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Reservoir evaluation of the eastern Tethyan Middle Eocene Larger Benthic Foraminifera dominated carbonates from Pakistan.

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Abstract

The Eocene Large Benthic Foraminiferal limestones of the Tethyan margins are proven hydrocarbon reservoirs. This study examines the controls on porosity and permeability development of the producing Middle Eocene Pirkoh Member of the Eastern Tethys using well core data from Well Zx-01 from the Punjab Platform area, Central Indus Basin, Pakistan.

The standard petrographic and core analysis techniques were adopted to determine these controls. Petrographic studies revealed three microfacies comprising bioclastic packstone to floatstone, bioclastic wackestone and mud-wackestone microfacies. The allochems belong to benthic foraminifera including *Nummulites* sp., *Discocyclinids* sp.., *Coralline algae, Assilina* sp., *Lockhartia* sp., Coralline algae and Gastropods along with the other bioclastic debris. These allochems were found embedded in the micritic matrix with extensive cementation of calcite. The diagenetic events included cementation, compaction, dolomitization, fracture filling and neomorphism. Based on microfacies, the environment of deposition is interpreted to be a high-energy zone of the middle ramp in shallow marine environment. Subsurface core indicates that the porosity of the reservoir is low to high ranging between 6 to 27.47% and permeability is found low to fair ranging between 0.03 to 7.73 mD, found closely related to microfacies and diagenetic modifications. This study is a first attempt to document the reservoir facies of the non-reefal carbonates of the Pirkoh limestone that would help to exploit the reservoir's potential of the carbonate platforms developed in similar settings worldwide.

Keywords: Carbonates reservoir characterization, greenhouse carbonates; large benthic foraminifera; middle Eocene; Pakistan.

1. Introduction

Carbonate platforms are the most promising hydrocarbon reservoirs containing more than 60% of the world's oil and gas reserves (Burchette, 2012; Abdullah, 2020). Reef constructors have remained the primary constituent of the giant carbonate reservoirs. Tropical shallow marine carbonates of late Paleocene to early Oligocene are characterized by the dominance of Large Benthic Foraminifera (LBF) (Höntzsch *et al.*, 2013; Bahman, 2022).

Recent developments in sequence stratigraphy gained the interest of petroleum geologists in identifying carbonate reservoir facies in the subsurface seismic images (Sarg, 1988; Handford and Loucks, 1993; Markello *et al.*, 2008; Garland *et al.*, 2012; Shahzad *et al.*, 2018; Shahzad *et al.*, 2019; Miraj *et al.* 2021; Asaad, 2021). The lack of understanding of the petrographic details also impacts the production and artificially enhanced fluid flow in the carbonate system. According to the traced research gap, this paper analyzes the in-situ reservoir characteristics of the middle Eocene Pirkoh limestone as a case study using industrial analysis techniques and petrography of the core data.

Pirkoh Member contains abundant Large Benthic Foraminifera (LBF) and serves as proven reservoir hosting the hydrocarbons in the Central Indus Basin such as Mari and Qadirpur gas fields (Khan *et al.*, 2016). It is a shallow producing reservoir at the depth of 610 m located on the Punjab Platform, therefore, the effect of burial is minimum with regionally stable tectonics, in comparison with the fractured Eocene carbonate reservoir of Sulaiman and Potwar Fold belts. Therefore, it represents an ideal workable example for establishing the depositional system of the Eocene carbonate reservoirs.

Currently, there is a lack of publicly available data concerning the evaluation of the Pirkoh Member. Therefore, it was decided to investigate the lithofacies, porosity, permeability, and the effect of diagenesis on the reservoir properties using core data and petrographic analysis techniques. Furthermore, efforts were made to assess reservoir quality and to make these data more widely available in the literature.

1.1 Regional Settings

The study area is in the Punjab Platform of the Central Indus Basin, west of Pakistan (Figure.1). It is located on the northwestern margin of the Indian Plate. This area represents the Cenozoic convergence between the Indian and the Eurasian Plates with the closure of the Neo Tethys in Eocene (Kazmi & Jan 1997). The Punjab Platform is a westward gently dipping monocline that extends from the Aravalli craton (Indian Shelf) and Bikaner–Nagaur Basin in the east to the Sulaiman Fold-thrust belt and Sulaiman Depression in the west originated due to the Himalayan orogeny. The study area is bounded by two main features of geological significance i.e., the Sargodha High and the Mari Kandhkot High in the north and south respectively. The Punjab part of the platform remained undisturbed during Late Cretaceous (Khalid *et al.*, 2014).

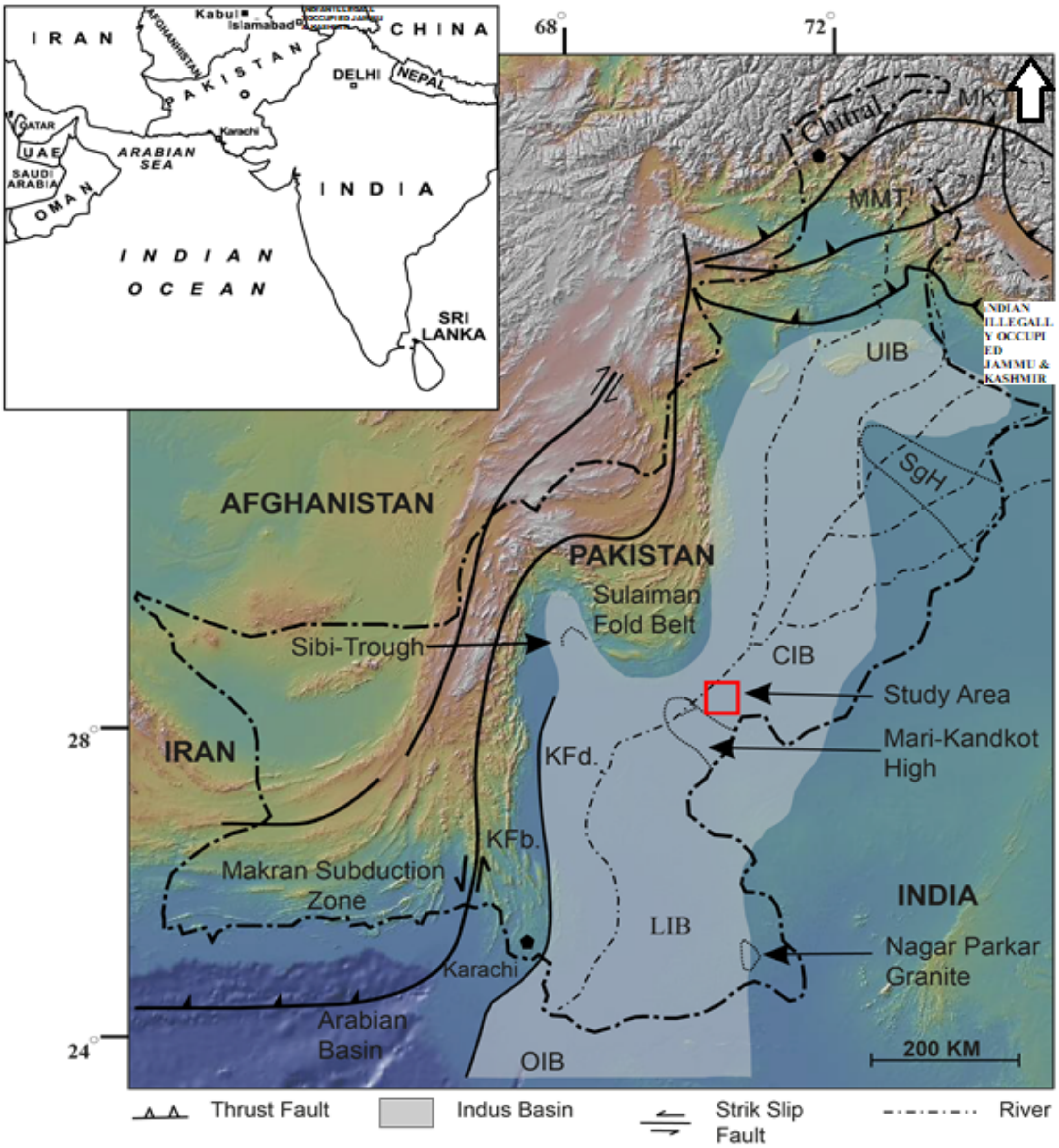

Fig. 1. Regional map of Pakistan with major tectonic and structural elements. Shaded zone shows the extent of Greater Indus Basin (onshore) (after Afzal et al 2009). Main Karakoram Thrust (MKT), Main Mantle Thrust (MMT), Main Boundary Thrust (MBT), Kohistan (island) Arc (KA), Upper Indus Basin (UIB), Central Indus Basin (CIB) Lower Indus Basin (LIB), Kirthar Foldbelt (KFb), Kirthar Foredeep (KFd).

During the Eocene, the western continental margin of Indian Plate was covered by the shallow, neritic, passive margin carbonates. Additionally, this plate was located near or at the equator during the Eocene (Shahzad *et al.*, 2018; Shahzad *et al.*, 2019). These shallow marine deposits were rich in LBFs and crop out in the series of doubly plunging north-south to NNW-SSE anticlines and elongate anticlinal ridges separated by broad synclines in the mountain areas of the Sulaiman-Kirthar Fold belts (Figure. 2a). Furthermore, these reservoirs were also encountered in Central Indus Basin and their correlative succession in the Northern and Southern Indus Basin (Siddiqui, 2004).

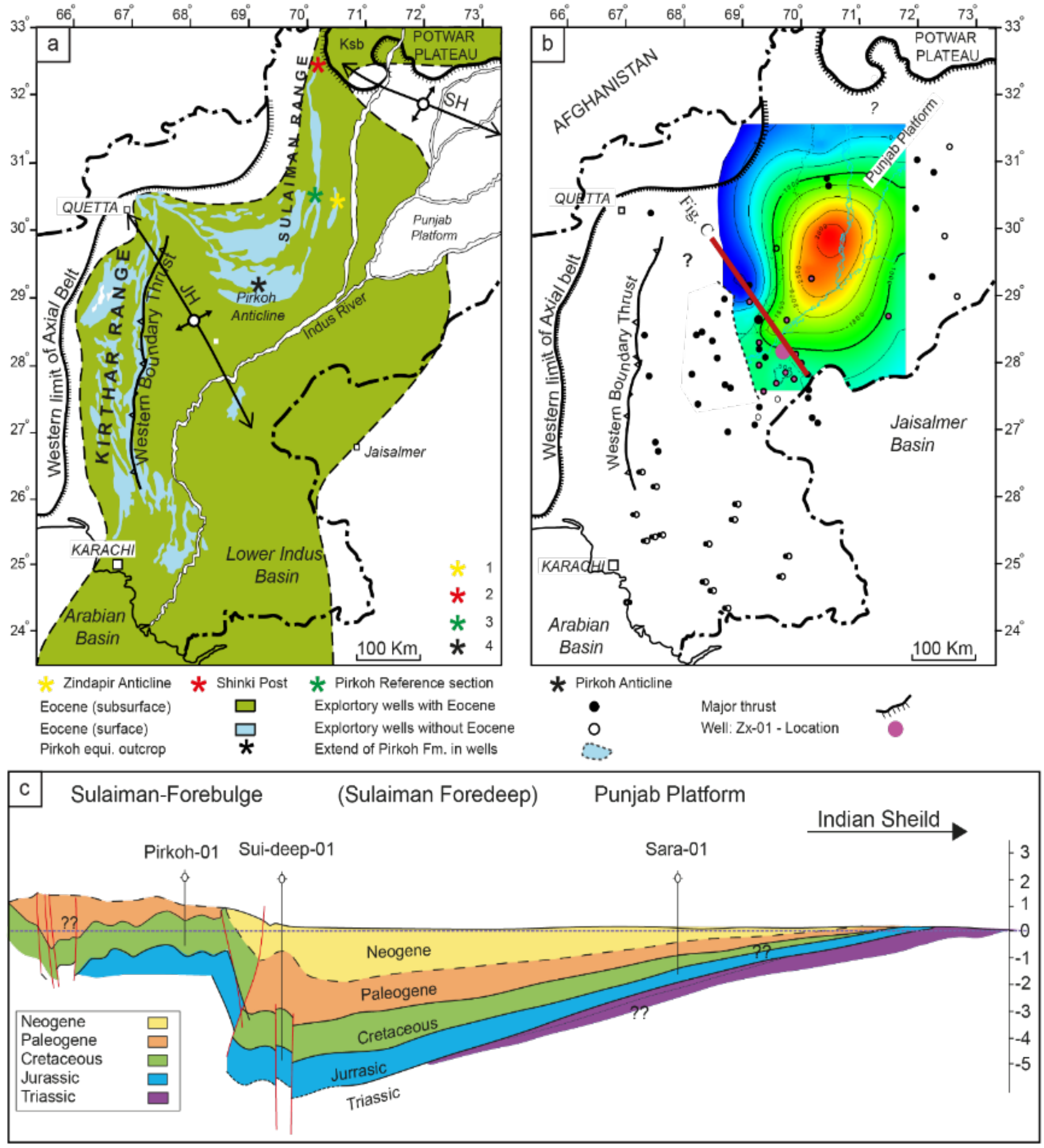

Fig. 2. a) A detailed map of location with type locality and regional extension of Eocene strata. b) Lateral extension of Pirkoh Member on Punjab Platform found in exploratory wells in the subsurface. The red line shows the regional cross-section in figure c. c) Regional geological cross-section along the red line in figure b. Depths in meter with standard above mean sea level (modified from Siddiqui, 2004; Wandrey *et al.*, 2004). Outcrops 1. Zindapir Anticline, 2. Sirki Post, 3. Pirkoh Reference Section, 4. Pirkoh Anticline.

1.2 Stratigraphy and Petroleum System of Well Zx-01

In Sulaiman Kirthar geological province, the sedimentary succession of the region is comprising stratigraphic units, i.e. (i) Precambrian basement rocks, (ii) Permian to Eocene shallow-marine shelf to deep marine strata, and (iii) Oligocene to Holocene molasse deposits (Figure. 2 and 3). Shallow marine to estuarine limestone interbedded with the calcareous shales makes up the Eocene succession. A biostratigraphic subdivision of the Eocene succession was developed based on the diagnostic planktic and benthic foraminiferal assemblages (Ali *et al.*, 2018). These deposits record the final stages of the diachronous closure of Tethyan seaway in Priabonian times in the Indus Basin (Kazmi and Abbasi, 2008).

Cretaceous and Paleocene rocks revealed good potential source characteristics in exploratory wells in the periphery of the studied area (Khan and Raza, 1986; Afzal *et al.*, 1997; Qayyum *et al.*, 2016; Ehsan *et al.*, 2018). The shales of the Drazinda Formation, which in places lies conformably above Pirkoh Member, act as a cap/seal rock along with the sealing beds of the Pirkoh Formation (Figure. 3) (Siddiqui, 2004).

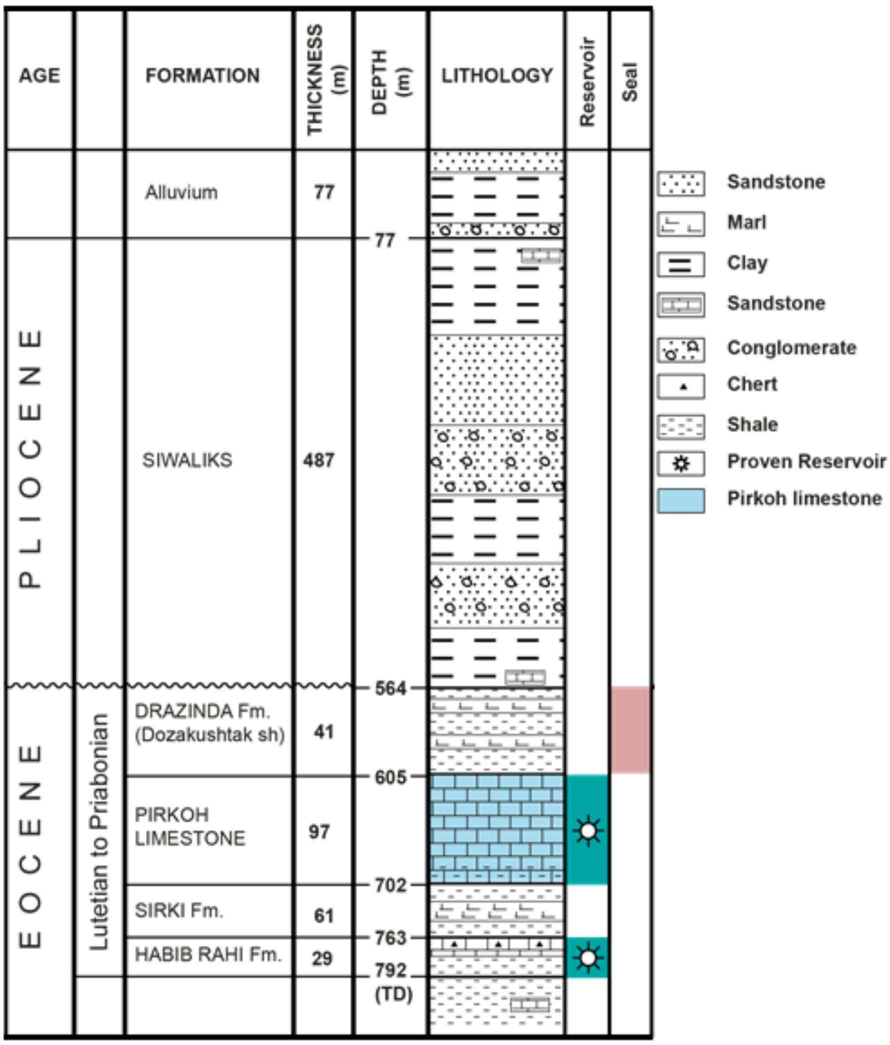

Fig. 3. Sedimentary Stratigraphic column encountered in the well Zx-01.

2. Material and methods

Thirty plug samples were taken from the Pirkoh Member that was encountered in the exploratory well Zx-01 well. The samples were taken at suitable intervals to prepare thin sections for the microfacies analysis, and reservoir characterization including porosity and permeability determination. The methodology adopted for this research was based majorly on core analysis techniques (Flügel, 2004). The Dunham classification (Dunham, 1962) was used for microfacies while the porosity and permeability, parameters were analyzed using Core Measurement System (CMS) 300 under standard protocols.

2.1 Petrography

Fourteen thin sections were prepared from core samples. Classification, depositional environment's interpretations, diagenetic alterations, and biostratigraphy were studied according to the standard procedures (Embry and Klovan, 1971; Flügel, 2004; Serra Kiel *et al.*, 1998).

2.2 Core Analysis

Thirty plug samples were taken at the regular intervals from 9 m long cores with the help of the plugging machine. These were then oven dried and weights were measured. The diameter and length of these plugs were measured using the Vernier Caliper. The bulk volume and permeability was calculated by the following formula.

$$\text{Bulk Volume} = (\text{diameter})^2 \times \text{length} \times 3.14 / 4 \quad (1)$$

$$Q = \frac{KA(P1-P2)}{(\mu L)} \quad (2)$$

Where:
Q = flow rate
K = permeability
A = area
P1 – P2 = pressure drop
L = path length
μ = dynamic viscosity (aka absolute viscosity or viscosity

3. Result and Discussion

3.1 Carbonate microfacies

Three microfacies were distinguished and described below:

3.1.1 MF1: Bioclastic Packstone to floatstone with Large Benthic Foraminifera (LBF)

The MF1 consists of light grey to brownish grey, fossiliferous, hard, and compact limestone. The MF1 is found in four thin sections (Table 1). *Nummulites* sp. and *Discocyclina* sp. are the dominant skeletal grains found in these microfacies (Figure. 4). Apart from these two, *Lockhartia* sp. And coralline algae with other bioclastic grains were also found. The common size of the skeletal grains ranged between 2 to 3 mm. The grains are poorly sorted and embedded in the micrite matrix. The cementation of calcite is also observed in these facies. The grain to matrix ratio found in this microfacie is 4:1.

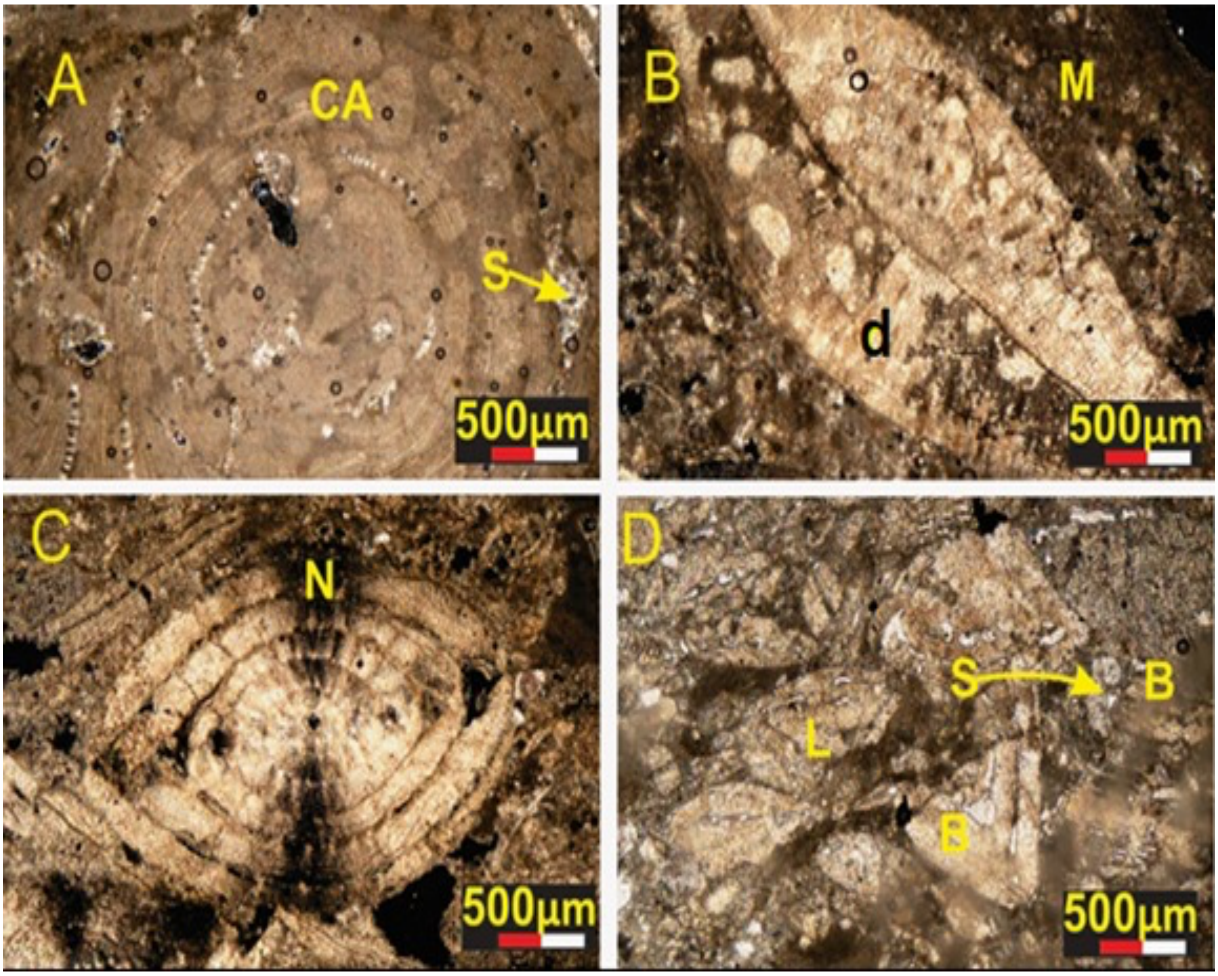

Fig. 4. Bioclastic packstone to floatstone Microfacies with Large Benthic Foraminifera (MF1), identified in Pirkoh Member, Zx-01. A: Coralline Algae(CA), spar (S). B: Micrite matrix (M), *Discocyclina* sp.(d). C: *Nummulites* sp. (N). D: *Lockhartia* sp. (L), spar cement (S) and broken fragments (B).

The MF1 represents shallow water settings with a relatively high-energy environment in oligotrophic and tropical conditions (Hallock and Glenn 1986; Hallock 1987). An abundance of LBF reflects the deposition in the middle ramp, below the Fair-Weather Wave Base (Figure.7). The occurrence of Nummulitids represents a water depth of less than 100 m (Hallock and Glenn, 1986; Hallock, 1987).

Table 1. Core sample analysis results discussed in this study.

Serial No.	Confining Pressure	Depth	Analysis No.	Porosity	Permeability		Samples
					Horizontal	Klinkenberg	
	Psi	(m)		%	(md)	(md)	
1	1000	610.3	A	16.27	1.14	0.84	■
2	1000	610.6	B	23.46	3.24	2.41	■
3	1000	610.9	C	21.29	1.95	1.42	
4	1000	611.2	D	14.27	0.51	0.47	
5	1000	611.5	E	11.10	0.12	0.08	
6	1000	611.8	F	12.43	0.12	0.08	■
7	1000	612.1	G				
8	1000	612.4	H	8.99	0.03	0.02	
9	1000	612.7	I	14.06	0.31	0.22	
10	1000	613.0	J	12.96	0.35	0.21	■
11	1000	613.3	K	25.96	7.73	6.14	■
12	1000	613.6	L	24.13	6.34	4.85	■
13	1000	613.9	M	23.18	4.07	3.50	
14	1000	614.2	N				
15	1000	614.5	O	6.24	0.03	0.02	
16	1000	614.8	P	13.86	0.11	0.06	■
17	1000	615.1	Q	12.23	0.48	0.27	
18	1000	615.4	R				■
19	1000	615.7	S	24.60	4.36	3.38	■
20	1000	616.0	T	20.31	2.76	2.04	
21	1000	616.3	U	27.47	1.94	1.45	■
22	1000	616.6	V	18.44	0.56	0.38	
23	1000	616.9	W	13.64	0.27	0.18	■
24	1000	617.2	X	16.04	1.18	0.85	■
25	1000	617.5	Y	12.29	1.37	1.05	
26	1000	617.8	Z	12.83	1.12	0.86	■
27	1000	618.1	A-1	10.29	0.12	0.07	■
28	1000	618.4	B-2	11.77	0.15	0.09	
29	1000	618.7	C-3	12.89	0.19	0.12	
30	1000	619.0	D-4	17.02	0.88	0.62	■

3.1.2 MF2: Bioclastic wackestone

The MF2 consists of medium grey to brownish grey colored, fossiliferous limestone. The MF2 is identified in nine thin sections (Table. 1). The allochems identified in these microfacies (Figure. 5) include *Nummulites* sp., Discocyclinids, *Assilina* sp., Coralline algae and *Lockhartia* sp. The grain size ranges from 1 to 2 mm. The fossil chambers of grains are often filled with the spar. These grains are mostly cemented by spar and calcite and micrite is also present as a matrix. The grain to matrix ratio in MF2 is 2:3 that shows a sixty percent matrix.

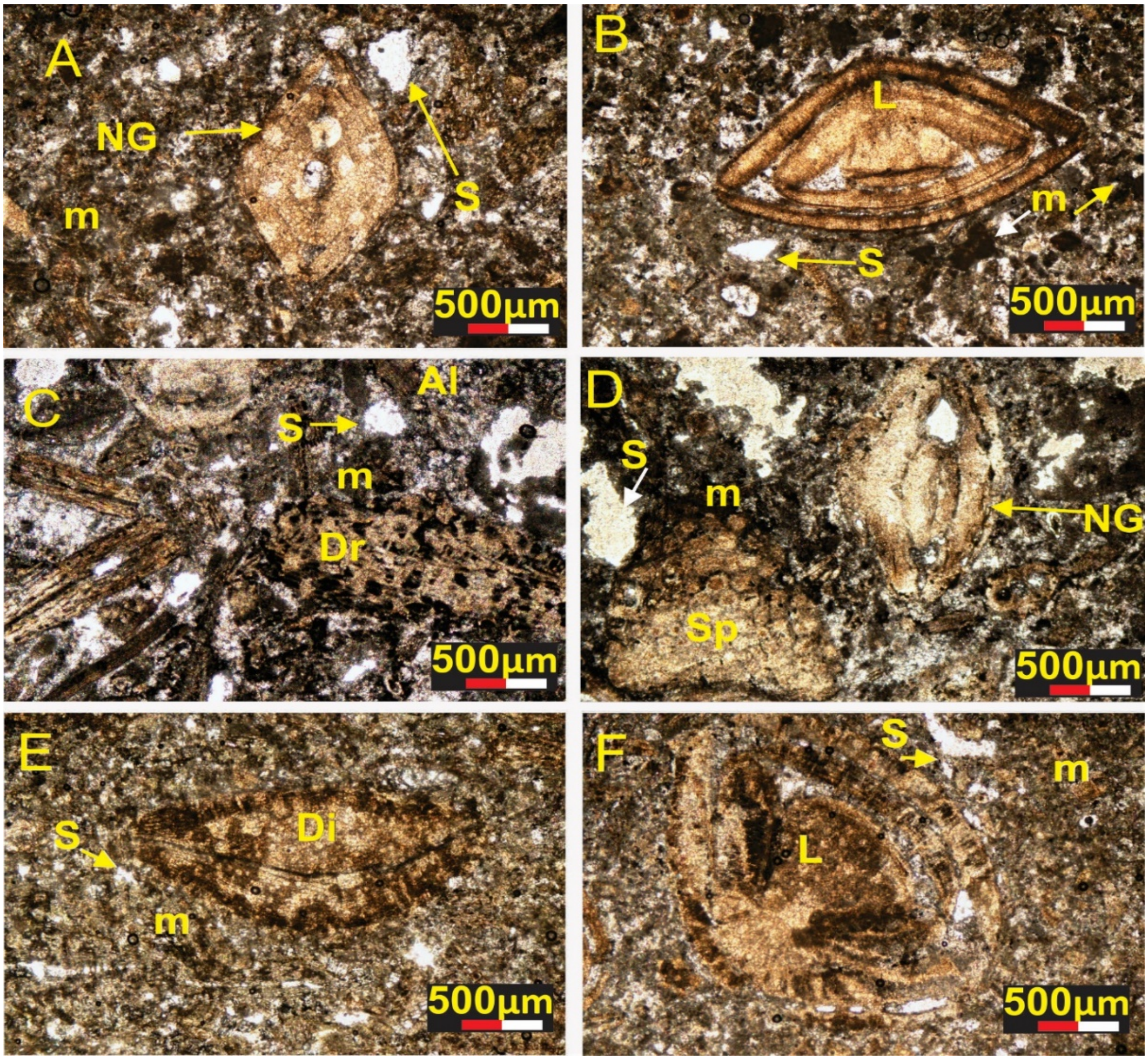

Fig. 5. Bioclastic wackestone Microfacies (MF2), identified in Pirkoh Member, Zx-01. A: *Nummulites globulus* (NG), Spar (S) as cement, matrix (m). B: Micrite matrix (m), spar (S), *Lockhartia* sp. (L). C: Spar cement (S), matrix (m), fragment of *Discocyclina ranikotensis* (DR), Calcareous algae Halimeda (Al). D: Sponge (Sp), *Nummulites globulus* (NG), Spar as cement (S), matrix (m). E):*Discocyclina* sp. (Di), Spar (S) as cement, matrix (m). F: *Lockhartia* sp. (L), Spar (S) as cement, matrix (m).

These features represent shallow marine environment in oligotrophic setting under the tropical to subtropical climatic conditions (Hallock and Glenn 1986; Hallock 1987). The occurrence of coralline algae represents high light penetration. Increased cement and bioclast represents agitated waters (Figure. 7) (Hallock and Schlager, 1986; Hallock, 1987)

3.1.3 MF3: Mudstone-wackestone microfacies

The MF3 consists of grey to brownish grey colored, hard, fractured limestone. The MF3 is identified in two thin sections (Table 1). The grains to matrix ratio in this microfacies are about 1:4. The allochems identified include *Assilina* sp., Discocyclinids and *Lockhartia* sp. with bioclasts (Figure. 6). The grains are less than 1mm in size. These grains are cemented majorly by spar. These grains are mostly supported by mud and cemented by microcrystalline calcite, whereas spar is minor.

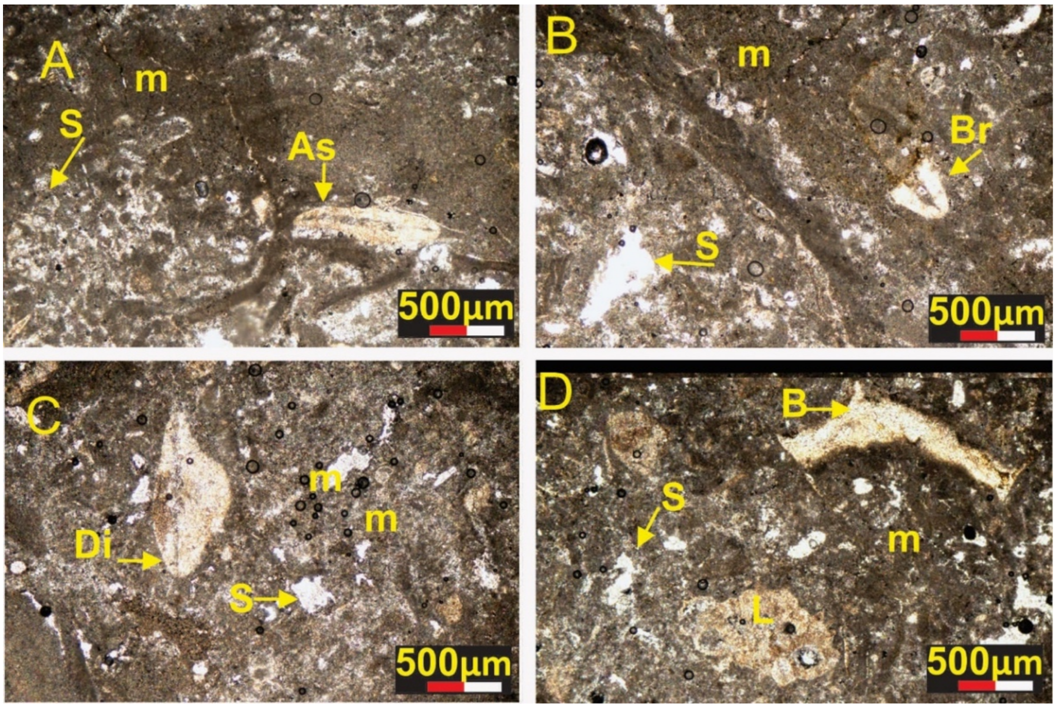

Fig. 6. Mudstone-wackestone microfacies (MF3), identified in Pirkoh Member, Zx-01. A: *Assilina laminose* (As), spar (S) as cement, matrix (m). B: Broken fragments (Br), spar (S) as cement, matrix (m). C: Discocyclinids (Di), spar (S) as cement, matrix (m). D: *Lockhartia* sp. (L), spar (S) as cement, matrix (m), broken fragment of bioclast (B).

The excessive occurrence of lime mud, broken, reworked and scarce LBF of MF3 represents calm shelf conditions and is interpreted to be deposited below the Fair-Weather Wave Base (FWWB) and above Storm Wave Base (SWB), upper and lower slope in non-rim setting or open carbonate platforms also confirmed by the other authors (Afzal *et al.*, 1997; Abbas1999). (Figure. 7)

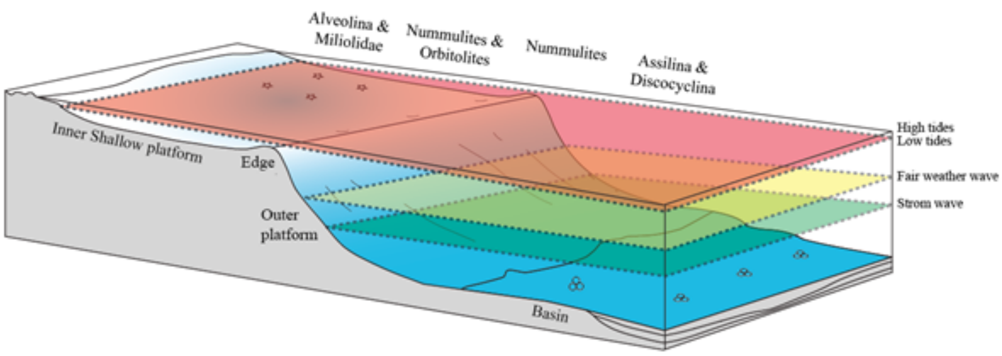

Fig. 7. A block diagram showing the distribution of the Large Benthic Foraminifera and environments of deposition.

3.2 Diagenesis

The identified diagenetic features include micritization, cementation, dissolution, reworked grains, fracture filling, neomorphism, compaction and dolomitization.

3.2.2 Micritization and cementation

The effect of micritization is observed in all three microfacies. The micritization is found from 20 to 80 percent in the three defined microfacies. MF2 and MF3 contain allomicrite (Figure. 8B) matrix related to abrasion and bioerosion (Flugel, 2004). It was also found that the MF3 contains micritic envelopes, indicating original aragonite (Figure. 8A) (Swei and Tucker, 2012).

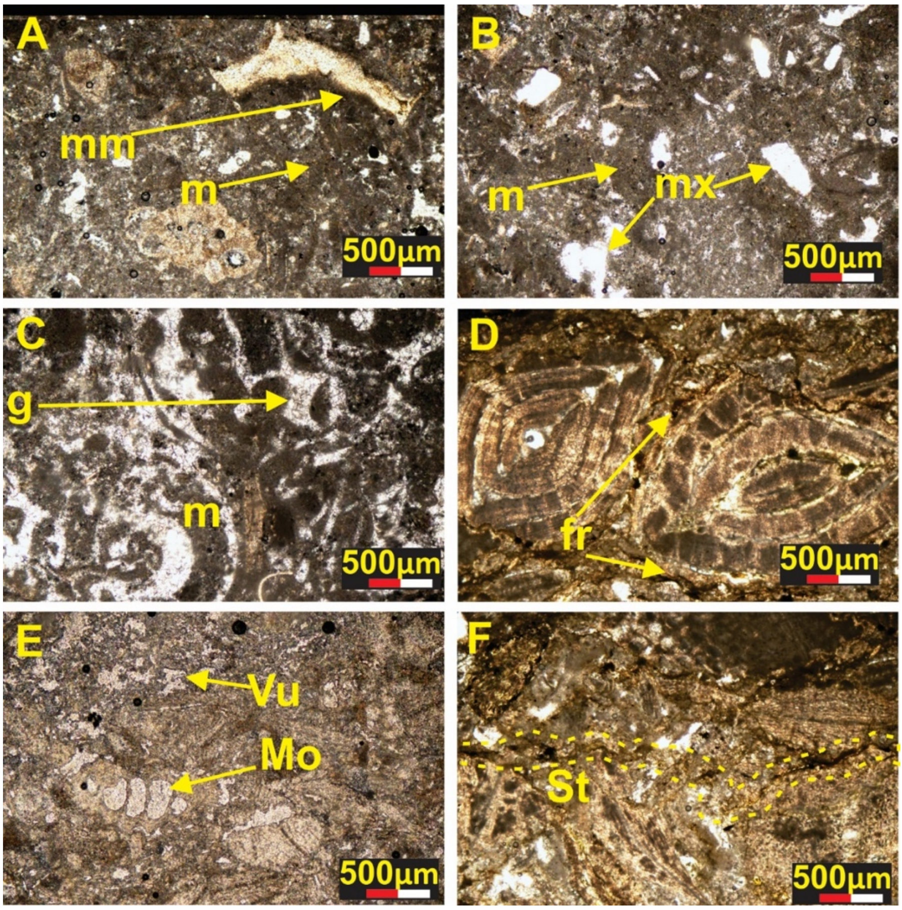

Fig. 8. Diagenetic features in Pirkoh limestone. A: Microbial micrite (Mm) in micrite matrix (m). B: pores filled by microcrystalline calcite (mx) and micrite (m) as matrix. C: granular cement fabric (g). D and E: fabric selective dissolution, fractures (fr), vuggy pore spaces (Vu) and molds (Mo). F: Stylolites (St).

The MF2 and MF3 mostly show microcrystalline (Figure. 8B) and granular (Figure. 8C) cement fabric comprising of calcite and dolomite minerals. Mostly this cement fills intraskeletal pores confirming the meteoric-vadose burial environment (Flügel, 2004). Apart from these cements, MF1 and MF2 display pyrite-filled pores and fractures that confirms the burial environment (Figure. 9C).

3.2.3 Neomorphism

Aggrading neomorphism has been extensively observed in many samples indicating a meteoric phreatic environment. The final stage of aggrading neomorphism is not found in any sample. This confirms the initial phase of aggrading neomorphism in this limestone.

3.2.4 Dissolution and compaction

Dissolution developed secondary porosity that includes molds, vugs, intra-particle and inter-particle pores i.e., fabric selective and non-fabric selective (Figure. 8D and 9B). Both physical (Figure. 9C) and chemical compaction (Figure. 8F) types were found in the form of abundant compaction features in MF1 and MF2. Furthermore, it is also apprehended that this compaction took place in the late stage of diagenesis.

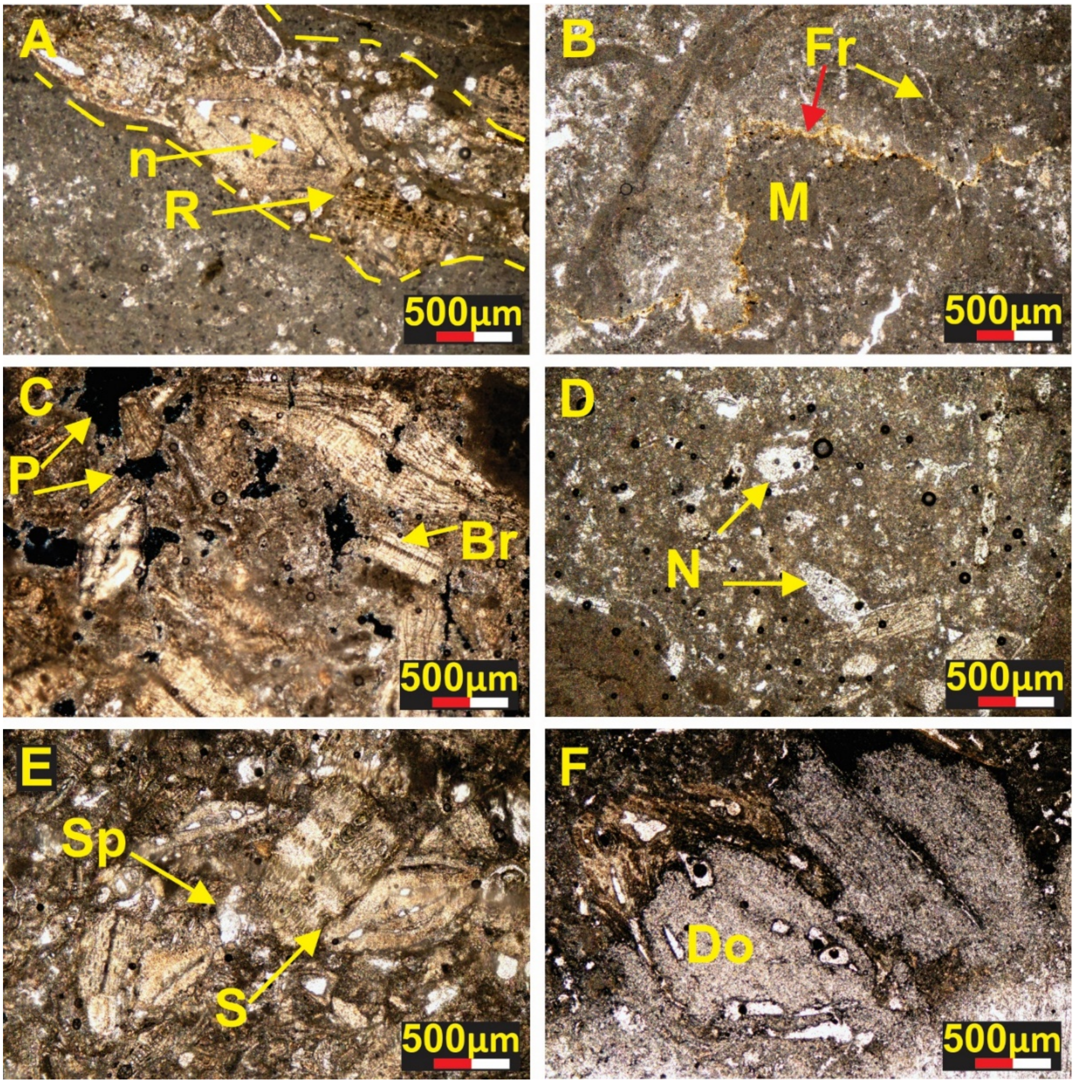

Fig. 9. Diagenetic features in Pirkoh limestone. A: Reworked sediments (R) including redeposited *Nummulites* sp. (n) and other bioclast in a fracture (marked by red dotted and dashed lines). B: fracture filling (Fr), two stages of fractures, an older stage shown by red arrow and a younger stage of fracture filling shown by white colored arrow. Micrite (M). C: pyritization (P) and broken fragments of bioclast (Br). D: Neomorphism (N). E: suturing (S). Spar (Sp). F: selective dolomitization (Do).

3.2.5 Dolomitization

The secondary type of dolomitization was observed in many thin sections (Figure. 9F). This type of dolomitization is termed fabric selective dolomitization and is an indicator of shallow water burial. MF2 and MF3 displayed fabric selective dolomitization.

3.3 Porosity and Permeability

The reservoir statistics based on the porosity and permeability test by the laboratory petrophysical measurements show porosity ranges between 6.24% to 27.47% with a mean value of 16.51%. The permeability varies from 0.11 to 6.59 mD whereas 2/3 of the samples show less than 1.5 mD (Figures. 10 and 11). Compared with the microfacies, Bioclastic wackestone shows the highest porosity which is 27.47 % as well as the lowest i.e., 6.21 % (Figure. 11).

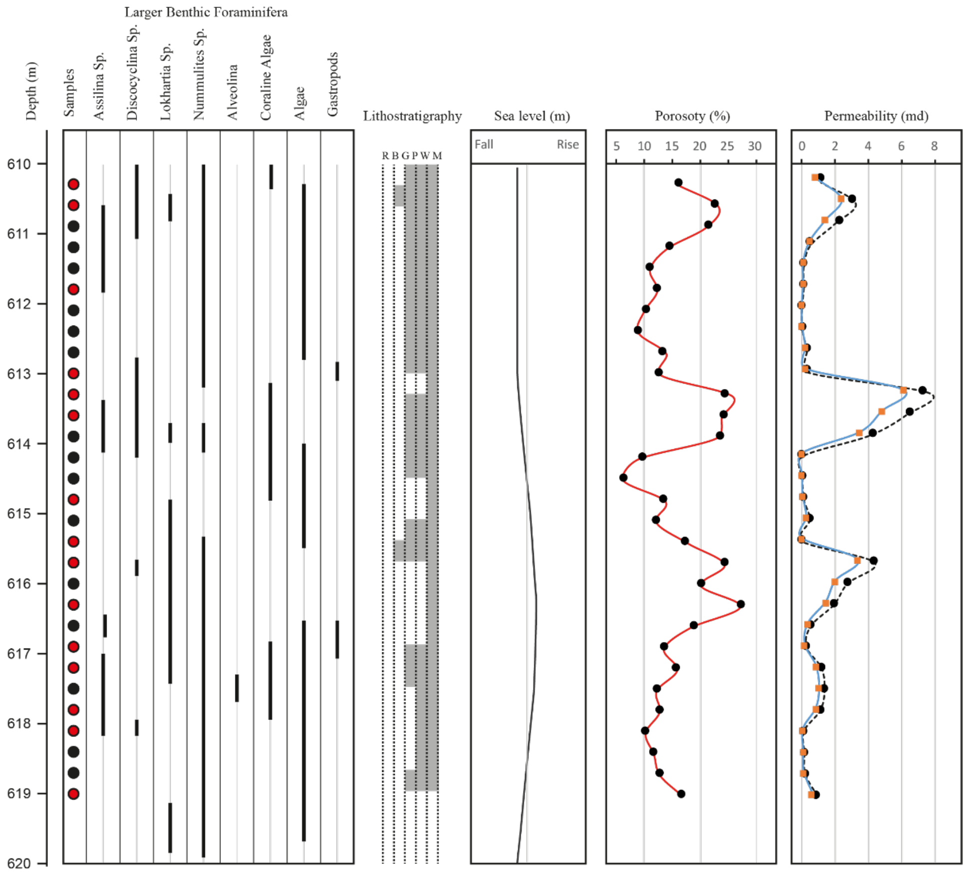

Fig. 10. Vertical distribution of microfacies, lithofacies, porosity and permeability with respective sea level curve in the study area.

Results show a reservoir potential of the Pirkoh Member with good to very good porosity. The primary porosity as interparticle and intraparticle porosity is the result of the depositional setting of varying grain size and void spaces in the foraminifera chambers such as Nummulitids (Jorry *et al.*, 2006). However, most of the depositional porosities are reduced due to cementation and compaction (Figures 8 and 9). Early cementation has reduced the depositional porosity. This was shown by pores and foraminiferal chambers that were subsequently occluded by complete or partial cementation by pyrite, calcite. Apart from this, visible filled molds were also found. These cements and molds were derived from matrix dissolution along stylolites at the mesogenetic stage (Figures. 8 and 9). Microfractures, open-closed fractures, and cemented fractures were all identified (Figure. 8D). Some of these fractures may act as a conduit of fluid flow, while others may act as a barrier to the reservoir fluids in the event of stylolites formation (Figure. 8F).

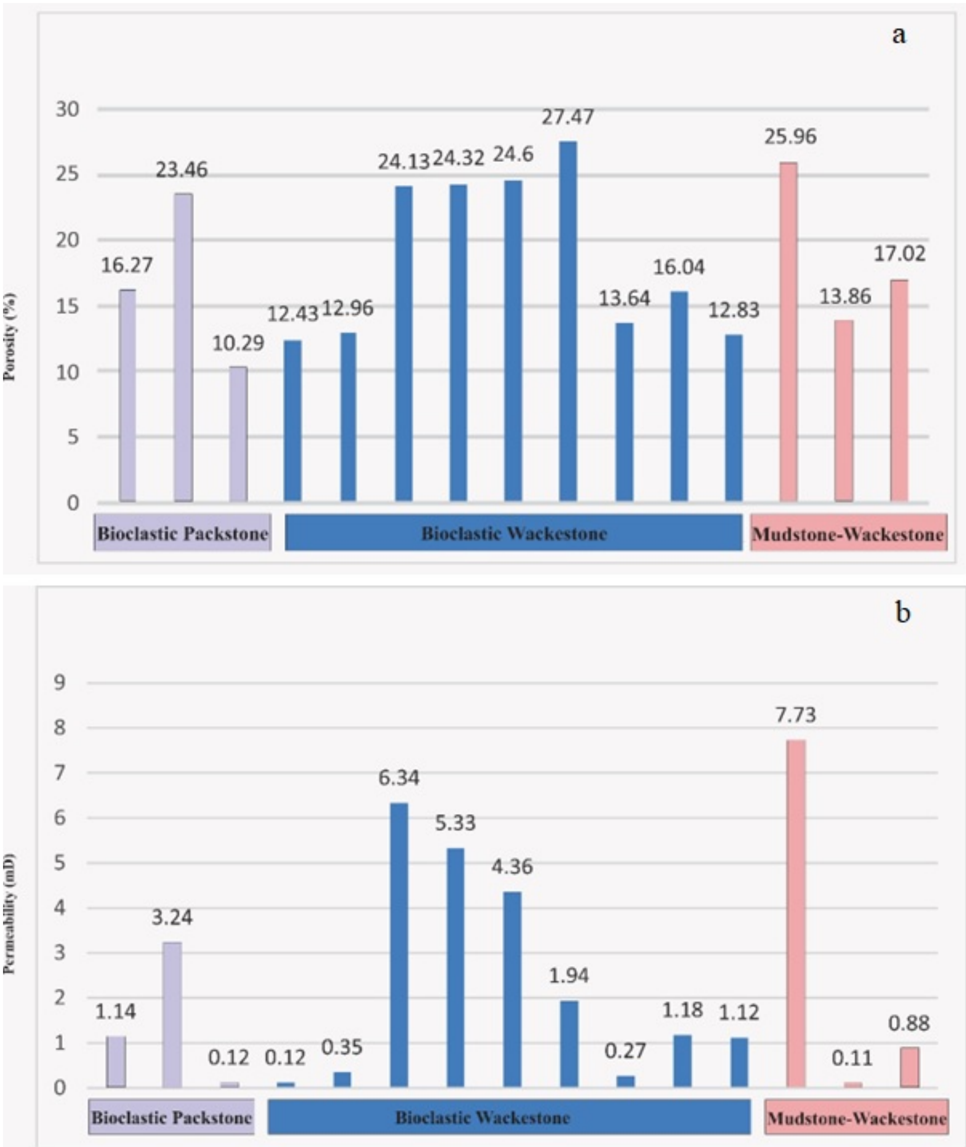

Fig. 11. Graphical distribution of the porosity (a) and permeability (b) with respect to microfacies.

A plot of porosity versus permeability (Figure. 12) reveals that permeability and porosity are correlated in an increasing trend suggest that permeability is directly related to the carbonate components and depositional framework. The reasons for the low permeability (Figure. 10) at certain intervals could be due to the argillaceous nature of limestone along with some diagenetic events including cementation, compaction and neomorphism.

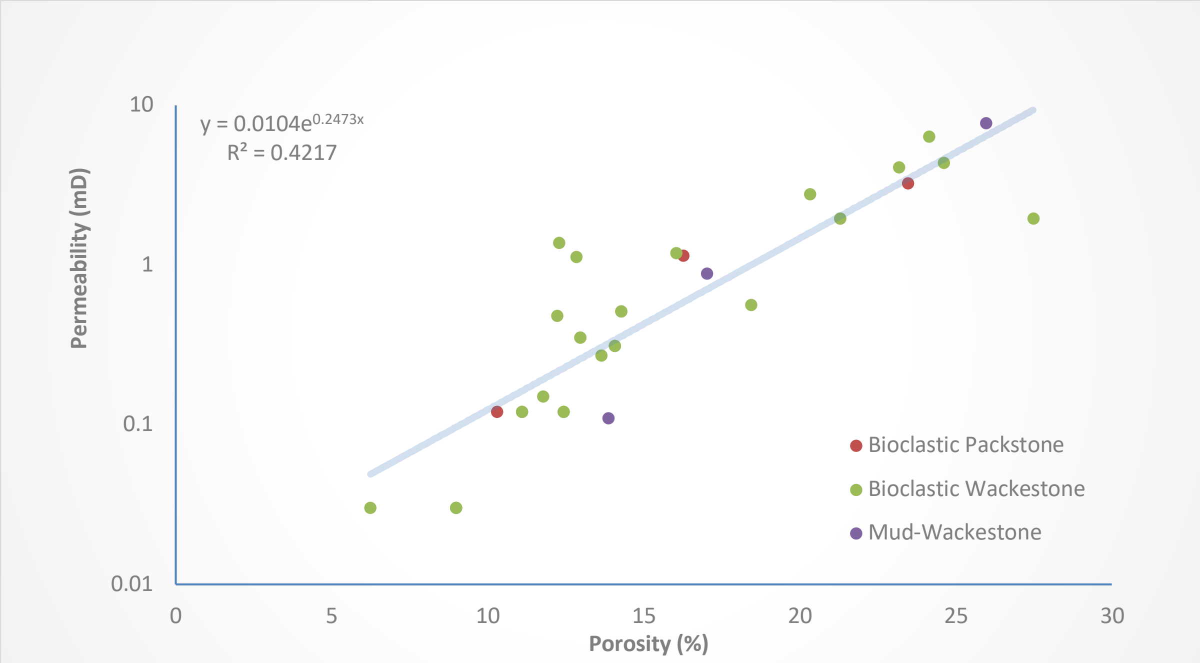

Fig. 12. Scatter-graph between Porosity and Permeability of Pirkoh Member.

4. Conclusions

The sedimentological studies show that the carbonate platform is predominantly composed of the *Nummulites* sp., *Lockhartia* sp., *Discocyclina* sp., and *Assilina* sp., and Coralline algae with micrite of the Middle Eocene age. This fossil assemblage represents a carbonate ramp setting developed in an oligotrophic tropical environment. Amongst three microfacies, bioclastic wackestone, bioclastic packstone to floatstone and mud-wackestone, reservoir potential of the carbonate is good with low to high porosity (6.24% to 27.47%), and low to fair permeability (0.11-6.59 mD). Variations in porosity and permeability are related to the depositional environment as well as other diagenetic processes that operated during the burial phase and altered the reservoir quality. The observed porosity is intra- and interparticle primary porosity and the secondary porosity developed due to fracturing and dissolution that enhanced the reservoir potential. Post burial diagenesis and the presence of clay or marly lithologies are potential reasons for low permeability. The findings of this study demonstrate good reservoir properties of the Eocene carbonates and help to correlate the vertical facies distribution of the reservoir characteristics.

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