Carbonates and Evaporites (2022) 37:75
https://doi.org/10.1007/s13146-022-00822-0

ORIGINAL ARTICLE

Sedimentological and diagenetic analysis of Early Eocene Margalla Hill Limestone, Shahdara area, Islamabad, Pakistan: implications for reservoir potential

Haroon Aziz[1,2] · Jabir Hussain[2] · Muhammad Tariq[1] · Muhsan Ehsan[2] · Salman Khurshid[3] · Saleem Khan[1] · Waleed Anwar[1]

Accepted: 13 October 2022 / Published online: 28 October 2022

Abstract

The role of the micro-facies and diagenesis was assessed to delineate the reservoir potential of the Early Eocene Margalla Hill Limestone, of the Shahdara section. The main focus of the study is the investigation and assessing the quality of the reservoir on the basis of diagenetic and depositional fabrics. Lithologically, the formation grades from thin to medium and massive bedded smaller to larger nodular limestone with sub-ordinate marl and shale inter-beds. Five micro-facies were established based on estimated allo-chemical and ortho-chemical constituent. The enumerated micro-facies include: Planktonic foraminiferal mud-wackestone (MHL-1); Lime mudstone (MHL-2); *Lockhartia*-rich mud-wackestone (MHL-3); Foraminiferal wackestone (MHL-4) and Bioclastic wackestone (MHL-5). These micro-facies are consistent with the deposition in the proximal outer ramp to proximal inner ramp settings of the gentle-sloping homoclinal ramp environment. The Margalla Hill Limestone is characterized by the fossil assemblages of mainly larger benthic foraminifera, such as *Lockhartia*, *Assilina*, *Nummulites*, rare *Operculina*, and *Rotalia* sp., and shallower fauna (echinoderms, algae and miliolids) and a few planktonic foraminifera including Morozovella cf. acuta, *Globigerinatheka* sp. and other Globogerinids. The fossil assemblages, allo-chemical and micritic constituents signify the depositional change from deep water toward the shallower setting, reflecting a coarsening upward trend during the deposition of the Margalla Hill Limestone. The Margalla Hill Limestone has been subjected to various diagenetic overprints which include micritization, cementation, neomorphism, compactions (mechanical and chemical), dissolution, dolomitization, and micro-calcite-filled fractures, representing early to syn- and post-depositional events. The diagenetic imprints of dissolution, micro-fractures, dolomitization enhance the reservoir characteristics, whereas cementation, micritization, neomorphism and chemical and mechanical compactions adversely affect the reservoir properties of the formation. In the Margalla Hill Limestone, the controlling factors of porosity and permeability distribution are attributed by depositional, diagenetic and deformational processes.

Keywords Eocene · Margalla Hill Limestone · Depositional environment · Diagenetic analysis · Reservoir quality

Introduction

Carbonate rocks are accountable for around more than 50% of hydrocarbon production in the world due to their tendency to produce multiple porosity systems (Fan et al. 2007; Huaiyou et al. 2008). The world's largest oil and gas fields (i.e., Ghawar and North Field/South Pars fields respectively) are both reservoirs and in carbonates (Garland et al. 2012). Petrographic analyses (e.g., Flügel 2004, 2010) partnered with diagenetic study of carbonates (e.g., Scholle and Ulmer-Scholle 2003) are imperative to envisage the carbonate depositional environments and characteristics of a petroleum reservoir. In Pakistan, the Potwar Basin is the oldest producing

✉ Muhsan Ehsan
muhsanehsan98@hotmail.com

1 Department of Earth Sciences, COMSAT's University, Abbottabad Campus, Islamabad, Pakistan

2 Department of Earth and Environmental Sciences, Bahria University, Islamabad, Pakistan

3 Department of Geology, University of Malakand, Dir Lower, Chakdara, Khyber Pakhtunkhwa, Pakistan

province which hosts many carbonate successions, where the first economic discovery was achieved in 1914 at Khaur (Moghal et al. 2007). Among the sedimentary successions of the Potwar Basin, Paleocene–Eocene carbonates are the major and pivotal source of hydrocarbon; specifically, the Eocene carbonates of (Chorgali and Sakesar formations) acting as producing carbonate reservoirs (Kadri 1995; Hussain et al. 2021). In the Potwar Basin, the Eocene stratigraphic successions are deposited which include the formations of Nammal, Sakesar, Chorgali and Margalla Hill Limestone respectively (Shah 2009). The Margalla Hill Limestone mainly crops out at the northern part of the basin and it is not present in the Salt Range.

The current study deals with the Margalla Hill Limestone at the Shahdara section in the Sub-Himalaya, which is a part of the Northern Potwar Deformed Zone (NPDZ) located to the northeast of Potwar Plateau, Upper Indus Basin of Pakistan (Fig. 1). The Shahdara section can be easily accessed through Shahdara road located in the vicinity of Quad-i-Azam University, Islamabad at coordinates of 33° 46′ 38″ N E and 73° 10′ 17″ E (Latitude and Longitude) respectively. There is a bulk of studies carried out on sedimentology and biostratigraphy of the Margalla Hill Limestone (i.e.,Munir et al. 1997; Ahsan and Chaudhry 2008; Swati et al. 2013, 2014; Yasin et al. 2017). The thickness of Margalla Hill Limestone in its stratotype, is 100 m, and it is composed of gray to dark gray and nodular to massive limestone having shale and marl intercalations. Structural and petroleum investigations have been carried out by (Iqbal et al. 2007) and in the recent work, Khitab et al. (2020) have investigated the micro-facies and diagenesis to depict the petroleum potential of carbonate strata of Eocene in Pakistan. The Margalla Hill Limestone exposed at Shahdara area, has not been investigated profoundly by sedimentologists, signifying a research gap. This study will utilize an integrated approach to precisely reinterpret paleo-depositional environment,

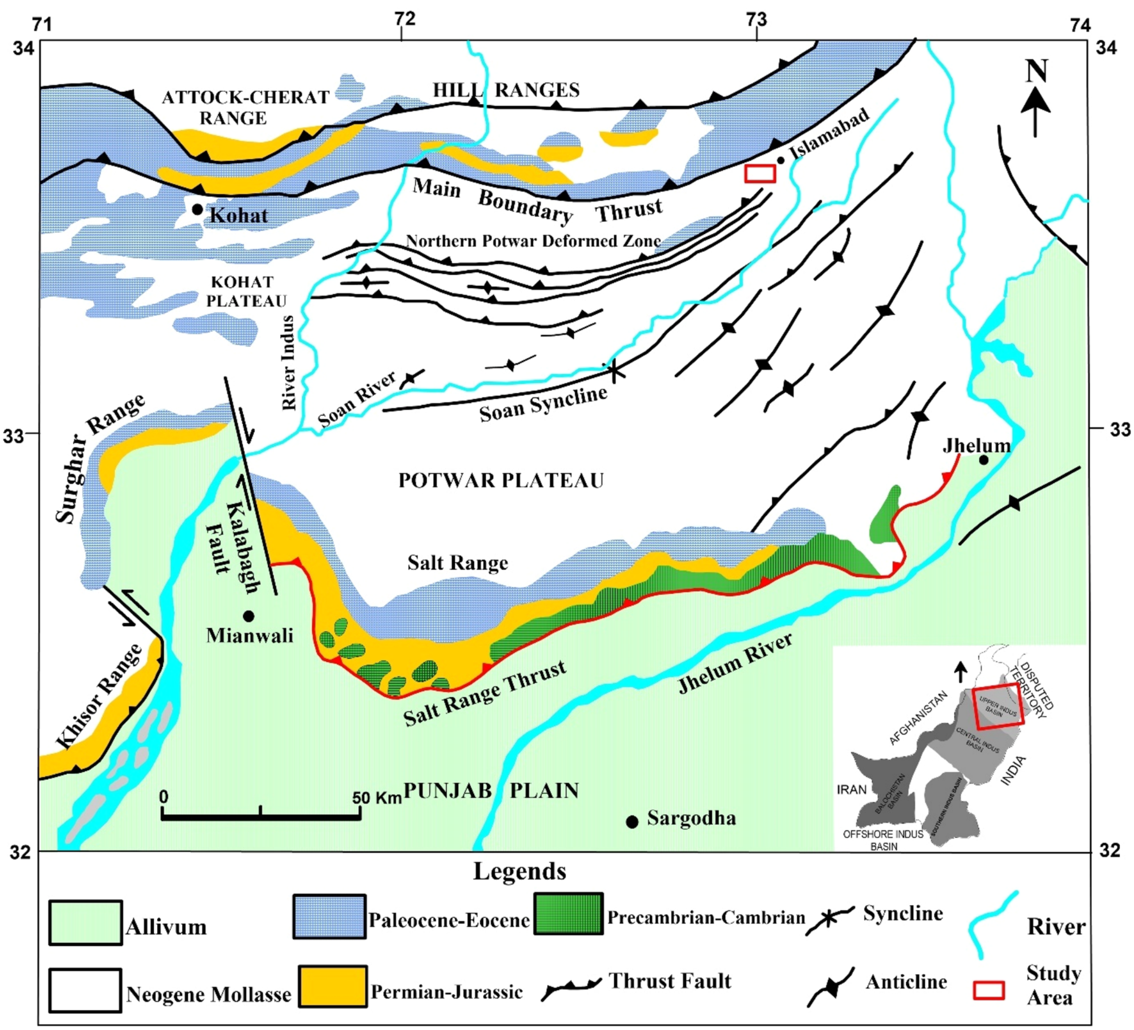

Fig. 1 Study area in the Potwar Basin, shown by a rectangular inset (after Kazmi and Rana 1982; Jaswal et al. 1997)

diagenetic history, and envisage the impact of diagenesis on the reservoir characteristics through petrographic and sedimentological tools.

This paper aims to investigate the Margalla Hill Limestone for the depositional and diagenetic history with the objectives of understanding its micro-facies, developing a detailed depositional model, and elucidating paragenetic sequences and the impacts of diagenetic events on reservoir attributes. This work may contribute to the development of Margalla Hills Limestone as a reservoir in future in many explored or unexplored oil or gas fields.

General geology

Geologically, the Shahdara area lies in NW Himalayan foreland fold-and-thrust belts (HFFTB), the northeastern periphery of the Potwar Basin of Pakistan. The area is located in the fault zone of the Main Boundary Thrust (MBT) and the Panjal Thrust. The NW Himalaya fold-and-thrust belt entails the southern part of the Lesser Himalaya (Burg et al. 2005). The Sub-Himalaya zone encompasses Potwar Basin and the Salt Range, and the former is an active tectonic feature of the Himalayas and is considered part of the foreland fold-and-thrust belt in northern Pakistan (Kamran and Siddiqi 2011). The study area is situated in the foothills of the Sub-Himalayan zone known as the foothills of the Himalaya encompassing the southward extension of Margalla Hills. The Maragalla Hills is located at the northern edge of Islamabad Capital Territory, comprising many ridges of Jurassic–Eocene carbonates and shales. The terrain of these hills, extends from lesser to Sub-Himalayas, and usually bounds the northern periphery of the Potwar Basin. The Main Boundary Thrust (MBT) runs through Margalla Hills, delineating the Lesser Himalayan zone from the Sub-Himalayan zone. Structurally, Main Boundary Thrust (MBT) and Salt Range Thrust (SRT) border the Potwar Basin to the north and to the south respectively, and toward the west and east, the Potwar Basin is bordered by Kalabagh and Jhelum faults, respectively (Moghal et al. 2007, Fig. 1). The Indian Foreland or the Sub-Himalaya represents a ten km thick, shallow marine succession of molasse deposits, in-filling the flexural basin that formed along the southern front of the Himalayan range (Burg et al. 2005). The drift of the Indian Plate toward the north and its collision with Eurasian Plate, later on, formed the Potwar Basin and Salt Range (Grelaud et al. 2002). A regional uplift occurred as a consequence of this collision, and this uplift reversed the direction of sediments supply from south–north to north–south, which provided a platform for deposition of carbonate sediments in Eocene age through Miocene age (Powell 1979). This thrusting has continuously propagated southward (Molnar and Tapponnier 1975); as a result, a compressional structure within the Himalayan foreland formed, which is known as the Salt Range (Grelaud et al., 2002).

Materials and methods

Around a 30-m-thick stratigraphic section of the target formation exposed at Shahdara section (Fig. 1), was measured, logged, and sampled by employing conventional methods. Field-based sedimentological and paleontological features of the Margalla Hills Limestone were carefully observed and recorded which include lithological, textural, and color variations, bedding characteristics, diagenetic features, etc. and a composite litho-stratigraphic log was constructed. The lower contact of the formation at an outcrop was not exposed while its upper contact was weathered and eroded. 25 outcrop samples of limestone from the fresh surface were collected based on the bedding change and the sampling was both random and stratified. This type of sampling helped to construct a composite lithology to achieve a homogenous group of samples from the limestone beds. The collected samples were labeled and numbered based on their positions at the outcrop or their bedding features and then they were thin-sectioned for detailed petrographic analysis. Traditional optical microscopy was employed for the petrographic study, diagenetic evaluation, and characterization of the reservoir, and their inventories were prepared for the relative chronological sequence and characteristics of the reservoir. Types of micro-facies established, are based on the classification scheme of Dunham (1962) through the sedimentological analysis of the representative samples (Flügel 2004). Fossil assemblages coupled with allo-chemical and ortho-chemical compositions are used as environmental proxies for the reconstruction of the depositional settings, as employed by Hussain et al. (2021).

Results and discussion

Lithological units

The exposed outcrop section (around 30 m) of the Margalla Hill Limestone has been divided into 4 lithological units based on field observations (Fig. 3).

Thin-bedded limestone with marl (L1)

The lowermost part of the outcrop encompasses mainly limestone with inter-bedded marl and marly shale intercalations and the limestone is slightly nodular, thin-bedded and having mesoscopic nodules (Figs. 2, 3). The limestone is yellowish to reddish at weathered and grayish at fresh surfaces. This lithological part is about 7 m thick and it is

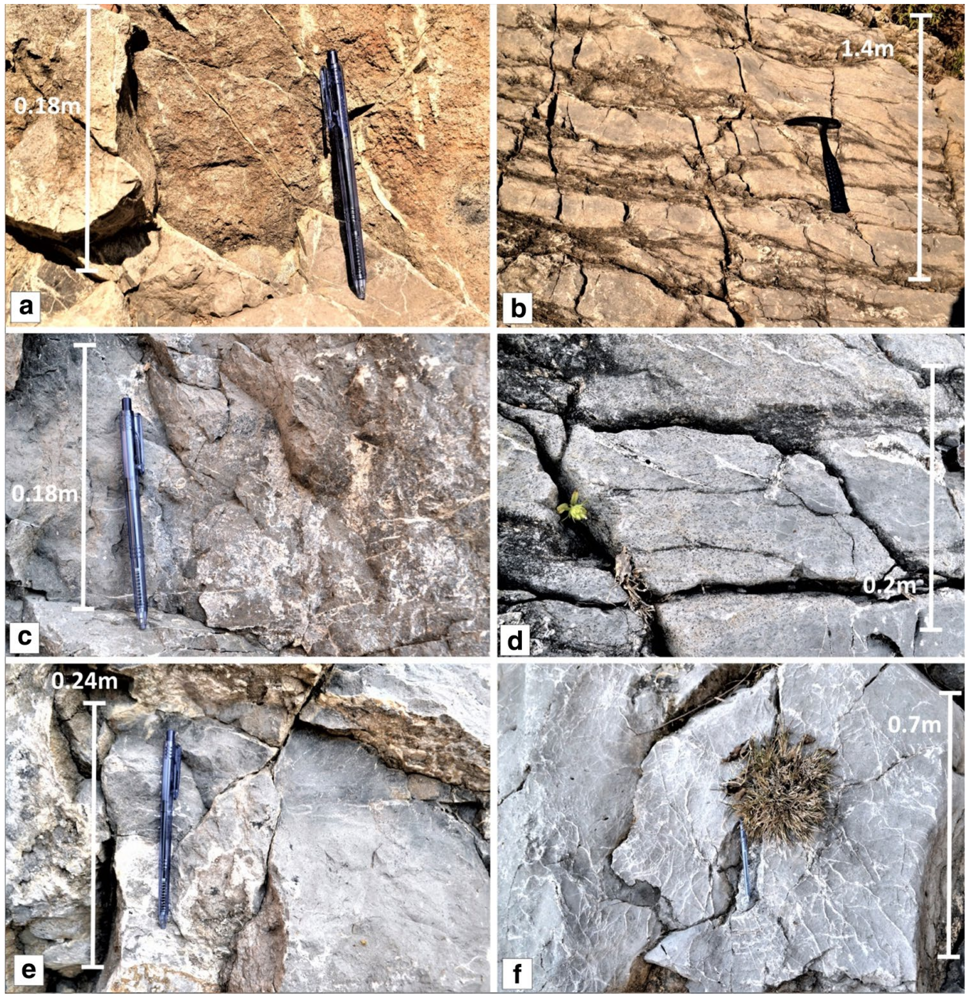

Fig. 2 Representative field photos that show an outcrop view reflecting lithological variations in the Margalla Hill Limestone at Shahdara section. **a** displays thin-bedded nodular limestone and multi-directional fractures. **b** shows medium to thick-bedded limestone coupled with marl and shale seams along with multi-directional fractures **c** denotes thin- to medium-bedded limestone **d** illustrates a closer view of medium- to thick-bedded limestone with multi-orientation fractures **e**–**f** shows thick to massively bedded limestone with large nodules and multi-directional fractures

highly fractured with cross-oriented and multi-directional fractures (Fig. 2a–b).

Thin–medium-bedded limestone with marly shale (L2)

This unit is about 8 m thick that lies on top of the unit L1. The L2 is composed of thin beds that grade and change into medium-bedded limestone with shale and marly shale intercalations (Figs. 2, 3). It encompasses limestone of dark gray to yellowish color on weathered and dark grayish color on the fresh surface (Fig. 2c) and its nodularity increases toward the top. The thickness of the lithological unit is about 8 m.

Medium- to thick-bedded limestone with shale and marl seams (L3)

This unit represents the middle and middle–upper part of the studied formation and constitutes around 5 m thickness (Fig. 3). It is typified by limestone which is medium- to thickly bedded with shale intercalations and some seams of marl (Fig. 2d). The limestone is characterized by small- to medium-size nodularity, having dark gray fresh color and multi-directional fracturing having thickness about 5 m.

Thick-massive-bedded limestone (L4)

It shows upper part of the target formation represented by thick to massive bedded limestone with larger nodules and limestone has yellowish to gray weathered and dark gray fresh surface colors (Figs. 2e–f, 3). This unit has about 10 m thickness and characterizes multi-directional fractures and vein and it records the abundance of bioclasts of shallower fauna and very rare larger benthic foraminifera.

Facies analysis

Petrographic analyses and field observations led to the identification of five micro-facies designated with MH-1 to MH-5 codes and the dominant depositional texture among them is the wackestone (Fig. 3). It is worth mentioning that all of the carbonate micro-facies were recognized from the competent limestone beds, though there were some patches

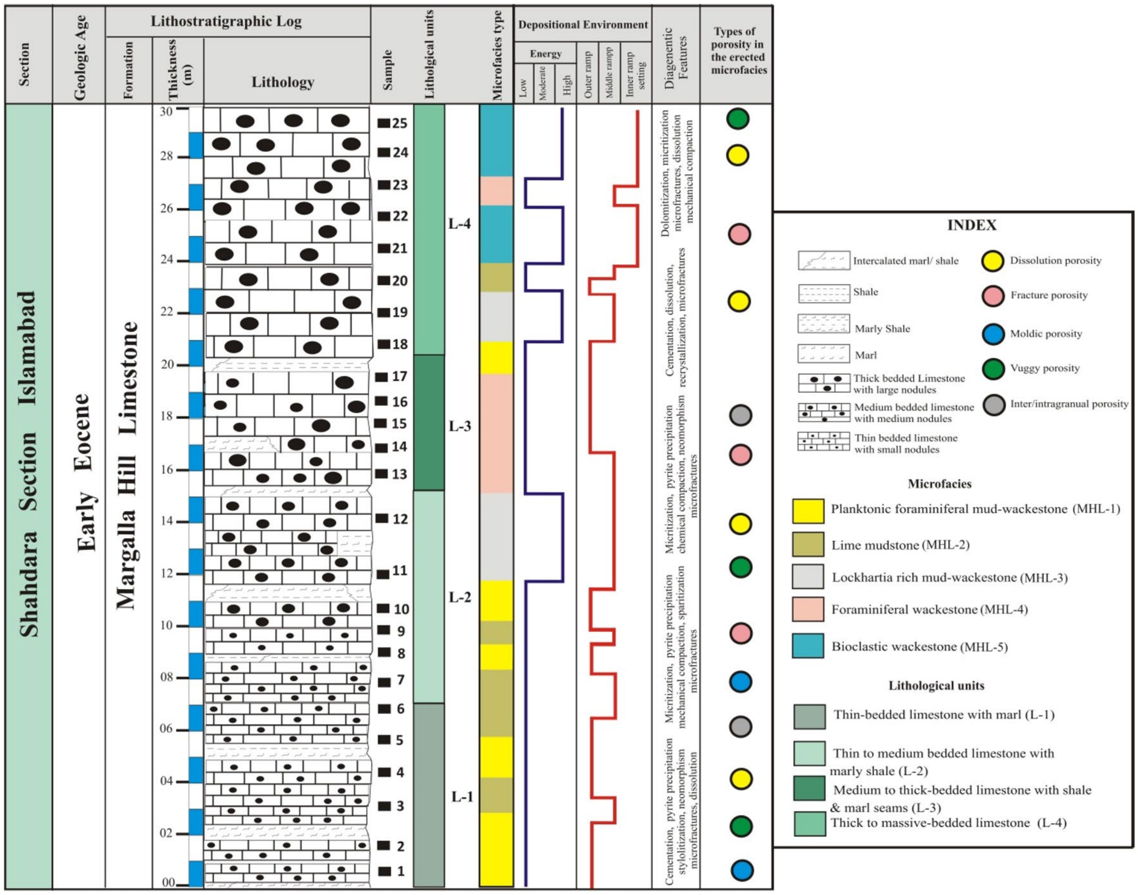

Fig. 3 Litho-stratigraphical log of the Margalla Hill Limestone at the study area

of shale and marl in between the carbonate succession at the study section (Fig. 3). Details of the identified micro-facies are as follows:

(1) Planktonic foraminiferal mud-wackestone micro-facies (MHL-1).
(2) Lime mudstone micro-facies (MHL-2).
(3) *Lockhartia*-rich mud-wackestone micro-facies (MHL-3).
(4) Foraminiferal wackestone micro-facies (MHL-4).
(5) Bioclastic wackestone micro-facies (MHL-5).

Planktonic foraminiferal mud-wackestone (MHL-1)

It is represented by samples of MH-1, MH2, MH4, MH8, and MH10. It is mainly typified by smaller benthic foraminifera and planktonic foraminifera dispersed in the micrite matrix (Fig. 4). The allochems of MHL-1 micro-facies are dominated by the planktonic foraminifera (*Morozovella cf. acuta*, and other *Globogerinids* species) along with biolcasts of *Lockhartia* sp. echinoderms, and other undifferentiated benthic foraminifers. The orthochems of the micro-facies are mainly micrite with rare microsparite (Fig. 4A, C). The enumerated allochems-to-matrix ratio of the micro-facies are roughly 1:4 (Table 1).

Interpretation Planktons in micritic matrix reflect calm and aphotic condition, bellow storm wave base (SWB) (Daraei et al. 2015) and their abundance points to the deeper offshore, usually exceeding 100 m and their diversity becomes greater below 200 m depth (Ahmad et al. 2020). In addition, an abundance of micrite indicates low-energy depositional conditions (Hussain et al. 2021). Based on the abundant planktonic and a few benthic foraminiferal assemblages in micrite, groundmass indicates deposition of the micro-facies in an open marine pelagic environment (Fahad et al. 2021) of proximal outer ramp setting below the fair weather wave base (FWWB; Fig. 9).

Lime mudstone (MHL-2)

MHL-2 micro-facies is represented by samples of MH3, MH-5, MH6, MH7, and MH9. Lime mudstone micro-facies are typified by mudstone depositional texture with

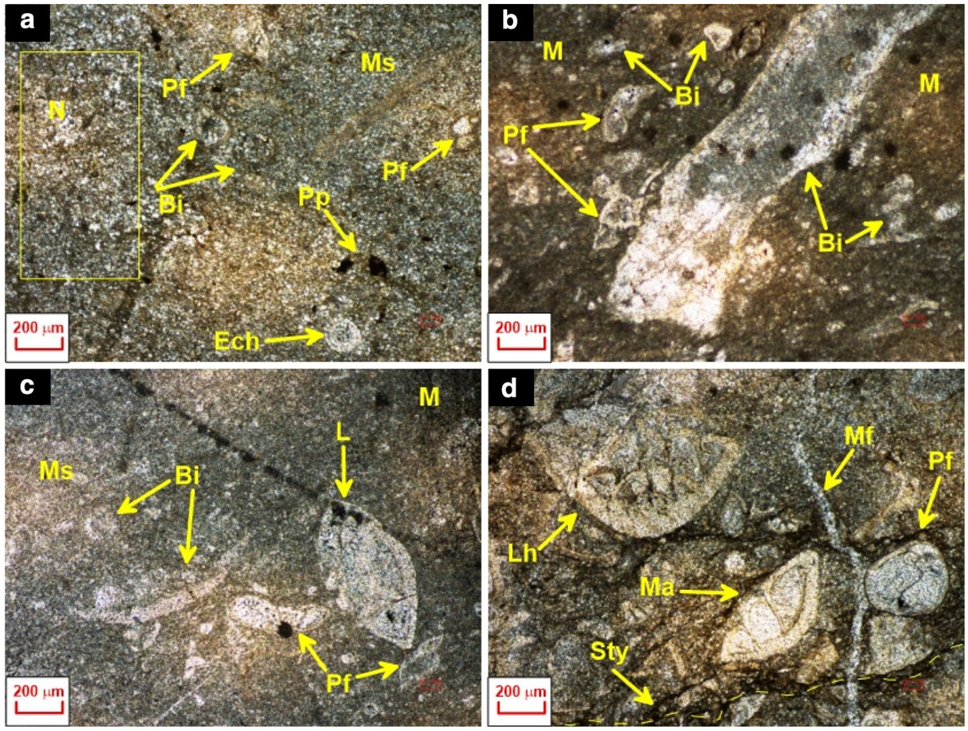

Fig. 4 Representative micrographs representing Planktonic foraminiferal mud-wackestone micro-facies (MHL-1) of the Margalla Hill Limestone. **A**, **B** represents planktonic foraminifera (Pf), biolclast (Bi), echinoderm (Ech) with pyrite precipitation (Pp), microsparite (Ms), micrite (M) and neomorphism (N). **C** shows planktonic foraminifera (Pf), *Lockhartia* (L), biolclast (Bi), microsparite (Ms), and micrite (M). **D** represents planktonic foraminifera (Pf), Morozovella cf. acuta (Ma), *Lockhartia haimei* (Lh) with stylolites (Sty) and microfracture filled with calcite (Mf)

less proportion of planktonic foraminifera having some skeletal bioclasts of echinoderm, planktonic and smaller benthic foraminifera supported by the micrite matrix. The allochems of the micro-facies mainly are bioclasts of planktonic foraminifera (*Globigerinatheka* sp., and other *Globogerinids*), echinoderms and unrecognized smaller benthic foraminifera (Fig. 5). The orthochems are mainly microcrystalline calcite or micrite matrix. Allochems-to-matrix ratio of the micro-facies is about 1:9 (Table 1).

Interpretation Micrite matrix manifests calm and low-energy conditions (Hussain et al. 2021). However, its deposition is associated with an open marine setting of outer carbonate ramp when associated with planktonic foraminifera (Flügel 2010; Ahmad 2011). The association of echinoderms bioclast, planktic/benthic foraminifera, and fabric supported by mud reflects the outer ramp environment of proximal parts (Flügel 2010; Mehrabi et al. 2014). The relative abundance of allochems and matrix typifies the deposition of the micro-facies in distal middle ramp to proximal outer ramp settings below fair weather-wave base (FWBB; Fig. 9).

Lockhartia-rich mud-wackestone (MHL-3)

MHL-3 microfacies is represented by samples of MH11, MH12, MH18, and MH19. Larger benthic foraminiferal assemblage mainly *Lockhartia* (*Lockhartia haimei*, *Lockhartia* sp.) followed by the *Rotalia*, *Assilina* and a very few planktonic foraminifera characterizes this micro-facies (Fig. 6). The allochems mainly are represented by biolcasts of larger benthic foraminifera, echinoderms, and rare smaller benthic foraminifera. The orthochems are mainly micrite matrix with rare microsparite. The allochems-to-matrix ratio estimated is almost 1:3 denoting mainly a wackestone depositional texture (Table 1).

Interpretation Deposition of *Lockhartia* sp. reflects inner to middle ramp environment (Racey 1994; Fahad et al. 2021), and presence of planktonic foraminifers, points toward deeper environments. Flat and large forms of Assilina are suggested to flourish in parts of the deeper photic zone (Racey 1994; Zamagni et al. 2008; Sarkar 2017) and presence of other larger foraminifera partnered with rotalia reflects deposition in middle ramp settings with oligotrophic conditions (Brandano et al. 2009; Shabafrooz et al. 2013). Based on the allo-chemical and ortho-chemical composition, this micro-facies is consistent to be deposited in proximal open marine middle ramp settings (Fig. 9).

Foraminiferal wackestone (MHL-4)

Samples of MH13, MH14, MH15, MH16, MH17 and MH23 represent MHL-4 microfacies. The Foraminiferal wackestone microfacies is characterized mainly by the presence of larger benthic foraminifera of genus *Assilina* (*Assilina laminose*, *Assilina subspinosa*, *Assilina* sp.), *Nummulites* (*Nummulites atacicus*, *Nummulites globulus*, *Nummulites*

Table 1 Estimated relative allo-chemical to ortho-chemical percentages in the micro-facies, established for Margalla Hill Limestone

Micro-facies of the Margalla Hill Limestone	Bioclast %	Plankton %	Num-mulite %	Assilina %	Lockhartia%	Rotalia %	Milliolid %	Algae %	Echi-noderm %	Benthic form %	Allochems %	Matrix%	Grain:Matrix	Classification Dunham (1962)
(MHL-1)	6	8	–		2	–	–	–	2	1	19	81	~1:4	Mud-wackestone
(MHL-2)	5	3	–	–	–	–	–	–	1	–	9	91	~1:9	Mudstone
(MHL-3)	6	1	2	2	6	2	–	–	3	2	24	76	~1:3	Mud-wackestone
(MHL-4)	4	–	3	4	3	1	2	1	2	–	20	80	~1:4	Wackestone
(MHL-5)	9	–	2	1	2	2	4	3	2	1	27	73	~1:3	Wackestone

mamilatus, *Nummulites* sp.), *Miliolids* sp. with very rare *Rotalia* sp. and rare shallower fauna include echinoderms and algae disseminated in micrite matrix (Fig. 7). The allochems are mainly the bioclasts of the larger benthic foraminifera and shallower fauna like algae. The estimated allochems and matrix in the microfacies are 20 and 80% constituting 1:4 ratio respectively represented by the wackestone depositional texture (Table 1).

Interpretation Accumulation of *Nummulites* reflects high rates of sediment production in mid-ramp waters (Pomar 2001; Barattolo et al. 2007; Sarkar 2017) and *Assilina* spp. have been reported to occupy a mid-ramp environment (Hussain et al. 2021)) and they denote mid–outer ramp setting competitively deeper than that of *Nummulites* and shallower than Discocyclina (Ahmad 2011; Hussain et al. 2021). The presence of larger benthic foraminifera coupled with mixed shallow water biota reflects deposition of MHL-4 microfacies in proximal middle ramp setting to distal inner ramp setting above the fair wave base (Fig. 9).

Bioclastic wackestone (MHL-5)

The MHL-5 micro-facies is represented by the samples of MH21, MH22, MH24, and MH25. The microfacies of Bioclastic wackestone is typified mainly of the bioclasts of shallower fauna like algae, echinoderms, *Miliolids* and a few larger benthic foraminifera (*Nummulites*, *Lockhartia*, *Rotalia* and very rare *Assilina*, Fig. 8). The allochems of the microfacies are present in the form of bioclasts and the groundmass composed of mainly carbonate mud (micrite) matrix, microsparite along with sparry calcite cement (Fig. 8A, C, D). The enumerated allochems-to-matrix percentage ratio about 1:3 represented by depositional texture of wackestone (Table 1).

Interpretation The presence of bioclasts in these microfacies indicates marine conditions with open circulation (Khan et al. 2020b). The dominance of miliolids and other small benthic foraminifera may reflect restricted shallow subtidal quiet water conditions probably lagoon setting (Hottinger 1997; Sallam et al. 2015; Wanas et al. 2020). In addition, miliolids live at calm, shallow water conditions and their high abundance shows that the inner ramp's marine environment was lagoonal- and nutrient-rich (Mehr and Adabi 2014; Fahad et al. 2021). However, fauna of mixed larger benthic and shallow water and their bio-debris in the microfacies is ascribed to above fair weather wave base proximal open ramp setting of inner ramp environment (Fig. 9).

Depositional environment

During Early Eocene, open marine platform conditions persisted (Ghazi et al. 2014; Fahad et al. 2021) and such

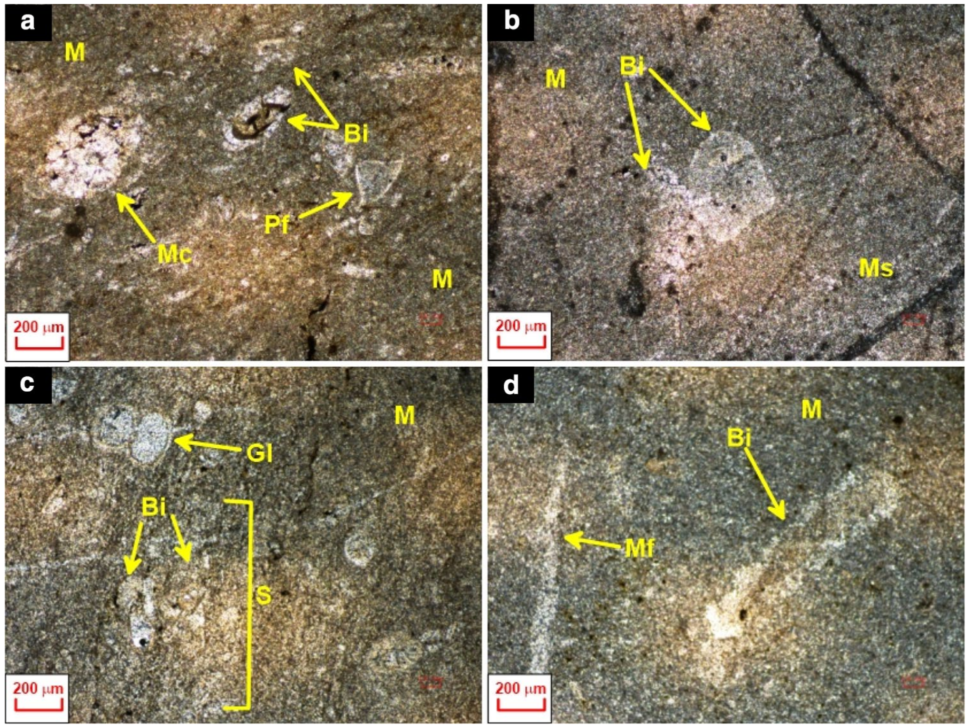

Fig. 5 Representative micrographs depicting lime mudstone microfacies (MHL-2) of the Margalla Hill Limestone. **A**, **B** shows planktonic foraminifera (Pf), biolclast (Bi), micritized bioclast (Mc), microsparite (Ms), and micrite (M). **C**, **D** represents *Globigerinatheka* sp. (Gl), bioclasts (Bi), sparite (S) and micrite (M) and micro-fracture filled with calcite (Mf)

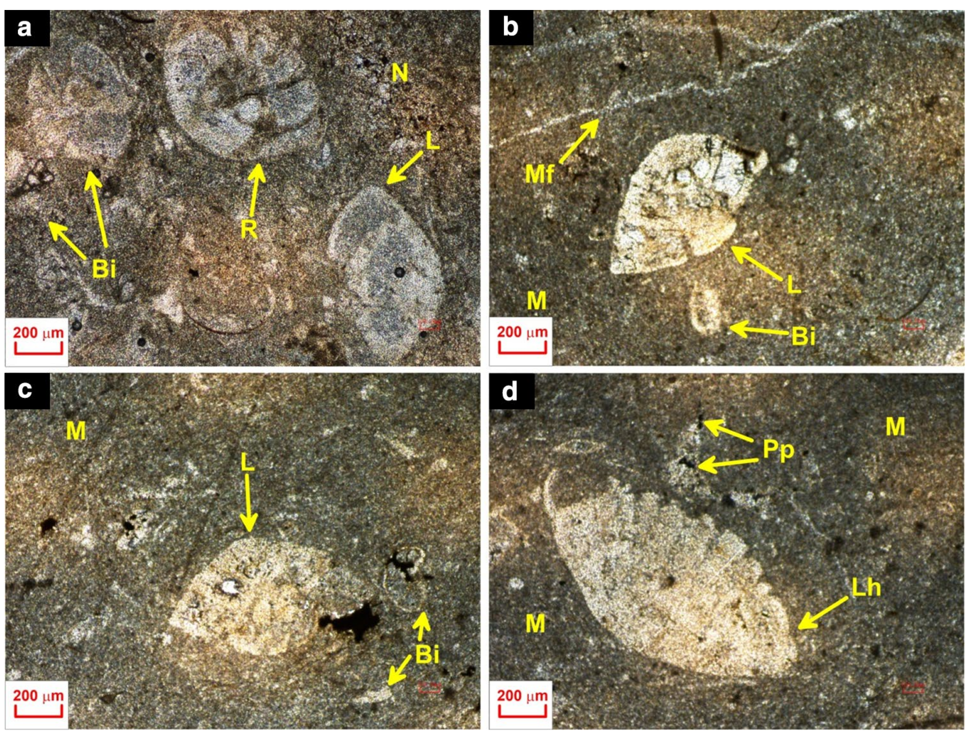

Fig. 6 Representative micrographs showing *Lockhartia*-rich mud-wackestone micro-facies (MHL-3) of the Margalla Hill Limestone. **A**, **B** shows *Rotalia* (Ro), *Lockhartia* species (L), biolclasts (Bi), neomorphism (N), microsparite (Ms), micro-fracture filled with calcite (Mf) and micrite (M). **C**, **D** shows *Lockhartia haimei* (Lh), *Lockhartia* sp. (L), bioclasts (Bi), pyrite precipitation (Pp) and micrite (M)

conditions have resulted in the deposition of Eocene strata. In the Salt Range, the Eocene strata have been deposited in form of the Chharat Group, comprising Nammal, Sakesar and Chorgali formations (Hussain et al. 2021; Fahad et al. 2021), and at the same, the deposition of Margalla Hill Limestone has also taken place. In this paper, detailed investigations of the skeletal grain, an abundance of micrite (matrix), distribution of microfacies vertically and association of recorded flora and fauna have been carried out to decipher the environment of deposition. The constituent

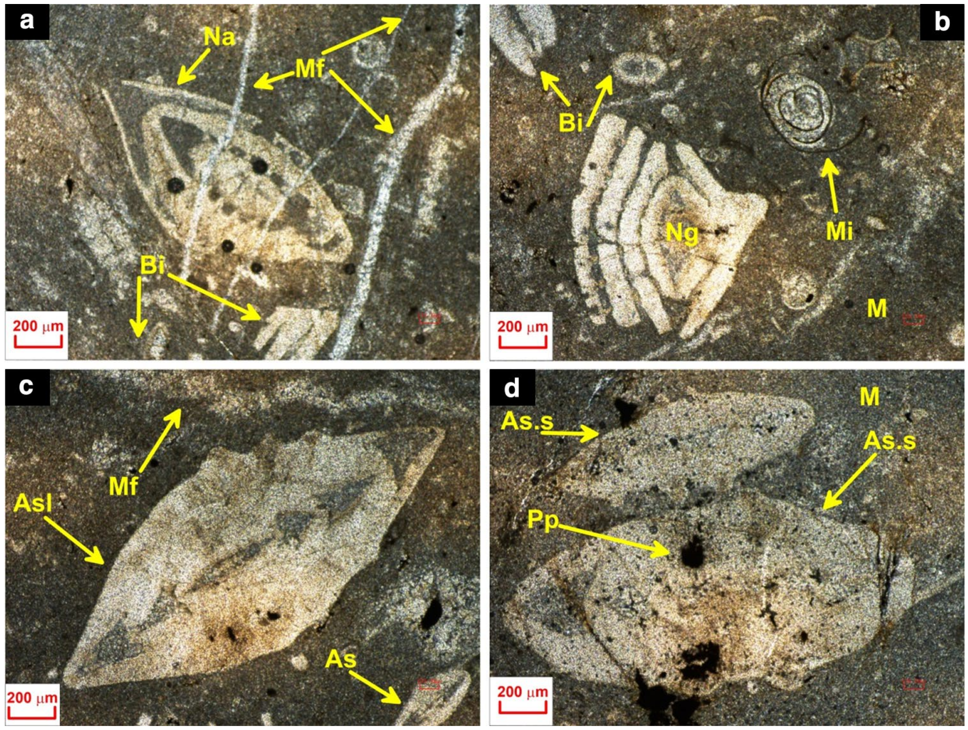

Fig. 7 Representative micrographs depicting foraminiferal wackestone micro-facies (MHL-4) of the Margalla Hill Limestone. **A**, **B** shows *Nummulites atacicus* (Na), *Nummulites globulus* (Ng), *Milliolid* (Mi), bioclasts (Bi), micro-fracture (Mf) and micrite (M). **C**, **D** shows *Assilina* species (As), *Assilina laminose* sp. (Asl), *Assilina subspinosa* (As. Ss), pyrite precipitation (Pp), micro-fracture filled (Mf) and micrite (M)

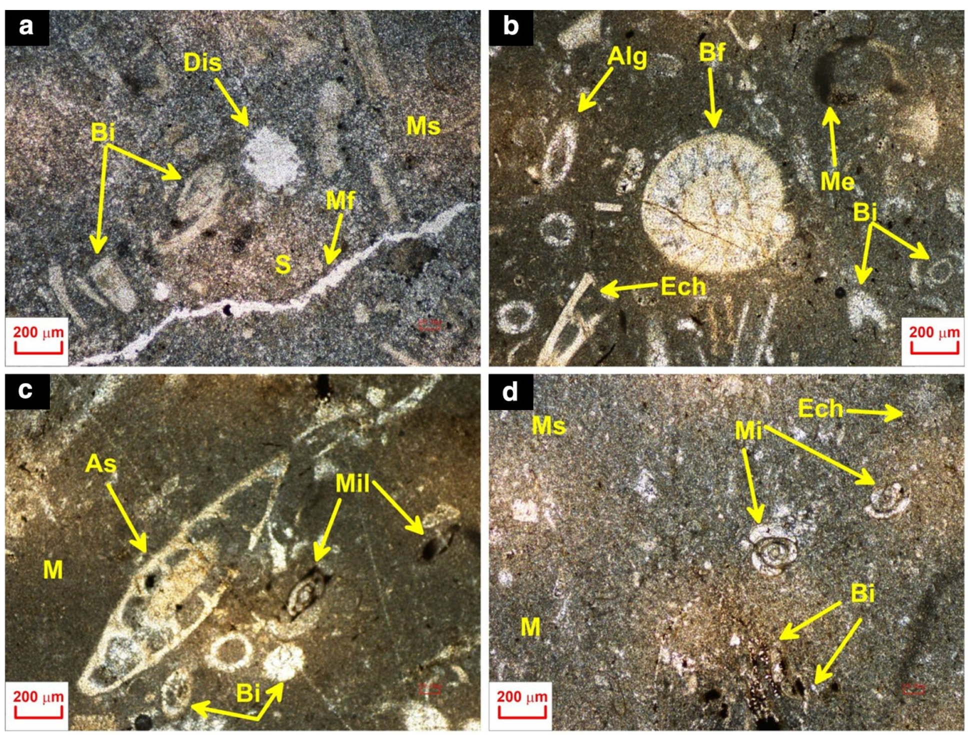

Fig. 8 Representative micrographs representing Bioclastic wackestone micro-facies (MHL-5) of the Margalla Hill Limestone. **A** shows bioclasts (Bi), micro-fracture filled with calcite (Mf), dissolution porosity (D) sparite (S) and microsparite (Ms). **B** represents benthic foraminifera (Bf), algae (Alg), echinoderm (Ech), bioclast (Bi) and micritic envelope (Me). **C**, **D** shows *Assilina* species (As), milliolids (Mil), echinoderm (Ech), bioclasts (Bi), pyrite precipitation (Pp), microsparite (Ms) and micrite (M)

fossil assemblages and allo-chemical partnered with ortho-chemical were used as environmental proxies for the paleo-ecology of the Margalla Hill Limestone. Based on the distribution of micro-facies and constituent allo-chemical and ortho-chemical abundances, the deposition of the Margalla Hill Limestone is consistent with the gentle-sloping homoclinal ramp environment of proximal outer ramp to proximal inner ramp settings (Fig. 9) which symbolizes the foraminiferal dominated carbonate ramp model of Burchette and Wright (1992). The carbonate model for the carbonate of

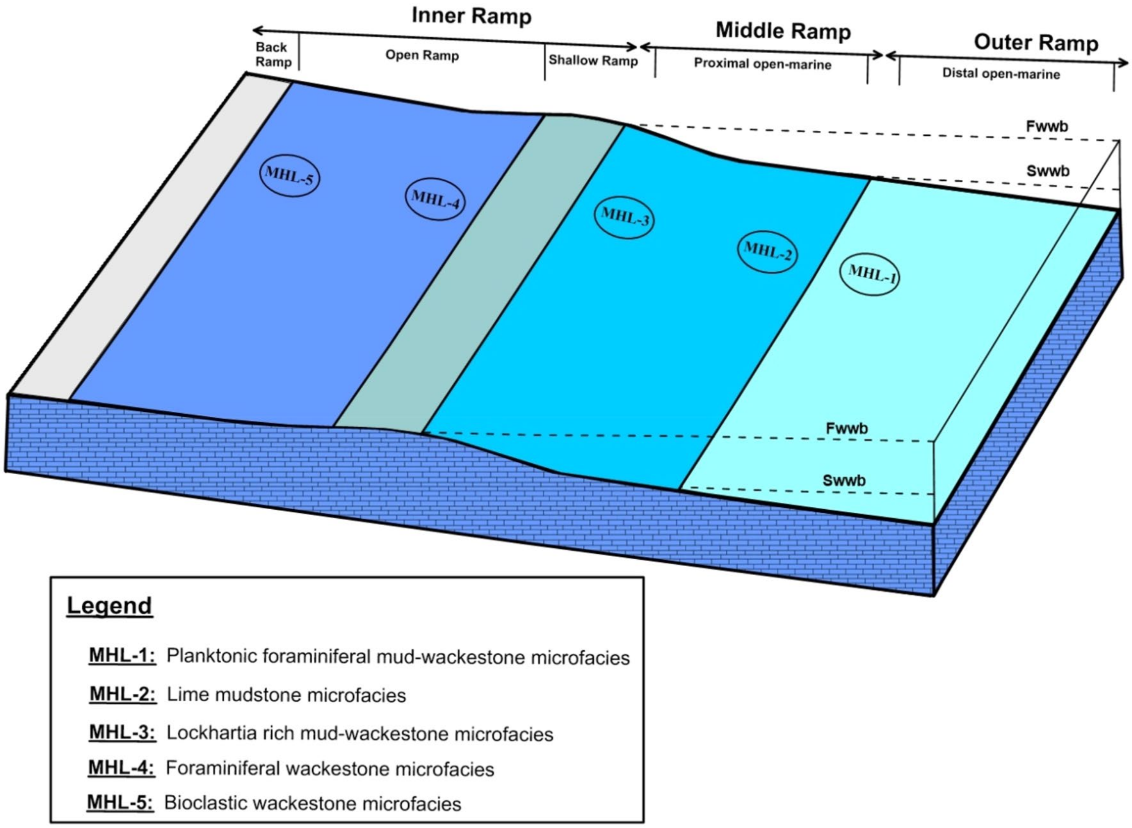

Fig. 9 A schematic depositional model of the Margalla Hill Limestone at the Shahdara section, Islamabad

the Margalla Hill Limestone also supports the absence of high-energy facies, sand shoals, reefal development, re-sedimentation evidence, and slump structures (Mehr and Adabi 2014; Hussain et al. 2021). From the shallow platform toward basin, a gradual deepening trend and abundance of micrite matrix mainly orthochems are more befitting with the ramp setting (Hussain et al. 2021).

Larger foraminifers are imperative proxies to erect the models of paleo-environments associated with shallow warm marine settings (Geel 2000) and they are pivotal tools for interpretation of facies (Rasser et al. 2005). Platform carbonates of the Paleogene preserve a diverse assemblage of the larger benthic foraminifera (Banerjee et al. 2018), and the abundance of larger benthic foraminifera in the investigated section, peeks at the upper part of the Margalla Hill Limestone. The abundance of the larger benthic foraminifera in the Margalla Hill Limestone is marked by genus *Nummulites* ((*Nummulites atacicus*, *Nummulites globulus*, *Nummulites mamilatus*, *Nummulites* sp.), *Assilina* (*Assilina laminose*, *Assilina subspinosa*, *Assilina* sp.); *Lockhartia* (*Lockhartia conditi, Lockhartia haimei*, *Lockhartia* sp.) and species of *Rotalia* and miliolids. Accumulation of *Nummulites* is the indication for high rates of sediment production in mid-ramp waters (Pomar 2001; Barattolo et al. 2007), large platforms of *Assilina* thrive in the parts of deeper photic zone (Racey 1994; Zamagni et al. 2008) and inner–middle ramp settings are being indicated by *Lockhartia* sp. (Racey 1994).

Large, flat perforate benthic foraminifera co-occurs with planktonic foraminifera on the middle to outer ramp setting, belonging to the oligotrophic zone (Romero et al. 2002). The occurrence of the planktonic foraminifera ((*Globigerinatheka* sp.*, Morozovella cf. acuta* sp. and other species of *Globogerinids)* mainly at the bottom part of the Margalla Hill Limestone, evidences the deep water conditions as recorded in the Planktonic foraminiferal mud-wackestone (MHL-1) micro-facies (Figs. 3, 9). However, the preservation of the planktonic foraminifera has been obliterated by the presence of some larger benthic foraminifera and shallow fauna and their bio-debris, such as *Lockhartia*, *Nummulites*, and echinoderms. Micritic matrix and high proportion of planktonic foraminifera point to the deposition in calm, motionless, and deep water setting (Corda and Brandano 2003; Ćosović et al. 2004; Flügel 2010; Kamalifar et al. 2020). As the ratio of the planktonic foraminifera to benthic foraminifera increases, the water depth also increases and vice versa (Hussain et al. 2021). The deep water conditions are recorded in the micro-facies of lime mudstone micro-facies (MHL-2) as well, constructed from the bottom part of the formation (Figs. 3, 9), resembling the same water depth conditions. Conversely, medium–large-sized and lenticular–globular *Nummulites* prefer to live in intermediate ramp environments (Adabi et al. 2008, Ishaq et al. 2019), but if it associates with *Assilina* sp., then it denotes a relatively deeper depositional settings (Payros et al. 2010; Mehr and Adabi 2014; Ishaq et al. 2019; Hussain et al. 2021).

This is also supported by the shift from the planktonic-dominated micro-facies to larger benthic foraminifera and bio-debris-rich micro-facies toward the top, reflecting the sea-level change from deep water settings toward the shallower setting (Hussain et al. 2021), overall, showing a coarsening upward trend. The trend of change in depositional conditions is recorded in the middle part of the Margalla Hill Limestone typified by the abundance of larger benthic foraminifera, including genus *Lockhartia* sp. (*Lockhartia conditi*, *Lockhartia haimei*, *Lockhartia* sp.), genus *Nummulites* ((*Nummulites atacicus*, *Nummulites globulus*, *Nummulites mamilatus*, *Nummulites* sp.), *Assilina* (*Assilina laminose*, *Assilina subspinosa*, *Assilina* sp.) and species of *Rotalia* and miliolids. Such abundance is manifested in *Lockhartia*-rich mud-wackestone micro-facies (MHL-3) and foraminiferal wackestone micro-facies (MHL-4) of the Margalla Hill Limestone (Figs. 6 and 7). The transgressive trend or rise in relative sea level continues up to the top of the formation, characterized by the diversity of bioclasts of shallow flora and fauna like miliolids, *Rotalids*, algae, echinoderms and bioclasts. Rotaliids live in shallow water (Geel 2000) and co-occurrence of Rotaliids and miliolids is ascribed to relatively quiet environments (Beavington-Penney and Racey 2004). The dominance of smaller miliolids is commonly reflected in the benthic environment and LBFs are replaced by miliolids when trophic resources keep increasing (Sarkar 2017). The rise of the sea level has been observed in the Margalla Hill Limestone based on the presence of the planktonic assemblages at the base of the formation, and such abundance has been replaced by the LBFs demarcating a depositional and ecological change (from deeper water and oligotrophic conditions to shallower setting of eutrophic conditions). This observation is propped by the records of bioclasts, abundance of disarticulated and fragmented LBF, bio-debris of algae with the dominance of miliolids, algae and presence of sparite to microspraite cement (Fig. 8; Table 1).

Diagenetic analysis

On the basis of petrography, several diagenetic fabrics have been discerned in the Margalla Hill Limestone which includes micritization, cementation, neomorphism, chemical and mechanical compactions, dolomitization, micro-fractures, and dissolution (Figs. 10, 11). Pyrite precipitation and neomorphism with micritization are common features. These diagenetic fabrics or features are inferred to represent the events of early to syn-depositional and post-depositional changes which prevailed in different diagenetic environments in the formation. The orthochems in form of micrite and sparite cement are also recognized in the petrography. The details of diagenetic processes that have affected the reservoir quality of Margalla Hill Limestone are as follows:

Micritization: It is considered to be the first diagenetic phase of the limestone that converts the allochems into the dense micrite through endolithic algae (Jafarian et al. 2018; Ahmad et al. 2020). The endolithic algae bore initially around the peripheries and, subsequently, the bores filled with micrite creating a micritic envelope. The micritization process is evidenced as micritic envelopes around the peripheries of skeletal fragment coupled with partial and complete micritization (Figs. 10A, B, 11A). The micritization has affected some core shapes of the skeletal and non-skeletal allochems also and it was observed in almost every sample of the Margalla Hill Limestone.

Cementation: The cementation is one of the common diagenetic features observed in the samples of the Margalla Hill Limestone. The types of cements observed are granular, isopachous fibrous, blocky calcite, sparry calcite and micritic cements (Figs. 10A, D, E; 11B, D). The isopachous fibrous cement (Fig. 11D) represents syn- sedimentary cementation (Vincent et al. 2007) and first-generation cement while the granular cement represents pore filling cements among grains (Both non-skeletal, skeletal) and are formed as sub-hedral-shape crystals (Mahboubi et al. 2010). The blocky cement (Fig. 11D) is less developed and occupies the intergranular, and in early dissolved grains' molds (Fig. 10E). The sparry calcite noted (Fig. 11B, D) mostly with the development of aggrading neomorphism coupled with the dolomite rhombs and rare skeletal and non-skeletal grains, whereas the micrite cement has mostly affected the skeletal grains. Moreover, the Margalla Hill Limestone contains, thin to thick (mm to cm), un-parallel fractures filled with sparite under microscopic observation. These occur in the form of single or a set of multiple fractures which cross-cut each other (Fig. 10A). These fractures can be inferred to belong to a deformational regime and may be subsequently filled with freshwater, sparite and thus are termed as calcite veins (Flügel 2004). Isopachous and granular cements are recorded in mainly MHL-1 and MHL-2 microfacies other than blocky and micritic cements which are also observed in these microfacies (Fig. 3).

Neomorphism: Aggrading neomorphism was observed in many samples of the target formation (Fig. 10C). The aggrading neomorphism is caused by recrystallization which increases of crystal sizes. The matrix of micrite micritic matrix passed from the continuous and succeeding stages from recrystallization to micro-spar toward final stage of sparite (Khalifa et al. 2009; Ishaq et al. 2019). The aggrading

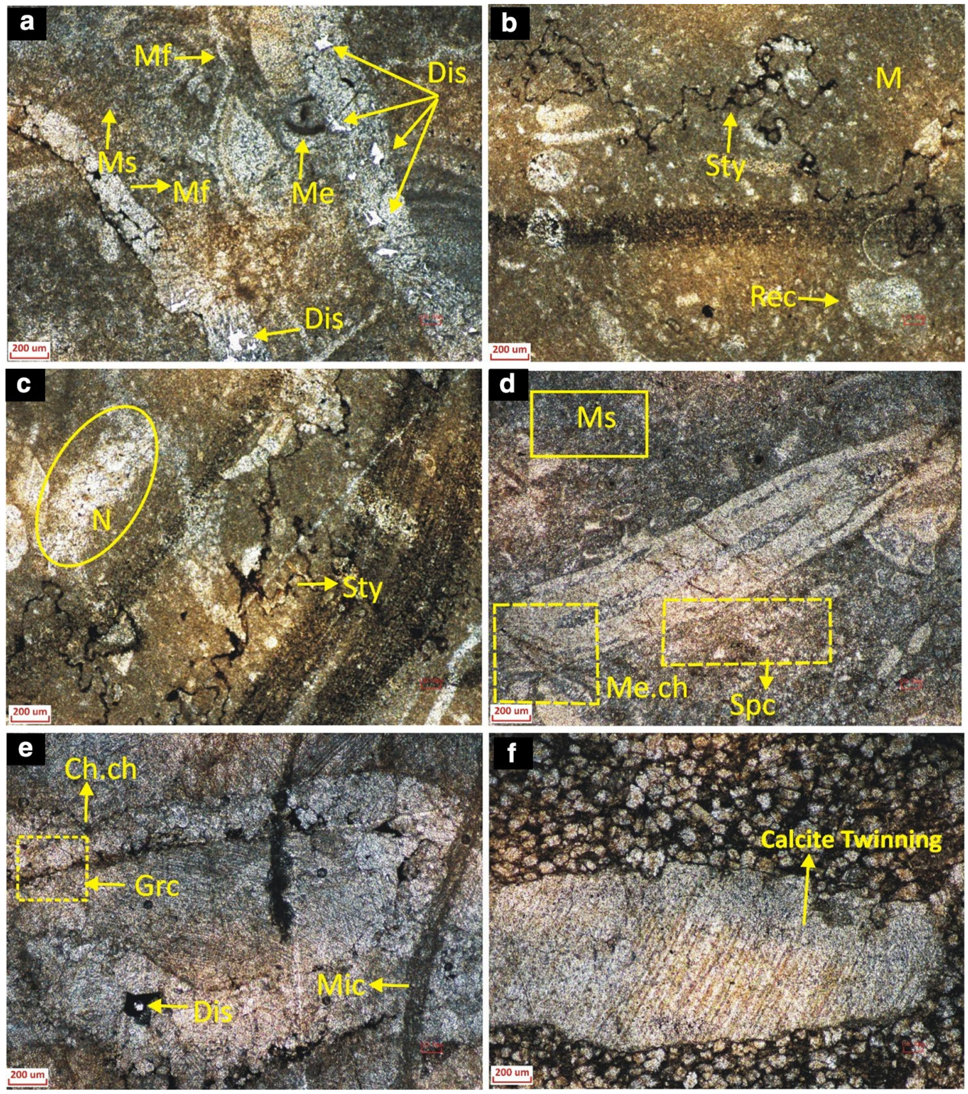

Fig. 10 Diagenetic imprints recorded in the Margalla Hill Limestone, Shahdara section of Islamabad. **A** represents the dominant dissolution porosity (Dis), Microfractures eventually filled with calcite (Mf), microsparite (Ms), micritic envelope (Me) and isopachous cement (Isc). **B**, **C** shows stylolitization (Sty), recrystallization of micrite (Rec), neomorphism (N) and micritization (M). **D**, **E** show mechanical compaction (Me.ch) in form of distortion and fossil dislocation. Sparite cement (Spc), microsparite (Ms), chemical compaction (Ch.ch) in form of stylolites (Sty), dissolution (Dis) and cementation in form of granular cement (Grc) and micritic cement (Mic). **F** represents dolomitization

neomorphism observed mostly with micrite matrix where coarser blocky cements continue to form toward center (Khalifa et al. 2009).

*Dissolution*It is present as a dominant diagenetic fabric of the Margalla Hill Limestone (Figs. 10A, E; 11C). Dissolution has resulted in formation of secondary porosities and has produced a variety of distinct textures and was considered the main porosity enhancement process (Fig. 12). Intergranular porosity was observed in some foraminiferal chambers (Fig. 13E, F). Moldic porosity may be generated through partial or complete dissolution of grains (Fig. 10A, 11C, 13A, C), whereas vuggy porosity may be resulted from dissolution of matrix, grains and cement (Fig. 10D, E).

Dolomitization: The most prominent diagenetic process observed in Margalla Hill Limestone was dolomitization, which enhances the reservoir efficacy appreciably and this diagenetic imprint has been dominant in MHL-5 microfacies (Figs. 10F, 12). The dolomitization involves reactions in which volume decrease occurs, i.e., the volume of minerals reduced with the conversion of calcite to dolomite, so that the number of voids within the reservoir increases (Iannace et al. 2011; Read et al. 2016; Yang et al. 2020). The texture of dolomite throughout the section varies from planer euhedral to planer sub-hedral and is interpreted as pervasive dolomitization (Fig. 10F). This type of dolomitization commonly occurs in low temperatures, which indicates an inner shelf environment. In some rock samples, partial to complete replacement of calcite by dolomite was identified that is suggested to be early dolomite. Dolomitization may not be obvious throughout the inner shelf facies which could be due to the parallel location of an inner shelf with the surface, where mixing of fluids was not so common.

Nodularity in Margalla Hill Limestone: Nodular structures in limestones usually associated with micrite but sometimes present in carbonate sand matrix, occur in various ancient carbonate sections (Boggs 2009). The nodularity in

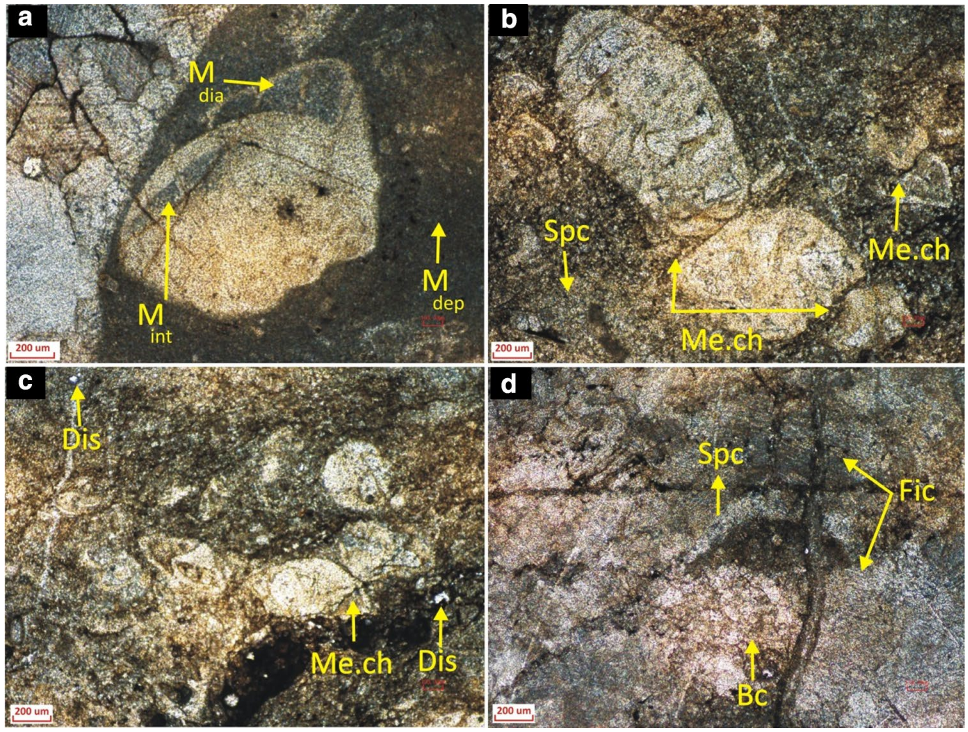

Fig. 11 Diagenetic imprints observed in the Margalla Hill Limestone. **A** shows the micritization types which are diagenetic micritization (M dia), depositional micritization (M dep) and internal or skeletal micritization (M int). **B** shows sparite cement (Spc) and mechanical compaction (Me.ch) represented by the breakage or distortion of skeletal segment of *Lockhartia*. **C** represents dissolution (Dis) and mechanical compaction (Me.ch) in form of distortion and fossil dislocation. **D** shows sparite cement (Spc), fibrous cement (Fic), and blocky cement (Bc)

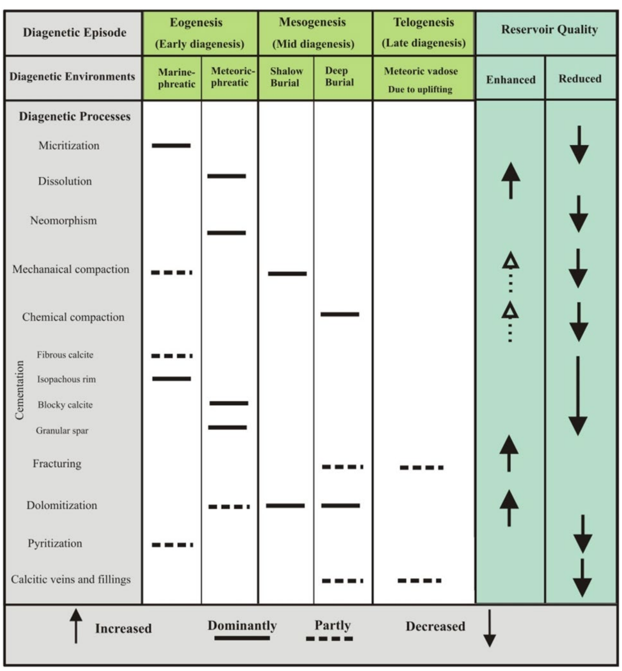

Fig. 12 Diagenetic imprints of the Margalla Hill Limestone and their impacts on the reservoir characteristics

the Margalla Hill Limestone is observed macroscopic in the study area (Fig. 2C, F). The nodular bedding of Margalla hill Limestone may be attributed to chemical compaction, burrowing and pressure dissolution of a discontinuous sequence of thin-bedded limestone and shale/marl. This interpretation is strongly supported by a large number of bedding-parallel seams in limestone and sutures having high amplitude (Fig. 10B, C). The nodules are of different sizes ranging from millimeters to centimeters, and from the middle section of 12 m till the top of the formation, nodules become larger and prominent (Fig. 3). Similarly, the morphology of nodules changes from sub-elliptical to irregular to rounded one (Fig. 2). Middle shelf facies mostly comprise this type of fabric. Diagenetic, sedimentary, and tectonic processes can all explain the nodular fabric of limestone (Flügel 2010). The growth of nodules in the sediment is one of the diagenetic processes and it underlines the role of transportation and re-deposition (Ishaq et al. 2019). The evolution of the nodularity cannot be inferred, yet evidence of pressure solution seams, alternating beds of limestone and marl, and the deposition in tectonically active area favors the origin of nodularity due to diagenetic and tectonic processes in the Margalla Hill Limestone.

Mechanical compaction: Compactions both chemical and mechanical are recorded in the Margalla Hill Limestone. In mechanical compaction, bulk volume is reduced, and the compaction can be witnessed by breakage, deformation, and orientation of grains (Ahmad et al. 2020; Hussain et al. 2021). Mechanical compaction in Margalla Hill Limestone is evident from skeletal grain deformation, for instance, foraminifer and brittle grains (Fig. 10D), and deformation has resulted in the bending of grains with breakage due to protrusion (Figs. 10D; 11B, C). Sutures resulted from

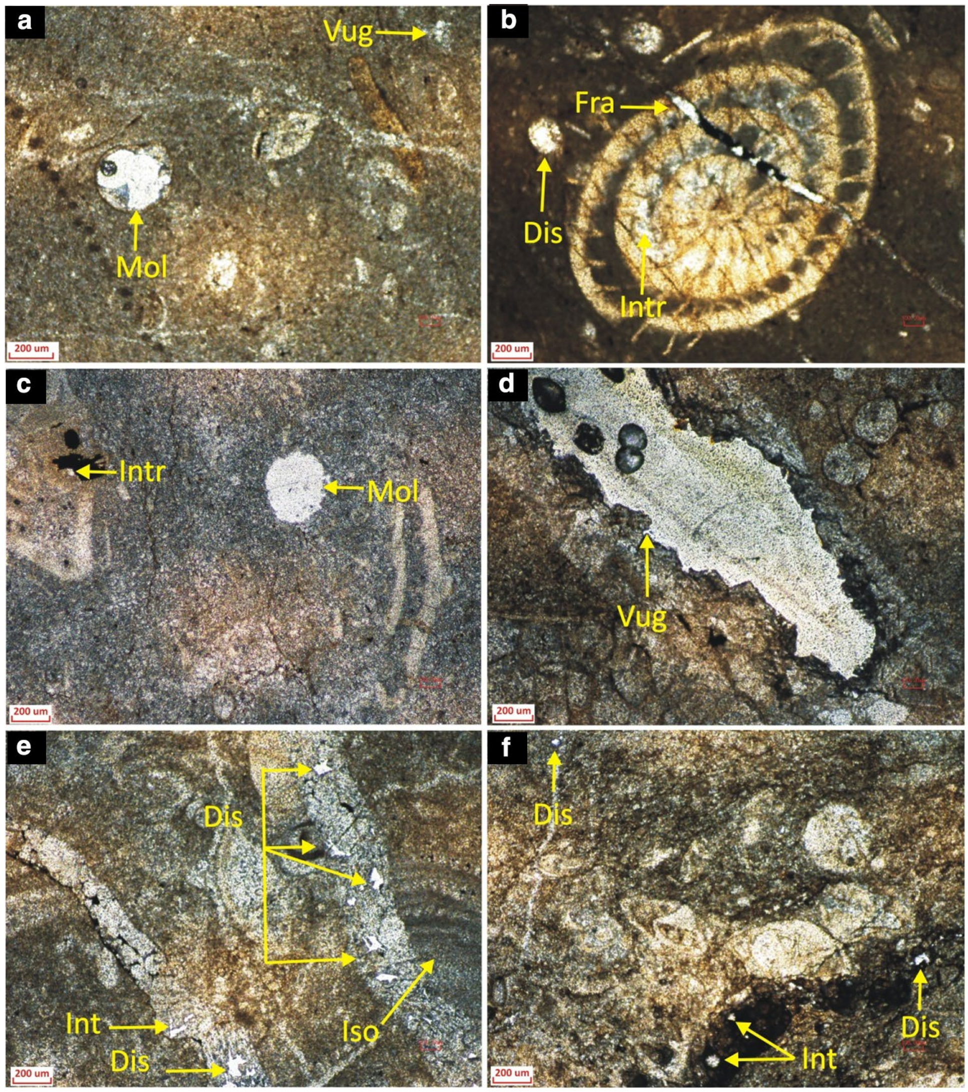

Fig. 13 Recorded porosity types in the Margalla Hill Limestone. **A** shows moldic (Mol) and vuggy (Vug) porosities. **B** represents the fracture (Fra), dissolution (Dis) and intra-granular (Intr) porosities. **C** shows intergranular (Int) and moldic (Mol) porosities. **D** represents the vuggy porosities. **E** shows the dominant dissolution (Dis) and inter-granular (Int) porosities and isopachous cement (Iso)

pressure solution are uncommon (Fig. 10B, C) and represented in form of micritic films. Pressure solution within the grains, breakage of bio-debris coupled with small dislocation reflects the post-cement mechanical compaction (Figs. 10D, E; 11B, C). Such changes in the Margalla Hill Limestone have resulted in a reduction in thickness, porosity and permeability (Fig. 12).

Chemical compaction: Initially, grain-to-grain contact occurs and subsequently transforms into planar and sutured grain contacts causing stylolites or so-called dissolution seams to form (Ahmad et al. 2020). Stylolites are irregular or zigzag patterns formed by the insoluble chemical solutions which interfinger across the bedding plan of the carbonates. The types of the stylolites recorded in the Margalla Hill Limestone include suture (Fig. 10B, C), simple wave like, seismogram pinning and stylolitic swarms. The stylolites are low to high, swarms or of irregular amplitude similar to a suture zone in carbonates and pressure solution observed in mostly wackestone micro-facies of the Margalla Hill Limestone which are evident within and around the peripheries of skeletal grains (Fig. 10B, C, E). The suture type stylolites are the most pronounced and they can have variable shapes. These can substantially generate fluid-flow barriers if enough sealing materials they collect, during their growth and if local spikes do not breach the barrier (Koehn et al. 2016). The Micro-suturing prevails also bioclasts reflecting minor to moderate chemical compaction along with minor stylolitic swarms (Fig. 10C). The diagenetic imprint of stylolites is observed mainly in the Bioclastic wackestone micro-facies (Fig. 3). Moreover, the intergranular pressure solution is recorded which occurs between the skeletal grains, where micritic rims have slightly been developed (Fig. 10E). The solution layers are separated by thin layers, often with deposits of insoluble calcite-filled fractures (Fig. 10A). According to Koehn et al. (2016), stylolites effect local fluid flow, mineral replacement reactions and, hence the permeability of the reservoir. Moreover, stylolites can act as barriers for local fluid flow as they intensify sealing capabilities of pinning layers. In contrast, the development of teeth and spikes offsets and hence destroys continuous stylolite seams so that the permeability across the stylolite remains very heterogeneous and they are no continuous barriers (Koehn et al. 2016). Some studies also argued that stylolites bear no effect on rocks; overall permeability (Lind et al. 1994; Heap et al. 2014; Koehn et al. 2016). However, both types of compactions i.e., chemical and mechanical compactions reduce the reservoir characteristics as they both result in compaction, precipitation, filling and choking of the void spaces (Fig. 12).

Paragenetic sequences

The studied carbonates of the Margalla Hill Limestone, present a complex diagenetic history comprising early, middle and late diagenetic processes. The petrographic study elucidates that the diagenetic settings of Margalla Hill Limestone were distinguished as marine, meteoric, burial and uplifting realms encompassed in three sequential diagenetic episodes of eogenesis, mesogenesis and telogenesis (Fig. 12).

Eogenesis (Early diagenesis)

It is the near surface and early diagenetic process which affects the carbonate sediments immediately after their deposition and before their burial (Hussein and Abd El-Rahman 2020). The Eogenetic realm is composed of marine and meteoric diagenetic environments (Nichols 2009; Fig. 12).

Marine environment Marine environment is characterized by the generation of micritization and non-ferron-isopachous fibrous cements (Vincent et al. 2007; Abu El Ghar et al. 2015; Ahmad et al. 2021). Micritization is predominant imprint of diagenesis recorded in the Margalla Hill Limestone (Figs. 5, 6, 7, 8) which is likely formed in marine environment. Micritization is recorded as envelops of micrite (Fig. 10A) skeletal (bioclasts) micritization, formed due to mechanical breakdown or biological erosion of calcareous biota having large size for instance endolithic algae, or *Nummulites* (Khalifa 2005; Ahmad et al. 2021). According to Hussein and Abd El-Rahman (2020), the marine–phreatic diagenetic overprints are typified by the consecutive processes of micritization, glauconitization, pyritization, marine cementation (fibrous and syntaxial rim cements), early dolomitization and early stages of mechanical compaction.

Meteoric environment The meteoric–phreatic overprints are characterized by the processes of neomorphism, dissolution, carbonate cementation and silicification (Hussein and Abd El-Rahman 2020). In the meteoric environment, the types of cements which are indicative of meteoric–phreatic diagenetic realms include, the granular calcite cement, blocky calcite cement, micritic cement, and the noemorphism as well dissolution of molds (Abu El Ghar et al. 2015; Ahmad et al. 2021). Metastable skeletal often dissolves along with non-skeletal grains during meteoric diagenesis, creating secondary fabric- and non-fabric selective porosities like inter-crystalline, intra-particles, and moldic/solution porosities (Fig. 13). Because it finally resulted in the production of blocky calcite cement, which displays varied crystal sizes from micro-spar into blocky calcite cement, the neomorphism observed in some micro-facies is of an aggrading kind.

Mesogenesis

In this stage, diagenetic processes strike the carbonates during their burial: beneath the near-surface marine and meteoric diagenetic environments and down to the metamorphic realm (Hussein and Abd El-Rahman 2020). Mesogentic stage represents the burial diagenetic environment. In the mesogenesis, the studied limestone has been overprinted by the diagenetic processes of mechanical and chemical (dissolution) compaction, cementation, dolomitization, calcite veins, and fracturing processes (Fig. 12).

Burial environment It is further divided into shallow and deep burial realms. The shallow burial diagenesis is characterized by the late stages of mechanical compaction and the development of dolomite cement and deep burial diagenesis leads to chemical compaction, formation of fractures and burial calcite cementation (i.e., fracture-filled sparry calcite cement; Hussein and Abd El-Rahman 2020; Fig. 11B). The features of chemical compaction for example stylolites and solution seams show the features of diagenesis which indicate shallow burial realm (Abuseda et al. 2015; Ishaq et al. 2019). The nodules originated in the Margalla Hill Limestone can be attributed to diagenetic and tectonic processes together. According to Mahboubi et al. (2010), compaction due to mechanical and chemical effects, silicification, recrystallization, and nodular fabric all reflect burial diagenetic environment (2010).

Telogenesis

The telogenesis episode is represented by the uplifting diagenesis and uplifting causes the formation of fractures and exposure of the studied carbonate strata to the meteoric–vadose zone. The exposure of strata to the meteoric–vadose diagenesis results in the precipitation of sparry calcite cements within some fractures (Hussein and Abd El-Rahman 2020).

Uplifting Fractures were formed in the Margalla Hill Limestone as a result of late diagenetic events that partially affected it after uplifting. Dissolution and fracture are the important processes that contributed to the generation of secondary porosity in some fractures that have been filled with calcitic cement.

Discussion of diagenetic imprints and their impacts on reservoir The Margalla Hill Limestone has been overprinted by many diagenetic changes and these changes include micritization, cementation, noemorphim, dissolution, compaction of both types i.e., chemical and mechanical, dolomitization and micro-fracturing (Fig. 12). These changes are representative of the diagenetic episodes of eogenesis, mesogenesis and telogenesis the Margalla Hill Limestone has been undergone through.

Among the diagenetic imprints, micritization, cementation, neomorphism adversely affect the reservoir properties and are the negatives for the reservoir, whereas chemical and mechanical compactions also reduce the reservoir properties and may partially enhance the porosity and permeability of the reservoir (Fig. 12). The micritization, being the early diagenetic imprint, has affected almost every microfacies of the Margalla Hill Limestone. The micritization chokes the flow pathways coupled with the voids within a rock by the in-filling of micrite and can diminish permeability, due to filled pore throats (Taghavi et al. 2006; Ishaq et al. 2019; Hussain et al. 2021). Hence, it reduces the reservoir quality, and it is considered destructive to reservoir porosity and permeability (Fig. 12). The cementation recorded in the Margalla Hill Limestone includes granular, isopachous fibrous, blocky calcite, sparry calcite and micritic cements (Figs. 10A, D, E; 11B, D; 12). The cementation decreases porosity or permeability as the fractures which are closed form barriers to fluid movement due to chemical precipitation or in-filling of dissolved minerals (Hussain et al. 2021). The neo-morphism noted in the Margalla Hill Limestone is manifested as the factor of key porosity reduction that resulted in reduction of the inter-crystalline voids by the growth of crystals of large size that choke the interstitial voids (Abuseda et al. 2015; Ishaq et al. 2019; Fig. 12). In the Margalla Hill Limestone, the compaction is recorded in both forms such as that chemical and mechanical compaction. The compaction of sediment can result in a reduction in the porosity as the enhancement in lithostatic pressure partnered with syn-depositional stresses affect compaction (Hussain et al. 2021). The chemical compaction is represented by the process of stylolitization, which thoroughly destroys porosity, and in dolomites, it perishes permeability, and improves permeability on the microstructural scale (Hassan 2007). However, the tectonic effects may cause some of the stylolites reopening that can occur with the generation of fluid flow channels (permeability) and porosity caused by stylolites (Ishaq et al. 2019). And the mechanical compaction represented by brittle deformation, fossil/bioclast or vein dislocation, and grain-to-grain suture contacts (Fig. 11B, C), causes tight packing and squashes pore throat and space between grains that can adversely affect the quality of the reservoir (Hussain et al. 2021). In addition, micro-fractures filled by calcite or other mineral precipitates also act as barriers to the flow of hydrocarbon.

Other than the micritization, neomorphism, cementation, and compactions, the diagenetic processes can enhance the reservoir quality include dissolution, dolomitization and micro-fractures. The dissolution affects the matrix, cement and skeletal allochems, causing the erasure of the original textures and development of secondary porosity, which enhances the reservoir properties (Moore 2001, Hussein and Abd El-Rahman 2020). The dolomitization is recorded in a limited extent in the upper part of the formation of the Margalla Hill Limestone. The dolomitization and fracturing have enhanced the reservoir quality as dissolution may have caused the formation of secondary pores in form of molds or/and vugs and indeed has resulted in the creation of dissolution porosity. Dissolution process plays a pivotal role in generating porosities like vuggy, intergranular and moldic (Khan et al. 2020a; Ahmad et al. 2021). Based on the visually estimated microscopic porosity, the dominant porosity recorded in the Margalla Hill Limestone is the dissolution porosity followed by vuggy porosity (Fig. 13). In addition, the observed microscopic porosity types in the Margalla Hill Limestone include intergranular, intra-granular, fracture and moldic (Fig. 13). The fractures, which are filled with calcite, render a negative effect, and the micro-fractures which represent pathways to flow, have positive impacts on the reservoir properties in the Margalla Hill Limestone (Fig. 12), and both types of fractures are observed.

The moldic and dissolution porosities are mainly dominant in the microfacies of the Planktonic foraminiferal mud-wackestone (MHL-1) and Foraminiferal wackestone (MHL-4), whereas the dominant vuggy porosity is recorded in Lime mudstone microfacies (MHL-2). Moreover, *Lockhartia*-rich mud-wackestone (MHL-3) and Bioclastic wackestone microfacies (MHL-5) record the porosity types, including vuggy, dissolution and fracture porosities (Fig. 13). The MHL-5 microfacies also manifests an abundance of diagenetic imprint of dolomitization demarcating an important microfacies in reference of reservoir aspects suiting best for the porosity and permeability conditions. The microfacies of MHL-3 and MHL-5 are the microfacies which incorporate mainly the dissolution and fracture porosities, making them good reservoir microfacies. The features they incorporate mainly include mainly dissolution, vugs, and micro-fractures making channel for the flow of hydrocarbons as well some dispersed pockets. Although in the microfacies of MHL-1 and MHL-2 and MHL-3, the pores of vugs and molds and fracture are created, but they are not interconnected which make them poor-to-average reservoir microfacies. The molds and vugs are of economic value, if they have interconnectivity to hold hydrocarbons but it will be of no economic value due to lack of permeability. However, if interconnectivity of fenestral, inter-crystalline, intra-particle, moldic, vuggy, and fracture porosity persists, the hydrocarbons can very easily move along this path (Awais et al. 2020). The MHL-1 and MHL-2 microfacies are mainly characterized by the precipitation of cementation types of micrite, blocky and granular, as well as micritization and neomorphism, although they have some pores due to dissolution and fracturing. The relatively same conditions of diagenesis and microscopic porosity persist in the MHL-4. The dominant porosity recorded in the Margalla Hill Limestone includes the dissolution porosity followed by the moldic, vuggy porosities, microfracture, intergranular and very less intra-granular porosities (Fig. 13). The Margalla Hill Limestone exposed in the Shahdara section, has no upper and lower exposed contacts with other formation. However, the reservoir aspects of the Margalla Hill Limestone can be correlated with other adjacent areas like Hazara Basin where it has lower and upper contacts exposed. In the Hazara basin, the Margalla Hill Limestone is overlain by the Chorgali Limestone and the clays of the Chorgali Formation can have sealing capacities for the overlain part of the reservoir of the Margalla Hill Limestone. The Foraminiferal wackestone (MHL-4) can also be a good reservoir micro-facies if the filled micro-fractures are reactivated and linked with open fractures, making interconnectivity, which enhances permeability. The dolomitized part of the Margalla Hill Limestone could be a good reservoir if the moldic and fracture porosity are interconnected and this microfacies is characterized by micritic matrix which is in abundance filling the pore throats and, hence reduce the porosity/permeability. The mud-wackestone micro-facies, with the least porosity/permeability, is a poor reservoir microfacies and it can act as carbonate seal. Therefore, such micro-facies can help in the development of reservoir compartmentalization within the Margalla Hill Limestone.

Conclusion

The Early Eocene Margalla Hill Limestone was investigated for lithological attributes, microfacies and diagenetic overprints and their impacts on reservoir potential were recorded. The Margalla Hill Limestone, exposed in Shahdara, is composed of dark gray to light nodular limestone with inter-beds of marl and shale. Micro-facies analysis established a total of five microfacies that include Planktonic foraminiferal mud-wackestone (MHL-1); Lime mudstone (MHL-2); *Lockhartia*-rich mud-wackestone (MHL-3); Foraminiferal wackestone (MHL-4) and Bioclastic wackestone (MHL-5). These micro-facies are consistent with the gently sloping homoclinal ramp environment of proximal outer ramp to proximal inner ramp settings. Mainly the fossil assemblage in the studied section of the Margalla Hill Limestone is typified by abundance of larger benthic foraminifera (LBFs) mainly of genus *Nummulites* ((*Nummulites atacicus*, *Nummulites mamilatus*, *Nummulites globulus and Nummulites* sp.), *Assilina* (*Assilina laminose*, *Assilina subspinosa*, *Assilina* sp.); *Lockhartia* (*Lockhartia conditi*, *Lockhartia haimei*, *Lockhartia* sp.) and species of *Rotalia* and miliolids in the mid to upper parts of formation. The basal part of the Margalla Hill Limestone encompasses the presence of planktonic species (*Globigerinatheka* sp., *Morozovella cf. acuta* sp. and other species of *Globogerinids)*. The presence of planktonic foraminifera at the base, and the abundance of LBFs at the top infers a transition from the deeper setting of oligotrophic conditions toward the shallower setting of the eutrophic environment during the deposition of the Margalla Hill Limestone reflecting the sea-level change from deep water settings toward the shallower setting, overall, exhibiting a coarsening upward trend. Petrographic studies revealed that the Margalla Hill Formation has undergone many diagenetic processes of micritization, cementation, neomorphishm, chemical and mechanical compactions, dissolution, dolomitization, micro-fractures, and nodular fabrics. These diagenetic imprints reflect the diagenetic stages of early to syn-depositional and post-depositional changes prevailed in different diagenetic environments in the formation. Among these, cementation, both chemical and mechanical compactions, micritization, neomorphism impede the reservoir quality, whereas the micro-fractures, dissolution, and dolomitization improve the quality of reservoir of the Margalla Hill Limestone. Moreover, the imprints of diagenesis are controlled by the deformational, diagenetic, and depositional processes. These diagenetic imprints of the Margalla Hill Limestone impart the suitable and acceptable reservoir attributes and ranges in terms of compartmentalization for exploration purposes for hydrocarbons.

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