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Evaluation of Reservoir Properties of Sylhet Limestone of Jaintia Group, North-Eastern Sylhet, Bangladesh

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ABSTRACT: The Sylhet Limestone in the Bengal Basin, formed in the Eocene Epoch and known for its fossil content, is significant in understanding the reservoir characteristics. Despite exposure in Jaflong and Takerghat of the Bengal Basin, little research has been conducted on reservoir characteristics. This study aimed to comprehensively examine the Sylhet Limestone Formation, encompassing its crystalline upper and fossiliferous lower sections. It utilized field investigations and laboratory analyses to address the gaps of sporadic or insufficient earlier studies. A thorough examination of thin sections from the Sylhet Limestone, exposed in the Dauki River area, provides insights into the textural and mineralogical attributes and the presence of skeletal fossils within the limestone. Based on the analysis of thin sections, the limestones are categorized as Rudestones and Packstones. The porosity observed in the exposed rocks ranges from 5% to 12%, with most pores associated with interconnected fractures and joints. However, thin-section studies also indicate evidence of diagenetic recrystallization and calcite cementation. Hence, closely spaced, interconnected joints and fractures filled with diagenetic calcite might deteriorate the reservoir quality. Notably, this limestone exhibits fossilized specimens such as *Nummulite, Discocyclina, Alveolina, Assilina*, and *Ostracoda*, among others. The combination of the fossil assemblage, limestone texture, and composition strongly suggests that this limestone formation was deposited in a shallow marine environment with minimal sediment input under a warm and humid climate. The petrographic analysis of the limestones concludes that the upper portion of the formation is fine-grained while the lower part is coarse-grained.

Keywords: Eocene; Limestone; Nummulites; Porosity; Reservoir

INTRODUCTION

This study aims to characterize the Eocene Sylhet Limestone of Jaintia Group petrographically to critically evaluate, define, and classify the formation from a reservoir and a depositional perspective. The petrographic information obtained from thin sections helps achieve this objective.

Limestone is a sedimentary rock mainly consisting of the skeletal remains of marine organisms like coral, foraminifera, green and red algae, and mollusks (Wilkinson, 1979). It is most frequently found in contemporary marine habitats with biological origins (Islam et al., 2021). There is a logical argument that sandstone and limestone reservoir performance do not differ materially. Correctly understanding limestones can ensure that differences exist regarding reservoir characterization (Craze, 1950). The crystalline and fossiliferous Eocene Sylhet Limestone unit is around 250m thick (Imam, 2013), but we observed a sequence of about 60m thick from bottom to top in the field. The sharp and faulted contact with the Kopili Formation is prominent because of the lithological change. However, basal contact with the Tura Sandstone Formation is not seen because of the lack of proper exposure (Jurgan, 1986). The base can be observed in Takerghat, which lies west of the study area along the boundary between Bangladesh and Meghalaya (Uddin et al., 2022). However, the bottom is not visible in the exposed section. This nummulitic Sylhet Limestone is deposited on a continental shelf (Khan, 1991; Reimann, 1993) and is considered a marker horizon in the seismic section.

Limestone (Carbonate) reservoirs comprise more than 60% of the world's oil reserves (Akbar et al., 2000). Without low fracturation and karst phenomenon, the limestone can be a potential reservoir if topographic and geological conditions are in favor. So far, the true potential of limestone in Bangladesh as a reservoir rock has yet to be addressed due to the minimal exposure of the limestone in Jaflong and Takerghat. Samples exposed on the surface do not accurately reflect the reservoir quality of the sub-surface, as they tend to

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develop solution pores through surface weathering, which are not present in the subsurface. However, proper investigation in the field and petrophysical analysis can reveal the reservoir quality of the limestone and add a new dimension to the national hydrocarbon reserve of Bangladesh.

The petrophysical characteristics of the exposed sections in the Jaflong area, the presence of interconnected joints, fractures, fissures, and microfractures, can act as a significant reservoir if present in the subsurface. The secondary porosity, like the dissolution porosity, can also add to the total void space of a formation, increasing the reservoir potential of the Sylhet Limestone Formation (Sarkar et al., 2022). The limestone unit is laterally extensive throughout the stable platform but has yet to be thoroughly studied. The regional seismic line along the Eocene Hinge Zone reveals the subsurface condition of the limestone reservoirs accurately, and this section was correlated with the outcrops of Jaflong. This integrated approach of seismic data and outcrop study qualifies the true capability of the Sylhet Limestone Formation as a reservoir.

GEOLOGICAL SETTING

The limestone deposits exposed in Jaflong to the left bank of the Dauki River section located in the Surma Basin, the latitude 25°10′45″ N and longitude 92°01′01″ E (Fig. 1), belong to the Eocene Sylhet Limestone Formation.

The stratigraphic table (Table 1) shows the position of the Sylhet Limestone Formation of the Early to Middle Eocene. This demonstrates the Formations' thickness, bounding conditions, and relative ages.

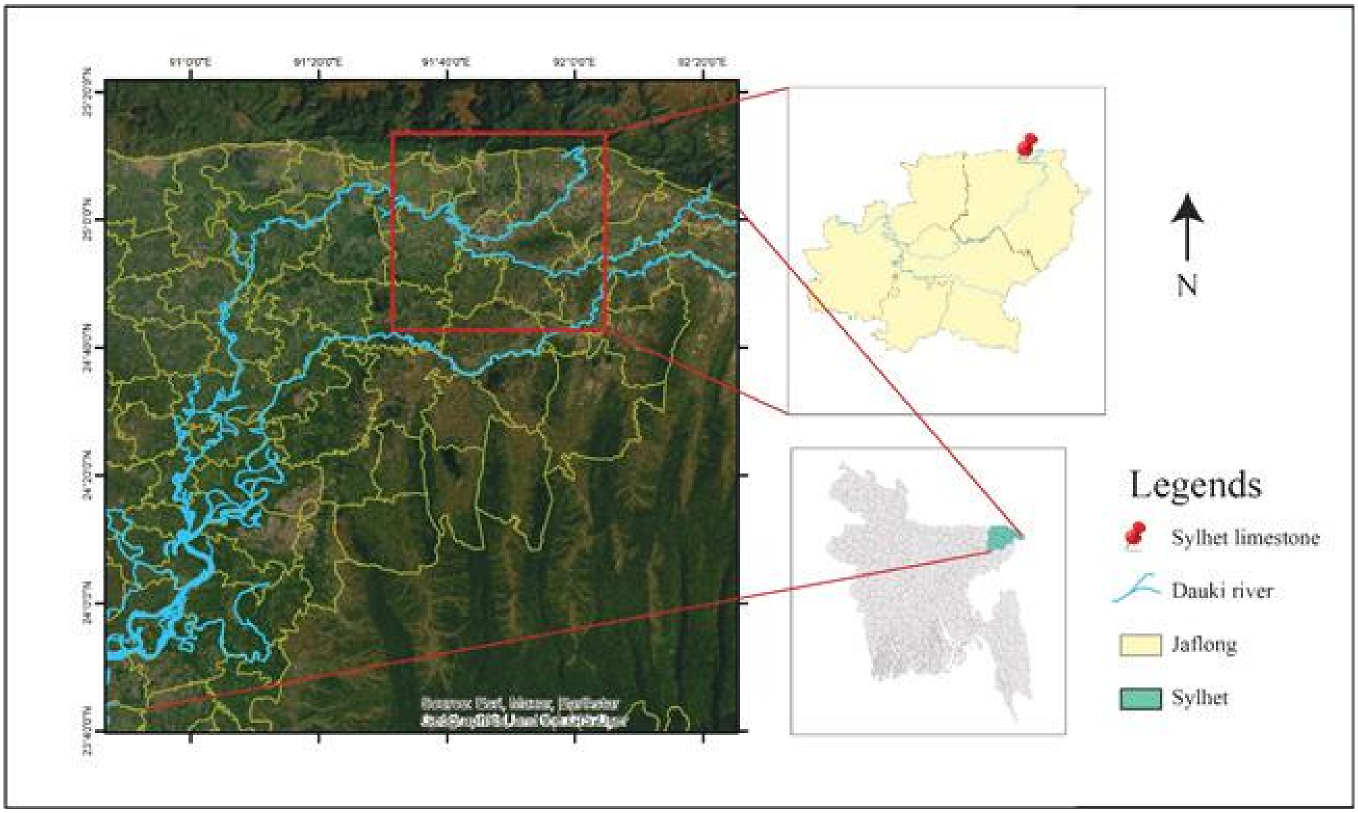

Figure 1: Location Map of the Sylhet Limestone Formation Location in the Study Area (Marked by a Red Square)

Table 1: Stratigraphic Succession Exposed Along with the Dauki River Section, Sylhet (Modified after Reimann, 1993). The Lithological Description, Relative Age, and Thickness are Provided in the Table According to the Formations. The Unconformity between Sylhet Limestone and Kopili Shale Formations, Along with Other Sharp and Faulted Contacts, are Shown in the Table by Red Dash Lines

Age	Formation	Lithological Description	Thickness (m)
Recent	Alluvium	Unconsolidated to partly consolidated sand, silt, clay, and some gravels.	1.0
Pleistocene	Dihing	Unconsolidated to partly consolidated graveliferous deposits, both debris flows and braided stream	Up to 5
Late Eocene	Kopili Shale	Black to dark grey shale, fissile, calcareous.	16.5
Early to Middle Eocene	Sylhet Limestone	Light to dark grey colored highly fossiliferous and non-fossiliferous Limestone. Hard and Compact, calcareous cementing materials are fractured at different places and are highly jointed.	40+ (Base not seen)

PREVIOUS STUDIES

Evans (1932) was the first to identify the Eocene Sylhet Limestone unit, which he described as a continuous sequence of limestone and sandstone that forms the central portion of the Jaintia Group (Brouwers et al., 1992).

The stage received its name from Sylhet, a village in the southern Shillong Plateau region. (Ambraseys et al., 2003; Bhandari et *al.*, 1973; Das Gupta, 1982).

The Sylhet Limestone Formation reaches 520 m thickness at its type area, the Jaintia Hills in Assam, India, and is divided into five members. The members, listed in descending order from top to bottom, consist of the Prang Limestone, Nurpah Sandstone, Umlatdoh Limestone, Lakadong Sandstone, and Lakadong Limestone. (Brouwers, et al., 1992).

In Bangladesh, the name "Sylhet Limestone" was initially employed by Khan (1963) to describe limestone deposits exposed in Sylhet. The Limestone Formations referred to as the Sylhet Limestone are found not only in Sylhet, Bangladesh (particularly in the Takerghat area) but also in various regions of India, including the Jaintia Hills, Khasia Hills, and Garo Hills, as well as beneath the surface in the Bogra district of Bangladesh, as documented by Khan and Muminullah (1988).

The topmost limestone layer in the Sylhet Limestone creates a distinctive seismic reflection, which is identifiable up to the Bhagirathi River (Johnson and Alam, 1991).

The subsurface Sylhet Limestone in West Bengal shares a resemblance in terms of both lithology and fossil content with the surface-exposed Sylhet Limestone found in the Garo Hills, known as the Siju Limestone "Stage," as well as in the Mikir Hills, as described by Biswas (1963).

Furthermore, the Sylhet Limestone in Bangladesh correlates with the Prang Limestone and the Siju Limestone in central and southern Assam. This correlation is based on similarities in lithology and the presence of foraminifera faunas, as documented by various researchers, including Nagappa (1956 and 1959), Zaher (1970), Ismail (1978), Mohan (1979), and Khan and Muminullah (1989).

Eocene Sylhet Limestone of Jaflong is the most fossiliferous rock unit, with an average thickness of 250 meters (Khan, 1990; Reimann, 1993; Imam, 2012). Due to its index fossils, Sylhet Limestone is known as Nummulitic Limestone (Islam et al., 2021).

In northeastern Bangladesh, the Sylhet Limestone and the Kopili Shale formations harbor numerous microfossils dating from the middle to late Eocene period (Sarkar, 2016, 2017; Bhattacharjya and Gogoi, 2018). The Sylhet Limestone (Nummulitic Limestone) is characterized by a rich and varied collection of larger foraminifera, a moderately diverse assembly of smaller benthic foraminifera, and a limited and less varied collection of ostracods (Sarkar, 2016, 2017; Bhattacharjya and Gogoi, 2018).

The connection between the Sylhet Limestone and other middle Eocene formations can be established through the examination of the larger foraminifera present *(Nummulites, Assilina, Discocyclina,* and *Alveolina*) (Sarkar, 2016, 2017; Bhattacharjya and Gogoi, 2018). The composition of microfossil assemblages within the Sylhet Limestone Formation undergoes alterations in direct response to the gradual shoaling trend observed in this particular region (Khan, 1991; Browers *et al.*, 1992). The Sylhet Limestone Formation exhibits various petrological components, such as micrites, diamictites, intramicrites, pelmicrites, sparites, intrasparites, pelsparites, and oosparites (Roy et al., 2008).

MATERIALS AND METHODS

Field Investigation

The study commenced with a comprehensive field investigation of the Sylhet Limestone exposure, aiming to gain insights into the rock type and acquire samples for further petrophysical analysis. To enhance comprehension, litho-columns were constructed to represent the various sections (Fig. 2), and the petrographic studies relied on microscopic thin sections prepared from the collected samples. Utilizing the Research Petrographic Microscope, a quantitative and qualitative analysis was conducted. The location chosen for sample collection was along the Dauki River, just South of the border with India (Fig. 1), from where ten samples (Figs. 3a and 4a) were obtained from the Sylhet Limestone Formation.

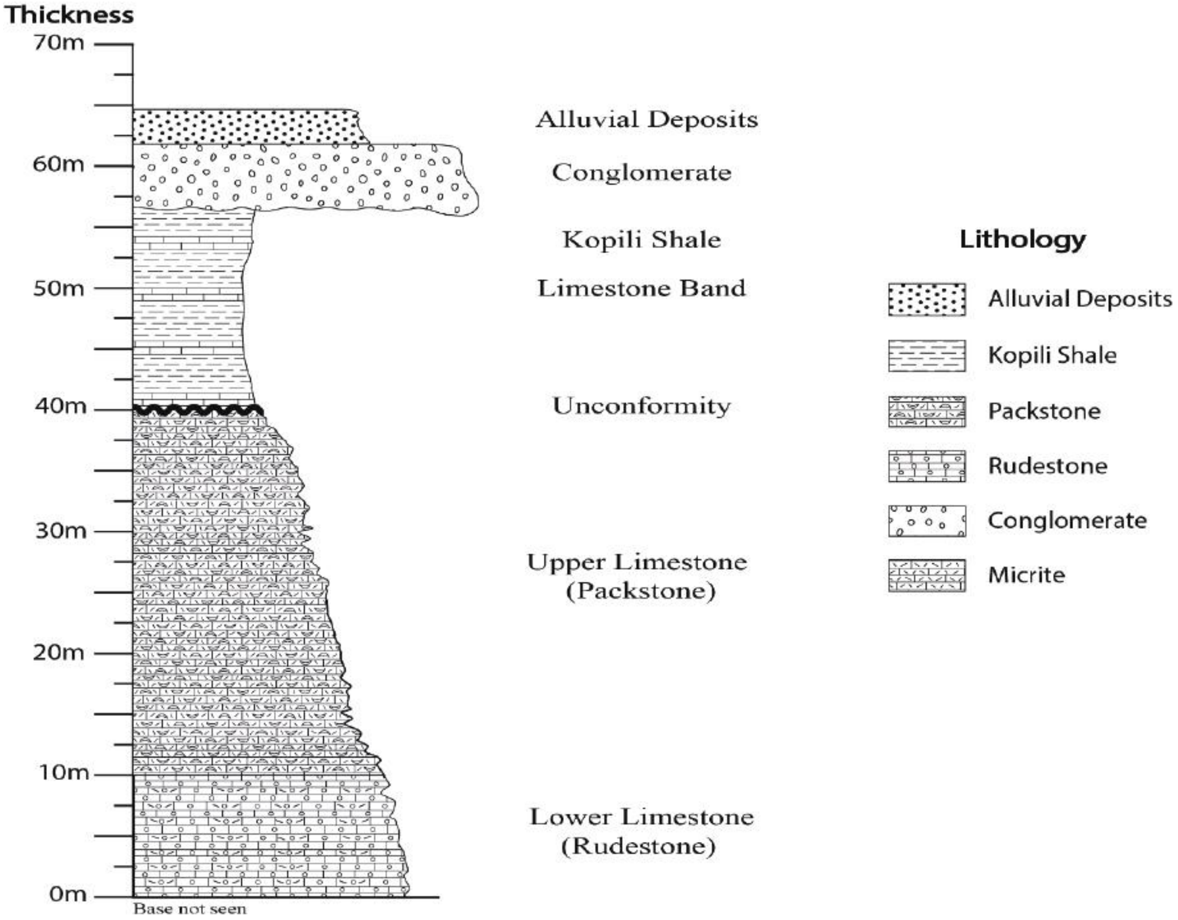

Figure 2: Figure Shows the Itho-Column of the Exposed Section in Jaflong, Sylhet, is about 65m Thick. The Log Indicates the Sequence Starting from the Bottom of Sylhet Limestone, Kopili Shale, Conglomerate, and Alluvial Deposits. A Bold black Wavy Line is Displayed as the Unconformity. The Lithology is Shown on the Right

Laboratory Analysis

The examination thoroughly assessed mineralogy, modal composition, and porosity. These microscopic observations yielded crucial information regarding textural relationships, mineralogical composition, and diagenetic changes.

Samples were cut into small slabs to prepare standard thin sections. Once impregnated, one side of each slab was sophistically polished and mounted onto clean microscope slides. The other side was carefully grinded until it achieved the desired thickness of 0.03 mm. Alizarin Red S stain differentiated limestone samples from dolomite and detrital fragments. Texture, mineralogy, composition, and diagenesis were thoroughly examined to assess the reservoir quality of the Sylhet Limestone Formation.

Scanning electron microscopy (SEM) generates highly detailed and magnified images of an object by scanning its surface with a focused electron beam, creating high-resolution visuals. These images reveal information about the object's composition and physical characteristics. Scanning electron microscopy (SEM) was utilized to investigate the dissolving pores within the limestone. This pore played a vital role in evaluating the reservoir quality of the formation.

RESULTS

The Texture of the Limestone

Limestone texture mostly depends on the type and characteristics of the fossils it consists of. The fossils' shape, size, and sorting determine the textural properties that vary with depth. In the lower part of the exposed Sylhet Limestone unit, up to 11m, the size of the skeletal grains ranges from 0.125 mm to 6 mm, and hence, most of the fossils that form the skeletal grain are visible to the naked eye. The hand specimen (Fig. 3a) exposed at the lower part (0 –11 m) of the unit indicates poor to moderately sorted (Fig. 3b) sediments, and sorting improves gradually in the upward direction. The skeletal grains in the lower section are oblate or disc-shaped and tabular to prolate or rod-shaped. In the upper part of the exposed Sylhet Limestone Unit, from 11m to 40 m, the microscopic study indicates that the size of the skeletal grains ranges from 0.0039 mm to 1.00 mm; hence, only a few are visible to the naked eye. Skeletal grains are oblate or disc-shaped, and very few are prolate or rod-shaped, and the grain size in the upper part of the exposed limestone unit ranges from 10.6 µm to 45 µm. Hand specimen (Fig. 4a) from the exposed upper part (11 – 40 m) of the Sylhet Limestone unit and their respective thin sections (Fig. 4b) indicates that the upper part is moderately sorted. The overall sorting in the studied limestone unit improves in an upward direction, and the skeletal grain size also decreases with time.

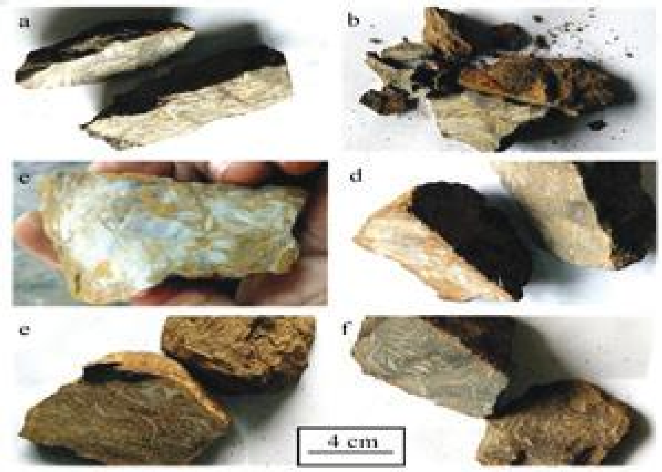

Figure 3(a): Collected Samples from the Lower Part of the Limestone Unit

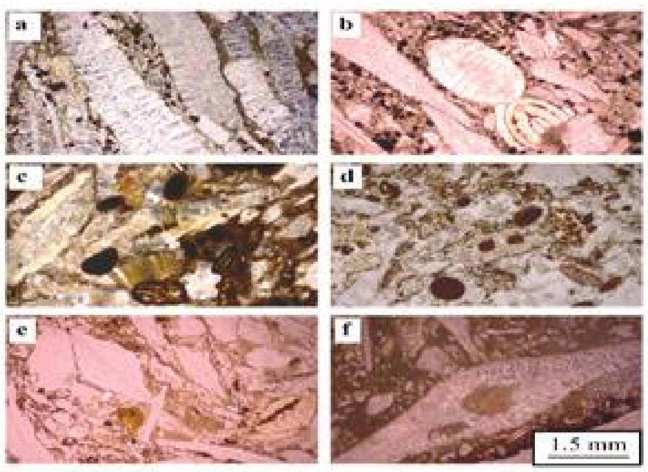

Figure 3(b): Corresponding Thin Sections Prepared from the Collected Sample of the Lower Part of the Limestone Unit (a, b, c, d, e, f, Respectively)

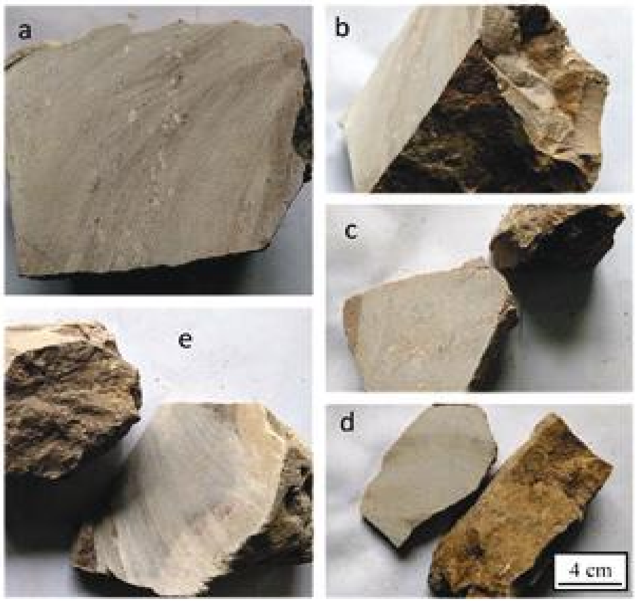

Figure 4(a): Collected Samples from the Upper Part of the Limestone Unit

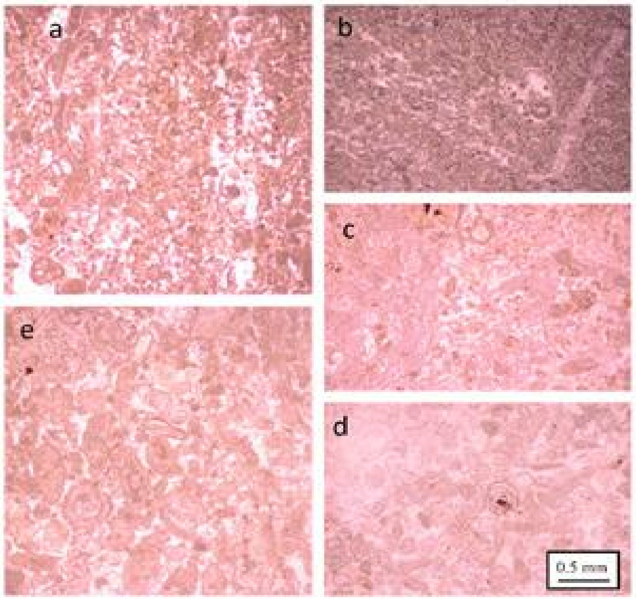

Figure 4(b): Corresponding Thin Sections prepared from the collected sample of the upper part of the limestone unit (a, b, c, d, e, respectively).

Composition of The Limestone

Non-skeletal Grains

Non-skeletal carbonate grains, called Ooids and Peloids, form through various processes, including aggregation, precipitation, and abrasion. These grains can reveal important details about the depositional environment and processes that influenced the creation of the carbonate rock because of their different textures and forms. Petrographic analysis can recognize, describe, and quantify these grains, which helps interpret paleoenvironments, sedimentary processes, and diagenetic changes. These non-skeletal grains impact reservoir quality by changing *in-situ* porosity and permeability. The presence of well-preserved *Ooids* or abundant *Peloids* contributes to higher porosity, thus enhancing reservoir quality.

Ooids and *Pisoids*

Ooid has been recognized by grains with a diameter of less than 2 mm, whereas *Pisoid* has been identified by grains with a similar shape but larger diameter (Tucker, 2011). *Ooids* and *Pisoids* (Fig. 5) can be seen in the finer-grained Packstone portion of the Sylhet Limestone Formation.

Figure 5: Photomicrograph Representing *Ooids* and *Pisoids* Under Plain Polarized Light. The Length of the Photo is 2mm

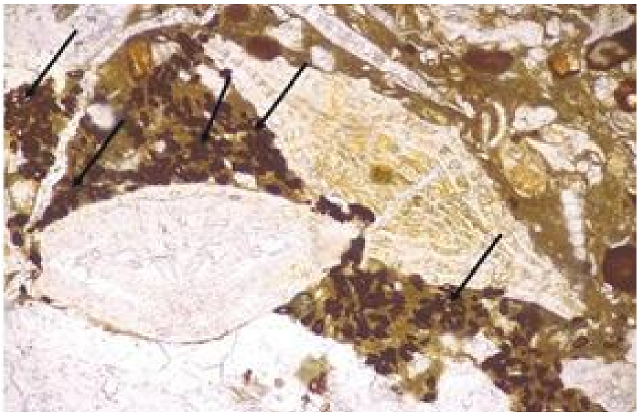

Figure 6: Photomicrograph Representing *Peloids* Under Plain Polarized Light. Black Arrow Marks *Peloids*. The Length of the Photo is 2mm

Peloids

Peloids are between 0.1 and 0.5 mm in diameter (Tucker, 2011). Sylhet Limestone Formation shows *Peloids* (Fig. 6) in the coarser-grained part, classified as Rudestone.

Skeletal Grains

The skeletal components of Limestone reflect the distribution of carbonate-secreting invertebrates through time and space. In the numerous carbonate sub-environments, the distribution and development of the organism are governed by environmental factors such as depth, temperature, salinity, substrate, and turbulence.

The studied limestone shows an abundance of foraminifera shells throughout the unit. Sylhet Limestone is rich in foraminifera, and larger foraminiferas are seen in the lower part of the unit, which is visible to the naked eye. Sylhet Limestone shows the presence of *Nummulite, Discocyclina,* and *Alveolina* and is also rich in other Foraminiferal tests. The Sylhet Limestone Unit abounds with *Nummulite* foraminifera (Fig. 7). These are located in the lowest portion of the unit, designating a particular Eocene period. It is the current Index Fossil, and the Sylhet Limestone Unit is also known as the Nummulitic Limestone because of this. Most foraminiferal tests are composed of Calcite, and some are aragonitic. All the photomicrographs of observed Foraminiferas are presented in this part.

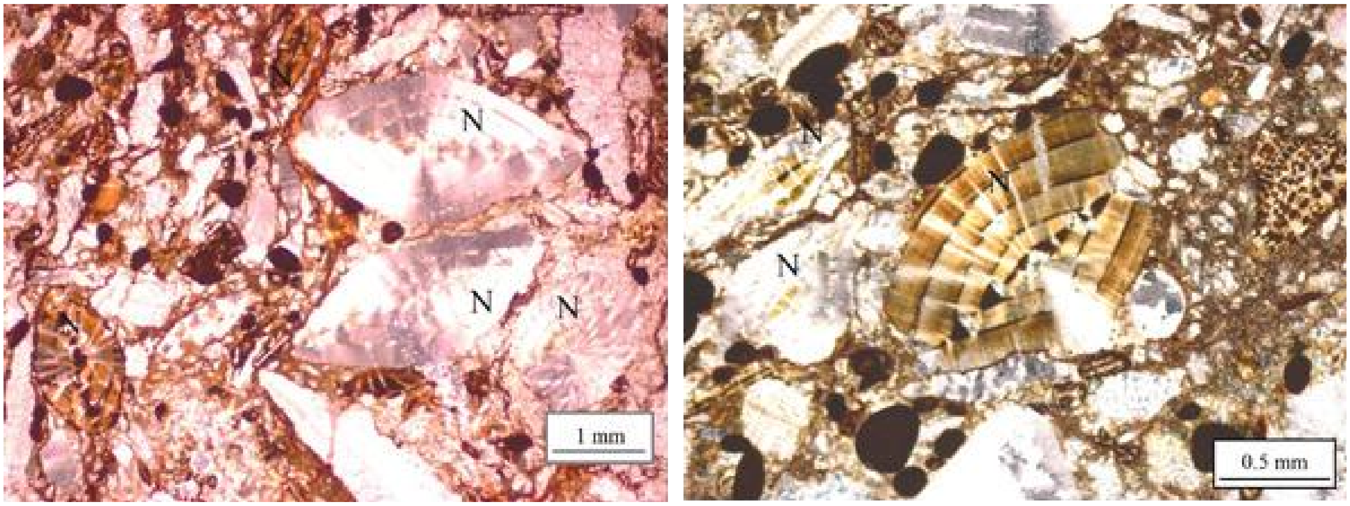

Figure 7: Photomicrographs Showing a Different Type of *Nummulite* Foraminiferal Tests Under Crossed Polarized Light. The Tests are Composed of Aragonite. Some Parts of the Tests are Converted to Calcite from Aragonite. The Tests are Denoted by the Letter N in the Photomicrograph

The studied unit shows a substantial presence of *Discocyclina* (Fig. 8). This type of foraminiferal test was found in the whole unit. It is located in a massive number in the lower part and decreases in number upwards. Different kinds of *Discocyclina* tests were observed in this unit.

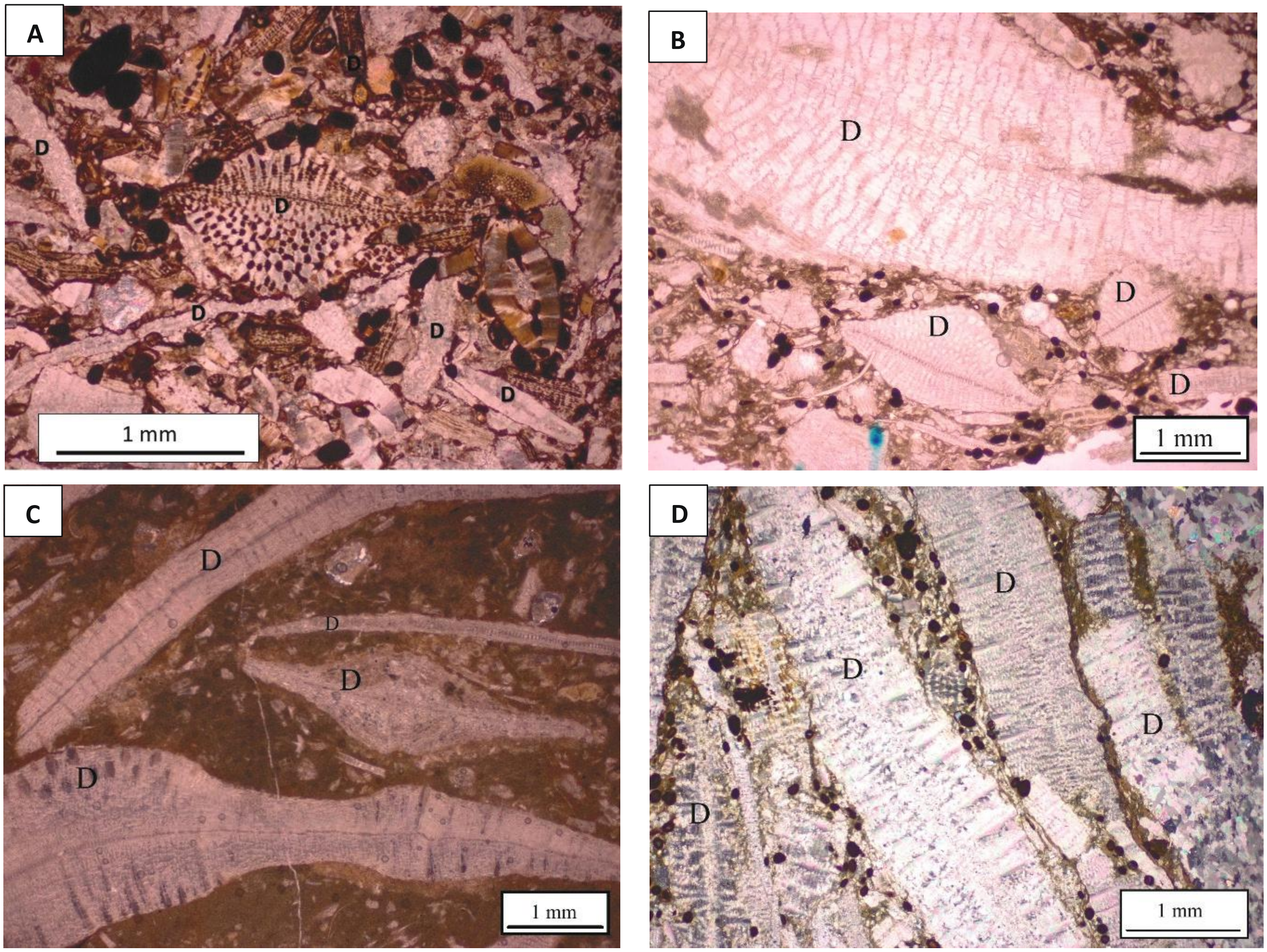

Figure 8: Photomicrographs (A, B, C, D) Showing Different Sizes and Shapes of the *Discocyclina* Foraminifera Test Under Crossed Polarized Lights from the Lower Part of the Sylhet Limestone Formation. A. Photomicrograph Representing Several *Discocyclina* Tests Found in the Thin Section Prepared from Sample c Shown in Figure 3a. B. Photomicrograph Representing *Discocyclina* Tests Found in the Thin Section Prepared from Sample b Shown in Figure 3a. C. Photomicrograph Representing a Few *Discocyclina* tests Found in the Thin Section Prepared from Sample e Shown in Figure 3a. D. Photomicrograph Representing *Discocyclina* Tests Found in the Thin Section Prepared from Sample a Shown in Figure 3a. *Discocyclina* Foraminifera Tests are Marked by the Letter D in the Photomicrograph

The study unit also shows *Alveolina*, *Allogromia* (Fig. 9a)*, Uniserial* (Fig. 9a)*, Globigerina* (Fig. 9b)*, Millioloid* (Fig. 9b)*, Rotalina* (Fig. 9d)*, Fusilinid* (Fig. 9c)*, Biserial, Spiroloculina, Rosalina*, *Trochospiral, and Helicolepidina* types foraminiferal tests in an insignificant amount.

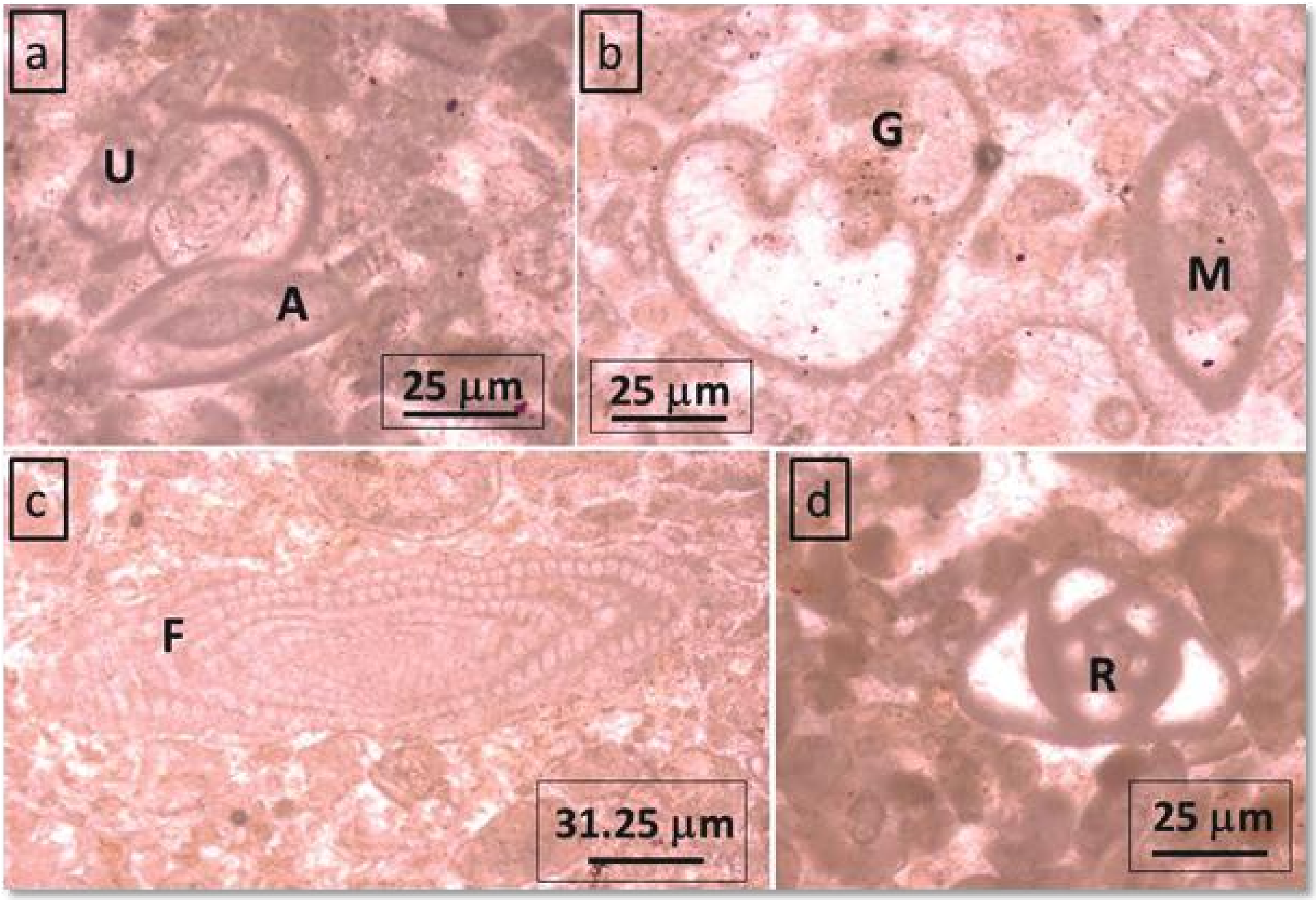

Figure 9: Photomicrograph of Different Kinds of Foraminiferal Tests. All of the Photomicrographs are Taken Under Plane-polarized Light. Scales are Shown at the Bottom of each Photo. (a) Photomicrograph of a *Uniserial* and *Allogromia*, *Uniserial* is Denoted by the Letter U, and *Allogromia* is Represented by the Letter A. (b) Photomicrograph of *Globigerina* and *Milioloid*, here *Globigerina* is Designated by Letter G and *Milioloid* is Indicated by Letter M. (c) Photomicrograph of *Fusilinid*, *Fusilind* is Represented by Letter F. (d) Photomicrograph of *Rotalina*, *Rotalina* is Denoted by Letter R

Micrite

Sylhet Limestone Formation has a fine-grained, usually dark matrix composed entirely of fine-grained carbonates. Micrite (Figs. 10 and 11) has been found in the lower part as the cementing material between the skeletal grains of coarse-grained Rudestone. Due to micrite's presence, the lower part of the Sylhet Limestone Formation displays a darker color than the upper part, and micrite represents an environment with a massive supply of organic matter.

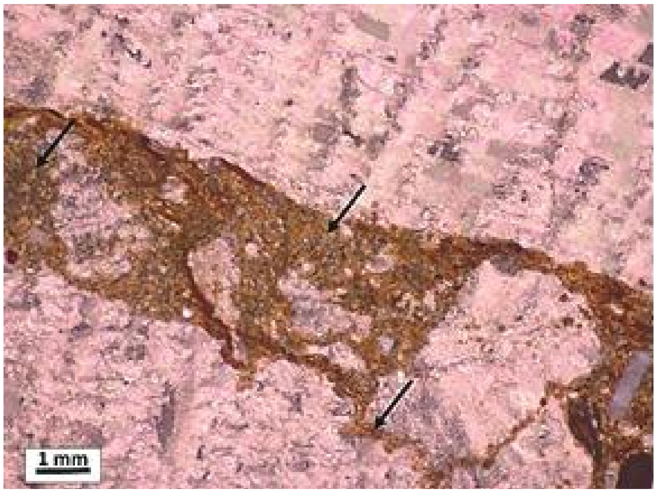

Figure 10: Photomicrograph of Micrite between Skeletal Fragments. The Black Arrowheads Represented Micrites between Grains in Crossed Nicoles. Micrites are Tributary to the Lower Part of the Sylhet Limestone Formation

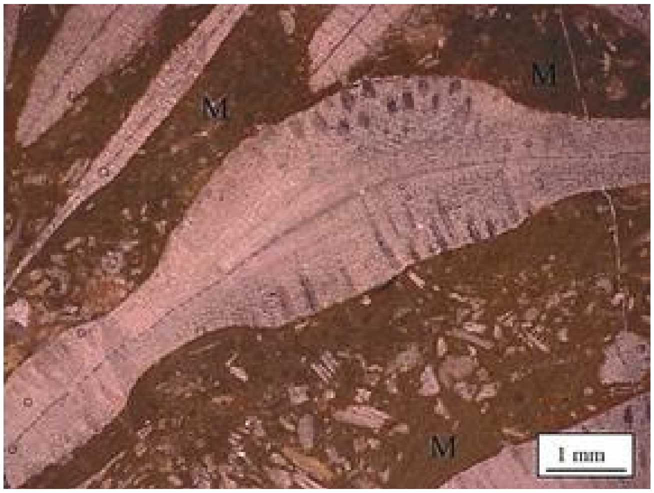

Figure 11: Photomicrograph of Micrite between Skeletal Fragments. Letter M Represents Micrites between Grains in Crossed Nicoles. Micrites are Tributary to the Lower Part of the Sylhet Limestone Formation

Cement

The cementing materials of Eocene Sylhet Limestone are Calcite (Fig. 12), characterized by its colorless appearance under plane-polarized light and pink color and inclined extinction under cross-polarized light. Petrographic analysis facilitates the identification and characterization of cement types, distribution, and relative abundance. This information is crucial for understanding diagenetic processes, cementation patterns, and their impact on porosity, permeability, and reservoir quality.

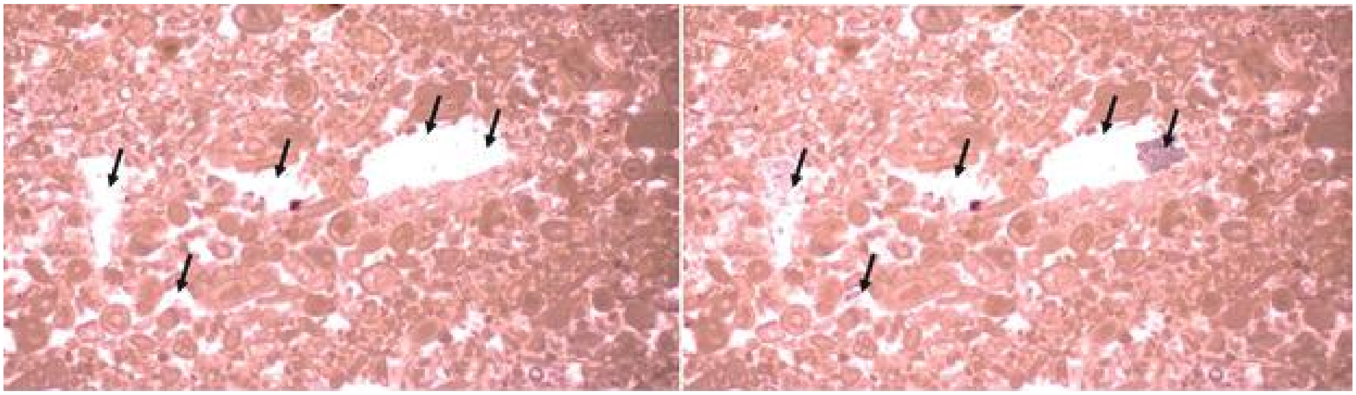

Figure 12: Photomicrograph of Calcite Cement. Arrow Symbols Represent the Presence of Calcite Cement between Skeletal Grains, both in-plane and Crossed-Nicols. This Photomicrograph also Shows the Presence of *ooid*s in the Formation. The Length of the Photo is 2mm

Mineralogy

Two Carbonate minerals, Aragonite and Calcite, are predominantly found in the study unit.

In the lower part, the fossil shells are composed of Aragonite (Fig. 13), characterized by a colorless appearance under plane-polarized light and grey and pale yellow colors under cross-polarized light in the microscope. Most Aragonite is concerted into calcite by in situ conversion or being replaced by drusy calcite.

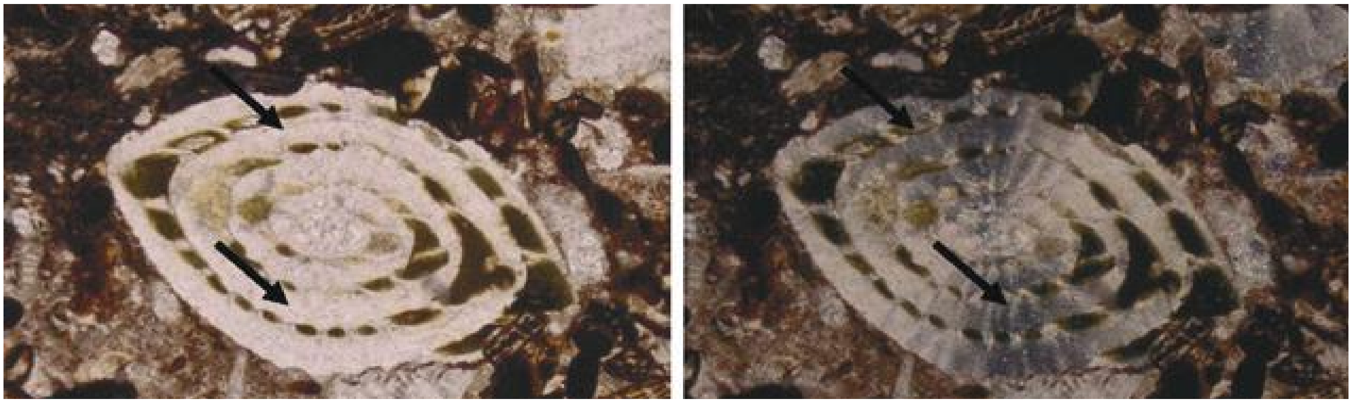

Figure 13: Photomicrograph of Aragonite Under Both Plane and Crossed-polarized Light. Aragonites are Indicated with a Greyish Color Under Crossed Polarized Light within the Fossils and Pointed by Black Arrows in the Figure. The Length of the Photo is 2mm

In the lower part of the exposed limestone formation, aragonites are converted to Calcite. In contrast, in the upper part of the exposed formation, the shells are composed of Calcite and are bound together by calcite cement. Under the petrographic microscope, Calcite is characterized by colorless appearance, variable relief, rhombohedral cleavage under plane-polarized light and pink color, rhombohedral cleavage, inclined extinction, and lamellar twinning under cross-polarized light (Fig. 14).

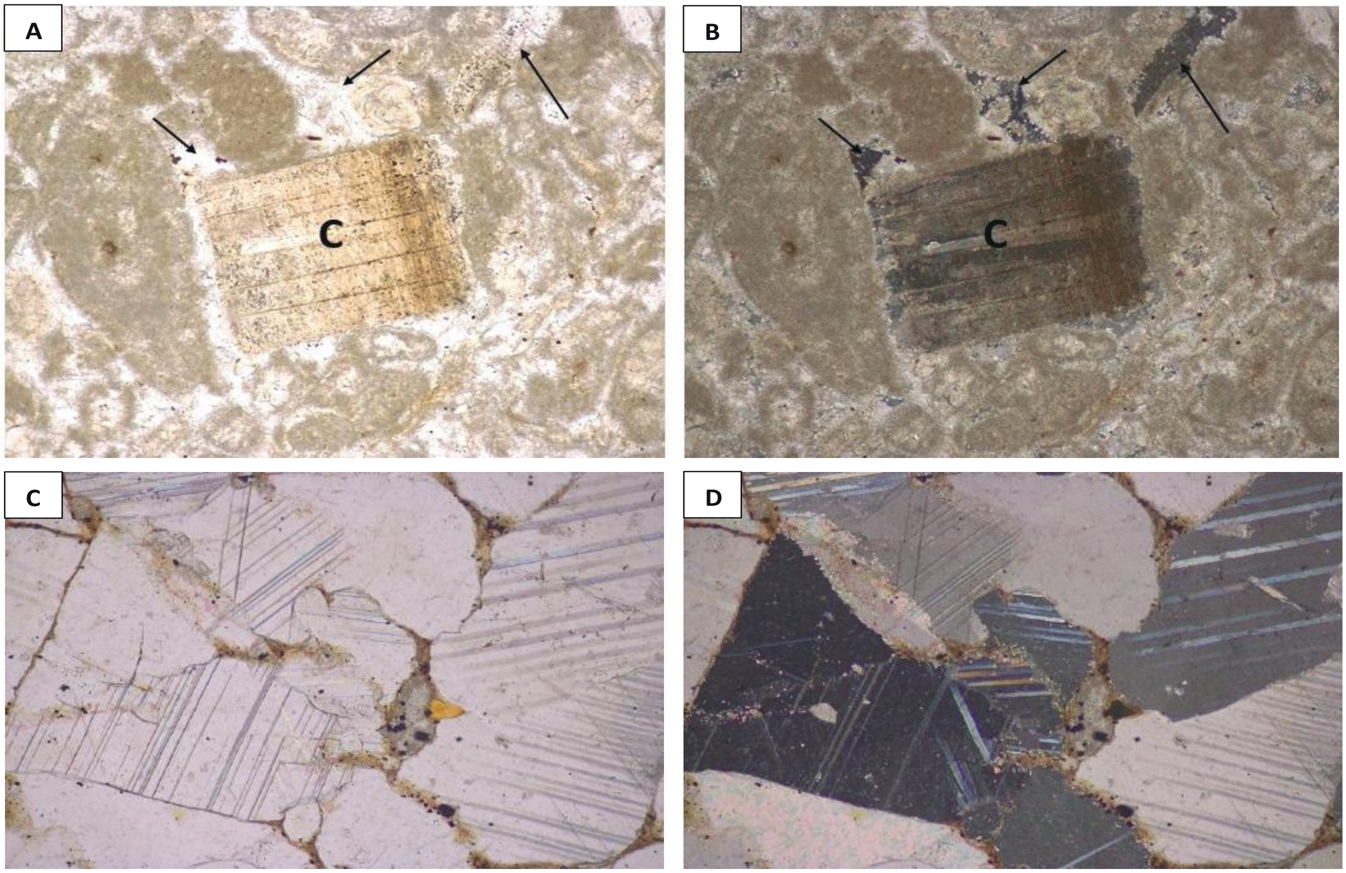

Figure 14: Photomicrograph of Calcite Under Plain- and Crossed-Nicols. The Section Shows Crystallized and Non-crystallized Calcite (A) and (B). The Figure Denotes the Crystallized Mineral Grain by the Letter 'C.' Black Arrow Marks Non-crystallised Calcites. Both (C) and (D) show Lamellar Twinning Among the Grains. The Length of the Photo is 2mm

Classification of The Sylhet Limestone

The limestone unit under investigation has been categorized using Embry and Klovan's (1971) modified Dunham's classification scheme, which focuses on the depositional textures of carbonate rocks, such as porosity and permeability (Tucker, 2001). It recognizes different fabric types and their influence on fluid flow, diagenesis, and reservoir quality. This information is crucial in understanding carbonate formations' potential reservoir characteristics and behavior in hydrocarbon exploration and production.

According to the classification scheme, the study unit can be divided into two types of Limestone. The bioclasts, fossils, and fossil fragments are visible to the naked eye in the lower part (Figs. 3a and 3b) of the Sylhet Limestone Formation (up to 11 m). Most of the bioclasts are over 2 mm in size. Bioclasts are close-packed and in physical contact, and the bioclasts or fossils are embedded in finer carbonates. From this, it is concluded that the lower part of the Sylhet Limestone formation is Rudestone, a coarse-grained equivalent of Grainstone and Packstone.

In the upper (Figs. 4a and 4b) part (from 11 m to 40 m) of the Sylhet Limestone Formation, most bioclasts are micro-sized, and very few bioclast or fossils are visible to the naked eye. However, in the thin section, all the microfossils can be seen. Bioclasts are closely packed, and some are in physical contact with others. From this observation, we can conclude that the upper part is Packstone, a finer-grained equivalent of Rudestone.

Reservoir Quality

The Eocene Sylhet Limestone unit exhibits a significant presence of fractures and joints. This attribute of the Sylhet Limestone enhances its suitability as a reservoir rock for the hydrocarbon system in Bangladesh.

The formation also includes microfractures (Fig. 16), which can also be added to the formation's total void spaces. Dissolution porosity is also evident in the limestones. Post-depositional diagenetic modifications lead to the dissolution of porosity. These dissolution pores (Fig. 17) are observed under a Scanning Electron Microscope. Even though they only slightly increase the total void space, a 1% increase in porosity considerably affects the formation's overall reservoir quality.

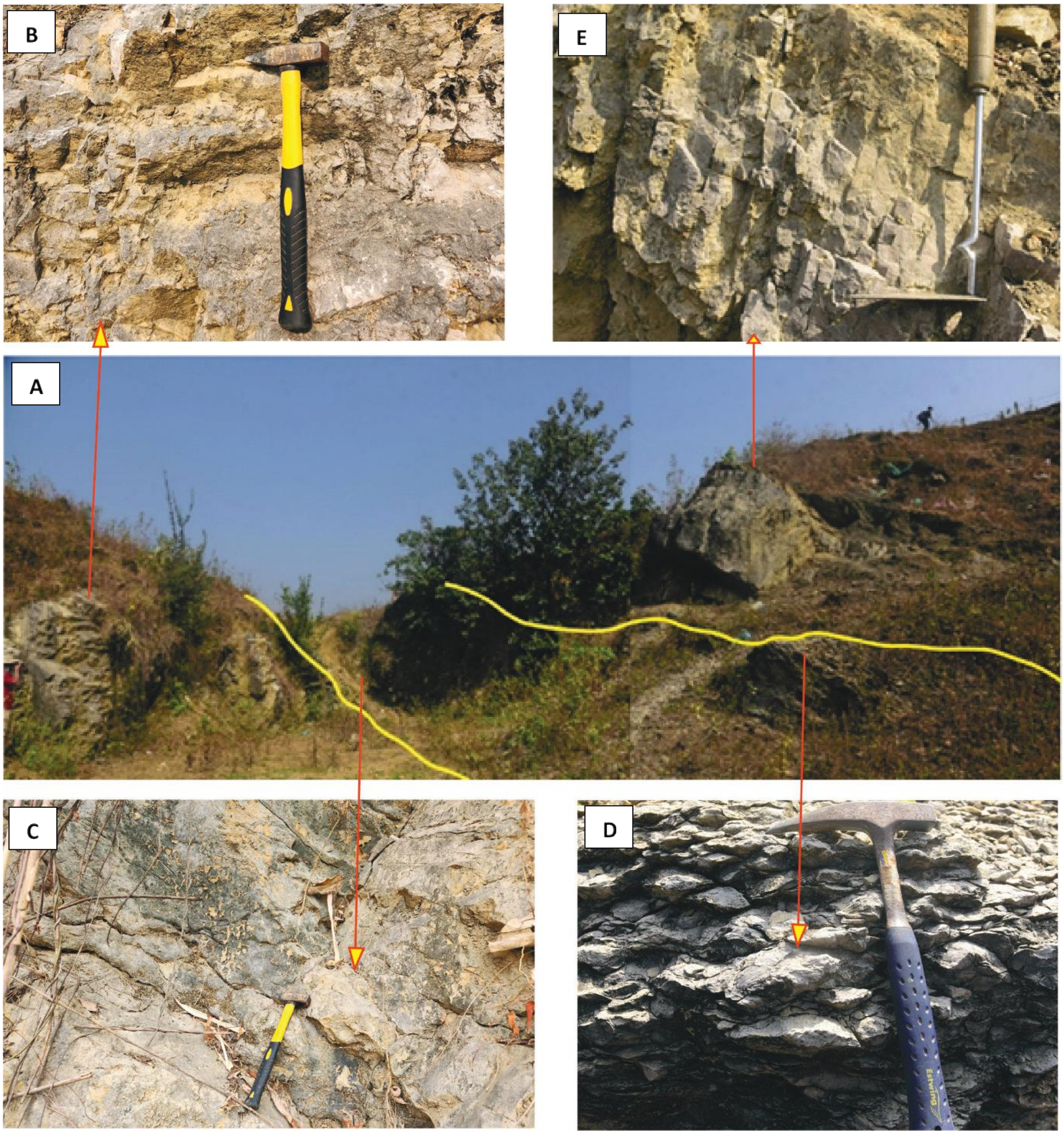

Figure 15: (A) The Total Limestone Section is Shown from the Upper Limestone on the Rightmost Part to the Lower Limestone on the Left Most Part. (B) The Exposed Lower Limestone Unit Shows the Bedding Joints. (C) The Middle Limestone Unit Exhibits the Fractured Zones in the Bedding Planes. (D) The Yellow Line Indicates a Layer of Extreme Fractured Zone between the Middle and Upper Limestone Unit. (E) Three-dimensional Sets of Bedding Joints and Fractures in the Upper Limestone Unit

Ten limestone samples from the exposed section were also analyzed to assess the reservoir quality (Table 2). The estimated porosity obtained from the thin section ranges from 5 to 12%, with slightly higher values in the lower part of the studied section. The trend of the porosity might be affected by diagenetic calcite cementation and/or recrystallization.

Table 2: Estimated Porosity Percentage of the Analyzed Limestone Samples Found in Northeastern Bangladesh by the Left Bank of the Dauki River Section. The Porosity Ranges from 5-12% in the Gathered Upper and Lower Limestone Samples

SAMPLE		POROSITY (%)
UPPER LIMESTONE	Sample - a	7
	Sample - b	10
	Sample – c	5
	Sample – d	8
	Sample – e	9
LOWER LIMESTONE	Sample – a	9
	Sample – b	12
	Sample – c	7
	Sample – d	11
	Sample - e	9

**Note: The value of permeability has not been estimated in the laboratory. The table provides quantitatively estimated porosity derived from thin sections. The qualitative porosity is determined based on outcrop analogy, considering interconnected fractures, fissures, and tectonic joints.*

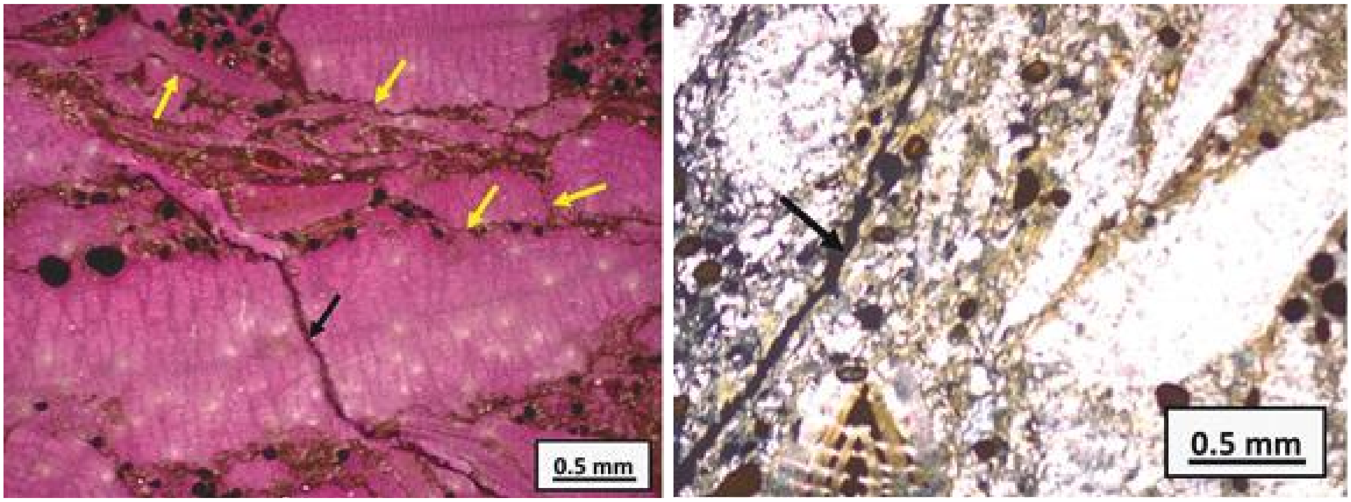

Figure 16: Photomicrograph of Limestone Formation Showing Fractures and Intergranular Pore Spaces. The Black Arrow Shows Fractures, and the Yellow Arrows Indicate Intergranular Pores. In the Left Picture, the Pore Spaces between the Fractures Might have been Filled by Cement. The Scale is Given on the Lower Right of the Figures

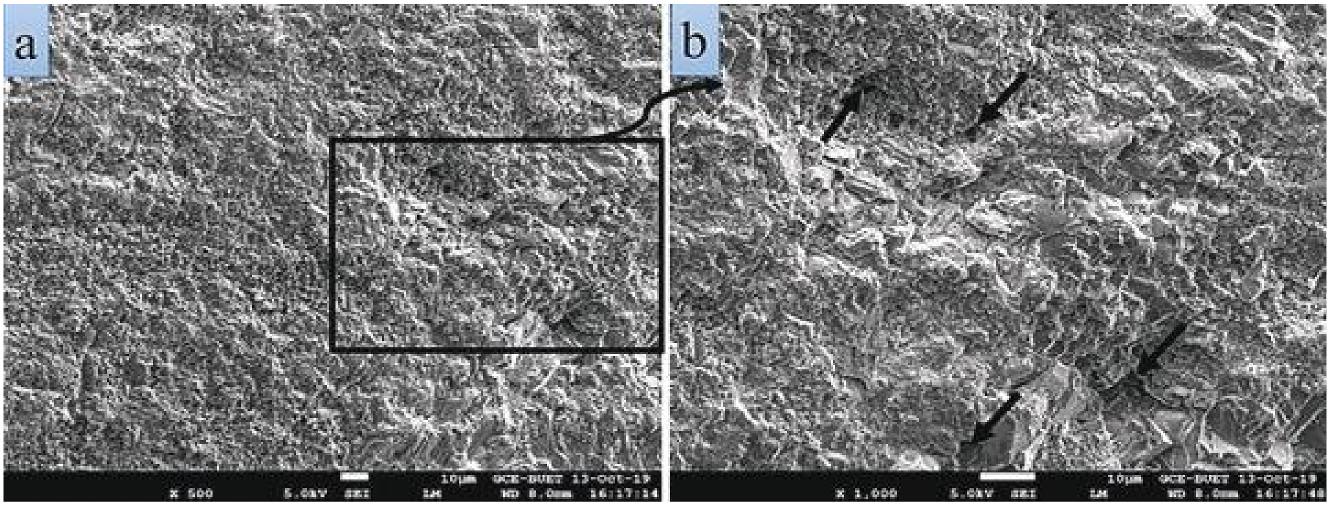

Figure 17: Image Obtained Using a Scanning Electron Microscope (SEM) Showcasing a Limestone Specimen. The Black Arrows Highlight the Pores Formed due to Increased Dissolution, Enhancing Secondary Porosity

The petrophysical characteristics of the exposed sections in the Jaflong area include interconnected joints, fractures, fissures, and microfractures, which can act as a significant reservoir if present in the subsurface. The secondary porosity, like the dissolution porosity, can also add to the total void space of a formation, increasing the reservoir potential of the Sylhet Limestone Formation. However, thin-section studies indicate evidence of diagenetic recrystallization and calcite cementation. Hence, dissolution pores, closely spaced, interconnected joints, and fractures filled with diagenetic calcite might deteriorate the reservoir quality (Fig. 14). The limestone unit is laterally extensive throughout the stable platform but has yet to be thoroughly studied. The analysis of exposed rock formations was linked with the broader seismic profile to gain a more comprehensive insight into the potential for petroleum in the region. The regional seismic line along the Eocene Hinge Zone reveals the subsurface characteristics of the limestone reservoirs, including lateral persistence, thickness, tectonic activities, and seismic anomaly (Salt *et.al.*, 1986) (Fig. 18).

This section was correlated with the outcrops of Jaflong. This integrated approach of seismic data and outcrop study qualifies the true capability of the Sylhet Limestone Formation as a reservoir. While the horizontally consistent stratum is crucial for a high-quality reservoir, it's necessary to investigate the Sylhet Limestone for additional verification.

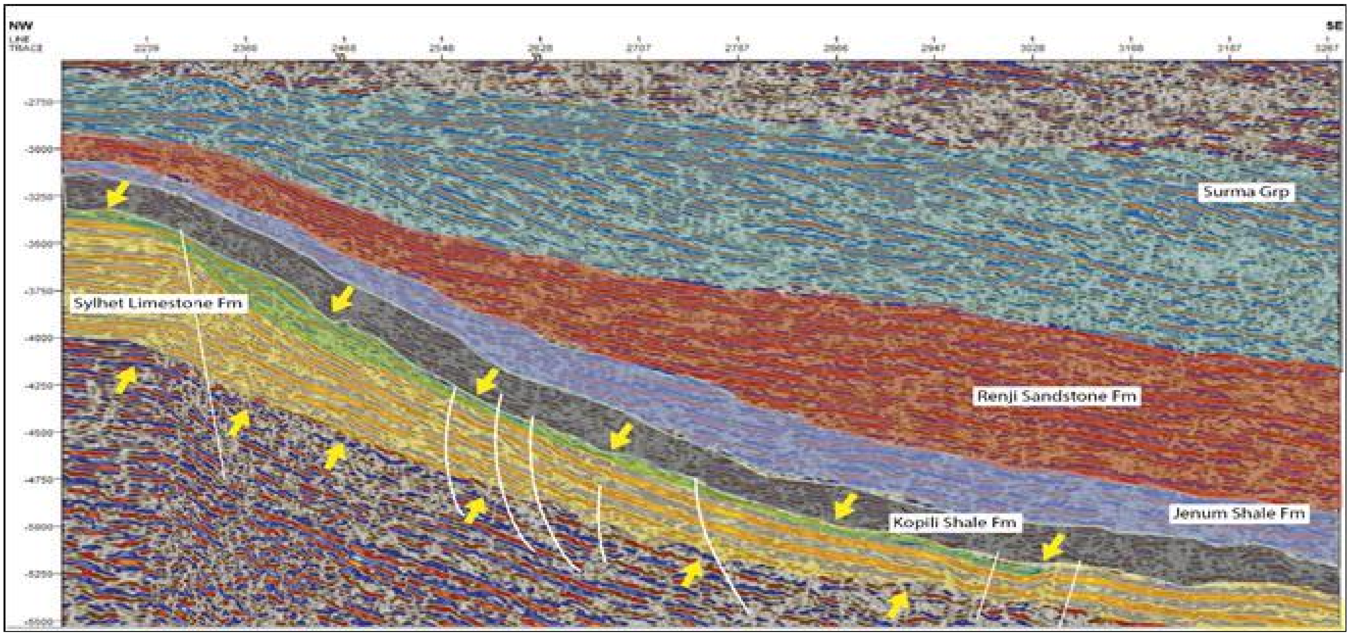

Figure 18: Seismic Section Parallel to Dip, Across "Hinge Slope." It is Shown here that the Prominent Eocene Slope Builds up at 3300ms to 3925ms, Which is the Targeted Sylhet Limestone Formation (Highlighted in Yellow and Indicated by Yellow Arrows). The Kopili Shale Formation Shows a Regional Extent above the Sylhet Limestone Formation (Highlighted in Dark Grey). Above that, the Jenum Shale Formation (Highlighted in Light Blue) is underlying the Renji Sandstone Formation (Highlighted in Red). The Prograding Oligocene Deltaic Shelf-fan Complex is also Shown in the Renji Formation Section— Horizontal Scale 1:50,000

Notably, there are substantial opportunities for hydrocarbon reservoirs, such as carbonate accumulations, within this formation, particularly near the Hinge Zone. Assessing limestone reservoirs involves examining the creation of secondary pores, their various forms, and how they interconnect.

DISCUSSION

Most large oil and gas fields are typically found in porous limestone, formed in tropical marine environments. However, in the case of Bangladesh, all of the gas and oil fields discovered so far are in sandstone reservoirs. The Sylhet Limestone was deposited in a low-energy, shallow marine environment, and the geochemical characteristics suggest very pure calcite-rich carbonate minerals in it (Hossain and Nahar, 2014).

Field experience suggests significant differences between a sandstone reservoir and a limestone reservoir. The geometric characteristics and sorting of sediments determine the porosity and permeability of intergranular rocks like sandstone. In contrast, there is no direct relationship between grain characteristics, porosity, and permeability in intermediate rocks. Limestone is classified as an intermediate media in general. Conducting a distinct study of limestone reservoirs from geological and physical perspectives is crucial. Recognizing that limestone reservoirs differ from sandstone reservoirs is the first step toward understanding their unique characteristics.

Besides the variations in chemical composition and mineralogy, the primary distinction between sandstone and limestone lies in the origin and geometry of their internal porosity. The geometry of the pore space differs significantly between sediment that has experienced deposition, compaction, and cementation alone and sediment that has undergone additional processes such as dissolution and fracturing, which are common in limestone. Unlike sandstone, limestone typically belongs to the latter category. The entire void space in sandstone is distinguished by a high degree of dispersion and connectivity among its parts.

A limestone is equivalent to an intergranular rock if it remains intact without undergoing treatments that enhance its internal space. However, in the case of the Eocene Sylhet Limestone, we have observed a heavily fractured rock formation (Figs. 15 and 16). A fractured limestone has a larger adequate volume than a highly porous sandstone. This is because, while a highly porous sandstone contains many pores, not all of them may be interconnected, resulting in lesser permeability. Conversely, the fractures and joints are interconnected in a fractured limestone, allowing for better fluid flow. This characteristic of limestone makes it a superior reservoir to sandstone (Fig. 15).

While the sandstone reservoirs have been the focus of hydrocarbon exploration in Bangladesh, this study highlights the potential significance of the limestone lithology. Due to the absence of established reservoir prospects in the Eocene Sylhet Limestone, it is preferable to prioritize in-depth investigations into the fluid movement and preservation aspects within the limestone layers. This emphasis could potentially lead to the discovery of new reservoir opportunities. The distinctions between sandstone and limestone reservoir petrography underscore the importance of tailored exploration strategies for different rock types.

The hydrocarbon system close to the Eocene Hinge Zone is underexplored in Bangladesh. However, HC potentiality was pointed out by Salt et al., (1986), particularly in the faulted blocks, carbonate buildups, and the Paleocene stratigraphic pinch-out sandstone (Tura Sandstone) traps underneath the Eocene Limestone. The overlying Kopili Shale might act as the seal and the source rocks in the HC system. Recent 2D seismic data over exploration blocks 8 and 11 indicate HC prospectivity in and around the Eocene Hinge Zone (personal communication with BAPEX), providing reasonable structural and stratigraphic traps. The studied seismic section also shows structural and stratigraphic traps close to the Eocene Hinge Zone (Fig. 18). Unfortunately, there is no core data on the Eocene Limestone to evaluate the reservoir properties, particularly the porosity and permeability. However, exposed limestone samples from the east bank of the Dauki River facilitate studying reservoir quality from outcrops and laboratory experiments. The findings from this study help evaluate the subsurface limestone encountered from seismic data.

The Sylhet Limestone, exposed in the Dauki River area, provides insights into the textural, mineralogical, and reservoir quality attributes. The study area is close to the tectonically active fault zone, the Dauki Fault system. The Sylhet Limestone is necessarily brittle and exhibits many closely spaced, interconnected joints and fractures (Figs. 15 and 16). The porosity observed in the exposed rocks ranges from 5% to 12%. However, thin-section studies also indicate evidence of diagenetic recrystallization and calcite cementation. Hence, closely spaced, interconnected joints and fractures filled with diagenetic calcite might deteriorate the reservoir quality.

LIMITATIONS AND RECOMMENDATIONS

The Eocene Sylhet Limestone Formation has not been proven a reservoir due to inadequate investigations. While we followed proper procedures to collect outcrop samples of the limestone for a comprehensive analysis, some of the exposures were severely weathered and covered with vegetation, making it challenging to obtain pristine samples. The samples collected during the fieldwork were surface samples. However, core samples would have provided more accurate results, and the available quantity needed to be increased for this study. There were also limitations in the laboratory analysis phase. SEM studies proved challenging due to inadequate facilities and processed samples. The unavailability of XRF analysis also restricted us. Despite these limitations and challenges, we tried to overcome them and obtain meaningful findings for our study.

This study could be improved with better SEM facilities. A better SEM facility could help us better understand the composition of the limestone and more precise diagenetic change, if any, particularly the development of secondary dissolution type porosity. One critical aspect of our study that would greatly benefit from an upgraded SEM facility is the investigation of dolomitization within the limestone formation. This recrystallization can significantly impact the porosity and permeability increase due to volumetric shrinkage. With an advanced SEM, we can precisely analyze the mineralogy and texture of the limestone samples, allowing us to identify dolomite crystals and assess the extent of dolomitization. Dolomitization often leads to a shrinkage in the formation and an increase in total porosity. An improved SEM facility would enable us to quantify these changes more accurately, providing valuable data regarding the evolution of porosity within the Sylhet Limestone Formation over time. This information is crucial for reservoir characterization in the context of hydrocarbon exploration.

More focus should be given to the independent investigation of fluid movement and the preservation of fluids in limestone, which may lead to the discovery of new reservoirs, as field studies show a significant difference between a sandstone reservoir and a limestone reservoir petrography.

CONCLUSION

This study conducts a comprehensive investigation, combining outcrop studies, thin section microscopic analysis, and Scanning Electron Microscopy of limestone samples from the Northeastern region of Bangladesh. The Sylhet Limestone, deposited in a shallow marine environment, shows characteristics of a clean non-clastic lithology in the Transgressive Systems Tract. Three units in the exposed Sylhet Limestone are identified, featuring mature, well-packed lithology rich in various foraminiferal tests. Extensive fractures and joints in the unit enhance reservoir properties by providing significant porosity (5-12%), while diagenetic calicle cementation and recrystallization, on the other hand, deteriorate the porosity and permeability. The Sylhet Limestone Formation extends from the northeast to the southwest and needs extensive investigation to evaluate HC productivity. As seismic data shows, structural features like faults and fractures visible on the surface may persist into the subsurface. This study underscores the importance of detailed geological investigations, offering insights into the region's geological evolution and the potential for untapped resources.

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