Journal of Sedimentary Environments (2020) 5:473–492
https://doi.org/10.1007/s43217-020-00027-2

ORIGINAL ARTICLE

The sedimentological and stratigraphical analysis of the Paleocene to Early Eocene Dungan Formation, Kirthar Fold and Thrust Belt, Pakistan: implications for reservoir potential

Sajjad Ahmad[1] · Bilal Wadood[2,3] · Suleman Khan[1] · Abd Ullah[1] · Ghazi Mustafa[1] · Muhammad Hanif[4] · Hasbee Ullah[1]

Received: 12 July 2020 / Revised: 19 August 2020 / Accepted: 24 August 2020 / Published online: 7 September 2020

Abstract

The present study aims to evaluate the Paleocene to Early Eocene carbonates of the Dungan Formation in the Kirthar Fold and Thrust Belt, Pakistan for its paleo-depositional environment, sequence stratigraphy, and diagenetic effects on reservoir potential. The utilization of outcrop data for faunal identification and microfacies techniques helped in interpreting the paleo-environments and sequence stratigraphic framework. The microfacies analysis revealed that carbonates of the Dungan Formation in the Kirthar Fold and Thrust Belt represent a distal middle shelf-deep basinal settings of deposition. We documented a sea-level rise of second-order (spanning from Middle Danian to Ypresian) that in turn consists of a Transgressive Systems Tract (TST) and a Regressive Systems Tract (RST) of third-order cyclicity, spanning from Danian–Selandian and Thanetian-Early Ypresian respectively. The comparison with published data, the sea-level oscillations is influenced by eustacy and local tectonics. The hydrocarbon reservoir rock characterization of the carbonates is achieved by recording marine, burial, and meteoric diagenetic phases. The processes of cementation, micritization, neomorphism, and compaction occluded the effective porosity while dissolution and fracturing have enhanced the porosity and permeability of the rock unit. The petrographic evidence augmented by quantitative plug porosity and permeability data suggest poor to moderate reservoir potential of the carbonates of the Dungan Formation.

Keywords Dungan Formation · Microfacies analysis · Depositional environment · Diagenesis · Sequence stratigraphy · Reservoir potential

1 Introduction

The studied section lies in the Central Kirthar Range, which is located at the north-western margin of the Indian Plate (Kazmi 1981; Fig. 1). The Kirthar Fold Belt extends from the southern end of the Sulaiman Range to Karachi and forms 380–400 km long and 50–70 km wide north–south trending fold and thrust belt (Kazmi and Jan 1997). The Sulaiman Fold and Thrust Belt bound the study area to the north and the Bela Ophiolite to the west. The Sibi Trough and Kirthar Fore Deep are located to the east while the Indian Ocean to the south of the study area (Fig. 1; Kazmi and Rana 1982). The intensely folded cover of sedimentary rocks of the Indo-Pakistan Plate formed major fold and thrust belts i.e. Kirthar, Sulaiman, and Salt ranges (Warraich 2000). Pakistan has two major sedimentary basins namely Indus and Baluchistan basins (Fig. 1; Shah 2009). The Chaman Transform Zone separates the Baluchistan and

Communicated by M. V. Alves Martins

✉ Bilal Wadood
bilalwadood@uoswabi.edu.pk

Sajjad Ahmad
dr.s_ahmed@uop.edu.pk

Suleman Khan
sulemanafridi@uop.edu.pk

1 Department of Geology, University of Peshawar, Peshawar, KPK, Pakistan

2 State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, Xi'an, Shaanxi, China

3 Department of Geology, University of Swabi, Anbar-Swabi, KPK, Pakistan

4 National Centre of Excellence in Geology, University of Peshawar, Peshawar, KPK, Pakistan

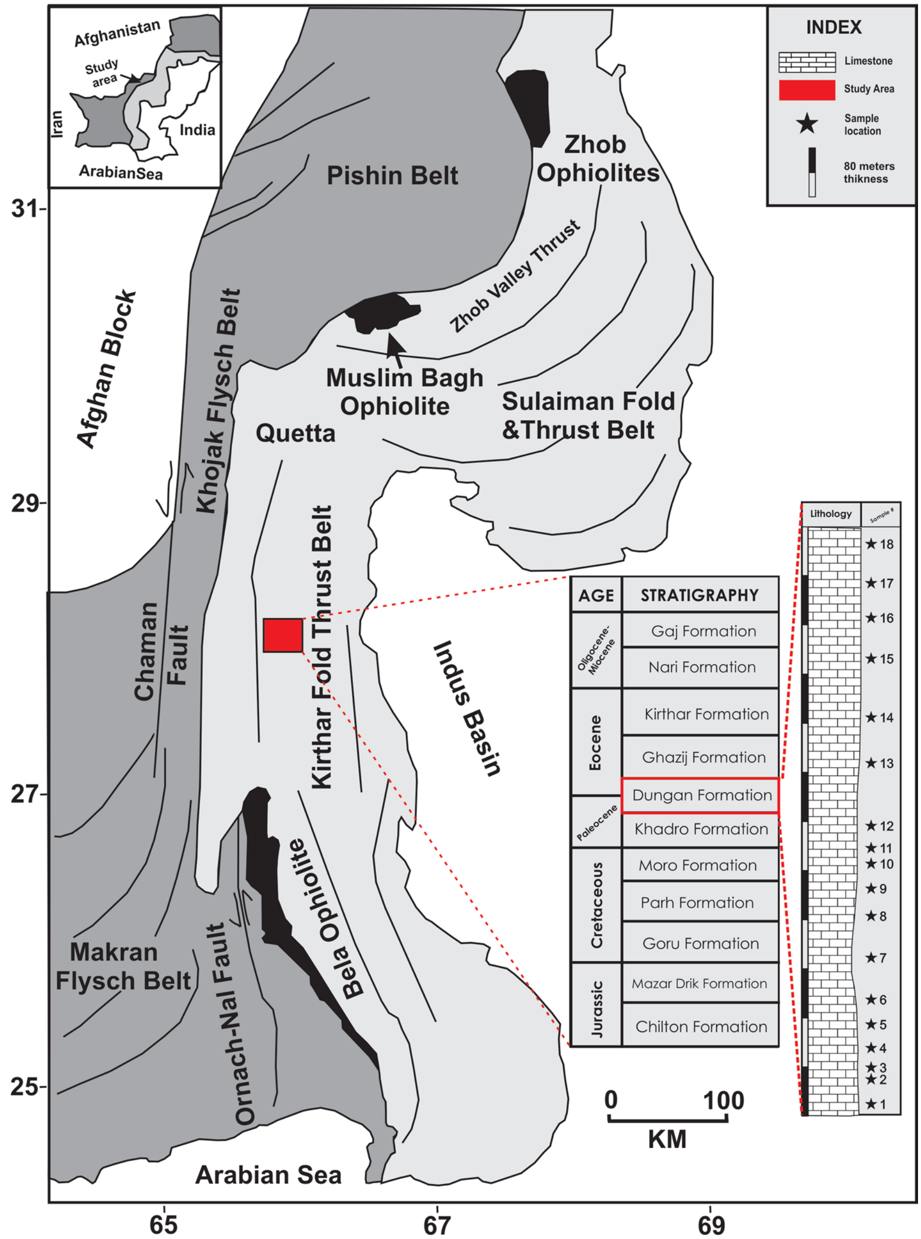

Fig. 1 Geological map of the study area (GPS: 27°46′37.51″ N, 66°29′49.19″ E; modified after Banks and Warburton 1986; Khan et al. 2017), the generalized stratigraphic column of the Kirthar Fold Thrust Belt (Shah 2009), and log of the Dungan Formation

Indus basins (Kadri 1995). The three depositional provinces of the Indus Basin have been called the Potwar-Kohat, the Sulaiman, and the Kirthar (Rahman 1963). The trough shape Kirthar depositional province extends from Karachi and Hyderabad in the south to Khuzdar in the north. The Kirthar province contains the thickest sequence of Paleocene rocks in the Indus Basin (Fig. 1; Meissner and Rahman 1973). The Dungan Formation at the Khuzdar area is an integral part of the Kirthar depositional province which occurs in the Lower Indus Basin of Pakistan (Afzal et al. 2011).

The Paleocene sequence of the Lower Indus Basin, particularly of the Kirthar Province, has been well studied since the mid-nineteenth century due to its rich foraminiferal and molluscan fauna. A wealth of research has been carried out on the sedimentology, stratigraphy, structure, economic geology, and paleontology of the Kirthar and Sulaiman ranges. William (1959) and the Hunting Survey Corporation (1960–1961) established the reconnaissance geology of the Kirthar Range. Paleocene age is assigned to the rock unit based on the presence of planktonic foraminifera by Latif (1964). However, Samanta (1973) dated the rock unit as Paleocene–Eocene. The formation in most parts of the Indus Basin is dominantly comprised of limestone with shales intercalations (Shah 2009). Banks and Warburton (1986) and Ahmed and Ali (1991) explained the structural framework of the studied section. The recent studies of Weiss (1993) re-confirmed the presence of planktonic foraminifera for dating the rock unit. The sedimentological analyses were undertaken to interpret the environment of deposition, sequence stratigraphy, tectonostratigraphy, and reservoir potential (Ahmad and Hudson 2000; Ahmed and Ahmed 2001; Hedley et al. 2001; Smewing et al. 2002; Khan et al. 2010). The discovery of the oil/gas seepages has attracted researchers to evaluate the rock unit for its reservoir potential (Kadri 1995).

As evidenced by the previous literature, the rock unit lacks an integrated approach of utilizing various tools to precisely evaluate its paleo-depositional environment, sequence stratigraphy, and reservoir potential. The present study, therefore, was conducted to integrate the faunal information, outcrop, and microfacies data to better understand the depositional environment, sequence stratigraphy, and hydrocarbon reservoir potential of the Paleocene to Early Eocene Dungan Formation in the Kirthar Fold and Thrust Belt, Pakistan. The present study aims to achieve the following objectives; 1. To use the ageing diagnostic foraminiferal fauna for determining the cyclicity within the Dungan Formation for devising a dynamic depositional model 2. To investigate the influence of local tectonics and global sea-level fluctuations on the deposition of the carbonate facies and 3. To unravel the diagenetic history and hydrocarbon reservoir characterization of different facies.

2 Stratigraphic framework

The Jurassic–Oligocene rocks are well exposed in the Kirthar Range, Pakistan (Fig. 1). The oldest Jurassic Chiltan Formation consists of a monotonous sequence of thick-bedded micritic, ooidal, bioclastic limestone (Shah 2009). The Chiltan Formation is overlain by interbedded limestone and shale of Middle Jurassic Mazar Drik Formation (Arkell 1956; Fatmi 1977). The carbonates of the Mazar Drik Formation preserve fragments of echinoids, pelecypods, brachiopods, and foraminifera (Fatmi 1977). It is widely distributed in Sibi, Kalat, and Khuzdar area of the Kirthar Range (Kazmi 1988). The Kirthar-Sulaiman Range shows a complete succession of the Cretaceous rocks consisting of siltstone, shale, and limestone (Kazmi and Jan 1997). The Cretaceous rocks of the study area comprised the Goru Formation, Parh Limestone, and Moro Formation. The Goru Formation of Cenomanian age (Alleman 1979) is composed of mudstone and shale with subordinate sandstone and siltstone, displaying a range of colors including light grey, dark grey, and occasionally maroon and white (Shah 2009). The rock unit predominantly contains planktonic foraminifera (Shafique and Danial 1990) and serves as a potential reservoir for hydrocarbons in the Indus Basin of Pakistan (Kadri 1995). The sandstone of Goru Formation is overlain transitionally by the Parh Limestone (Anwar 1991). The Upper Cretaceous Parh Limestone (Kazmi 1981) is dominantly comprised of limestone, subordinate shale, and marl having porcellaneous and platy conchoidal fractures (Muhammad et al. 2018). The Parh Limestone has gradational upper contact with the Moro Formation (Hunting Survey Corporation 1961). The Moro Formation consists of gray, medium to thick-bedded, argillaceous limestone, gray to dark gray marl, and dark gray to green calcareous shale with minor sandstone and conglomerate (Fatmi 1977).

The Tertiary rocks are also widely distributed in the Kirthar-Sulaiman Range, Axial Belt, and Kohat-Potwar Province. The Paleocene and Eocene rocks of the Kirthar Range are dominantly comprised of carbonates, shale, and sandstone of the Khadro Formation, Dungan Formation, Ghazij Formation, and Kirthar Formation (Shah 2009). The Khadro Formation is dominantly comprised of a variety of calcareous sandstone with alternate beds of limestone at places. The unit is highly fossiliferous and the Early Paleocene age is assigned to it (Eames 1952; Shah 1977). The contacts of the Khadro Formation are disconformable with underlying Moro Formation and overlying Dungan Formation (Kazmi 1988). The Dungan Formation is mainly well-developed in the Sulaiman and Kirthar provinces. The Dungan Formation in the study area dominantly consists of thin-thick bedded (Fig. 2a) and massive limestone (Fig. 2b, c). At places, subordinate shale, conglomerates, and limestone are also seen (Fig. 2d). The thickness of the formation varies from place to place and ranges from 100 to 600 m (Cheema 1977). The formation is rich in fossils including larger benthic foraminifera (LBF), planktonic foraminifera, red algae, and bryozoans (Shah 2009). The larger foraminifera includes *Miscellanea, Lockartia, Operculina, Discocyclina, Nummulites,* and *Assilina*. (Davies 1941; Ahmed 1996). The Dungan Formation has been assigned to Late Paleocene to Early Eocene age (Latif 1964) and is correlated with the Hangu-Patala stratigraphic sequence of the Kohat-Potwar Plateau (Ahmad and Pedley 1997). The Late Paleocene abundant foraminiferal assemblages' are documented from various sections of western Sulaiman Fold and Thrust Belt which are endemic to the Eastern Tethys (Rehman et al. 2018). Similarly, the co-existence of benthic foraminifera with dinoflagellates and planktonic foraminifera show a well connected bathyal to open marine deposition of the P/E Dungan Formation (Hanif et al. 2014). The petrographic based microfacies interpretation of the rock unit in Central Kirthar Fold and Thrust Belt represents deposition in carbonate ramp with consistent deepening upward trends of facies (Khan et al. 2010). Its lower contact is unconformable at various stratigraphic sections in the basin (Williams 1959). In the study area, the Dungan Formation has upper contact with Ghazij Formation (Kassi and Kakar 1997). The Ghazij Formation dominantly consists of shale with subordinate limestone, however, it shows the variation in lithology at places and hence five lithostratigraphic units have been

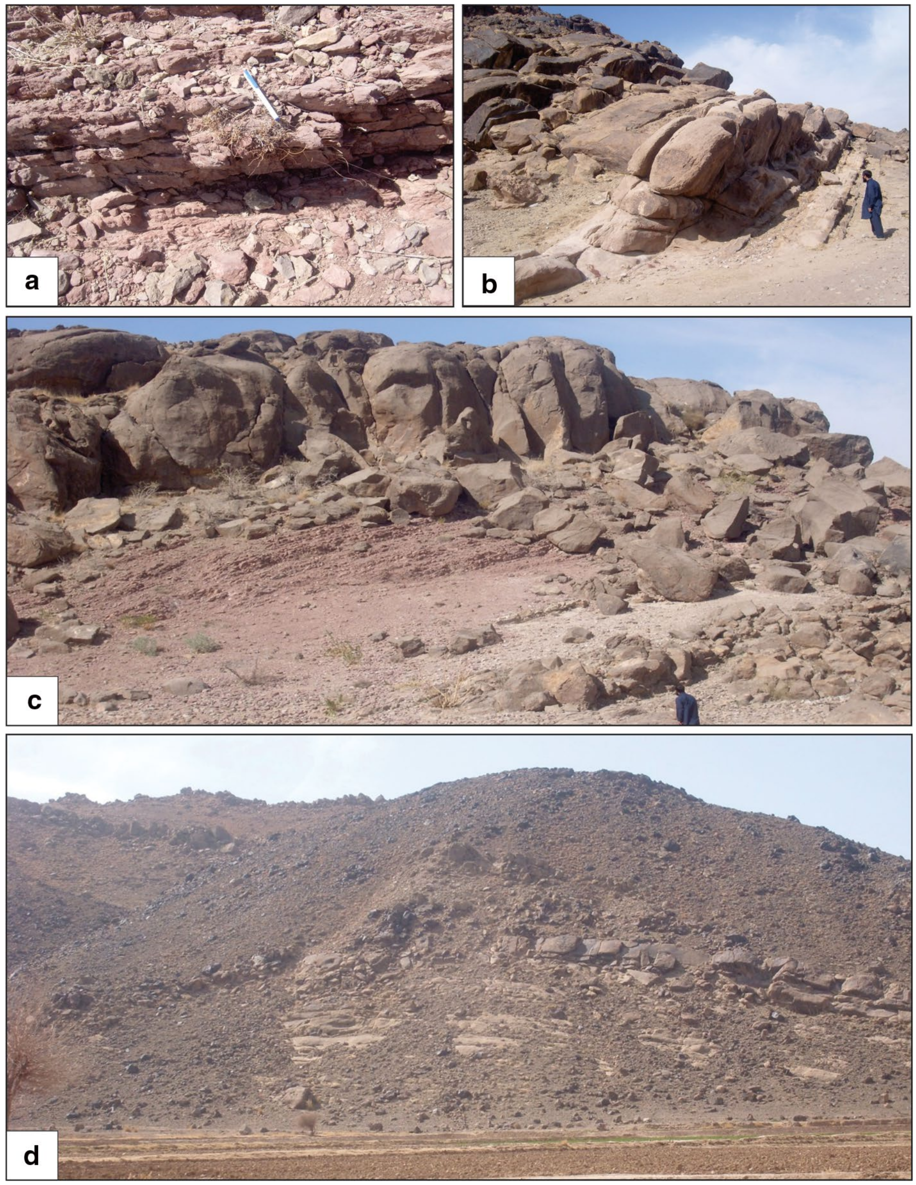

Fig. 2 Field photographs showing Dungan Formation. **a** thin-medium bedded limestone, **b** massive bedded limestone, **c** thin-massive bedded limestone, **d** panoramic view of the Dungan Formation

defined within Ghazij Formation (Hunting Survey Corporation 1961; Hemphill and Kidwai 1973; Shah 2009). The rock unit has conformable lower and upper contact with Dungan and Kirthar formations respectively, however, at some places, it is reported to unconformably overly the Dungan Formation (Kassi et al. 1987). Early Eocene age is assigned to the rock unit. The Kirthar Formation demonstrates stratigraphic variations in the basin and is divided into Habib Rahi Limestone, Domanda, Pirkoh, and Drazinda Member (Hemphill et al. 1973). It has lower and upper conformable contacts with Ghazij and Oligocene Nari Formation (Kazmi 1988). A Middle Eocene age has been assigned to this formation.

The Nari Formation is comprised of mixed lithology of limestone, sandstone, and shale. Bed of conglomerate and ironstone are present either at the base or in the upper part (Shah 1977). The Nari Formation is conformably overlain by Gaj Formation in the Sulaiman and Kirthar provinces (Shah 2009). Foraminifera, Corals, Molluscs, Echinoids, and Algae have been recorded by Duncan and Sladen (1884). Hunting Survey Corporation (1961) assigned an Oligocene to Early Miocene age to the Nari Formation.

3 Materials and methods

The geological fieldwork was conducted at the Makkali Section, District Khuzdar, Pakistan (GPS: 27˚46′37.51″ N, 66˚29′49.19″ E; Fig. 1). Field-based sedimentological and paleontological features were recorded including measurement of the stratigraphic thickness and rock sampling of the key horizons where lithological, textural, and paleontological changes were observed and consequently a composite lithostratigraphic log was prepared. A total of 18 samples were collected for detailed petrographic study using a polarized microscope (Olympus BX41) Housed at the Department of Geology, University of Peshawar, Pakistan. The percentages of different parameters including types of allochems (skeletal and non-skeletal), matrix, and the ratio of matrix/grains were calculated and presented in Table 1. Dunhum (1962) classification was used to classify the carbonates. Photomicrographs were taken by a Digital Camera fitted with the polarizing microscope (to identify age diagnostic foraminifera, various petrographic features related to the depositional and diagenetic fabric of the microfacies). Different microfacies types have been identified by using the limestone composition, depositional texture, and fossil distribution of specific samples (see e.g. Tucker and Wright 1990; Flügel 2004). The microfacies interpretation, in turn, is used to predict the model of sedimentation, depositional environment, diagenetic evolution, and formation of porosity and permeability (Carozzi 1988). Microfacies analysis aided with outcrop and fossils interpretation yields sufficient information about paleo-environments, sea-level changes and is important for the construction of a sequence stratigraphic framework for carbonate or clastic mixed systems (Serra-Kiel et al. 2003).

4 Results and discussion

4.1 Microfacies and paleo-environments

Based on a detailed petrographic study, four microfacies are recognized within the Dungan Formation. These are as follows:

1. *Discocyclina-Nummulites*-Red algal packstone microfacies (MF-1)
2. Milliolid-*Alveolina*-Red algal packstone microfacies (MF-2)
3. Planktonic-benthic foraminiferal packstone microfacies (MF-3)
4. Planktonic foraminiferal wackestone-packstone microfacies (MF-4)

4.1.1 *Discocyclina-Nummulites*-red algal packstone microfacies (MF-1)

4.1.1.1 Description This microfacies is represented by allochems (87%) and micrite matrix (13%). Allochems are predominantly composed by LBF and red algae. The LBF are represented by *Discocyclina* sp. (11%), *Nummulites* sp. (4%), *Miscellanea miscella* (7%), *Lepidocyclina* sp. (9%), *Ranikothalia* sp. (5%), *Assilina* sp. (4%), biserial foraminifera (2%), red algae (14%), bryozoans (4%) and unidentified benthic foraminifera (27%) (Fig. 3a–f).

4.1.1.2 Interpretation The LBF were the major constituents of shallow marine shelf carbonates formed in warm waters since the Late Paleozoic time (Flügel 2004). *Nummulites* sp. lived in shallow waters both inner and outer platform or ramp settings (Flügel 2004) and occurred at a depth of 20–130 m (Reiss and Hottinger 1984). *Lepidocyclina* sp. represents shallow lagoon settings (Flügel 2004). *Miscellanea miscella* indicates a warm shallow water environment (Levin 1957). *Ranikothalia* sp. has a worldwide distribution in shallow water facies (Fleury et al. 1985). *Discocyclina* sp. indicates a deeper water environment (Myers 1943). Coralline red algae depend on light, temperature, depth, and salinity for their survival and occur in clear, shallow, and warm waters (Ahmad and Pedley 1997).

It can be concluded that red algae represent a middle shelf environment i.e. slightly deeper water environment. Bryozoans live in normal seawater with a salinity of roughly 35ppt (Taylor 2005). The micritic matrix also confirms subtidal calm conditions of deposition. Based on biodiversity, faunal/floral paleoecology, and presence of micritic matrix, it is interpreted that MF-1 is deposited in the distal middle shelf settings (Fig. 4). This microfacies resembles SMF Type 12 of Wilson (1975) and Flügel (2004).

4.1.2 Milliolid-*Alveolina*-red algal packstone microfacies (MF-2)

4.1.2.1 Description The allochems are the dominant constituents in this microfacies, ranging up to 88% and the matrix is 12%. Allochems are predominantly composed by LBF and red algae along with bryozoans. The LBF is represented by *Discocyclina* (9%), *Nummulites* (3%), *Miscellanea miscella* (7%), *Lockhartia* (2%), *Lepidocyclina* (8%), *Ranikothalia* (5%), *Assilina* (4%), *Alveolina* (4%), Miliolid (3%), uniserial and biserial foraminifera (3%). Red algae (13%) and bryozoans (3%) are also present. Unidentified benthic foraminifera range up to 24%. Glauconite (3%) is also identified (Fig. 3g–k).

4.1.2.2 Interpretation The MF-2 shows the presence of varied fauna majorly includes LBF, bryozoans, and red algae. The LBF, in general, are mostly linked with tropical-subtropical regions in shallow marine carbonates (Hottinger 1983). The species of *Nummulites* mostly indicate shallow inner to outer ramp setting (Reiss and Hottinger 1984; Flügel 2004). *Assilina* and *Nummulites* are found in the same environment. Miliolid indicates a restricted lagoonal hypersaline marine environment (Geel 2000) and *Lepidocyclina* is common in shallow subtidal environments (Flügel 2004). *Miscellanea miscella* associated with *Lockhartia*

Table 1 The visually estimated percentages of petrographic constituents in the Dungan Formation

Thin-section #	Skeletal Allochems																Others		Glau-conite %	Total Allo-chems %	Matrix %	Grain: Matrix	Clas-sification (Dun-hum 1962)
	Benthic Foraminifera												Planktic Foraminifera										
	Disco-cyclina	Mis-cel-lanea mis-cella	Lepi-docly-clina	Num-mulites	Ran-ikothalia	Assilina	Alveo-lina	Milli-olids	Lock-artia	Unise-rial Forams	Bise-rial Forams	Bio-clasts	Morozo-villa	Sub-bot-ina	Acarin-ina	Bio-clasts	Red algae	Bryo-zoans					
18	8	7	8	5	4	5	4	4			2	21					13	3	3	87	13	7:1	Pack-stone
17	9	5	9		5	2	4	5	1	3	1	24					13	3	3	87	13	7:1	Pack-stone
16	9	6	9	2	4	1	3	4	1		3	28					12	3	3	88	12	7:3	Pack-stone
15	8	6	8	5	4	4	5	3				26					13	3	3	88	12	7:3	Pack-stone
14	8	7	8		5		4	4			4	27					13	4	3	87	13	7:1	Pack-stone
13	9	6	8	4	5	4	5	2	3	3		19					12	4	3	88	12	7:3	Pack-stone
12													19	18	16	26				79	21	4:1	Wack-stone
11													20	21	15	24				80	20	4:1	Wack-stone
10													20	19	14	25				78	22	4:1	Wack-stone
9								4	3	3		7	11	10	11	17	13	4	4	89	11	8:1	Pack-stone
8								5	2	4		6	13	12	10	15	11	5	4	87	13	7:1	Pack-stone
7			-					3	3	3		7	15	14	10	11	12	5	4	87	13	7:1	Pack-stone
6	9	6	8		5		3	4			3	29					13	4	3	88	12	7:3	Pack-stone
5	9	6	7	4	4	4	3	4	3		3	21					13	3	3	88	12	7:3	Pack-stone
4	11	5	8	4	5	5	3	3	2		2	25					12	2		88	12	7:3	Pack-stone
3	8	6	8	4	5	5	3	4	2		2	20					13	4	3	88	12	7:3	Pack-stone
2	12	8	6	5	5	4					3	27					14	3		87	13	7:1	Pack-stone
1	11	6	9	4	5	4					3	27					14	4		87	13	7:1	Pack-stone

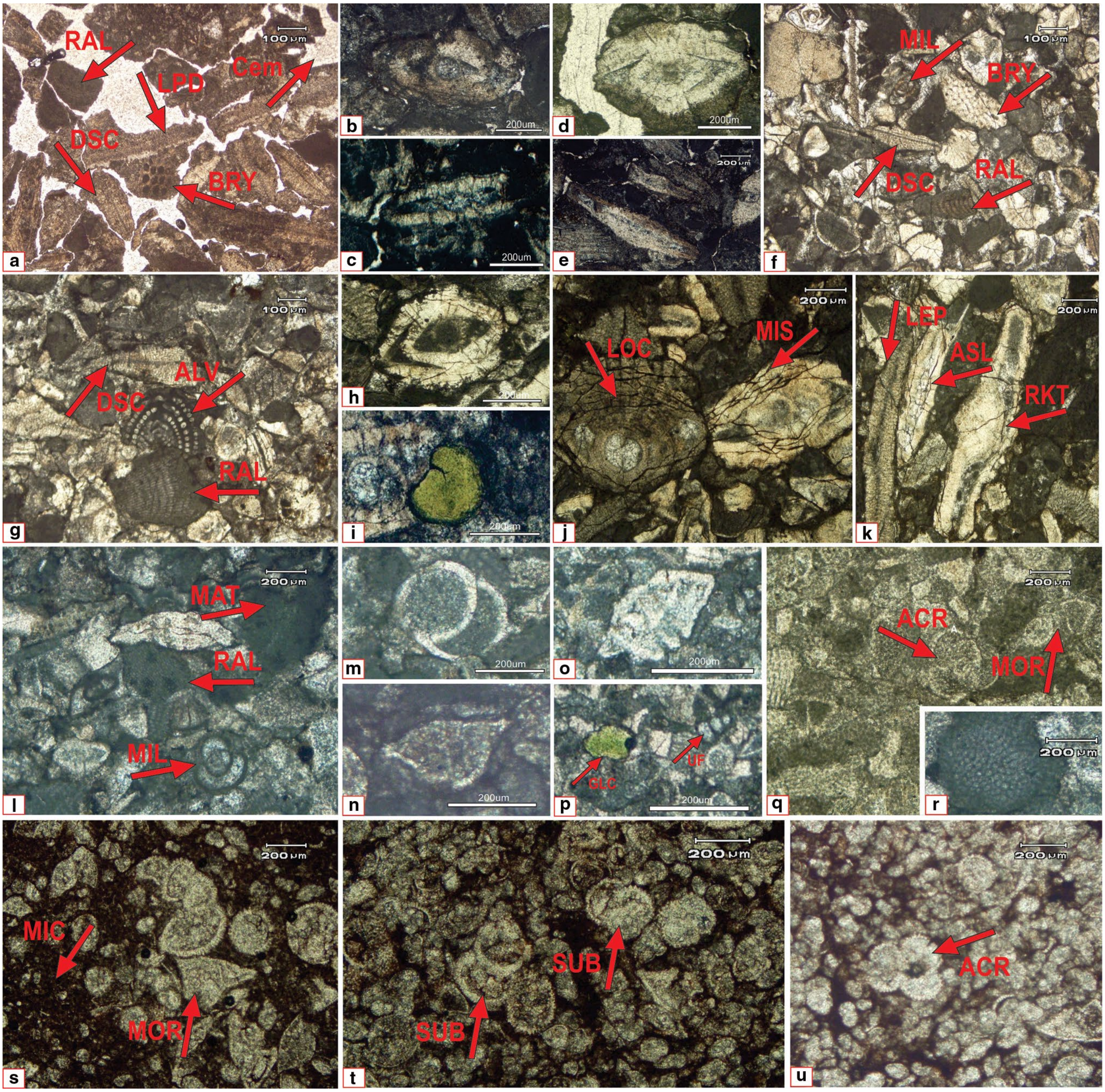

Fig. 3 Photomicrographs of the microfacies of the Dungan Formation. *Discocyclina-Nummulites*-Red algal packstone microfacies (MF-1), cementation (Cem in **a**), *Lepidocyclina* (LPD in a), *Discocyclina* (DSC in **a** and **f**), Bryozoan (BRY in **a** and **f**) and red algae (RAL in **a** and **f**), *Miscellanea miscella* in b which surrounds matrix, *Assilina* in c, *Nummulities* in d, *Ranikothalia* in e, Miliolid in f. Milliolid-*Alveolina*-Red algal packstone microfacies (MF-2), *Discocyclina* (DSC in **g**), *Alveolina* (ALV in **g**), red algae (RAL in **g**), *Nummulites* in h, Glauconite in I, *Lockhartia* (LOC in **j**), *Miscellanea miscella* (MIS in **j**), *Ranikothalia* (RKT in **k**), *Assilina* (ASL in **k**), *Lepidocyclina* (LEP in **k**). Planktonic-benthic foraminiferal packstone microfacies (MF-3), Matrix (MAT in **l**), Red algae (RAL in l), Miliolid (MIL in l), *Subbotina* in m, *Morozovella* in n, *Lockhartia* in o, Uniserial foraminifera (UF in **p**), Glauconite (GLC in **p**), *Acarinina* (ACR in **q**), *Morozovella* (MOR in **q**), Bryozoans in *r*. Planktonic foraminiferal wackestone-packstone microfacies (MF-4), *Morozovella* (MOR in **s**) and micrite matrix (MIC in **s**), *Subbotina* (SUB in **t**) and *Acarinina* (ACR in **u**)

indicates a shallow marine warm water condition (Levin 1957). *Alveolina* is in general shallow water neritic dwellers (Loeblich et al. 1964) and is found in inner shelf settings (Flügel 2004). *Ranikothalia* lives in shallow water facies (Fleury et al. 1985). *Discocyclina* is a typical fore-reef group (Henson 1950) and its paleoecology is similar to that of Nummulites (Ahmad and Pedley 1997) and it indicates a deeper water environment (Myers 1943). The distribution of

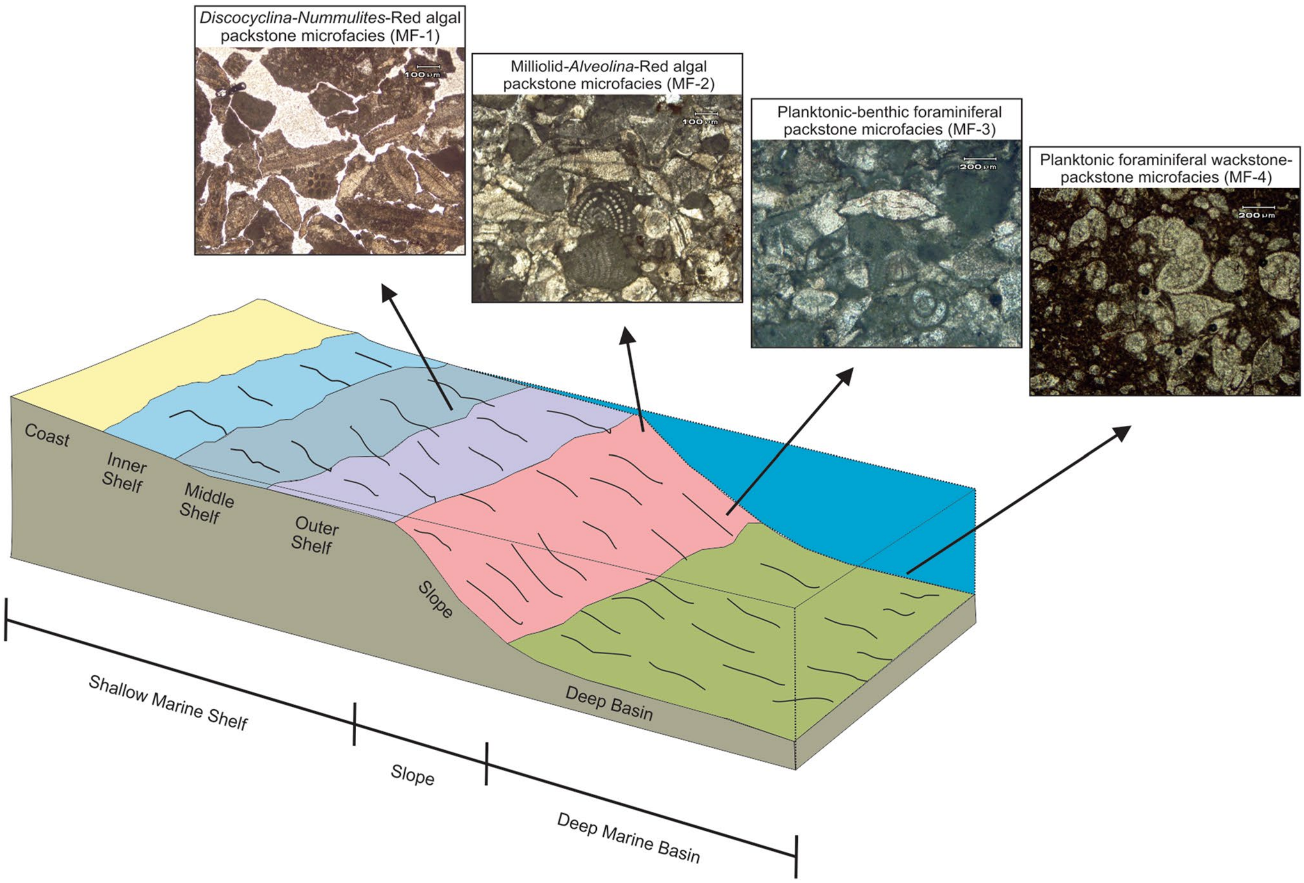

Fig. 4 Depositional model of Dungan Formation showing depositional environments of various microfacies

coralline red algae commonly occurs within the photic zone, characterized by warm water (Adey and Macintyre 1973) i.e. coralline red algae shows a slightly deeper environment. Bryozoans are abundant between the intertidal zone at about 80 m and are common constituents of modern and ancient cold water shelf carbonates (Flügel 2004). Recent bryozoans occur in continental shelves as well as in reefal settings (Cuffey 1972). Mineral glauconite is a seafloor diagenetic product formed primarily in middle to outer shelf environment (Scholle and Ulmer-Scholle 2003). The existence of drusy cement between the allochems in this microfacies also suggests high energy conditions (Flügel 2004). Benthic foraminifera assemblage mainly represents shallow depth for their survival.

Based on the paleoecology of the above-discussed fauna, it is interpreted that mixing of the shallow inner shelf and distal middle shelf fauna has occurred along with the presence of glauconite, which indicates upper slope setting for the deposition of MF 2 (Fig. 4; Racey 1995; Anketell and Mriheel 2000). A similar example of MF 2 microfacies is reported from the Middle Eocene Naranjo Formation, Coamo Springs Member, Ponce-Coamo area, Puerto Rico (Scholle and Ulmer-Scholle 2003). This microfacies can be correlated with the SMF Type-10 of Wilson (1975) and Flügel (2004).

4.1.3 Planktonic-benthic foraminiferal packstone microfacies (MF-3)

4.1.3.1 Description This microfacies is dominated by allochems that range up to 87% and the matrix is about 13%. The allochems are mainly planktonic foraminifera with some LBF along with red algae and bryozoans. The planktonic foraminifera is generally globigerinids that range up to 37% and are represented by *Morozovella* (14%), *Subbotina* (12%), and *Acarinina* (11%). LBF is represented by *Lockhartia* (2%), in addition, this microfacies also includes Milliolids (4%), uniserial foraminifera (3%), red algae (12%), bryozoans (4%) and unidentified benthic foraminifera (8%). Partial replacement of the allochems by spar and the presence of glauconite is also noted (4%) (Fig. 3l–r).

4.1.3.2 Interpretation Planktonic foraminifera indicate the deeper offshore, usually exceeding 100 m and their abundance becomes greater below 200 m depth (Walton 1964; Hunter et al. 1979). However, globigerinids can live up to a range of more than 500 m as their skeletons are resistant to dissolution processes as compared to other planktonic organisms (Parker 1971). The species of miliolids including *Quinqueloculina, Triloculina, Biloculina, Spiroloculina* have been encountered in these microfacies. The same species are reported from the Arabian Gulf in multiple lagoonal settings, representing restricted/protected lagoon to proximal inner ramp setting in hypersaline, restricted lagoonal setting (Chassefiere et al.1969; Geel 2000; Sarkar 2019). The presence of species of *Lockhartia* can be interpreted as a shallow warm water environment (Levin 1957). Coralline red algae occur in clear, slightly deeper, and warm waters (Ahmad and Pedley 1997). The distribution of red algae commonly occurs within the photic zone characterized by normal salinity (Adey and Macintyre 1973). Bryozoans live in normal seawater with a salinity of roughly 35 ppt (Taylor 2005).

Based on faunal paleoecology, the mixing of planktonic and benthic fauna has occurred. Benthic foraminifera, red algae, and bryozoans show shallower environments in comparison with planktonic foraminifera (Flügel 2004). Glauconite present is a seafloor diagenetic product formed primarily in middle to outer shelf settings (Scholle and Ulmer-Scholle 2003). The miliolid foraminifera like *Quinqueloculina, Triloculina, Biloculina, Spiroloculina* are the inhabitants of shallow shelfal lagoonal setting, the red algae, and bryozoans are the dwellers of the middle shelf while the planktonic foraminifera represents outer shelf open marine settings. The mixing of ecologically distinct fossils of inner and middle shelf affinity has occurred. Similarly, the Middle Eocene Naranjo Formation, Coamo Springs Member, Ponce-Coamo area, Puerto Rico has shown the mixing of the shallow inner shelf and distal middle shelf fauna, representing the upper slope settings (Scholle and Ulmer-Scholle 2003). Based on the above discussion and paleoecology, it is interpreted that mixing of the shallow inner shelf and distal middle shelf fauna has occurred which indicates the upper slope setting (Racey 1995; Anketell and Mriheel 2000; Fig. 4). This microfacies resembles SMF type 10 of Wilson (1975) and Flügel (2004).

4.1.4 Planktonic foraminiferal wackestone-packstone microfacies (MF-4)

4.1.4.1 Description This microfacies is dominated by allochems that range up to 79%, the rest remains the micritic matrix (21%). The allochems are planktonic foraminifera and are dominated by the globigerinids but *Morozovella* (20%), *Acarinina* (15%), *Subbotina* (19%), and unidentified planktonic foraminifera (25%) are also present. Partial replacement of the allochems by spar is common in this microfacies (Fig. 3s–u).

4.1.4.2 Interpretation Planktonic foraminifera are the dwellers of the upper 400 m column of open ocean waters and in modern marine settings they become more abundant seaward (Tucker and Wright 1990) and their greatest abundance occurs in depths greater than 200 m (Walton 1964; Hunter 1979). During normal conditions planktonic to benthic ratio increases as the water depth increases (Murray 1973; Shahin 2001). The productivity of planktonic foraminifera is higher in open pelagic waters and that of benthic foraminifera is higher in the shallow neritic environment (Van-der Zwaan 1982; Van-Morkhoven et al. 1986; Shahin 2001). Globigerinids are more resistant to the dissolution and can survive at a depth of more than 500 m (Parker 1971; Stainbank et al. 2019). The habitat of *Morozovella* and *Acarinina* is the surface mixed layer which indicated surface warmer water, however, *Subbotina* has little deeper habitat (Shackleton et al. 1985; Lu and Keller 1993, 1995; Canudo et al. 1995). The matrix of this microfacies is composed of micrite which indicates generally low energy subtidal environment below fair-weather wave base conditions (Flügel 2004).

Based on the paleoecology, presence of the micrite matrix, and the depositional texture of this microfacies, it is interpreted that this microfacies indicate deep basinal settings (Fig. 4). This microfacies resembles SMF type 3 of Wilson (1975) and Flügel (2004). Similar microfacies is reported from the Miocene Camposauro of the southern Apennines, Italy (Flügel 2004), and Lower Tertiary Amuri Limestone, Marlborough, New Zealand (Scholle and Ulmer-Scholle 2003).

4.2 Depositional model

Based on a detailed petrographic study of the Dungan Formation, it is concluded that rock unit has been deposited on the oceanic shelf to the deep basinal environment as it consists of benthic and planktonic foraminifera along with other fossils like red algae and bryozoans (Fig. 4). The *Discocyclina-Nummulites*-Red algal packstone microfacies (MF-1) has been deposited in the distal middle shelf settings. The Milliolid-*Alveolina*-Red algal packstone microfacies (MF-2) has been deposited in the upper slope environment as the mixing of shallow and deep fauna is seen. Planktonic-benthic foraminiferal packstone microfacies (MF-3) has been deposited in the lower slope environment as benthic and planktonic fossils are seen together. Planktonic foraminiferal wacke-packstone microfacies (MF-4) has been deposited in the deep basinal setting as this microfacies is dominated by entirely planktonic foraminifera. The environments of deposition of each of the above mentioned four microfacies of Dungan Formation are shown in the depositional model (Fig. 4). The principal components i.e. planktonic foraminifera, benthic foraminifera, and red algae have been analyzed (Fig. 5). The occurrence of planktonic foraminifera is associated with wackestone while it is rare or absent in the packstone microfacies. Likewise, the benthic foraminifera and red algae are recorded in the packstone microfacies and are completely absent in the wackestone microfacies. The association of these faunas/floras with different microfacies also gives clues of variation in depositional environments from mid-shelf to deeper slope conditions during the deposition of Dungan Formation.

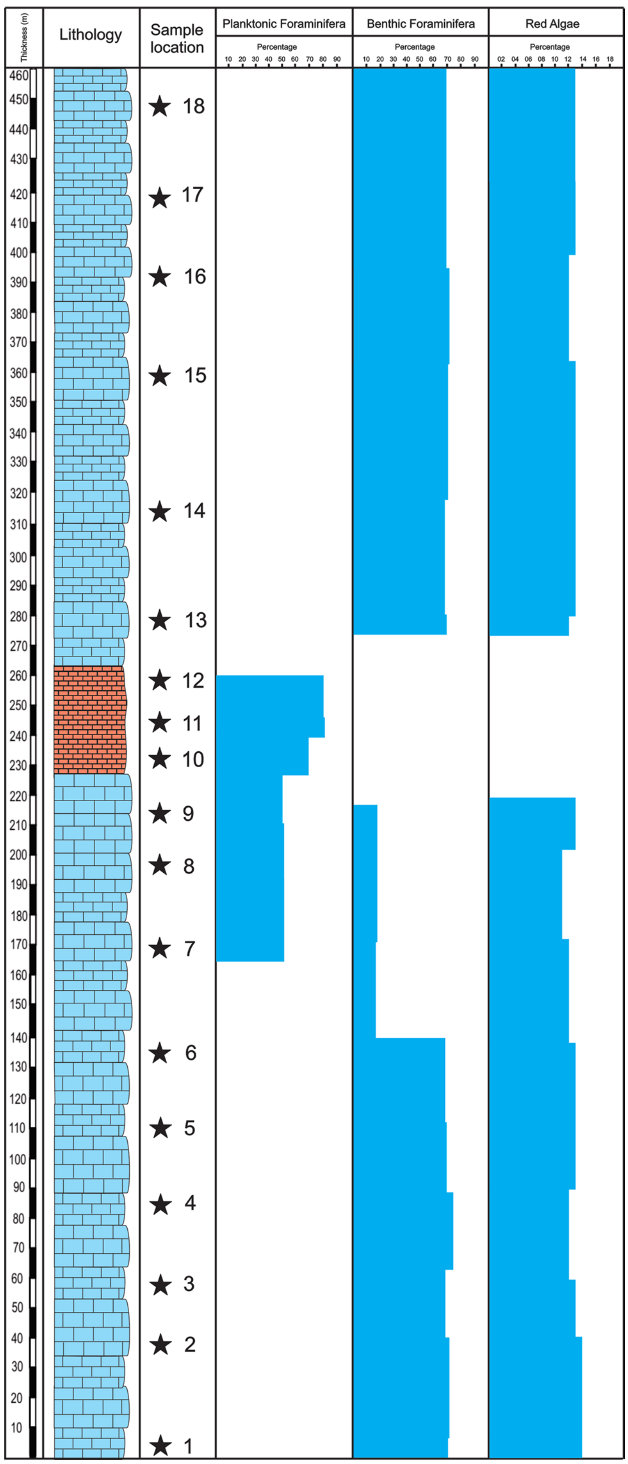

Fig. 5 The distribution of principal components (planktonic foraminifera, benthic foraminifera, and red algae) in the vertical section of Dungan Formation

4.3 Diagenesis

The Dungan Formation underwent diagenesis which obliterated its original components and texture since the time of their initial deposition. This section deals with the diagenetic features and processes of the Dungan Formation that has affected the evolution of the porosity of the rock unit.

4.3.1 Micritization

The micritization has been observed in all the microfacies of the Dungan Formation (Fig. 6a, b). At places, the whole grain is micritized while at other, partial micritization has developed micritic envelopes. The boring and burrowing of skeletons are caused by encrusting algae and boring organisms and are later on filled by fine micrite producing a layer of micrite around the grains (Wadood et al. 2019). These envelopes not only define but also preserve the outline and morphology of the carbonate grains over which it has developed. A micrite envelope has been identified within all the microfacies of the Dungan Formation (Fig. 6a, b).

4.3.2 Cementation

The cementation has been identified within Milliolid-*Alveolina*-Red algal packstone microfacies (MF-2; Fig. 6c, d) and not seen in other microfacies. The most dominant type of cementation includes drusy mosaic cement which records burial and near-surface meteoric environments (see e.g. Flügel 2004).

4.3.3 Dissolution

Dissolution is the process in which leaching of unstable or metastable minerals takes place that forms secondary pores, vugs, or caverns (Scholle and Ulmer-Scholle 2003). The dissolution has been recognized in mixed Milliolid-*Alveolina*-Red algal packstone microfacies (MF-2), however, the rest of microfacies are devoid of dissolution activities (Fig. 6e, f). The dissolution is particularly effective in shallow near-surface meteoric environments, but can also take place in deep burial and cold waters (Steinsund and Hald 1994) as well in the deep sea (Berelson et al. 1994). This may occur soon after deposition or later on when limestone is uplifted to the surface conditions (Tucker and Wright 1990). It has a direct relation to the development of porosity in the rock unit (Ahmad and Hudson 2000).

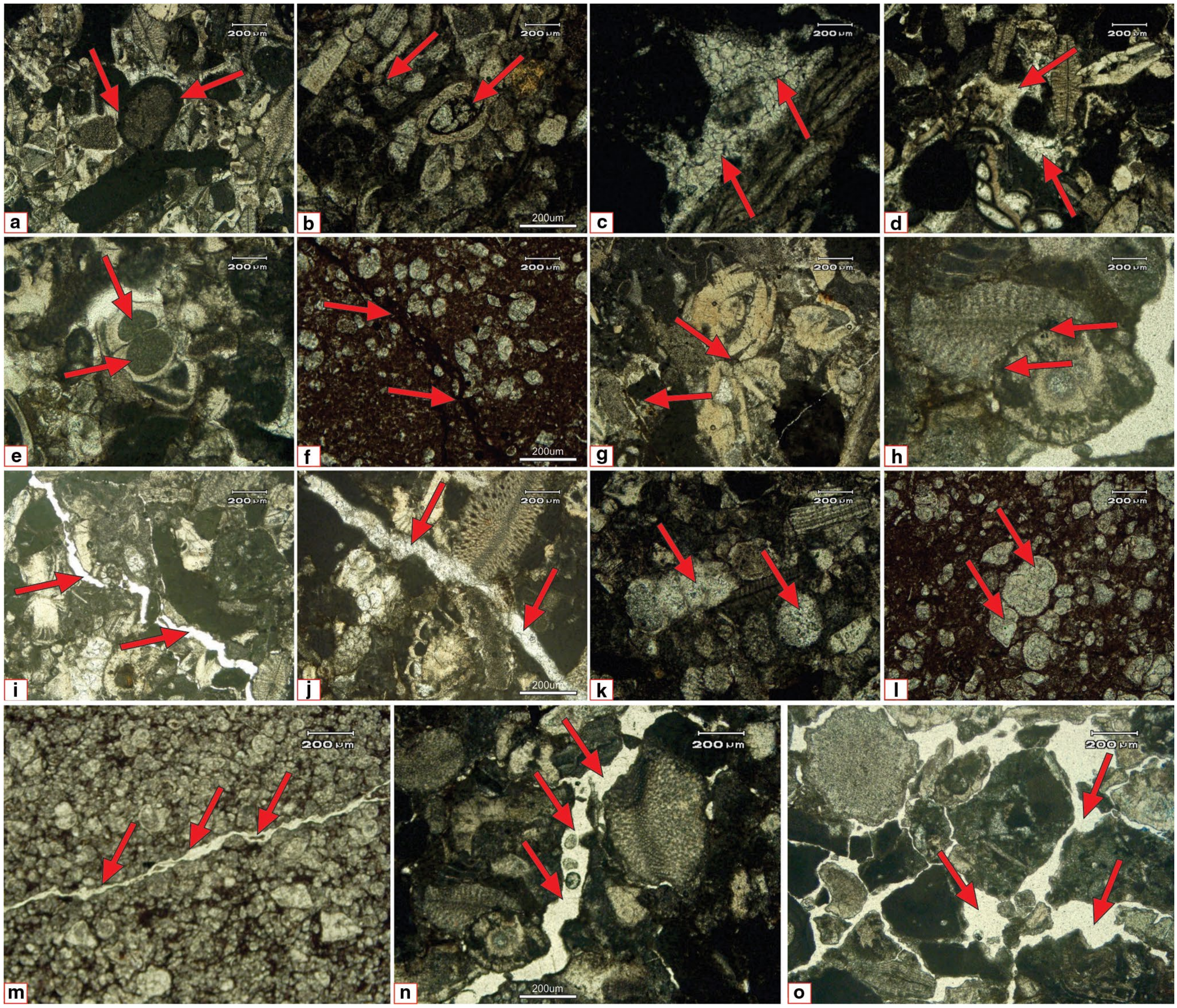

Fig. 6 Diagenetic features and porosities in Dungan Formation. Micrite envelops in **a,** micritization in **b,** drusy mosaic cementation in **c,** cementation in **d,** dissolution in **e** and **f**, mechanical compaction in **g**, chemical compaction **h**, fractures in **i**, calcite filled fractures in **j**, neomorphism in **k** and **l**, fracture porosity in **m** and **n**, interparticle porosity in **o**

4.3.4 Compaction

The compaction has been recognized only in the Milliolid-*Alveolina*-Red algal packstone microfacies (MF-2) (Fig. 6g). The sediment overburden results in a general reduction of porosity, sediment thickness, and rock volume, and therefore the mechanical failure of grains occurs. It is inhibited by early cementation. The mechanical compaction eventually can continue to chemical compaction if the grains begin to dissolve at their contacts (Flügel 2004). The mechanical compaction begins soon after deposition (Tucker and Wright 1990). Mechanical processes decrease the bulk volume of single grains (grain deformation) or cause closer packing of grains i.e. reorientation (Budd 2002). Likewise, chemical compaction is also pronounced in the rock unit. The chemical compaction has been identified in red *Discocyclina-Nummulites*-Red algal packstone microfacies (MF-1), Milliolid-*Alveolina*-Red algal packstone microfacies (MF-2), and Planktonic-benthic foraminiferal packstone microfacies (MF-3) (Fig. 6h). The chemical compaction involves a strong reduction in rock bulk volume and cement minerals (Budd 2002). The stylolites have often a zigzag form due to differences in the solubility of different components. It often cross-cut the whole rock, intersecting grains, matrix, and cement. The insoluble material usually clay or hydrocarbons concentrate along the stylolites surface (Flügel 2004) The stylolites formation requires increased overburden pressure or undersaturated fluid (Becher and Moore 1976).

4.3.5 Fracturing

The fracturing is a common phenomenon in carbonate rocks and it marks the late diagenetic events (Scholle and Ulmer-Scholle 2003). In Dungan Formation, the sparry calcite has occluded fractures (Fig. 6j) while some of the fractures are open and devoid of cement filling (Fig. 6i). Fractures occur as a product of tectonic stresses and solution slump in the post-depositional history of the rock. Fracturing enhances the porosity and permeability of the rocks. Fracturing has been recognized in *Discocyclina-Nummulites*-Red algal packstone microfacies (MF-1), Milliolid-*Alveolina*-Red algal packstone microfacies (MF-2), and planktonic foraminiferal wackestone-packstone microfacies (MF-4). However, it is absent in Planktonic-benthic foraminiferal packstone microfacies (MF-3).

4.3.6 Neomorphism

The neomorphism includes processes of replacement, inversion, and recrystallization (Folk 1965). It leads to crystal enlargement or diminution (Flügel 2004). Mostly limestones undergo an aggrading type of neomorphism that is leading to a general increase in crystal size. The opposite process i.e. degrading neomorphism is not common (Tucker and Wright 1990). The neomorphism takes place in meteoric (Heckle 1983) as well as in the subsurface diagenetic environment (Boggs 2014). It has been identified in all the microfacies and it is of aggrading type (Fig. 6k, l).

4.4 Diagenetic history

The carbonates of Dungan Formation have undergone three stages of diagenesis i.e. Marine diagenesis, Burial diagenesis, and Uplift/Unroofing (Fig. 7).

4.4.1 Marine diagenesis

The marine diagenesis takes place on the seafloor and just below it. The initial period of diagenesis operates on the seafloor and may occur in the meteoric realm (Boggs 2014). The presence of LBF, red algae, and bryozoans show deposition of carbonates of the Dungan Formation in the shallow marine environment. The seafloor diagenesis is characterized by the micritization of grains and the precipitation of cement (Tucker and Wright 1990). The first stage of diagenesis identified in sediments of the Dungan Formation after its deposition in the marine environment is micritization as most carbonates are deposited in the marine environment. The cementation process is favored by a low sedimentation rate and high water input. The marine diagenesis is characterized by a specific diagenetic fabric, including bored grains, cement infilled bores, and formation of the micritic envelope.

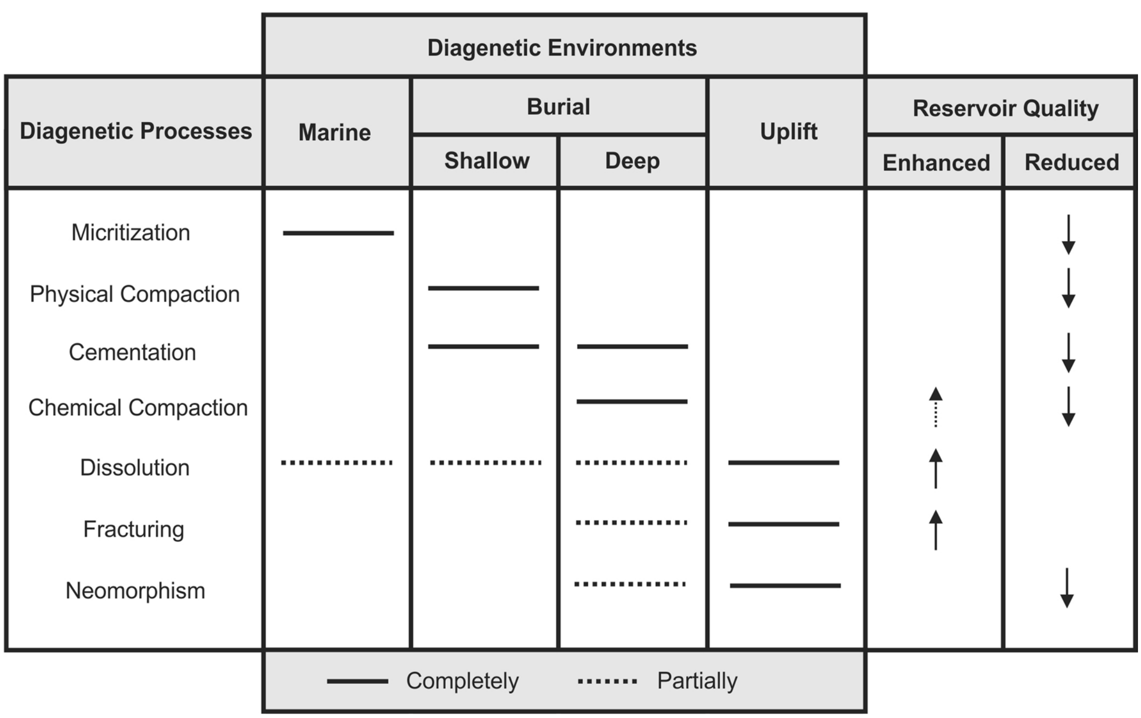

Fig. 7 The different diagenetic features and their effect on reservoir quality of the carbonates of Dungan Formation

4.4.2 Burial diagenesis

As the sediments of the Dungan Formation confronted an initial period of diagenesis on the seafloor, these sediments were gradually buried and subjected to increased pressure, higher temperature, and compositionally changed pore fluid in the subsurface realm. The burial diagenesis refers to the alteration below the zone of near-surface water circulation (Scholle and Ulmer-Scholle 2003). Characteristic diagenetic fabrics under these conditions comprised mostly of porosity reduction, burial related mechanical compaction features (closer grain packing, brittle grain deformation, and fracturing) and chemical compaction features (stylolites formation, sutured boundaries between grains and pressure solution structures). The porosity reduction is caused due to processes related to compaction (Flügel 2004). The neomorphism particularly occurs in meteoric (Heckle 1983) as well as in the subsurface diagenetic environment (Boggs 2014). As the sediments get buried, the pressure of overlying sediments causes grain reorientation and tighter packing (Boggs 2014). The physical compaction is relatively shallower than chemical compaction. The sediments are affected by mechanical compaction and due to sustained burial caused chemical compaction. The cement morphology includes bladed, granular, drusy, blocky, and equant calcite mosaic and drusy calcite cement (Tucker and Wright 1990).

In the *Discocyclina*-*Nummulites*-Red algal packstone microfacies (MF-1) the burial diagenesis is identified by the presence of chemical compaction and open fractures. In the Milliolid-*Alveolina*-Red algal packstone microfacies (MF-2) burial diagenesis has been identified by the presence of chemical compaction, mechanical compaction, open fractures, and drusy type of cementation. In the Planktonic-benthic foraminiferal packstone microfacies (MF-3), chemical compaction and microstylolites show the burial stage of diagenesis. In the planktonic foraminiferal wackestone-packstone microfacies (MF-4) open fractures and dissolution seams have been identified which show the burial phase of diagenesis.

4.4.3 Uplift and unroofing

Three major processes operate during this phase of diagenesis, i.e. dissolution, precipitation (cementation), and mineralogical transformation. In addition, limestones may be uplifted and exposed at the earth's surface many millions of years after deposition and then subjected to meteoric diagenesis (Tucker and Wright 1990). The dissolution of unstable carbonate minerals (aragonite and high magnesium calcite) followed by precipitation of more stable carbonates (low magnesium calcite) take place here. Therefore, primary porosity is lost and secondary porosity is generated during meteoric diagenesis (Scholle and Ulmer-Scholle 2003).

This phase of diagenesis took place in the sediments of the Dungan Formation near-surface meteoric environment. The indication of this phase of meteoric diagenesis is aggrading neomorphism, calcite filled fractures, and dissolution. The aggrading neomorphism is observed in the *Discocyclina-Nummulites*-Red algal packstone microfacies (MF-1), Milliolid-*Alveolina*-Red algal packstone microfacies (MF-2), Planktonic-benthic foraminiferal packstone microfacies (MF-3) and planktonic foraminiferal wackestone-packstone microfacies (MF-4). The calcite filled fractures are identified in the Milliolid-*Alveolina*-Red algal packstone microfacies (MF-2) and planktonic foraminiferal wackestone-packstone microfacies (MF-4). Dissolution is seen only in Milliolid-*Alveolina*-Red algal packstone microfacies (MF-2).

4.5 Diagenetic controls on reservoir quality

The diagenetic modifications in the Paleocene to Early Eocene Dungan Formation have overall altered the original primary porosity and permeability (Fig. 7). The rock unit has pronounced dissolved cavities and fractures that might have enhanced the reservoir potential of the strata. The dissolution phenomenon is restricted to the Milliolid-*Alveolina*-Red algal packstone microfacies. Likewise, fractures have been identified; however, most of the fractures are occupied by calcitic cement thereby adversely affecting the reservoir quality. At places, open fractures have been recognized in the *Discocyclina-Nummulites*-Red algal packstone microfacies (MF-1), mixed Milliolid-*Alveolina*-Red algal packstone microfacies (MF-2) and planktonic foraminiferal wackestone-packstone microfacies (MF-4) (Fig. 6m, n) while the Planktonic-benthic foraminiferal packstone microfacies (MF-3) is devoid of fractures; thus added to the overall porosity of the rock unit. At places, inter-particle porosity has been observed (Fig. 6o). In addition, micritization, neomorphism, cementation, and compaction reduce the reservoir quality thereby making carbonates of the Dungan Formation a poor reservoir facies (Fig. 7). The micritization can be seen in all microfacies and has mostly occurred at the margins of allochems which can reduce permeability (see e.g. Taghavi et al. 2006). In most of the places, the porous skeletal grains are also occupied by micrite and has weakened the porosity reservoir quality (Wadood et al. 2019; Ahmad et al. 2020). The cementation, an important diagenetic process (Wilson and Stanton 1994) is most prominent in the Milliolid-*Alveolina*-Red algal packstone microfacies (MF-2). It has cemented the micropores and inter/intragranular porosity. Overall, the diagenetic processes have greatly reshaped the porosity and permeability of the rock unit. The visual estimated results of the reservoir potential of the Dungan Formation are further augmented by the published quantitative plug porosity and permeability data (Table 2).

Table 2 The visually estimated percentages and plug porosity/permeability analyses of the Dungan Formation

Sample #	Intergranular	Intragranular	Fracture	Moldaic	Visual Porosity	Permeability Description	Plug Porosity and Permeability	
							Porosity (%)	Permeability (Ka mD)
01	A	A	R	A	P	L	0.20	0.00
03	A	A	R	A	P	L	0.14	0.00
06	A	A	R	A	P	L	0.59	0.00
09	A	A	R	R	P	L	0.28	0.00
13	R	A	R	R	P	M	0.99	0.00
16	C	A	R	C	M	M	1.45	0.00
18	C	A	C	R	M	M	2.18	0.00

A Absent, *R* Rare, *C* Common, *P* Poor, *M* Moderate, *L* Low, *%* Percentage, *mD* Millidarcy

The quantitative analyses show that carbonates of the Dungan Formation posses' porosity range from 0.17 to 2.23% with no permeability, which suggests the poor-moderate reservoir.

4.6 Sequence stratigraphy

The sequence stratigraphic analysis refers to a sedimentary response to sea-level changes and the recognition of depositional sequences that emerge from these changes (Haq et al. 1987). The sequence stratigraphy is the subdivision of sedimentary basin fills into genetic packages bounded by unconformities and their correlative conformities (Emery and Myers 2009) and is primarily concerned with the description of unconformity bounded packages of strata termed sequences, and with the understanding of the geologic controls which drives the deposition of sequences, especially concerning changing sea levels (Carter 1998). The sequence stratigraphy aims to divide the rock history into sequences and system tracts which delineates the distribution of rocks in space and time (Emery and Myers 2009). The sequence stratigraphy of the unit is established using Embry and Johannessen's (1992) model.

According to Afzal et al. (2011), the Dungan Formation contains shallow benthic zones SBZ1 to SBZ9 and overall it covers the period from 63 to 53 million years which equates with planktonic foraminifera zones P1c up to E4 of Berggren and Pearson (2005) zonal scheme. The *Miscellanea miscella* ranges from SBZ4 to SBZ5 (Serra-Kiel et al. 1998). The Paleocene assemblages are dominated by Miscellanids, Ranikothalids, and *Assilina* while index fossils for the lower Eocene are *Alveolina* and *Nummulites* which appear within SBZ5 and younger (Scheibner and Speijer 2009). Based on these observations it is concluded that the age of Dungan Formation is Paleocene (Middle Danian to Thanetian, 63–55.5 Ma) to Early Eocene (Ypresian 53 Ma). Numerical ages are assigned according to Haq et al. (1987) and Berggren and Pearson (2005). The total time span from the Middle Danian to the Ypresian stage is 10 Ma. Hence it is concluded that the Dungan Formation was deposited during the time span of 10 Ma which falls in the duration of second-order (3–50 Ma) of cyclicity (Fig. 8; Haq et al. 1987).

4.6.1 Systems tracts in Dungan Formation

Following the sequence depositional model of Embry and Johannessen (1992) two types of systems tracts have been identified in the Dungan Formation (Fig. 8). These are Transgressive Systems Tracts and Regressive Systems Tracts.

4.6.1.1 Transgressive systems tract (TST) In Dungan Formation, TST is comprised of four microfacies up section, which are *Discocyclina-Nummulites*-Red algal packstone microfacies (MF-1), Milliolid-*Alveolina*-Red algal packstone microfacies (MF-2), Planktonic-benthic foraminiferal packstone microfacies (MF-3), and planktonic foraminiferal wackestone-packstone microfacies (MF-4). Deposition during this cycle is spanning from Danian to Selandian (Fig. 8). The MF-1 has been interpreted to be deposited in the distal middle shelf, MF-2, and MF-3 both in the slope environment while MF-4 occurs in deep basinal settings. MF-1 and MF-2 microfacies are comprised of LBF and red algae, preceded by MF-3 containing a mixed LBF and planktonic foraminifera (Fig. 8). The MF-3 is overlain by MF-4 which entirely consists of planktonic foraminifera (Fig. 8) the vertical succession of microfacies shows deepening upward facies trend in fossils i.e. deep marine fossil assemblages upon shallow ones. The peak transgression is marked by MF-4 because of the presence of planktonic foraminifera, which is the climax of deep marine conditions, and from

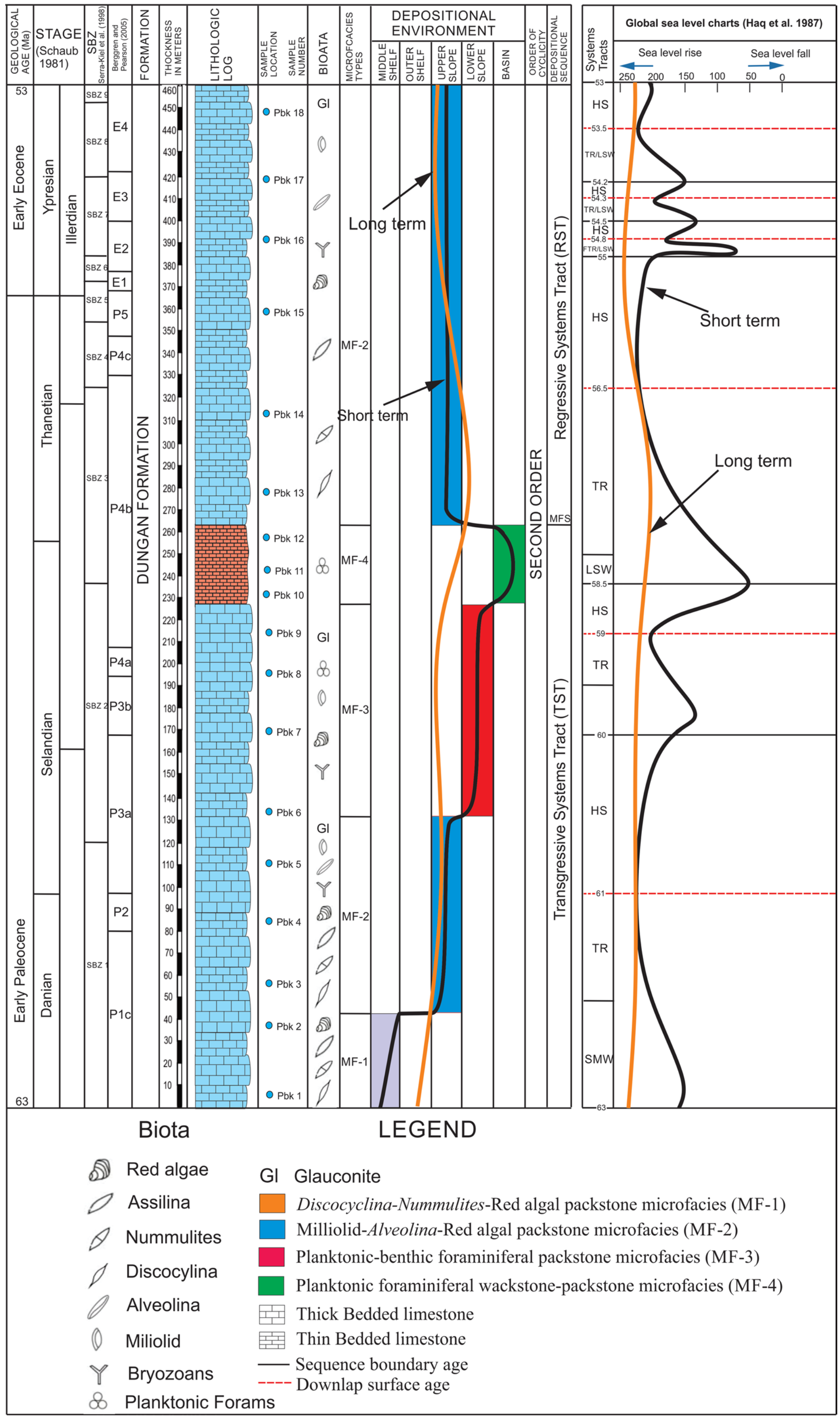

Fig. 8 Lithological log, biota, depositional environments, sequence stratigraphy, and comparison of global sea level charts with the relative sea-level curve of Paleocene to Early Eocene Dungan Formation

this point onwards decline in sea level rise is seen. The TST has a total thickness of 260 m (Fig. 8).

The maximum flooding surface (MFS) marks a change from a deepening-upward trend to a shallowing-upward (Embry 2002) and represents the maximum landward extent of open marine planktonic foraminifera and deeper water benthic foraminifera (Loutit et al. 1988; Allen et al. 1991; Armentrout and Clement 1991; Armentrout et al. 1991). Paleontologically the maximum flooding surface is recognized by the presence of more diverse open marine planktonic foraminifera and possible deeper water benthic fauna and sedimentologically the MFS can be recognized as the surface between a retrograding unit and an overlying prograding unit (Emery and Myers 2009). In Dungan Formation, the top of planktonic foraminiferal wackestone-packstone microfacies (MF-4) contains abundant planktonic foraminifera and shows deep basinal settings and mark the maximum flooding surface (MFS) on the top of TST (Fig. 8).

4.6.1.2 Regressive systems tract (RST) In Dungan Formation, the repetition of the Milliolid-*Alveolina*-Red algal packstone microfacies MF-2 (deposited in slope environment) in the upper portion of the sequence after the MFS, shows regressive systems tract (RST) (Fig. 8). As MF-2 overlies the MF-4 i.e. basinal facies are overlain by slope facies, it shows shallowing upward facies trend or regression. Deposition during this cycle is spanning from Thanetian to Early Ypresian (Fig. 8). The RST has a total thickness of 200 m (Fig. 8).

4.6.2 Relative and Eustatic Sea level comparison

The relative sea-level changes represent variation in the distance between sea level and the local datum (Embry 2002). These changes take place due to tectonics and eustasy. Tectonism results in the downward and upward movement of local datum i.e. subsidence and uplift respectively, consequently sea level rises due to subsidence and falls due to uplift. Assigning relative age to a stratigraphic unit under study is crucial for comparison with the chronology of eustatic sea-level fluctuations. The age of the Dungan Formation is Paleocene to Early Eocene and its magnitude is 10 Ma marking cyclicity of second-order (Haq et al. 1987). The sea-level curve of the Dungan Formation is constructed from the recognition of its microfacies types and their inferred depositional settings (Fig. 8).

In the long term, the sea-level curve of the Dungan Formation shows overall one episode of sea-level rise of second-order, depositing transgressive systems tract and deposition during this cycle is spanning from Danian to Selandian stage. Starting from Danian up to Selandian there is a gradual sea-level rise and from Thanetian onwards up to Early Ypresian, there is a drastic fall in sea level rise (Fig. 8). The Haq et al. (1987) global sea-level curve, in the long term, shows that a gradual decline of sea level began in the latest Cretaceous and continued throughout the Cenozoic. With the exception of relatively higher levels in the Danian, Ypresian, Rupelian, Langhian through early Serravallian and Zancian, this trend toward lower sea levels continues to the present time (Haq et al. 1987). Hence it is concluded that the long term sea-level changes observed in the Dungan Formation resemble long term sea-level changes in Haq et al. (1987) curve.

In short term, the sea-level curve of the Dungan Formation displays two episodes of sea-level rise and one episode of fall of third-order cyclicity which deposited TST and RST (Fig. 8) while on a short term basis in the Haq et al. (1987) sea-level curve, there are six episodes of the rise and seven episodes of fall, spanning from Danian up to Early Ypresian (Fig. 8). The major sea-level falls occurred at early Thanetian and latest Ypresian and throughout the late Pliocene–Pleistocene interval. This difference in the short term basis between the sea-level curve of the Dungan Formation and that of Haq et al. (1987) may be ascribed to local tectonic variations (Hubbard 1988).

The Indus Basin of Pakistan has preserved the signs of intense tectonics during the Mesozoic and Cenozoic era (Kazmi and Jan 1997). Such tectonic disturbance may greatly influence the deposition of sediments in cycles due to local fluctuation in sea level (Emery and Myers 2009). Furthermore, it caused the diachroneity in the closure of Seaway in the northern and southern Pakistan (Wadood et al. 2020). The tectonic influenced sedimentary depositional fluctuations can be observed in the Paleocene carbonate sediments (Lockart Formation) of the Upper Indus Basin and its correlative part (Dungan Formation) in the Lower Indus Basin (Hanif et al. 2014). The carbonate platform in the Upper Indus Basin during the Paleocene represents tectonically effected depositional lows in the western Kohat area, which is surrounded by depositional highs in the western and central Salt Range area (Afzal et al. 2011). Such depositional highs/lows have caused variation in the deposition of Lockart carbonates throughout the Upper Indus Basin (Hanif et al. 2014). The Lockart Formation is equivalent to the Dungan Formation of Lower Indus Basin (Hanif et al. 2014). The Dungan Formation also posses variation in lithology throughout the basin (Rahman et al. 2018). Carbonates of the Dungan Formation show an open marine depositional environment based on an abundance of planktonic foraminifera in the Sulaiman Range (Waraich 2000). However, the present study shows mid-shelf to slope conditions for deposition of the rock strata and thus witnesses variation in the basin. The transitional from Cretaceous to Paleocene in Lower Indus Basin is marked by diverse lithologies during late Cretaceous (Shah 2009). In the Mughal Kot Section of Sulaiman Range, this transition is marked by the transition from deltaic late Cretaceous sediments (Pab Formation) to carbonate of Dungan Formation (Khan 2013). However, in the Rakhi Nala Section of the Sulaiman Range, this transition is characterized by shallow carbonates equivalent to late Cretaceous Pab Formation (Umer et al. 2011). Further south in the vicinity of Quetta, the transition is marked by late Cretaceous agglomerates of Bibai Formation (Shah 2009). In short, the pronounced variations in thickness and facies of Paleocene carbonates of the Dungan Formation and its equivalent in the Upper Indus Basin suggest a strong tectonic influence on the Paleocene carbonate platform sediments of the Dungan Formation. The effect of tectonic is further augmented by the pronounced facies variations in late Cretaceous at the lower contact of the Dungan Formation. During the stage of deposition of the Dungan Formation, the northwestern margins of Indian Plate have experienced a phase of ophiolitic obduction initiated by the collision of the Island arc (Khan et al. 2009). Such ophiolitic obduction might have caused the deepening of the shelf basin consequently received more clastic input (Hinsch et al. 2019). Moreover, during this period the northwestern margins of Indian Plate have also experienced anomalous quiescent phases, preserved in the form of widespread deposition of the Dungan Formation with the occasional change in the depositional environment in the Sulaiman and Kirthar Provinces (Hinsch et al. 2019). Therefore, the short term sea-level curve of Haq et al. (1987) is quite dissimilar with the existing curve of the Dungan Formation in the study area.

5 Conclusions

The Dungan Formation in the study area is 460 m thick and is entirely composed of limestone which is maroon to dark grey characterized by thin to massive bedding. It is highly fossiliferous and its microfacies contain skeletal allochems which include LBF, planktonic foraminifera, red algae, and bryozoans. In the study area, the identified biota include LBF, are represented by *Discocyclina, Miscellanea miscella, Lepidocyclina, Nummulites, Ranikothalia, Assilina, Alveolina, Miliolid,* and *Lockhartia.* We have identified four microfacies within the Dungan Formation. These microfacies are *Discocyclina-Nummulites*-Red algal packstone microfacies (MF-1), Milliolid-*Alveolina*-Red algal packstone microfacies (MF-2), Planktonic-benthic foraminiferal packstone microfacies (MF-3), Planktonic foraminiferal wackestone-packstone microfacies (MF-4), and their interpreted environment of deposition are distal middle shelf, upper slope, lower slope, and deep marine basinal environment respectively. Different diagenetic features include micritization, dissolution, neomorphism, compaction, cementation, fractures have been identified and based on these features it is concluded that the Dungan Formation underwent diagenesis under marine, meteoric and burial conditions. The diagenetic alterations have modified the carbonates of Dungan Formation, making a poor-moderate reservoir. This interpretation is further supported by the plug porosity and permeability analyses. The presence of age diagnostic LBF like *Miscellanea miscella*, *Ranikothalia, Alveolina,* and *Nummulites* determines the age of the Dungan Formation as Paleocene-Early Eocene and determines second-order cyclicity which marks one episode of sea-level rise which in turn deposited TST and RST of third-order cyclicity. In the vertical succession, the microfacies are lying as MF-1 at the base and MF-4 at the top. The repetition of MF-2 in the vertical succession shows a shallowing upward trend in fossils. Comparison of the relative sea-level curve of Dungan Formation with the global sea-level curve demonstrates that long term sea-level fluctuations show uniformity while the short term differences in these two curves are due to local tectonics.

Acknowledgement Authors are thankful to the Department of Geology, University of Peshawar, Pakistan for providing laboratory facilities to carry out microscopic studies.

Funding Not applicable.

Availability of data and material The data used in this manuscript can be obtained from the corresponding author upon reasonable request.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Adey, W. H., & Macintyre, I. (1973). Crustose coralline algae: a re-evaluation in the geological sciences. *Geological Society of America Bulletin, 84*(3), 883–904.

Afzal, J., Williams, M., Leng, M. J., Aldridge, R. J., & Stephenson, M. H. (2011). Evolution of Paleocene to Early Eocene larger benthic foraminifer assemblages of the Indus Basin, Pakistan. *Lethaia, 44*(3), 299–320.

Aḥmad, Nī. (1996). *Palaeoenvironments, diagenesis, and geochemical studies of the Dungan Formation (Palaeocene), eastern Sulaiman Range*. Leicester: University of Leicester.

Ahmad, N., & Ahmad, S. (2001). Petrography of the dungan formation eastern sulaiman range, Pakistan. *Geological Bulletin Punjab University, 36*, 1–16.

Ahmad, N., & Hudson, J. (2000). Diagenetic environments of the Dungan Formation, eastern Sulaiman Range, Pakistan. *Geological Bulletin of the Punjab University, 35*, 21–36.

Ahmad, N., & Pedley, H. M. (1997). Facies and Paleo-environments of the Dungan Formation, Eastern Sulaiman Range, Pakistan. *Geological Bulletin University of Punjab*, 31–32.

Ahmad, S., Wadood, B., Khan, S., Ahmed, S., Ali, F., & Saboor, A. (2020). Integrating the palynostratigraphy, petrography, X-ray diffraction and scanning electron microscopy data for evaluating hydrocarbon reservoir potential of Jurassic rocks in the Kala Chitta Range, Northwest Pakistan. *Journal of Petroleum Exploration and Production Technology*. https://doi.org/10.1007/s13202-020-00957-7.

Ahmed, R., & Ali, S. M. (1991). Tectonic and structural development of the eastern part of Kirthar Fold Belt and its hydrocarbon prospects. *Pakistan Journal of Hydrocarbon Research, 3*(2), 19–31.

Allemann, F. (1979). *Time of emplacement of the Zhob Valley ophiolites and Bela ophiolites, Baluchistan (preliminary report)* (pp. 215–242). Quetta: Geodynamics of Pakistan. Geological Survey of Pakistan.

Allen, S., Coterill, K., Eisner, P., Perez-Cruz, G., Wornardt, W., & Vail, P. Micropaleontology, well log and seismic sequence stratigraphy of the Plio-Pleistocene depositional sequences—offshore Texas. In *Sequence Stratigraphy as an Exploration Tool: Concepts and Practices, Eleventh Annual Conference, June, 1991* (pp. 2–5)

Anketell, J., & Mriheel, I. (2000). Depositional environment and diagenesis of the Eocene Jdeir Formation, Gabes-Tripoli basin, Western Offshore, Libya. *Journal of Petroleum Geology, 23*(4), 425–447.

Anwar, M. (1991). Revised nomenclature and stratigraphy of Ferozabad, Alozai and Mona Jhal Groups of Balochistan (Axial Belt) Pakistan. *Acta Mineral. Pakistan, 5*, 46–61.

Arkell, W. (1956). *Jurassic geology of the world:Oliver and Boyd Ltd*. London: Edinburgh.

Armentrout, J., & Clement, J. Biostratigraphic calibration of depositional cycles: a case study in High Island-Galveston-East Breaks areas, offshore Texas. In *Gulf Coast Section SEPM 11th Annual Research Conference, 1990* (pp. 21–51)

Armentrout, J. M., Echols, R. J., & Lee, T. D. (1991). Patterns of foraminiferal abundance and diversity: implications for sequence stratigraphic analysis. *AAPG Bulletin (American Association of Petroleum Geologists);(United States), 75*(CONF-910403).

Banks, C., & Warburton, J. (1986). 'Passive-roof'duplex geometry in the frontal structures of the Kirthar and Sulaiman mountain belts, Pakistan. *Journal of structural Geology, 8*(3–4), 229–237.

Becher, J. W., & Moore, C. H. (1976). The Walker Creek Field: a Smackover diagenetic trap. *Transactions of Gulf Coast Association of Geological Societies*, *26*, 34–56.

Berelson, W. M., Hammond, D. E., McManus, J., & Kilgore, T. E. (1994). Dissolution kinetics of calcium carbonate in equatorial Pacific sediments. *Global Biogeochemical Cycles, 8*(2), 219–235.

Berggren, W. A., & Pearson, P. N. (2005). A revised tropical to subtropical Paleogene planktonic foraminiferal zonation. *The Journal of Foraminiferal Research, 35*(4), 279–298.

Boggs, S, Jr. (2014). *Principles of sedimentology and stratigraphy*. London, UK: Pearson Education.

Budd, D. A. (2002). The relative roles of compaction and early cementation in the destruction of permeability in carbonate grainstones: a case study from the Paleogene of west-central Florida, USA. *Journal of Sedimentary Research*, *72*(1), 116–128.

Canudo, J., Keller, G., Molina, E., & Ortiz, N. (1995). Planktic foraminiferal turnover and δ13C isotopes across the Paleocene-Eocene transition at Caravaca and Zumaya, Spain. *Palaeogeography, Palaeoclimatology, Palaeoecology, 114*(1), 75–100.

Carozzi, A. V. (1988). *Carbonate rock depositional models: A microfacies approach*. Englewood Cliffs: Prentice Hall.

Carter, R. M. (1998). Two models: global sea-level change and sequence stratigraphic architecture. *Sedimentary Geology, 122*(1–4), 23–36.

Chassefiere, B., Lundhardt, O., & Levy, A. (1969). Données nouvelles sur les cadoules (édifices coquilliers) de la lagune de Thau (Hérault.). *Compte rendu sommaire des séances de la Société Géologique de France, 5*, 140–142.

Cheema, M. (1977). Cainozoic. Stratigraphy of Pakistan. *Memoirs of the Geological Survey of Pakistan Quetta, 12*, 1–138.

Cuffey, R. J. (1972). The roles of bryozoans in modern coral reefs. *Geologische Rundschau, 61*(2), 542–550.

Davies, L. M. (1941). The "Dunghan" limestone, and Ranikot beds in Baluchistan. *Geological Magazine, 78*(4), 316–317.

Duncan, P., & Sladen, W. (1884). Description of the fossil Echinoidea from the Khirthar Series of Nummulitic strata in Western Sind. *Palaeontologia Indica, Series, 14*, 101–246.

Dunham, R. J. (1962). Classification of carbonate rocks according to depositional texture. In W. E. Ham (Ed.), *Classification of carbonate rocks* (pp. 108–121). Tulsa, OK: Memoir American Association of Petroleum Geologists.

Eames, F. (1952). A contribution to the study of the Eocene in western Pakistan and western India C. The description of the Scaphopoda and Gastropoda from Standard sections in the Rakhi Nala and Zinda Pir areas of the western Punjab and in the Kohat district. *Philosophical Transactions of the Royal Society of London Series B, Biological Sciences*, *236*, 1–168.

Embry, A. F. Transgressive-regressive (TR) sequence stratigraphy. In *Gulf Coast SEPM Conference Proceedings, Houston, 2002* (pp. 151–172)

Embry, A., & Johannessen, E. (1992). T–R sequence stratigraphy, facies analysis and reservoir distribution in the uppermost Triassic–Lower Jurassic succession, western Sverdrup Basin, Arctic Canada. In *Norwegian Petroleum Society Special Publications* (Vol. 2, pp. 121–146): Elsevier.

Emery, D., & Myers, K. (2009). *Sequence stratigraphy*. Hoboken: Wiley.

Fatmi, A. (1977). Mesozoic. *Stratigraphy of Pakistan, 12*, 29–56.

Fleury, J.-J., Bignot, G., Blondeau, A., & Poignant, A. (1985). Biogéographie de Foraminifères benthiques téthysiens du Sénonien à l'Éocène supérieur. *Bulletin de la Société géologique de France, 1*(5), 757–770.

Flügel, E. (2004). *Microfacies of carbonate rocks-analysis, interpretation and application*. Berlin: Springer.

Folk, R. L. (1965). Some aspects of recrystallization in ancient limestones. In L. C. Pray & R. C. Murray (Eds.), *Dolomitization and Limestone Diagenesis* (pp. 14–48). Tulsa, OK: Society Economic Paleontologists and Mineralogists.

Fruth, L., Orme, G., & Donath, F. (1966). Experimental compaction effects in carbonate sediments. *Journal of Sedimentary Research, 36*(3), 747–754.

Geel, T. (2000). Recognition of stratigraphic sequences in carbonate platform and slope deposits: empirical models based on microfacies analysis of Palaeogene deposits in southeastern Spain. *Palaeogeography, Palaeoclimatology, Palaeoecology, 155*(3–4), 211–238.

Hanif, M., Imraz, M., Ali, F., Haneef, M., Saboor, A., Iqbal, S., et al. (2014). The inner ramp facies of the Thanetian Lockhart Formation, western Salt Range, Indus Basin, Pakistan. *Arabian Journal of Geosciences, 7*(11), 4911–4926.

Haq, B. U., Hardenbol, J., & Vail, P. R. (1987). Chronology of fluctuating sea levels since the Triassic. *Science, 235*(4793), 1156–1167.

Heckel, P. H. (1983). Diagenetic model for carbonate rocks in Midcontinent Pennsylvanian eustatic cyclothems. *Journal of Sedimentary Research*, *53*(3), 733–759.

Hedley, R., Warburton, J., & Smewing, J. (2001). Sequence stratigraphy and tectonics in the Kirthar Foldbelt, Pakistan. *Geology and climate of the Arabian Sea region, Geol Society London*.

Hemphill, W. R., & Kidwai, A. H. (1973a). Stratigraphy of the Bannu and Dera Ismail Khan areas, Pakistan.

Hemphill, W. R., & Kidwai, A. H. (1973b). Stratigraphy of the Bannu and Dera Ismail Khan areas, Pakistan.

Henson, F. (1950). Cretaceous and Tertiary reef formations and associated sediments in Middle East. *AAPG Bulletin, 34*(2), 215–238.

Hinsch, R., Asmar, C., Nasim, M., Abbas, M. A., & Sultan, S. (2019). Linked thick-to thin-skinned inversion in the central Kirthar Fold Belt of Pakistan. *Solid Earth, 10*(2), 425–446.

Hottinger, L. (1983). Processes determining the distribution of larger foraminifera in space and time. *Utrecht Micropaleontological Bulletins, 30*, 239–253.

Hubbard, R. J. (1988). Age and significance of sequence boundaries on Jurassic and Early Cretaceous rifted continental margins. *AAPG Bulletin, 72*(1), 49–72.

Hunter, R. E., Clifton, H. E., & Phillips, R. L. (1979). Depositional processes, sedimentary structures, and predicted vertical sequences in barred nearshore systems, southern Oregon coast. *Journal of Sedimentary Research, 49*(3), 711–726.

Kadri, I. B. (1995). *Petroleum geology of Pakistan*. Karachi: Graphic Publishers.

Kakar, D., & Kassi, A. (1997). Lithostratigraphy, sedimentation and petrology of the Ghazij Formation, Sor Range area, Quetta District, Pakistan. *Acta Mineral Pakistan, 8*, 73–85.

Kassi, A. M., Qureshi, A. R., & Kakar, D. M. (1987). Sedimentology of the Ghazij Formation, Kach area, Balochistan. *Geological Bulletin of the University of Peshawar, 20*, 53–62.

Kazmi, A. (1981). Stratigraphy And sedimentation of the jurassic in north-eastern baluchistan. *Geological Bulletin of the University of Peshawar, 14*, 193–198.

Kazmi, A. H. (1988). Stratigraphy of the Dungan Group in Kach-Ziarat Area, NE Balochistan. *Journal of Himalayan Earth Sciences*, *21*, 117–130.

Kazmi, A. H., & Jan, M. Q. (1997). *Geology and tectonics of Pakistan*. Karachi: Graphic publishers.

Kazmi, A. H., & Rana, R. A. (1982). *Tectonic Map of Pakistan 1: 2 000 000*: Elite Print.

Khan, R. A., Haneef, M., & Khan, M. A. (2010). Microfacies and depositional environments of the Jurassic to Paleocene carbonates in the Kharzan area, Khuzdar, Balochistan. *Journal of Himalayan Earth Sciences, 43*, 45–45.

Khan, S. (2013). Biostratigraphy and microfacies of the Cretaceous Sediments in the Indus Basin, Pakistan. Ph.D. dissertation. University of Edinburgh, Edinburgh.

Khan, S., Wadood, B., Ahmed, S., Khan, A., Ahmed, F., & Khan, H. (2017). Evaluating paleoceanographic and planktonic foraminiferal diversification from the Cretaceous Mughal Kot Formation, Mughal Kot Section, Lower Indus Basin. *Pakistan. Journal of Himalayan Earth Science*, *50*(2), 27–43.

Khan, S. D., Walker, D. J., Hall, S. A., Burke, K. C., Shah, M. T., & Stockli, L. (2009). Did the Kohistan-Ladakh island arc collide first with India? *Geological Society of America Bulletin, 121*(3–4), 366–384.

Latif, M. (1964). Variations in abundance and morphology of pelagic Foraminifera in the Paleocene–Eocene of the Rakhi Nala, West Pakistan. *Geological Bulletin of Punjab University, 4*, 29–100.

Levin, H. L. (1957). Micropaleontology of the Oldsmar limestone (Eocene) of Florida. *Micropaleontology*, *3*(2), 137–154.

Loeblich, A., Jr. (1964). *Sarcodina, chiefly" thecamoebians" and Foraminiferida* (p. 2). Protista: Treatise on invertebrate paleontology.

Loutit, T. S., Hardenbol, J., Vail, P. R. & Baum, G. R. (1988). Condensed sections: the key to age dating and correlation of continental margin sequences. In C. K. Wilgus, B. S. Hastings, et al. (Eds.), Sea level changes: an integrated approach (Vol 42, pp. 183–216). Special Publication of the Society of Economists, Paleontologists and Mineralogists.

Lu, G., & Keller, G. (1993). The Paleocene–Eocene transition in the Antarctic Indian Ocean: Inference from planktic foraminifera. *Marine Micropaleontology, 21*(1–3), 101–142.

Lu, G., & Keller, G. (1995). Planktic foraminiferal faunal turnovers in the subtropical Pacific during the late Paleocene to early Eocene. *The Journal of Foraminiferal Research, 25*(2), 97–116.

Meissner, C. R. (1973). Distribution, thickness, and lithology of Paleocene rocks in Pakistan (No. 716-E). US Geological Survey.

Muhammad, B., Khan, S., Mohibullah, M., Kasi, A. K., & Ghani, M. (2018). Planktonic foraminiferal biostratigraphy and depositional setting of the Cretaceous Parh Limestone, Quetta, western Sulaiman Fold-Thrust Belt, Balochistan, Pakistan. *Journal of Himalayan Earth Sciences, 51*(2A), 8–23.

Murray, J. W. (1973). Distribution and ecology of living benthic foraminiferids. Crane Russak & Co., New York. xiii+ 274 p. $24.75. *Limnology and Oceanography, 18*(6), 1011–1011.

Myers, E. (1943). Ecologic relationships of larger foraminifera. *Rep. Comm. mar. Ecol. Paleont. Wash*, 26–33.

Parker, F. L. (1971). Distribution of planktonic foraminifera in recent deep-sea sediments. In B. M. Funnel & W. R. Riedel (Eds.), *Micropaleontology of oceans* (pp. 289–307). Cambridge: Cambridge University Press.

Racey, A. (1995). Lithostratigraphy and larger foraminiferal (nummulitid) biostratigraphy of the Tertiary of northern Oman. *Micropaleontology*, *41*, 1–123.

Rahman, H. N. Geology of petroleum in Pakistan. In *6th World Petroleum Congress, 1963*: World Petroleum Congress

Rehman, H., Mohibullah, M., Kasi, A. K., & Hussain, H. S. (2018). Foraminiferal biostratigraphy of the Dungan Formation, Harnai area, western Sulaiman Fold-Thrust Belt Pakistan. *Journal Of Himalayan Earth Sciences, 51*(2A), 34–43.

Reiss, Z., & Hottinger, L. (1984). *The Gulf of Aquaba: Ecological Micropaleontology*. New York: Spnrnger.

Samanta, B. K. (1973). Planktonic foraminifera from the Paleocene-Eocene succession in the Rakhi Nala, Sulaiman Range, Pakistan. *Bulletins of the British Museum (Natural History) Geology, 22*, 433–481.

Sarkar, S. (2019). Alveolina-dominated assemblages in the early Eocene carbonates of Jaintia Hills, NE India: Biostratigraphic and palaeoenvironmental implications. *Comptes Rendus Palevol, 18*(8), 949–966.

Scheibner, C., & Speijer, R. (2009). Recalibration of the Tethyan shallow-benthic zonation across the Paleocene-Eocene boundary: the Egyptian record. *Geologica Acta, 7*(1), 195–214.

Scholle, P. A., & Ulmer-Scholle, D. S. (2003). *A color guide to the petrography of carbonate rocks: Grains, Textures, Porosity, Diagenesis, AAPG Memoir 77* (Vol. 77): AAPG.

Serra-Kiel, J., Hottinger, L., Caus, E., Drobne, K., Ferrandez, C., Jauhri, A. K., et al. (1998). Larger foraminiferal biostratigraphy of the Tethyan Paleocene and Eocene. *Bulletin de la Société géologique de France, 169*(2), 281–299.

Serra-Kiel, J., i Herrero, A. T., i Palós, E. M., Briansó, E. S., i Cañadell, C. F., i Angrill, J. T., & i Masip, J. V. (2003). Marine and Transitional Middle/Upper Eocene Units of the Southeastern Pyrenean Forelan Basin (NE spain). Geologica Acta, 1(2), 177–177.

Shackleton, N., Corfield, R., & Hall, M. (1985). Stable isotope data and the ontogeny of Paleocene planktonic foraminifera. *The Journal of Foraminiferal Research, 15*(4), 321–336.

Shafique, N. A., & Daniels, C. (1990). Foraminiferal zonation of Upper Goru Formation-Bawani area, Kirthar Range, Pakistan. *Journal of Hydrocarbon Research, 2*(2), 67–84.

Shah, S. (1977). Stratigraphy of Pakistan, Geological Survey of Pakistan Memoirs 12. *Islamabad, Pakistan: Geol Surv Pakistan*

Shah, S. M. I. (2009). Stratigraphy of Pakistan. *Geological Survey Pakistan Membership, 22*, 1–381.

Shahin, A. (2001). Mass extinction and bioevents across the Paleocene-Eocene boundary in the western Sinai, Egypt. *Neues Jahrbuch für Geologie und Paläontologie-Monatshefte*, 1–20.

Smewing, J. D., Warburton, J., Daley, T., Copestake, P., & Ul-Haq, N. (2002). Sequence stratigraphy of the southern Kirthar fold belt and middle Indus basin, Pakistan. *Geological Society, London, Special Publications, 195*(1), 273–299.

Stainbank, S., Kroon, D., Rüggeberg, A., Raddatz, J., de Leau, E. S., Zhang, M., et al. (2019). Controls on planktonic foraminifera apparent calcification depths for the northern equatorial Indian Ocean. *PLoS One, 14*(9), e0222299.

Steinsund, P. I., & Hald, M. (1994). Recent calcium carbonate dissolution in the Barents Sea: Paleoceanographic applications. *Marine Geology, 117*(1–4), 303–316.

Taghavi, A. A., Mørk, A., & Emadi, M. A. (2006). Sequence stratigraphically controlled diagenesis governs reservoir quality in the carbonate Dehluran Field, southwest Iran. *Petroleum Geoscience, 12*(2), 115–126.

Taylor, P. D. (2005). Bryozoans and palaeoenvironmental interpretation. *Journal of the Palaeontological Society of India, 50*(2), 1–11.

Tucker, M., & Wright, V. (1990). *Modern carbonate environments, Carbonate Sedimentology* (pp. 101–126). London: Blackwell Scientific Publications.

Umar, M., Friis, H., Khan, A. S., Kassi, A. M., & Kasi, A. K. (2011). The effects of diagenesis on the reservoir characters in sandstones of the Late Cretaceous Pab Formation, Kirthar Fold Belt, southern Pakistan. *Journal of Asian Earth Sciences, 40*(2), 622–635.

Van-der Zwaan, G. J. (1982). *Paleoecology of late Miocene Mediterranean foraminifera*. Utrecht University,

Van-Morkhoven, F. M., Berggren, W. A., & Edwards, A. S. (1986). Cenozoic cosmopolitan deep-water benthic foraminifera. *Bulletin des centres de Recherches exploration-production elf-aquitaine* (11).

Wadood, B., Awais, M., Khan, S., Ahmad, S., Ahmad, L., & Muslim, M. (2019). Diagenetic studies of the Cretaceous turbidities, Sulaiman Range, Pakistan: Implications for reservoir quality. *Journal of Himalayan Earth Sciences, 52*(1), 106–119.

Wadood, B., Khan, S., Khan, A., Khan, M., Liu, Y., Li, H., et al. (2020). Diachroneity in the closure of the eastern Tethys Seaway: evidence from the cessation of marine sedimentation in northern Pakistan. *Australian Journal of Earth Sciences*. https://doi.org/10.1080/08120099.2020.1782472.

Walton, W. R. (1964). Recent foraminiferal ecology and paleoecology. *Approaches to paleoecology, 1*, 151–237.

Warraich, M. Y. (2000). Paleogene planktonic foraminiferal biostratigraphy of the Sulaiman range, Southern Indus basin, Pakistan. *Unpublished PhD Thesis, University of Tsukuba*.

Weiss, W. (1993). Age assignments of larger foraminiferal assemblages of Maastrichtian to Eocene age in northern Pakistan. *Zitteliana, 20*, 223–252.

Williams, M. D. 19. Stratigraphy of the Lower Indus Basin, West Pakistan. In *5th World petroleum congress, 1959*: World Petroleum Congress

Wilson, J. L. (1975). The stratigraphy of carbonate deposits. In *Carbonate Facies in Geologic History* (pp. 20–55): Springer.

Wilson, M. D., & Stanton, P. T. (1994). Diagenetic mechanisms of porosity and permeability reduction and enhancement.