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ORIGINAL ARTICLE

Detailed sedimentological investigation of the late cretaceous fort munro formation, western sulaiman range, Pakistan

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Abstract
The late Cretaceous Fort Munro Formation in the western Sulaiman Range represents medium to thick-bedded, dark grey limestone displaying rich skeletal components, particularly larger benthic foraminifera (LBF), and bivalves. Three sections from the western Sulaiman Range, namely Spera Ragha, Murree Brewery, and Hanna Lake, were studied for detailed microfacies analysis and diagenetic investigation. A total of nine microfacies have been recognized, including 1 mudstone, 4 wackestone, 2 packstone, and 2 grainstone. Considering the proportionate prevalence of biota, their groupings, and the existence of a micritic matrix in different microfacies, it is deduced that the Fort Munro Formation was deposited inner to middle ramp setting. The inner ramp setting is more widespread than the corresponding middle ramp and is characterized by sub depositional environments including semi-restricted, storm-induced skeletal shoals, lagoons, low energy and protected inner ramp, storm induced skeletal shoals, and open marine. The Fort Munro Formation has undergone significant diagenetic alteration due to various diagenetic events. These events have altered the primary and secondary porosities. The observed diagenetic processes include micritization, cementation, dissolution, neomorphism, mechanical compaction, stylolitization, fractures and veins formation. Paragenetic sequence reveals that the studied carbonates are modified in marine, meteoric, and burial diagenetic environments. Detailed diagenetic analysis of the Fort Munro Formation reveals that most of the primary as well as secondary porosities are deteriorated by the precipitation of different type of cements in a variety of diagenetic environments.

Keywords Fort Munro formation · Microfacies · Depositional environments · Sulaiman range · Diagenesis · Paragenetic sequence · Pakistan

Introduction

The Sulaiman Fold-Thrust Belt (SFTB) of Pakistan (Fig. 1) represents excellent Mesozoic and Cenozoic sedimentary rock strata. The Mesozoic and lower Cenozoic (Paleocene-Eocene) were deposited in a marine environment, whereas the younger strata represent a fluvial system (Kassi et al. 2009; Babar et al. 2018; Muhammad et al. 2018; Rehman et al. 2018). The Cretaceous strata are well exposed through the SFTB and the Fort Munro Formation forms part of the thick Cretaceous marine succession. The formation was first recognized as Hippuritic Limestone (Blanford 1878) and Hemipneustes Limestone (Vredenburg 1909). Williams (1959) considered it as a member of Mughal Kot Formation (Williams 1959), which was later given the status of a formation due to its distinct lithology and wide lateral extension throughout the Lower Indus Basin (Fatmi 1977). The Fort Munro Formation is named after its type section in the hills of Fort Munro along the Fort Munro-Dera Ghazi Khan road (Williams 1959). It is exposed in various regions of the Kirthar and Sulaiman provinces of the Lower Indus Basin. The Fort Munro Formation is 200 m thick in the Rakhi Nala section in eastern Sulaiman ranges near Dera Ghazi District of Punjab which is designated as the type section (Rizwan

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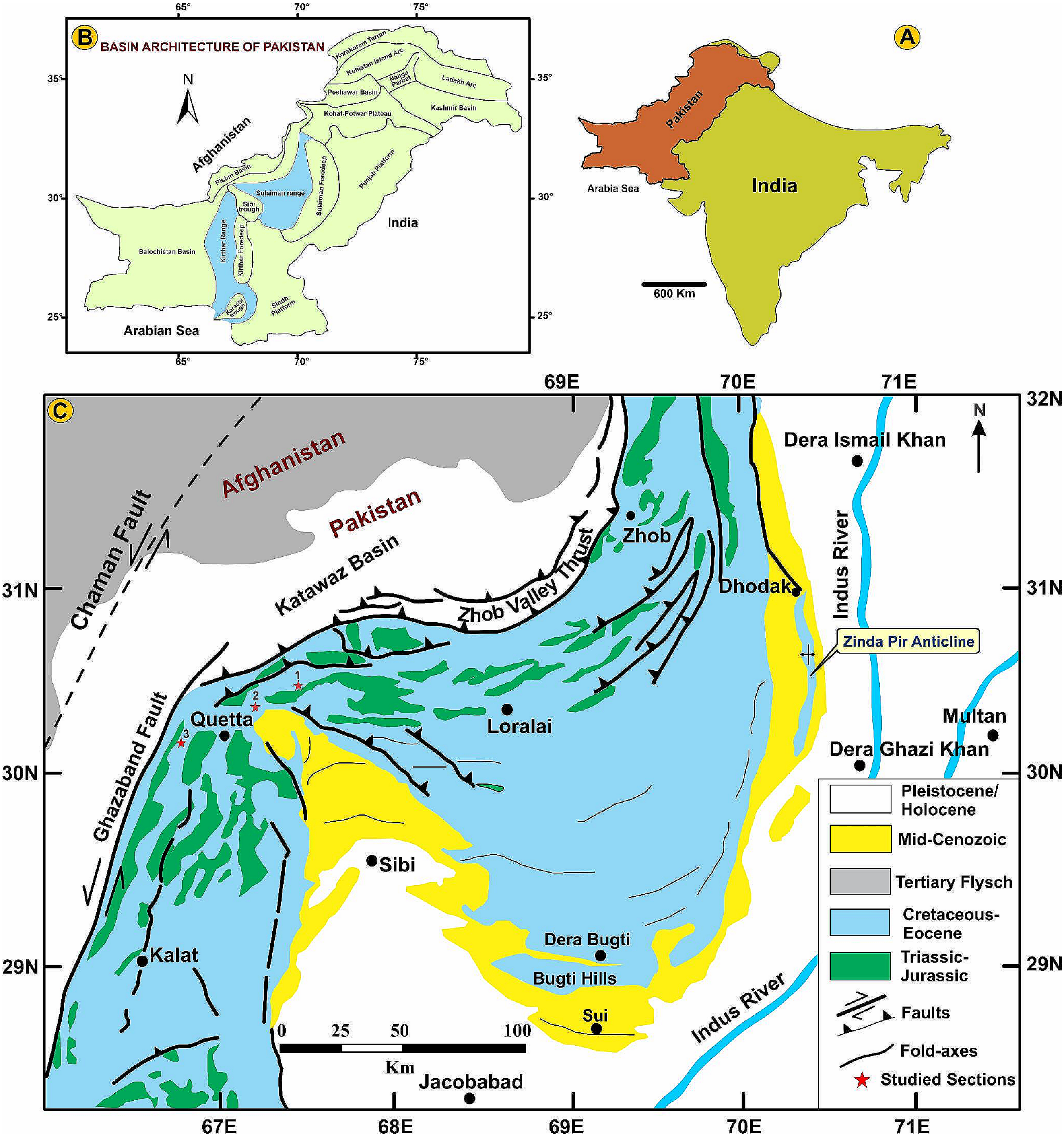


Fig. 1 Geological map of the Lower Indus Basin Pakistan, showing the location of studied sections. **A** Geographic position of Pakistan in Indian Plate. **B** Basin architecture map of Pakistan, and **C** Geological map of the Sulaiman range showing the studied sections as follows; 1 - Spera Ragha, 2 - Hanna Lake, and 3 - Muree Brewery (after Raza et al. 2002)

et al. 2020). The formation is 15 m thick in the Murre Brewery and 8 m thick in the Spera Ragha sections western Sulaiman range (Kassi et al. 2009; Shah 2009; this work). The Fort Munro Formation is dominantly limestones with minor occurrences of greenish-grey shales. The limestone is brown, medium to dark grey, micritic to biomicritic and partly nodular (Kassi et al. 2009).

The Fort Munro Formation conformably and transitionally overlies the Mughal Kot Formation in the Sulaiman Province (Shah 2009). However, in some areas (e.g. Quetta) where facies of the Mughal Kot Formation was not developed, it forms an unconformable contact with the underlying Parh Group. In most of the SFTB, the formation forms a conformable contact with the overlying Pab Formation, while in some areas like Quetta, it is disconformably overlain by the Paleocene-Eocene Dungan Formation (Shah 2009; Kassi et al. 2009). The disconformable contact with the Dungan Formation is marked by a lateritic bed (Kassi et al. 2009).

The Fort Munro Formation is reported to have preserved abundant fauna especially bivalves (*Hippurites*) and benthic larger foraminifera (*Orbitoides media*, *O. tissoti minima*, *Omphalocyclus macropora*, *Actinosipon punjabensis*, and species of *Siderolites*). Based on the above-mentioned fauna, different ages have been assigned to the formation by different authors (Marks 1962). Hunting Survey Corporation (1961) assigned Maastrichtian age to the unit in the Kirthar Province based on the presence of *Actinosipon punjabensis*, *Orbitoides media*, *Orbitoides tissoti minima* and a species of *Siderolites*. Marks (1962) dated the unit as middle to late Campanian since *Orbitoides tissoti minima* recovered from its basal and middle part in the Rakhi Nala section.

The formation is rich in shallow marine fossil assemblages and shows significant lateral facies variations. However, detailed studies of its fauna and microfacies beyond its earliest pilot studies are lacking (Blanford 1878). However, most recently Rizwan et al. (2020 and 2023) has documented its detailed microfacies and diagenetic analyses from the Rakhi Nala Section. He interpreted that the Fort Munro Formation has been deposited in moderately storm-dominated homoclinal ramp settings and concluded that the formation is subjected to a variety of diagenetic processes in different diagenetic environments. Here, in this study, our aims are to document microfacies types of the Fort Munro Formation in the western SFTB, interpret the paleo-depositional environments using microfacies analysis, and unravel the diagenetic history.

Geological setting

The SFTB is the widest fold thrust belt of Pakistan (Reynolds et al. 2015); with a width of 75 to 200 km and length of 630 km (Muhammad et al. 2018), positioned on the northwestern margin of the Indian Plate. The belt is bordered by the Kirthar Belt in the south, Pishin Belt in the west and Punjab platform in the east (Banks and Warburton 1986) (Fig. 1). The belt is composed of a passive margin succession of the Mesozoic carbonates, shale, muds, sands and volcanics, showing a deep-water affinity toward the north. Transitionally, these deposits are covered by younger siliciclastic sediments derived from the newly forming Himalaya during the Eocene and onwards deposited in a shallow-water deltaic environment corresponding to the modern Indus delta fan depositional system (Eames 1952; Humayon et al. 1991; Treloar and Izatt 1993; Qayyum et al. 1996, 2001; Kassi et al. 2009). This SFTB started folding and uplifting around 55 million years ago, after the collision of Indian and Eurasian plates (Powell 1979; Le Pichon et al. 1992), however, the main period of uplifting and folding took place during Pliocene to Recent (Fitzsimmons et al. 2005). The Indian Plate then went through basement splitting, resulting in the evolution of the SFTB between the Kirthar and Sulaiman basement faults (Bannert et al. 1992; Searle et al. 1997). During this period the Muslim Bagh-Zhob Ophiolite, was obducted on to the northwest margin of Indian Plate along thrust of Zhob valley (Alleman 1979; Gnos et al. 1997; Kakar et al. 2012). Until the late Oligocene flysh sedimentation continued in the Pishin Belt and Himalaya-Karakorum was sourced of these deposits. Later in Miocene, sedimentation shifted to the east to develop the Kirthar and Sulaiman foredeeps (Qayyum et al. 1996). Continued collision along the northwestern margin of the of the Indian Plate with the Afghan Block, at the Chaman-Nushki Fault System (Powel 1979; Furuya and Satyabal 2008), resulted in the appearance of clastic deposition of the Siwalik Group of westerly sources of the Sulaiman and Kirthar fold-thrust belts locally replaced the northerly sourced sediments from the Karakorum-Himalayan (Qayyum et al. 1996; Kassi et al. 2009).

The stratigraphy of Sulaiman ranges consists of a thick succession of sedimentary rocks ranging from Triassic to Recent (Fitzsimmons et al. 2005; Shah 2009) (Fig. 2). The (Campanian to Early Maastrichtian) period in the Sulaiman range is marked by limited clastic deposition, leading to the formation of a storm wave dominated carbonate ramp Fort Munro Formation. The carbonate deposition came to an abrupt halt in the Maastrichtian, transitioning into a series of storm-wave-dominated strand plains that were supplied by a contemporaneous fluvial system known as the Pab Formation. The Fort Munro Formation in the studied section is characterized by medium to thick bedded limestone. The marl interbed are dominated in their lower part (Fig. 3d-h). The color of the limestone varies from light grey to cream and light to dark grey on the weathered and fresh surface respectively (Fig. 3a-h). The limestone is highly fossiliferous in the lower part of the formation in the studied sections and characterized by abundant LBF together with the bivalves (Fig. 3a-b, g). The limestone is nodular at places (Fig. 3c). The Formation is also characterized by thin laminated limestone interbedded with shale in the lowermost part in the Spera Ragha section (Fig. 3h).

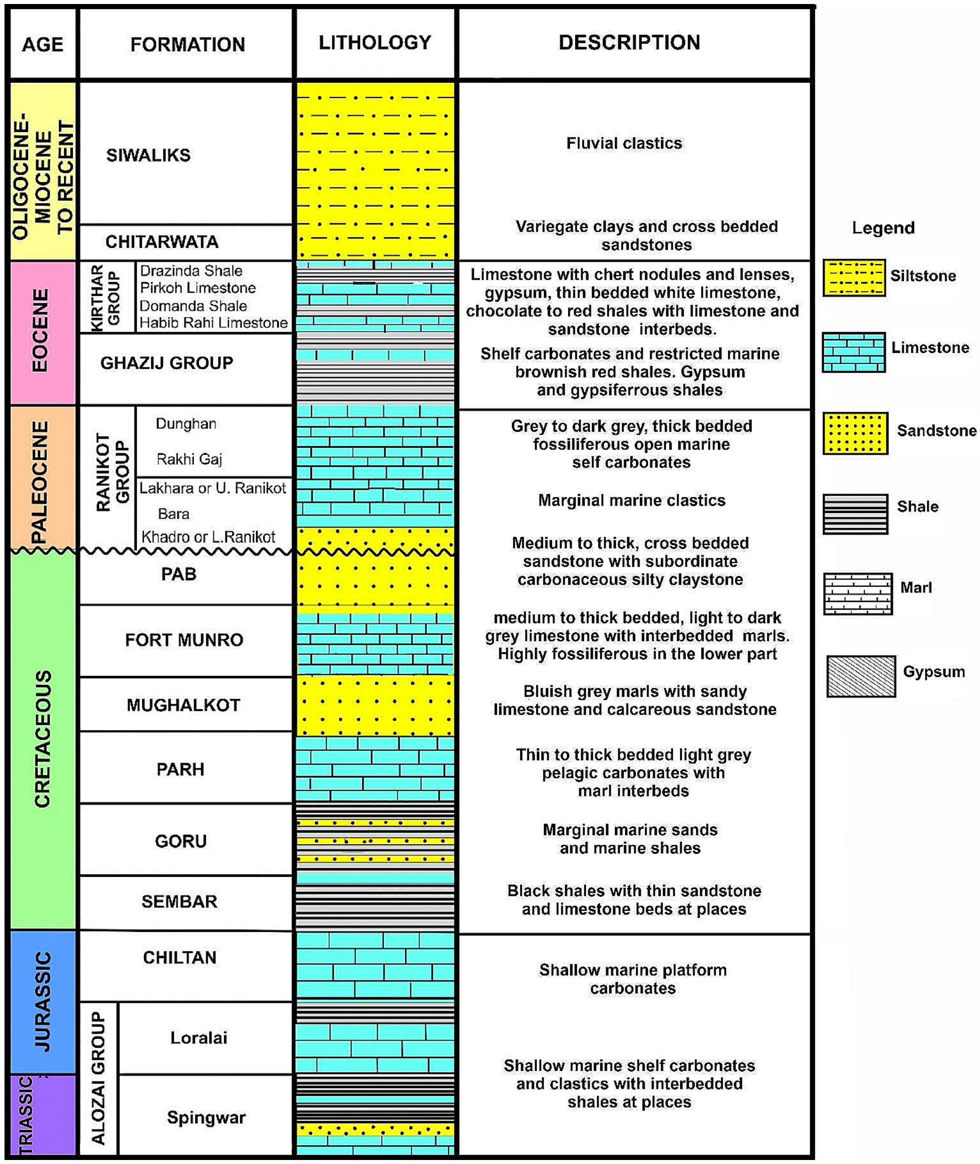


Fig. 2 Geological stratigraphic column of the Sulaiman Range (modified after Hemphill and Kidwai 1973)

Methodology

The late Cretaceous Fort Munro Formation was measured and logged at the Spera Ragha (30° 31′ 49.21″ N, 67 ° 38′ 17.67″ E), Murree Brewery (30° 11′ 11.50″ N, 66 ° 56′ 52.10″ E) and Hanna Lake (30° 15′ 08.22″ N, 67 ° 06′ 06.86″ E) sections in the western Sulaiman Range. Spera Ragha section belongs to the District Ziarat, whereas Muree Brewery and Hanna Lake sections belong to the District Quetta. A total of 23 limestone samples were collected for detailed microfacies analysis and diagenesis. The abbreviation for samples collected from the Spera Ragha section is SRB, from the Murree Brewery section is MBB, and from the Hanna Lake section is HLB (Figs. 4, 5 and 6). Thin sections were prepared in the Rock Cutting Laboratory of National Centre of Excellence in Mineralogy University of Balochistan, Quetta. The photomicrographs were taken using an OLYMPUS UC30 Digital Camera attached to the LEICA DM LP microscope. All selected samples were analyzed for microfacies analysis to determine their paleoenvironmental depositional conditions. Visual estimation method has been used for the calculation of percentages of different allochemical constituents and matrix. Different microfacies are classified based on the Dunham (1962) classification scheme, i.e., mudstone, wackestone, packstone, and grainstone. Low to high abundance of allochemical constituents are used in naming the different microfacies. Depositional paleoenvironments were reconstructed based on the observed sedimentological characteristics during fieldwork and interpreted sedimentary facies analysis, and through comparison with additional outcropped data known from the existing literature on time equivalent deposits.

Results and discussion

Microfacies analysis

The Fort Munro Formation of the western SFTB is exposed in the Spera Ragha, Murree Brewery and Hanna Lake areas. Petrographic study of the measured sections revealed the microfacies such as mudstone, wackestone, packstone and grainstone, which were further subdivided in various sub-microfacies (Figs. 4, 5 and 6), which are described and interpreted as follows:

Bioclastic siliciclastic mudstone (A)

Description

The limestone is light to dark gray, micritic, thick bedded, nodular limestone at the base of thin bedded limestone succession. The top surface of limestone succession is highly erosional indicating a depositional break (disconformity). This microfacies is represented by samples MBB-1, SRB-5 and SRB-6 (Figs. 4 and 5). Allochems ranges from 1 to 5% with an average of 4%, and siliciclasts constitutes 1%. Allochems mainly consist of bioclasts including foraminifera and bivalve fragments. The remaining 95% is micrite with patches of sparite. Fractures are mostly filled with calcite and iron oxide (Fig. 7a).

Interpretation

The very low diversity, absence of fauna, minor fine grained siliciclastic input and mudstone texture suggest low energy conditions in near shore inner ramp lagoonal environment, which resembles with RMF-19 of Flügel (2010) (Fig. 10).

Miliolids bioclastic intraclastic wackestone microfacies (B)

Description

Limestone succession in the field is medium to dark gray, weathering brownish gray, arenaceous, bioclastic, nodular, interbedded with thin shale horizons. Bivalves, gastropods, and brachiopods are also present. This microfacies is represented by sample number SRB-1 (Fig. 6). Siliciclasts constitutes 2% and average allochems are calculated as 23%. Allochems are comprised of bioclasts, including bivalve (2%), gastropods (2%), echinoderm (1%), undifferentiated bioclasts (1%), intraclasts (8%) and foraminifera (4%), mostly miliolids (3%). The remaining 75% is comprised of micritic matrix (Fig .7b). This microfacies can be compared with the RMF 16 of Flügel (2010).

Interpretation

The occurrence of the miliolids indicates a restricted inner ramp low-energy euphotic zone environment (Geel 2000; Romero et al. 2002; Rizwan et al. 2020). The presence of echinoderms, gastropods and bivalves show normal marine settings (Scholle and Ulmer 2003; Sallam et al. 2015; Sallam and Ruban 2020). Therefore, minor amount of miliolids with shallow marine fauna, such as echinoderm, bivalves, gastropods, and association of derived siliciclasts and intraclasts from peritidal zone suggest the semi-restricted inner ramp depositional environment.

Orbitoides bearing bioclastic wackestone (C)

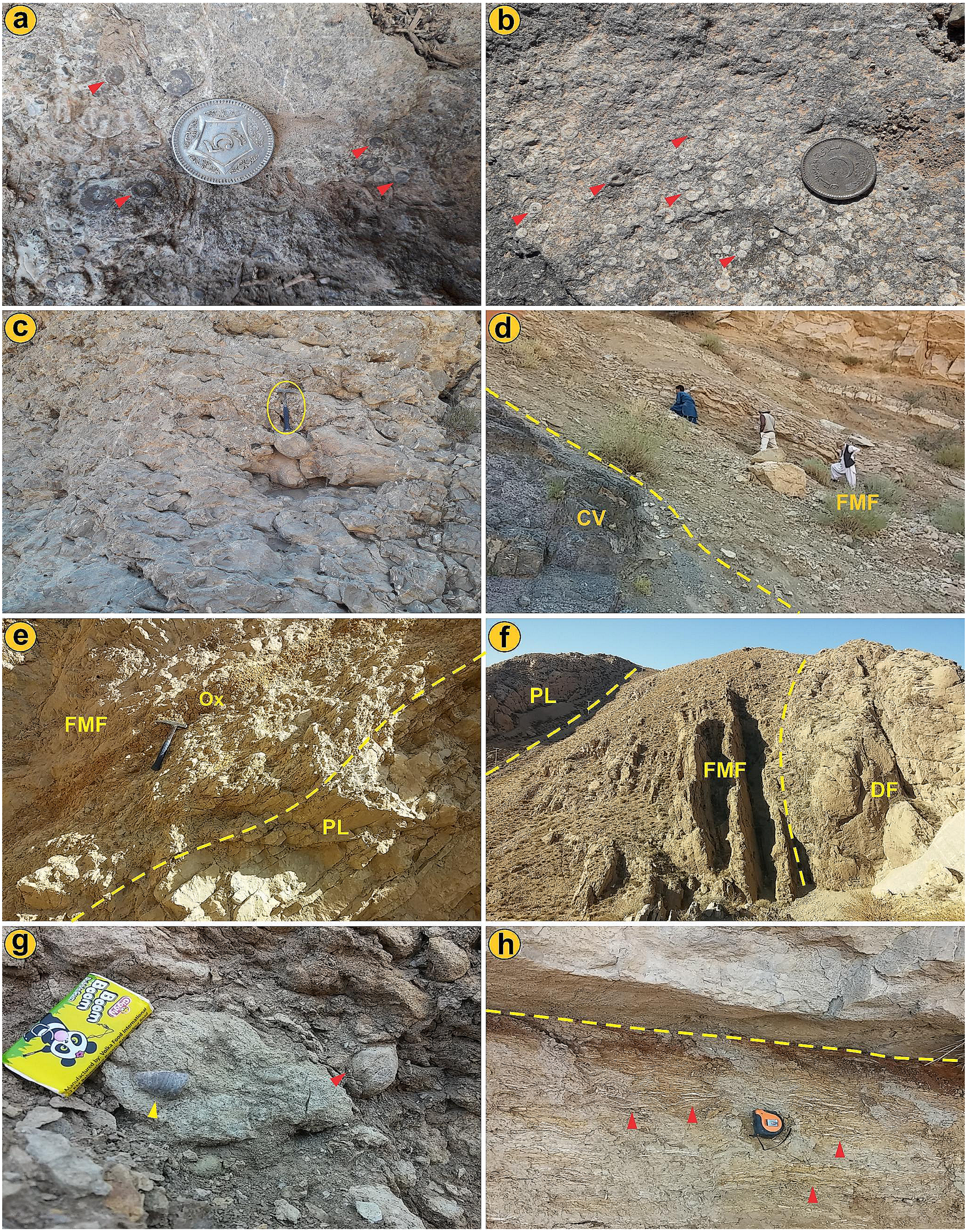
Description

Spera Ragha Section This microfacies consists of bioclastic limestone containing bivalves and *Orbitoides* and is present in the upper part of the formation (SRB-9; Fig. 6). Siliciclasts are 1% and average allochems are calculated as 27%. Allochems are dominantly bioclasts of echinoderms (4%), bivalves (2%), undifferentiated bioclasts (7%) and foraminifera (11%). Foraminifera includes *Orbitoides* (9%), miliolids (0.25%) and other undifferentiated foraminifera (1.75%). The remaining 72% is comprised of micrite (Fig .7c).

Muree Brewery Section The limestone in the field is dark gray nodular, thick bedded, micritic, fossiliferous; containing bivalves, foraminifera and *Orbtoidies*, represented by samples HLB-1, MBB-3, MBB-4, MBB-5, and MBB-9 (Figs. 5 and 7). The average allochems are calculated as 26%, which mainly comprises skeletal grains, including echinoderms (6%), bivalve (2%), and foraminifera (13%). Foraminifera consists of *Orbitoides* (4%), miliolids (1%), rotaliids (2%) and other foraminifera (8%). The remaining 74% is comprised of micrite matrix (Fig. 7d). Characters of this microfacies support its comparison with RMF13 of Flügel, (2010).

Interpretation

Spera Ragha Section This microfacies is dominantly composed of shallow marine biota i.e., echinoderms, LBF (*Orbitoides*) and bivalves. Echinoderms are abundant in open shelf and normal marine deposits (Scholle and Ulmar-Scholle 2003). *Orbitoides* suggests open marine environment with slight terrigenous input (Goldbech 2007). On the basis of shallow marine fauna, this microfacies suggests having been deposited in an open marine inner ramp


a
b
c
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CV
FMF
e
Ox
FMF
PL
f
PL
FMF
DF
g
h

Fig. 3 Field photographs: **a-b** *Orbitoides* (indicated by red arrows) rich thick bedded limestone in middle to upper part of the Fort Munro Formation (Coin diameter = 2.4 cm for scale). **c** thick bedded nodular limestone in upper part. **d** lower contact of Fort Munro Formation (FMF) with Chingin volcanics (CV) in Spera Ragha section. **e** lower contact of Fort Munro Formation (FMF) with Parh limestone (PL) in Murree Brewery section. FMF also shows the oxidized bed (OX). **f** contacts between Fort Munro Formation (FMF), Parh limestone (PL) and Dungan Formation (DF) in Hanna Lake section. **g** gastropod (indicated by yellow arrow) and brachiopod (red arrow) in the lower part of Spera Ragha section. **h** thin laminated limestone (indicated by red arrows) interbedded with shale in lowermost part of the Fort Munro Formation in Spera Ragha section

environment. The rare occurrence of miliolids suggests their transportation from restricted environment.

Muree Brewery Section The presence of *Orbitoides* reflects an open marine environment, with a little terrigenous input (Goldbech, 2007). Corals are common in ramp and shelf environments (Flügel 2010). The presence of the echinoderms and bivalves indicate normal marine settings (Scholle and Ulmer Scholle 2003; Sallam et al. 2015; Sallam and Ruban 2020). Rotaliids also indicate shallow marine environment (Haynes 1981). The presence of shallow marine fauna, associated with echinoderms suggests storm-induced skeletal shoals of the inner ramp settings.

Orbitoides bearing miliolids siliciclastic wackestone (D)

Description

In the field, this microfacies is composed of light gray, thick bedded, fossiliferous limestone, represented by sample HLB-2 (Fig. 7). Siliciclastic constituents 20%. Average allochems are calculated as 24%. Allochems are mostly comprised of skeletal grains including, echinoderm (6%), bivalves (2%), undifferentiated bioclasts (4%) and foraminifera (12%). Foraminifera includes *Orbitoides* (2%), miliolids (9%) and other foraminifera (1%). The remaining 56% is comprised of micrite matrix (Fig. 7e).

Interpretation

Miliolids are common in a restricted environment with low water energy conditions (Geel 2000). *Orbitoides* occupied the inner ramp open marine to middle ramp environments in late Cretaceous (Grafe 2005; Goldbeck 2007). The occurrence of miliolids with echinoderms and other rare skeletal grains suggest deposition in a low-energy, protected inner ramp setting (Flügel 2010). Therefore, the common occurrence of miliolids with *Orbitoides* and echinoderms in this microfacies supports its deposition in a semi-restricted inner ramp environment. Siliciclasts are transported from the adjacent land to the ocean. The constituents of this microfacies suggest its comparison with RMF 16 of Flügel (2010).

Bioclastic echinoderm packstone (E)

Description

In the field the succession consists of arenaceous, reddish brown, fossiliferous bioclastic, intraclastic limestone, showing wavy bedding/lamination with erosional contacts, represented by sample SRB-7. Siliciclasts constitute 1%, whereas the average allochems are estimated as 63%. Allochems are skeletal grains (55%), intraclasts (3%) and peloids (5%). Bioclasts dominantly comprise echinoderms (38%) with some bryozoans (2%), bivalves 1%, sponges (1%), undifferentiated bioclasts (7%) and foraminifera 6%. Foraminifera includes *Orbitoides* (1%) and other foraminifera (5%). The remaining matrix is comprised of micrite (28%) and sparite (8%) (Fig. 7f).

Interpretation

Echinoderms are abundant in normal shallow marine conditions and the packstone texture reflects high energy conditions (Scholle and Ulmer-Scholle 2003). Thus, suggesting the deposition of this microfacies in inner ramp storm induced (shoal) environment. These characters are comparable with the RMF 27 of Flügel (2010).

Bioclastic orbitoidal packstone (F)

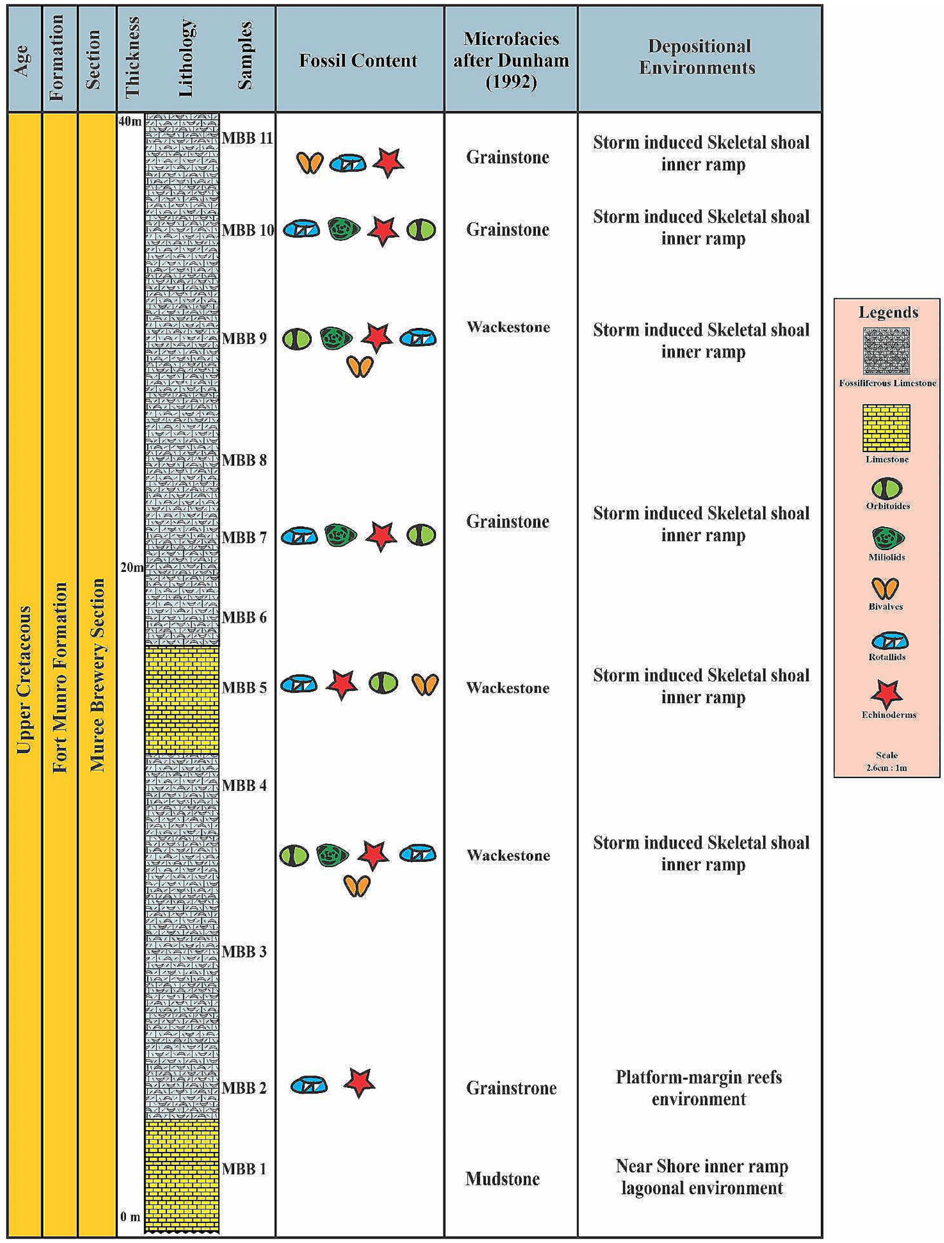
Description

This microfacies consists of arenaceous, bioclastic (bivalves and *Orbitoides)* limestone, present in the upper part of the formation in the Spera Ragha Section (sample SRB-8 and SRB-10). Siliciclasts constitute 2% and the average allochems are estimated as 52%. Allochems comprise of peloids (2%), intraclasts (2%) and skeleton grains (48%). Skeleton grains comprise of echinoderm (3%), ostracods (2%), bivalves (2%), brachiopods (1%), undifferentiated bioclasts (15%) and foraminifera (25%). Foraminifera include *Orbitoides* (20%), miliolids (1%), rotaliids (1%), smaller benthic foraminifera (1%) and undifferentiated foraminifera (2%). The remaining matrix (46%) is comprised of micrite 30% and sparite 16% (Fig. 8a).

Interpretation

This microfacies dominantly consists of *Orbitoides* and minor fragments of shallow marine fauna. *Orbitoides*

Fig. 4 Vertical distribution of the identified microfacies in the Fort Munro Formation at the Murre Brewery Section, Quetta



suggests inner ramp open marine environment with little terrigenous input (Goldbech 2007) and ranges to middle ramp (Grafe 2005). The presence of echinoderm supports shallow marine conditions (Scholle and Ulmar-Scholle 2003). Thus, the presence of abundant *Orbitoides*, shallow marine fauna and its packstone texture of this microfacies suggest a distal open inner ramp depositional environment. Characters of this microfacies are comparable with RMF 13 of Flügel (2010) and SMF 18 of Wilson (1975).

Bioclastic miliolids grainstone (G)

Description

In the field the limestone consists of dark gray, micritic, thick bedded, fossiliferous, nodular limestone and thin bedded at the base. This microfacies is represented by sample number SRB-2 SRB-3 and SRB-4. The average allochems are estimated as 32%, which constitute peloids (1%) and skeletal grains (31%). Bioclasts include echinoderm (3%), ostracodes (1%), undifferentiated bioclasts (6%) and foraminifera (21%). Foraminifera comprises of miliolids (12%), rotaliids (7%) and other foraminifera (2%). The remaining matrix comprises sparite (65%) and micrite (3%) (Fig. 8b).

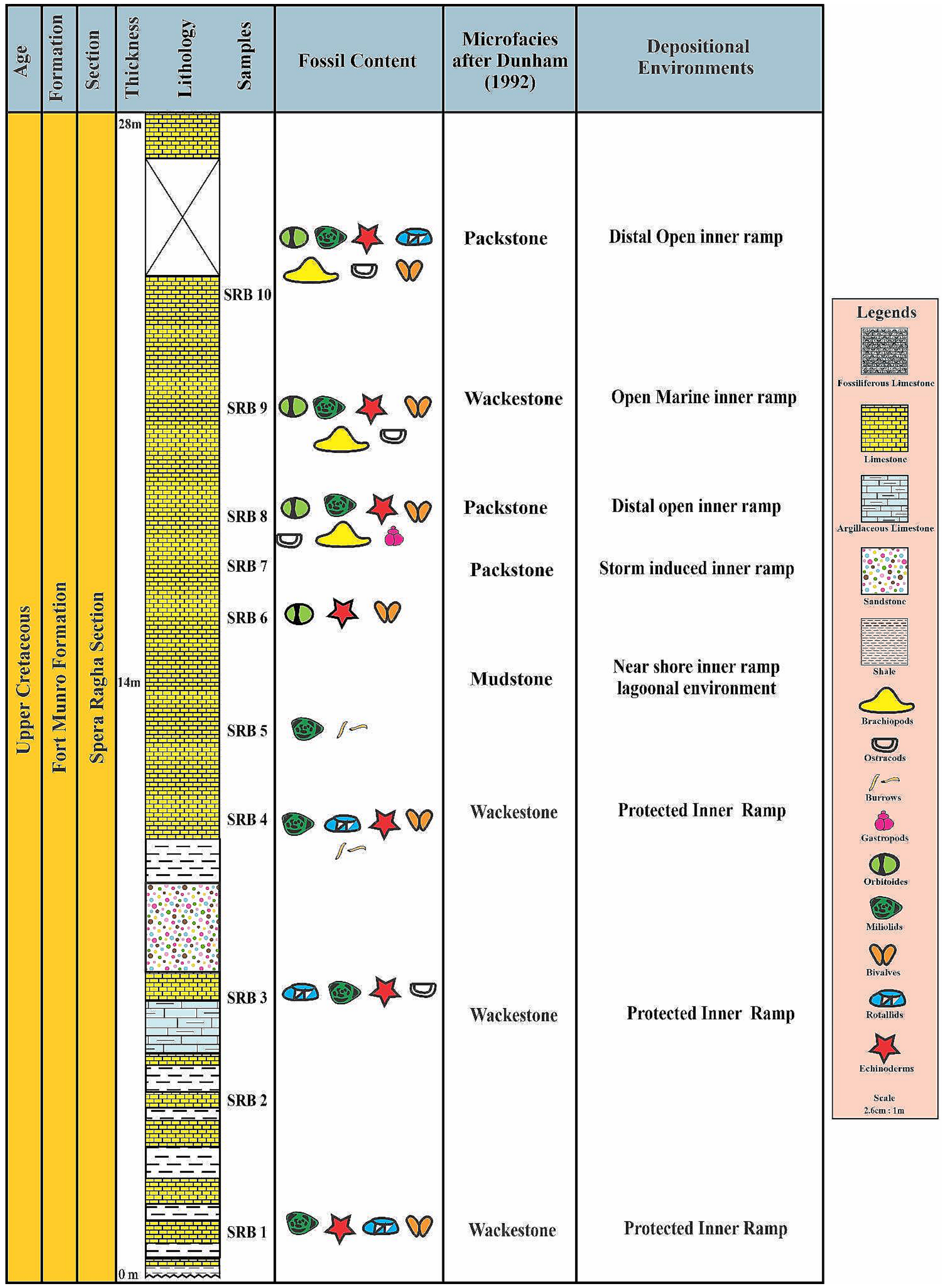


Fig. 5 Vertical distribution of the identified microfacies in the Fort Munro Formation at the Spera Ragha Section, Ziarat

Interpretation

This microfacies mainly comprises miliolids, rotaliids and some other bioclasts. Miliolids suggest low-energy, restricted conditions (Geel 2000; Romero et al. 2002), and are widely distributed in lagoonal inner ramps environments of Mesozoic and Cenozoic (Flügel and Munnecke 2010). Rotaliids indicate shallow marine environment (Haynes 1981). The presence of echinoderms indicates shallow marine condition (Scholle and Ulmar-Scholle 2003). Thus, the co-occurrence of miliolids, rotaliids with echinoderms in this microfacies strongly suggests storm-induced skeletal shoals inner ramp depositional environment.

Peloidal bioclastic grainstone (H)

Description

This facies comprises dark gray, micritic, fossiliferous nodular limestone containing bivalves and *Orbtoides;* top surface of the bed is wavy in the field. The microfacies is represented by sample number MBB-2. Silicilclasts are (1%) and allochems (42%). Allochems comprise of peloids

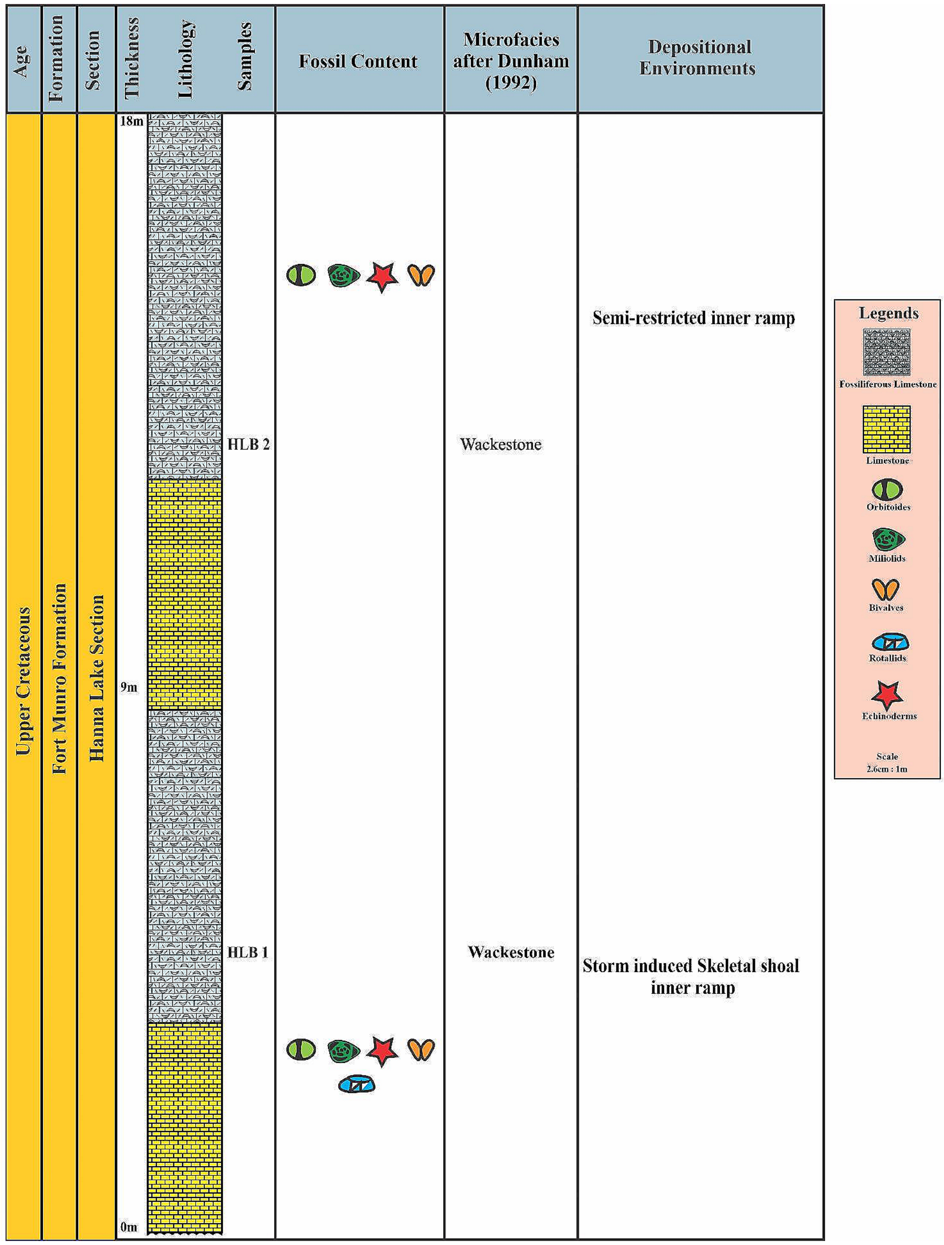


Fig. 6 Vertical distribution of the identified microfacies in the Fort Munro Formation at the Hanna Lake Section, Quetta

(12%) and skeletal grains (30%). Bioclasts comprise of echinoderms (10%), undifferentiated bioclasts (22%) and foraminifera (8%). Foraminifera include Rotaliids (3%) and other foraminifera (5%). The remaining (57%) comprise matrix of sparite (50%) and micrite (7%) (Fig. 8c). This microfacies is represented by bioclasts coated by micrite. Some bioclasts are enveloped by micrite; others are completely micritized, turning into peloids within sparry cement. Other grains include peloids and bioclasts of other foraminifera, and echinoderms.

Interpretation

Echinoderms indicate shallow marine conditions (Scholle and Ulmar-Scholle 2003). Corals are common in ramp and shelf environments (Flügel 2010). Sparry matrix points to high-energy conditions (Flügel and Munnecke 2010). Platform-margin reefs environment is suggested for this microfacies. This microfacies is comparable with SMF 11 of Wilson (1975).

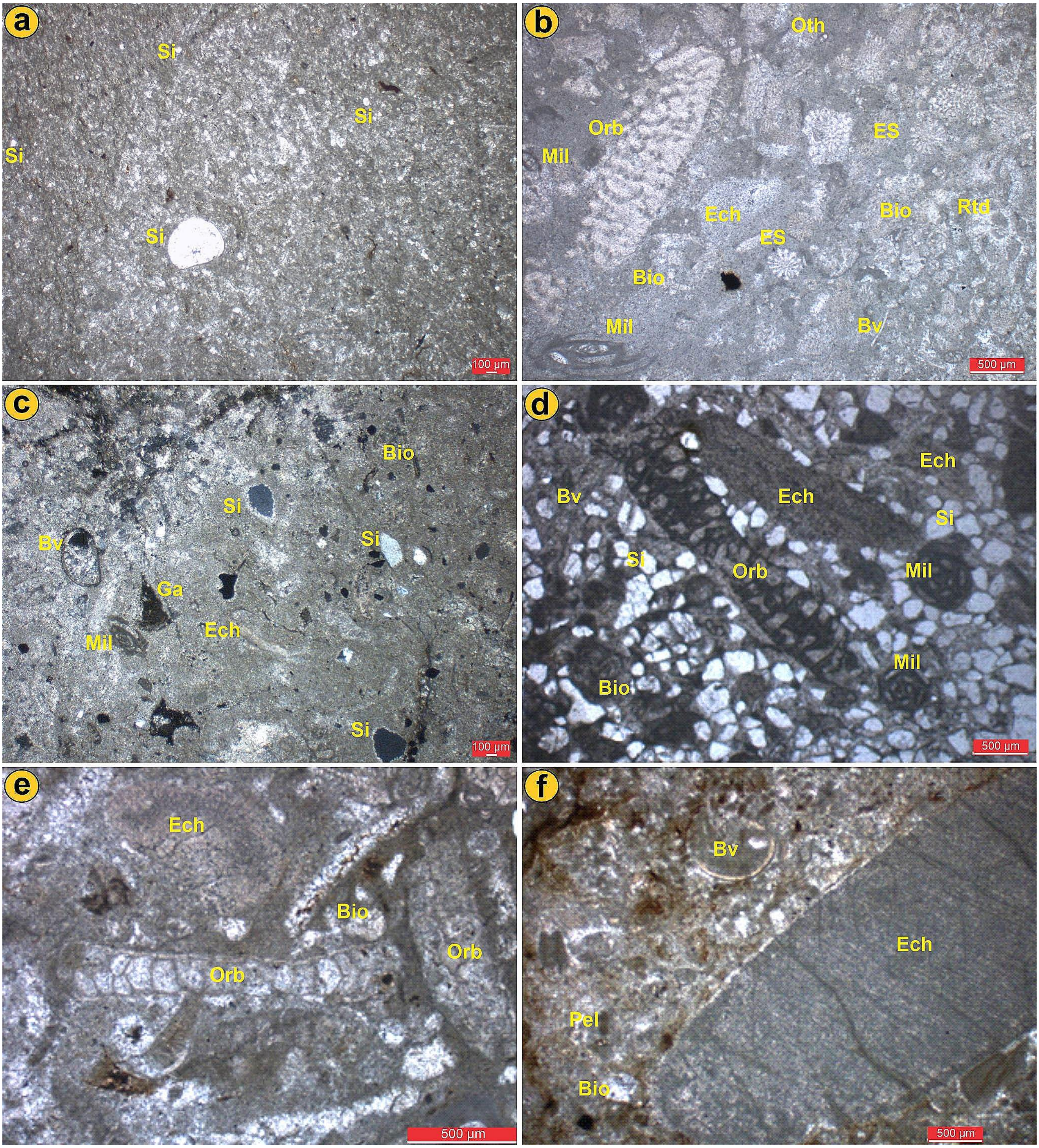


Fig. 7 Photomicrographs showing: **a** Siliciclastic mudstone microfacies showing siliciclasts (si). **b** Miliolids-intraclastic wackestone microfacies showing bivalve (Bv), siliciclasts (Si), miliolids (Mil), bioclasts (Bio), gastropod (Ga), echinoderm (Ech). **c***Orbitoides* bearing bioclastic wackestone showing echinoderm (Ech), *Orbitoides* (Orb), bioclasts (Bio). **D***Orbitoides* bearing bioclastic wackestone showing miliolids (Mil), *Orbitoides* (Orb), echinoid spine (ES), echinoderm (Ech), bioclasts (Bio), rotaliid (Rtd), other foraminifera (Oth). **e***Orbitoides* bearing miliolids siliciclastic wackestone microfacies showing bivalve (Bv), echinoderm (Ech), *Orbitoides* (Orb), bivalve (Bv), siliciclasts (Si), bioclasts (Bio), miliolids (Mil). **f** Bioclastic echinoderm packstone microfacies showing bivalve (Bv), echinoderm (Ech), bioclasts (Bio), peloids (Pel)

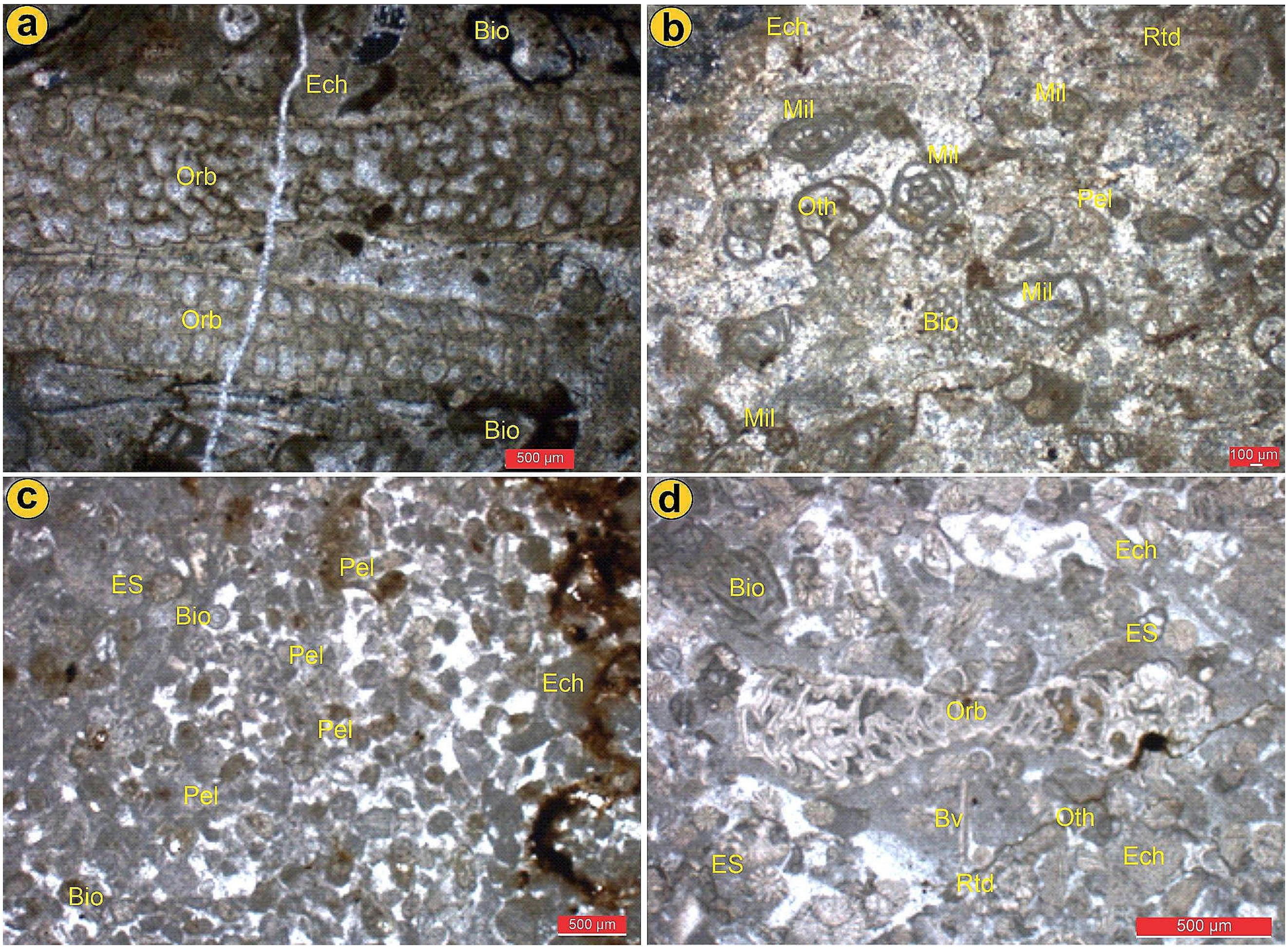


Fig. 8 photomicrographs showing: **a** Bioclastic orbitoidal packstone microfacies showing *Orbitoides* (Orb), echinoderm (Ech), bioclasts (Bio). **b** Bioclastic miliolids grainstone microfacies showing miliolids (Mil), echinoderm (Ech), rotaliid (Rtd), peloids (Pel), echinoid spine (ES), bioclasts (Bio), other foraminifera (Oth). **c** Peloidal bioclastic grainstone microfacies showing peloids (Pel), echinoderm (Ech), bioclasts (Bio). **d** *Orbitoides* bearing bioclastic grainstone microfacies showing *Orbitoides* (Orb), echinoid spine (ES), echinoderms (Ech), bivalve (Bv), rotaliid (Rtd), bioclasts (Bio), other foraminifera (Oth)

Orbitoides bearing bioclastic peloidal grainstone (I)

Description

This microfacies is comprised of thick bedded, dark gray limestone, which is highly fossiliferous with foraminifera, bivalves and *Orbitoides*, present in the upper part of the Murre Brewery section (MBB-6, MBB-7, MBB-8, MBB-10 and MBB-11). The allochems are composed of peloids (25%) and skeletal grains (41%). Skeletal allochems comprising of echinoderm (5%), and foraminifera (11%). Foraminifera include *Orbitoides* (2%), rotaliids (5%), miliolids (2%), smaller benthic foraminifera (1%) and undifferentiated foraminifera (1%). The remaining matrix comprises of sparite (59%) (Fig. 8d).

Interpretation

This microfacies is dominantly represented by peloids with normal shallow marine fauna. The texture of grainstone and presence of sparite indicates high-energy conditions (Flügel 2010). *Orbitoides* are common in open marine environment of the inner ramp (Goldbech 2007) and has ranges middle ramp (Grafe 2005), whereas, miliolids are abundant in restricted environment of the inner ramp but can be found throughout the inner ramp (Geel 2000; Romero et al. 2002). Presence of echinoderms indicates normal shallow marine condition (Scholle and Ulmar-Scholle 2003). Peloids, classified as micritized bioclasts, undergo internal structure deterioration either due to organism activity in low-energy inner ramp conditions or during diagenesis. Therefore, on the basis of grainstone texture, abundant peloids, sparry matrix, together with the mixing of restricted

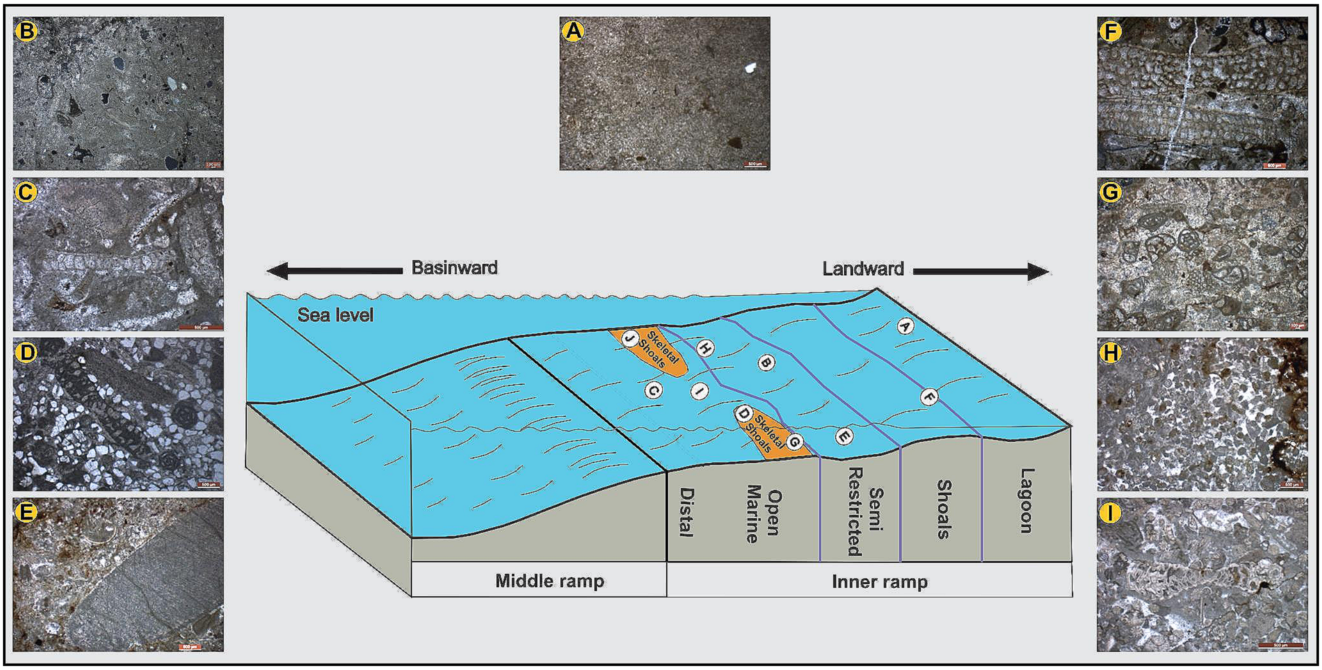


Fig. 9 Proposed Depositional Model of the Upper Cretaceous Fort Munro Formation in the western Sulaiman Range, Quetta, Pakistan

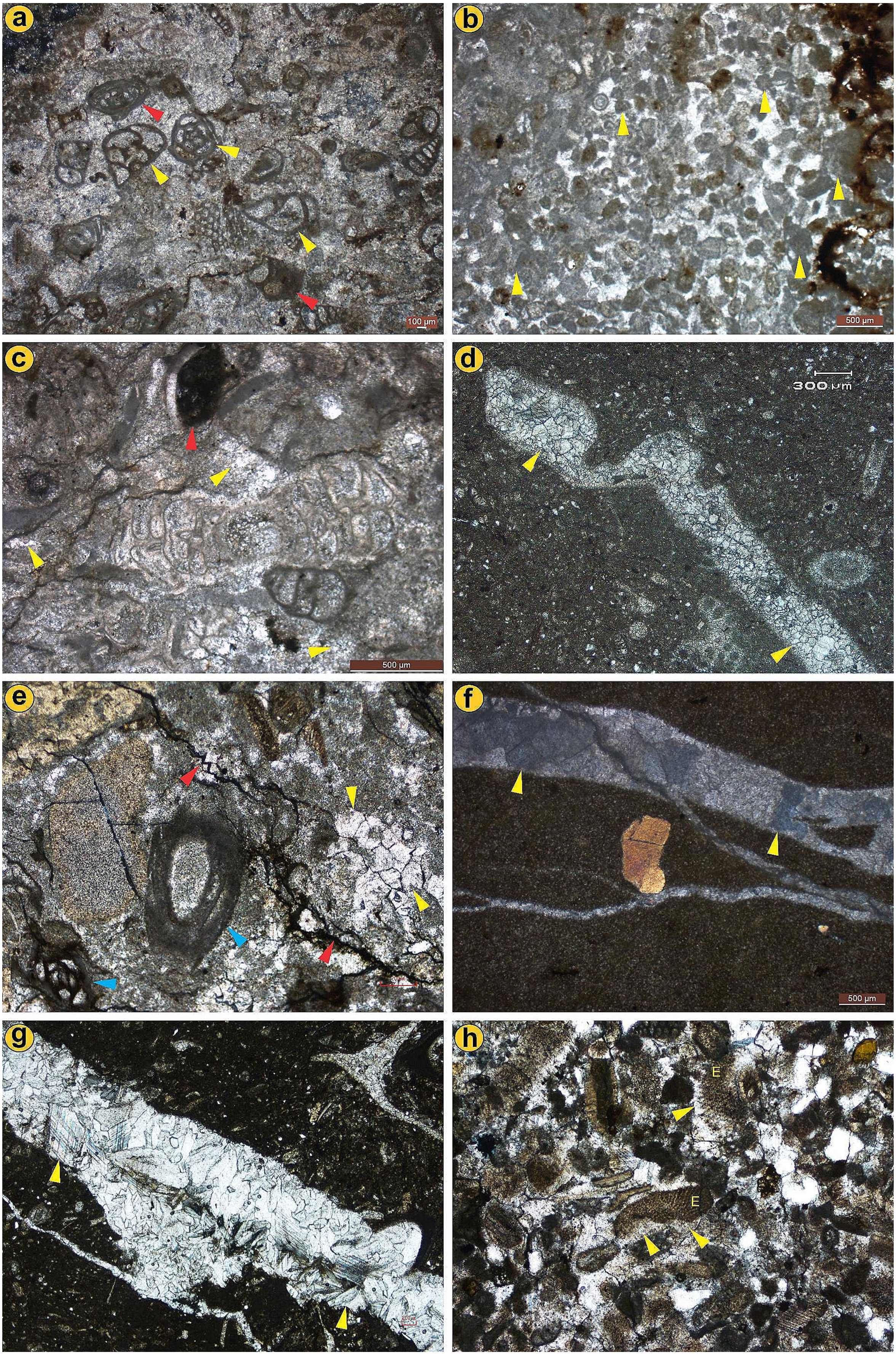
and open marine fauna strongly suggests the deposition of this microfacies in storm induced skeletal shoal inner ramp depositional environment. This microfacies is comparable with RMF 26 of Flügel and Munnecke (2010).

Depositional model

The diverse biota, dominant micritic matrix with some sparite, vertical facies variation, association of different biotic components and the interpreted environment for each microfacies suggests an overall deposition in an inner ramp environment for the Fort Munro Formation (Fig. 10). In this study the distribution of different biota, such as *Orbitoides*, milliolids, corals, echinoderms, bivalves, algae, matrix types and their ratio to different biogenic allochems, have been used to infer depositional environments of these carbonates. The diversity and richness of each fossil group reflects a specific environment and water depth (Wright and Burchette 1998; Racey 2001); e.g. the larger benthic foraminifera *Orbitoides* are dominant in a distal inner ramp environment (Grafe 2005; Goldbeck 2007), miliolids are common in a restricted lagoonal environment (Geel 2000; Abdullah et al. 2023), whereas, rich and diverse assemblages of echinoderms and other shallow water fauna such as bivalves and gastropods suggest an inner ramp shoal environment (Scholle and Ulmer Scholle 2003; Sallam et al. 2015; Sallam and Ruban 2020). Thus, different types of foraminifera, echinoderms, molluscs, corals and other biogenic allochems are instrumental in deciphering the paleo–environments of the studied succession. A proposed depositional model for the Fort Munro Formation is shown in the Fig. 9.

Therefore, the microfacies recognized in the Cretaceous Fort Munro Formation suggest following environments:

1. The microfacies A with rare occurrence of biogenic components and dominated by micrite with a mudstone texture reflects a lagoonal environment.
2. The microfacies B, D and G dominated by miliolids along with gastropods, echinoderms and bivalves suggest a semi-restricted Inner Ramp Environment.
3. Microfacies C and I dominated by normal shallow marine fauna along with some restricted fauna such as miliolids suggest an inner ramp skeletal shoal environment.
4. The microfacies C and H are dominated by shallow marine fauna such as echinoderms, bivalves, *Orbitoides*, corals with peloids and some siliciclastic input representing an Inner Ramp Open Marine Environment.
5. The microfacies E is dominated by echinoderms with high energy condition indicating a storm induced Inner Ramp Environment.
6. The microfacies F are dominated by *Orbitoides* reflecting a Distal Open Marine Environment.


a
b
c
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e
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g
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100 μm
500 μm
500 μm
300 μm
500 μm
E
E

Fig. 10 Photomicrographs showing the different diagenetic processes in Fort Munro Formation. **a** Micrite envelopes around a bioclasts (indicated by yellow arrows) partially micritized bioclasts with recognizable internal structure (red arrows) in bioclastic miliolids grainstone microfacies. **b** Completely micritized bioclasts (indicated by yellow arrows) showing no relict internal structure in peloidal bioclastic grainstone microfacies. **c** Replacement of early micrite by the granular mosaic cements (indicated by yellow arrows) due to aggrading neomorphism in bioclastic orbitoidal packstone microfacies. also showing the completely micritized bioclast (red arrow). **d** Inversion neomorphism in which the aragonitic bivalve shell has been transformed to blocky calcite cements (BC-1) in bioclastic siliciclastic mudstone microfacies. **e** Blocky calcite cements (BC-3 indicated by yellow arrows) occluded the dissolution porosity in miliolids bioclastic Intraclastic wackestone microfacies. Also, the stylolites (red arrows) and partially micritized bioclasts (blue arrow) can be seen. **f-g** Late-stage fracture filling blocky calcite cements (BC-3) in bioclastic siliciclastic mudstone microfacies. **h** syntaxial overgrowth cements (yellow arrows) over echinoderm (E) host grain have occluded the pre-existing porosity

Comparison with the section from eastern sulaiman range

The Fort Munro Formation is well exposed (about 200m thick) in the Rakhi Nala section of the eastern Sulaiman Range, which is designated as its type locality. Detailed microfacies analysis were carried out by Rizwan et al. 2020. They have recognized several carbonate marine depositional environments including the inner ramp and middle ramp of Burchette and Wright (1992) (Fig. 3 in Rizwan et al. 2020). Inner ramp includes open-marine, storm-induced skeletal shoals, semi-restricted shallow marine, carbonate sand shoals and banks, and lagoonal depositional environments. Siliciclasts are consistently present across the formation, exhibiting a gradual increase towards the upper portion. The uppermost part of the formation has accumulated a substantial quantity of siliciclasts, resulting in a distinctive sandstone depositional texture. The prevalence of late Cretaceous *Orbitoides* diminishes as clastic input increases, gradually decreases towards the uppermost part of the formation where the supply of clastic is abundant, which is attributed to its preference for shallow marine environments. The late Cretaceous *Orbitoides* is interpreted to have lived in “deeper environments” in the upper photic zone at depths of about 40–80 m (Hottinger 1997; Hohenegger 1999). In the western Sulaiman range in this study, the Fort Munro Formation pinches out and their maximum thickness reaches up to 40m in the Muree Brewery Section (Figs. 4–6). Inner ramp depositional environment is more widespread in the western sections like the eastern counterpart includes open-marine, storm-induced skeletal shoals, semi-restricted shallow marine, carbonate sand shoals and banks, and lagoonal depositional environments.

The Muree Brewery Section is characterized by lagoonal depositional environments which is represented by sample MBB-1. The remaining represents the inner ramp storm-induced skeletal shoal depositional environment. In the Spera Ragha Section the lowermost samples represent the protected inner ramp then followed by a relatively deeper depositional environments up to the distal open marine inner ramp. The complete vertical section of the investigated formation is exposed in the eastern Sulaiman range which represents a complete record of sedimentation in a variety of sedimentary environments. Whereas, in the western Sulaiman range the formation shows a very less variation in lithology and depositional environments and clearly demonstrates the pinching of Fort Munro Formation towards the western and distal part of the basin.

Diagenesis

The limestones within the investigated Fort Munro Formation have undergone diverse diagenetic processes, encompassing micritization, cementation, dissolution, and neomorphism, along with both mechanical and chemical compaction. These diagenetic processes accurately reflect the alteration conditions, aligning with the changes that occurred over time. Diagenetic processes are primarily governed by the chemical attributes of pore fluids, the influx rate through the pore system, and the temperature and pressure conditions in which rock-water interactions occur (Flügel 2010). These diagenetic processes impact and alter porosity by dissolving pre-existing carbonate phases and/or precipitating new cement phases (Moore 1989). The studied carbonates have undergone a variety of diagenetic processes from early marine diagenesis followed by burial to meteoric diagenesis. These diagenetic processes can either enhance or diminish fluid pathways within the rock. Hence, diagenetic processes exert significant control over subsurface fluid chemistry and porosity distribution.

Micritization

Micritization is the process by which bioclasts are altered while on the seafloor or just below by endolithic algae, fungi, and bacteria (Tucker and Wright 1990). The term micrite envelope was first used by Bathurst (1966) in the study of syngenetic and early diagenetic changes affecting modern skeletal grains. Micritic envelopes resulting from endolithic cyanobacteria can serve as a depth criterion, signifying deposition within the photic zone, typically less than 100–200 m (Zeff and Perkins 1979; Flugel 2010). The micritization process has been observed in nearly all microfacies of the investigated carbonates, spanning from the bottom to the top (Fig. 10a, b). Micritization predates all other diagenetic features and very passive in the grainstone microfacies. Micritization occurs in the form of a micritic

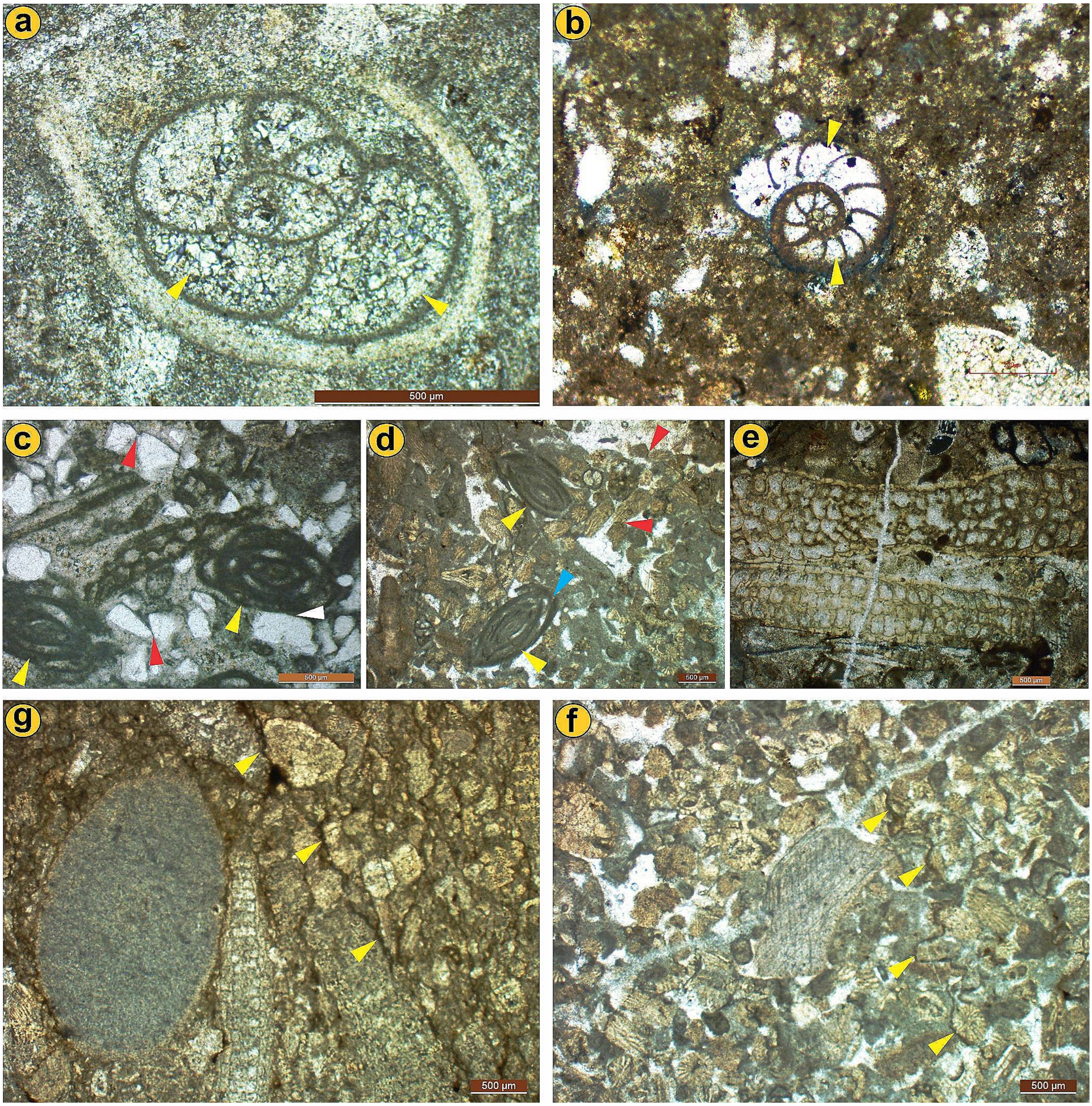

Fig. 11 Photomicrographs showing the different diagenetic processes in Fort Munro Formation. **a-b** Granular mosaic calcite cements in the chambers of foraminifera and have occluded the intragranular porosity in *Orbitoides* bearing bioclastic wackestone microfacies. **c-d** Mechanical grain packing and distortion in *Orbitoides* bearing miliolids siliciclastic wackestone and *Orbitoides* bearing bioclastic grainstone microfacies. Observe the bioclasts distortion (yellow arrows), point contacts (red arrows), straight grain contacts (white arrows), and grain breaking (blue arrow). **e** Micro fracturing during the shallow burial crosscuts skeletal allochems subsequently filled by the granular cements in bioclastic orbitoidal packstone microfacies. **f-g** Multi-grain pattern non-parallel reticulate stylolites following the bioclasts (indicated by yellow arrow) in *Orbitoides* bearing bioclastic wackestone (f) and *Orbitoides* bearing bioclastic grainstone microfacies

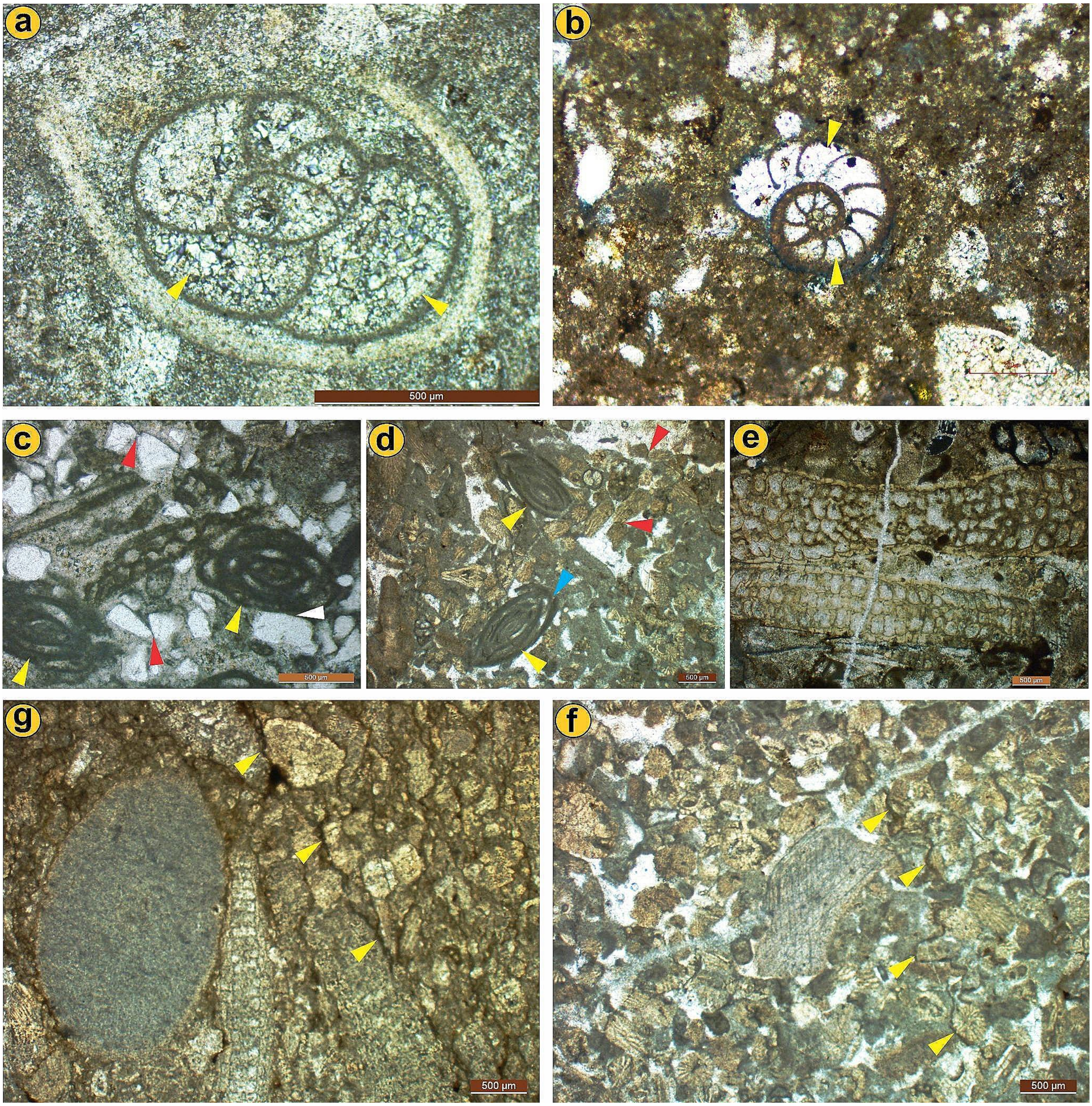

Fig. 12 Paragenetic sequence of the Upper Cretaceous Fort Munro Formation based on the observed diagenetic processes and stages, and their impact on the reservoir quality. Relative timing of diagenetic features is inferred from petrography

envelope around the periphery of skeletal fragments including foraminifera, ostracodes, echinoderms, and bivalves. Almost all of the peloids in the grainstone microfacies are the micritized allochems the internal structure of which has been completely destroyed as a result of processes associated with the endolithic algae. The micritization process aids in preserving the outlines of grains in slightly neomorphosed rocks by forming micrite envelopes.

Neomorphism

Neomorphism refers to a transformation occurring within a mineral, involving either the mineral itself or a polymorph. It excludes simple pore-filling, as the older crystals must undergo a gradual consumption, allowing new crystals of the same mineral or a polymorph to take their place simultaneously (Folk 1974; Bathurst 1972; Chafetz 1972). Dissolution and re-precipitation occur within a thin film, without

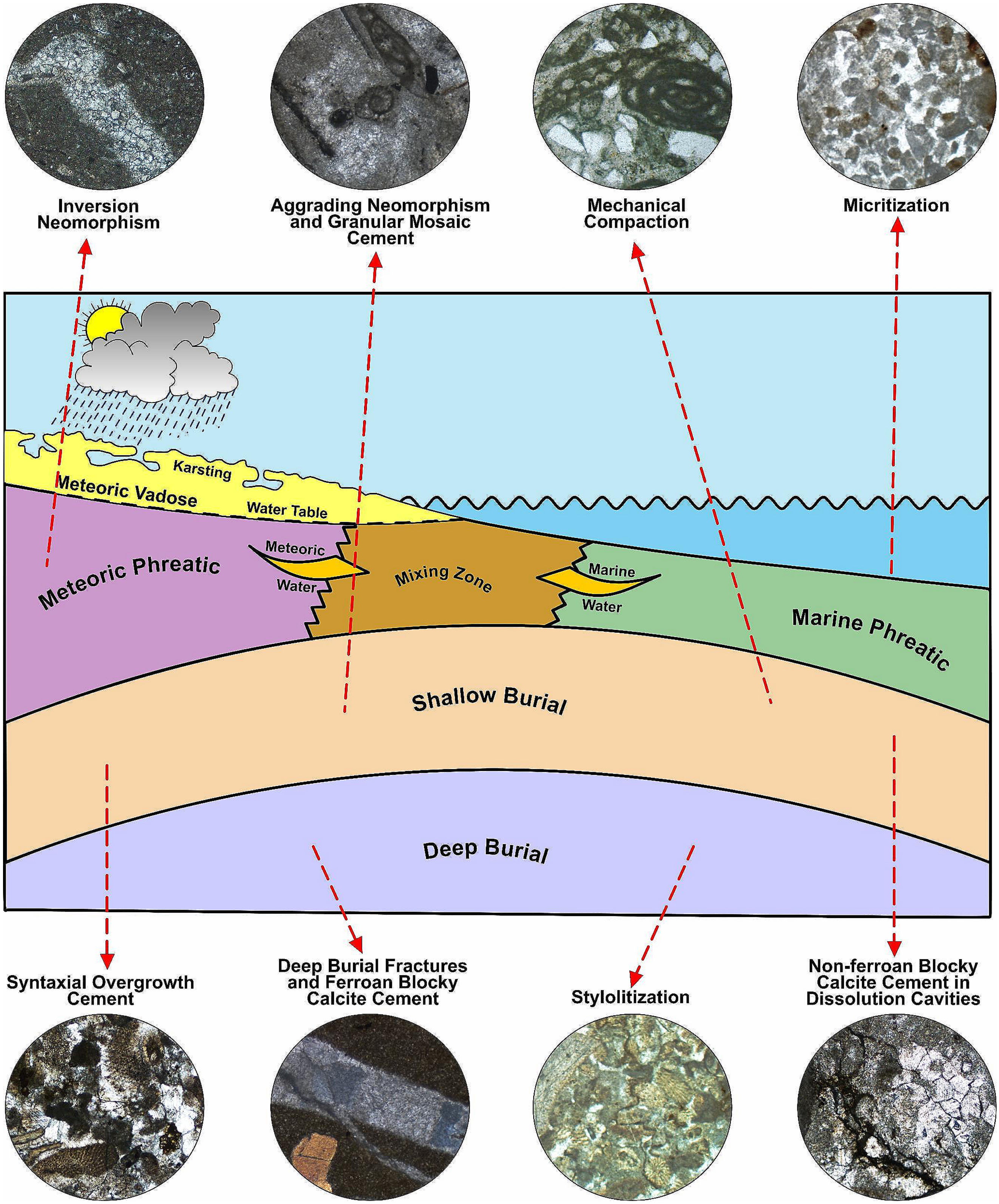

Fig. 13 Schematic diagram illustrating the proposed diagenetic environments for the Upper Cretaceous Fort Munro Formation in the western Sulaiman Range, Lower Indus Basin, Pakistan

substantial dissolution or the formation of porosity on a large scale (Adams and Mackenzie 1998). Neomorphism in the investigated carbonates including aggrading and inversion or polymorphic transformation. The aggrading neomorphism is represented by an increase in grain size where the calcite crystals grow at the expense of other crystals. Aggrading neomorphism is the process wherein a finely crystalline carbonate mosaic is substituted by a coarser (sparry) mosaic of the same mineral or its polymorph, occurring without the intermediate creation of observable porosity (Folk 1965; Maliva 1995). Aggrading neomorphism is a widespread diagenetic process in the investigated carbonates after the micritization and more pervasive in the wackestone, Packstone, and grainstone microfacies (Fig. 10c). This type of aggrading neomorphism shows that the Fort Munro Formation undergone meteoric and marine to deep burial diagenesis. These neomorphic processes are wet processes that occur in the presence of water through a dissolution to reprecipitation (Tucker and Wright 1990; Bathurst 1972).

Inversion neomorphism is a process in which calcite replaces the aragonite. In this replacement, the gradual dissolution of the original mineral (aragonite) leads to the precipitation of calcite, preserving the original shell remnants or mold in the form of neomorphic calcite. Inversion process is mostly observed in the mudstone and Wackestone microfacies and is represented by the calcite transformation of gastropods and aragonitic bivalve shell fragments. The moldic voids are gradually filled with blocky calcite cements, indicating a very early diagenetic process. This initial aragonite dissolution could have taken place within a marine diagenetic environment or during a relatively shallow burial (Palmer et al. 1988; Ferry et al. 2007; Maliva et al. 2000). The upper portion of the meteoric phreatic environment, specifically the area with active circulation, strongly indicates the occurrence of wet aragonitic transformation followed by the precipitation of early blocky calcite cement (Rizwan et al. 2023).

Cementation

Cementation occurs through the entire diagenetic process, wherein chemical precipitates, taking the form of new crystals, develop within the pores of sediment or rock, effectively binding the grains together (McIlreath and Morrow 1990). The mineralogy, shapes, and crystal forms of carbonate cements undergo alterations as diagenetic environments and water chemistry transition from marine phreatic conditions to meteoric phreatic conditions and further to shallow and deep subsurface waters (Ahr 2008). The source of $CaCO_3$ differs; in marine environments, it originates from seawater, whereas in meteoric and burial realms, it is derived from the dissolved material within the sediments themselves (Tucker and Wright 1990). The investigated carbonate rocks contain various types of cement as follows.

Blocky calcite cement Blocky calcite cement occluded a variety of pore spaces including intergranular in dissolution cavities and fractures. Detailed petrographic observation reveals the three categories of blocky calcite cements in the Fort Munro Formation: BC-1, BC-2, and BC-3. BC-1 occurred as intergranular cement filling up the moldic porosity of the aragonitic shells (Fig. 10d). It is not an original pore-filing but has been formed by the neomorphic inversion of aragonitic skeletal allochems. In meteoric water environments, the low Mg^{2+} content facilitates the precipitation of calcite cements (block shaped cement) and mainly formed in meteoric phreatic diagenetic environments (Choquette & James 1990; Flügel 2010; Tucker 2001; Zhang et al. 2006). BC-2 occurred in dissolution cavities, mostly subhedral in shape with clear boundaries, and ranging in size from 40 to 650 µm (Fig. 10e). BC-2 indicates a moderate to deep burial diagenetic environment, as they hinder the dissolution processes associated with meteoric to shallow burial diagenetic environments. BC-3 is a third type of blocky cement entirely the late-stage fractures (Fig. 10f, g). This stage corresponds to a singular generation of blocky cement in the investigated carbonates, identified by undulatory extinction, which is diagnostic of burial realms (Andre 2003; Vincent et al. 2007). This phase of blocky calcite cement is compositionally characterized as ferroan, low-magnesium calcite (Vincent et al. 2007; Brigaud et al. 2009).

Syntaxial overgrowth cement Syntaxial overgrowth of calcite is commonly observed in the Packstone and grainstone microfacies around echinoderms host fragment. Syntaxial overgrowth of calcite on an existing nucleus is well-documented, particularly in the context of single crystals of echinoid fragments (Fig. 10h). The echinoderm exhibits a porous structure that is gradually filled through cement growth. The overgrowth exhibited a strongly preferred orientation and optic continuity with the host echinoderm nucleus. The micrite envelope on some of the echinoderm grains in the outer pores obliterated the development of syntaxial rim cement.

Granular cement Granular mosaic cement is the most widespread cement type in Fort Munro Formation. Granular cement is observed in almost all the microfacies and is comprised of small, equidimensional pore-filling calcite crystals. Granular mosaic cement commonly occurred as filling cement in intragranular porosity and filling the chambers of skeletal allochems and represented as GM-1 (Fig. 11a, b). Granular cement is also observed in the early thin fractures as a filling material and represented as GM-2. Granular mosaic cement is reported from meteoric vadose, meteoric phreatic, and burial diagenetic environments (Flügel 2010).

Compaction

Compaction is a term used to describe any process that diminishes the bulk volume of rocks. The compaction process impacted the Fort Munro Formation after deposition, resulting in physical and chemical rearrangements and variations in the bulk volume of sediments. The compaction process in the Fort Munro Formation at the studied section is divided into two types: mechanical compaction and chemical compaction.

Mechanical compaction The sedimentary overburden leads to a widespread decrease in porosity, sediment thickness, and rock volume, consequently causing mechanical grain failure. This process can occur in both shallow and deep-burial diagenetic environments (Tucker and Wright 1990; Tucker 2001). Mechanical processes reduce the bulk volume of individual grains through grain deformation or induce closer packing of grains, such as reorientation. Mechanical compaction in the Fort Munro Formation resulted in the packing of grains, the breakage and distortion of skeletal allochems, and very thin microfractures subsequently filled by granular cement (Fig. 11c-g). When the brittle or ductile strength of the grains and matrix is surpassed, the breaking of grains and fracturing occurs (Fig. 11d).

Chemical compaction (stylolites) Chemical compaction in the Fort Munro Formation manifests as dissolution seams and fitted fabrics formed by stylolites in the interstitial spaces between grains. Stylolites are formed through pressure solution because of chemical compaction influenced by the overburden of sediments or tectonic stresses (Wanless 1979). Mechanical compaction can eventually transition into chemical compaction if the grains start to dissolve at their contacts (Flügel 2010). It frequently crosscuts the entire rock, intersecting grains, matrix, and cement. Insoluble materials, typically clay or hydrocarbons, tend to concentrate along the surface of the stylolites (Flügel 2010). The formation of stylolites necessitates an increase in overburden pressure or the presence of undersaturated fluid. The factors influencing the shape and type of stylolites include laminations, clay content, and cementation (Burges and Petor 1985). Stylolitization is a significant diagenetic process in the Fort Munro Formation, commonly observed, especially in the form of bedding-parallel stylolites.

Fractures

Fractures and veins are evident at both microscopic and macroscopic scales in the studied Fort Munro Formation. The macrofractures identified in the Sakessar Limestone primarily exhibit extensional characteristics. At microscopic scales, fractures are filled with calcite cement, some of which are several 500 µm wide. These fractures could be tectonic in nature, potentially associated with folding or regional tectonic activity. In fractured carbonate reservoirs, fluid movement primarily relies on pore types, the internal fracture network, and pore connectivity (Loucks et al. 2012). Almost all the fractures are filled with late-stage blocky calcite cements (BC-3) in the deep burial diagenetic environment and have occluded most of the secondary porosity (Fig. 10f, g).

Paragenetic sequence and diagenetic environments

Detailed petrographic analysis of the Fort Munro Formation in the studied section reveals the three diagenetic settings: shallow water normal marine, meteoric, and burial diagenetic environments. Each of these diagenetic environments possesses specific characteristics and diagnostic features, which are briefly discussed in the following lines. The sequence of diagenetic processes in carbonate rocks is dependent on sediment composition, grain size and texture, mineralogy, characteristics of pore fluids, and climatic conditions (Tucker and Wright 1990; Flügel 2010). Some diagenetic processes, such as cementation, compaction, and selective dissolution, are closely linked to depositional texture and mineralogy (Lucia et al., 1999). The paragenetic sequence and diagenetic model for the Fort Munro Formation are shown in Figs. 10 and 11, respectively.

Marine diagenetic environment (eogenetic stage)

Marine diagenesis occurs on the seafloor and just below it. The initial phase of diagenesis occurs on the seafloor and may extend into the meteoric realm (Boggs and Boggs 2009). Based on sedimentary petrographic analysis, the shallow-water normal-marine diagenetic environment is characterized by slight grain deformation, syntaxial overgrowth cements, and micritization of skeletal allochems, influenced by mechanical compaction and marine phreatic cementation. Micritization likely formed through the boring activity of endolithic algae and precipitation in a manner where the ambient waters were supersaturated with calcium carbonate on the seafloor or sediment–water interface (Bathurst 1966; Fig. 7). Bioclastic micritization represents the early stage of paragenetic sequence and is a very common diagenetic process of the Fort Munro Formation and observed in almost all the microfacies.

syntaxial overgrowths on echinoderm grains lacking micrite envelopes is also a characteristic of marine diagenetic environments (Brigaud et al. 2009). Textural evidence indicates that the overgrowth formed concurrently with early marine cements. Syntaxial cements precipitate during the early diagenesis period in an oxidizing environment and primarily have a marine origin (Sanders 2001). Some studies associate the overgrowth with a freshwater diagenetic environment (Land 1970; Jacka and Brand 1977; Meyers 1978; Halley and Harris 1979; Longman 1980). Syntaxial overgrowth represents the transition from a marine phreatic to a freshwater phreatic diagenetic environment (Tobia 2018). Syntaxial overgrowth occurred under meteoric diagenetic conditions (Bathurst 1972). However, it sometimes participates in other diagenetic environments, such as meteoric and burial diagenesis (Vincent et al. 2007).

Meteoric diagenetic environment (eogenetic stage)

This environment initiates with the loss of magnesium from High-Mg calcite, followed by the disappearance of aragonite, and its eventual replacement by calcite (Flügel 2010). Inversion neomorphism and BC-1 blocky calcite cements are the most common process in the investigated carbonates, formed in the meteoric diagenetic environment. The common process observed in the Fort Munro Formation involves the skeletal metastable aragonitic transformation to stable low-magnesian calcite. This transformation occurs when carbonates are exposed to meteoric water conditions (Briguad et al. 2009; Flügel and Munnecke 2010; Ali 2014; Amel et al. 2015; Arosi and Wilson 2015). The dissolution of metastable skeletal allochems in meteoric phreatic conditions has led to the formation of vugs and molds. However, these cavities were concurrently filled by non-ferroan blocky calcite cement (BC-1), completely occluding the secondary porosity.

Burial diagenetic environment (mesogenetic stage)

As the sediments of the Dungan Formation underwent an initial period of diagenesis on the seafloor, they were gradually buried and exposed to increased pressure, higher temperature, and a compositional change in pore fluid in the subsurface realm. The investigated carbonates was subjected to the burial diagenetic environment and represents a major phase of diagenesis. Burial diagenesis pertains to alterations occurring below the zone of near-surface water circulation (Scholle and Ulmer-Scholle 2003). Under these conditions, characteristic diagenetic fabrics primarily include the aggrading neomorphism, porosity reduction, mechanical compaction features related to burial (such as closer grain packing, brittle grain deformation, and fracturing), fracturing, BC-2 blocky calcite cements in fracture, chemical compaction features (stylolites formation, sutured boundaries between grains, and pressure solution structures). The burial diagenetic realms are conventionally divided into shallow burial and deep burial; however, the exact boundary is not well-defined (Vincent et al. 2007; Flügel 2010). Aggrading neomorphism commonly occurs during shallow to moderate burial conditions (Amel et al. 2015; Ahmad et al. 2021). Chemical compaction is a crucial diagenetic process in the deep burial environment, leading to the dissolution of grains and matrix.

Impact of diagenesis on the reservoir

The diagenetic processes in the studied Fort Munro Formation contributed to the modification of reservoir characteristics. Diagenetic processes in carbonates either enhance or deteriorate the porosities. As a result, porosity is compromised, particularly due to marine cementation in marine environments. While dolomitization, dissolution, the development of moldic pores, and fracturing have led to an augmentation in pore volume. Through an in-depth petrographic analysis, it is determined that Fort Munro Formation contains both primary and secondary porosities. Diagenetic mechanisms, including processes like calcite cementation, micritization, and compaction, played a role in diminishing pore spaces. Primary porosity mainly exists in the form of intragranular porosity in the skeletal allochems including foraminifera (both larger and smaller), gastropods, and ostracodes. Under shallow-water, normal-marine conditions, the primary diagenetic processes that altered porosity were microbial micritization, early (mechanical) compaction, and marine phreatic cementation. The variations in petrophysical properties induced by diagenetic processes significantly influence the reservoir quality of the Fort Munro Formation. The reservoir quality of the Fort Munro Formation undergoes considerable modification as a result of marine, meteoric, and burial diagenetic environments. Diagenetic process enhancing the reservoir quality of Fort Munro Formation includes dissolution, fracturing, and stylolites. Micritization is the most common diagenetic process in the studied formation, preserving itself through the presence of endolithic micritic envelopes surrounding grains and exhibiting either partial or complete skeletal grains destruction. This process resulted in the filling of intraparticle and interparticle porosity, consequently reducing permeability through a decrease in pore throat size.

(Taghavi et al. 2006). Therefore, micritization has a detrimental effect on the reservoir potential of the Fort Munro Formation.

Neomorphism contributes to the reduction of porosity and the conversion of aragonite to calcite stands out as a crucial process in the diagenesis of carbonates observed in the Chorgali Formation. It directly governs the petrophysical characteristics of limestones (Banner 1995; Maliva 1998). The transition from aragonite to calcite leads to a rise in the overall rock volume by 8%, consequently causing an 8% decline in porosity (Selley 2000). Sediment compaction can lead to a reduction in porosity. The rise in lithostatic pressure, stemming from burial, induces compaction, and simultaneous tectonic stresses during deposition can also contribute to compaction. The formation of stylolites entirely eradicates porosity and eliminates permeability in dolomites. However, on a microstructural level, it improves horizontal permeability (Hassan 2007). Mechanical compaction leads to a dense rock structure, potentially impacting reservoir quality adversely. Microfractures serve as pathways that facilitate fluid flow and contribute to the porosity and permeability of the Fort Munro Formation.

Cementation is the primary diagenetic mechanism in the Fort Munro Formation, leading to a reduction in both porosity and permeability. Therefore, the meteoric (freshwater) environment possesses the capacity to create porosity through dissolution processes and, simultaneously, reduce porosity through extensive cementation (Moore 1989). The principal cement impeding porosity precipitated during the early diagenetic history of the Fort Munro Formation, where both intraparticle and interparticle pore spaces were filled by calcite cements, thereby diminishing the reservoir potential. In the investigated carbonates, the original porosity decreased due to mechanical compaction and cementation.

Conclusions

Detailed sedimentological investigation of the Fort Munro Formation in the studied sections in Ziarat District reveals the following conclusions: Detailed microfacies analysis reveals the nine microfacies including Siliciclastic mudstone (A), Miliolids Intraclastic wackestone (B), *Orbitoides* bearing Bioclastic wackestone (C), *Orbitoides* bearing Miliolidal Siliciclastic wackestone (D), Bioclastic Echinoderm packstone (E), Bioclastic Orbitoidal packstone (F), Bioclastic Miliolids wackestone (G), Peloidal Bioclastic grainstone (H), and *Orbitoides* bearing Bioclastic Peloidal grainstone (I).

- Several carbonate depositional environments are space removed before are recognized including inner ramp and middle ramp. The inner ramp depositional environment is more widespread than the middle ramp and includes open-marine, skeletal shoals, semi-restricted, carbonate sand shoals and banks and lagoon depositional environments.
- Various diagenetic features, including micritization, dolomitization, cementation, neomorphism, dissolution, compaction (both mechanical and chemical, such as stylolitization), and fracturing, have altered the Fort Munro Formation. These diagenetic events and processes indicate that the Fort Munro Formation has undergone marine, meteoric phreatic, and burial diagenesis.
- Early diagenesis includes the micritization, syntaxial overgrowths over echinoderm host grains, and mechanical compaction. The diagenetic environment influenced by meteoric conditions is marked by inversion neomorphism and early blocky cement. burial is the major phase of diagenesis in the studied carbonates and is evident by aggrading neomorphism, mechanical compaction, granular mosaic cement, fracturing, blocky calcite cement, and chemical compaction.
- It is concluded that calcite cementation, micritization, and compaction deteriorate the reservoir characteristics. whereas, dissolution, moldic pores, and fracturing increased the pore volumes in the studied carbonates.
- Cementation is regarded as a primary diagenetic process that significantly contributes to the reduction of both primary and secondary porosities in various diagenetic environments.

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Author contributions Author A conducted the entire research as part of his M.Phil. thesis. Both B and C has assisted the A in geological field work and also supervised the whole research work. E conducted the diagenetic analysis. E also completed the graphical work, prepared the final draft of the manuscript, and handled correspondence. All authors reviewed manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.
The authors claim that they have no known financial conflicts of interest or close personal relations that would appear to have affected the research revealed in this study.

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