SANDSTONE DIAGENESIS OF THE NEOGENE SURMA GROUP FROM THE SHAHBAZPUR GAS FIELD, SOUTHERN BENGAL BASIN, BANGLADESH

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KEYWORDS

Shahbazpur well
Surma Group
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ABSTRACT

This study examines the various diagenetic controls of the Neogene Surma Group reservoir sandstones encountered in the Shahbazpur-1 petroleum exploration well from the southern part of the Bengal Basin, Bangladesh. The principal diagenetic minerals in the Surma Group sandstones are quartz overgrowths, Fe-carbonates (mainly Fe-calcite) and authigenic clay minerals dominantly chlorite, illite-smectite and mnor kaolinite. Compaction played a more extensive role than cementation in destroying primary porosity. Cementation was important in drastically reducing porosity and permeability in sandstones at depths of 1796.5, 2015.5 and 3019 m and is typically poikilotopic, pore-filling blocky Fe-calcite cement. Illite-smectite and chlorite occur as pore-filling and pore-lining authigenic phases. Sandstones having good porosities (20% to 30%) and high permeabilities (20 mD to 415 mD) are well sorted, and tend to be relatively coarse grained and more loosely packed with better rounded grains. They are typically found at depths ranging from ~2290 m to ~3411 m. These high quality reservoir rocks are, however, not uniformly distributed resulting in compartmentalization of the reservoir-quality units, which are interbedded with sandstone layers showing low to moderate porosity (1 to <20%) and low permeability (0.6 to 4.5 mD). These sandstones are typically poorly sorted, strongly compacted and contain significant higher proportions of cements.

Diese Arbeit untersucht die unterschiedliche diagenetische Kontrolle von Reservoirqualitäten der Sandsteine der neogenen Surma-Gruppe aus der Shahbazpur-1 Explorationsbohrung im südlichen Teil des Bengal Beckens in Bangladesh. Die prinzipiellen diagenetischen Minerale in den Sandsteinen der Surma-Gruppe sind Quarz-Anwachssäume, eisenführende Karbonate (vor allem Fe-Calcit) und authigene Tonminerale, vor allem Chlorit, Illit-Smectit und Kaolinit. Kompaktion spielte die Hauptrolle in der Reduktion der primären Porositäten. Zementation reduzierte Sandstein-Porositäten und -Permeabilitäten drastisch in Tiefen von 1796,5, 2015,5 und 3019 m, typischerweise als poikolotopischer, porenfüllender Fe-Calcit-Blockzement ausgebildet. Illit-Smectit und Chlorit treten als porenfüllende und porenauskleidende authigene Phasen auf. Sandsteine mit guten Porositäten (20 bis 30%) und hohen Permeabilitäten (20 md bis 415 mD) sind gut sortiert und vor allem grobkörnig, nicht dicht gepackt mit besser gerundeten Körner. Sie finden sich typischerweise in Tiefen von ~2290 m bis ~3411 m. Diese hochqualitativen Reservoirgesteine sind allerdings nicht durchgehend ausgebildet, die Reservoirqualitäten sind durch Kompartimentierungen eingeschränkt. Diese Sandsteinzwischenlagen zeigen geringe bis mäßige Porositäten (1 bis <20%) und geringe Permeabilitäten (0.6 bis 4.5 mD). Diese Sandsteine sind typischerweise schlecht sortiert, stark kompaktiert und beinhalten signifikant höhere Anteile an Zementphasen.

1. INTRODUCTION

The Bengal Basin lies in the north-eastern part of the Indian subcontinent and contains a ±22 km thick sedimentary succession of the Cretaceous to Holocene (Fig. 1). The Neogene deposits attain a thickness of > 6 km within the basin of which the Surma Group contains the most important sandstone reservoirs. Most of the hydrocarbons discovered so far in the Bengal Basin are located in reservoir sands of this group (Table 1). Of 22 discovered gas fields in Bangladesh, three are located in the southern petroleum province of which the Shahbazpur gas field is one of the three commercial gas fields discovered in this province (Fig. 1).

Reservoir quality is one of the key controls in petroleum exploration and, therefore, it is important to have a detailed understanding of the various diagenetic controls and their effects. Several workers (e.g. Lietz and Kabir, 1982; Hiller and Elahi, 1984; Khan et al., 1988; Johnson and Alam, 1991; Shamsuddin et al., 2001; Rahman et al., 2009) have made significant contributions towards understanding of the regional geology, sedimentology, tectonic evolution and petroleum prospectivity of the Surma Basin in Bangladesh, especially for the north eastern petroleum province. Only a few publications (Imam and Shaw, 1987; Islam, 2009) exist on the diagenetic history and its effects on reservoir quality of the Surma Group sandstones from the central part of the Bengal Basin. However, there is yet no published work on the diagenetic history of this important reservoir sandstone in the southern delta and offshore areas, the southern petroleum province in the Bengal Basin.

The aim of this study is to present a detailed diagenetic analysis of the sandstones in the southern petroleum province of the Bengal Basin in order to narrow the gap between our understanding of diagenesis and its effects on the reservoir properties. In particular, we examined sandstones from the Neogene clastic succession encountered in the Shahbazpur-1 well (Shahbazpur anticlinal structure) in the southern Bengal Basin (Fig. 1). Sandstones (core material) ranging from depths 997 to 3411 m including Surma Group reservoir sandstones from ~2016 m to 3411 m were used in this study (Fig. 2). This study is based on earlier works (Imam and Shaw, 1987; Islam, 2009) by including petrographic data as well as reports on the diagenetic controls of the Neogene Surma Group sandstones from the southern petroleum province in the Bengal Basin.

2. Geological setting

The Bengal Basin lies on the eastern side of the Indian subcontinent between the Shillong Plateau to the north and the Indo-Burman Ranges to the east and occupies most of Bangladesh and West Bengal (India) as well as part of the Bay of Bengal (Fig. 1). The Dauki Fault system represents the contact between the Surma Basin and the Shillong Plateau.The basin had its origin during the collision of India with Eurasia and Burma, building the extensive Himalayan and Indo-Burman Ranges and, thereby, loading the lithosphere to form flanking sedimentary basins (Uddin and Lundberg, 1998). The basin-fill of the onshore part of the basin has traditionally been divided into platform or shelf, slope or 'hinge', and basinal facies (Fig. 1) (Evans, 1964).

The Shahbazpur-1 well in the Hatia Trough is located in the eastern folded belt of the Bengal Basin (Fig. 1) and has been drilled by BAPEX (Bangladesh Petroleum Exploration Company) to a depth of 3750 m.

Tectonically, the area is gently deformed; existing structures are mainly large and gentle NNW-SSE trending anticlinal forms. The estimated recoverable reserve is < 0.5 TCF. The gases are dry and composed mainly of methane. The age of the reservoirs extends from Late Miocene to Early Pliocene.

The sediments of the Neogene Surma Group, with a thickness of 4 to 5 km, are subdivided into the Bhuban and Boka Bil formations and were deposited under marine-deltaic to fluvial-deltaic conditions. The lower Bhuban Formation consists of fine grained, well indurated, massive to thick-bedded

Age	Group/Formation (Fm.)	Lithology	Environment of deposition
Pliocene	Tipam Group	Massive to cross-bedded sandstone; Minor shale and clay	Fluvial
Miocene	Surma Group: Boka Bil Fm.	Alternating siltstone and shale with sandstone	
	Surma Group: Bhuban Fm.	Alteration of siltstone with shale and sandstone; Silty and sandy shale; Sandstone and sandy shale	Deltaic-shallow marine
		Unconformity	
Oligocene	Barail Group	Sandstone, shale, coal	Deltaic-shallow marine
Eocene	Jaintia Group	Limestone, sandstone, shale	Open marine

Table 1: Overview on the Cenozoic succession of the Bengal Basin, Bangladesh (modified after Imam and Shaw, 1987).

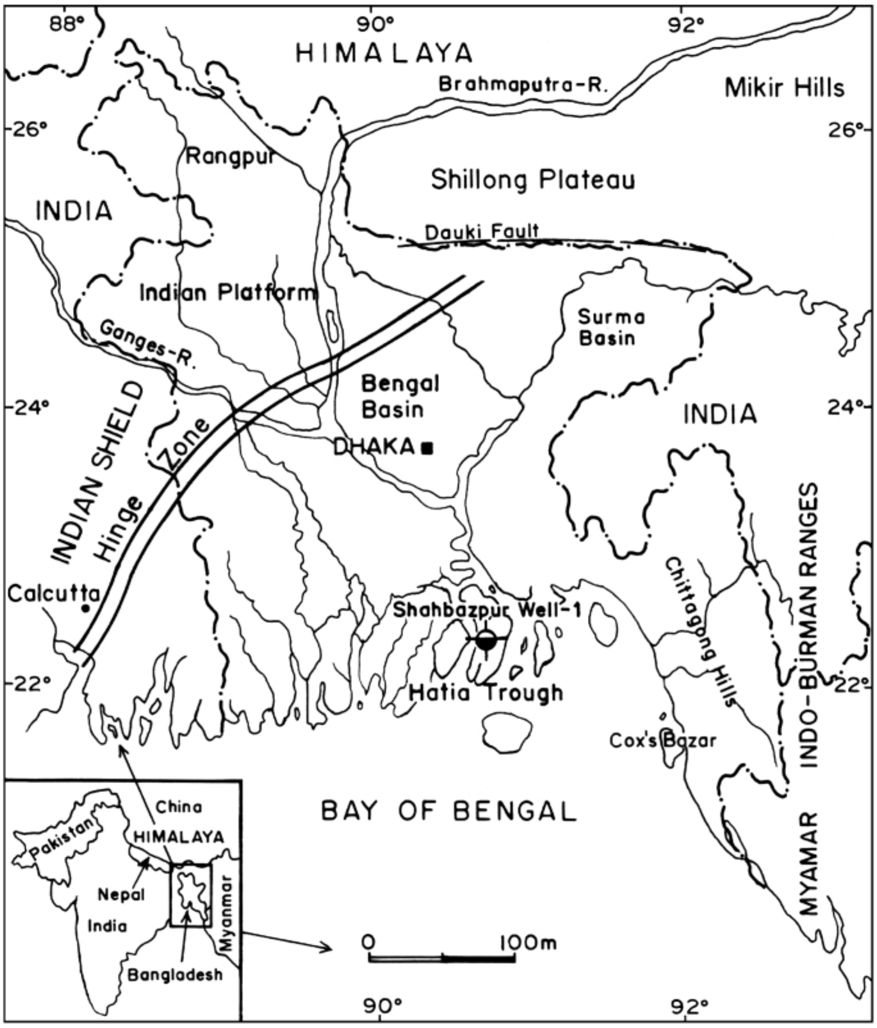

Figure 1: Major tectonic elements of the Bengal Basin (Alam et al., 2003); the map also shows the location of the Shahbazpur well-1.

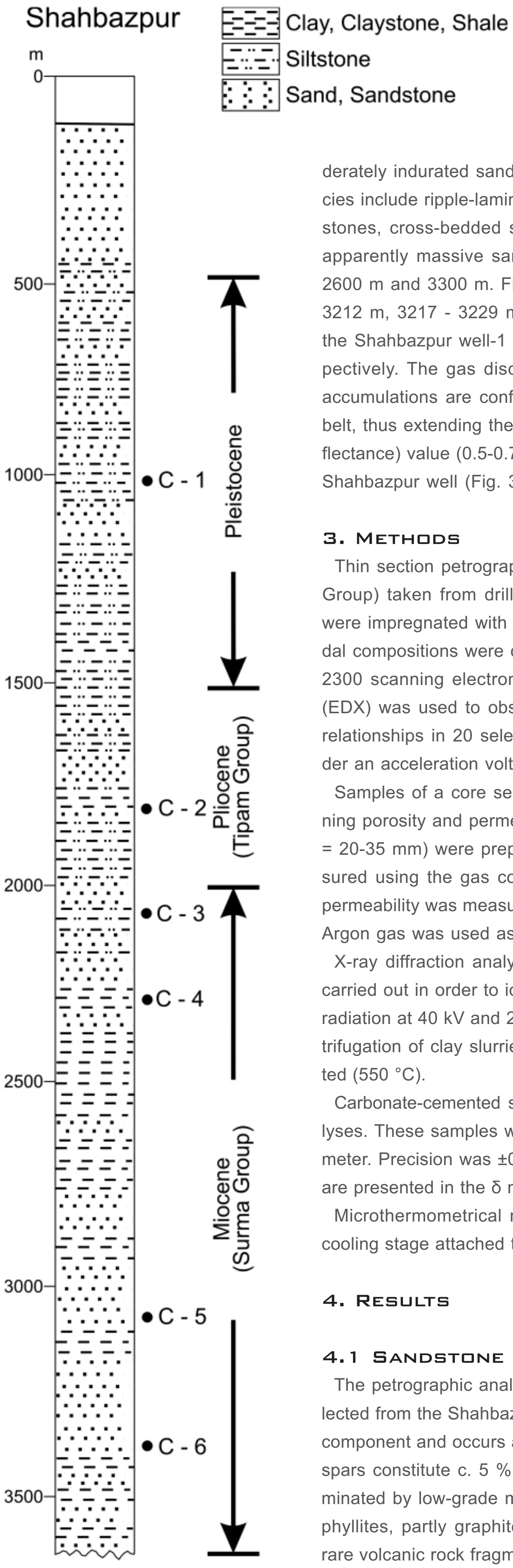

Figure 2: Lithology of the Neogene succession in the Shahbazpur well-1 (C-1: core 1…..C-6: core 6).

sandstones, shales, claystones and siltstones. The upper Boka Bil Formation is composed of fine- to medium- grained moderately indurated sandstones with shales, silty shales and siltstones. Characteristic lithofacies include ripple-laminated sandstones, partly with flaser bedding, parallel-laminated sandstones, cross-bedded sandstones, cross-bedded sandstones with lags of mud clasts and apparently massive sandstones. The gas-bearing sandstones were encountered between 2600 m and 3300 m. Five gas zones in total have been recorded at 2578 - 2590 m, 3154 - 3212 m, 3217 - 3229 m, 3332 - 3377 m and 3379 - 3433 m. The borehole temperature in the Shahbazpur well-1 at 1000 and 3400 m depth was measured as 48°C and 130°C, respectively. The gas discovery within the Shahbazpur structure indicates that hydrocarbon accumulations are confined in the gently-folded structure of the outer margin of the folded belt, thus extending the hydrocarbon potentiality to the west of the area. The R_o (vitrinite reflectance) value (0.5-0.7%) suggests early maturation of the hydrocarbon encountered in the Shahbazpur well (Fig. 3).

3. Methods

Thin section petrographic analysis was performed on a total of 24 samples (21 for Surma Group) taken from drill cores of different depths. Samples selected for thin-section study were impregnated with blue epoxy under vacuum in order to highlight the porosity. The modal compositions were determined by counting 600 points per thin section. A Cam Scan MV 2300 scanning electron microscope (SEM) fitted with an energy dispersive X-ray spectra (EDX) was used to observe authigenic minerals, cements, pore geometry and paragenetic relationships in 20 selected sandstones. The samples were gold coated and examined under an acceleration voltage of 20 kV and a beam current of 33 microA.

Samples of a core segment from depths of c. 1005 to 3407 m were selected for determining porosity and permeability. Three directional cylindrical plugs (diameter = 30 mm, length = 20-35 mm) were prepared and the porosity and matrix density of the samples were measured using the gas compression/expansion method (cf. Tiab and Donaldson, 2004). The permeability was measured in a gas-autoclave using the modified pressure transient method. Argon gas was used as the permeating medium.

X-ray diffraction analysis of shale layers within the sandstones of the Surma Group was carried out in order to identify clay minerals using a BRUKER-AXS D8 ADVANCE with Cukα radiation at 40 kV and 20 mA. Clay mineral fractions of less than 2µm were obtained by centrifugation of clay slurries. The samples were run as air-dried, ethylene glycolated and heated (550 °C).

Carbonate-cemented sandstone samples were selected for carbon and oxygen isotope analyses. These samples were analyzed using a Finnigan MAT 251 Isotope ratio mass spectrometer. Precision was ±0.08 per mil for O and ± 0.06 for C. Oxygen and carbon isotope data are presented in the δ notation relative to the Vienna Pee Dee Belemnite (VPDB) standards.

Microthermometrical measurements were performed with a LINKAM THMS 600 heating cooling stage attached to a Leitz microscope at RWTH Aachen University.

4. Results

4.1 Sandstone composition

The petrographic analyses of the detrital constituents of the Surma Group sandstones collected from the Shahbazpur-1 are presented in Table 2. Quartz is the predominant framework component and occurs as monocrystalline (av. 31%) and polycrystalline grains (~13%). Feldspars constitute c. 5 % of the total detrital grains. Unstable lithic fragments (~11%) are dominated by low-grade metamorphic (mainly fine-grained mica schist, quartz-mica schist and phyllites, partly graphite-bearing) and sedimentary (mainly chert, shale) rocks, as well as rare volcanic rock fragments. Phyllosilicates constitute c. 6% with biotite predominating (4%).

The biotites commonly show varying degrees of alteration to chlorite. Matrix content ranges from 2% to 11% (average 5%). Calcite and dolomites are occasionally found as detrital grains. Iron-bearing carbonates (mainly Fe-calcite, few Fe-dolomites) are mainly found as cements.

The Surma Group sandstones have subarkosic to sublithic composition (Fig. 4) with abundant low-grade metamorphic and sedimentary lithics and rare volcanic fragments.

4.2 Diagenetic minerals

The most common diagenetic minerals in the Surma Group sandstones are ferroan carbonates, quartz, chlorite, illite-smectite and kaolinite (Table 3). The diagenetic constituents are described below in order of their abundance.

4.2.1 Carbonate cements

Diagenetic carbonates in the sandstones occur in varying amounts (trace to 34%; av. 4%) as microcrystalline to coarse crystalline poikilotopic, pore-filling blocky or mosaic aggregates (Fig. 5A), which occur both as partial and/or total replacement of detrital grains, as well as isolated pore- filling cements; suggesting precipitation in various diagenetic regimes. Fe-calcite has been found partly altered to Fe-dolomite. The poikilotopic, pore-filling blocky Fe-calcite cements were observed at depths of 1796.5, 2015.5 and 3019 m in the Shahbazpur structure and appear to have a syncompactional to mesogenetic origin. In the case of pervasive carbonate cements, the pores have been drastically reduced.

The isotopic composition of the carbonate-cement revealed a narrow range of $\delta^{18}O$ values (-10.3‰ to -13.4‰) and a wide range of $\delta^{13}C$ values (-1.4‰ to -11.1‰) (Table 4). In comparison to the north-eastern Bengal Basin (Surma Basin), the carbon isotope results are less negative but the oxygen isotopes show no significant variation (Fig. 6).

4.2.2 Silica cements

Quartz cements occur as euhedral, syntaxial overgrowths around detrital quartz grains (Fig. 5B, C, D; Fig. 7A, D) ranging from trace to 7.3 % with an av. of 2.7 %. Quartz overgrowths are common near sites of intergranular crystals. In some cases, the boundaries between the detrital quartz and the quartz overgrowths are marked by clay coatings and dust lines. Quartz overgrowths often enclosed chlorites interlocking pore throats (Fig. 7D). Quartz overgrowths are also common where the chlorite cements are rare or present in small amounts. In some cases, quartz overgrowth was inhibited by the presence of chlorite rims as recorded by the presence of small/incomplete quartz overgrowths (Fig. 7D). The presence of quartz cement as a syntaxial overgrowth near sites of intergranular dissolution and around tightly packed detrital quartz grains indicates a mesogenetic origin (e.g. McBride, 1989; Worden and Morad, 2000). SEM observations revealed that in some cases, microquartz coats occur (Fig. 7E).

Most of the overgrowths are inclusion free. At some places two phases (LV) fluid inclusions can be seen, which are main-

	Mean	Range
Monocrystalline quartz	31 %	22-38 %
Polycrystalline quartz	13 %	4-19 %
Chert	7 %	2-11%
K-feldspar	3 %	1-6 %
Plagioclase	2 %	1-6 %
Unstable lithic grains	4 %	Trace -10 %
Phyllosilicates (mainly biotite and muscovite)	6 %	1-20 %
Matrix	5 %	2-10 %

Table 2: Average composition of the detrital constituents of the Neogene Surma Group sandstones in vol-% from the Shahbazpur well-1 (n=21).

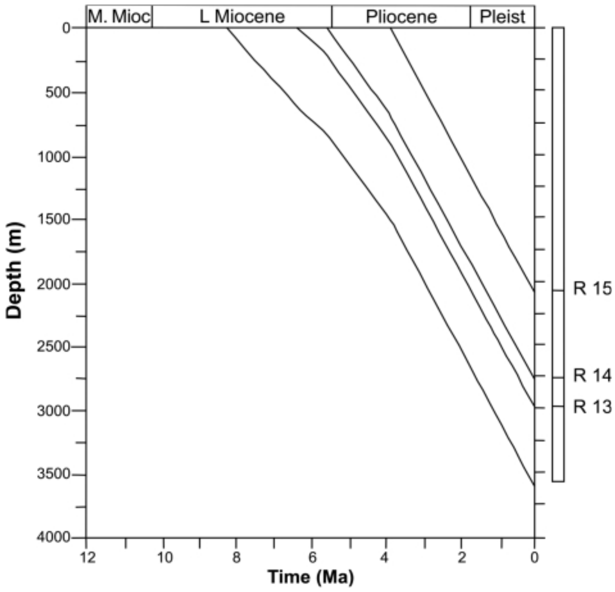

Figure 3: Burial history diagram of Shahbazpur gas field (BAPEX, 1996), southern Bengal Basin, Bangladesh; R – 15, R – 14 and R – 13 are the reflectors of the top of seismic sub-sequences: R – 15, R – 14 and R - 13 interpreted as shale at 2060m, sandstone with occasional thinly laminated shale at 2756 and sandstone with frequent interbedded shale at 2998m respectively.

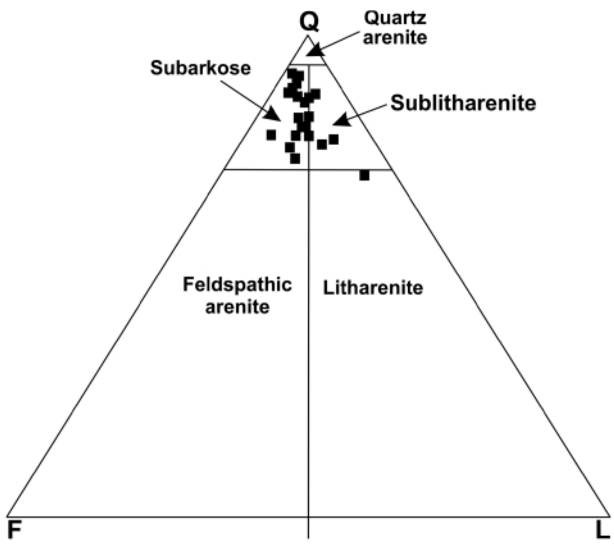

Figure 4: Triangular diagram (Folk, 1974) showing the modal composition and classification of the Surma Group sandstones in the Shahbazpur well-1.

ly too small to measure (Fig. 9 A, B). These low-saline inclusions appear to be primary in the overgrowths (e.g. Fig. 9 C) and a low formation temperature can be assumed. Exact melting temperatures (T_m) and homogenization temperatures (T_h) could be determined only from one fluid inclusion. The T_m at -3.5°C indicates a low salinity (about 5.71 mass% NaCl, (Bodnar, 1993) NaCl-H_2O fluid. The T_h (LV→L) was measured at 113° C.

Clay cements identified in the Surma Group reservoir sandstones include mainly chlorite, illite-smectite and a small amount of kaolinite.

Authigenic chlorite occurs in the Surma Group reservoir in three different forms: grain coating (pore-lining), rims and pore-filling up to 6% (av. 1.5%). The chlorite rims are generally thin and discontinuous (Fig. 5 C). Chlorite consists of small irregular to pseudo hexagonal platelets, 2-3 μm in length, aligned in grain-perpendicular form (Fig. 7 D; Fig. 8 B, C), occasionally enclosed by quartz overgrowths (Fig. 7 D). Chlorite has been often found partly replacing biotite. Many chert grains are found to be coated with chlorite (Fig. 5 E). In some cases,

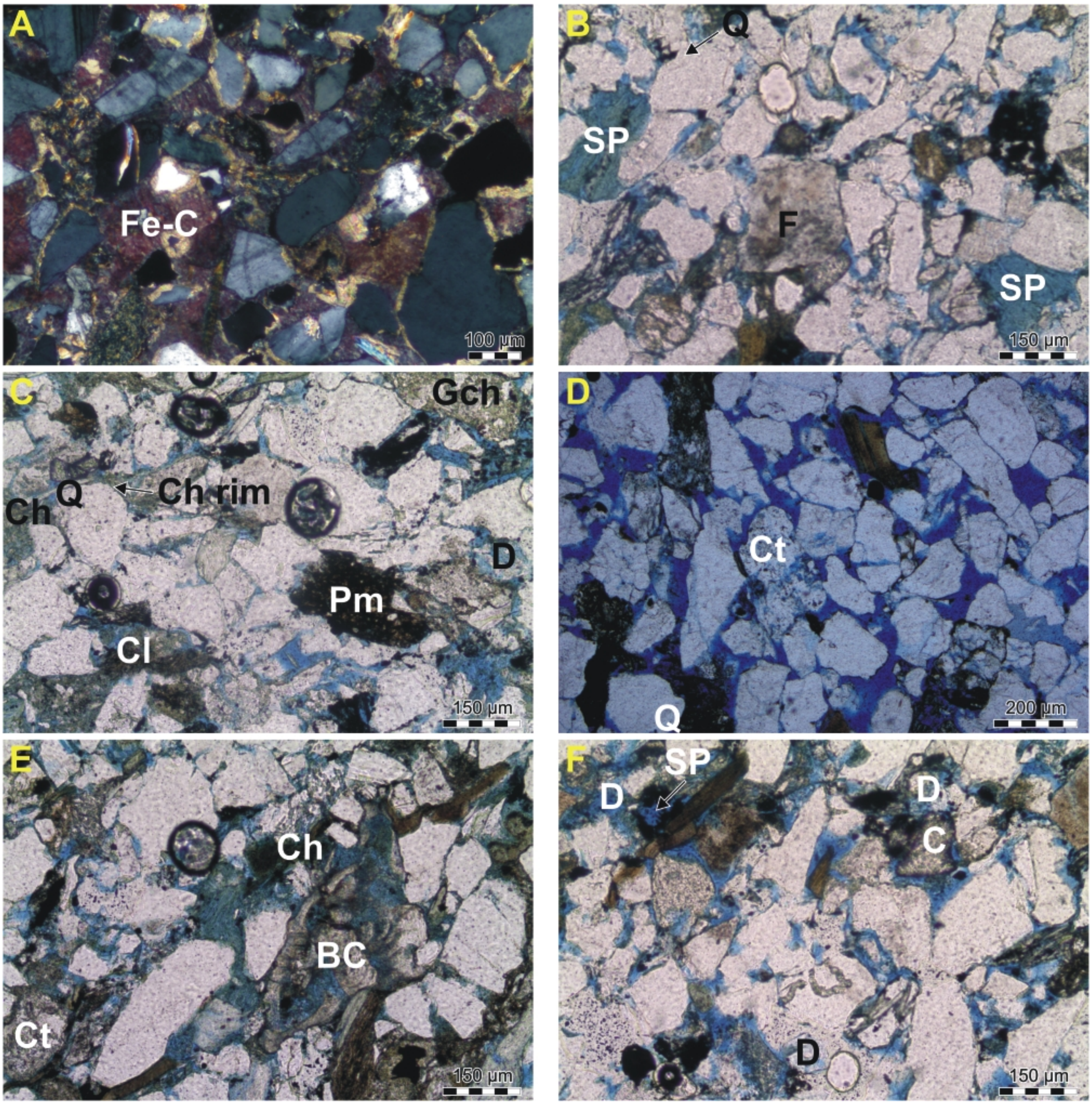

Figure 5: Photomicrographs of sandstones from the Shahbazpur well-1: A (ppl). Poikilotopic pore-filling Fe-calcite cement (Fe-C)-depth 3019m; B. Secondary porosity (SP), Quartz overgrowth (Q), decomposition of feldspar (F) - depth 3020 m; C. grain-coating chlorite (Gch), chlorite rim (ch rim), pore-filling chlorite cement (Ch), clay cement (Cl), pseudomatrix (Pm), partial dissolution (D)-depth 3021; D. Partial dissolution in chert (Ct) and unstable grains-depth 2291 m; E. chert (ct) coated with chlorite; chlorite cement (Ch); carbonate bio-clast (BC)-depth 3017.5 m; F. Secondary porosity, molds outlined by clay rim (SP), carbonate clast (C) and dissolution (D) of carbonates-depth 3021.5 m. In all photomicrographs (ppl), porosities are marked as blue stained.

chlorite has been found overgrown on quartz overgrowths (Fig. 7 A).

Illite-smectite occurs as a grain coating (pore-lining) (Fig. 8 A) and also as a grain replacement of coating clays and micas. Pore-filling and pore-bridging illites (Fig. 7 B) also occur. Illite-smectite is often represented by lath-, hair-like crystals oriented perpendicular to the detrital grain surfaces. A fibrous variety of illite occurs rarely in these sandstones. Mixed layer clay minerals, such as illite-smectite (I/S) are common. Under SEM, I/S show either corn flake morphology with short honeycomb-like crystals/ or lath-like form. The hair-like, lath-like and honeycombs-like habit of illites is more observed in these sandstones than the fibrous variety, indicating that illite is mixed with some smectite.

Kaolinite occurs as thin stacks of pseudo-hexagonal plates or books. Kaolinite crystals formed in primary pore spaces, partially entrapped in chlorite (Fig. 8 C) and mica flakes.

4.2 Porosity and Permeability

Three types of porosity were revealed from thin section and SEM analysis: (1) primary intergranular pores, which are the most abundant form, comprising 69 to 99% (av. 84%) of the total porosity; (2) secondary porosity (1% to 31%; av. 16%) and (3) micro pores. Secondary porosities are associated with the dissolution of unstable rock fragments, feldspars and carbonates cements and clasts. Secondary pores are also found in cherts. Micro porosity is associated with clays. Measured core porosities range from 18% to 24%. Point-count thin section porosities (~20%) are broadly in agreement with those of the core plug porosities. The permeability of the studied sandstones shows a wide range of < 0.6 to 415 mD. The degree of mechanical compaction and cementation are the major controls on porosity and permeability in the Surma Group reservoirs. Sandstones with minor amounts of cement are characterized by permeability ranging from 20 to 415 mD, while carbonate- and clay-cemented sandstones show permeabilities in the range of 0.6 to 4.6 mD.

5. Discussion

Grain-coating clays are observed in the investigated sandstones that occur as platelets, tangentially arranged around detrital grain surfaces, and are typically formed by mechanical infiltration immediately subsequent to deposition (c.f. Matlack et al., 1989, Moraes and De Ros, 1992). With increasing depth, the sandstones suffered moderate degree of compaction as grain contacts changed from point to long and concavo-convex types. In moderately to deep burial zones, mechanical compaction in the sandstones is evidenced by the fracturing of quartz, feldspars, micas and labile lithic fragments. The shale fragments in some cases are found deformed which may lead to formation of pseudomatrix (Fig. 5 C).

Authigenic chlorite has been noted throughout a depth range from 997 to 3411 m. Authigenic chlorite rims have been reported in the sandstones of the overlying Tipam Group at depths as shallow as 500 m in the central part of the Bengal Basin,

Depth (m)	Authigenic chlorite	Quartz cement	Carbonate cement	Clay cement	Thin section porosity
997	2.2	2.0	1.5	2.2	24
1005.6	6.3	1.0	2.0	5.7	14
1796.5	2.7	0.3	20.7	1.3	7
2015.5	5.0	2.3	9.7	5.3	8
2290	0.3	4.5	0.3	1.0	23
2291	0.3	7.3	0.7	1.0	24
3016	2.8	2.7	1.2	0.0	19
3016.5	1.3	6.0	4.3	1.0	23
3017	1.7	2.7	1.7	4.0	11
3017.5	0.3	1.2	1.5	1.5	29
3018	0.3	2.0	1.0	0.3	16
3019	2.7	0.3	34.0	4.0	1
3020	0.0	3.5	0.7	0.0	21
3020.5	0.3	3.3	0.7	0.0	30
3021	2.3	2.8	1.3	1.2	19
3021.5	1.2	4.8	1.0	1.0	23
3022	0.0	2.3	1.3	0.7	27
3022.5	1.8	1.2	1.8	0.3	21
3404	1.0	5.3	2.5	0.5	15
3404.7	0.0	1.3	1.7	0.7	31
3407	2.0	1.8	2.5	1.5	25
3408	0.3	2.0	1.7	0.7	12
3409	0.5	2.0	1.5	0.0	30
3411	0.7	1.7	3.3	0.3	23
	1.5	**2.7**	**4.1**	**1.4**	**19.8**

Table 3: Abundance of cements and porosities of the Neogene succession with Surma Group sandstones (depth from 2015.5 m – 3411 m) with depth of burial from the Shahbazpur well-1.

Sample	Well	Depth (m)	$\delta^{13}C$ VPDB	$\delta^{18}O$ VPDB
SBZ -5	Shahbazpur-1(SB)	3017.5	-6.05	-13.06
SBZ-5(1)	Shahbazpur-1(SB)	3019	-4.94	-12.10
SBZ-5(2)	Shahbazpur-1(SB)	3020.5	-1.35	-10.28
SBZ C-6	Shahbazpur-1(SB)	3404.7	-11.07	-13.40

Table 4: Stable isotope analysis of carbonate cements of the Neogene Surma Group sandstones in the Shahbazpur (For well location, see Fig. 1).

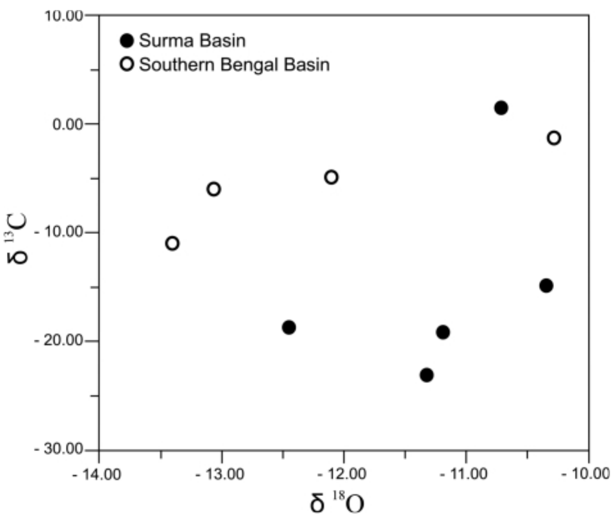

Figure 6: $\delta^{18}O$ versus $\delta^{13}C$ for carbonate cements of the Surma Group sandstones from Shahbazpur, southern Bengal Basin (open circle) and northeastern Bengal Basin (Surma Basin) (closed circle) (For location see Fig. 1).

corresponding to an estimated temperature of approximately 40°C (Imam and Shaw, 1987). Chlorite can have a number of origins but typically develops at temperatures of > 60-70°C (Worden and Morad, 2003). Chlorite may form in deltaic deposits by the transformation of eogenetic, grain-coating berthierine or odinite during deep burial to temperatures of >90-100°C (Galloway, 1979; Ehrenberg, 1993; Gringsby, 1999; Worden and Morad, 2003) but no evidence of berthierine and/or odi-

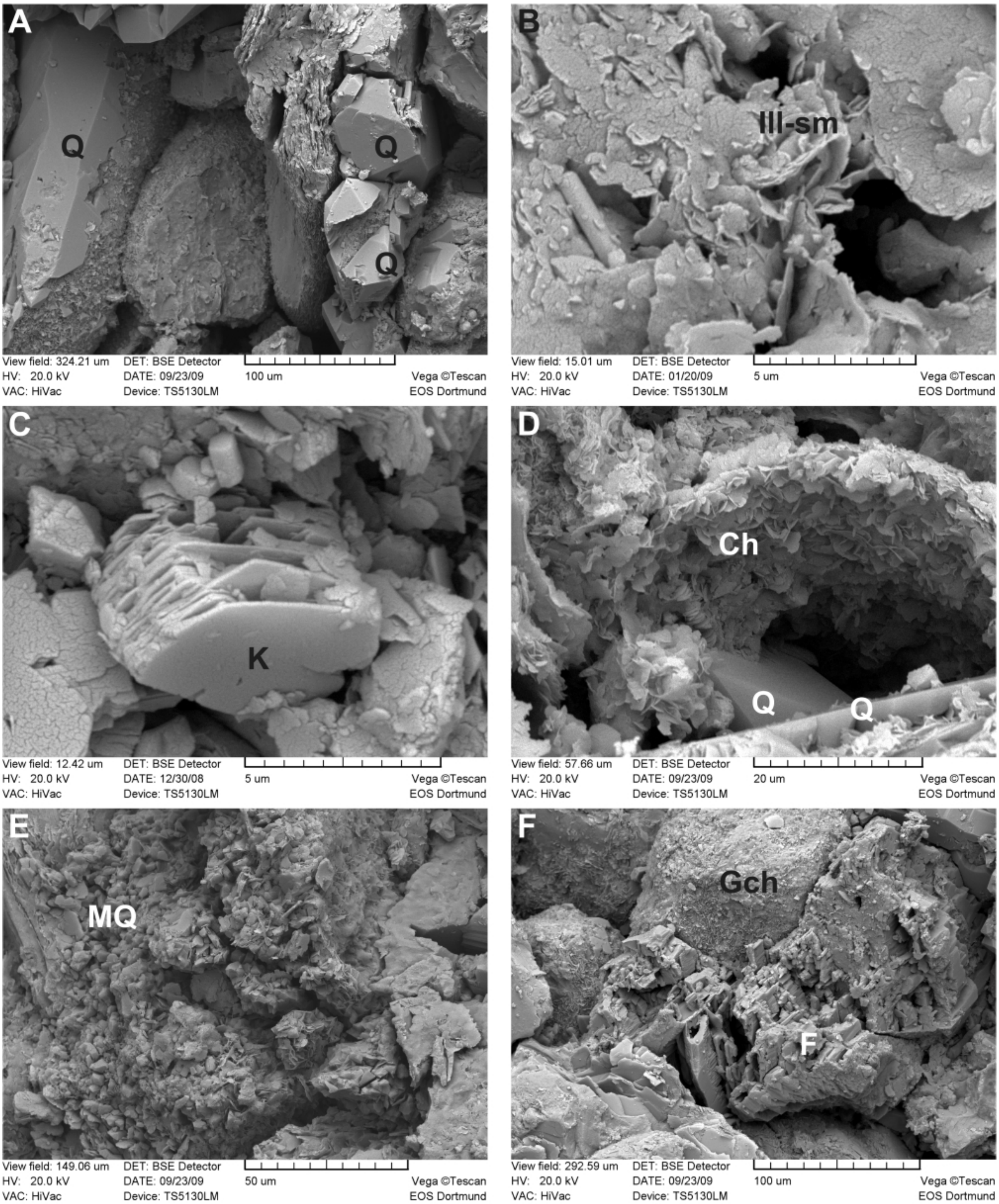

Figure 7: Scanning electron micrographs of sandstones from the Shahbazpur well-1: A. Quartz overgrowths (Q) partly occludated pore-throats - depth 3016.5 m; B. Illite-smectite (ill-sm) tends to bridge pore-throats - depth 3021 m; C. Pore-filling kaolinite (K)-depth 2290 m; D. Incomplete quartz overgrowth (Q) inhibited by chlorite platelets (Ch)-depth 3021.5 m; E. Microquartz (MQ)-depth 3016 m; F. Grain-coating chlorite (Gch), dissolution of feldspar (F) - depth 3017 m.

nite have been found as a possible precursor. Petrographic observations revealed that authigenic chlorite is often associated with altered biotite and, consequently, higher authigenic chlorite abundances are associated with biotite-rich sandstones. SEM observations imply that chlorites were also likely derived from the replacement of kaolinite (Fig. 7C). The authigenic chlorites were Fe-rich chamosites as suggested by (Imam and Shaw, 1987). The presence of Fe-rich chlorite may inhibit quartz overgrowth and preserve porosity, and tends to attract the polar compounds in liquid petroleum, encouraging oil wetting and preventing the access of water to grain surfaces, thus stopping aqueous geochemical processes such as quartz cementation (Al-Ramadan et al., 2004).

Kaolinite is predominant at depths of 997 to 1006 m and is less abundant at a depth of 2200 m and its absence is noted in deeper burial sandstones. The lower abundance of kaolinite in the samples implies that pore waters may have been depleted in Si and Al ions and/or transformed into chlorite and illite in the late diagenetic environment. As evidenced from the occurrence of thin chlorite plates on surfaces of kaolinite at depth ~2290 m (Fig. 7 C), it is possible that kaolinite might have been altered to chlorite during progressive burial.

Early carbonate cement, typically poikilotopic, was observed at a depth of 1796.5 m (Plio-Pleistocene) and its growth precedes that of quartz cements. This early Fe-calcite dominant cement fills relatively large pores between loosely packed framework grains as well as the partial replacement of grains, and it is interpreted to have formed prior to any significant compaction. Fe-calcite (partly altered to Fe-dolomite) has also been noted. The Fe-calcite cement was also formed at a greater depth (3019 m), and occur as pore-filling blocky, fracture filling cements as well as isolated pore-filling cements. They would appear to have a syncompactional to mesogenetic origin. The second mode of generation of Fe-calcite as an isolated pore filling cement impedes the phase of quartz cementation and formed within more compacted sandstones.

Using the $\delta^{18}O$ VPDB values (-10.3‰ to -13.4‰) of the carbonate cements, the fractionation equation of (Friedman and O'Neil, 1977), and assuming a $\delta^{18}O$ SMOW value for the evolved pore water of between ~-6‰ and 0‰ relative to the mixed marine-meteoric waters (-6‰ and -4‰), would suggest that the precipitation of carbonate occurred at temperatures of 85°-115°C (see El-ghali et al., 2009). These temperatures are in agreement with the present borehole temperatures (BHT ~75°C-108°C) at the depth of cement occurrence encountered in the well. Temperatures up to 44-67°C are required if calcite cements were derived from marine ($\delta^{18}O$=0) or mixed marine-meteoric waters (Salem et al., 2005). The $\delta^{13}C$ VPDB values of the carbonate cements (-1.4‰ to -11.1‰) reflect that carbon was most likely derived from the thermal maturation of organic matter during burial (Morad, 1998), as well as from the dissolution of isolated carbonate clasts. Introducing Fe^{2+} bicarbonate and hydroxyl ions into pore waters from adjacent shales (Curtis, 1983) could have contributed significantly to the formation of the poikilotopic, pore-filling blocky cements. Carbonate cements from the southern part of the Bengal Basin have lower $\delta^{13}C$ negative values compared to those of the Surma Basin (north-eastern Bengal Basin) (Fig. 6), suggesting that dissolved carbon in the Bengal Basin was derived from multiple sources, such as the thermal alteration

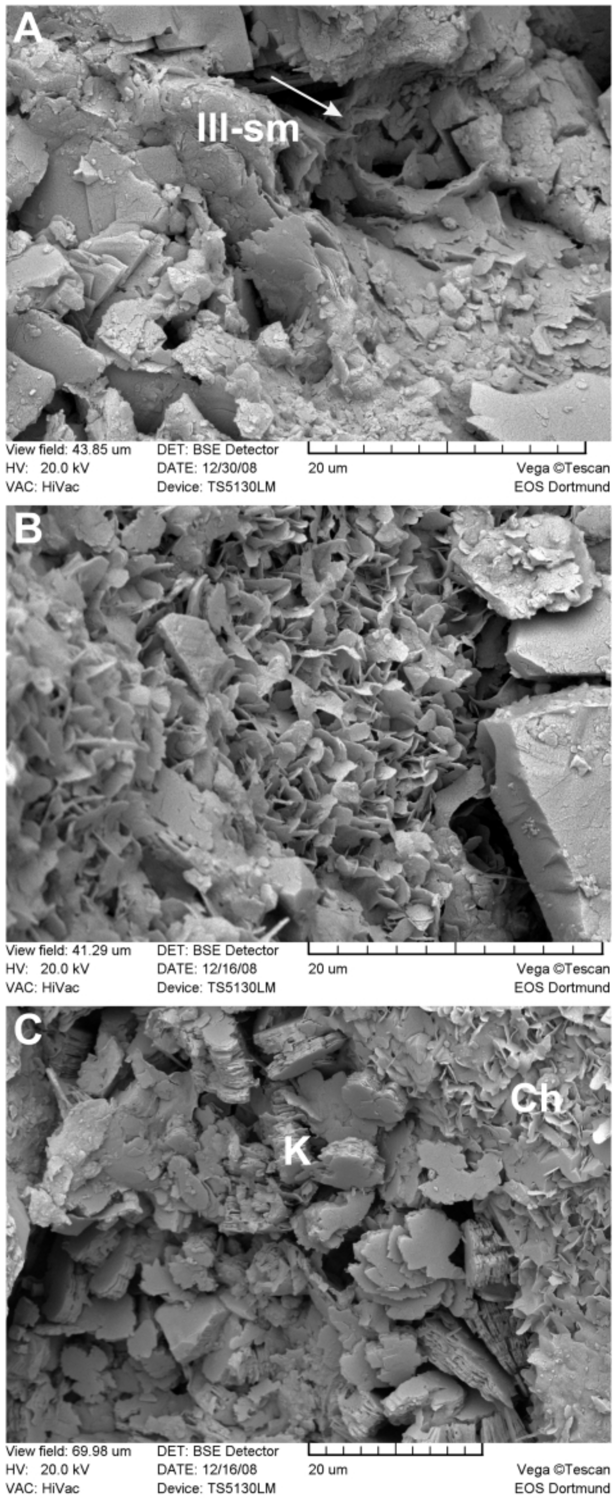

Figure 8: Scanning electron micrographs of sandstones from the Shahbazpur well-1: A. Pore-lining illite/smectite (ill-sm)-depth 1006 m; B. Pore-filling as well as grain-coating (pore-lining) chlorite - depth 997 m; C. Pore-filling kaolinite (K) as well as grain-coating (pore-lining) chlorite (Ch) -depth 997 m.

of organic matter in adjacent shales, the dissolution of plagioclase feldspars as well as the formation of early eogenetic carbonate cements.

The generation of early poikilotopic cements in the Surma Group sandstones of the Bengal Basin is thought to be as a result of the recrystallization of the significant amounts of skeletal debris present within the sand bodies (Imam and Shaw, 1987). However, the present study suggests that the sandstones contain only few biogenic clasts (Fig. 5 E) and detrital carbonate fragments are very rare. Thus, the isolated pore-filling, late calcite cements in these sandstones are most probably associated with the dissolution of plagioclase as revealed by petrographic observations. This would support the idea that the typically isolated pore-filling late calcite cements were precipitated during the dissolution of plagioclase and were formed during the emplacement of hydrocarbons (cf. Boles, 1998).

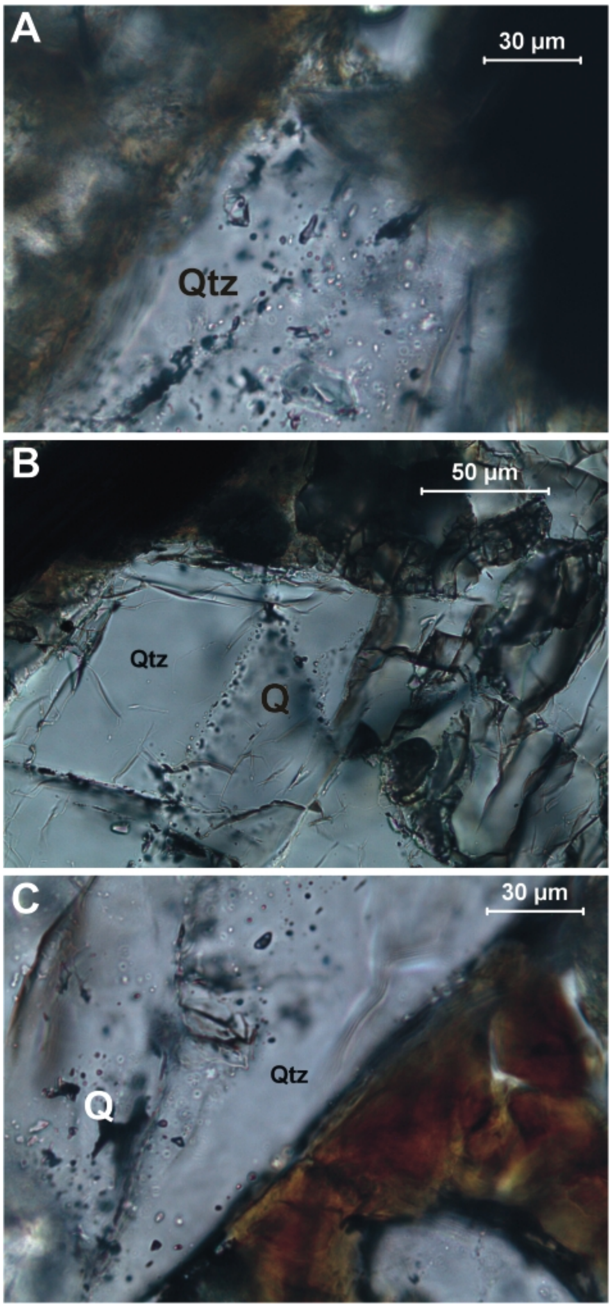

Figure 9: Photomicrograph of some fluid inclusions on quartz/quartz overgrowths in sandstones at a depth of around 3000 m. A. Large detrital quartz grain with primary fluid inclusions B. Secondary fluid inclusions in quartz with contact to the cement phase (Q), C. Detrital quartz grain with an overgrowth (Q) and low temperature fluid inclusions.

The noticeable presence of quartz overgrowth has been noted in the studied sandstones having numerous long intergranular concavo-convex contacts and some suture contacts. The presence of quartz cement as a syntaxial overgrowth near the sites of intergranular dissolution and around tightly-packed detrital quartz grains indicates a mesogenetic origin (cf. McBride, 1989; Worden and Morad, 2000). Quartz cements have multiple sources (Worden and Morad, 2000). Various internal sources of silica have been proposed, including intergranular pressure, the dissolution/transformation of smectite to illite and the solution reaction of detrital feldspars. Quartz cements are notably scare in samples from shallow depths. Indeed, its presence is more significant in samples from deeper burial depths. Quartz overgrowths (> 1%) have been found mainly at depths of 2000 m to 3400 m (Fig. 10). It would, therefore, appear that in situ pressure solution can account for the bulk of the cement present, although other internal sources such as the partial dissolution of K-feldspar and the progressive transformation of smectite to illite could provide additional sources (McKinley et al., 2003). The occurrence of micro-quartz could be originated from highly silica-saturated pore (Bloch et al., 2002).

Hair-like, lath-like and honeycomblike illite (rather than the fibrous variety) are observed in the sandstones, indicating that illite, where present, is mixed with some smectite. The presence of grain coating, hair-like and honeycomb-like crystals with spiny terminations indicates a diagenetic origin (Morad et

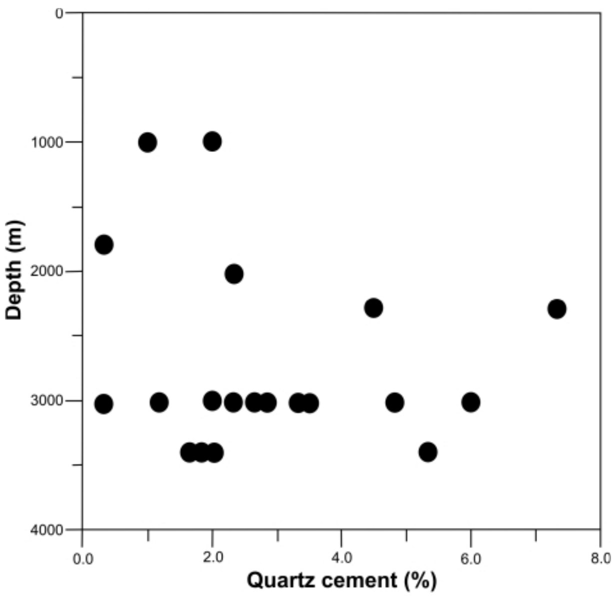

Figure 10: Distribution of quartz cement vs. depth in the Surma Group sandstones in the Shahbazpur well-1.

al., 2000; Lemon and Cubitt, 2003). Illite which typically forms during progressive burial (mesodiagenetic) through the transformation of infiltered clays (smectites via mixed layer illite-smectite) (Keller et al., 1986; Morad et al., 2000) under high temperatures (90°-130°C) requires high K^+/H^+ ratios in pore waters (Keller et al., 1986; Ehrenberg, 1993; Morad and De Ros, 1994). Shale lamina within the sandstone facies of the Surma Group in the Shahbazpur have the same clay mineral composition, with illite/smectite-chlorite being the dominant clay mineral in the interbedded shale facies. The gradual decrease of smectite in the shale lamina within the sandstones during progressive burial (Fig. 11) reflects the gradual transformation into illite. Based on the dominant diagenetic features of the sandstones of the Surma Group, as determined from the mutual textural relationships in thin section and SEM analysis, a sequence of diagenetic processes can be presented (Fig. 12).

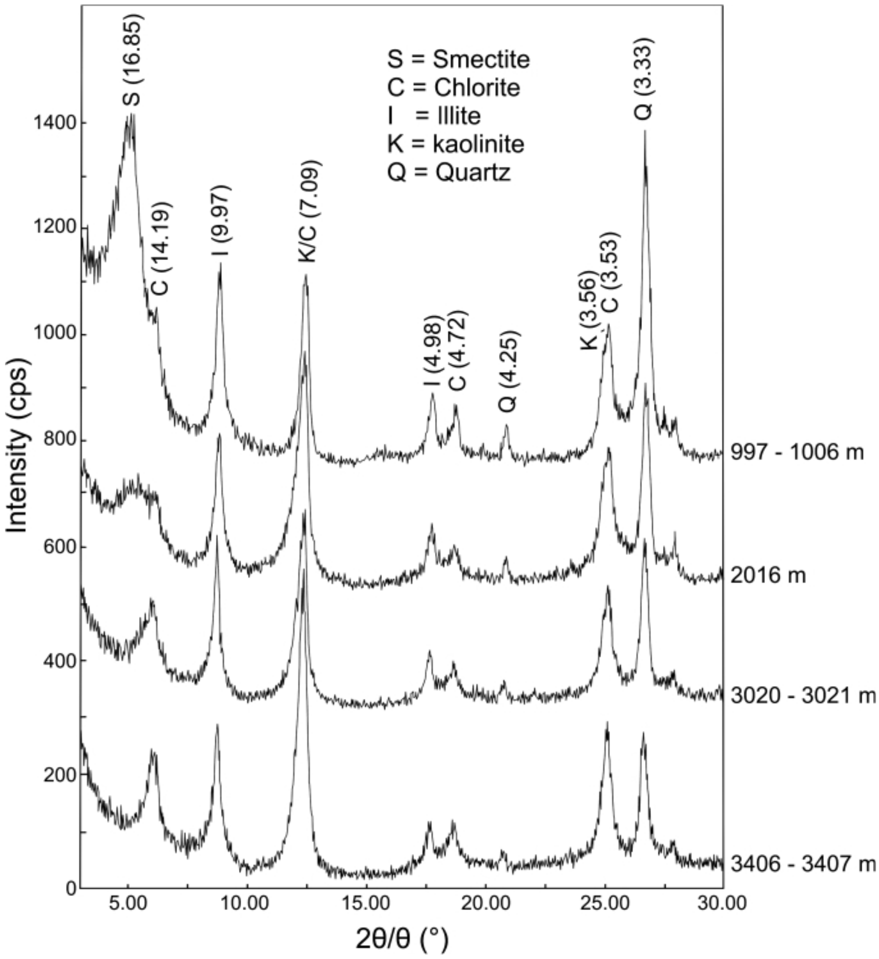

Figure 11: Characteristic X-ray diffraction diagrams (glycolated) of clay minerals from shale lamina within sandstones of the Surma Group from the Shahbazpur well-1.

5.1 Reservoir Implications

Regarding reservoir quality, compaction played the major role in destroying primary porosity. Grain contacts, with long and concavo-convex types, dominate in these sandstones, suggesting a moderate degree of compaction. In moderately to deeper burial zones, micas and labile lithic fragments are often deformed. The changes in grain contacts reduced primary intergranular porosity and pore throat radii.

Quartz and clay cements have been observed in the Surma Group sandstones in trace amounts up to 7%, with generally small amounts of carbonate cement. Thus, authigenic phases have a secondary control on the reservoir quality of these sandstones. In sandstones of the Surma Group encountered at depths of 2015.5, 3017 and 3019 m, porosity and permeability was significantly reduced as a result of pore-filling chlorites, quartz cements and pore-filling blocky, poikilotopic carbonate cements. Carbonate cementation was important in drastically reducing porosity and permeability in sandstones at a depth of 1796.5 m (Plio-Pleistocene section), 2015.5 m and in areas of deeper burial at 3019 m in the Surma Group. Carbonate-cemented sandstones have porosities of 1 to 7% and permeabilities of <0.6 to 4.6 mD.

Although high contents of quartz cement were not observed in these sandstones, the small amounts of quartz present may have played a subordinate role in reducing porosity and permeability by occluding pore throats (Fig. 7A, D). Quartz overgrowths are an important reservoir quality deteriorating mechanism in many deep hydrocarbon reservoirs (Worden and Morad, 2000). Quartz cementation, specifically syntaxial quartz overgrowth, is a major cause of porosity–loss in many petroleum reservoirs in both moderately to deeply buried reservoirs (Imam and Shaw, 1987; Worden and Morad, 2003). Mixed layer illite-smectite and quartz cements are also associated with pore-filling and pore-lining chlorites. The presence of Fe-

Diagenetic Processes	Relative timing of the processes Early → Late
Infiltration of clay coatings	
Mechanical compaction	
Chlorite authigenesis	
Intermediate to deep burial poikilotopic Fe-carbonate cement as well as isolated pore-filling	
Dissolution	
Quartz overgrowth	
Authigenic illite	

Figure 12: Relative succession of the diagenetic processes within the sandstones of the Neogene succession from the Shahbazpur well-1.

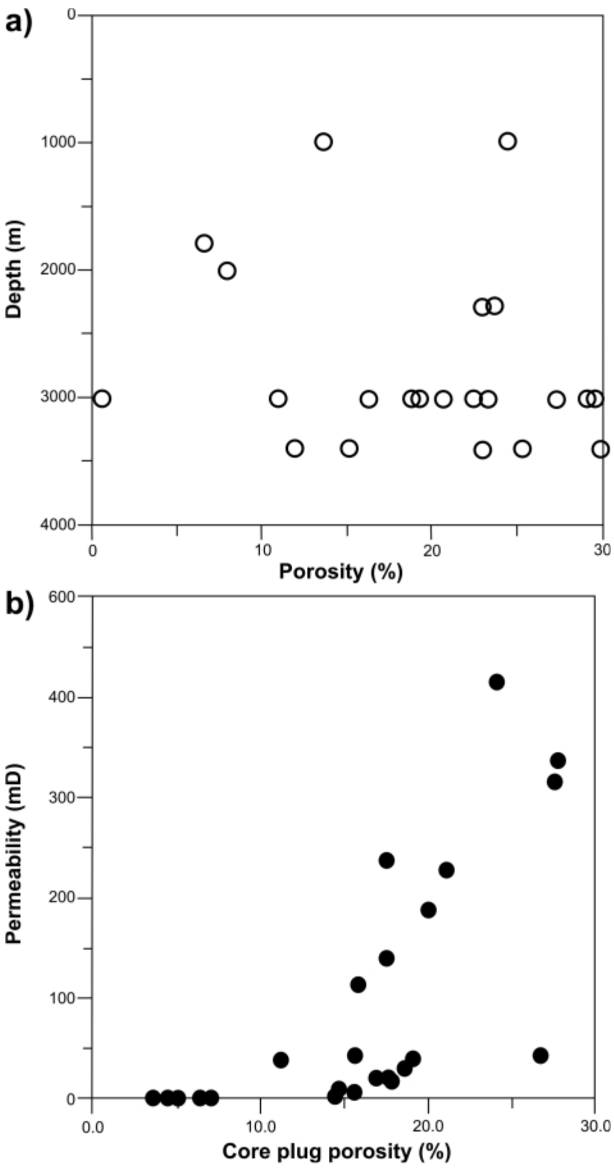

Figure 13: a) Porosity (%) vs. depth and b) Core plug porosity vs. permeability in the Surma Group sandstones in the Shahbazpur well-1.

rich chlorite may inhibit quartz overgrowth and preserve porosity. As revealed from SEM observations, the presence of microquartz coats may inhibit the precipitation of pore-filling normal quartz overgrowths (Bloch et al., 2002). Microquartz crystals may resist pressure solution by solidifying contacts between quartz grains (Bloch et al., 2002).

Sandstone porosity is still largely primary and is dependent mainly on the textural maturity of the sediments, which in turn is largely controlled by the depositional processes and environment. Sandstones with good porosities (20% to 30%) and high permeabilities (20 to 415 mD) have been observed at depth ranges of ~2290 to ~3411m (Fig. 13). Secondary porosity constituting c. 16% of the total porosity is a significant contributor in enhancing reservoir porosity in these sandstones. Most of the secondary porosity was created by partial to complete dissolution of carbonate cements, feldspars, polycrystalline quartz, volcanic rock fragments and other unstable grains (Fig. 5 B, C, D). Secondary pores are also noticed in many chert fragments (Fig. 5 D) of the analyzed sandstones. Though chert is not labile rock fragment but porosity in chert can be formed through differential silica diagenesis of siliceous sediments (Ruppel and Hovorka, 1995). Secondary porosity is also evidenced as molds outlined by clay rim (Fig. 5 F) and oversized pores in these sandstones (Fig. 7B). Fracture, shrinkage and elongated narrow pores are insignificant but these types of secondary porosity may have enhanced permeability. Fluids that cause dissolution should be undersaturated with respect to the solid phase. Such fluids can either be meteoric water (review by Hesse and Abid, 1998) or acidic, generated during diagenesis by organic matter degraded reactions and clay diagenetic reactions (review by Hesse and Abid, 1998) in shales interbedded with sandstones.

6. Conclusions

- The principal diagenetic minerals in order of abundance in the subarkosic to sublithic sandstones from cores of the Surma Group are ferroan carbonates, quartz, chlorite, illite-smectite and kaolinite. The sandstones experienced loss of primary porosity mainly due to compaction. However, cementation played a major role in drastically reducing porosity and permeability with poikilotopic, pore-filling blocky cements in sandstone at depth 1796.5 m (Plio-Pleistocene) and in areas of intermediate depth of 2015.5 m and deep burial (3019 m) of the Surma Group. The $\delta^{18}O$ VPDB value of the carbonate cements implies that cementation evolved from pore water with $\delta^{18}O$ SMOW value of ~-6‰ and 0‰ and would have been precipitated from mixed marine-meteoric waters. The $\delta^{13}C$ VPDB values (-1.4‰ to -11.1‰) of the carbonate cements indicates that carbon was likely derived from the thermal maturation of organic matter associated with adjacent shales during burial and a minor amount from the dissolution of isolated carbonate clasts.
- The primary porosity of these sandstones is largely controlled by depositional process and textural maturity. Sandstones with good porosities (20% to 30%) and high permeabilities (20 mD to 415 mD) have been observed at a depth range of ~2290m to ~3411m. Secondary porosity caused by partial to complete dissolution of carbonate cements, feldspars, polycrystalline quartz, volcanic rock fragments and other unstable grains is a significant contributor in enhancing reservoir porosity in these sandstones.
- The reservoir quality of the Surma Group sandstones is thus mainly controlled by depositional environments and diagenetic processes. The best reservoir sandstones lie at a depth of ~2290 m to ~3411 m and show good sorting, are relatively coarse grained, more loosely packed and with grains which are better rounded. Minor quartz cements and authigenic clays have been observed in this area together with generally small amounts of carbonate cement. However, the good quality reservoir rocks are not uniformly distributed and are compartmentalized at frequent intervals by intervening sandstones of low to moderate porosity, per-

meability with poorly sorting and which are tightly compacted and have considerable cements.

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References

Alam, M., Alam, M.M., Curray, J.R., Chowdhury, M.L.R and Gani, M.R., 2003. An overview of the sedimentary geology of the Bengal Basin in relation to the regional tectonic framework and basin-fill history. In: Alam, M.M. and Curray, J.R. (eds.), Sedimentary geology of the Bengal Basin, Bangladesh, in relation to the Asia-Greater India collision and the evolution of the eastern Bay of Bengal. Sedimentary Geology, 155, 179-208.

Al-Ramadan, K.A., Hussain, M., Imam, B. and Saner, S., 2004. Lithologic characteristics and diagenesis of the Devonian Jauf sandstone at Ghawar Field, Eastern Saudi Arabia. Marine and Petroleum Geology, 21, 1221-1234.

BAEX, 1996. Petroleum Geology of Bangladesh, Core Lab. Report, 139 p.

Bloch, S., Lander, R.H. and Bonnell, L., 2002. Anomalously high porosity and permeability in deeply buried sandstone reservoirs: origin and predictability. AAPG Bulletin, 86, 301-328.

Bodnar, R.J., 1993. Revised equation and table for determining the freezing point depression of H,O-NaCl solutions. Geochimica et Cosmochimica Acta, 57, 683-684.

Boles, J.R., 1998. Carbonate cementation in Tertiary sandstones, San Joaquin basin, California. In: Morad, S. (ed.), Carbonate Cementation in Sandstones. International Association of Sedimentologists, Special Publication, 26, pp. 261-283.

Curtis, C.D., 1983. Geochemistry of porosity enhancement and reduction in clastic sediments. In: Ed. Brooks, J. (ed.), Petroleum Geochemistry of NW Europe. (Geological Society London, Special Publication, 12, pp. 113-126.

Ehrenberg, S.N., 1993. Preservation of anomalously high porosity in deeply buried sandstones by grain-coating chlorite: examples from the Norwegian continental shelf: AAPG Bulletin., 77, 1260-1286.

El-ghali, M.A.K., Morad, S., Mansurbeg, H., Miguel A. Caja, Sirat, M. and Ogle, N., 2009. Diagenetic alterations related to marine transgression and regression in fluvial and shallow marine sandstones of the Triassic Buntsandstein and Keuper sequence, the Paris Basin, France. Marine and Petroleum Geology, 26, 289-309.

Evans, P., 1964. Tectonic framework of Assam. Journal of the Geophysical Society of India, 5, 80-96.

Folk, R.L., 1974. Petrology of Sedimentary Rocks. Hemphills, Austin, Texas.

Friedman, L. and O'Neil, J.R., 1977. Composition of stable isotopic fractionation factors of geochemical interest. In: Fleisher, M. (ed.), Data of Geochemistry, 6th ed., US Geological Survey, Professional Paper 440, pp. 1-12.

Galloway, W.E., 1979. Diagenetic control of reservoir quality in arc-derived sandstones: Implications for petroleum exploration. In: P.A. Scholle, & P.R. Schluger, Aspects of diagenesis. SEPM Special Publication 26, 251–262.

Gringsby, J.D., 1999. Origin of chlorite grain coats in sandstones of the lower Vicksburg Formation, South Texas: AAPG Bulletin, Annual Meeting abstracts, p. A51 (Tulsa).

Hesse, R. and Abid, I.A., 1998. Carbonate cementation-the key to reservoir properties of four sandstone levels (Cretaceous) in the Hibernia Oilfield, Jeanne d'Arc Basin, Newfoundland, Canada. In: Morad, S. (ed.), Carbonate Cementation in Sandstones. International Association of Sedimentologists, Special Publication, 26, pp. 363-393.

Hiller, K. and Elahi, M., 1984. Structural development and hydrocarbon entrapment in the Surma Basin, Bangladesh (northeast Indo-Burman fold belt). Proceed. 5th Offshore South Asia Conf., Singapore.

Imam, M.B. and Shaw, H.F., 1987. Diagenetic controls on the reservoir properties of gas bearing Neogene Surma Group sandstones in the Bengal Basin, Bangladesh. Marine and Petroleum Geology, 4, 103-110.

Islam M.A., 2009. Diagenesis and reservoir quality of Bhuban sandstones (Neogene), Titas Gas Field, Bengal Basin, Bangladesh. Journal of Asian Earth Sciences, 35, 89-100.

Johnson, S.Y. and Alam, A.M.N., 1991. Sedimentation and tectonics of the Sylhet trough, Bangladesh. Geological Society of America Bulletin, 103, 1513-1527.

Keller, W.D., Reynolds, R.C. and Inoue, A., 1986. Morphology of clay minerals in the smectite-to –illite-conversion series by scanning electron microscopy. Clays and Clay Minerals, 34, 187-197.

Khan, M.A.M., Ismail, M. and Ahmed, M., 1988. Geology and Hydrocarbon prospects of the Surma Basin, Bangladesh. 7th Offshore South Asia Conf., Singapore, 364-387.

Lemon, N.M. and Cubitt, C.J., 2003. Illite fluorescence microscopy: a new technique in the study of illite in the Merrimelia Formation. Cooper Basin, Australia. In: Worden, R.H., Morad, S. (eds.), Clay Mineral Cements in Sandstones, 34. International Association of Sedimentologists, Special Publication, 34, 411-424.

Lietz, J.K. and Kabir, J., 1982. Prospects and constraints of oil exploration in Bangladesh. Proceed. 4th Offshore Southeast Asia Conf., Singapore, pp. 1-4.

Matlack, K.S., Houseknecht, D.W. and Applin, K.R., 1989. Emplacement of clay into sand by infiltration. Journal of Sedimentary Petrology, 59, 77-87.

McBride, E.F., 1989. Quartz cement in sandstones: A review. Earth Sciences Reviews, 26, 69-112.

McKinley, J.M., Worden, R., Ruffell, H. and Morad, S., 2003. Smectite in sandstones: a review of the controls on occurrence and behavior during diagenesis. In: Worden, R. H., Morad, S. (eds.), Clay Minerals Cement in sandstones. International Association of Sedimentologists, Special Publication, 34, 109-128.

Morad, S., 1998. Carbonate cementation in sandstones; distribution patterns and geochemical evolution. In: Morad, S. (ed.), Carbonate Cementation in Sandstones. International Association of Sedimentologists, Special Publication, 26, 1-26.

Morad, S. and De Ros, L.F., 1994. Geochemistry and diagenesis of strata bound calcite cement layers within the Rannoch Formation of the Brent Group, Murchison Field, North Viking Graben (northern North Sea), discussion and reply. Sedimentary Geology, 93, 135-147.

Morad, S., Ketzer, J.M. and De Ros, F., 2000. Spatial and temporal distribution of diagenetic alterations in siliciclastic rocks: implications for mass transfer in sedimentary basins. Sedimentology, 47, 95-120.

Moraes, M.A.S. and De Ros, L.F., 1992. Depositional, infiltrated and authigenic clays in fluvial sandstones of the Jurassic Sergi Formation, Recôncavo Basin, northeastern Brazil. In: Houseknecht, D.W., Pittman, E.W. (Eds.), Origin, Diagenesis and Petrophysics of Clay Minerals in Sandstones. Society of Economic Paleontologists and Mineralogists, pp. 197–208.

Rahman, M.J.J., Faupl, P. and Alam, M.M., 2009. Depositional facies of the subsurface Neogene Surma group in the Sylhet trough of the Bengal Basin, Bangladesh: record of tidal sedimentation. International Journal of Earth Sciences, 98, 1971-1980.

Ruppel, S.C. and Hovorka, S.D., 1995. Controls on Reservoir Development in Devonian Chert: Permian Basin, Texas. AAPG Bulletin, 79, 1757-1785.

Salem, A.M., Ketzer, J.M., Morad, S., Rizk, R.R. and Al-Aasm, I.S., 2005. 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, 75, 572-584.

Shamsuddin, A.H.M., Brown, T., Lee, S. and Curiale, J., 2001. Petroleum Systems of Bangladesh. Proceedings 13th Southeast Asia Petroleum Exploration Society (SEAPEX) Exploration Conf. Singapore 4th- 6th April.

Tiab, D. and Donaldson, E.C., 2004. Petrophysics – Theory and practice of measuring reservoir rock and fluid transport properties. Gulf Professional Publishing, pp 1-899.

Uddin, A. and Lundberg, N., 1998. Unroofing history of the eastern Himalaya and the Indo-Burman Ranges: Heavy-mineral study of Cenozoic sediments from the Bengal Basin, Bangladesh. Journal of Sedimentary Research, 68, 465-472.

Worden, R. and Morad, S., 2000. Quartz cement in oil field sandstones: a review of the critical problems. In: Worden, R.H., Morad, S. (eds.), Quartz Cementation in sandstones. International Association of Sedimentolgists, Special Publication, 29, 1-20.

Worden, R. and Morad, S., 2003. Clay minerals in sandstones: controls on formation, distribution and evolution. In: Worden, R. H., Morad, S. (eds.), Clay Minerals Cement in Sandstones. International Association of Sedimentolgists, Special Publication, 34, 3-41.

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