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Petrography and Diagenesis of Thin-Bed Reservoirs from the Eastern Folded Belt of Bangladesh

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ABSTRACT

The main purpose of the study is to identify the thin-bed reservoirs of the Eastern Folded Belt (Sylhet and Bandarban) and characterize them with diligence. A detailed qualitative and quantitative analysis has been carried out. It is based on thin-section petrographic analyses of sandstone samples. These samples are from the reservoir horizons of the Sylhet region and Bandarban region fields. The purpose of this analysis is to characterize the textural and mineralogical properties.

Additionally, it aims to evaluate the post-depositional diagenetic changes. The results obtained from the field and laboratory analysis are studied extensively to characterize the thin-bed reservoirs. Samples from the Sylhet area are medium-coarse-grained, fairly sorted, tight packing, submature-mature sublithic characteristics. Contrarily, samples from the Bandarban region are mature-submature sublithic arenites, which are fine-medium-grained, moderately well-sorted, and moderately loosely packed. Despite the similarity of the detrital elements (quartz, feldspar, lithic grains, mica, etc.) in the two areas, silica cementation is more frequent in Sylhet region samples than early carbonate cementation in Bandarban region samples. Comparatively speaking, the sediments in the Sylhet region are more compact than those in the Bandarban region. The most important outcome of this study is that the thin bed of the unconventional reservoir and the conventional reservoir are in close proximity. The Thin-bed reservoir units of the Eastern Folded Belt are found to be medium to fine-grained and well sorted, with frequent alteration of sand-shale with the prevalence of parallel bedded sandstone. Average porosity is 4% to 12%, and pore spaces are interconnected. So, the permeability rate is good enough to flow the hydrocarbon through these pore spaces.

Most importantly, the thin bed and tight reservoir (average porosity 4% to 12%, but pore spaces are not interconnected) are not more prominent than 1 meter or 2 meters. Subsequently, though the vertical thickness is not so high, they keep up a momentous tirelessness of horizontal progression. On the contrary, at whatever point it comes to a conventional reservoir, the vertical thickness is higher than that of the unconventional reservoir. But their lateral persistence is not as long as unconventional ones.

INTRODUCTION

Bangladesh, a country with finite energy resources, has predominantly relied on natural gas as its primary energy source since 1990. The nation is presently undergoing a profound energy crisis. There is widespread concern regarding the potential depletion of natural gas reserves within 10 years or slightly longer, considering the projected annual increase in gas demand exceeding 5 percent. Since 2005, a notable scarcity of gas has been observed, primarily attributed to escalating gas demand surpassing the available supply (Islam & Lupin 2020). In the geographical expanse encompassing Bangladesh's central and eastern regions, particularly the northeastern Sylhet basin, the focus of exploration endeavors has been terrestrial investigations (Rahman & Faupl 2003). The East Delta Hill Tract province in Bangladesh is a relatively uncharted territory within hydrocarbon provinces (Islam & Lupin 2020, Khan et al. 2018, Rahman & Faupl 2003).

Nevertheless, a comprehensive analysis of the factors contributing to the depletion of the exploratory well in the Sitakund anticline has failed to yield a coherent and scientifically substantiated explanation. Despite the considerable endeavors invested in the Chittagong Hill Tracts region, the outcomes have been lacking in cumulative or descriptive attributes. The Chittagong Hill Tracts of Bangladesh have garnered considerable attention from oil and gas companies due to the existence of anticlinal structures such as the Sitakund anticline, Sitapahar anticline, Bandarban anticline, and Teknaf anticline (Connelly et al. 2019, Islam & Lupin 2020). As a result, the region has become a focal point for drilling activities by various companies in the oil and gas industry. The exploration efforts in the Chittagong Hill Tracts have thus far been limited to conventional anticlinal formations. An alternative methodology for exploration endeavors could potentially center on investigating unconventional and stratigraphic traps. The identification of these entities presents a challenge due to their lack of association with any specific fold structure. Instead, their presence is determined by the natural lithological changes, commonly referred to as facies variations, within the underlying rock strata (Connelly et al. 2019, Johnson & Nur Alam 1991, Rahman & Faupl 2003).

The Sylhet Basin, located in the north-eastern part of the Bengal Basin, has been examined in numerous geological studies (Alam et al. 2003, Johnson & Nur Alam 1991, Shamsuddin & Khan 1991). The stratigraphic succession was primarily established by lithologic correlation with sections in neighboring Assam and north-eastern India (Khan et al. 2010). The Bandarban structure lies in the middle zone of the folded part of the Chittagong hill tracts. Sedimentation in this part of the Bengal Basin was controlled by the collision of the Indian plate with the Burmese and the Tibetan plates and by the uplift and erosion of the Himalayan and Indo-Burma mountain ranges (Alam et al. 2003). The stratigraphic succession of the Chittagong-Tripura Folded Belt (CTFB) is of a Neogene age, starting with the basal Surma Group, which is overlain by the Tipam and Dupi Tila sandstones, respectively. The Surma Group of the Bengal Basin is the result of a major delta pro-gradation since the beginning of Neogene times (Miocene). It is thought to have been characterized by repetitive transgressive and regressive phases that resulted from subsidence as well as relative sea-level changes (Rahman & Faupl 2003).

In geology, the expression "thin beds" pertains to specific sedimentary layers or rock strata that exhibit a reduced thickness compared to the surrounding rock formations. The thickness of these thin beds exhibits a considerable range, spanning from a few millimeters to several centimeters. The differentiation of certain strata from their surrounding counterparts can be attributed to their unique characteristics, including but not limited to mineral composition, sedimentary structures, and chromatic properties (Bhuiyan & Hossain 2020). The observed stratification exhibits a series of slender layers, which may encompass a diverse range of sedimentary materials such as sand, silt, clay, or other analogous substances (Bhuiyan & Hossain 2020).

Thin-bed reservoirs present unique opportunities and challenges within hydrocarbon exploration and reservoir engineering. Thin bed reservoirs exhibit inherent diversity due to multiple layers with distinct characteristics. The spatial distribution of porosity and permeability within geological layers can vary due to these strata's heterogeneous composition, particle size, and depositional attributes (Ehrenberg 1993). These properties play a crucial role in facilitating the storage and movement of fluids within the subsurface environment. The fluid flow in thin-bed reservoirs is a complex phenomenon primarily attributed to the intricate interactions among the different layers. The efficacy of a reservoir characterized by thin beds is contingent upon the interconnectivity of its pore spaces, the existence of seals to impede fluid flow, and the overall permeability distribution across the layers (Bhuiyan & Hossain 2020, Ehrenberg 1993).

The reservoir horizons of the Sylhet and Bandarban fields exhibit variations in depth, thereby implying potential disparities in their petrographic and diagenetic characteristics. Reservoir characterization and field development necessitate precisely identifying variations in texture, mineralogy, and diagenetic alterations within the reservoir horizons of the two fields under investigation (Akter et al. 2023, Johnson & Nur Alam 1991, Khan et al. 2018). The present study aims to comprehensively analyze and compare reservoir horizons within the domains of petrography and diagenesis. The primary objectives of this study are to identify and analyze post-depositional diagenetic alterations in sandstone reservoirs, assess their impact on reservoir qualities, categorize the sandstones, and characterize the textural and mineralogical attributes of sandstone samples obtained from the Sylhet and Bandarban fields. By achieving these objectives, a comprehensive understanding of the diagenetic processes and their effects on reservoir properties can be obtained, contributing to the overall knowledge of sandstone reservoir systems (Akter et al. 2023, Ehrenberg 1990, Hossain et al. 2020, Johnson & Nur Alam 1991, Khan et al. 2018, Rahman & Faupl 2003).

The primary objective of this current investigation is to thoroughly analyze and assess the sandstones found within the Surma Group. This research aims to achieve two specific goals: i) to identify and thoroughly describe the thin-bed reservoirs present within the Surma Group sandstones, and ii) to elucidate the post-depositional diagenetic alterations that have occurred and their subsequent impact on the properties of these reservoirs.

MATERIALS AND METHODS

Field Investigation

To facilitate the objectives of the current investigation, an extensive fieldwork campaign was conducted in various road cuts and stream sections located within the Sylhet Trough and Bandarban district.

Sylhet

The Jaintiapur area, situated in the Sylhet district, has been selected as one of the study sites for investigation. It is geographically positioned between latitudes 25° 05' N to 25° 11' N and longitudes 92° 00' E to 92° 11' 15'' E (Fig. 1). For field investigation, three specific sections within the Jaintiapur area have been chosen.

The Shari River section is approximately 12 km south of Jaintiapur Thana and stretches from Sharighat to Tetulghat, near the border of India. This investigation is characterized by fault-controlled features observed along the river's meandering course. The lithology of this section consists of alternating bluish shale and yellowish sandstone, with intermittent calcareous sandstone bands.

The Tetulghat section primarily represents a stream-cut area that offers a highly advantageous view of the underlying sediments belonging to the Surma Group. The present section exhibits a remarkable sequence of alternating bluish-grey shale, silty shale, sandy shale, yellowish-brown sandstone, mudstone, and calcareous sandstone interbeds. Unconventional reservoirs, specifically thin beds, and tight reservoirs, are predominantly observed within this sub-section.

The examination of Nayagang River cut sections provides an opportunity for conducting field-based research aimed at the identification and assessment of unconventional reservoirs. The Naya Gang section exhibits a noteworthy sequence consisting of heterolithic beds, fine-grained sandstones with parallel lamination, and sandstones with trough cross-bedding. The bottom portion of the succession exhibits sedimentary structures such as laminated and trough crossbedding, which are indicative of conventional reservoirs. These features have been selected for a comparison analysis with unconventional reservoirs.

Bandarban

The Bandarban Anticline is a region of interest situated in the Bandarban district. It is geographically located between latitudes 22°05' N to 22°13' N and longitudes 92°08' E to 92°15' E. For field inquiry, four specific parts within the Bandarban area were selected.

The Sangu River section encompasses conventional and unconventional reservoirs and subsurface geological formations containing hydrocarbon resources. This section observes a prominent sandstone unit of considerable thickness, which is subsequently covered by a series of

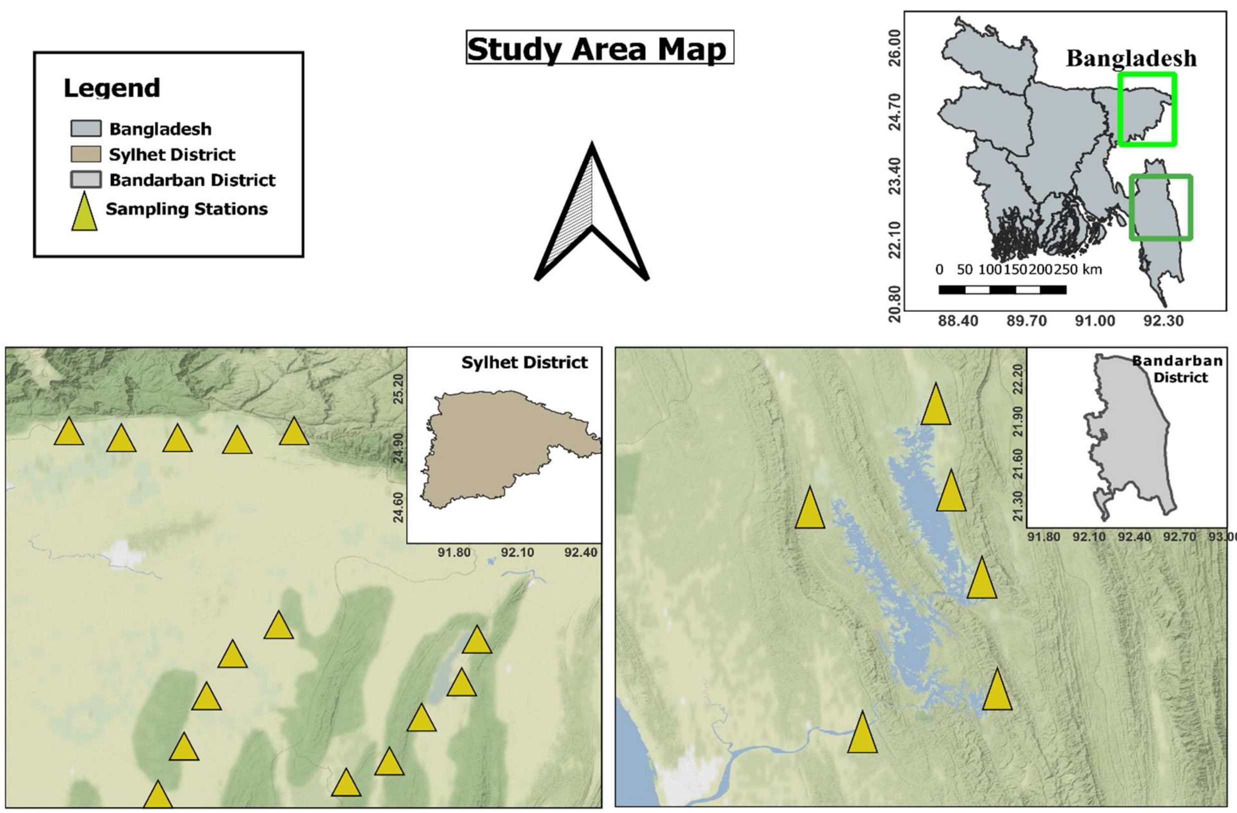

Fig. 1: Study area map showing sampling locations both in Sylhet region and Bandarban region.

heterolithic beds. These beds exhibit an intertidal sequence characterized by flaser, wavy, and lenticular bedding structures.

Bonopropat channel sand section is situated approximately 2 kilometers in the southwest direction from the town of Bandarban. The examination of sedimentary structures presented in this particular section, in conjunction with the associated facies assemblage, provides an advantageous opportunity to investigate the distinctive attributes of the unconventional reservoir.

The Shoilopropat section is situated approximately 5 kilometers to the south of Bandarban town. The Shoilopropat section is characterized by a remarkable sequence of hetero-lithic beds, comprising thin-bedded play, exhibiting alternating sandstone and shale layers.

Rupali Jhorna section is approximately 8 kilometres in the southwest direction from the urban center of Bandarban. This succession is characterized by a prominent sandstone unit at its base, followed by heterolithic beds.

Laboratory Analysis

The samples that were chosen for analysis were observed to be in either a loose or moderately indurated state. The impregnation process was deemed crucial for the successful preparation of each sample. Subsequent procedures were executed following the impregnation process to facilitate the production of thin sections.

Preparation of Standard Thin Section

At first, slabs were cut with a knife, and the prepared slabs were washed with water and acetone to remove gases. Araldite resin and Araldite hardener were mixed 1:1 and diluted with toluene to increase viscosity (30% glue, 70% toluene). After submerging the samples in it for 3 days, the solution penetrated them. The indurated samples were then heated in an oven at 40°C temperature for 2 days to increase their rigidity. One side of the impregnated slab was polished on a coarse grinding lap and a glass plate until smooth and flat. Then, this was mounted on a clean microscope slide, applying Araldite glue (resin: hardener = 1:1) on the polished surface. The sample's free face was ground on a coarse lap until light could pass through. The rock sample's thickness was tested regularly using a polarising microscope until it reached 0.03 mm. After adding Canada balsam to the heated rock slide, a thin coverslip was applied.

Staining

The requisite solution was prepared by dissolving 0.1 grams of Alizarin Red S in 100 milliliters of 0.2% hydrochloric acid (HCl). The experimental procedure involved the immersion of precisely one-half of the slide into the designated solution for 2-3 minutes. Subsequently, the slide underwent a thorough washing process using distilled water. In the context of mineralogy, it has been observed that calcite exhibits a distinctive red coloration upon staining, whereas dolomite, on the other hand, does not manifest any discernible reaction.

Thin Section Petrography

The present study involved implementing a comprehensive qualitative and quantitative analysis, employing the esteemed Research Petrographic Microscope (LEICA), specifically the DM750P model. The images were captured utilizing the LEICA ICC50E module, seamlessly integrated with the microscope apparatus.

SEM

The 7600F is a state-of-the-art field-emission scanning electron microscope (FE-SEM) designed to visualize and image objects at the nanoscale level. A series of images were captured using the JEOL JSM-7600F scanning electron microscope (SEM) equipped with a backscattered electron detector operated at the Department of Nanomaterials and Ceramic Engineering (NCE), Bangladesh University of Engineering and Technology (BUET), Dhaka.

RESULTS AND DISCUSSION

Texture

Based on visual comparisons to a reference slide, the analysis of grain size estimations in thin slices suggests that the Bhuban sandstone generally exhibits a finer-grained nature in comparison to the Bokabil sandstone. There is observable evidence of a progressive increase in grain size, consistent with the overall geological and sedimentological evolution of the Bengal Basin. This evolution is characterized by a gradual shallowing of the deltaic basin, leading to the dominance of the fluvial system at the uppermost level. The findings of the study suggest that a majority of the grains exhibit subangular to subrounded shapes, as well as subspherical to subprismoidal forms.

Based on the findings of this investigation, it has been determined that the sandstones within the Surma Group exhibit a high degree of sorting, ranging from well to very well sorted. The collected data reveals that among the total number of samples analyzed, 61% exhibit a well-sorted nature. Furthermore, 22% of the samples demonstrate a very well-sorted characteristic. Additionally, 11% of the samples fall within the range of being classified as well as very well sorted. Lastly, a minor proportion of 6% of the samples display a moderate level of sorting (Fig. 2).

The majority of the collected samples exhibit a matrix composition ranging from 1% to 4%, with only a limited number of specimens being entirely devoid of any matrix material. The analysis of grain size, sorting, and matrix composition in the sandstone samples indicates a predominance of texturally mature and clean characteristics.

Porosity

The quantification of thin section porosity was conducted through a visual comparative analysis for every individual sample. The findings consistently demonstrated that thin section porosity values were consistently lower than those obtained through porosimeter analysis, exhibiting an average disparity of 13.5 percent (Fig. 3).

The findings of the current investigation demonstrate that the porosity of thin-bed reservoirs within the Bhuban formation exhibits a range of 4 to 12% when analyzed using thin-section techniques. The findings of this investigation demonstrate a discernible pattern in the porosity values observed within the samples obtained from the Bhuban Formation. Specifically, it is observed that the porosity values exhibit a decreasing trend up to a certain depth, followed by a subsequent increase to a significant extent at greater depths.

Detrital Components

The detrital components observed in this study are the by-products resulting from the disintegration and decomposition processes of pre-existing rocks, including igneous, metamorphic, and sedimentary rocks (Fig. 4 & 5). These components are subsequently deposited within the basin following varying durations of transportation via water and/or wind mechanisms.

Detrital Framework Grains

The detrital framework grains found within sandstone

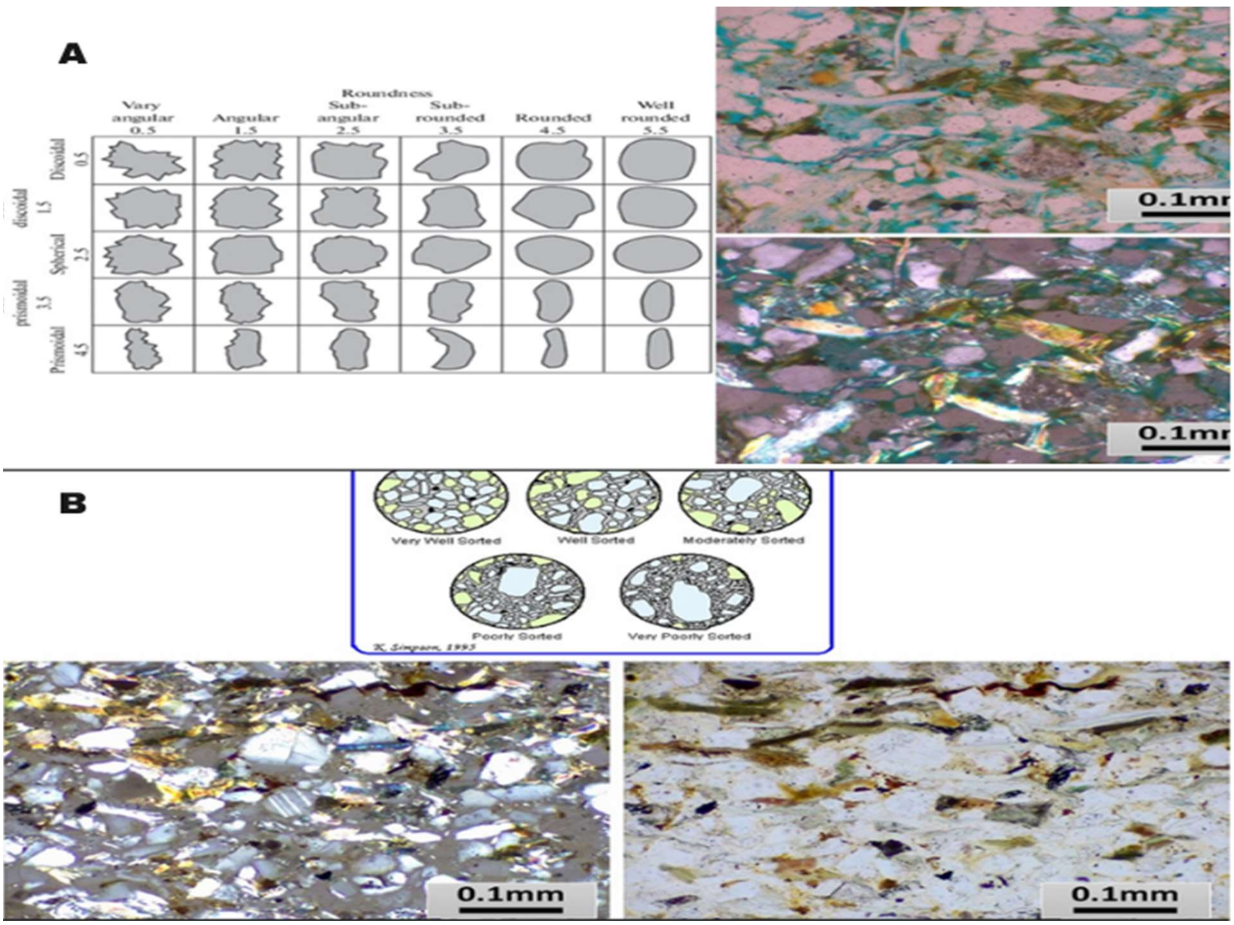

Fig. 2: A visual comparison chart for estimating roundness and sphericity (after Power 1982), subangular to subrounded and Subspherical (A), well to very well sorted (B).

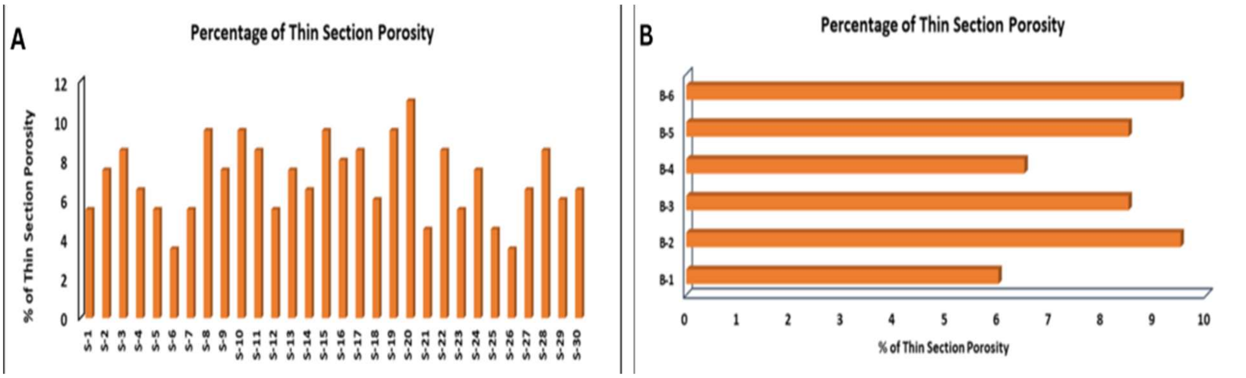

Fig. 3: Percentage of thin section porosity at Sylhet region (A) and Bandarban region (B).

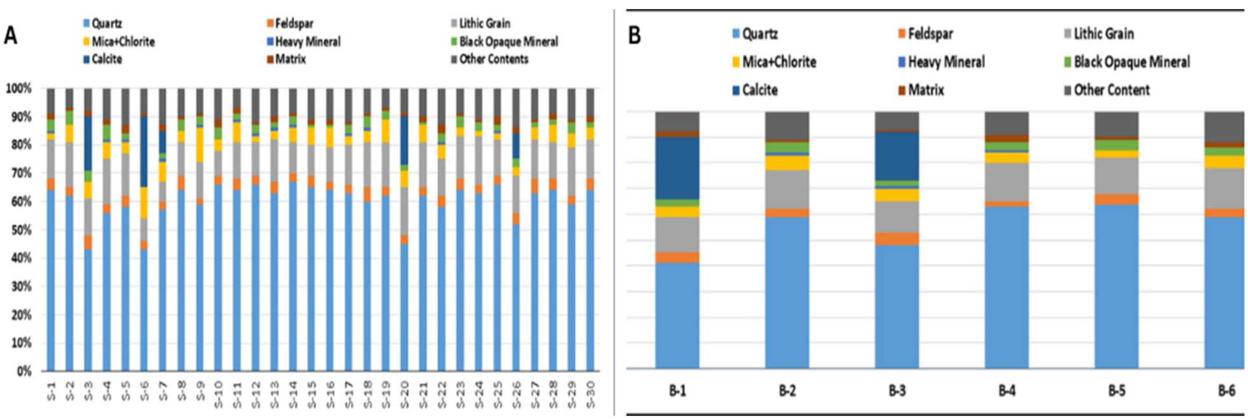

Fig. 4: Mineralogical composition from Sylhet region (A) and Bandarban region (B).

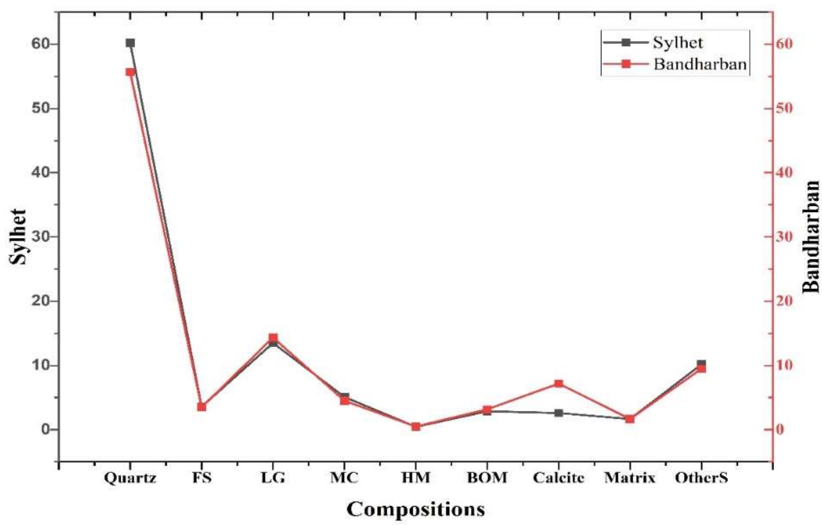

Fig. 5: Comparison of Thin section petrographic data (mineralogical composition, including Quartz, FS=Feldspar, LG=Lithic Grain, MC=Mica+Chlorite, HM=Heavy Mineral, BOM=Black Opaque Mineral).

Table 1: Framework of grains in the studied samples from Sylhet region and Bandarban Region.

Major	Minor	Minor Accessories
Quartz	Chlorite	Non-opaque heavy minerals
Feldspar	Mica Muscovite	Dark opaque grains
Lithic Grains	Biotite	Organic matters

deposits consist of sand-sized particles that can be classified as either monomineralic or polymineralic. Monomineralic grains, such as quartz, feldspars, and mica, are composed of a single mineral species. On the other hand, polymineralic grains, known as lithic grains, are comprised of multiple mineral species (Table 1).

Quartz, as determined through meticulous analysis, has been identified as the predominant constituent within the sandstone samples under investigation. The mineral quartz is primarily found in two forms: monocrystalline grains, which can be either strained or unstrained, and polycrystalline grains (Fig. 6).

Siltstone fragments are commonly encountered lithic grains of sedimentary origin, typically comprised of silt-sized quartz, feldspars, mica, and various other constituents, which are held together by a clay-rich matrix or alternative cementing agents. The lithic types mentioned herein are frequently encountered and account for a range of 5% to 20% in terms of the overall lithic grain composition (Fig. 6).

Cherts exhibit a dominant composition of quartz, with the occurrence of larger quartz crystals as well as minor impurities. The present study focuses on the characterization of ubiquitous rock fragments, which are found to constitute a significant proportion ranging from 1% to 7% of the overall lithic grains.

Quartz-mica aggregates potentially originate from igneous sources. These grains consist primarily of quartz and mica minerals, lacking any discernible preferred planar fabric. The lithic grains under consideration in this study are found to comprise a range of 1% to 6% of the overall sample (Fig. 6).

The present study investigates the relative abundance of lithic grains within the sample, specifically focusing on a subset of grains categorized as “types of grains.” These particular grains are found to comprise a range of 4% to 13% of the total lithic grain population.

Among the detrital framework grains of sandstone, feldspars hold significant importance alongside quartz and lithic grains. Our findings reveal that feldspars account for a range of 0 to 3% and 1% to 4% in these sandstone formations. The sandstone samples under investigation exhibit the coexistence of both potassium and plagioclase feldspars (Fig. 6).

Chlorite, a prevalent detrital mineral, has been observed in abundance within the sandstone samples under investigation. The observed phenomenon manifests as substantial detrital flakes measuring between 0.2 and 0.5 mm in size. These flakes frequently exhibit splayed-out ends and are distinguished by their distinct green hue and pronounced pleochroism (Fig. 6 K-L).

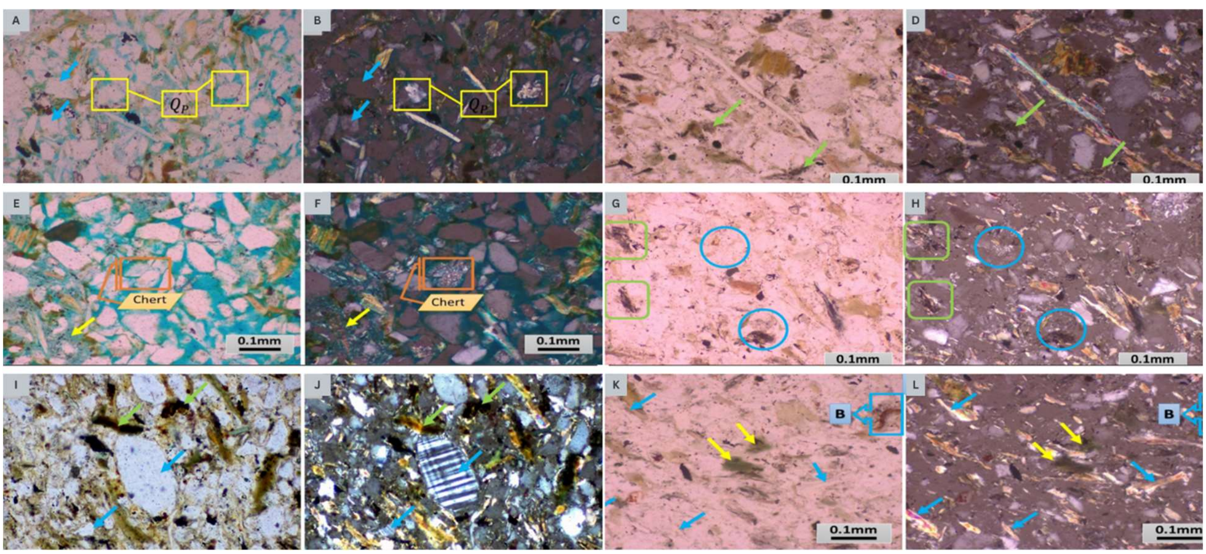

Fig. 6: A-B: Monocrystalline quartz (blue arrow) and polycrystalline quartz (yellow box); C-D: Siltstone fragments (green arrow), E-F: Chert (orange box) and matrix (yellow arrow); G-H: Quartz-mica aggregates (green box) and chert (blue circle); I-J: Feldspar (blue arrow) and organic matter (green arrow); K-L: Chlorite (yellow arrow), muscovite (blue arrow) and biotite (blue box).

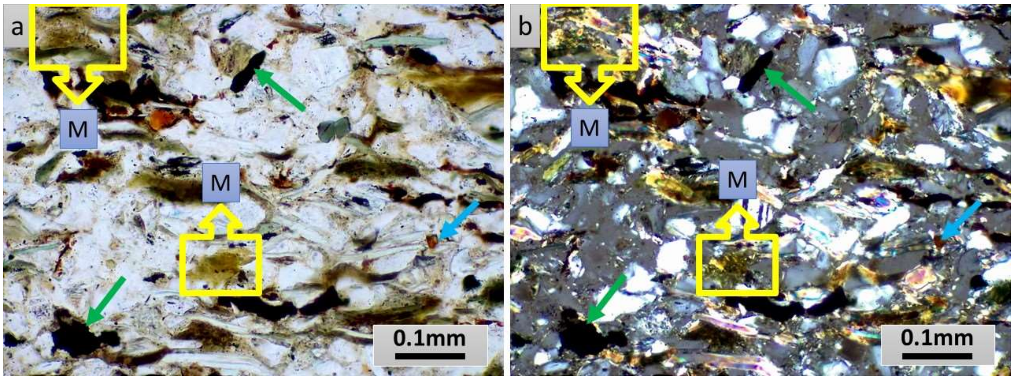

Fig. 7: Heavy minerals (blue arrow), indeterminate (green arrow) and matrix (yellow box).

The present investigation employs thin-section petrographic analysis to examine the occurrence of muscovite and biotite as detrital flakes, characterized by frequently observed splayed-out ends (Fig. 6). The relative abundance of muscovite is typically greater in comparison to biotite. Chlorite and mica, two distinct mineral species, are collectively classified as monocrystalline phyllosilicates within the realm of mineralogy. The sandstones of the Bhuban Formation exhibit a notable presence of constituents ranging from 2% to 11% within thin-bed reservoirs.

Various categories of dense minerals are present in small quantities as subordinate sedimentary particles, collectively comprising a range of 0 to 3% of the overall constituents of the rock. The assemblage of heavy minerals comprises various mineral species, such as garnet, zircon, tourmaline, epidote, rutile, Kyanite sillimanite, hornblende, augite, and other unidentified black opaque grains (Fig. 7). The observed range of black opaque grains spans from 0% to 3% of the total rock constituents.

The matrix comprises fine clastic mineral particles that are interstitial to the framework grains and are deposited concurrently with the supporting grains. The analysis of point count data reveals that the overall matrix content is consistently low, with a majority of the samples exhibiting levels below 4%.

The identification of the mineralogy within the matrix is challenging due to its exceptionally fine-grained composition. The identified constituents of the specimens under investigation are confirmed to be quartz and clay minerals, specifically kaolinite, illite, and chlorite (Fig. 7).

In certain instances, the pseudo matrix exhibits similarities to the matrix. The identification of pseudomatrix can be accomplished through the application of specific criteria, as established by Dickinson in 1970 (Dickinson 1970).

Authigenic Components

The presence of authigenic kaolinites has been exclusively observed within the lower segment of the Bhuban formation sequence. The findings from scanning electron microscopy (SEM) analysis and eye estimation techniques reveal that the presence of authigenic kaolinite in the rock composition is limited to a range of 0.1% to 2%. Two distinct modes of occurrence have been duly acknowledged in the scientific literature. The first mode, referred to as pore-filling kaolinites, is characterized by the absence of any discernible association with precursor minerals (Fig. 8). These kaolinites are observed to occupy discrete pore spaces within well-sorted sandstones. In the context of thin sections, the observed specimens exhibit a colorless appearance when examined under plane-polarized light. Furthermore, their birefringence, as determined under a 20X Nicols microscope, is found to be relatively low. The composition of these specimens primarily consists of particles of kaolinite, with an average size in the range of several microns.

The assemblage of authigenic non-clay minerals in the studied geological formation encompasses various mineral species, such as quartz, ferroan calcite, and siderite, among others. The aforementioned phenomena manifest themselves in the form of substances that fill the pores and replace the grains. The presence of authigenic quartz, specifically in the form of quartz overgrowths, has been identified as a prevalent diagenetic mineral within the Bhuban sandstones located in the Eastern folded belt of Bangladesh. The presence of quartz overgrowth cement in thin-bed reservoir sandstones is observed to range from 0 to 1% and 1% to 4% of the overall rock composition (Fig. 9).

Quartz overgrowths within thin sections, when observed through the conventional polarizing microscope, can be identified based on two distinct characteristics. Firstly, the presence of a “dust line” demarcating the boundary between the detrital grain nuclei and the overgrowths serves

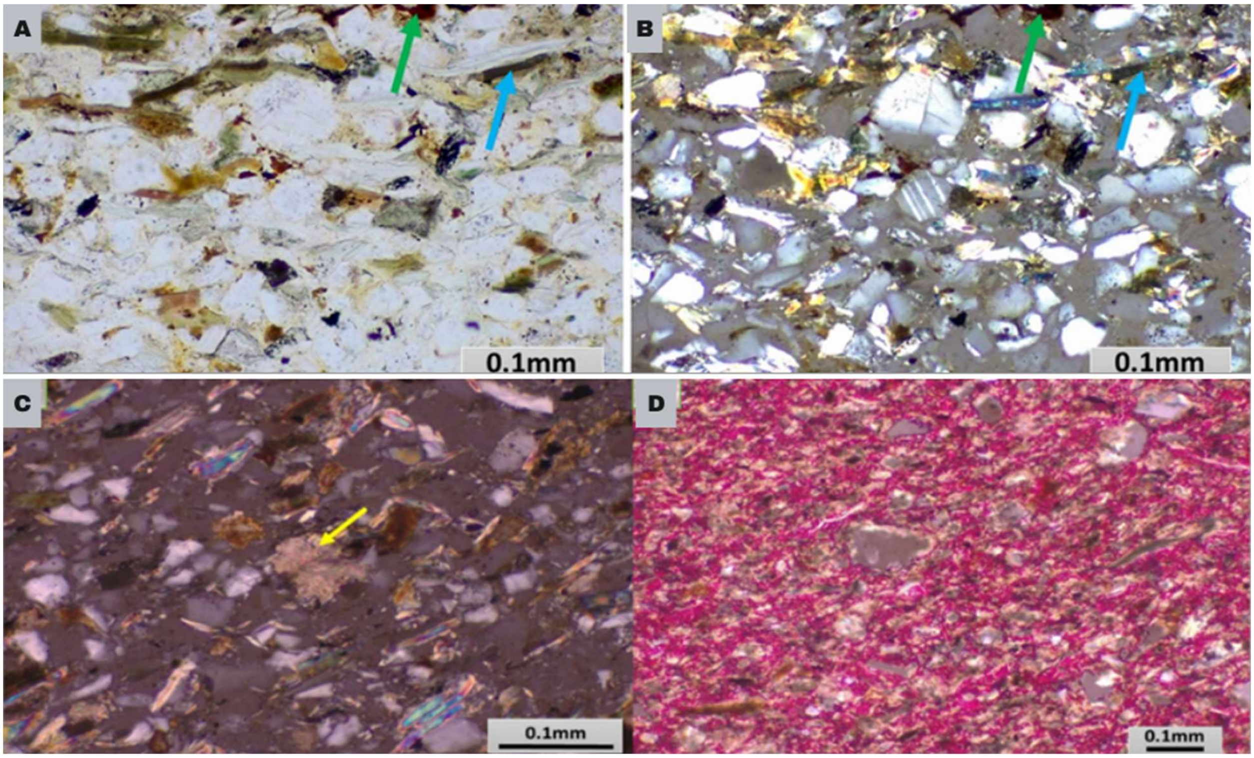

Fig. 8: A-B: Pore-filling grain (green arrow) and chlorite rim (blue arrow); C-D: Isolated pore-filling calcite (yellow arrow).

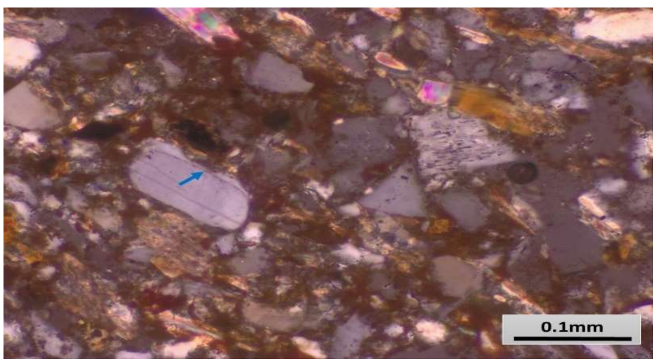

Fig. 9: Photomicrograph of quartz overgrowth.

as a reliable indicator. Alternatively, the identification can be made by observing the well-formed crystal faces of the overgrowths, which exhibit a distinctive morphology (Fig. 9). The formation of dust lines is a prevalent phenomenon attributed to the presence of a delicate layer of illite clay, characterized by its discernible high birefringence. In addition to the presence of clay films or coatings, the occurrence of dust lines is frequently observed due to the formation of various impurities between the overgrowths and nuclei.

Calcite cement, an extensively prevalent authigenic mineral, has been observed within the sandstones of the Surma Group in the Eastern folded belt of Bangladesh. The petrographic examination of calcite cement reveals its colorless appearance, variable relief under plane light, and rhombohedral cleavages. The Bhuban sandstones exhibit a variable calcite cement content, ranging from 0% to 26% of the overall rock composition. The presence of calcite cement within geological formations manifests in two distinct forms: i) as isolated pore-filling and replacive Fe-calcite cement and ii) as poikilotopic ferroan calcite.

Isolated pore-filling and replacive Fe-calcite cement: The prevalent forms of calcite cement within the Surma sandstones (Fig. 8) encompass the infilling of isolated pore spaces by ferroan calcite cement, as well as the replacement of detrital grains by calcite cement. In the present study, it has been observed that calcite predominantly undergoes replacement in the marginal region of detrital grains. However, it is noteworthy that certain samples exhibit extensive grain replacement, leading to a substantial augmentation in the proportion of ferroan calcite. Specifically, the content of ferroan calcite has been found to range from 17% to 35% of the overall constituents of the rock.

Poikilotopic ferroan calcite: The occurrence of poikilotopic ferroan calcite cement is limited to a small number of samples, wherein it fills the pore spaces, resulting in a complete reduction of both porosity and permeability to a value of zero (Fig. 8). Through the SEM method, it has been determined that poikilotopic calcite cement accounts for approximately 35% to 41% of the overall rock components. These crystals exhibit a euhedral morphology and display a size range spanning from 0.5 mm to over 1.0 mm. The phenomenon of poikilotopic cement crystallization has been proposed to involve the expansion of intergranular space, leading to subsequent rearrangements in the packing of detrital grains and an increase in the separation between these grains (Dapples 1971).

Classification and Nomenclature of the Studied Sandstone Samples

By the established criterion, it has been determined that all specimens under examination exhibit a matrix content of less than 15%. Consequently, these specimens have been initially categorized as clean sands or arenites. The proportions of quartz, feldspars, and lithic grains were recalculated to yield a total of 100% (Fig. 10).

Diagenesis

The term diagenesis encompasses a comprehensive array of physical, physico-chemical, and chemical processes that occur after sediment burial. The sediments undergo diagenetic alterations after their burial, resulting in their transformation into lithified rocks. The diagenetic alterations in the composition and texture of sediments give rise to the modification of the reservoir properties of sandstones.

Diagenetic Processes

The Surma Group of sediments is primarily characterized by a nearly equal distribution of alternating sandstones and shales, accompanied by lesser amounts of siltstones and minimal conglomerates. The sandstone formations, which consist of both detrital and authigenic constituents, predominantly exhibit characteristics of fine-grained and well-sorted arenites, with a minor presence of matrix material ranging from 0 to 4%. The diagenesis of Surma sandstones in the Eastern folded belt structure is characterized by notable alterations like grain contacts and the deformation of soft lithic grains.

Compaction

The initial diagenetic process that exerts an influence on sand deposits shortly after their deposition and subsequent burial beneath the sediment-water interface is known as compaction. The overburden pressure experienced by sediments primarily drives this process. The observed phenomenon exhibits a positive correlation between its intensity and the depth of burial.

The initial reaction of compaction entails the reconfiguration of detrital grains, commonly referred

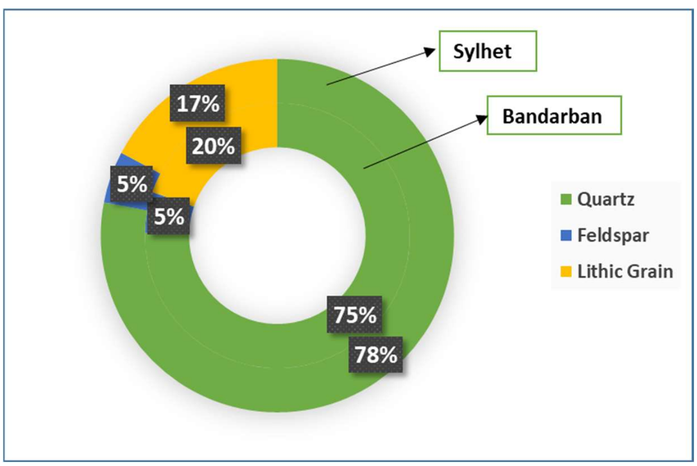

Fig. 10: Relative abundance of Quartz, Feldspar, and Lithic grains (recalculated to 100%).

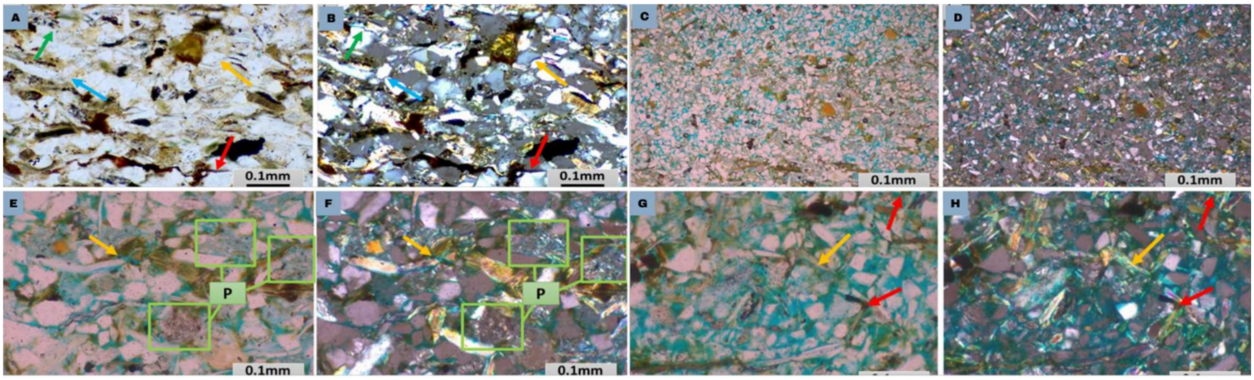

Fig. 11: A-B: Concavo convex (orange arrow), grain coating (red arrow), point contact (blue arrow) and suture contact concavo (green arrow); C-D: Pseudomatrix and mica fracturing; E-F: Pseudomatrix (green box) and mica fracturing (orange arrow); G-H: Gentle bending (orange arrow), grain fracturing and tight packing (red arrow).

to as packing readjustment. This phenomenon leads to a more densely packed arrangement of grains (Fig. 11). The readjustment is characterized by alterations like grain contacts. Initially, at shallow depths, the contacts between grains are primarily point contacts. However, as the depth increases, these contacts gradually transform into elongated, concavo-convex, and sutured contacts (Fig. 11).

Ductile or labile grains, including shale, claystone, siltstone, phyllite, schist fragments, and others, play a significant role as constituents within Surma sandstones. These sandstones undergo permanent deformation as a result of compression from neighboring rigid grains in response to the applied overburden pressure. The process of compression frequently results in the displacement of pliable lithic particles into neighboring pore spaces, causing them to undergo significant deformation and adopt the characteristics of an interstitial matrix, commonly known as a pseudo-matrix (Fig. 11).

The occurrence of flexural deformation in mica and chlorite minerals, as well as the propensity for brittle fracture in feldspar, lithic grains, and heavy minerals, is a prevalent phenomenon observed within the Surma Sandstone formation. The phenomenon of mica bending is observed to vary in response to the magnitude of overburden stress. However, under more substantial overburden stress, mica undergoes more pronounced bending, resulting in a distinctive zigzag shape. In such cases, the bending may be accompanied by fracturing (Fig. 11). Feldspars exhibit a higher degree of susceptibility toward fracturing (Fig. 11). This fracturing phenomenon primarily occurs along the cleavage planes of feldspars. However, it is worth noting that fracturing is also a prevalent occurrence in brittle lithic grains (Fig. 11).

Pressure Solution

The phenomenon of pressure solution entails the dissolution of mineral grains occurring at the precise locations where they come into contact under the influence of external stress. This process leads to the formation of densely packed grains and subsequently enhances the compaction of the surrounding rocks. Within the Surma Sandstones, the dominant mineral implicated in pressure solution phenomena is quartz. As a secondary process, quartz overgrowths have precipitated from the fluid residing within the pore spaces. The investigation of pressure solution phenomena within the current geological sequence has primarily focused on the Bhuban Formation. At the same time, its significance within the BokaBil Formation appears to be comparatively less pronounced. The aforementioned phenomenon represents a significant contributor to the formation of quartz overgrowth cement.

Cementation

The process of cementation, which involves the chemical precipitation of authigenic minerals from subsurface pore fluids, is a significant phenomenon in geological formations. These minerals, commonly referred to as authigenic minerals or cement, play a crucial role in the consolidation and alteration of sedimentary rocks. The examined samples have exhibited the presence of various cementing minerals, including silica in the form of quartz overgrowth, ferroan calcite, chlorite, kaolinite, illite, and siderite. The presence of cementitious materials is observed consistently across the entire sequence, with occasional occurrences limited to specific horizons.

The occurrence of secondary enlargement of quartz grains, specifically in the form of quartz overgrowths, has been extensively documented in the sandstone samples under investigation. These overgrowths are commonly observed in abundance within the lower section of the sequence, while their presence is relatively scarce in the upper portion. The presence of more sophisticated forms of quartz overgrowths (Fig. 9) in the lower portion of the sequence indicates a significant flow of pore water enriched with silica throughout the corresponding sedimentary layers.

The phenomenon of silicate replacement by calcite and the dissolution of feldspars have been observed in numerous samples. The present study reveals compelling evidence about the phenomenon of silicate replacement within calcareous sandstones, as well as the dissolution of feldspars, predominantly observed in the lower portion of the investigated strata. It is important to note that these occurrences are limited to specific horizons within the geological formation under examination.

The prevalence of calcite cement is the predominant diagenetic characteristic observed in the examined specimens. The calcite cement present in the studied sample exhibits a ferroan composition, indicating the presence of iron within its mineral structure. The cementation process has effectively occupied all pore spaces, resulting in a complete reduction of both porosity and permeability to an absolute minimum. The present study investigates a specific form of cementation characterized by the loose arrangement of particles, colloquially referred to as "floating" grains, and the absence of compactional features and most diagenetic minerals. The phenomenon of calcite generation of this particular type has been observed in a limited number of samples (Fig. 12).

Authigenic chlorites, specifically chlorite rims and pore-filling chlorites, have been identified as prevalent diagenetic minerals in the sandstone samples examined (Fig. 12). These chlorites manifest as grain-coating chlorites and pore-filling chlorites and have been observed across a wide range of sandstone specimens. The presence of alternative chlorite cement has been observed, albeit infrequently. The presence of chlorite rims has been observed to exert an indirect influence on the preservation of porosity through the inhibition of quartz overgrowth growth. The mechanisms responsible for the generation of these enigmatic features, characterized by their delicate occurrence and intricate textural associations with detrital grains and diagenetic minerals, remain elusive.

The final diagenetic phase observed in Early Miocene sandstones, specifically in the lower portion of the sequence, is the cementation by kaolinite. The prevalence of pore-filling kaolinite (Fig. 12) surpasses that of in situ alteration kaolinite. However, it is worth noting that the impact of kaolinite precipitation on porosity is comparatively less significant when compared to the effects of Fe calcite or quartz cementation.

The presence of authigenic illite, a diagenetic mineral, was observed in the sandstone samples. In terms of volumetric considerations, its impact on reservoir properties is relatively inconsequential. However, it assumes a catalytic role in facilitating pressure solution (Fig. 12) of quartz grains, which serves as a prominent mechanism for the formation of quartz overgrowth cement.

Replacement

The Surma sequence typically exhibits the replacement of silicates, such as quartz and feldspars, as well as certain lithic grains. The predominant replacive agents observed in this study are primarily composed of calcite, with a lesser extent of chlorite. The phenomenon of replacement has been observed to manifest primarily through the following

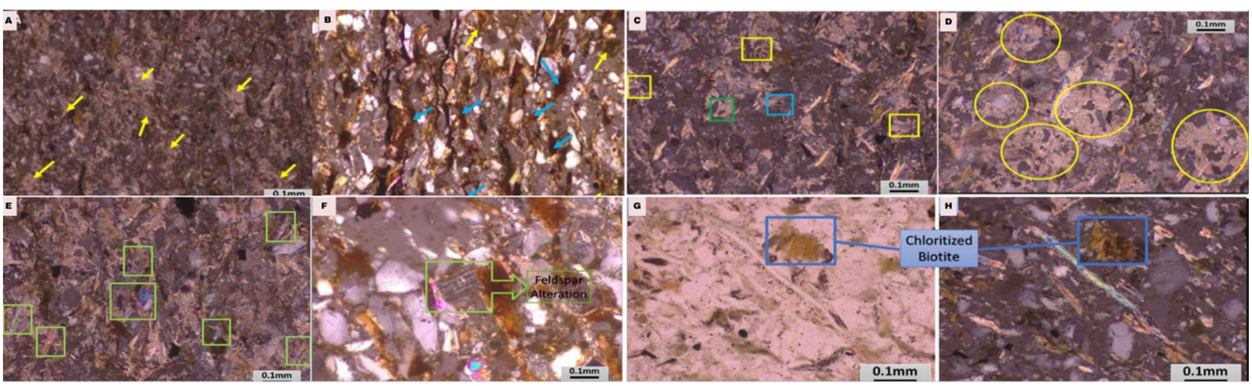

Fig. 12: A-B: Calcite and chlorite cementation (yellow arrow), kaolinite/illite cementation (blue arrow); C-D: Feldspar replacement by calcite (blue box), remnant quartz (green box), corroded grain and quartz replacement by calcite (yellow box), quartz grains replacement by calcite (yellow circle); E-F: Mica replacement by calcite (green box) and feldspar alteration along the cleavage plane (green arrow); G-H: Chloritized biotite (blue box)..

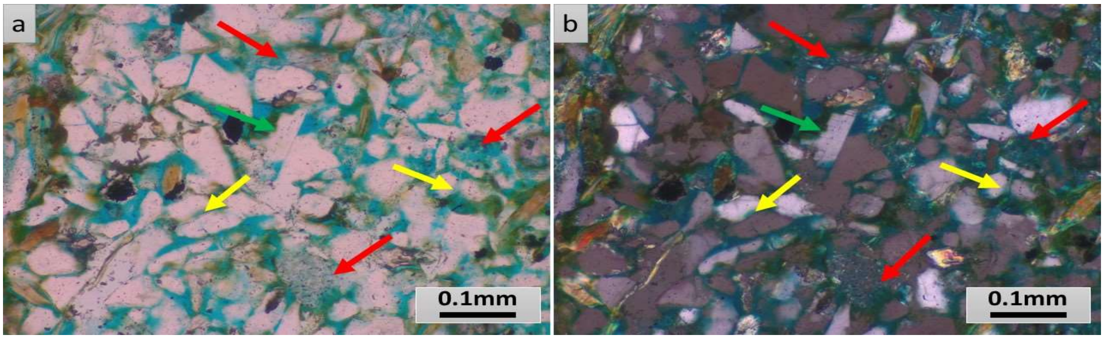

Fig. 13: Dissolution of quartz (yellow arrow), dissolution of feldspar (green arrow) and dissolution of lithic grains (red arrow).

modalities: a) Corroded replacement, characterized by the presence of corroded and crenulated grain boundaries. Quartz predominantly serves as the substituting agent, wherein it undergoes replacement by calcite (Fig. 12). b) Skeletal Remnants: The presence of skeletal grains is noted after the process of replacement. The phenomenon of skeletal replacement has predominantly been observed in feldspars and lithic grains. The replacement of feldspar grains occurs specifically along the cleavage planes or areas of weakness, while the lithic grains' siliceous component undergoes replacement by calcite (Fig. 12). c) Remnant Replacement: A minuscule fraction of detrital grains, such as quartz or feldspars, has been observed to persist as remnant grains after the replacement process. The presence of calcite cement in the vicinity of remnant grains is a commonly observed phenomenon. Multiple remnants exhibit consistent extinction properties that resemble the individual components of a singular grain (Fig. 12).

The process of biotite alteration, resulting in the formation of chlorite, is commonly referred to as chloritized biotite. Chloritized biotite (Fig. 12) exhibits distinctive characteristics, including a laminar morphology and a brown hue with a discernible greenish undertone.

Alteration

The present study has yielded compelling evidence of discernible alteration within the examined sandstone samples. The petrographic evidence about alteration exhibits a degree of ambiguity, as observed in instances where a grain possessing the characteristic geometry of a precursor mineral, such as feldspar, is found to be comprised of novel minerals, specifically small aggregates or filaments of kaolinite.

The alteration of feldspar and biotite minerals has been observed and documented (Fig. 12). The present investigation has revealed the occurrence of both partial and complete alterations within the examined sandstone specimens. Within the realm of feldspars, it has been observed that plagioclase and orthoclase feldspars exhibit a higher degree of susceptibility to alteration when compared to their microcline counterparts.

Dissolution

The phenomenon of dissolution of soluble constituents in sandstones, whether completely or partially, has been documented in select samples of the Early Miocene sequence within the Eastern folded belt structure. The aforementioned process has induced the formation of secondary porosity within the sandstone formations, thereby leading to a general augmentation in the overall porosity of said rocks (Fig. 13). The dissolution of various materials, including feldspars, lithic grains, and ferroan calcite cement, has been observed and documented. In certain specimens, the dissolution of constituents within the rock matrix is observed to occur at a significant magnitude, resulting in the development of porosity. This porosity, attributed to dissolution processes, accounts for approximately 35% to 40% of the overall porosity exhibited by the rock samples under investigation.

CONCLUSION

The petrographic investigations were carried out quantitatively and qualitatively on thin layers of the sandstone samples from the Sylhet and Bandarban regions. The sediments in Sylhet samples are submature-mature, densely packed, subangular-subrounded, poorly sorted, and of medium-coarse grain size. Contrarily, Bandarban samples are mature-sub mature, moderately-loosely packed sediments with fine-medium-grained, subangular-subrounded, moderate-well sorted, and these characteristics. The sandstones in both fields are quartz arenites that are subarkosic and mostly made of quartz, feldspar, mica, lithic grains, clay, and other authigenic minerals other than clay. The field study demonstrates that thin beds are fine to medium-grained (sometimes very fine-grained), sub-angular to sub-rounded, and well-sorted. Frequent change of sand-shale with the predominance of parallel bedded sandstone is observed. Both inner-granular and intra-granular, along with the pore canal, are the recognizable proof observed from laboratory analysis. The average porosity ranges from 4% to 12%, most of which are interconnected. The pore spaces within the tight reservoir are not interconnected despite a considerable amount of pore spaces (average porosity 4% - 8%) there. Here, the permeability is very low.

On the other hand, conventional reservoirs are medium to fine-grained, well-sorted, and contain an average porosity of 10% to 20%, most of which are connected. The foremost imperative disclosure made from this study is that the thin beds of the unconventional and conventional reservoirs have similar poro-perm values. The most vital difference is that the thickness of the thin bed and tight reservoir is not more than 1 or 2 meters. Along these lines, even though the vertical thickness is not so high, they keep up an extensive lateral persistence. Therefore, thin-bed reservoirs might be considered as good as conventional ones. Bangladesh is facing an impending energy crisis. To reduce the dependency on the conventional reservoir, serious steps have to be focused on an unconventional reservoir, particularly a thin-bed reservoir.

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