

# Petrographic study of Umlatdoh limestone in parts of Meghalaya, north-east India with an emphasis on diagenetic and depositional attributes

Anni Rani Das, Meghali Baruah\*, Mrinal Kanti Pathak, Devesh Walia and Shikhar Kumar

Department of Geology, North-Eastern Hill University, Shillong – 793022 (India)

\*Corresponding author: meghaligeo33@gmail.com

## ABSTRACT

Early Eocene Umlatdoh Limestone of Sylhet Limestone Group have been studied to understand their framework constituents and diagenetic processes. Additionally, an approach was made to infer the depositional environment of this limestone based on the abundance of biogenic assemblages. Two vertical profile sections were measured and representative rock samples were collected for petrographic study. The limestones of the study area are classified as wackestone, packstone and grainstone, dominated by calcareous green algae (Dasycladalean algae) and large benthic foraminifers. An open lagoonal to proximal middle shelf environment has been envisaged during the deposition of the studied limestone. The diagenetic overprints of these limestones are characterized by several key diagenetic features, including micritization, cementation, compaction, dissolution and neomorphism. These diagenetic processes occurred in marine phreatic, meteoric phreatic, mixed meteoric phreatic, and burial diagenetic environments. Micritization of allochems, cementation by isopachous and granular calcite, neomorphism, and bioclast recrystallization occurred during meteoric-phreatic diagenesis. Meteoric-vadose diagenesis led to extensive dissolution and the infilling of fractures with sparry calcite. During burial diagenesis, blocky calcite cementation appears to have become prominent.

**Keywords:** Umlatdoh Limestone, Meghalaya, Petrography, Diagenesis, Depositional environment

## INTRODUCTION

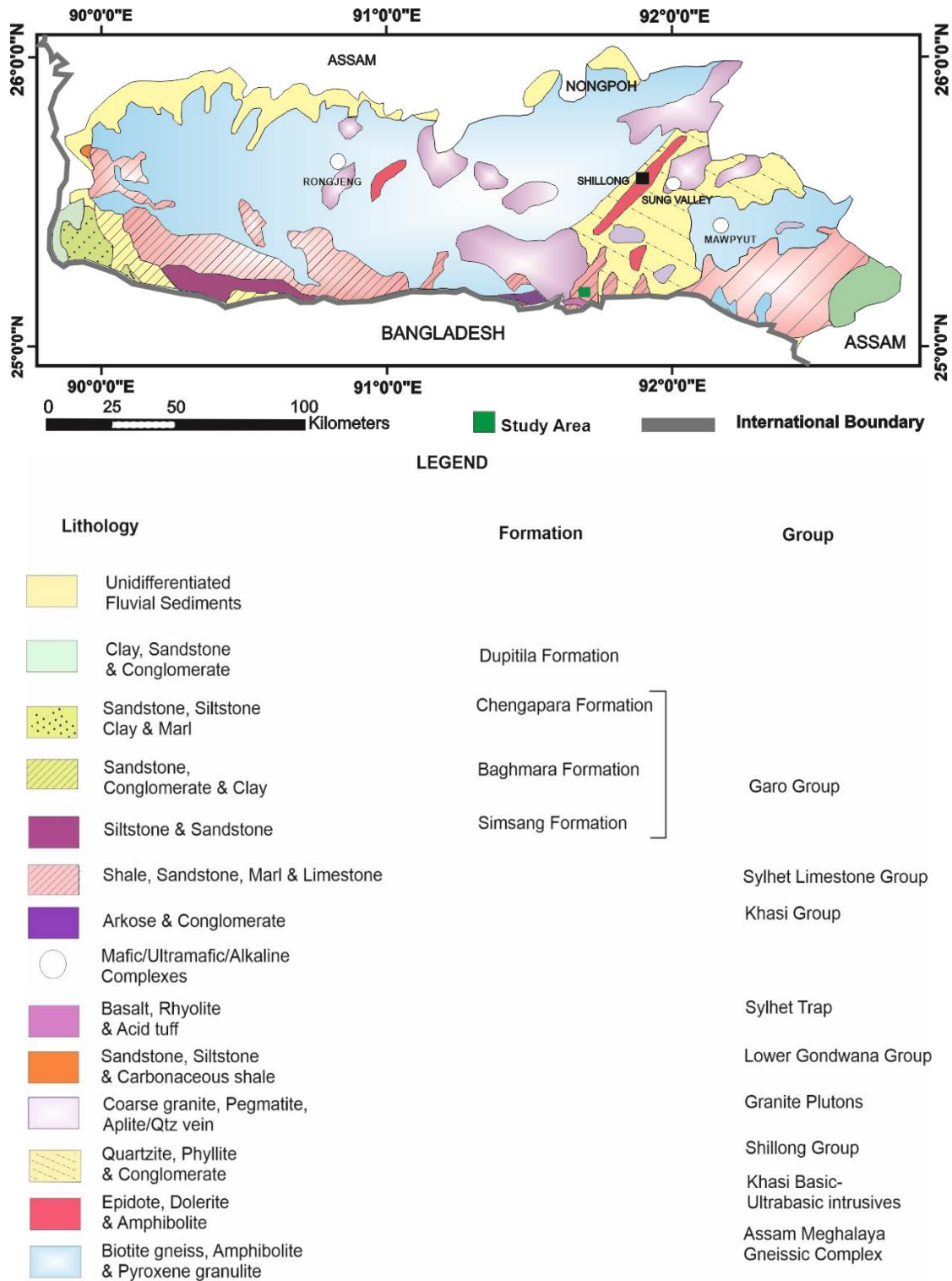
The Sylhet Limestone Group is well known for its captivating lithology as developed in the Cherrapunjee area of Meghalaya, Northeast India. Thick alternating carbonate and siliciclastic sequences, ranging in age from Late Palaeocene to Middle Eocene (Tewari et al., 2010a,b; Ghosh and Sarkar, 2013; Sarkar, 2015a,b, 2016) characterize the group. Larger benthic foraminiferal (LBF) assemblages and calcareous algae, dominate the carbonate sequences. Although the larger benthic foraminiferal (LBF) assemblages from Palaeogene succession of Meghalaya have been correlated with both the Tethyan and Indo-Pacific provinces (Jauhri, 1994; Jauhri et al., 2016), very little is known about their palaeo-environmental implications, including enormous development of carbonate build-ups, and large accretion of marine biota (Saraswati et al., 2018; Srivastava and Singh, 2019). Further, abundance of biogenic assemblages in shallow water carbonate depositional systems is substantially influenced by environmental factors like tides, waves, and occasional storms (Boothroyd, 1985; Hallock and Glenn, 1986; Jones and Hunter, 1992; Scoffin, 1993; Li et al., 1997, 1998; Shaghude et al., 2002; Gischler et al., 2003; Beavington-Penney and Racey, 2004; Wilson et al., 2010). The present study aims to identify different biogenic assemblages as well as various diagenetic attributes preserved in the Early Eocene Umlatdoh Limestone (Sylhet Limestone Group), employing microscopic analysis (Adams and MacKanzie, 1998) and their interpretation in terms of diagenetic vis-à-vis depositional environments.

## GEOLOGICAL SETTING OF THE STUDY AREA

The study area forms a part of the southern Shillong Plateau and includes localities surrounding Wahrew Bridge of

Meghalaya (25°10'50.68''- 25°10'50.70'' N; 91°45'52.67''- 91°45'51.57'' E; Figure 1). The Shillong Plateau is a northeastern extension of the Peninsular India which is bounded by E-W trending Brahmaputra Fault system to the North and the Dauki Fault to the south. The N-S trending Jamuna Fault defines the western limit while eastern margin of the plateau is marked by NW-SE Kopili Fracture zone (Evans, 1964; Desikachar, 1974; Acharyya et al., 1986; Nandy, 1986; Gupta and Sen, 1988; Ray et al., 2011; Nandy, 2017). The Southern Shillong Plateau is covered by Cretaceous and Cenozoic sedimentary deposits forming a raised topography in the foreland of the Himalayas (Nagappa, 1959; Garg and Jain, 1995; Biswas et al., 2007; Kalita and Gogoi, 2015; Najman et al., 2016). Overlying conformably the Cretaceous cover, Southern Shillong Plateau spectacularly exposes the complete Paleocene -Eocene succession (Table 1) (Sarkar, 2020).

The Therria sandstone comprising intercalated sandstone – shale with minor coal units, marks the beginning of Tertiary succession. The Sylhet Limestone Group divisible into lower Lakadong, middle Umlatdoh, and upper Prang Formations conformably overlies the Therria sandstone. The lower and middle divisions of the Sylhet Limestone are comprised of calcareous (lower) and arenaceous (upper) members, while youngest Prang Formation is predominantly calcareous. Further, the three formations of Sylhet Limestone Group are considered to have resulted in response to three successive marine transgressions during the late Paleocene, early Eocene, and the middle Eocene periods respectively. The late Eocene Kopili Formation on the top, marks the closer of Tertiary succession in the region (Jauhri, 1994, 1998; Sarkar, 2020).



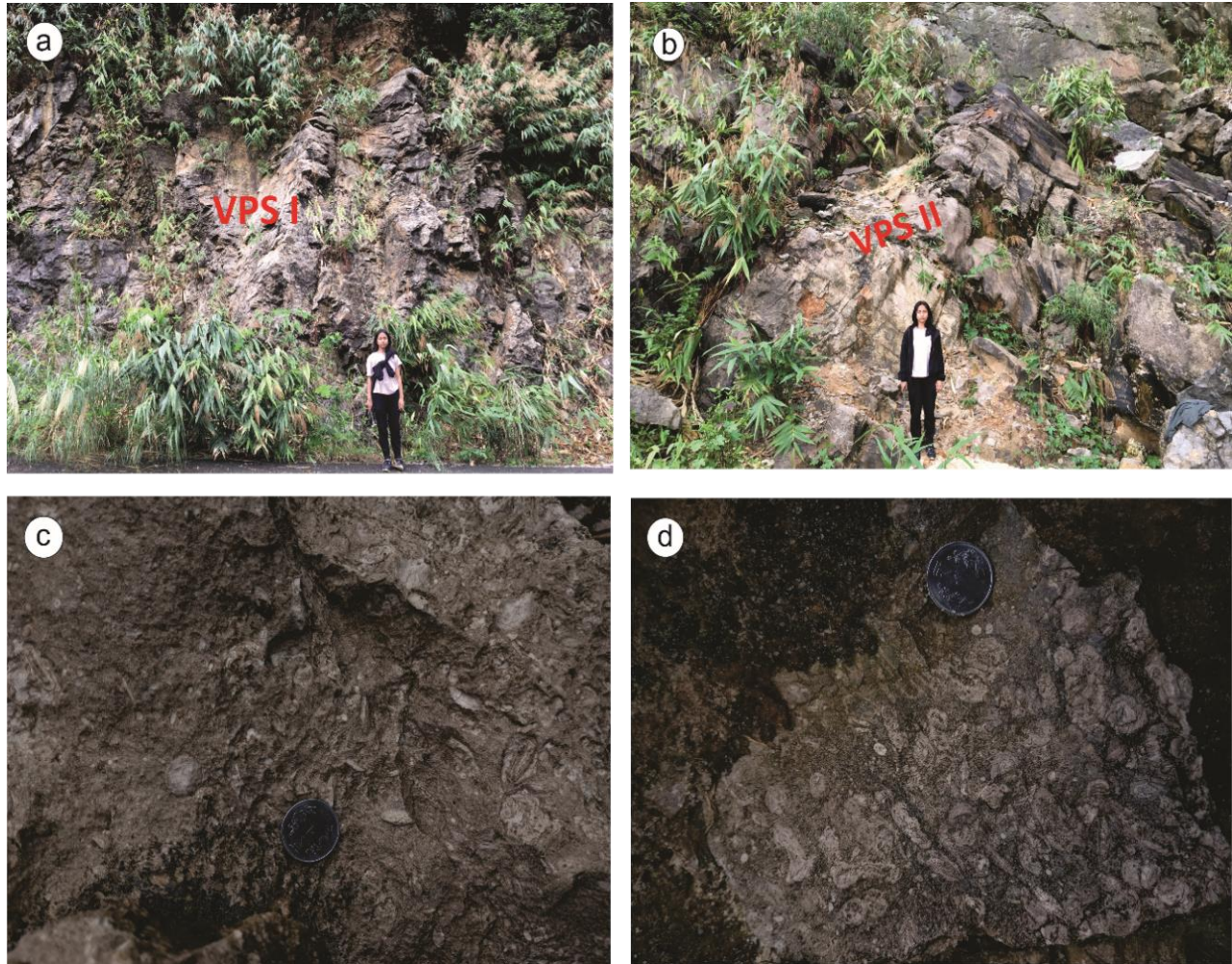
**Figure 1.** Generalized geological map of the Shillong Plateau, Northeast India, showing location of the study area (modified after Sahoo et al., 2024).

The study area comprises of Umlatdoh Formation, divisible into lower Umlatdoh Limestone and upper Narpuh Sandstone (Nagappa, 1959; Mehrotra and Banerji, 1973; Jauhri and Agarwal, 2001; Sarkar, 2016, 2020) members. The

Umlatdoh Limestone (Figure 2 a–d) around which the present study is centred, displays 2-6 meters thick algal – foraminiferal carbonate with occasional dolomite.

**Table 1.** Lithostratigraphic succession of the study area (after Sarkar, 2020)

Age	Lithostratigraphic unit	Lithology
Late Eocene	<i>Kopili Formation</i>	Alternations of shale and sandstone
Middle Eocene	Sylhet Limestone Group	<i>Prang Formation</i>
Early Eocene		<i>Umlatdoh Formation</i> Narpuh Sandstone Umlatdoh Limestone
Late Palaeocene -earliest Eocene		<i>Lakadong Formation</i> Lakadong Sandstone Lakadong Limestone
Late Palaeocene	<i>Therria Sandstone</i>	Medium to - coarse grained sandstone, shale with minor coal units
Early Palaeocene	<i>Langpar Formation</i>	Calcareous shale with limestone bands



**Figure 2.** (a) and (b) Field photographs showing outcrops of Umlatdoh Limestone used in the measurement of vertical profile sections (VPS – I & II). (c) and (d) depicts parallel layering of fossil Nummulites in hand specimens.

**METHODOLOGY**

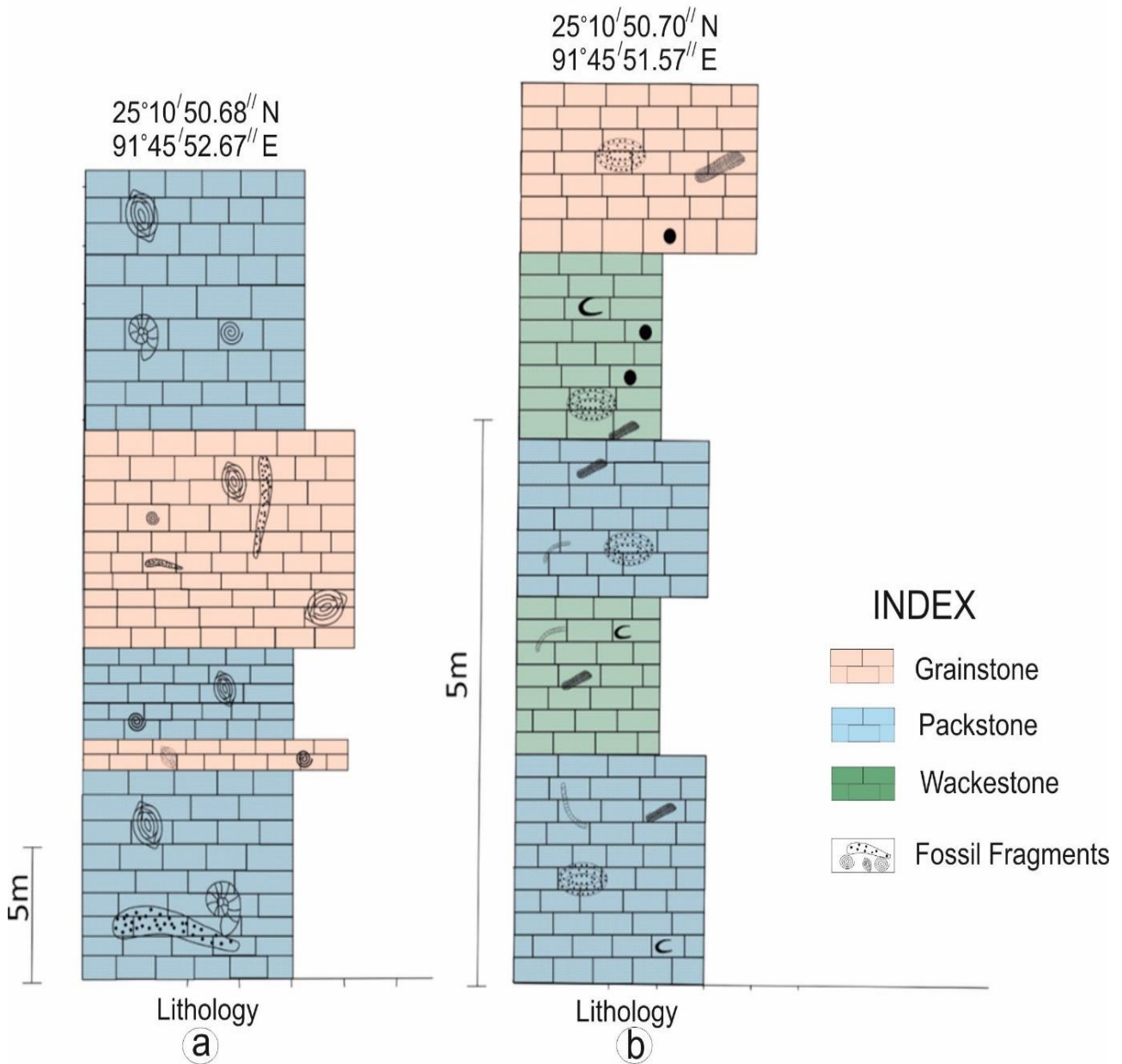
Two outcrop locations along the road cuttings near Wahrew Bridge, Sohbar (Figure 2a,b) were identified for detailed measurements and recording of vertical profile sections. Based on textural and lithological variations, colour, nature of bedding etc. two vertical profile sections were documented (Figure 3a,b) besides collection of samples in time and space. Thin sections were prepared for the purpose of detailed microscopic analysis using Euromax research microscope at the Department of Geology, North Eastern Hill University,

Shillong. The Umlatdoh Limestones were then classified using the classification scheme after Dunham (1962).

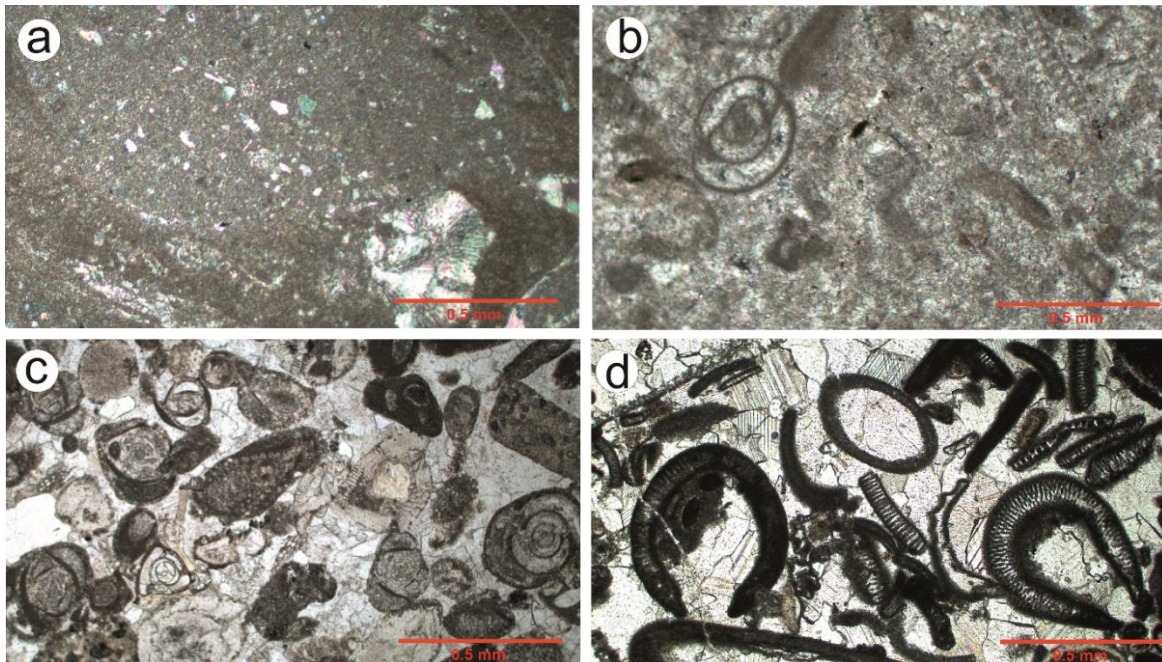
**RESULTS**

**Petrography**

Based on the classification scheme after Dunham (1962), Umlatdoh Limestone were classified as wackestone, packstone and grainstone (Figure 4 a-d), the major components of these limestones being skeletal grains, non-skeletal grains, and cement including micrite and sparry calcite.



**Figure 3.** (a) and (b). Vertical profile sections of Umlatdoh Limestone recorded near Wahrew Bridge, Sohbar, Meghalaya.



**Figure 4.** Photomicrographs of Umlatdoh Limestone showing (a) Wackestone and neomorphism of bioclasts (XPL), (b) Packstone and neomorphism of bioclasts (PPL), (c) Miliolid Grainstone (PPL) and (d) Algal Grainstone (PPL).

### Skeletal grains

Skeletal grains are mostly comprised of large benthic foraminiferal remains including *Nummulites* sp. (Figure 5a), *Assilina* sp. (Figure 5e), *Alveolina* sp. (Figure 5b), *Discocyclina* sp. (Figure 5c), *Biloculina* sp. (Figure 5d), *Quinqueloculina* sp. (Figures 5f & 6i), *Periloculina* sp. (Figure 6h) and *Lockhartia* sp. (Figure 6g). Dasycladalean algae appears abundantly in almost all the thin sections (Figure 6 a–f). Shell structures are generally well preserved, yet a few skeletal grains are filled with sparry calcite.

### Non-skeletal grains

Non-skeletal grains mainly consist of intraclasts, ooids, and peloids. Aggregates bounded by organic matter or several carbonate particles, cemented together by microcrystalline cement, can also be observed. Intraclasts, thus present, are fragments of lithified or partly lithified carbonate sediments (Figure 5g). Lithified or partly lithified irregularly shaped discrete carbonate fragments of varied sizes have been termed as intraclast (Azizi et al., 2014). These also occur as composite grains bounded together by organic matter as well as microcrystalline carbonate cement (Figure 5g).

Ooids, in the studied thin sections, occur as more or less spherical bodies having 2 mm diameter with concentric rims around a nucleus (Figure 5g, h). Cylindrical to elliptical grains of micritic composition ranging between 0.1–0.2 mm in diameter have been identified as of peloids (Figure 5g).

### Diagenesis

Diagenesis refers to all those processes leading to destruction, dissolution and formation of new minerals in sediments simultaneous to or slightly after burial till the sediment eventually consolidates and lithifies into sedimentary rock (Tucker, 1993; Melim et al., 2002; Boggs, 2009; Azizi et al., 2014; Nader, 2017; Ishaq et al., 2019). Petrographic studies reveal the presence of diagenetic processes like micritization, compaction, cementation, dissolution, neomorphism and internal filling responsible for the lithification and subsequent consolidation of the Umlatdoh Limestone.

### Micritization

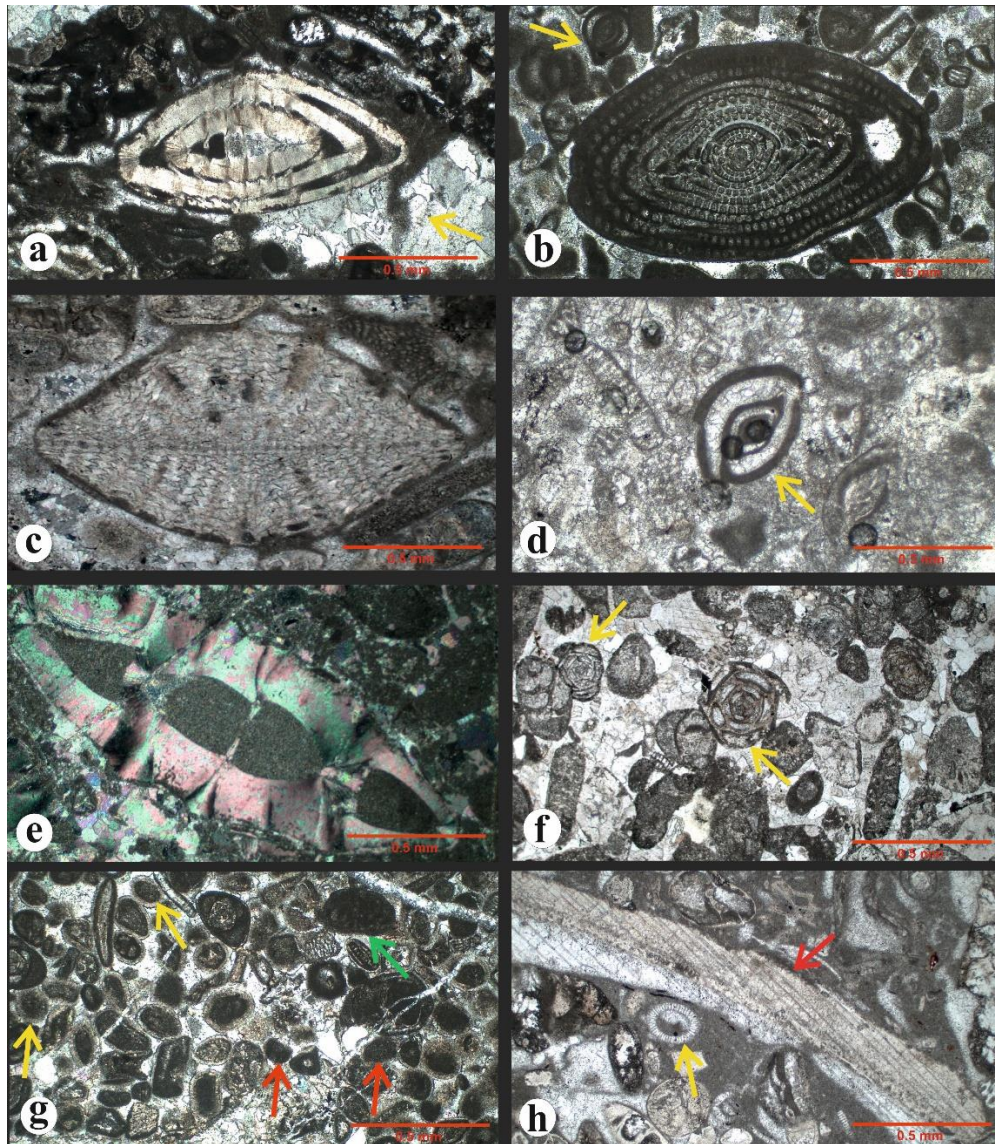
Micritization involves conversion of certain allochemical grains into dense micrite by the activity of endolithic algae (Longman, 1980; Adabi, 2009; Jafarian et al., 2017, 2018). It takes place in disturbed or shallow water environment at or just below the sediment – water interface where margins of carbonate grains are replaced by micrite (Wei, 1995; Adams and MacKenzie, 1998; Kabanov, 2000). In the present context, development of micritic envelope around skeletal fragments such as *Nummulites* sp. (Figure 5a), *Assilina* sp. (Figure 5e), *Alveolina* sp. (Figure 5b), *Discocyclina* sp. (Figures 5c and 7h), *Biloculina* sp. (Figure 5d and 7e) has been attributed to micritization besides modification of internal architectures of a few non-skeletal grains (Figure 5g).

### Compaction

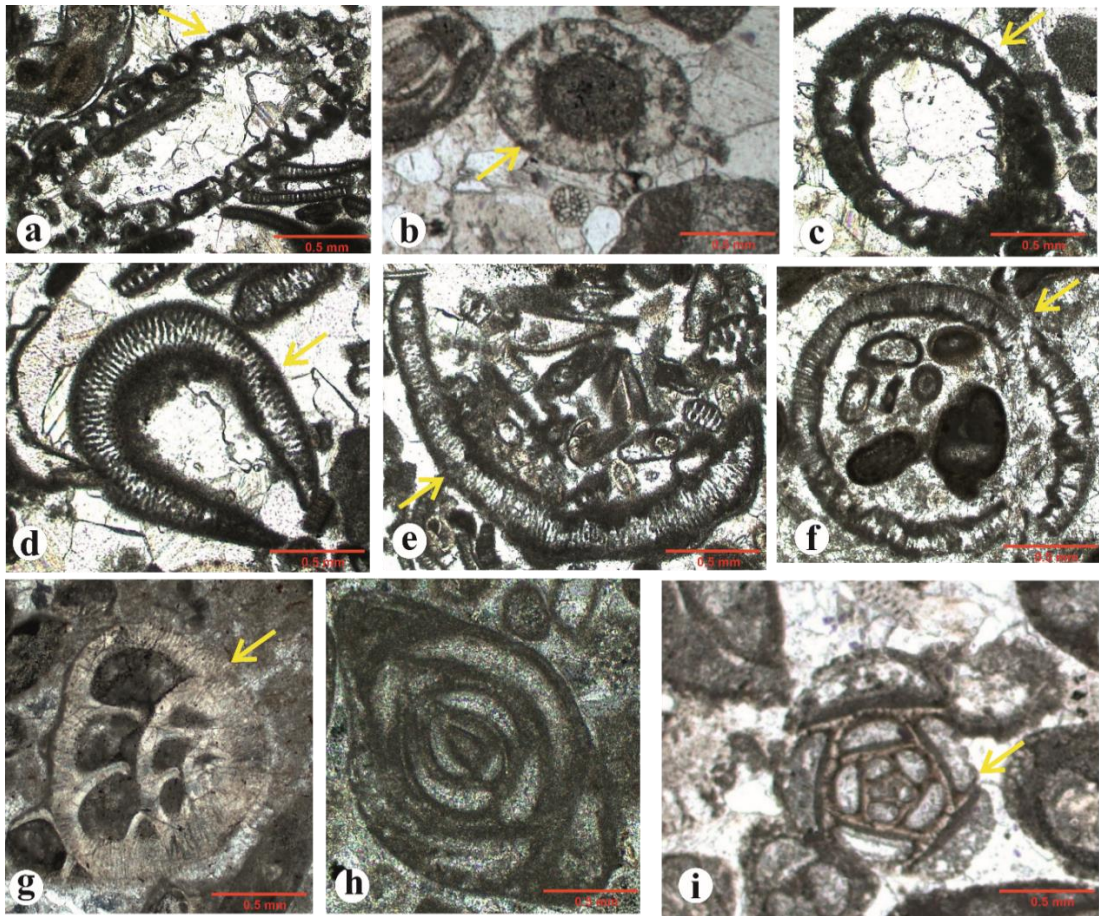
The process of sediment volume reduction under the influence of several variables including overburden, subsurface temperature and pressure, burial stress, pore pressure and the chemistry of pore-water, is referred to as compaction. Petrographic studies on Umlatdoh Limestone provide evidences in favour of both mechanical as well as chemical compaction. Modifications in grain contacts from point to long, concavo-convex, and sutured contact has been attributed to mechanical compaction (Figures 5g,f and 8d). In the studied thin sections, *Assilina* sp. (Figures 5e and 7a)

generally display evidences of mechanical compaction due to progressive increase in the overburden pressure during burial.

The later stage of diagenesis resulted from increased compaction caused by overburden and tectonic stresses. Initially, grain-to-grain contacts formed due to the overburden, which gradually evolved into planar and sutured grain contacts. This process led to the development of stylolites (Figures 5f and 7b), also known as dissolution seams or chemical compaction.



**Figure 5.** Photomicrographs of Umlatdoh Limestone showing (a) *Nummulites* sp. (PPL), (b) *Alveolina* sp. (PPL), (c) *Discocyclus* sp. (PPL), (d) *Biloculina* sp. (PPL), (e) *Assilina* sp. (XPL), (f) *Quinqueloculina* sp. (sutured grain contacts, yellow arrow, PPL), (g) Spherical ooids (yellow arrow) with complete micritization that has destroyed the internal structures of ooids, with outer rim preserved, Intraclast (green arrow), Peloids (red arrow), point and tangential grain contacts and calcite veinlets (PPL), (h) Calcite vein (red arrow) and Spherical ooids (yellow arrow, PPL).



**Figure 6.** Photomicrographs of Umlatdoh Limestone showing (a) – (f) Dasycladalean algae with blocky calcite cement which occurs as a pore-filing in the intergranular pore spaces (PPL), (g) *Lockhartia* sp. (PPL), (h) *Periloculina* sp. with well-preserved micrite coating/envelope around the bioclasts indicating micritization (XPL), (i) *Quinqueloculina* sp. with well-preserved micrite coating/envelope around the bioclasts indicating micritization (yellow arrow, PPL).

### Cementation

Cementation occurs throughout the entire diagenetic process, where chemical precipitates (in the form of new crystals) form within the pores of sediment, binding the grains together (McIlreath and Morrow, 1990). The mineralogy, shape, and crystal structure of carbonate cements evolve as the diagenetic environment and water chemistry transform from marine phreatic to meteoric phreatic, and then to shallow and deep subsurface waters (Ahr, 2008). The Umlatdoh Limestone contain various types of cements as follows.

#### *Fibrous calcite cement*

Fibrous calcite cement appeared as bundles of calcite crystals embedded within a micritic groundmass. It forms along the outer margins of allochem grains, occurring as fine crystalline spars with a thickness of 0.1–0.5 mm (Figure 8d), indicating a shallow marine environment (Flügel, 1982). The presence of fibrous cement is widely recognized as the

clearest evidence of syndimentary cementation (Longman, 1980; Flügel, 2010).

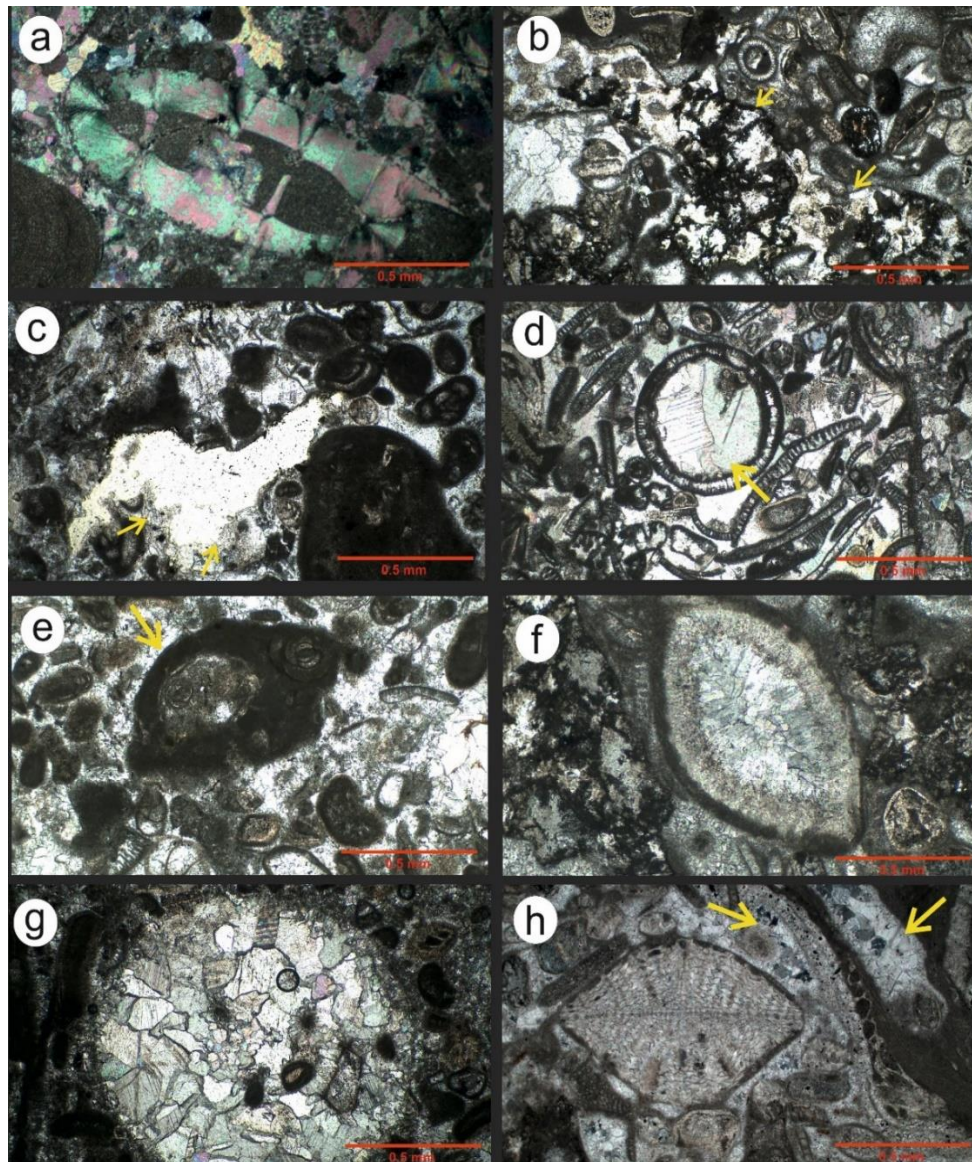
#### *Granular calcite cement*

Granular cement, also known as blocky cement, occupied both intergranular and intra-particle pore spaces (Figure 7g). It consists of subhedral to anhedral crystals with crystal size increasing as they grow away from the substrate. The presence of granular calcite cement in both skeletal and non-skeletal grains indicates a low Mg/Ca ratio in the fluids (Purser, 1978). In meteoric water environment, the low Mg<sup>2+</sup> content promotes the precipitation of calcite in a granular or blocky form, indicate freshwater diagenesis. In the meteoric phreatic zone, where pore spaces are predominantly filled with water, the cementation is more uniform, resulting in larger blocky calcite crystals (Wright and Tucker, 1990; Khalifa, 2005; Zhang et al., 2006; Flügel, 2010; Abu El Ghar et al., 2015). The filling of macropores with coarse crystalline cements is interpreted as evidence of burial cementation (Guo et al., 2016).

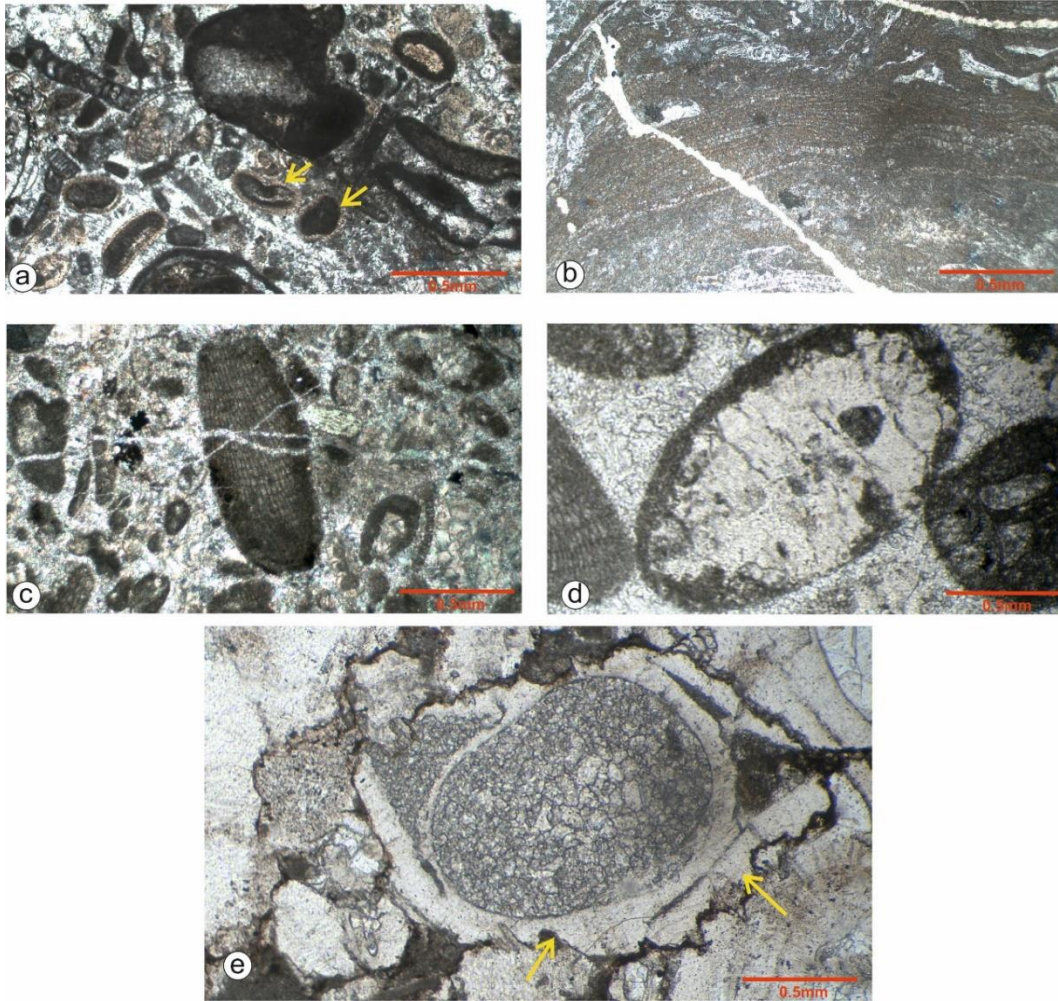
### ***Blocky calcite cement***

The next generation after fibrous cement is the blocky calcite cement, filled the remaining voids between allochems. It consists of fine- to coarse-grained, subhedral to anhedral crystals ranging from 0.5 to 3 mm in size and also fills internal cavities within bioclasts as intergranular cement (Figure 6c & 7d). In meteoric water environments, low  $Mg^{2+}$  content promotes the precipitation of blocky calcite cements (Choquette et al., 1990; Tucker, 2001; Zhang et al., 2006; Flügel, 2010). These cementations occur during both eodiagenesis and mesodiagenesis, filling the voids.

In this study, some instances show dissolution features in the central blocky cement within pores, suggesting deep burial diagenesis (Oldershaw, 1971; Folk, 1974; Bathurst, 1975; Wong and Oldershaw, 1981; Ahmad et al., 2006). In other cases, blocky calcite cement is associated with calcite veins, marking the final phase of cementation and likely formed in a deep phreatic burial environment (Singh, 1987). Carbonate rocks containing this late-stage cement retain some of their primary porosity.



**Figure 7.** Photomicrographs of Umlatdoh Limestone showing (a) Compaction effects on *Assilina* sp. (XPL), (b) Development of stylolite (yellow arrows) due to compaction (PPL), (c) Development of stylolite (yellow arrows) due to pressure dissolution (PPL), (d) Blocky calcite cement occurs as a pore-filling in the intergranular pore spaces, (XPL), (e) Micritization around *Biloculina* sp. (PPL), (f) Growth of drusy calcite cement in *Miliolid* sp. (XPL), (g) Granular calcite cement exhibits fillings of intra-granular pores (XPL), (h) Growth of drusy calcite cement (yellow arrows, XPL).



**Figure 8.** Photomicrographs of Umlatdoh Limestone showing (a) fine crystals of rim cements around intraclasts (arrows, PPL), (b) cement in fractures (PPL), (c) cement in fractures (XPL), (d) point contact (PPL), with isopachous fibrous cements around bioclasts, (e) Growth of syntaxial calcite cement (yellow arrow).

### Neomorphism

Neomorphism encompasses both aggrading and degrading recrystallization, involving transformations within a mineral or its polymorph. The resulting crystals may vary in size or shape from the original ones. In the studied carbonate rock, a specific type of neomorphism, known as calcitization, is observed. This process involves the recrystallization of aragonite shells into sparry calcite, which plays a significant role in carbonate diagenesis (Figures 4a, b). Calcitization is well developed in the micritic matrix, indicating the influence of a meteoric phreatic environment (Choquette and James, 1987; Shaaban, 2004; Kiefer-Ollier et al., 2010; Heidari et al., 2014).

### DISCUSSION

Petrographic studies of the Umlatdoh Limestone reveal distinct diagenetic environments as marine, meteoric, and

burial realms based on diagenetic features, mineralogical compositions, cement types, and microfabrics. Characteristics of the marine environment include bioturbation, micritization, physical compaction, neomorphism, and isopachous fibrous calcite cement. The meteoric environment is marked by granular and blocky calcite cement, mechanical compaction, and neomorphism. In the burial environment, key processes include blocky calcite cement, mechanical and chemical compaction, fracturing, and the formation of calcite veins.

The petrographic analysis further indicates that the Umlatdoh Limestone underwent two primary diagenetic stages: eodiagenesis and mesodiagenesis, each associated with significant diagenetic events in distinct environments (Figure 9). During the eodiagenesis stage, micritization affected various allochems, including both skeletal (bioclasts, Figure 6h, i) and non-skeletal grains (Figure 5g). This process was

likely driven by microbial activity, including algae and fungi (Llinas, 2002; Vincent et al., 2007; Jadoul and Galli, 2008; Ronchi et al., 2011). Following micritization, marine isopachous rim cement formed around both skeletal and non-skeletal grains.

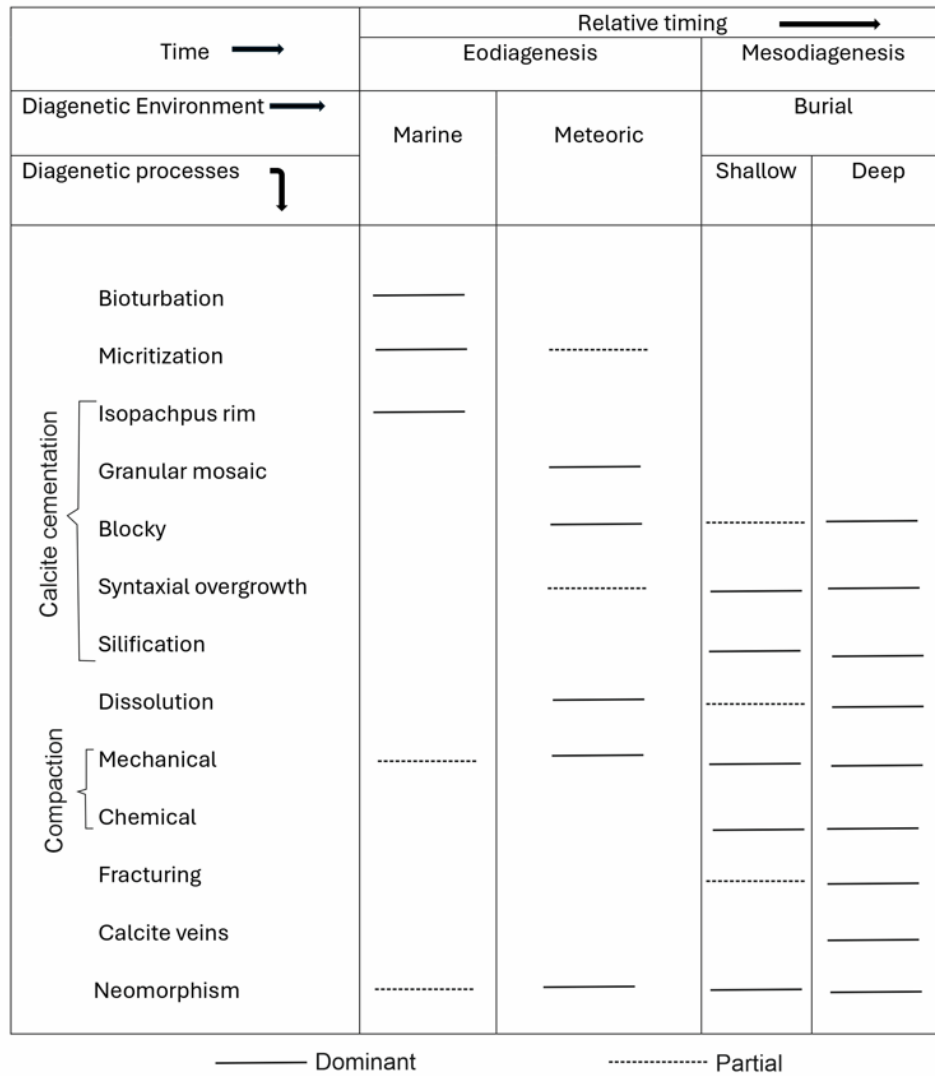
**Marine environment**

Marine diagenetic environments are characterized by early micritization and the formation of non-ferron-isopachous fibrous cements (Khalifa, 2005; Taghavi et al., 2006; Vincent et al., 2007; Mahboubi et al., 2010; Abu El Ghar et al., 2015). Micritization is one of the most prominent diagenetic features identified in the Umlatdoh Limestones, suggesting formation in a marine setting. It appears as micritic envelopes and micritized skeletal (bioclasts, Figure 6h, i) and non-skeletal grains (Figure 5g), likely caused by mechanical

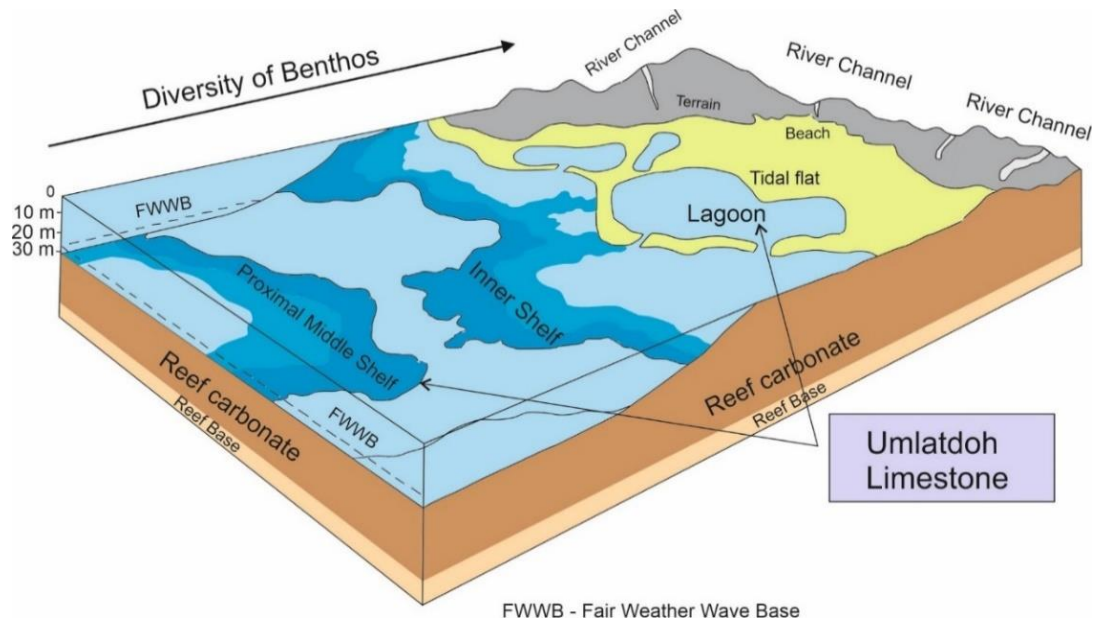
disintegration or bioerosion of large calcareous organisms, such as Nummulites and algae, by endolithic algae (El Ghar and Hussein, 2005; Khalifa, 2005; Melim et al., 2002). The precipitation of isopachous and pore-filling calcite and calcite overgrowths (Figure 8e) is typically associated with marine and mixed marine-meteoric processes.

**Meteoric environment and Mesodiagenesis processes**

The presence of granular calcite cement, early-stage blocky calcite cement, micritic cement, dissolution of molds, and neomorphism all indicate meteoric-phreatic diagenetic realms (Melim et al., 2002; Vincent et al., 2007; Abu El Ghar et al., 2015). Similarly, in the mesodiagenesis processes, such as mechanical and chemical compaction, cementation, neomorphism, formation of calcite veins, and fracturing processes impacted the studied limestone (Figures 5h, 8b, c).



**Figure 9.** Detailed paragenetic sequence of the Umlatdoh Limestone, representing different diagenetic events observed in thin sections



**Figure 10.** Conceptual depositional model of Umlatdoh Limestone of the study area.

### Burial environment

The Umlatdoh Limestone possess features such as sutured and concavo-convex contacts, fractures, veins, and blocky and granular calcite cements. During cementation, calcite crystals formed as overgrowths and blocky textures, suggesting precipitation under burial conditions (Moore, 1989). Burial diagenetic realms are typically divided into shallow and deep burial, though the exact boundary between them is not clearly defined (Vincent et al., 2007; Flügel, 2010). Mechanical compaction features, such as suture and concavo-convex contacts, are indicative of shallow burial condition (Vincent et al., 2007; Mahboubi et al., 2010; Abuseda et al., 2015). Characteristics of chemical compaction such as stylolites and dissolution seams, also appear to develop in shallow burial environments (Mahboubi et al., 2010; Abuseda et al., 2015). In the deep burial realm, fractures, dissolution, and calcite veins, along with blocky calcite cements, are prevalent.

The Umlatdoh Limestone are rich in skeletal grains, including larger benthic foraminifera namely *Nummulites* sp., *Assilina* sp., *Alveolina* sp., *Discocyclusina* sp., *Biloculina* sp., *Quinqueloculina* sp., *Periloculina* sp., *Lockhartia* sp., and *Dasycladalean* algae. Abundance of *Dasycladalean* algae and large benthic foraminifera in the Umlatdoh Limestone clearly indicate that these carbonates are analogous to modern shallow-marine carbonates. Based on biogenic assemblages, the depositional environment of the Umlatdoh Limestone is interpreted as an open lagoonal to proximal middle shelf environment (Figure 10).

### CONCLUSIONS

The present study deals with the diagenetic characteristics and depositional environment of Umlatdoh Limestone exposed in southern Shillong Plateau, Meghalaya. The following conclusions are drawn from the present study:

- (1) The fine- to medium-grained Umlatdoh Limestone are rich in both skeletal and non-skeletal grains classified as wackestone, packstone and grainstone.
- (2) The non-skeletal grains consist of intraclasts, ooids, and peloids, while skeletal grains include foraminifera (*Nummulites* sp., *Assilina* sp., *Alveolina* sp., *Discocyclusina* sp., *Biloculina* sp., *Quinqueloculina* sp., *Periloculina* sp., *Lockhartia* sp.), *Dasycladalean* algae and *Coraline* algae.
- (3) The abundance of biogenic assemblages suggests that the depositional environment of the Umlatdoh Limestone was an open lagoonal to proximal middle shelf environment.
- (4) The Umlatdoh Limestone underwent various diagenetic processes, including micritization, cementation, compaction, dissolution, and neomorphism.
- (5) Based on mineralogical and textural variations in the studied limestones, distinct diagenetic environments were identified, including meteoric-phreatic (freshwater), marine phreatic, mixed marine phreatic, and burial diagenetic settings.

## ACKNOWLEDGMENTS

We would like to express our sincere gratitude to Dr. O.P. Pandey for his invaluable contribution in reviewing the manuscript. We acknowledge the Regional Laboratory, ONGC, Sivasagar, Assam, for the necessary help during the preparation of thin sections. The authors also express their gratitude to two anonymous referees who made precise reviews, which helped us in the improvement of the final version of the manuscript.

## Author Credit Statement

A Das, M Baruah and M K Pathak carried out fieldwork, analyzed the samples and performed interpretations and writing. D Walia conceptualized the idea, carried out fieldwork and performed writing and editing. S Kumar helped in compilation of research paper.

## Data Availability

The data will be shared on request to the corresponding author.

## Compliance with Ethical standards

No conflict of interest and adhere to copyright norms

## REFERENCES

- Abu El Ghar, M. S., Khalifa, M. A. and Hussein, A. W., 2015. Carbonate diagenesis of the mixed clastic-carbonate Galala formation, north eastern Desert, Egypt. *Arabian J. Geosci.*, 8, 2551-2565.
- Abuseda, H., Kassab, M. A., LaLa, A. M. and El Sayed, N. A., 2015. Integrated petrographical and petrophysical studies of some Eocene carbonate rocks, Southwest Sinai, Egypt. *Egyptian J. Petr.*, 24(2), 213-230.
- Acharyya, S.K., Mitra, N.D. and Nandy, D.R., 1986. Regional geology and tectonic setting of northeast India and adjoining region. *Mem. Geol. Survey India*, 119, 6-12.
- Adabi, M.H., 2009. Multistage Dolomitization of Upper Jurassic Mozduran Formation, Kopet-Dagh Basin, N.E. Iran. *Carbonates and Evaporites*, 24(1), 16-32.
- Adams, A.E and Mackenzie, W.S., 1998. *A Colour Atlas of Carbonate Sediments and Rocks Under the Microscope*. 180.
- Ahmad, A. H. M., Bhat, G. M. and Khan, M. H. A., 2006. Depositional environments and diagenesis of the kuldhar and Keera Dome carbonates (Late Bathonian-Early Callovian) of Western India. *J. Asian Earth Sci.*, 27(6), 765-778.
- Ahr, W.M., 2008. A new genetic classification of carbonate porosity and its application to reservoir characterization. In *Am. Assoc. Petr. Geol. Annual convention (Abstract)*, San Antonio, Apr. 20-23.
- Azizi, S.H.H., Shabestari, G.M. and Khazaei, A., 2014. Petrography and geochemistry of Paleocene-Eocene limestones in the Ching-dar syncline, eastern Iran. *Geosci. Frontiers*, 5(3), 429-438.
- Bathurst, R. G. C., 1975. Carbonate sediments and their diagenesis (*Developments in Sedimentology* 12), Amsterdam, the Netherlands: Elsevier, 658.
- Beavington-Penney, S. J. and Racey, A., 2004. Ecology of extant nummulitids and other larger benthic foraminifera: applications in palaeoenvironmental analysis. *Earth-Sci. Rev.*, 67(3-4), 219-265.
- Biswas, S., Coutand, I., Grujic, D., Hager, C., Stöckli, D. and Grasmann, B., 2007. Exhumation and uplift of the Shillong plateau and its influence on the eastern Himalayas: New constraints from apatite and zircon (U-Th-[Sm])/He and apatite fission track analyses. *Tectonics*, 26(6).
- Boggs, Jr. S., 2009: *Petrology of Sedimentary Rocks*. 2nd Ed., Cambridge University Press, New York, 600.
- Boothroyd, J.C., 1985. Tidal inlets and tidal deltas. In *Coastal sedimentary environments*. Springer, New York, 445-532.
- Choquette, P. W. and James, N. P., 1987. Diagenesis# 12. Diagenesis in Limestones-3. The deep burial environment. *Geosci. Can.*, 14(1), 3-35.
- Choquette, P. W., James, N., McIlreath, I. and Morrow, D., 1990. Diagenesis. *Geosci. Can.*, 10(4).
- Desikachar, S.V., 1974. A review of the tectonic and geological history of eastern India in terms of 'plate tectonics' theory. *J. Geol. Soc. India*, 15, 137-149.
- Dunham, R. J., 1962. Classification of carbonate rocks according to depositional textures, In: *Classification of Carbonate Rocks — A Symposium* ., ed. by Ham, William E.. AAPG Memoir, 1 . AAPG (American Association of Petroleum Geologists), Tulsa, Oklahoma, pp. 108-121
- El Ghar, M. A. and Hussein, A. W., 2005. Post-depositional changes of the lower-middle Eocene limestones of the area between Assiut and Minia, West of the Nile Valley, Egypt. In *Proc. first int. conf. on the geology of the Tethys*, 224-248.
- Evans, P., 1964. Tectonic framework of Assam. *J. Geol. Soc. India*, 5, 80-96.
- Flügel, E., 1982. Introduction to facies analysis. *Microfacies Analysis of Limestones*, 1-26.
- Flügel, E., 2010. *Microfacies of carbonate rocks: Analysis, Interpretation and Application*. Berlin Heidelberg: Springer-Verlag, 984.
- Folk, R. L., 1974. The natural history of crystalline calcium carbonate; effect of magnesium content and salinity. *J. Sediment. Res.*, 44(1), 40-53.
- Garg, R. and Jain, K.P., 1995. Significance of the terminal Cretaceous calcareous nannofossil marker *Micula prinsii* at the Cretaceous-Tertiary boundary in the Um Sohryngkew section, Meghalaya, India. *Curr. Sci.*, 69(12), 1012-1017.
- Ghosh, A.K. and Sarkar, S., 2013. Palaeoecological implications of coralline red algae and halimedacean green algae from the Prang Formation of South Shillong Plateau, Meghalaya. *J. Geol. Soc. India*, 81, 531-542.
- Gischler, E., Hauser, I., Heinrich, K. and Scheitel, U., 2003. Characterization of depositional environments in isolated carbonate platforms based on benthic foraminifera, Belize, Central America. *Palaios*, 18(3), 236-255.
- Guo, C., Chen, D., Qing, H., Dong, S., Li, G., Wang, D. and Liu, C., 2016. Multiple dolomitization and later hydrothermal alteration on the Upper Cambrian-Lower Ordovician carbonates in the northern Tarim Basin, China. *Mar. Pet. Geol.*, 72, 295-316.

- Gupta, R.P. and Sen, A.K., 1988. Imprints of the ninety-east ridge in the Shillong Plateau, Indian Shield. *Tectonophysics*, 154(3-4), 335-341.
- Hallock, P. and Glenn, E.C., 1986. Larger foraminifera: a tool for paleoenvironmental analysis of Cenozoic carbonate depositional facies. *Palaaios*, 1, 55-64.
- Heidari, A., Gonzalez, L. A., Mahboubi, A., Moussavi-Harami, R., Ludvigson, G. A. and Chakrapani, G. J., 2014. Diagenetic model of carbonate rocks of Guri Member of Mishan Formation (lower to middle Miocene) SE Zagros Basin, Iran. *J. Geol. Soc. India*, 84, 87-104.
- Ishaq, M., Jan, I.U., Hanif, M. and Awais, M., 2019. Microfacies and diagenetic studies of the early Eocene Sakesar Limestone, Potwar Plateau, Pakistan: approach of reservoir evaluation using outcrop analogue. *Carbonates Evaporites*, 34(3), 623-656.
- Jadoul, F. and Galli, M. T., 2008. The Hettangian shallow water carbonates after the Triassic/Jurassic biocalcification crisis: the Albenza Formation in the Western Southern Alps. *Riv. Ital. Paleontol. Stratigr.*, 114(3), 453-470.
- Jafarian, A., Fallah-Baghtash, R., Mattern F. and Heubeck C., 2017. Reservoir quality along a homoclinal carbonate ramp deposit: The Permian Upper Dalan Formation, South Pars Field, Persian Gulf Basin. *Mar. Petrol. Geol.*, 88, 587-604.
- Jafarian, A., Javanbakht, M., Koeshidayatullah, A., Pimentel, N., Salad Hersi, O., Yahyaei, A. and Beigi, M., 2018. Paleoenvironmental, diagenetic, and eustatic controls on the Permo-Triassic carbonate-evaporite reservoir quality, Upper Dalan and Kangan formations, Lavan Gas Field, Zagros Basin. *Geol. J.*, 53(4), 1442-1457.
- Jauhri, A.K., 1994. Carbonate buildup in the Lakadong Formation of the South Shillong Plateau, NE India: A micropaleontological perspective. *Boll. Soc. Paleontol. Ital.*, 33, 157-170.
- Jauhri, A.K., 1998. *Miscellanea Pfender, 1935 (foraminiferida) from the south shillong region, NE India*. *J. Palaeontol. Soc. Ind.*, 43, 73-83.
- Jauhri, A.K. and Agarwal, K.K., 2001. Early Palaeogene in the south Shillong Plateau, NE India: local biostratigraphic signals of global tectonic and oceanic changes. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 168(1-2), 187-203.
- Jauhri, A. K., Kishore, S., Singh, A. P., Singh, S. K., Misra, P. K. and Tiwari, R. P., 2016. Coralline algal and larger foraminiferal facies in the Prang Formation (Middle-Upper Eocene), Jaintia Hills, Meghalaya, NE India. *J. Palaeontol. Soc. Ind.*, 61(1), 99-109.
- Jones, B. and Hunter, I.G., 1992. Very large boulders on the coast of Grand Cayman: the effects of giant waves on rocky coastlines. *J. Coast. Res.*, 8(4), 763-774.
- Kabanov, P.B., 2000. Grain micritization as facial indicator in shallow water marine carbonate rocks. *Byull. Moskovsk. Obshch. Isp. Prir., Otd. Biol.*, 75(4), 39-48.
- Kalita, K.D. and Gogoi, H., 2015. Microfacies types (MFT) and palaeoenvironment of the Umlatodoh carbonates in the Shillong Plateau of Meghalaya, NE India. *J. Geol. Soc. India*, 85(6), 686-696.
- Khalifa, M. A., 2005. Lithofacies, diagenesis and cyclicity of the 'lowermember' of the Khuff Formation (Late Permian), Al Qasim Province, Saudi Arabia. *J. Asian Earth Sci.*, 25(5), 719-734.
- Kiefer-Ollier, E., Loisy, C. and Cerepi, A., 2010. Diagenetic signature of the Mid-Paleocene exposure surface in the southeastern Pyrenean platform. *C. R. Geosci.*, 342(6), 483-491.
- Li, C., Jones, B. and Blanchon, P., 1997. Lagoon-shelf sediment exchange by storms--evidence from foraminiferal assemblages, east coast of Grand Cayman, British West Indies. *J. Sediment. Res.*, 67(1), 17-25.
- Li, C., Jones, B. and Kalbfleisch, W.B., 1998. Carbonate sediment transport pathways based on foraminifera: case study from Frank Sound, Grand Cayman, British West Indies. *Sedimentology*, 45(1), 109-120.
- Llinas, J.C., 2002. Diagenetic history of the Upper Jurassic Smackover Formation and its Effects on Reservoir Properties: Vocation Field, Manila Sub-Basin, Eastern Gulf Coastal Plain. *Trans. Gulf Coast Assoc. Geol. Soc. (GCAGS)*, 52, 631-644.
- Longman, M.W., 1980. Carbonate diagenetic textures from near surface diagenetic environments. *AAPG bull.*, 64(4), 461-487.
- Mahboubi, A., Moussavi-Harami, R., Carpenter, S. J., Aghaei, A. and Collins, L. B., 2010. Petrographical and geochemical evidences for paragenetic sequence interpretation of diagenesis in mixed siliciclastic-carbonate sediments: Mozduran Formation (Upper Jurassic), south of Agh-Darband, NE Iran. *Carbonates and Evaporites*, 25, 231-246.
- McIlreath, I. A. and Morrow, D. W., 1990. *Diagenesis*. Reprint Series 4. Geosci. Canada. Geological Association of Canada, 338.
- Mehrotra, K.K. and Banerji, R.K., 1973. Middle-Upper Eocene Biostratigraphy of Khasi and Jaintia Hills based on planktonic and larger foraminifera. *J. Palaeontol. Soc. India*, 18, 22-26.
- Melim, L.A., Westphal, H., Swart, P.K., Eberli, G.P. and Munnecke, A., 2002. Questioning carbonate diagenetic paradigms: evidence from the Neogene of the Bahamas. *Mar. Geol.*, 185(1-2), 27-53.
- Moore, C.H., 1989. *Carbonate diagenesis and porosity*. Elsevier, 317.
- Nader, F.H., 2017. Introduction. In: *Multi-scale quantitative diagenesis and impacts on heterogeneity of Carbonate Reservoir Rocks*. Springer, New York, 1-13.
- Nagappa, Y., 1959. Foraminiferal biostratigraphy of the Cretaceous-Eocene succession in the India-Pakistan-Burma region. *Micropaleontology*, 5(2), 145-177.
- Najman, Y., Bracciali, L., Parrish, R.R., Chisty, E. and Copley, A., 2016. Evolving strain partitioning in the Eastern Himalaya: The growth of the Shillong Plateau. *Earth Planet. Sci. Lett.*, 433, 1-9.
- Nandy, D.R., 1986. Tectonics, seismicity and gravity of northeastern India and adjoining region. *Mem. Geol. Surv. India*, 119, 13-17.
- Nandy, D.R., 2017. *Geodynamics of Northeastern India and the adjoining region*. Scientific Book Centre.
- Oldershaw, A. E., 1971. The significance of ferroan and nonferroan calcite cements in the Halkin and Wenlock limestones (Great Britain). *Carbonate Cements: Johns Hopkins Univ. Studies in Geol*, 19, 225-232.
- Purser, B. H., 1978. Early diagenesis and the preservation of porosity in Jurassic limestones. *J. Pet. Geol.*, 1(2), 83-94.
- Ray, J., Saha, A., Ganguly, S., Balaram, V., Krishna, A.K. and Hazra, S., 2011. Geochemistry and petrogenesis of Neoproterozoic Mylliem granitoids, Meghalaya Plateau, northeastern India. *J. Earth Syst. Sci.*, 120(3), 459-473.

- Ronchi, P., Jadoul, F., Ceriani, A., Di Giulio, A., Scotti, P., Ortenzi, A. and Previde Massara, E., 2011. Multistage dolomitization and distribution of dolomitized bodies in Early Jurassic carbonate platforms (Southern Alps, Italy). *Sedimentology*, 58(2), 532-565.
- Sahoo, S., Gogoi, B. and Mahanta, B. N., 2024. Petrology, mineral chemistry and geochemistry of lamprophyres from Rongjeng–Nongchram area, East Garo Hills, Shillong Plateau, Meghalaya, Northeast India. *J. Earth Syst. Sci.*, 133(1), 16.
- Saraswati, P. K., Khanolkar, S. and Banerjee, S., 2018. Paleogene stratigraphy of Kutch, India: an update about progress in foraminiferal biostratigraphy. *Geodinamica Acta*, 30(1), 100-118.
- Sarkar, S., 2015a. Thanetian-Ilerdian coralline algae-benthic foraminifera from north-east India: microfacies analysis and new insights into the Tethyan perspective. *Lethaia*, 48, 13- 28.
- Sarkar, S., 2015b. Calcareous algal-rich carbonate sediments from Assam Shelf, N-E India: An overview of the palaeoenvironmental implications. In: S. Mukherjee (Ed.), *Pet. Geosci. Indian Contexts*. Springer Geology, Switzerland, 175-189.
- Sarkar, S., 2016. Early Eocene calcareous algae and benthic foraminifera from Meghalaya, NE India: A new record of microfacies and palaeoenvironment. *J. Geol. Soc. India*, 88(3), 281-294.
- Sarkar, S., 2020. Ecostratigraphic implications of a Late Palaeocene shallow-marine benthic community from the Jaintia Hills, Meghalaya, NE India. *J. Earth Syst. Sci.*, 129(1), 10.
- Scoffin, T.P., 1993. The geological effects of hurricanes on coral reefs and the interpretation of storm deposits. *Coral Reefs*, 12(3), 203-221.
- Shaaban, M. N., 2004. Diagenesis of the lower Eocene Thebes Formation, Gebel Rewagen area, Eastern Desert, Egypt. *Sediment. Geol.*, 165(1-2), 53-65.
- Shaghude, Y.W., Wannas, K.O. and Mahongo, S.B., 2002. Biogenic assemblage and hydrodynamic settings of the tidally dominated reef platform sediments of the Zanzibar Channel. *West Indian Ocean J. Mar. Sci.*, 1(2), 107-116.
- Singh, U., 1987. Ooids and cements from the Late Precambrian of the Flinders Ranges, South Australia. *J. Sediment. Res.*, 57(1), 117-127.
- Srivastava, V.K. and Singh, B.P., 2019. Depositional environments and sources for the middle Eocene Fulra Limestone Formation, Kachchh Basin, western India: Evidences from facies analysis, mineralogy, and geochemistry. *Geol. J.*, 54(1), 62-82.
- Taghavi, A. A., Mørk, A. and Emadi, M. A., 2006. Sequence stratigraphically controlled diagenesis governs reservoir quality in the carbonate Dehloran Field, southwest Iran. *Pet. Geosci.*, 12(2), 115-126.
- Tewari, V.C., Kumar, K., Lokho, K. and Siddaiah, N.S., 2010a. Lakadong limestone: Paleocene-Eocene boundary carbonates sedimentation in Meghalaya, northeastern India. *Curr. Sci.*, 98, 88-95.
- Tewari, V.C., Lokho, K., Kumar, K. and Siddaiah, N.S., 2010b. Late Cretaceous-Paleogene Basin Architecture and Evolution of the Shillong Shelf Sedimentation, Meghalaya, Northeast India. *Jour. Indian Geol. Cong.*, 2, 61-73.
- Tucker, M.E., 1993. Carbonate diagenesis and sequence stratigraphy. *Sedimentology Review*, 1, 51-72.
- Tucker, M.E., 2001. *Sedimentary Petrology: An Introduction to the Origin of Sedimentary Rocks*. Blackwell Science, Oxford, p. 260.
- Vincent, B., Emmanuel, L., Houel, P. and Loreau, J.P., 2007. Geodynamic control on carbonate diagenesis: petrographic and isotopic investigation of the Upper Jurassic formations of the Paris Basin (France). *Sediment. Geol.*, 197(3-4), 267-289.
- Wei, L.M., 1995. Study on the micritization of carbonate grains by bacteria and algae. *Acta Sedimentol. Sin.*, 13(3), 89-97.
- Wilson, B., Jones, B. and Birjue, K., 2010. Paleoenvironmental interpretations based on foraminiferal abundance biozones, Mayo Limestone, Trinidad, West Indies, including alpha and beta diversities. *Palaios*, 25(3), 158-166.
- Wong, P. K. and Oldershaw, A., 1981. Burial cementation in the Devonian, Kaybob reef complex, Alberta, Canada. *J. Sediment. Res.*, 51(2), 507-520.
- Wright, V. P. and Tucker, M., 1990. Carbonate sediments and limestones: constituents. *Carbonate Sedimentology*. Blackwell, Oxford, 1-27.
- Zhang, H., Ding, L., Wang, X., Wang, L., Wang, Q. and Xia, G., 2006. Carbonate diagenesis controlled by glacioeustatic sea-level changes: a case study from the Carboniferous-Permian Boundary Section at Xikou, China. *J. China Univ. Geosci.*, 17(2), 103-114.

Received on: 08-02-2024 ; Revised on: 15-11-2024 ; Accepted on:18-11-2024