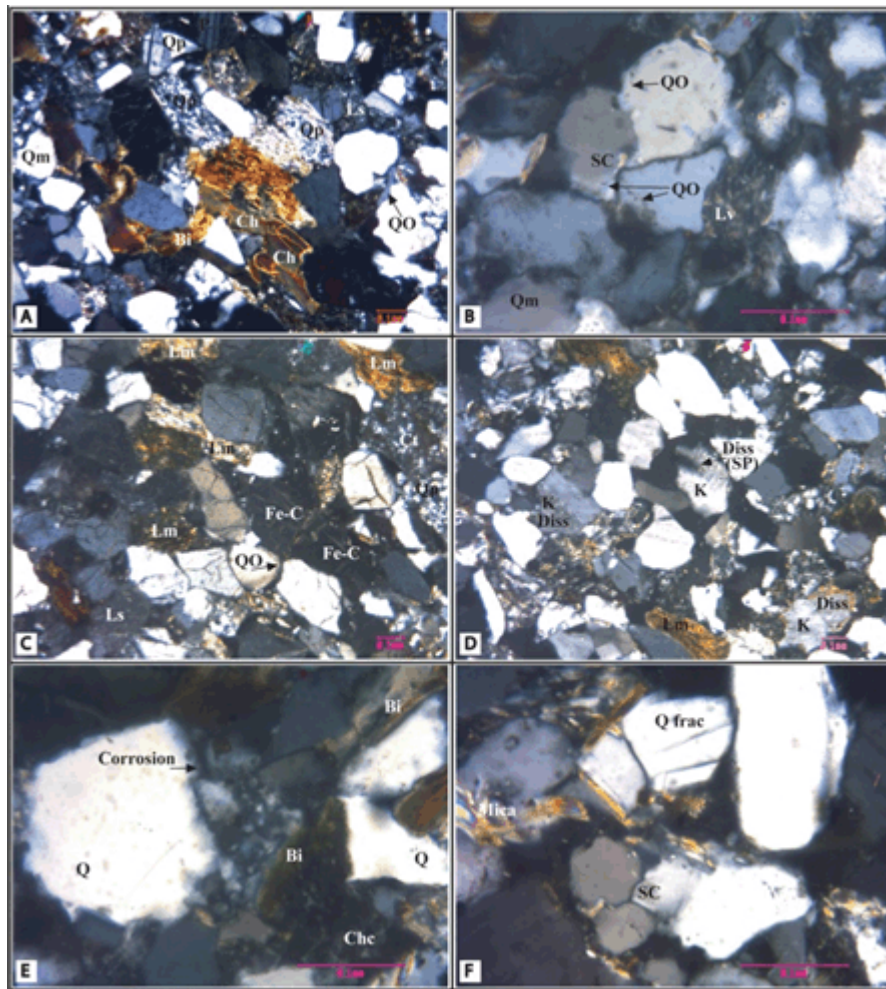
The clay minerals of the Tertiary sandstone and shale samples were studied using PANalytical Empyrean XRD equipped with PIXcel3D detection system placed at the Geology Department, UM. PANalytical's XRD software package (X'Pert HighScore) was used for identification and analysis of the clay minerals. Initially the samples were gently crushed into fine powder. The < 2  $\mu\text{m}$  fractions were

then separated by centrifugation and were subsequently placed into a test tube mixed with distilled water. The dispersing reagent ammonia solution was mixed with the sample in a test tube in order to prevent the flocculation. The test tube (with sample solution) was remained at room temperature for 24 hours so that the finer clay fractionation settles at the top of the suspension. The top clay fraction was then transferred by pipetting onto a small glass slide to prepare the XRD mounts. These mounts were then analyzed after air-drying and vapor saturation with ethylene glycol at 80 °C for one hour. The samples were also heated in two steps, including 350 °C and 550 °C in order to observe the changes in the XRD responses to different clay minerals present in the sandstones studied.

## 4. Results

### 4.1. Sandstone Texture and Sorting

The investigated Surma Group sandstones consist of very fine to medium grained. Subrounded to subangular grains are observed in the studied sandstone samples along with the rounded grains. The subangular nature is found especially among the smaller grains whereby the larger grains show better rounded nature. The feldspar grains are observed mostly as subangular to even angular nature, especially in subfeldspathic arenite types. Some other minerals were found moderately well sorted to well sorted showing its maturity in textural point of view [5].



Note: Thin sections under crossed nicols.

**Figure 5.** Photomicrographs: (A) The brownish coarse mica biotite (Bi) which is bended (compaction effect) because of diagenesis and altered (transformation) to greenish clay chlorite (Ch); Quartz overgrowth (QO) (cementation) is also shown; depth 3265m at Fenchuganj well-2 (FN2ST20). (B) Moderate stage diagenetic components, quartz overgrowth (QO) and suture contact (SC) associated with volcanic lithic grain (Lv); depth 3404m at Shahbazpur well-1 (SB1ST19). (C) Framework grain metamorphic rock fragment schist or mica schist (Lm), sedimentary rock fragment shale or siltstone (Ls) and chert (Ct) in association with diagenetic constituent quartz overgrowth (QO) and dark brownish blocky Fe-carbonate (Fe-C) cement; depth 2757m at Rashidpur well-4 (RP4ST12). (D) Potash feldspar dissolution (Diss) creates secondary porosity (SP) which enhanced the porosity and permeability; depth 3262m at Kailas Tila well-4 (KT4ST5). (E) Corrosion of quartz grain occurred due to digenesis; Brownish coarse mica biotite (Bi) that also altered to dark greenish chlorite (Ch); depth 3380m at Kamta well-1 (KM1ST12). (F) Quartz grains fractured because of the compaction effect at moderate stage diagenesis, which is also corresponded by suture grain contact (SC) and mica bending; depth 3577m at Begumganj well-1 (BG1ST18) [31].

### 4.2. Sandstone Composition

Particle composition may influence on the economic importance of sandstones as hydrocarbon (oil and gas) reservoirs. It has a considerable contribution in the course of diagenesis in sandstones and thus impact ultimately on the porosity and permeability of the particular sandstones [6]. The compositional description of the investigated Surma Group sandstones is mentioned below.

#### 4.2.1. Framework grains

The studied Surma Group sandstones are composed of a variety of major detrital minerals and rock fragments (labile lithic grains) together with some accessory minerals (Table 1). The framework grains of the analyzed sandstone samples are composed predominantly of quartz (76-91%) and nearly equal amounts of feldspar (3-14%) and rock fragments (5-16). Several other detrital minerals such as chlorite, muscovite, biotite, calcite and heavy minerals are also found in lesser amounts of the investigated samples.

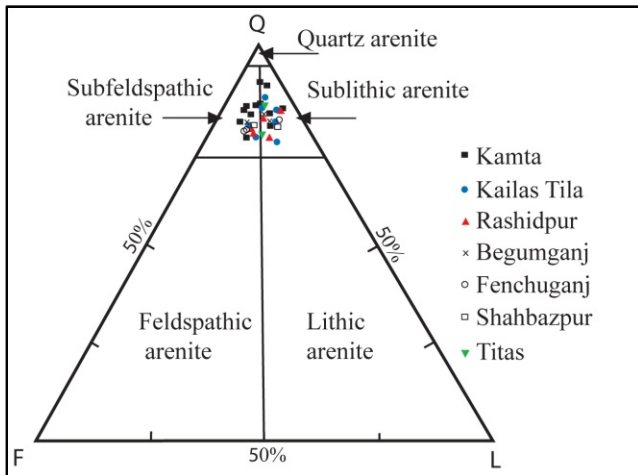


Figure 6. Triplot diagram for sandstone classification [111].

#### 4.2.2. Clay mineral authigenesis

Authigenic minerals are formed in place within sediments either shortly after deposition or during burial and diagenesis. These minerals can occur as cements or crystallize in pore space as new minerals that do not act as cements or form by replacement of original detrital grains. The most important clay cement identified in the analyzed Surma Group samples is chlorite and it ranged from trace to 5.3%. XRD results show the highest relative abundance of chlorite compared to other related clay minerals in the studied samples (Fig.7A). In thin section the authigenic chlorite cement forms thin and uniform green rims around the detrital grains (Fig.4F).

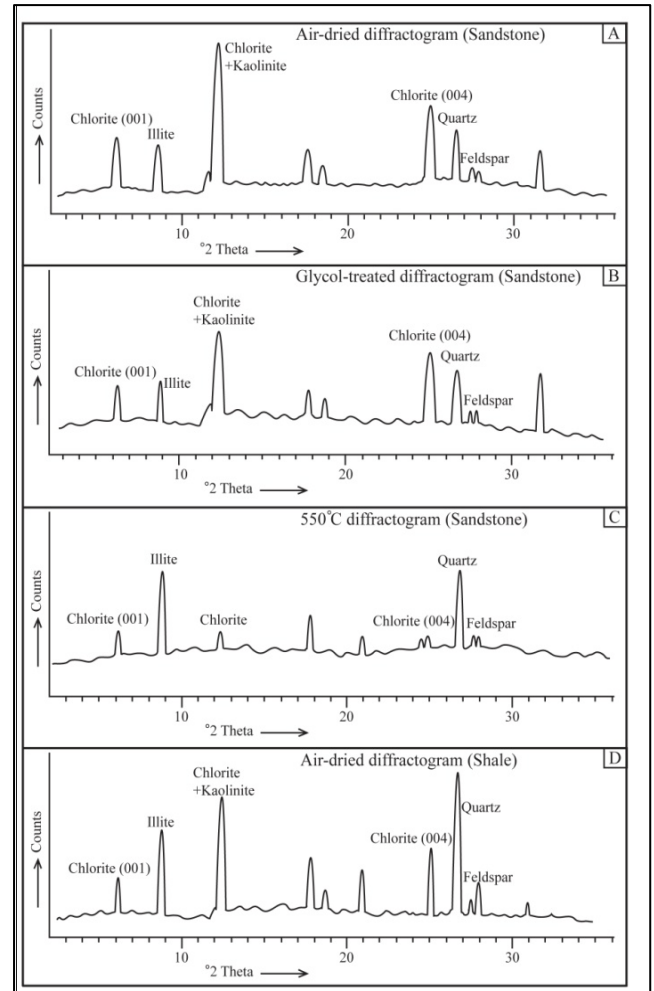
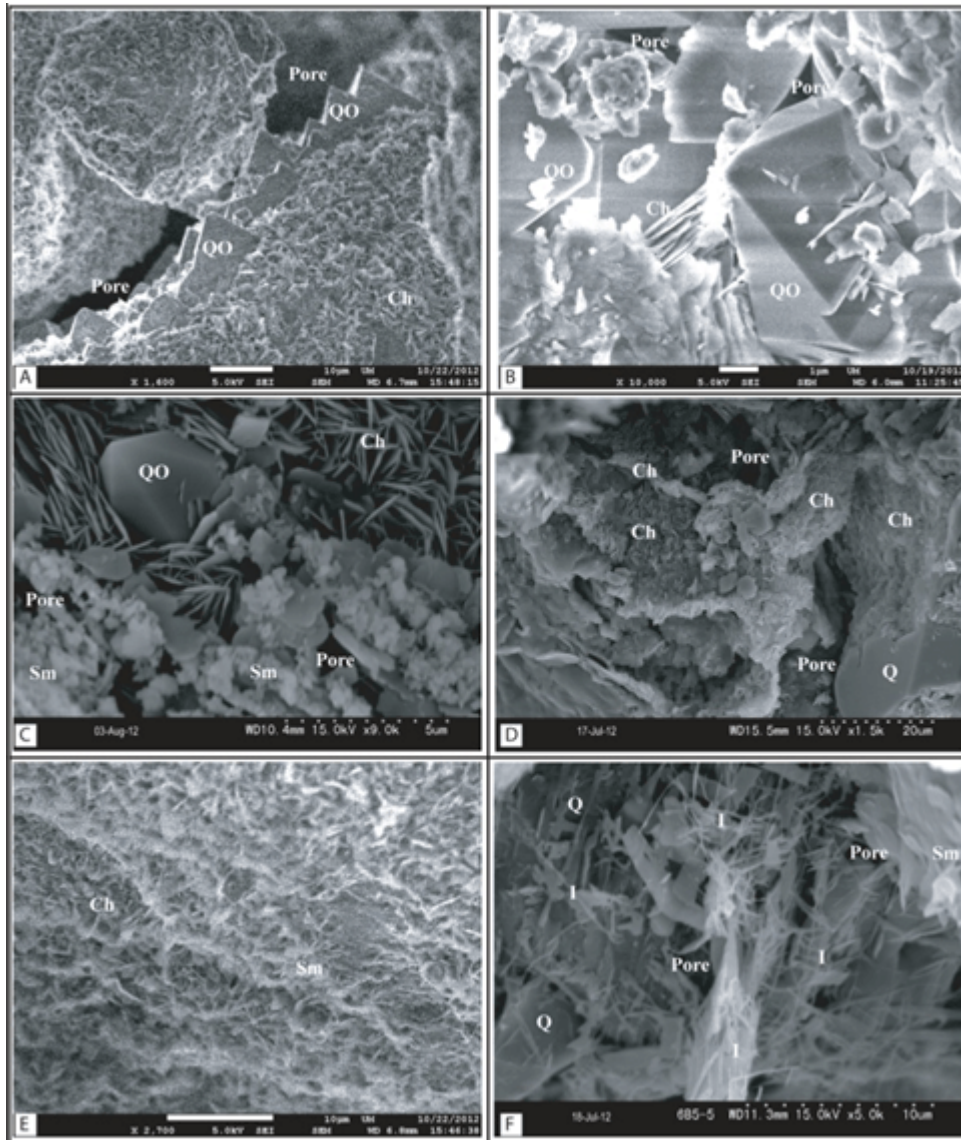


Figure 7. X-ray diffraction analysis of clay minerals identified in the analyzed reservoir sandstones and interlayered shales; (A) non-treated air-dried diffractogram of sandstone samples; (B) Glycol saturated diffractogram of sandstone samples; it shows relative high abundance of clay mineral chlorite compared to others; Both air-dried and glycol-treated diffractograms show the similar responses due to the absence of smectite swelling clay; (C) 550 °C heated diffractogram of sandstone sample and hence the kaolinite peak is disappeared remained a small peak for chlorite; (D) non-treated air-dried diffractogram of the interlayered shale sample is also shown which indicates the similar clay responses compared to those found in sandstone sample (A and B) and it suggests the similar genetic origin for the clay minerals found both in sandstones and shales [31,32].

Under SEM the chlorite is identified by the typical euhedral and pseudo-hexagonal crystals or platelets that are arranged in different forms and pattern such as rosette pattern, fan shaped, cluster pattern and face-to-face stacked pattern (Figs.8C, 8D). It is found either as individual crystal or composite crystal or mixed layer clays filling partly the pores in the studied sandstones (Fig.8E). Other important observed authigenic clay minerals include illite, smectite, kaolinite and mixed layer illite-smectite.



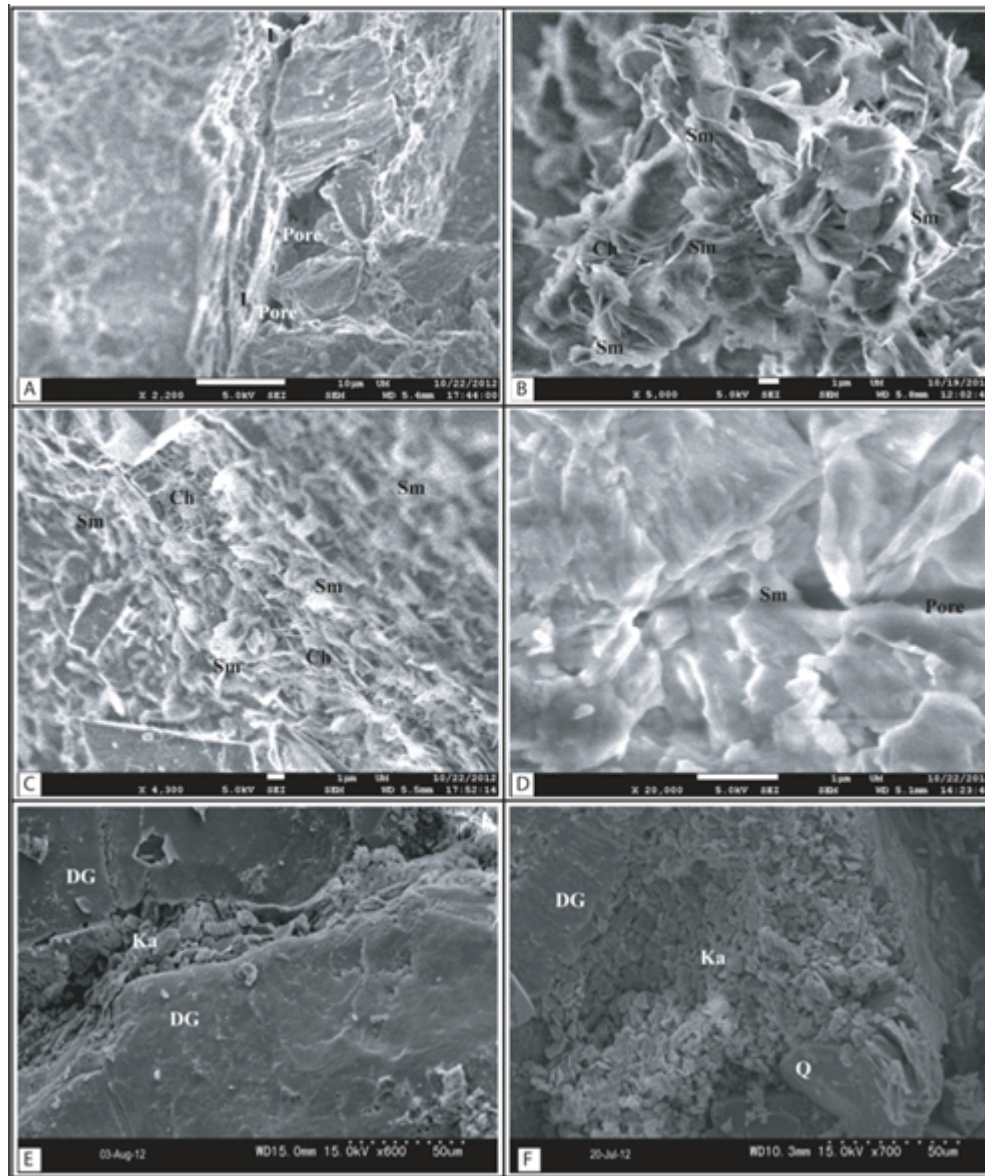
Note: Scanning electron micrographs of reservoir sandstones.

**Figure 8.** Photomicrographs: (A) Pore-lining authigenic quartz overgrowths (OO) show irregular boundaries partially filled the cavities; depth 2699m at Titas well-11 (T11ST23). (B) Pore-filling pyramidal shaped quartz overgrowths associated with chlorite (Ch) stack; depth 3409m at Shahbazpur well-1 (SB1ST22). (C) Clusters of pore-filling euhedral and pseudo-hexagonal chlorite crystals associated with quartz overgrowth and smectite (Sm); depth 3578m at Begumganj well-1 (BG1ST19). (D) Pore-filling and pore-bridging euhedral chlorite platelets which dramatically reduced the permeability; depth 3380m at Kamta well-1 (KM1ST12). (E) Frequently found mixed layer chlorite and webby smectite; depth 3620m at Fenchuganj well-2 (FN2ST21). (F) The filamentous illite (I) coating the detrital grain surfaces associated with crenulated morphology smectite; depth 3119.3m at Kailas Tila well-4 (KT4ST3); quartz overgrowths and smectite-chlorite were formed during intermediate stages of diagenesis [31].

In the studied sandstone samples, the illite is characterized by its filamentous or fibrous habit under SEM (Fig.8F). But it looks brownish in thin section which, in sometimes, made thin 'dust line' separating the detrital quartz grain from its authigenic growths. It is found as pore-lining as well as pore-bridging which could have acted as permeability barriers for fluid (especially hydrocarbons) movement. Sometimes the thin ribbons form a mat-like feature lining the pore coating the detrital grain surfaces (Fig.9A). Even the development of illite helps to preserve porosity by covering potential quartz nucleation sites, thus inhibiting quartz growth and cementation. Smectite is distinguished by the highly crenulated, thin, webby and flaky morphology partly

coating the detrital quartz grains (Fig.9B). In some cases the chlorite-smectite mixed with blocky kaolinite books is also observed in the samples under SEM (Fig.9C). The mixed layer clay of filamentous illite and webby smectite are fairly common in the samples analyzed. The pore-bridging smectite is rarely found in the studied samples (Fig.9D).

In thin section, dark brown patches of kaolinite partly filling the pores between detrital quartz and carbonate grains are identified in the samples. It occurs as face-to-face stacks of pseudo-hexagonal plates or books (typical morphology) partly filling the pore spaces under SEM (Figs.9E, 9F) [33]. The locally developed vermicular clay is also found in the samples.

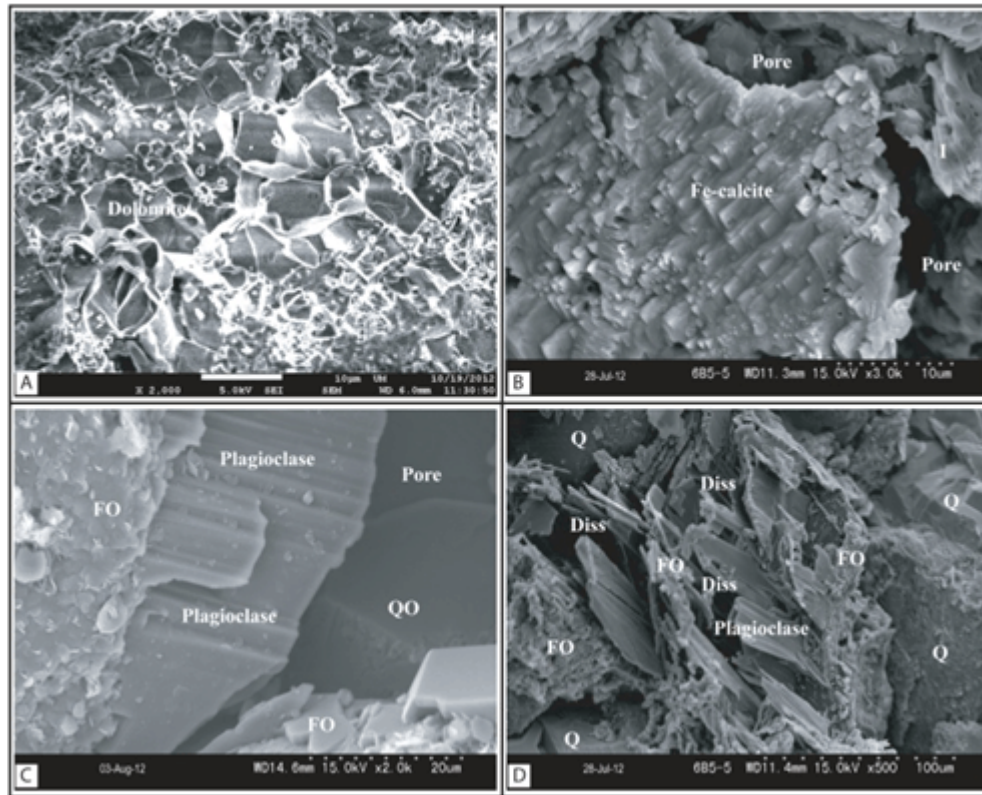


**Figure 9.** Photomicrographs: (A) The illite (I) thin ribbons formed a mat-like feature lining the pore coating the detrital grain surfaces; pore-bridging illite is also shown and it reduced the porosity-permeability; depth 3377m at Kamta well-1 (KM1ST10). (B) Typical webby and crenulated morphology smectite (Sm); depth 3404m at Shahbazpur well-1 (SB1ST19). (C) Mixed layer webby smectite and euhedral pseudo-hexagonal chlorite (Ch); depth 2752m at Rashidpur well- (RP4ST11). (D) Pore-bridging smectite that reduced the porosity and permeability; depth 3578m at Begumganj well-1 (BG1ST19). (E) and (F) Kaolinite books (face-to-face stacks of pseudo-hexagonal plates) partly occluded the pore throats; it is altered from detrital feldspars during early diagenetic stage; depth 2398.5m at Kailas Tila well-5 (KT5ST6) [31].

#### 4.2.3. Carbonate cements

Both precipitation and dissolution of carbonate minerals can take place during diagenesis until the chemical equilibrium is established. However the carbonate cements identified in the analyzed samples are both ferroan calcite (siderite) and nonferroan pure calcite together with some dolomite that ranged from trace to 9.8%. Dolomite is found in the samples as clusters of small rhombic crystals under SEM (Fig.10A). The Fe-calcite (and pure calcite) cement is recognized easily by pore filling mosaic of fine crystals (blocky habit) albeit single large crystal is not uncommon in

the analyzed thin sections (Fig.5C). In some cases the distribution is rather patchy and displacive locally although some uniform pore filling large area is also covered by calcite cement. This single crystal is even so large to surround the detrital grain producing the poikilotopic texture. The lenses or stringers of calcite cement are observed in the samples as well. The Fe-calcite is also identified by its blocky habits under SEM filling the pores (Fig.10B). The considerable presence of blocky carbonate cements significantly reduces the porosity of the reservoir sandstones analyzed.



Note: Scanning electron micrographs of reservoir sandstones.

**Figure 10.** Photomicrographs: (A) Rhombic morphology dolomite surrounded by other detrital grains; depth 2840m at Kamta well-1 (KM1ST2). (B) A mosaic of blocky habit Fe-calcites precipitated in pores associated with filamentous illite which occluded the pores; depth 2757m at Rashidpur well-4 (RP4ST12). (C) K-feldspar overgrowth (FO) developed on the original clean detrital plagioclases; depth 3136.5m at Kailas Tila well-4 (KT4ST1). (D) Rimmed K-feldspar authigenesis (FO) over the original plagioclase feldspars; Dissolution (Diss) resulted the secondary porosity during diagenesis; depth 2784m at Titas well-11 (T11ST27) [31].

#### 4.4.4. Feldspar authigenesis

Nonetheless the a few amount of feldspar overgrowth is also seen in the studied samples. The overgrowths are identified either as rimmed K-feldspar authigenesis over the original plagioclase detrital grains or as blocky euhedral to irregular faced K-feldspar over the original clean detrital plagioclases (Figs.10C, 10D) [34].

#### 4.2.5. Dissolution and replacement

The replacement involves dissolution of one mineral and essentially simultaneous precipitation of another mineral in its place. It occurs as a partial or complete dissolution-replacement event in the samples analyzed (Fig.5D). Several kinds of minerals are observed as dissolved and subsequently replaced either partially or fully in the analyzed siliciclastic sandstones. The most commonly is found as albitization whereby the albite plagioclase replaced the K-feldspar or calcic plagioclase and chloritization whereas the chlorite replaced the biotite (Fig.4F). The replacement clay matrix by carbonate minerals is also identified. Even the dissolution of detrital quartz as a result of corrosion is recognized in few cases under microscope (Fig.5E).

### 4.3. Compaction and grain packing

Compaction is the decrease of sediment volume and concomitant shrinking of porosity as a result of grain rearrangement and other processes caused by sediment load and tectonic forces. The compaction signatures while diagenesis of the investigated samples is recognized by the estimation of grain packing, ductile grains, primary porosity and grain fractures. The grain packing in turn involves with the presence of various grain contacts and grain deformation. The five different types of grain contacts defined by Taylor [35] such as floating, tangential (point-point), long (straight), concavo-convex (embayed) and sutured (serrated) are observed in the studied siliciclastic sandstone thin sections (Figs.4C, 5F). The floating and tangential contacts are less common than those of concavo-convex and suture ones. Nonetheless the bending of flexible grains such as mica flakes, deformation of ductile grains and the fractured grains is the visual evidence of the compaction (Fig.5F).

## 5. Discussion and Reservoir Implications

The cementation involves the reduction of reservoir porosity and permeability. It is already stated that the

development of silica cement (quartz overgrowth) while diagenesis is dealing with the silica source, timing and mechanisms. The multiple source of quartz is explained by many workers [6, 36]. Pressure solution of quartz grains at points of contact and various mineral reactions that release silica appeared to be the most reasonable source of silica cement (quartz overgrowth) in the analyzed siliciclastic sandstones at intermediate and deeper depths [6]. The major phase of quartz cementation (overgrowth) in the studied samples most likely occurred at temperatures of 50-75 °C at shallow burial depths as it was explained earlier by Blatt [37] and Dutton and Diggs [38]. The minor quartz cementation would also have continued at deeper depth and temperature of 200 °C. The observed straight and long contacts of individual quartz grains correspond to the early stage of diagenesis, whereas the concave-convex and suture contacts represent the comparatively later stage of diagenesis [39].

Clay mineral diagenesis is influenced by temperature and chemical reactions that affect the composition of the pore-water [40]. It is also associated with the time factor, for example, the chlorite and illite are statistically increased with time [41, 42]. This interpretation is supported by the comparative higher presence of chlorite and illite in the studied Surma Group sandstones (Figs.7A, 7B, 7C). In fact, a range of diagenetic stage is suggested in the analyzed sandstones. For example, the presence of kaolinite (feldspar transformation) corresponds to the early stage of diagenesis whereby the smectite-chlorite (clay transformation) represents the moderate stage of diagenesis (SEM Photomicrographs) [43, 44]. The identified kaolinite is possibly formed from the feldspar transformation since it is found mostly overlying the feldspar grains under SEM. The chlorite could be of a number of origins [8, 45]. But in the analyzed sandstone the most possible mechanism of chlorite precipitation was either the direct replacement from detrital biotite or precursor clay transformation (from smectite to chlorite) or direct precipitation from pore water [46]. The chlorite is frequently found in association with altered biotite. The similar clay mineral composition (chlorite-smectite-illite) is also found in the interlayered shale lamina which is considered as the major source of clay minerals in the studied sandstones (Figs.7A, 7D). The pore-lining chlorite (SEM) acts as the barrier of local development of quartz cement which preserved the porosity and permeability. The identified illite-smectite mixed layer clay would have generated at the comparatively intermediate diagenetic stage (mesogenesis) at temperature of 100-200 °C whereby the smectite was at 55-100 °C [43, 45]. This mixed diagenetic stage is also consistent with the interpretation based on silica cement (quartz overgrowth).

A range of diagenetic regime has been reflected by the presence of microcrystalline to coarse crystalline, patchy to blocky, isolated stringers of carbonate cements in the pores. The observed patchy distribution of the calcite cement reflects the initial partial removal of more evenly distributed cement at the early stage of diagenesis subsequently followed by complete carbonate precipitation during the

comparatively later stage of diagenesis and burial (Figs.5C, 10C, 10D). In cementation process the bicarbonate ions are supplied by organic matter reactions. A source of calcium must also be available to form calcite cements. Dolomite precipitation further requires a source of magnesium and iron source is essential for Fe-calcite (siderite and ankerite) cements. Many authors stated that a steady contribution of both cations and anions must be continued in pore water for carbonate cementation [6, 47, 48]. In the studied Tertiary sandstone samples, most possibly the mixing marine-nonmarine sources (with parallel oxidation and sulfate reduction) contributed for carbonate cementation at the early stage of diagenesis [49]. The dissolution of skeletal grains of the sandstones furnished the bicarbonate, calcium and magnesium ions in the pore water. The organic matter fermentation (methanogenesis) and sulfate reduction would also have contributed to these ions. The additional Fe, Ca and Mg were supplied from the dissolution of ferromagnesian minerals, calcium feldspar and smectite. This hypothesis is also applicable for organic rich shales interbedded with the studied sandstones and in fact, it is more appropriate for the succession consisting of alternating sandstone and shale like the present studied group [48]. They proposed that the temperature of 120-160 °C is suitable for Fe-carbonate cementation however if the sources are available. Using isotope study Rahman and McCann [17] supported this type of mixing source (nonmarine-marine) for carbonate cementation in the same succession. However Imam and Shaw [15] and Islam [16] emphasized on the skeletal dissolution for carbonate cements in the sandstones.

The decementation and destruction of framework grains increase the porosity as a result of the development of secondary porosity in the analyzed Surma Group sandstones (Figs.5D, 10D) [5, 6, 50]. The precipitated silica, quartz overgrowth as a result of pressure solution reduces the porosity. The replacement process, like dissolution, affected the porosity evolution of the studied sandstones during diagenesis. The principal causes include alteration of feldspar (albitization and kaolinization) and micas to clay minerals (chloritization) with concomitant increase in volume (Fig.4F). It is tended to plug the pore spaces which ultimately reduce its porosity and permeability.

Wolf and Chilingarian [51] stated that the compatibility of sandstone is a function of grain size, sorting, shape, orientation, composition, matrix content and cements. As a result of grain rearrangements the mechanical compaction has been considered as the dominant process at the initial stage of diagenesis up to 1.5 km in the studied siliciclastic sandstones. It is evidenced by the high presence of long and concavo-convex grain contacts (Fig.4F). Subsequently, in the deeper part at the later stage of diagenesis, it is dominated by chemical compaction while the additional mechanical compaction is indicated by mica bending and fractured quartz (Fig.5A) [52]. At the intermediate stage of diagenesis the chemical compaction is marked by the proof of dissolution and replacement (Fig.5D). The well sorted sandstone samples looks less compacted while diagenesis

followed by less porosity reduction than those with moderately sorted samples followed by greater porosity reduction [53]. The observed long and concavo-convex contacts would have developed either during diagenesis (as a result of deformation or solution) or deposition (depending on grain shapes). The suture contacts are thought to have generated as a result of dissolution (pressure solution) during moderate stage of diagenesis in the sandstones analyzed [35, 54]. A summary of diagenetic events and their respective comparative stages are shown in Fig.11.

### 5.1. Implications to Reservoir Porosity and Permeability

Porosity in sandstones is the aggregate total of all the openings or interstices in a rock framework and within grains. It could be either primary porosity that is created during deposition or secondary porosity that is formed during diagenesis [55]. However, in petroleum aspect the interconnected pores (effective porosity) are the most important element for reservoir evaluation. On the other hand permeability of any sandstone is its property to permits the passage of fluids (e.g., petroleum) through these interconnected pores. Both porosity and permeability are the controlling parameters for the movement of petroleum in the reservoir. The measured total thin section porosity of the studied Surma Group siliciclastic sandstones ranges from 10 to 23% with an average of 18% and it is mostly primary porosity developed during its deposition. The well connected pores (permeable) including intergranular porosity (dominant) and solution porosity are observed in many of the analyzed samples. However, some researchers [16, 17, 56] also measured the average porosity of the same group sandstone which were 20%, 19% and 18% respectively. The porosity values calculated for the current investigation is consistent with the earlier interpretations mentioned above. However in the present analysis, comparatively less sorted samples show lower porosity (e.g., RP4ST12 = 12%) than that found in well sorted samples (e.g., T11ST27= 20%). Similarly, relatively deeper samples show lower porosity value (e.g., BG1ST8= 14%) than that measured in shallower samples (e.g., T11ST27= 20%) although it is always not the true case in the analyzed samples. Hence the mechanical compaction (as a result of sediment load) is the controlling factor affecting the porosities of the samples with burial depth and time. As a result of grain rearrangement and reorientation significantly reduce the primary porosity in the sandstones. The overall porosity of the investigated Tertiary sandstone samples decreases with depth. At deeper depths, few samples show high porosity compared to relatively shallower samples. It occurs due to the development of secondary porosity (e.g. dissolution) during intermediate diagenetic stage. Nonetheless, at shallow depths, few samples show low porosity compared to deeper samples. The early diagenetic constituents (e.g., patchy carbonate cements) are considered for this porosity reduction at these shallow depths. The cementation has played an important role here to reduce the porosity and permeability in the sandstones

analyzed. The pore-filling blocky Fe-calcite cement, pore lining authigenic clays (chlorite-illite-smectite) and quartz overgrowths decrease the porosity and permeability. In very few cases the pore-bridging mixed layer clay (illite-smectite) plays the most significant role to deteriorate its reservoir quality through the reduction of permeability (SEM photomicrographs). It is also noted that the reservoir permeability is not affected significantly by the diagenetic constituents.

Diagenetic event	Early	Relative time	Late
Mechanical infiltration of clays	█		
Mechanical compaction	█	█	
Chlorite authogenesis		█	
Feldspar overgrowth			█
Patchy, poikilotopic Fe-carbonate dominantly Fe-calcite	█		
Blocky, mosaic Fe-carbonate cement			█
Dolomite precipitation			█
Dissolution and replacement			█
Quartz overgrowth			█
Authigenic illite			█
Authigenic smectite		█	
Authigenic kaolinite			█

**Figure 11.** A summary of diagenetic events and their respective comparative stages of the Surma Group Sand stone

The secondary porosity is observed in the studied sample that was developed because of the dissolution of carbonate cements, feldspars and other unstable constituents during diagenesis (Figs.5D, 10D). It increases the total porosity of the reservoir sandstone, although its amount is not too high compared to the primary porosity. This type of secondary porosity has been observed mostly in the moderate to deeper parts of the reservoir and it has improved the reservoir quality increasing the total porosity with depth. Nevertheless the dissolution followed by subsequent replacement again reduce (or unchanged) its porosity status. The quantitative measurement of permeability is not carried out in the present research. But previously it was measured for the same group sandstone by a few workers, for example, 100-400 millidarcy by Imam [56]. However, on the basis of the discussion above, the analyzed sandstone, can be ranked as good to excellent petroleum reservoir which is also supported by Islam [16], Rahman and McCann [17] and Imam and Hussain [18].

## 6. Conclusions

The principal framework grains identified in the analyzed siliciclastic Surma Group sandstones include quartz, feldspar and lithic grains. The studied sandstones are classified as sublithic arenite to subfeldspathic arenite. The observed most important diagenetic constituents include quartz cement (overgrowth), authigenic clays, carbonate cements and dissolution-replacement together with the compaction. The measured average thin section porosity is 18% although

it is mostly of primary origin. The primary porosity is controlled chiefly by textural maturity as a function of grain size, sorting and fabric during burial. A range of diagenetic stages early to intermediate has been estimated on the basis of several distinguishing properties such as compaction effects, alterations, cements and clay mineral authigenesis. The dissolution of unstable grains and cements increase the porosity (secondary) and thus enhance the permeability and reservoir quality. The precipitation of cements (quartz overgrowth, carbonate, clays) greatly influenced the porosity reduction. SEM reveals that the pore-bridging authigenic constituents (illite-smectite) tend to plug the pore throats, which reduced its permeability drastically albeit it is very rare. The pores and its passage throats are distributed more or less consistently in the samples analyzed. The studied Surma Group sandstone is characterized as good to excellent petroleum reservoir.

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## REFERENCES

- [1] Noh J, Lee I. Diagenetic pore fluid evolution in the Pohang Miocene sediments: oxygen isotopic evidence of septarian carbonate concretions and authigenic mineral phases. *Geosciences Journal* 1999; 3:141-149.
- [2] Zou C, Zhu R, Liu K, Su L, Bai B, Zhang X, Yuan X, Wang J. Tight gas sandstone reservoirs in China: characteristics and recognition criteria. *Journal of Petroleum Science and Engineering* 2012; 88-89:82-91.
- [3] Honarmand J, Amini A. Diagenetic processes and reservoir properties in the ooid grainstones of the Asmari Formation, Cheshmeh Khush Oil Field, SW Iran. *Journal of Petroleum Science and Engineering* 2012; 81:70-79.
- [4] Salem AM, Ketzer JM, Morad S, Rizk RR, Al-Aasm IS. Diagenesis and Reservoir-Quality Evolution of Incised-Valley Sandstones: Evidence from the Abu Madi Gas Reservoirs (Upper Miocene), the Nile Delta Basin, Egypt. *Journal of Sedimentary Research* 2005; 75:572-584.
- [5] Folk RL. *Petrology of sedimentary rocks*. Hemphill Pub Co, Texas 1980; 184p.
- [6] Boggs, SJ. *Petrology of Sedimentary Rocks*, 2nd ed. Cambridge Univ. Press, New York 2009; 600p.
- [7] Mansurbeg H, Morad S, Salem A, Marfil R, El-Ghali MAK, Nystuen JP, Caja MA, Amorosi A, Garcia D, Iglesia LA. Diagenesis and reservoir quality evolution of palaeocene deep-water, marine sandstones, the Shetland-Faroes Basin, British continental shelf. *Marine and Petroleum Geology* 2008; 25:514-543.
- [8] Worden RH, Morad S. *Clay Minerals in Sandstones: Controls on Formation, Distribution and Evolution*. In: Worden, R.H., Morad, S. (eds.), *Clay mineral cements in sandstones*. Blackwell Publication Ltd 2009:1-41.
- [9] Rahman M.J.J. and Faupl P.. (2003) The composition of the subsurface Neogene shales of the Surma group from the Sylhet Trough, Bengal Basin, Bangladesh. *Sedimentary Geology*, 155, 47-417.
- [10] Hossain H.M.Z., Roser B.P. and Kimura J-I. (2010) Petrography and whole-rock geochemistry of the Tertiary Sylhet succession, northeastern Bengal Basin, Bangladesh: Provenance and source area weathering. *Sedimentary Geology*, 228, 171-183.
- [11] Roy D.K. and Roser B.P. (2012) geochemistry of tertiary sequence in shahbajpur-1 well, hatia trough, bengal basin, bangladesh: provenance, source weathering and province affinity. *Journal of Life and Earth Sciences*, 7, 1-13.
- [12] Islam, M.S., Hosain, M., Jolly, Y.N., Hossain, M.S., Akter, S. and Kabir, J., 2015. Geochemical analysis of the reservoir rocks of Surma basin, Bangladesh, *Geosciences*, 5 (1), 1-7.
- [13] Islam, M.S., Alam, M. and Biswas, P.K., 2015. Petrography and Geochemical analysis of the reservoir rocks of Fenchugang Well # 2 Sylhet Bangladesh. *SUST Journal of Science and Technology*, Accepted (In press).
- [14] Mannan, M.A. (2002) Stratigraphic evolution and geochemistry of the Neogene Surma Group, Surma Basin, Sylhet, Bangladesh, PhD Dissertation, Department of Geology, University of Oulu.
- [15] Imam MB, Shaw HF. The diagenesis of Neogene clastic sediments from the Bengal Basin, Bangladesh. *Journal of Sedimentary Research* 1985; 55:665-671.
- [16] Islam MA. Diagenesis and reservoir quality of Bhuban sandstones (Neogene), Titas Gas Field, Bengal Basin, Bangladesh. *Journal Asian Earth Sciences* 2009; 35:89-100.
- [17] Rahman MJJ, McCann T. Diagenetic history of the Surma Group sandstones (Miocene) in the Surma Basin, Bangladesh. *Journal of Asian Earth Sciences* 2012; 45:65-78.
- [18] Imam MB, Hussain M. A review of hydrocarbon habitats in Bangladesh. *Journal of Petroleum Geology* 2002; 25:31-52.
- [19] Farhaduzzaman M, Wan Hasiah A, Islam MA. Petrographic characteristics and palaeoenvironment of the Permian coal resources of the Barapukuria and Dighipara Basins, Bangladesh. *Journal of Asian Earth Sciences* 2013;

- 64:272-287.
- [20] Farhaduzzaman M, Wan Hasiah A, Islam MA. Hydrocarbon source potential and depositional environment of the Surma Group shales of Bengal basin, Bangladesh. *Journal of the Geological Society of India* 2014; 83(4):433-446.
- [21] Islam MA. Petrography and provenance of subsurface Neogene sandstones of Bengal Basin, Bangladesh. *Journal of the Geological Society of India* 2010; 76:493-504.
- [22] Farhaduzzaman M, Wan Hasiah A, Islam MA. Depositional environment and hydrocarbon source potential of the Permian Gondwana coals from the Barapukuria Basin, Northwest Bangladesh. *International Journal of Coal Geology* 2012; 90-91:162-179.
- [23] Khan FH. *Geology of Bangladesh*. University Press Ltd., Dhaka 1991; 207p.
- [24] Reimann KU. *Geology of Bangladesh*. Berlin-Stuttgart, Germany, 1993; 160p.
- [25] Jamaluddin M, Nasrin N, Rahman M, Anwara H, Bygdevold J. Bangladesh petroleum potential and resource assessment 2001. HCU-NPD Dhaka 2001; 63p.
- [26] Shamsuddin AKM, Huq MM, Faruque MA, Chudhury Z, Akhteruzzaman M, Rahman M, Haque A, Talukder MW, Bygdevoll J, Rafdal J. Bangladesh gas reserve estimation 2003. HCU-NPD, Dhaka 2004; 254p.
- [27] Hossain MMA. Pump oil, outshine debate. *Fortnightly Energy and Power* 2012; 9:9-12.
- [28] Daily gas production of different gas fields in Bangladesh, <http://www.petrobangla.org.bd/daily%20gas%20product.pdf>, last visit, 07 Feb 2014.
- [29] Adams AE., Mackenzie WS, Guilford C. *Atlas of sedimentary rocks under the microscope*. English Language Book Society, Longman, UK, 1988; 104p.
- [30] Method SEM
- [31] Farhaduzzaman M. Characterization of selected petroleum source rocks and reservoir rocks of Bengal Basin (Bangladesh) based on geochemical, petrographical and petrophysical methods, PhD Thesis submitted to the Department of Geology. University of Malaya, Kuala Lumpur 2013; p.308.
- [32] Moore DM, Reynolds RCJ. *X-Ray Diffraction and the Identification and Analysis of Clay Minerals*. Oxford University Press, USA 1979; 400p.
- [33] Mozherovsky A, Terekhov E. Authigenic minerals in Early Cretaceous and Paleocene sedimentary rocks of the Yamato Ridge, East Sea. *Geosciences Journal* 1998; 2:148-159.
- [34] Yu KM, Boggs S, Seyedolali A, Ko J. Albitization of feldspars in sandstones from the Gohan (Permian) and Donggo (Permo-Triassic) formations, Gohan area, Kangwondo, Korea. *Geosciences Journal* 1997; 1:26-31.
- [35] Taylor JM. Pore-space reduction in sandstones. *AAPG Bulletin* 1950; 54:1748-1749.
- [36] Al-Gailani MB, Ala MA. Effects of epidiagenesis on reservoir characteristics of rocks beneath concealed unconformities in England and the Western Desert, Iraq. *Journal of Petroleum Geology* 1984; 7:189-212.
- [37] Blatt H. Diagenetic processes in sandstones. In: Scholle, P.A. and Schluger, P.R. (eds.), *Aspects of diagenesis*. Soc. Eco. Paleont. Mineral 1979; p.141-157.
- [38] Dutton SP, Diggs TN. History of quartz cementation in the Lower Cretaceous Travis Peak Formation, East Texas. *Journal of Sedimentary Petrology* 1990; 60:191-202.
- [39] Estupiñan J, Marfil R, Scherer M, Permanyer A. Reservoir sandstones of the Cretaceous Napo Formation U and T members in the Oriente Basin, Ecuador: links between diagenesis and sequence stratigraphy. *Journal of Petroleum Geology* 2010; 33:221-245.
- [40] Pittman ED. Recent advances in sandstone diagenesis. *Annual Review of Earth and Planetary Sciences* 1979; 7:39-62.
- [41] Blatt H, Middleton G, Murray R. *Origin of sedimentary rocks*. Prentice Hall Inc., Englewood Cliffs, New Jersey 1980; 782p.
- [42] Garrels, R.M. and Mackenzie, F.T., 1971, *Evolution of sedimentary rocks*. W.W. Norton, New York, 397p.
- [43] Bjorlykke K. Diagenetic reactions in sandstones. In: Parker, A. and Sellwood, B.W. (eds.), *Sediment diagenesis*. D. Reidel, The Netherlands 1983; p.169-213.
- [44] Lee M, Aronson JL, Savin SM. Timing and conditions of Permian Rotliegende sandstone diagenesis, Southern North Sea: K/Ar and oxygen isotopic data. *AAPG Bulletin* 1989; 73:195-215.
- [45] Al-Juboury AI, Al-Ghrear JS, Al-Rubaii MA. Petrography and diagenetic characteristics of the Upper Oligocene-Lower Miocene Ghar formation in SE Iraq. *Journal of Petroleum Geology* 2010; 33:67-85.
- [46] Zhang X, Lin CM, Cai YF, Qu CW, Chen ZY. Pore-lining chlorite cements in lacustrine-deltaic sandstones from the upper Triassic Yanchang Formation, Ordos Basin, China. *Journal of Petroleum Geology* 2012; 35:273-290.
- [47] Berner RA. *Early diagenesis*. Princeton University Press, Princeton 1980; 241p.
- [48] Morad S, Bergan M, Knarud R, Nystuen JP. Albitization of detrital plagioclase in Triassic reservoir sandstones from the Snorre Field, Norwegian North Sea. *Journal of Sedimentary Petrology* 1990; 60:411-425.
- [49] Curtis CD, Coleman ML. Controls on the precipitation of early diagenetic calcite, dolomite and siderite concretions in complex depositional sequences. In: Gautier DL (ed.), *Roles of organic matter in sediment diagenesis*. Soc. Eco. Paleont. Mineral 1986; P.23-33.
- [50] Reed JK, Gipson M, Neese DG. Hydrocarbon potential of sandstone reservoirs in the Neogene East Slovakian Basin Part I: a petrographic examination of lithology, porosity, and diagenesis. *Journal of Petroleum Geology* 1993; 16:89-108.
- [51] Wolf KH, Chlingaraian GV. Diagenesis of sandstones and compaction. In: Chlingaraian GV, Wolf KH (eds.), *Compaction of coarse grained sediments II*. Elsevier, Amsterdam 1976; P.69-444.
- [52] Schmidt V, McDonald DA. Secondary reservoir porosity in the course of sandstone diagenesis. *The AAPG Tulsa* 1979; 126p.
- [53] Houseknecht DW. Assessing the relative importance of compaction processes and cementation to reduction of

porosity in sandstones. AAPG Bulletin 1987; 71:633-642.

- [54] Hoholick JD, Metarko TA, Potter PE. Weighted contact packing - improved formula for grain packing of quartz arenites. Mountain Geologist 1982; 19:79-82.
- [55] Worden RH, Burley SD. Sandstone diagenesis: the evolution of sand to stone. In: Burley SD, Worden RH (eds.), Sandstone diagenesis: Recent and ancients. Blackwell Publishing Ltd., UK 2003; P.1-46.
- [56] Imam, M.B., 2013. Energy Resources of Bangladesh, 2nd Edition (UGC, Bangladesh).