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ORIGINAL PAPER

Microfacies analysis and reservoir evaluation based on diagenetic features and log analysis of the Nammal Formation, Western and Central Salt Range, Upper Indus Basin, Pakistan

Jabir Hussain[1] · Tahseenullah Khan[1] · Birkhez Aslam Shami[2] · Muhammad Zafar[1] · Tassawar Hayat[3]

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Abstract
The Nammal Formation of Early Eocene age crops out at Nammal Gorge (NG) and Pail (PL) in the Salt Range, Upper Indus Basin, Pakistan. It comprises mainly medium to thick-bedded and rare thin-bedded limestone with mixed carbonate sequences of limestone, marl, and shale. Allochemical constituents and micrite estimated ratio leads in recognizing seven microfacies including Foraminifer wackestone, mudstone-wackestone, Foraminifer mudstone, and *Assilina* wackestone in the NG section and Foraminifer wackestone-packstone, Foraminifer wackestone, and Bioclastic packstone in PL section. Based on microfacies and fossil assemblages, the Nammal Formation is interpreted to have been deposited in outer to mid and inner ramp settings. The formation is largely transformed by diverse diagenetic episodes comprising micritization, cementation, dissolution, neomorphism, mechanical compaction, stylolitization, fractures, and vein formation. Fractures and dissolution are inferred to augment the prospect of hydrocarbon for reservoir of the Nammal Formation. ImageJ calculated porosities and log estimated average effective porosity range from 4 to 6% and 1 to 2%, respectively. The calculated log values in Dhermund-01 and Pindori-02 wells suggest that at certain limestone intervals of the encountered Nammal Formation, there is a compacted limestone that can be regarded as a tight reservoir for hydrocarbon accumulation.

Keywords Early Eocene · Microfacies · Nammal Formation · Reservoir evaluation · Salt Range · Pakistan

Introduction

Eocene is the most vital epoch in the geological history of Pakistan as it demonstrates the highest hydrocarbon yield; specifically, the Eocene (Chorgali and Sakesar formations), which act as carbonate reservoirs. The Early Eocene Nammal Formation of the Chharat Group or Nammal Group has a good exposure in Western, Central, and Eastern Salt Range and Surghar Range of Upper Indus Basin. The Western and Central Salt Range host Nammal Formation, referred here as the Nammal Gorge section (NG) and the Pail section (PL) respectively (Fig. 1). This formation has been studied in the past in terms of faunal assemblages, biostratigraphy, paleo-environment, microfacies analysis, and surface and subsurface correlation (e.g., Haque 1956; Cheema et al. 1977; Köthe et al. 1988; Laurel and Jean 1988; Gibson 1990; Afzal 1996; Ghazi et al. 2004). The Nammal Formation has also been regarded as a reservoir and source for hydrocarbons (Aamir and Siddiqui 2006; Asif and Fazeelat 2012; Hasany and Saleem 2012; Jadoon et al. 2015). Previously, the Nammal Formation could not be thoroughly investigated for the hydrocarbon exploration due to the limited study of the exposed basal limestone and shale in the Salt Range. This study helps in devising a model for the exploration of Paleocene-Eocene plays in the adjacent Indus Basin. Previously, slight deliberation was rewarded to the sedimentological aspects due to deficiency in integrated approach to precisely determine the environment of past deposition history, paleo-diagenetic sequences, and reservoir prospect.

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✉ Tahseenullah Khan
tkhan.buic@bahria.edu.pk

[1] Department of Earth and Environmental Sciences, Bahria University, Islamabad, Pakistan

[2] Hydrocarbon Development Institute of Pakistan, Islamabad, Pakistan

[3] LMK Resources Pakistan (Private) Limited, PTET/Ufone Tower, Jinnah Avenue, Islamabad, Pakistan

Therefore, the current study coins to fit in the faunal assemblage and microfacies investigations to better unravel the depositional environment, diagenetic overprints, and hydrocarbon reservoir potential. This work may provide some knowledge for understanding the Nammal Formation as a hydrocarbon reservoir. Moreover, the study on the depositional setting and the fossil assemblages can be utilized for biostratigraphic and other sedimentological correlation across the adjacent and regional basins.

Geological setting of the area

The Salt Range Formation comprises a complex anticlinorium structure with a series of salt anticlines that occurs in the Upper Indus Basin of Pakistan (Sarwar and DeJong 1979; Gee 1989) (Fig. 1). It displays an extensive range of sedimentary rocks, from Precambrian to Quaternary excluding Ordovician to Carboniferous, along the Salt Range Thrust (Kazmi and Jan 1997). The exposed Paleocene and Eocene stratigraphic successions at the studied outcrop at the NG in Western Salt Range are represented by the Late Paleocene Patala Formation and overlying Early Eocene Nammal and Sakesar formations (Figs. 2 and 3) and at PL section, the oldest Patala Formation of the Paleocene succession is not exposed at the outcrop scale (Fig. 4). The upper contact of the Nammal Formation at the NG and PL is conformable with the Sakesar Limestone (Figs. 4 C and 5 A, B).

Structurally, the Salt Range continuously experiences compressional, transform, and extensional type deformation. The compressional deformation is manifested by thrusting and the uplift of the locally called Salt Range Thrust or regionally known the Main Frontal Thrust (MFT) that occurs at the southern margin of the Salt Range, between Indus and Jhelum rivers (Fig. 1). The transform deformation is evidenced by the Kala Bagh sinistral and Jhelum dextral strike-slip faults whereas the southern part of the Salt Range exhibits extensional deformation. The Salt Range, from north to south, comprises four main tectonic zones, viz. the Northern Potwar Deformed Zone (NPDZ; Jaswal et al. 1997), Soan Syncline, the Southern Potwar Platform Zone (SPPZ; Shami and Baig 2002), and the Salt Range (Gee 1980). The northern and southern peripheries of the Salt Range are marked by the Main Boundary Thrust and Salt Range Thrust, respectively, whereas the eastern and western peripheries are marked by Jhelum and the Kalabagh Faults, respectively (e.g., Kazmi and Jan 1997).

Materials and methods

This work focuses on the petrographic study to know the environment of deposition and diagenetic features of the Nammal Formation at NG and PL sections, which are the type localities. A total of 27 representative carbonate samples were collected from the studied outcrop sections. Outcrop scale field observation of the formations was recorded and analyzed. Petrographic study was employed for the analysis of microfacies, diagenesis, and reservoir characterization for

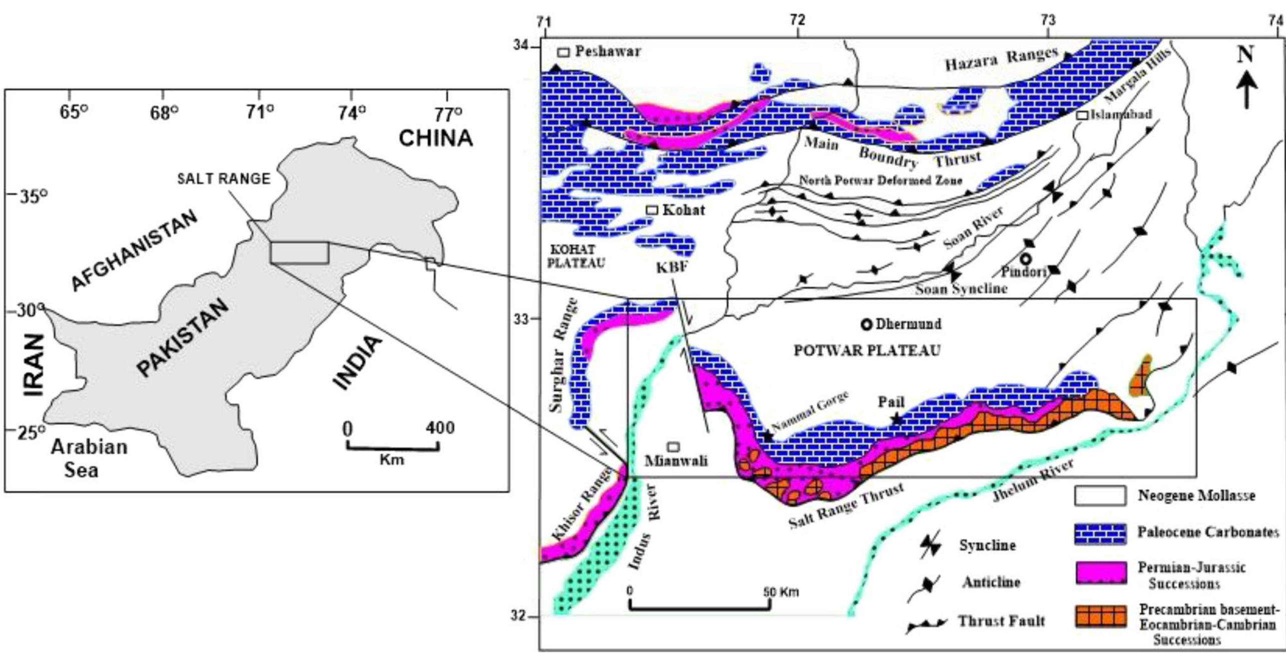


Fig. 1 Regional geological map showing the Trans-Indus ranges and the present study area shown by insets therein (after Alam et al. 2017)

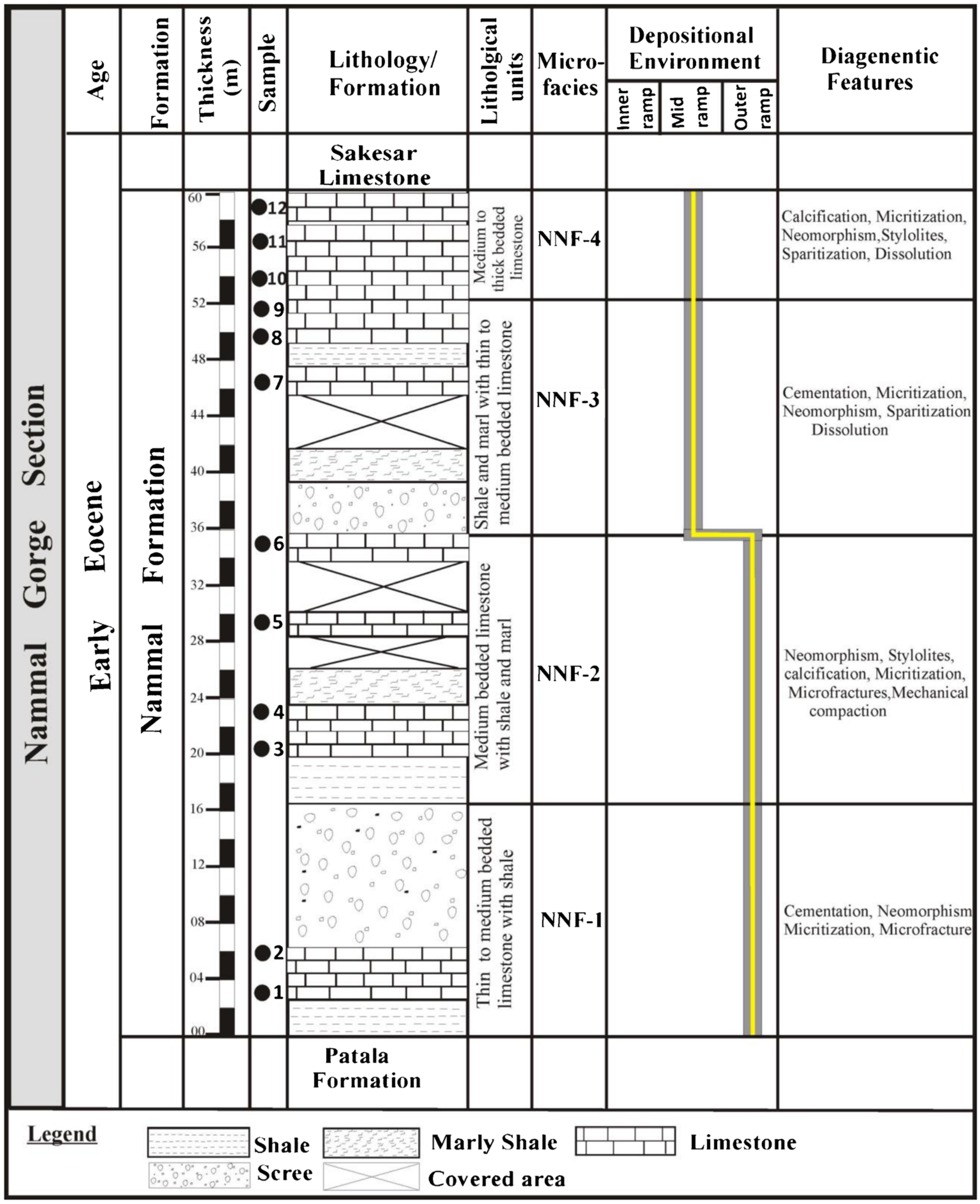


Fig. 2 Litholog of the Nammal Formation depicting the identified microfacies at Nammal Gorge section (NG)

hydrocarbon prospectively. Orthochemical and allochemical compositions coupled with the fossil assemblages were used as environmental proxies for the inference of depositional settings of the Nammal Formation. Microfacies were identified and constructed on Dunham's classification (1962). The allochem to matrix ratios was visually estimated by taking their average values by considering the chart of Scholle and Ulmer-Scholle (2003) for estimating abundances of constituents in thin sections. ImageJ software was used on the specific and representative photomicrographs at the grayscale and their relative porosity measurements were made. The petrophysical data of geophysical logs Dhermund-01 and Pindori-02 wells were employed to calculate porosities (ϕ) and permeability (K) from the porosity logs.

Results

Microfacies analysis through petrography

Based on the petrographic data, microfacies are delineated and used to interpret the environments of deposition of the Nammal Formation. The petrographic features include the type of allochem grains (both skeletal and non-skeletal) and orthochems which comprises the groundmass made up of micrite and cement (sparite or spars) (Tables 1 and 2), and the type of pores. Petrographic features in two of the sections at NG and PL mainly encompass skeletal grains scattered in micrite matrix (Figs. 6 and 7); however, some of the samples possess sparse sparite too (Fig. 6 B, H). The samples of the

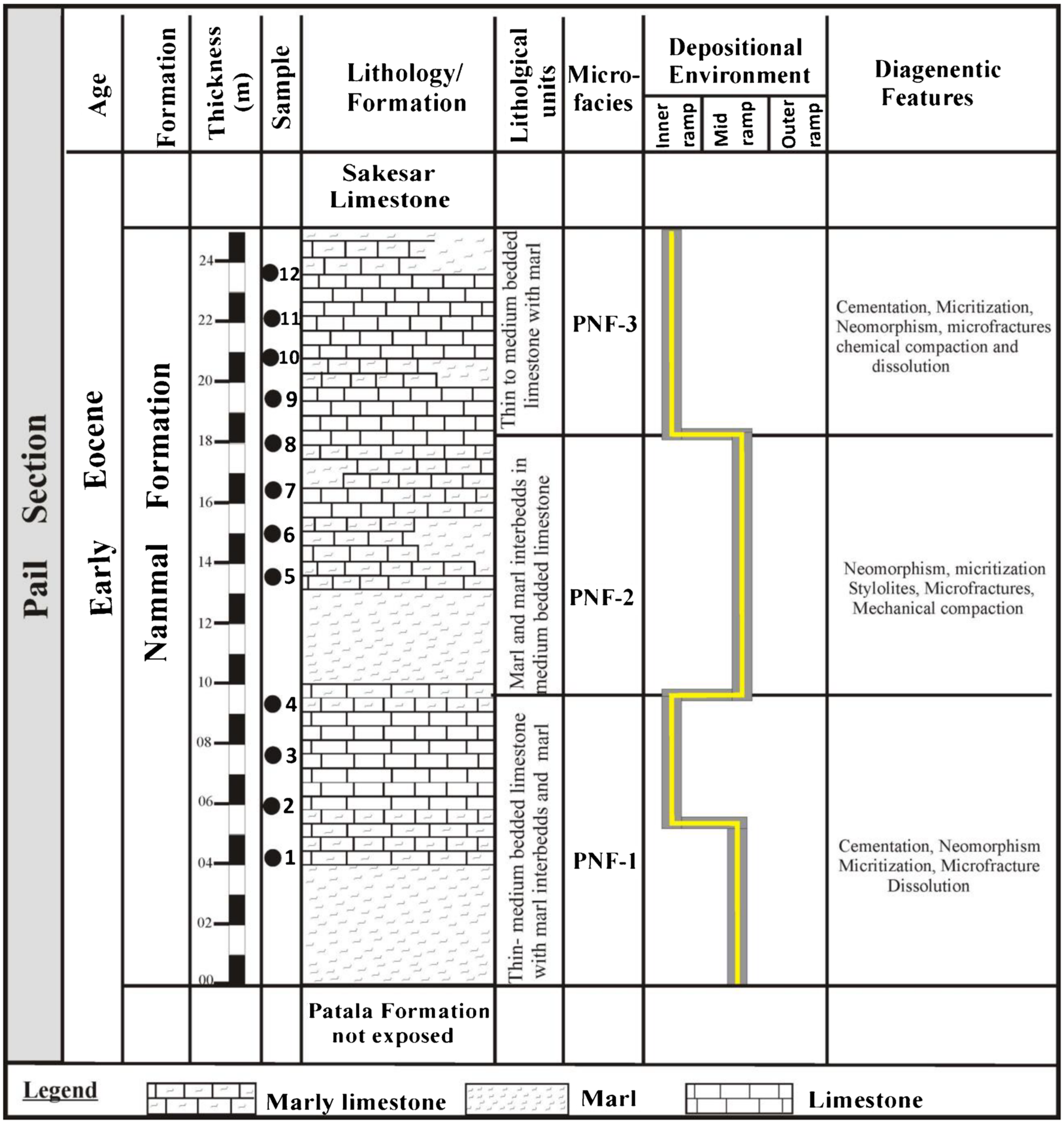


Fig. 3 Litholog of the Nammal Formation showing identified microfacies at the Pail section (PL)

NG section have poor preservation of the planktonic foraminifera (Fig. 6) whereas the PL section has relatively well preserved larger benthic foraminifera (Fig. 7). Among the allochems, the skeletal grains of the Nammal Formation at NG section comprise dominantly planktonic foraminifera usually globogerinids with rare larger benthic foraminifera of genus *Asslina* and *Nummulites* whereas, in the upper part of the section, the assemblage of the larger benthic foraminifera seems to increase. Here the larger benthonic foraminifera are mainly the species of *Assilina*, *Nummulites*, *Lockhartia*, and *Alveolina* with rare other fossils like miliolids, *discocyclina*, *operculina*, echinoderms, and uniserial foraminifera. On the contrary, at the PL section, the planktonic foraminifera are absent and the rocks are characterized by the presence of larger benthic foraminifera and other fossils like algae of green color, fragmented gastropods, echinoids, pelecypods, biodebris, and few traces of the larger benthic foraminifera (Fig. 7).

Microfacies of the Nammal Formation at Nammal Gorge section

The microfacies of the Nammal Formation in the NG section have been delineated from the bottom (at basal contact with the Patala Formation) to the top of the Nammal Formation by employing Dunham's classification (1962). In this stratigraphic section of NG (Fig. 1), the Nammal Formation is comprised mainly of microfacies of wackestone and mudstone-

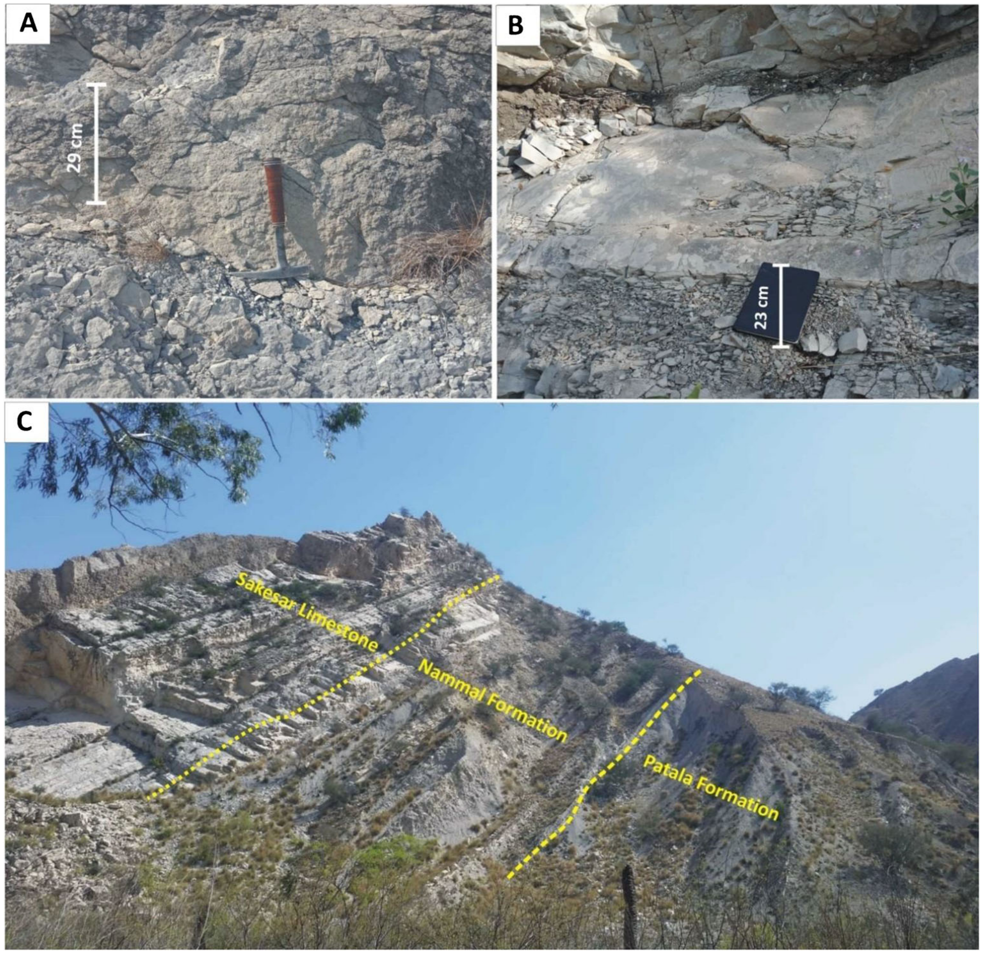


Fig. 4 Field photographs displaying an outcrop view representing lithological variation in the Nammal Formation at NG. (A) displays shale and limestone contact; (B) denotes shale, limestone, and interbedded marl; and (C) represents a panoramic view of the contacts of the Nammal Formation with basal Patala Formation and upper Sakesar Limestone at NG (not to scale)

wackestone. Four microfacies, i.e., NNF-1, NNF-2, NNF-3, and NNF-4 have also been identified (Fig. 2). These microfacies have the orthochems of micritic matrix with rare microsparite and sparite cement coupled with allochems of planktonic foraminifera at the NG section whereas, at the PL section, fossil assemblages identified include larger benthic foraminifera with other fossils like echinoderm, pelecypod, echinoids, and foraminifer bioclasts.

Foraminifer wackestone (NNF-1) microfacies

It encompasses two representative samples of (NFN-1, NFN-2) of limestone beds starting from the base at the NG recognizable by wackestone depositional texture. The microfacies have moderate to poor preservation of biogenic contents and the dominant constituents include micrite matrix and allochems. The skeletal grains or bioclasts vary between 12 and 18% with average allochem to matrix ratio 1:3 (Table 1). The predominant allochems are characterized by planktonic foraminifera (Fig. 6 A, B), followed by broken bioclasts and non-existent smaller benthic formanifera and *Assilina* and *Nummulites* of larger benthic foraminifera. The identified diagenetic features include sparitization, micritization, micitic envelope formation, microfractures cementation, and neomorphism.

Mudstone-wackestone (NNF-2) microfacies

Planktonic foraminifera mainly characterize the microfacies but comparatively less than the NNF-1 microfacies (Fig. 6 C, D). In the NNF-2 microfacies, there are a very rare species of larger benthic foraminifera that includes *Nummulites* and *Assilina*, with uniserial foraminifera and achinoids (rock samples NFN-3, NFN-4, NFN-5, and NFN-6). The allochems include mainly the micritized bioclasts and micrite matrix occupies most of the facies matrix with some patches of sparite. Here allochems to matrix ratio are 1:3 (Table 1) forming mainly wackestone with marginal limit of the mudstone texture. The diagenetic features identified in this microfacies include micritization, microfractures, neomorphism, stylolitization, and mechanical compaction.

Foraminifer mudstone (NNF-3) microfacies

It constitutes the middle part of the formation (rock samples NFN-7, NFN-8, and NFN-9). The NNF-3 microfacies contain

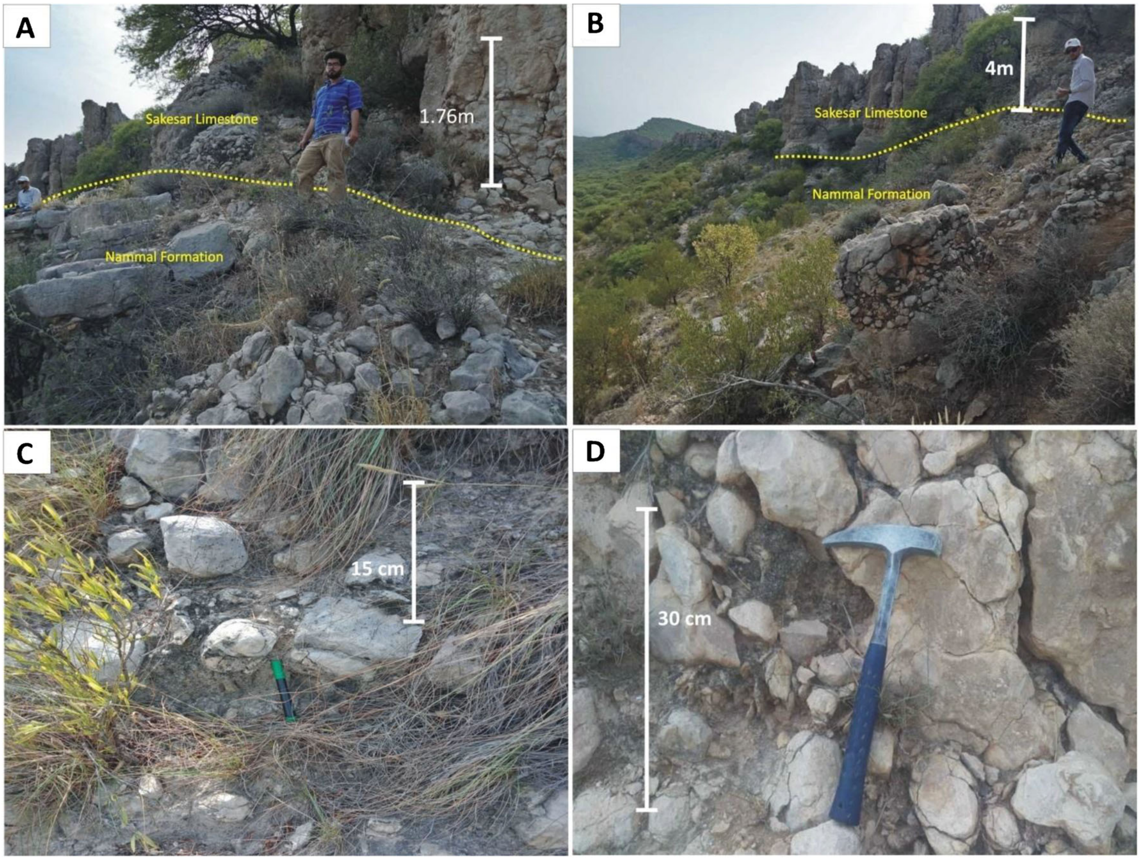


Fig. 5 An outcrop view of the Nammal and Sakesar formations at the Pail section (PL). Photographs (A) and (B) display the upper contact of the Nammal Formation with the Sakesar Limestone, and (C) and (D) show the lithologies of limestone and marl

a few planktonic foraminifera with rare to very rare benthic foraminifera including *Nummulites*, *Assilina*, miliolids, and biserial foraminifera too. The allochems include micritized clasts of fossils, bioclasts, and rare non-skeletal clasts (Fig. 6 E, F). Here, the main matrix constituent is the micritic matrix with some mixed storm-driven smaller non-skeletal grains with rare patches of sparite cement that are associated with neomorphism. Allochems to matrix ratio is 9:91 which is about 1:9 (Table 1). The identified diagenetic features include micritization, sparitization, cementation, neomorphism, and dissolution.

Assilina wackestone (NNF-4) microfacies

The *Assilina* wackestone microfacies occupies the upper part of the formation (rock samples NFN 10, NFN 11, and NFN 12). It contains rare broken planktonic foraminifera, with some benthic foraminifera including *Nummulites*, major dominance of *Assilina* followed by miliolids, and rare uniserial foraminifera (Fig. 6 G, H). The allochems include mainly bioclasts, some of which are micritized with rare pyritized clasts and rare non-skeletal clasts. In the NNF-4 microfacies, matrix constituent comprises mainly the micritic and rare microsparite. Here allochems to matrix ratio are 1:9 (Table 1). The identified diagenetic features of these microfacies include neomorphism, micritization, sparitization, stylolitization, calcification or veins formation, and dissolution.

Microfacies of the Nammal Formation at Pail section

In the Pail section, the basal boundary of the Nammal Formation with the Patala Formation is missing at the outcrop scale whereas the Sakesar Limestone conformably overlies it. The Nammal Formation at PL shows slight variations. Here, the main lithology is gray limestone with interbedded marl. The limestone is scattered, thin to medium bedded with marl intercalations. The thickness of the formation is about 25 m. At PL, three microfacies (PNF-1, PNF-2, and PNF-3; Fig. 7) have been identified.

Foraminifer wackestone-packstone (PNF-1) microfacies

This PNF-1 micofacies represents four representative samples (NF-P1, NF-P2, NF-P3, and NF-P4; Fig. 4). PNF-1 microfacies mainly contain larger benthic foraminifera with the abundance of *Lockhartia* followed by *Assilina* with rare algae, clasts of brachiopod, pelecypods, and *Rotalia* (Fig. 7 A,

Table 1 Visually estimated petrographical constituents (allochems, orthochems, and fossils) of the Nammal Formation at the Nammal Gorge section (NG)

Thin section #	Bioclasts %	Nummulites %	Asssilina %	Echinoids %	Planktons %	Miliolids %	Algae %	Alveolina %	Lockhartia %	Allochems %	Matrix%	Grain: matrix	Classification of Dunham (1962)
NsNF-1	12	1	1	2	6	1	2			25	75	1:3	Wackestone
NsNF-2	9	2	2	2	4		3			22	78	1:3	Mud-wackestone
NsNF-3	2	2	1		2	1	1			9	91	1:9	Mudstone
NsNF-4	3	1	4		1	1				10	90	1:9	Mud-wackestone

Table 2 Visually estimated petrographical constituents (allochems, orthochems, and fossils) of the Nammal Formation at the Pail section (PL)

Thin section #	Bioclasts	Nummulite %	Asssilina %	Miscellane %	Brachiopod %	Milliolid %	Algae %	Alveolina %	Lockhartia %	Allochems %	Matrix%	Grain: matrix	Classification of Dunham (1962)
(PNF-1)	15	1	6	3	2	6	3	5	6	47	53	1:1	Wackestone-packstone
(PNF-2)	10	3	4	1		2	1	3	3	27	73	1:3	Wackestone
(PNF-3)	16	6	5	2	2	5	3	2	5	46	54	1:1	Packstone

B). These fossils along with allochems like micritized clasts and skeletal debris are dispersed in micrite matrix. The average allochems to matrix ratio are 1:1 (Table 2). The identified diagenetic features of these microfacies include cementation, neomorphism, micritization, micritic envelope formation, microfractures, and dissolution.

Foraminifer wackestone (PNF-2) microfacies

This microfacies represents rock samples NF-P5, NF-P 6, NF-P7, and NF-P8. It contains mainly larger benthic foraminifera of genera *Lockhartia*, *Nummulites*, *Alveolina* (Fig. 7 A, B, C, D) with rare fossil assemblage of *Rotalia*, ostracode, and nonexistent and poorly preserved *Discocyclina* and echinoid spines. The allochem constituents include micritized skeletal fragments and bioclasts with diagenetic features like micritization, neomorphism, and stylolitization. The average allochems to matrix ratio is 1:3 (Table 2). The diagenetic features identified in these microfacies are cementation, neomorphism, micritization, stylolitization, microfractures, and mechanical compaction.

Bioclastic packstone (PNF-3) microfacies

It comprises a light gray limestone bed intercalated with yellowish marl and occupies the top of the formation at the contact with the Sakesar Limestone. This microfacies includes representative samples of (NF-P9, NF-P 10, NF-P11, and NF-P12) and contains larger benthic foraminifera of genera *Nummulites*, rare *Assilina* with rare *Rotalia*, pelecypods, and echinoderms (Fig.7 E, F). The average allochems to the matrix ratio is 1:1 (Table 2) which forms a packstone depositional texture. The identified diagenetic features of these microfacies include cementation, neomorphism, micritization, chemical compaction, and dissolution.

Depositional environment of the Nammal Formation

Discussion

Contrary to siliciclastic rocks, in carbonates, the paleoecological reconstruction of skeletal grains coupled with microfacies analyses merely is a well-grounded benchmark to elucidate the environments of deposition owing to the absence of sedimentary structures (Reading 2009; Tucker 2009; Flugel 2004; Dodd and Stanton 1990). In this study, the in-depth investigations of the skeletal grains and its paleoecology have been employed to decipher the environment of deposition for the sequence of limestone, shale, marl, and marly shale of the Nammal Formation. The petrographic study revealed that the Nammal Formation mainly has the fossil assemblage of foraminifera and minor presence of other fossils. The nature of the identified microfacies and their distribution in the Nammal Formation propose that the depositional conditions are consistent with a carbonate ramp (Burchette and Wright 1992) which is foraminifera dominated and also gentle-dipping. The gentle-slopping ramp is further buttressed by the absence of sand shoals or high energy grain stone microfacies, reef-building organisms and facies, lack of re-sedimentation, absence of slump structures, and dominant occurrence of micrite that are more befitting with a ramp setting unlikely with a shelf (Wright 1986; Mehr and Adabi 2014).

Larger benthonic foraminifera is the varied and broadly distributed benthic groups which reside in shallow-marine environments and act as an excellent tool in biostratigraphic studies together with the reconstruction of palaeoenvironments (e.g., Beavington-Penney and Racey 2004; BouDagher-Fadel et al. 2015; Matsumaru and Sarma 2010; Pomar et al. 2017). According to Murray (1973), planktonic foraminifera to benthic foraminifera ratio increases with increase in the water depth during normal conditions and the gradual augmentation in the frequency of planktons and decrease in detrital content designates gradual increase in the water depth too (Tucker and Wright 1990; Butt 1986; Frank et al. 2010). Furthermore, high frequency of planktons, absence of benthons, and lack of detrital material generally characterized the outer ramp facies (Tucker and Wright 1990; Flugel 2004; Tucker 2009; Wilson 2012) and the abundance of micrite indicates low-energy depositional conditions. The Nammal Formation, biostratigraphically, has a higher abundance of planktonic foraminifera and nonexistent benthic foraminifera (except the *Assilina*) at NG (Western Salt Range) in mostly micritic matrix, whereas in the PL (Central Salt Range), it encompasses rare to nonexistent planktonic foraminifera dispersed in micritic matrix and rare microsparite (Figs. 6, 7, and 8). This implies that at the Western Salt Range, during deposition of the Nammal Formation, deeper water conditions prevailed whereas at the Central Salt Range, shallower conditions prevailed or deposition took place relatively at shallow water depths. This is also propped by the presence of *Alveolina* and miliolids (Fig. 8) at the PL section whereas, at the NG section, the Nammal Formation is devoid of *Alveolina* and miliolids underscoring that at the Western Salt Range, the deposition of the Nammal Formation was relatively at higher water depths (outer ramp setting) and deeper conditions prevailed. The presence of *Alveolina* shows shallow and warm water conditions with a depth ranging from 5 to 80 m (Buxton and Pedley 1989; Hohenegger et al. 1999; Beavington-Penney and Racey 2004). Based on such evidences, it can be inferred that during deposition of the Nammal Formation at the time of Neo-Tethys closure, western margin of the Indian plate, including western part of the Salt Range, was relatively at higher depth as compared to the eastern margin of the Indian plate (eastern to western sides of

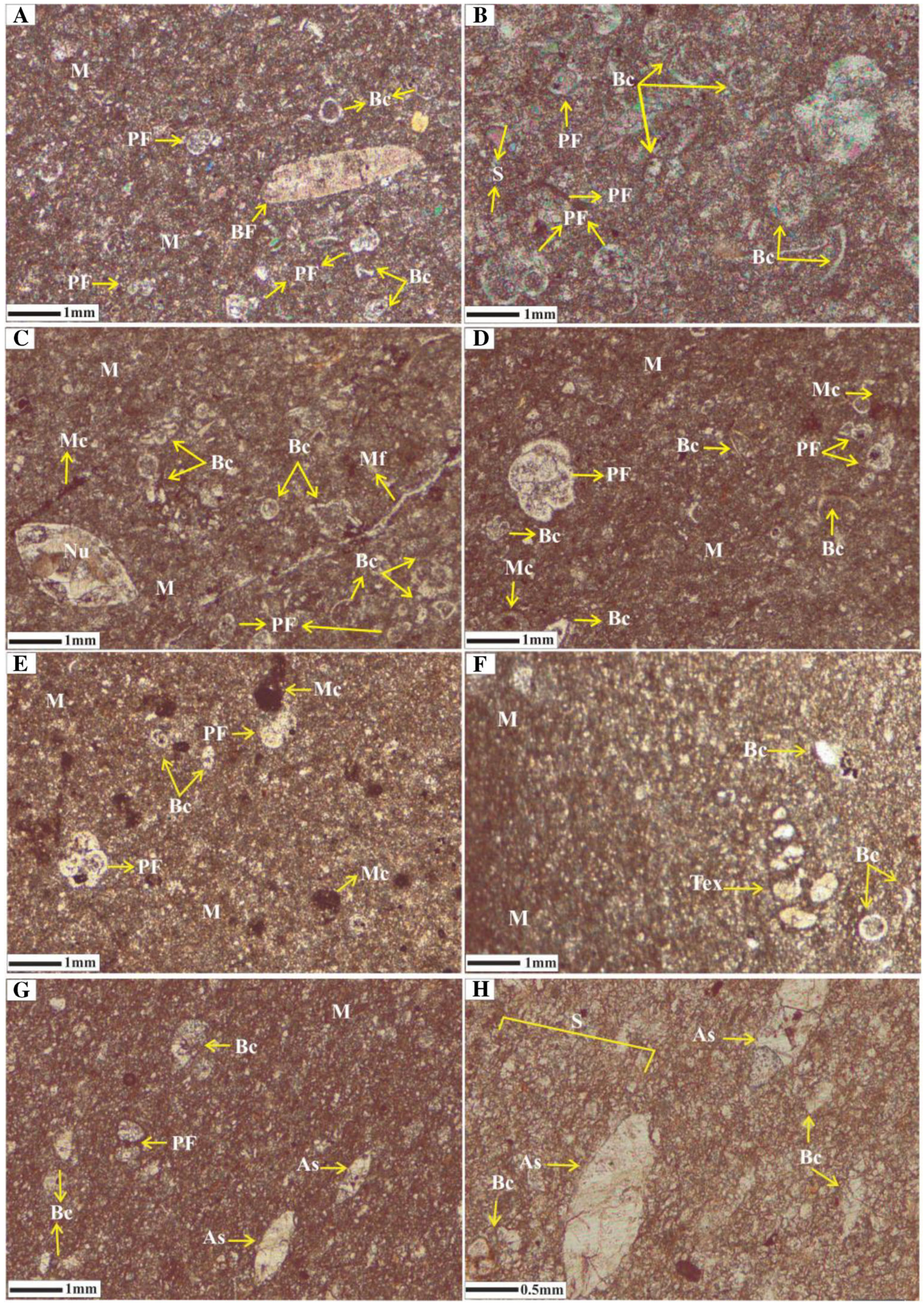


Fig. 6 Representative photomicrographs of the identified microfacies NNF-1, NNF-2, NNF-3, and NNF-4 of the Nammal Formation at NG. Microfacies NNF-1 is represented by (A) and (B) micrographs, microfacies NNF-2 is shown by (C) and (D) micrographs, microfacies NNF-3 is displayed by (E) and (F) micrographs, and microfacies NNF-4 is shown by (G) and (H) micrographs. The allochems and orthochems of the microfacies are represented by the *Planktonic foraminifera* (PF) in (A), (B), (C), (D), (E), and (G); Benthic foraminifera (BF) in (A); *Nummulite* (Nu) in (C); *Textularia* (Tex) in (F); *Assilina* (As) in (G) and (H); Bioclasts (Bc), micritization, or micrite matrix (M) in (A), (B), (C), (D), (E), (F), (G), and (H); and sparite cement in (B) and (H)

the Salt Range). This observation is also evidenced by the fact that the Nammal Formation gets thinner towards Central and Eastern Salt Range as compared to the Western Salt Range where it has relatively a greater thickness.

Planktonic foraminifera in micritic matrix or mud matrix along with broken shells of planktonic foraminifera show low energy environment of deposition under wave base through deep water conditions in the outer ramp to open shelf (Barbieri et al. 2006; Flügel 2010). The *Assilina* denotes mid-outer ramp setting competitively deeper than that of *Nummulites* and shallower than *Discocyclina* (Ahmed 2011). Based on the dominance of planktonic foraminifera at the NG and the presence of *Assilina* microfacies, the Nammal Formation is consistent with outer to distal middle ramp settings (Fig. 9). On the other hand, the larger benthic foraminifera with micritic matrix and mud designate adequate energy settings and demonstrate a depositional environment at a shallow shelf (Akhtar and Butt 1999). According to Mehr and Adabi (2014), Alveolinids and miliolids characterize inner ramp settings and are the dominant microfacies types, and

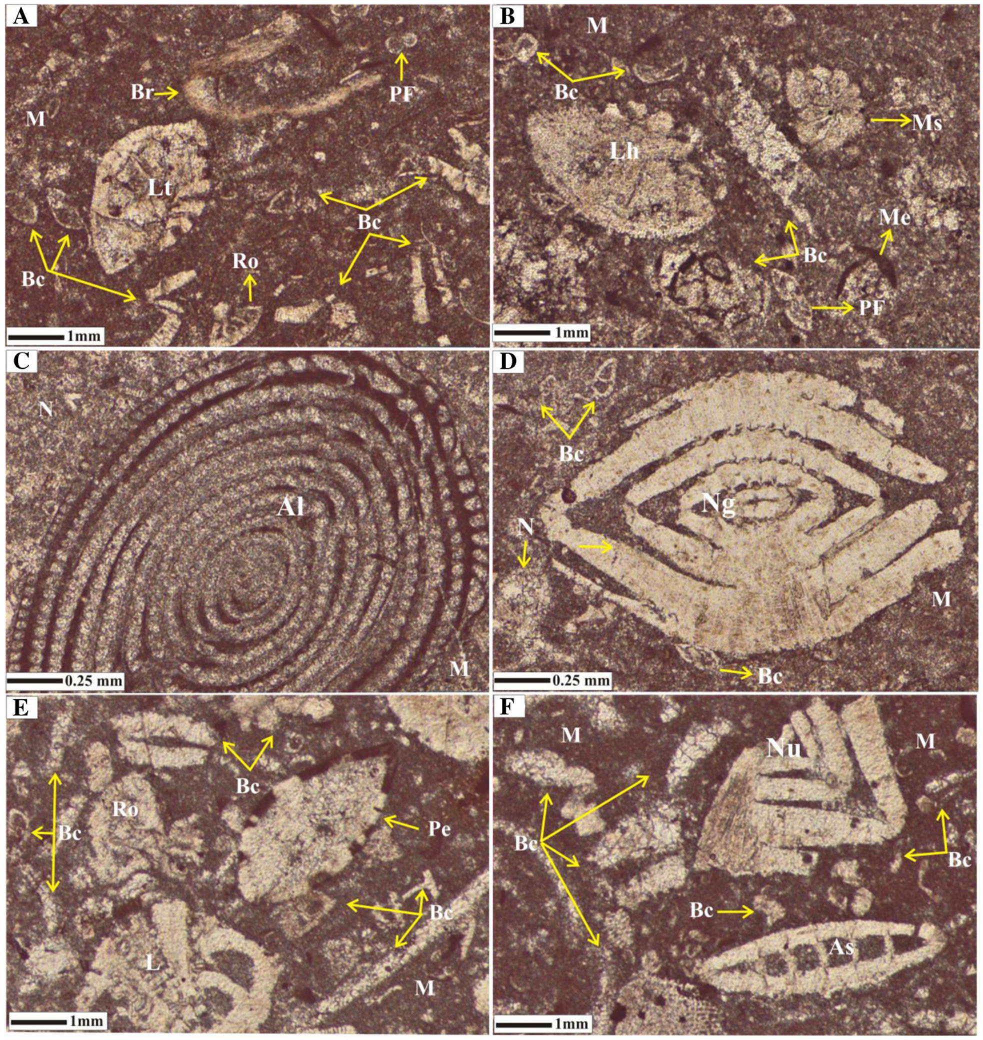


Fig. 7 Representative photomicrographs of the identified microfacies PNF-1, PNF-2, and PNF-3 of the Nammal Formation at PL. Microfacies PNF-1 is represented by (A) and (B) micrographs, microfacies PNF-2 is shown by (C) and (D) micrographs, and microfacies PNF-3 is represented by (E) and (F) micrographs. The allochems and orthochems of the microfacies are represented by *Lockhartia* (L); *Lockhartia tipper* (Lt); *Lockhartia haimei* (Lh) in (A), (B), and (E); *Planktonic foraminifera* (PF) in (A) and (B); brachiopod (Br), *Rotalia* in (A) and (E); *Miscellanea* (Ms) in (B); *Alveolina* (Al) in (C); *Nummulites globolus* (Ng) in (D); *Nummulites* (Nu) in (F); Pelecypod (Pe) in (E); *Assilina* (As) in (F); Bioclasts (Bc), micritization, or micrite matrix (M) in (A), (B), (C), (D), (E), and (F); micrite envelop (Me) in (B); and neomorphism (N) in (C) and (D)

Nummulitids and *Discocyclinids* characterize middle ramp settings whereas outer ramp settings consist mainly of *Radiolaria* and spong spicules. The *Alveolinids* withstand a broad temperature and salinity conditions; hence, they occur in various zones of shallow-marine carbonate platforms (Drobne et al. 2011; Hadi et al. 2018). The *Nummulitids* are benthic fauna, which flourish at depths < 30 m, but usually abundant at mesophotic to oligophotic depths >30 m (Hohenegger 2005; Spanicek et al. 2017). Based on the ecophenotypical correlative studies with their modern counterparts, the nummulitids are associated with water depths between 40 and 80 m (Goeting et al. 2018; Hadi et al. 2016). The *Alveolina* is described to live in an agitated environment with water depths down to about 60 m (Hottinger 1973) with an ideal distribution depth of 15–35 m to indicate a shallow marine environment. This is followed by *Nummulites* and rare *Assilina* to indicate water depths of 10–80 m with an ideal distribution depths of 30–60 m and 50–80 m, respectively (Beavington-Penney and Racey 2004). The range of Nummulitic foraminifera is from 20 to 130 m and normally occurs in a subtidal habitat where salinity favors the deposition of lime mud (Reiss and Hottinger 1984) and they predominantly represent middle ramp environment (Racey 1994). The miliolids are indicative of a muddy inner platform (Flugel 2004). The *Lockhartia* shows inner to middle ramp setting (Racey 1995) and *Discocyclina* shows mid–outer ramp settings (Racey 1994; Anketell and Miriheel 2000). Due to the predominance of the larger benthic foraminifera of mainly *Lockhartia* species, *Nummulites* species, and *Assilina* species followed by *Alveolina species* and very rare *Discocyclina species*, the Nammal Formation at the PL is compatible with distal middle to inner ramp settings.

The Nammal Formation comprises mainly of limestone along with marl and shale. The dominant facies of the formation are wackestone to wackestone-packstone. The fossil assemblages of the Nammal Formation include planktonic foraminifera generally *Globigerinoides*; larger benthic foraminifera such as *Nummulitids* including *Nummulites* species (*Nummulites globulus*, *Nummulites mamilatus*, *Nummulites atacicus*, *Nummulites pinfoldi*), *Assilina* species (*Assilina*

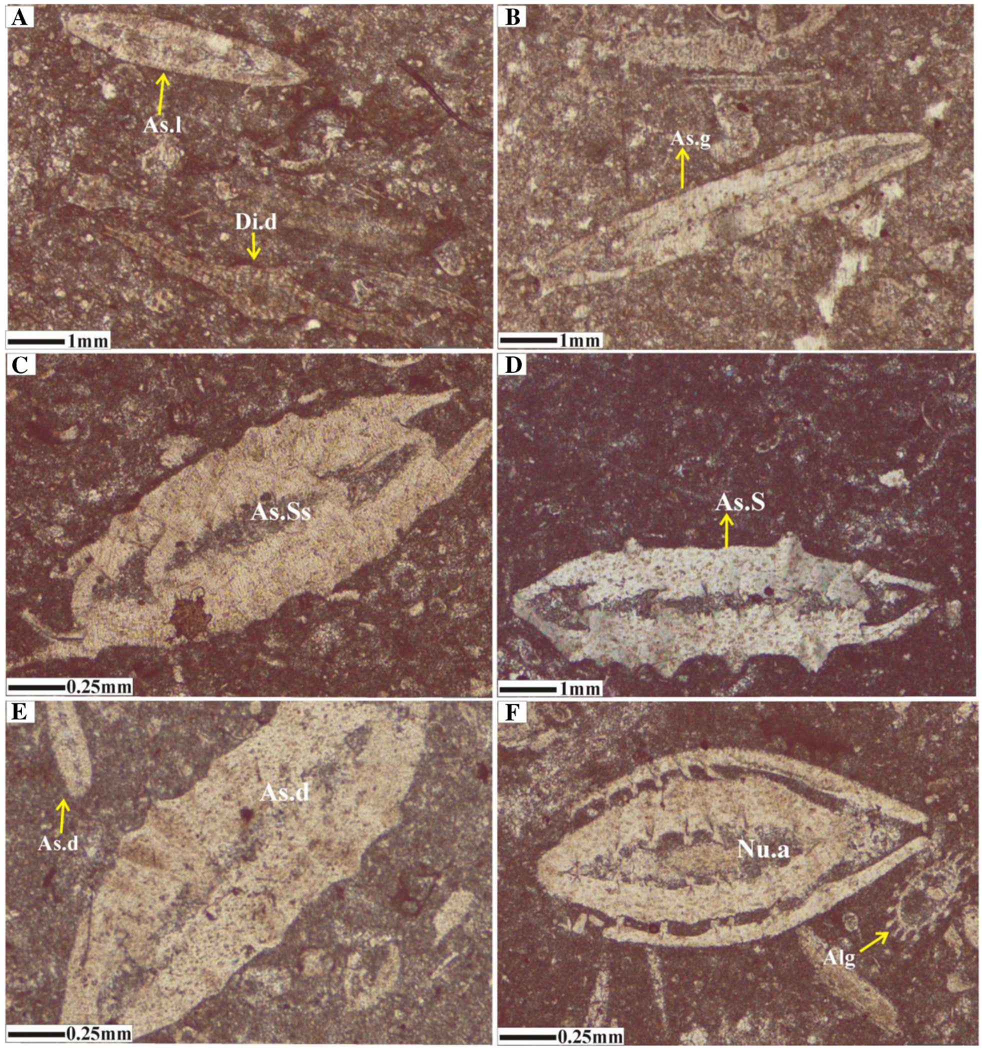


Fig. 8 Micrographs showing some of the LBFs; species of *Assilina*, a *Nummulites*, and a *Discocyclina* of the Nammal Formation. *Assilina laminosa* (As.l) and *Discocyclina dispansa* (Di.d) in (A); *Assilina granulosa* (As.g) in (B); *Assilina subspinosa* (As.Ss) in (C); *Assilina spinosa* (As.S) in (D); *Assilina dandotika* (As.d) in (E); and *Nummulites atacicus* (Nu.a) and algae (Alg) in (F)

spinosa, *Assilina subspinosa*, *Assilina dandotika*, *Assilina granulosa*, *Assilina laxispira*), *Lockhartia* species (*Lockhartia haimei*, *Lockhartia conditi*, *Lockhartia tipperi*), and *Alveolina* (i.e., *Alveolina elliptica*); and poorly preserved nonexistent *Discocyclina.* Moreover, the Nammal Formation also contains miliolids, rare *Operculina*, echinoid fragments, and biodebris of other fossils. The occurrence of *Alveolina* with *Assilina laxispira* (Fig. 7 F), *Nummulites globulus*, and *Nummulites atacicus* (Fig. 8 F) in the Nammal Formation assigns an early Eocene (Cuisian) age as both species are restricted to earlier horizons of Eocene age according to Serra-Kiel et al. (1998). The presence of foraminifers' fossil assemblages, their water depth ranges, and their depositional settings, the Nammal Formation signifies the rise in sea level which in turn reflects retrogradational depositional trend of the shallowing upward facies. This is also inferred from the planktonic to benthonic foraminifera ratio as this planktonic foraminifera to benthic foraminifera ratio augments, the water depth is higher and vice versa; therefore, in case of the Nammal Formation, this planktonic to benthonic foraminifera ratio decreases depicting rising, sea-level conditions and transgressive phase during the deposition of the Nammal Formation. Based on the fossil assemblages, the Nammal Formation is suggested to be deposited in open marine to shallow marine settings and most likely at the outer ramp to middle and distal inner ramp settings (Fig. 9).

Diagenetic changes in the Nammal Formation and their impacts on reservoir quality

A comprehensive petrographic investigation revealed that the Nammal Formation has been subjected to many diagenetic changes like micritization, dissolution, neomorhphism, cementation, chemical, and mechanical compaction, fracturing, and microfractures filled with calcite (Fig. 10). Based on the diagenetic fabrics identified, the Nammal Formation has been undergone through marine, meteoric, burial, and uplift realms (Fig. 11). The micritization is the distinct partial to severe diagenetic feature and it also prevails in the form of micritic envelopes (Fig. 10 E). Three types of cement are observed in

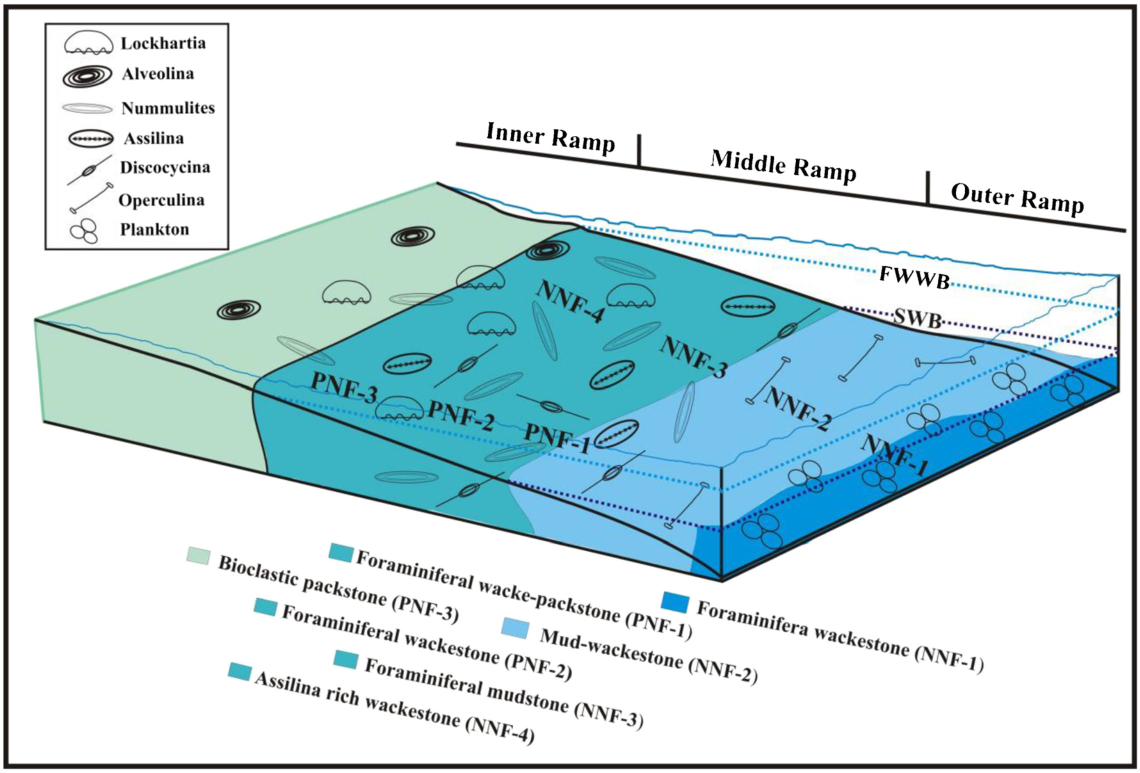


Fig. 9 A proposed depositional model of the Nammal Formation from the NG and PL sections (after Racey 1994, 1995; Anketell and Miriheel 2000; Beavington-Penney and Racey 2004; Pomar et al. 2004)

the Nammal Formation which includes non-ferroan isopachous fibrous cement blocky and granular mosaic calcite cement (Fig. 10). The identified neomorphism (Fig. 10 E) in the Nammal Formation is of aggrading type subsequently resulted in the formation of calcite cement of blocky nature ranging from microspar to blocky calcite cement. Dissolution and microfractures are also observed in the Nammal Formation. The dissolution of metastable skeletal and non-skeletal grains could have resulted in the formation of secondary fabric and non-fabric selective porosities like moldic/solution, intercrystalline, and intraparticle in meteoric-phreatic stages (e.g., Abu-El Ghar et al. 2015). Both mechanical and chemical compactions (Fig. 10 E, F) are identified. The features of the mechanical compaction include brittle deformation, fossil/bioclast or vein dislocation (Fig. 10 D), and grain to grain suture contacts (Fig. 10 F). The features of chemical compaction are dissolution (in form of vugs, molds, stylolites (Fig. 10 E), and the solution seams).

Among the diagenetic features, micritization and non-ferroan isopachous fibrous cement represent marine diagenetic environments (Melim et al. 2001; Khalifa 2005; Vincent et al. 2007; Mahboubi et al. 2010; Abu-El Ghar et al. 2015). The diagenetic features like granular mosaic and blocky cement, dissolution of molds and micritic cement and neomorphism, all demarcate the meteoric-phreatic diagenetic realm (Melim et al. 2001; Khalifa 2005; Vincent et al. 2007; Moradpour et al. 2008; Khalifa et al. 2009; Mahboubi et al. 2010; Abu-El Ghar et al. 2015). Both the features of mechanical compaction and chemical compaction delineate shallow burial area (e.g., Vincent et al. 2007; Mahboubi et al. 2010; Abuseda et al. 2015). Uplift which is late diagenetic event has affected the Nammal Formation and caused the formation of fractures which subsequently filled with calcite veins.

Dissolution features are noted in the Nammal Formation, may also contribute towards the porosity of carbonates. The dissolution process has caused in the expansion of intergranular openings. The development of molds played substantially in the development of vuggy, moldic, and fenestral porosities. The dissolution process may enhance the porosity of the Nammal Formation which may have positive impacts on the reservoir quality. Moreover, the microfractures at a microscopic level and fractures at mesoscopic level may also bear positive impact on reservoir quality, which increase the storage capacity and permeability for movement of hydrocarbon fluids of the Nammal Formation (e.g., Ferket et al. 2003). Therefore, the fractures/microfractures pave the way in carbonates to migrate or flow the fluid which added to the porosity/permeability of the Nammal Formation. Among the diagenetic fabrics of the Nammal Formation, the diagenesis influencing fracture dominate within the four of the microfacies of the formation then it is followed by diagenetic aspect dominancy and rare depositional dominating fracturing, which affect the general reservoir efficacy.

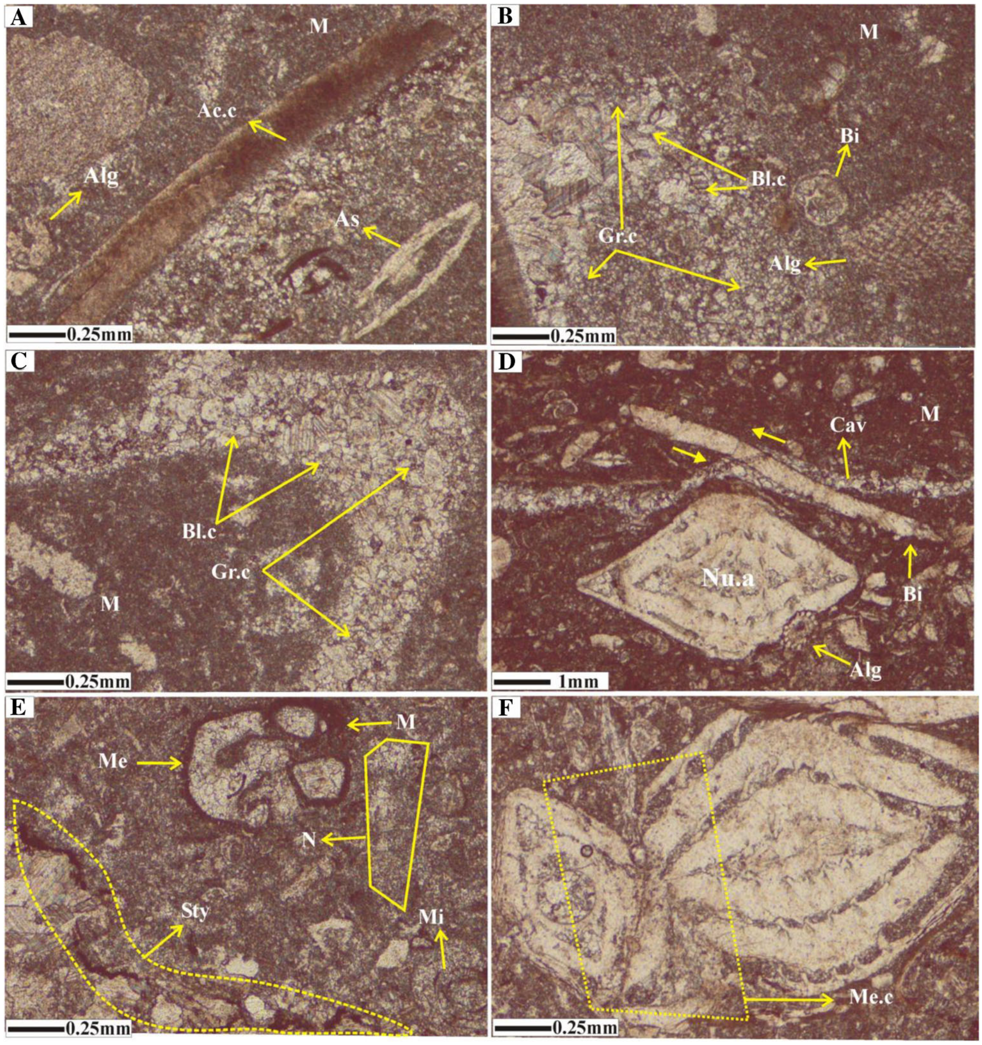


Fig. 10 Micrographs showing diagenetic features and some fossils of the Nammal Formation including acicular cement (Ac.c), micritization (M), algae (Alg), and *Assilina* (As) in (A); blocky (Bl,c) and granular cement (Gr.c) types with micritization (M) and algae (Alg) in (B) and (C); *Nummulites atacicus* (Nu. a), bioclast (Bi), calcite vein/filled microfractures (Cav), and arrow heads indicate vein dislocation in (D); miliolid (Mi) and diagenetic features like stylolitization (Sty), miritic envelope (Me), neomorphism (N), and micritization (M) in (E); and mechanical compaction (Me.c) in (F)

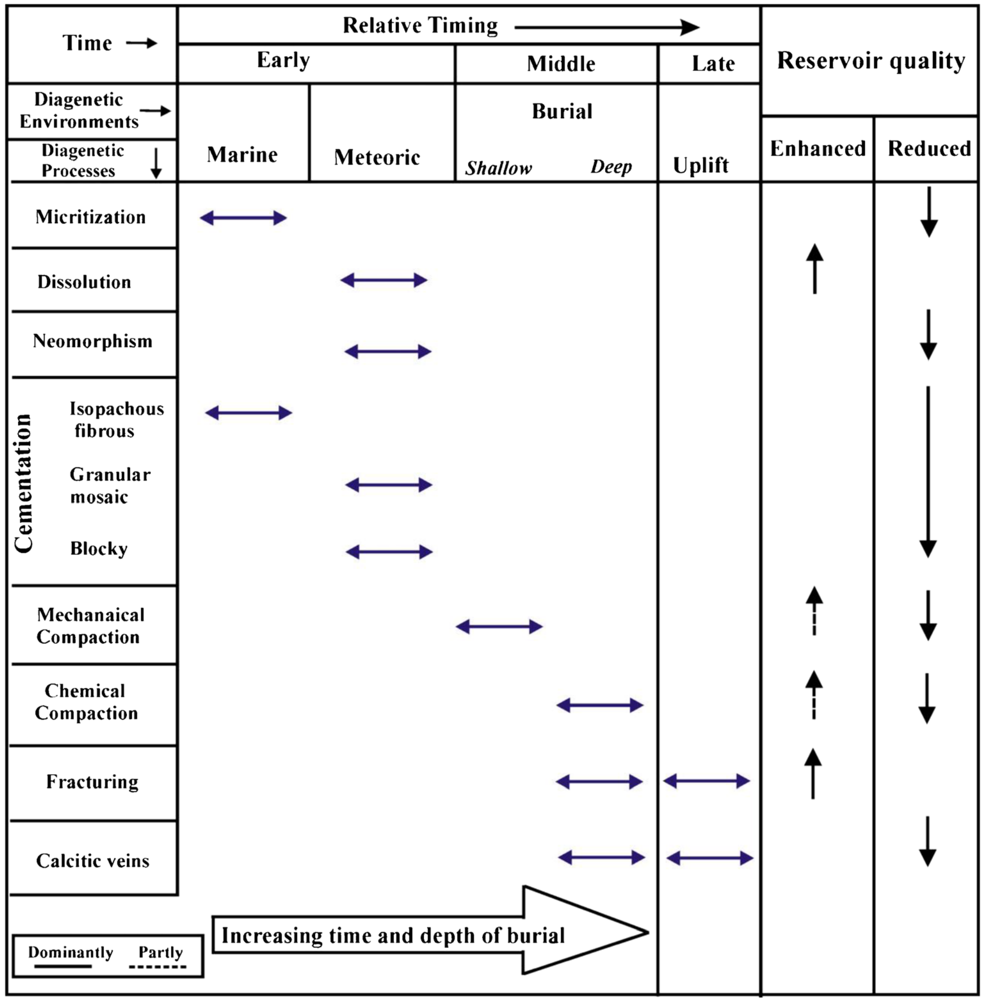
The diagenetic features like micritization, cementation, neomorphism, and sediment compaction have negatively affected the reservoir quality of the Nammal Formation (Fig. 11). Micrite can diminish permeability, due to filled pore throats (Taghavi et al. 2006). In the Nammal Formation, some of the skeletal grains are micritized and micrite has occupied the pore space and, therefore, it is considered detrimental or negative for reservoir quality. The cementation decreases porosity or permeability as the fractures which are closed make hindrances to fluid movement owing to chemical precipitation or in-filling of dissolved minerals like calcite. The process of neomorphism also diminishes the porosity and transformation of aragonite to calcite is one of the most imperative processes in lithology of the Nammal Formation. It dominates over the petrophysical properties of limestones (e.g., Banner 1995; Maliva 1998) and transformation of aragonite to calcite causes an increase in total rock volume of 8%, and eventually porosity reduces by 8% (e.g., Selley 2000). The compaction of sediment can result in a reduction in the porosity as the enhancement in lithostatic pressure coupled with syn-depositional stresses affect compaction. The process of stylolitization thoroughly destroys porosity and in dolomites, it perishes permeability, and improving permeability on the microstructural scale (Hassan 2007). And the mechanical compaction causes tight packing and squashes pore throat and space between grains that can adversely affect the quality of the reservoir. The effects of such diagenetic processes on reservoir quality are given in Fig. 11.

Reservoir aspect of the Nammal Formation

Thin section visual porosity

Thin section visual porosity analysis is done to determine pore geometry, type of pores and type of porosity, nature, and quality of fractures and cavities. Visual porosity of the Nammal Formation at two sections that are the

Fig. 11 Diagenetic changes in the Nammal Formation and their effects on reservoir quality



Nammal Gorge and the Pail sections includes mainly fracture porosity and very rare fenestral, moldic, vuggy porosities (Fig. 12), and the intrafossil porosity inferred from Lucia (1995). The average microporosity of the Nammal Formation that is visually estimated for the NG varies between 0.57 and 2.25%. The dominant porosity that Nammal Formation holds is the fracture porosity which is observed in samples mainly of PL and rarely in NG sections. The fracture porosity in form of filled fractures or stylolitic fractures and rare open fractures is the most commonly porosity identified (Fig. 12 E, F, G, H). The secondary porosities in the Nammal Formation play an active and integral part for porosity development and ultimately paving waves for the fluid flow.

ImageJ software analysis of porosity

The porosity ranges in the Nammal Formation determined by imageJ software are between 2 and 10% with average porosity distribution 2–6% in the samples of the Nammal Formation at both of the Nammal and Pail sections (Fig. 13). In the samples of the NG, the estimated average porosity values range from 5 to 7% with the maximum value being about 10.8 to 11% (Fig. 13). At the Pail section, the average porosities of the Nammal Formation are about 4 to 6% with a maximum porosity of 11.5% (Fig. 12). In imageJ software, the lower threshold values for porosity analysis are assigned 50 to 70 with the grayscale format and the porosities are shown in the form of the red spots along with their respective traces (Fig. 13).

Microporosity classification

A newly proposed genetic carbonate porosity classification scheme by (Ahr 2008) is employed to determine three processes namely diagenetic, depositional, and fracturing. These processes are plotted in the form of a triangular diagram (Fig. 14) as of end members and with their hybrid pore types on sides of the triangular diagram. The

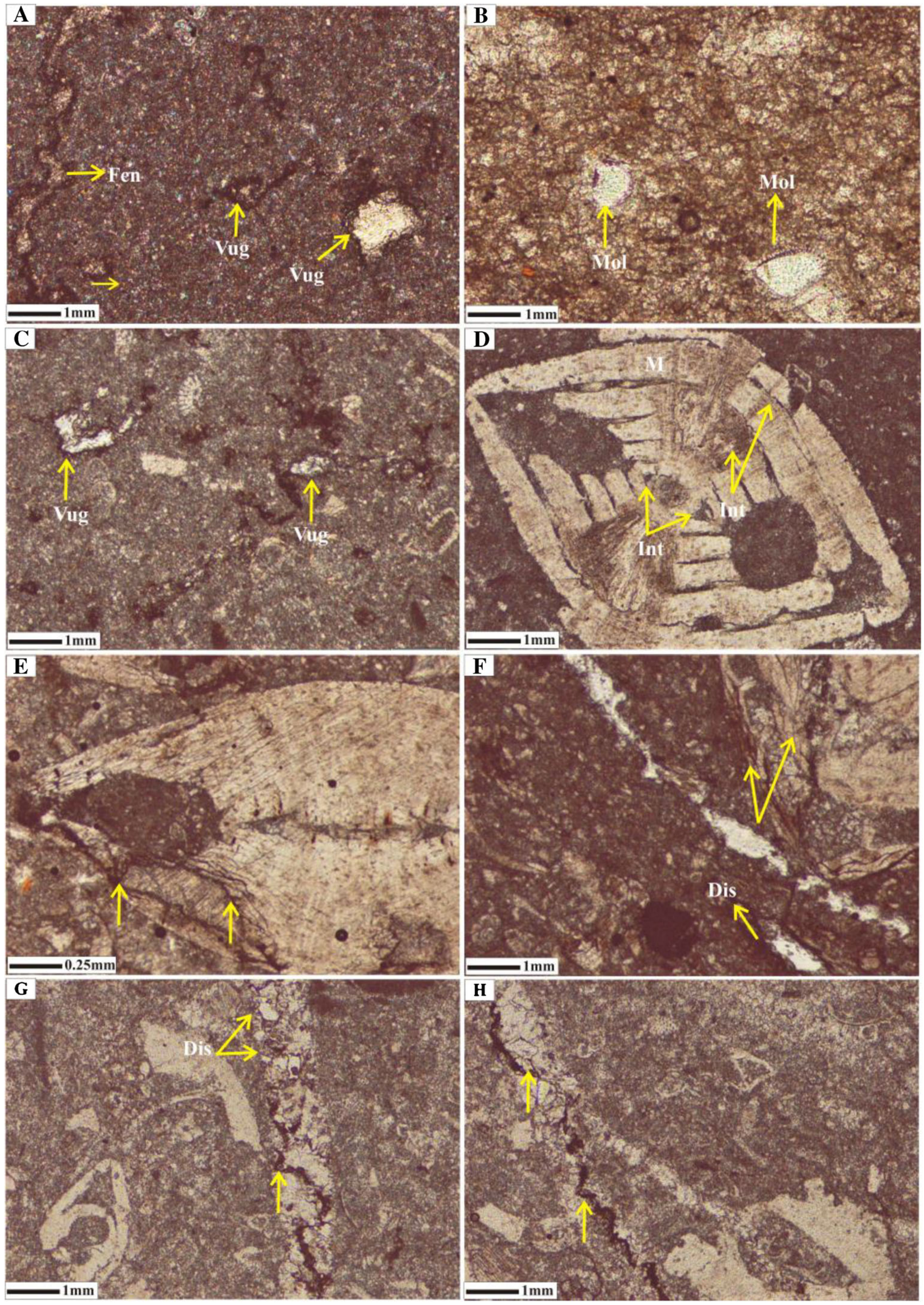


Fig. 12 Visual porosities distribution in the representative samples of the Nammal Formation at the NG and PL sections. Fenestral (Fen), vuggy (Vug), moldic (Mol), and intrafossil or intraparticle (Int) porosities in the Nammal Formation in (A), (B), (C), and (D). Fracture porosity in the Nammal Formation is shown by arrows in (E), (F), (G), and (H) along with the dissolution (Dis) porosity in (F) and (G)

end member processes, i.e., diagenetic, depositional, and fracturing, are independent whereas hybrid pore types on the sides of the triangular diagram indicate more than one mechanism affecting the formation during its genetic history. Among the identified seven microfacies of the Nammal Formation, the Foraminifer wackestone and mudstone-wackestone microfacies at the Nammal Gorge section form pores where the diagenetic aspects exceeds whereas, Foraminifer mudstone and *Assilina* wackestone microfacies encompass pores which are hybrid of diagenetic and fracture processes (Fig. 14). At the Pail section, Foraminifer wackestone-packstone microfacies has pores that are hybrid of diagenetic and fracture processes while Foraminifer wackestone microfacies at the Pail section

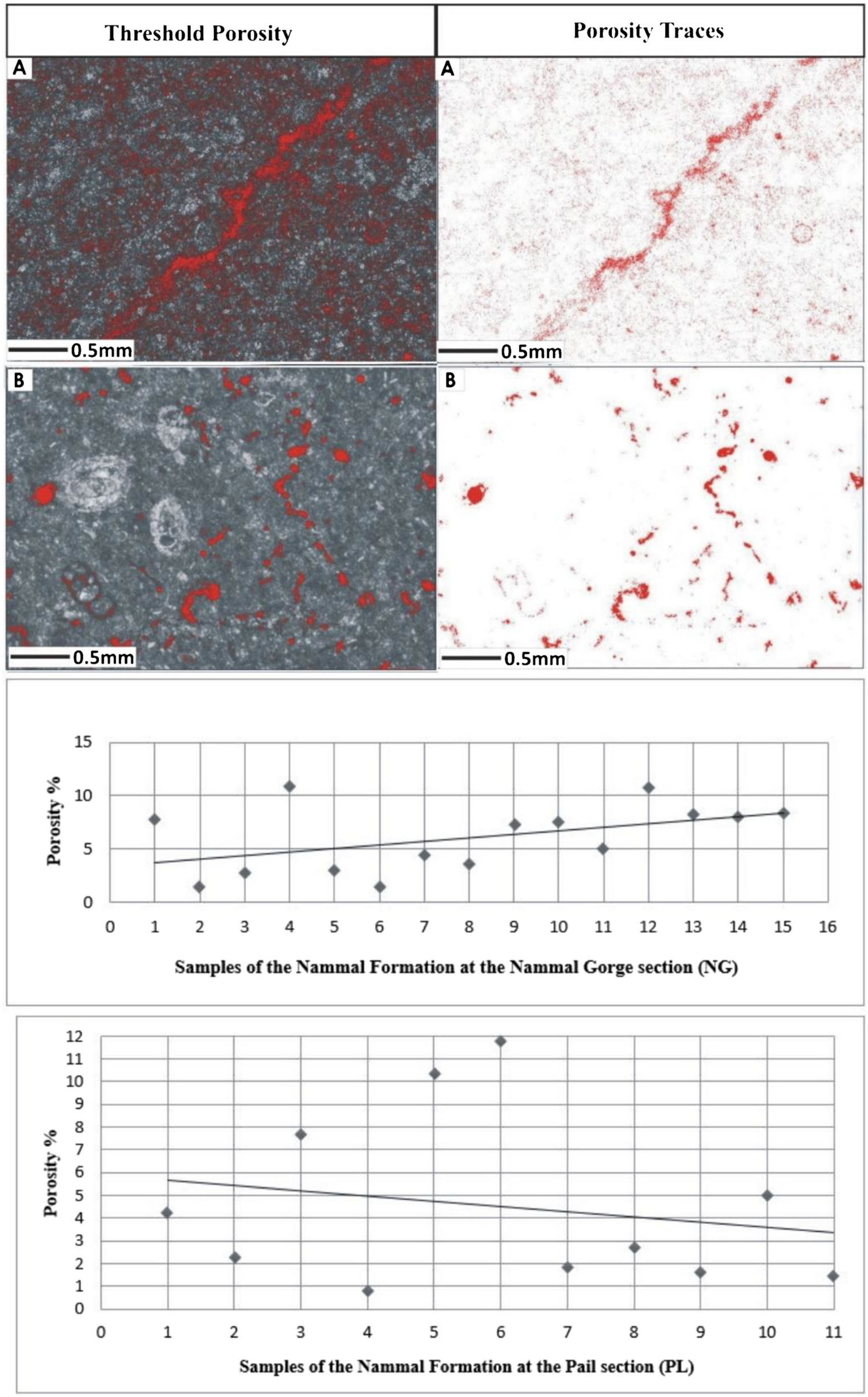


Fig. 13 Porosity distribution in the representative samples of the Nammal Formation at the NG and PL sections in (A) and (B) respectively and their average trend lines of the porosity distribution

possess pore types that predominantly consist of fracture porosity and the Bioclastic packstone microfacies occupies the pores that are hybrid of depositional and fracture processes (Fig. 14).

Log analysis and interpretation

This is the third technique employed for evaluation of reservoir potential of the Nammal Formation and it is

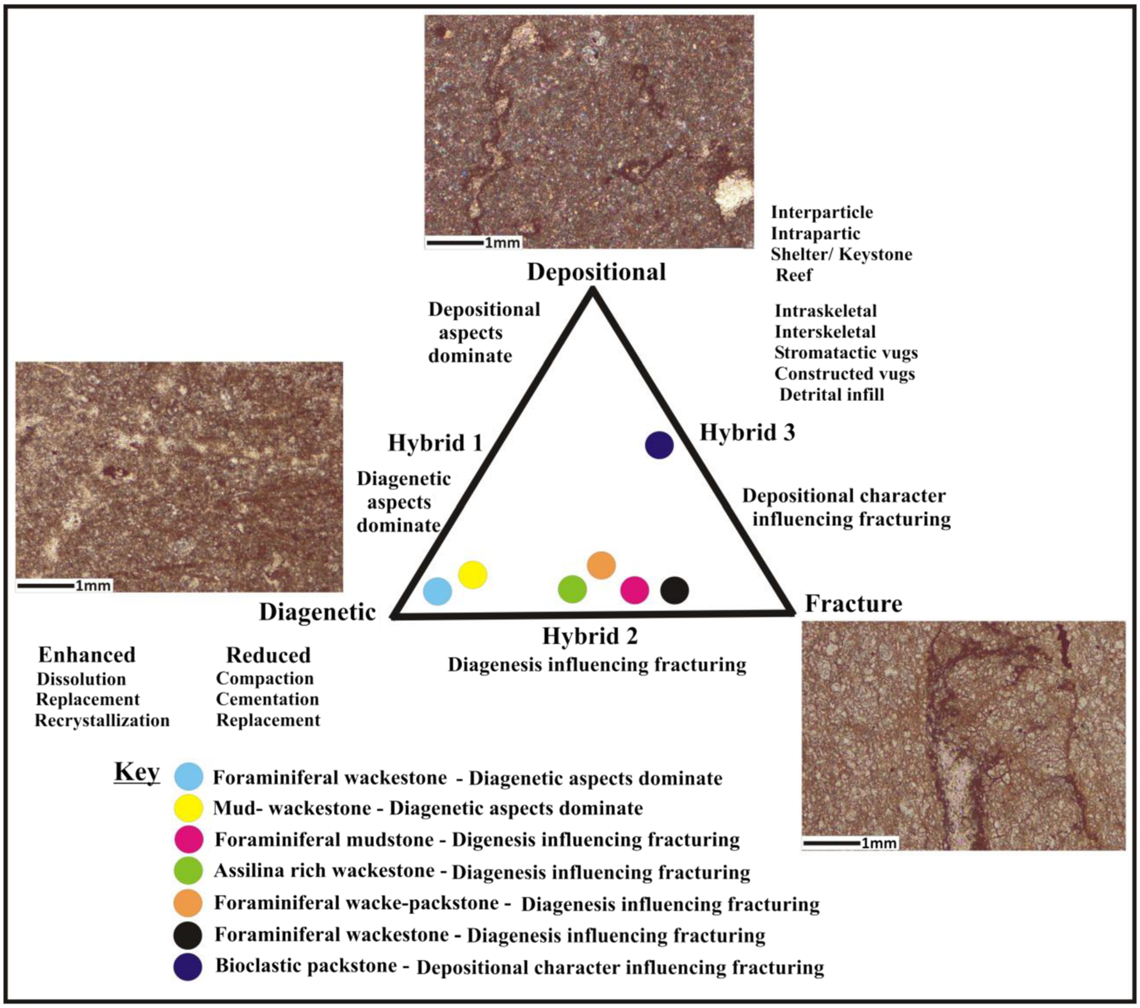


Fig. 14 A genetic classification model of porosity for the Nammal Formation at the Nammal Gorge section (modified after Ahr 2008)

based on wireline logging. Log data of Pindori-02 and Dhermund-01 wells were interpreted to determine the porosity and hydrocarbon saturation. Well tops data of Dharmand-01 and Pindori-02 show that the Nammal Formation was encountered at the depth of 3232 m and 4121.30 m respectively. The zone of interest is marked by using GR log, Caliper, Resistivity, Neutron log, and Sonic log. At the intervals of washouts, a density log is not used because of the poor borehole conditions. In Pindori-02, the maximum value of Vsh is 0.14 or 14% and the average value of Vsh is 0.038 or 3.8% (Fig. 15). The maximum value of Vsh ranges from 80 to 95% observed at the depth of 3323 m in Dhermund-01 well and the average value of Vsh in the whole formation encountered in Dhermund-01 well is about 0.285 or 30% (Fig. 16). The average volume of the clean zone is about 70% in the Dhermund-01 and 96% in the Pindori-02 representing limestone and marl sequences. The average sonic porosity of the Nammal Formation in Dhermund-01 is 0.14 or 14% and Pindori-02 is 0.02 or 2% and at some depth of the wells, the quality of data is questioned. The Average porosity represents the average of neutron and sonic porosity. As neutron and density logs are not used so sonic porosity is taken as average porosity. The average effective porosity is 0.01 or 1% only in Pindori-02 well while it is 0.02 or 2% in Dhermund-01 well (Figs. 15 and 16).

Based on log analysis of Dhermund-01 and Pindori-02 wells, there is 1 to 2% effective porosity or primary porosity that signifies poor to moderate range. Shale lithology has been encountered at Dhermund-01 at a depth ranging from 3272 to 3290 m and 3321 to 3325 m and the rest of the well has limestone and marl. In Pindori-02, there is no major shale appeared that is interpreted to have mainly limestone lithology with minor shale. The encountered marl and shale lithology in the Nammal Formation are of no economic and reservoir importance rather they pose negative impacts on the reservoir properties due to which they are neglected here in reservoir evaluation of

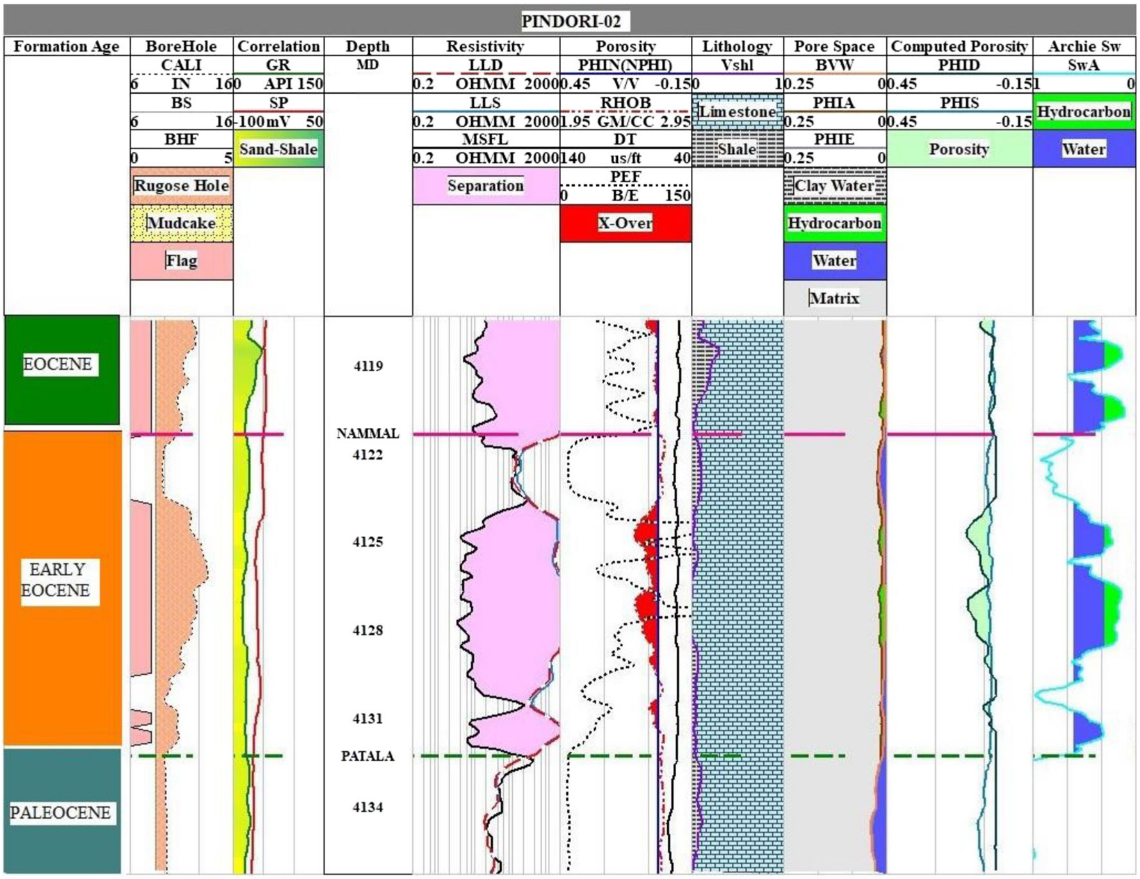


Fig. 15 A Log view of the zone of interest of the Nammal Formation in Pindori-02 well

the Nammal Formation. In Pindori-02 well, there is a bit of separation between MSFL, LLS, and LLD curves of Resistivity log and there is an overlying trend of LLS and LLD curves on the higher side of resistivity scale that signifies compactness (Fig. 15) and sonic, neutron, average, and effective porosities are in the range of poor to negligible. In Dhermund-01, there is a zone at depth of 3232 to 3352 m of thickness 20 m (Fig. 16) that is regarded as a prolific zone where there are high resistivity and saturation of hydrocarbon values, less porosity, and Gamma rays values which overall delineate the competent limestone and at such an interval, the Nammal Formation can be regarded as a tight reservoir. However, there are limitations of some washout and data quality and DT at such a depth shows lesser value, and resistivity logs are missing at this depth. Based on log analysis, it is inferred that there is a poor range of effective or primary porosity in the wells of Dhermund-01 and Pindori-02 and the main porosity that plays role in the Nammal Formation, to act as a tight reservoir, is the secondary porosity generated by fracture and dissolution.

Conclusions

The Chharat Group represents good outcrop exposures in the Salt Range and predominantly constitutes the Eocene carbonates ranging in age from Early to Late Eocene. Among the formations of the Chharat Group, the Nammal Formation contains a higher abundance of planktonic foraminifera depicting relatively deeper-level deposition. A total of seven microfacies of the Nammal Formation have been identified which represent wackestone to packstone and rarely mudstone depositional textures, consistent with outer, middle, and inner ramp depositional settings. The fossil assemblages of the Nammal Formation include planktonic foraminifera and larger benthic foraminifera such as Nummulitids including *Nummulites* species (*Nummulites globulus*, *Nummulites mamilatus*, *Nummulites atacicus*, *Nummulites pinfoldi*) and *Assilina* species (*Assilina spinosa*, *Assilina subspinosa*, *Assilina dandotika*, *Assilina granulosa*, *Assilina laxispira*). Moreover, the Nammal Formation contains miliolids; *Operculina*;

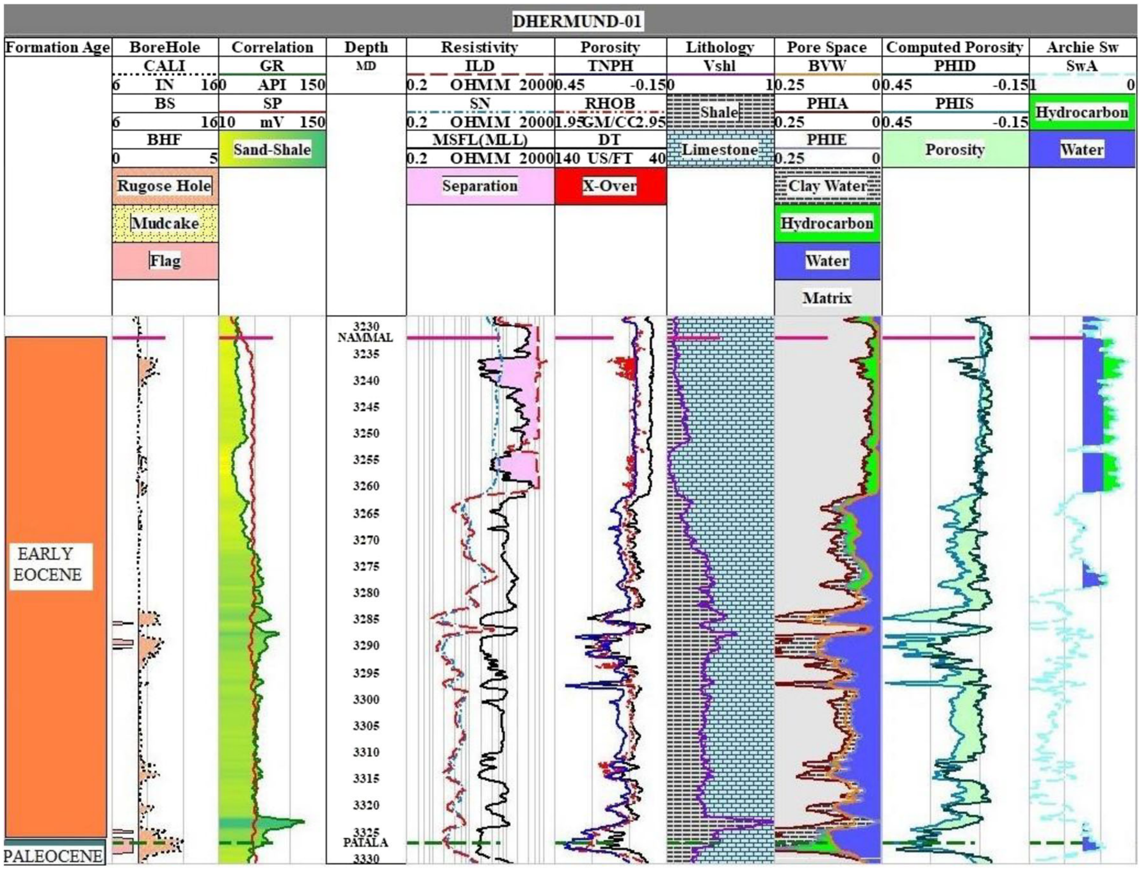


Fig. 16 A log view of the zone of interest of the Nammal Formation at the Dhermund-01 well

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Lockhartia species including *Lockhartia haimei*, *Lockhartia conditi*, and *Lockhartia tipperi*; rare *Alveolina (Alveolina elliptica)*; *Rotalia*; smaller *Miscellanea*; brachiopods and nonexistent *Discocyclina* (i.e., *Discocyclina dispansa*); pelecypods; and other non-skeleton fossils. Based on the fossil assemblages, the Nammal Formation of Early Eocene age demonstrates retrogradational depositional facies as the planktonic to benthonic foraminifera ratio diminishes upwards.

Among the diagenetic features, the fractures and dissolution on microscopic scales are the leading factors that increase the hydrocarbon prospect of reservoir of the Nammal Formation. The identified visual porosity types of the Nammal Formation include very rare intraparticle, vuggy, moldic, fenestral, and dominant fracture and the microfacies of the Nammal Formation have pores where diagenetic aspects dominate along with both diagenesis and depositional character influencing fractures and some microfacies have pores that predominantly contain fracture porosities. And the imageJ calculated porosities range from 4 to 6% whereas log estimated average effective porosities calculated in Dhermund-01 and Pindori-02 are 2 to 4% show that the secondary porosities play main reservoir potentiality role.

Based on these studies, it is suggested that at certain limestone intervals of the Nammal Formation, there is compacted limestone that can be regarded as a tight reservoir. And intervals of shale and marl sequences do not have any reservoir aspects.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

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