ISSN 0869-5938, Stratigraphy and Geological Correlation, 2020, Vol. 28, No. 7, pp. 745–764. © Pleiades Publishing, Ltd., 2020.

Sedimentology and Stratigraphic Evolution of the Early Eocene Nammal Formation, Salt Range, Pakistan

Shahid Ghazi[a], **Sadaf Sharif**[a], **Tehseen Zafar**[a, b], **Muhammad Riaz**[c, d, *], **Rashid Haider**[a], **and Tanzeela Hanif**[a]

[a] *Institute of Geology, University of Punjab, Quaid-e-Azam Campus, Lahore, 54590 Pakistan*
[b] *Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, 550081 China*
[c] *State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Chengdu University of Technology, Chengdu, 610059 China*
[d] *College of Energy Resources, Chengdu University of Technology, Chengdu-610059 China*
**e-mail: riazjass@yahoo.com*

Received March 14, 2019; revised September 2, 2019; accepted November 20, 2019

Abstract—The Early Eocene succession of the Salt Range from base to top comprises the Nammal Formation, Sakesar Limestone and Chor Gali Formation. The Nammal Formation of Ypresian age is well exposed throughout the Salt Range. Detailed sedimentological and palaeontological analyses of the Nammal Formation were carried out, based on six stratigraphically important measured sections in the Salt Range. Lithologically, the formation is predominantly composed of interbedded nodular limestone, marl and shale. Wackestone, packstone, wackestone to packstone, dolomitic limestone and grainstone facies dominate the Nammal Formation in a fine-grained bioclastic matrix with abundant grains of larger benthic foraminifera. The diagnostic larger benthic foraminifera are recorded, which includes *Nummulites mamillatus, Assilina spinosa, Assilina subspinosa, Assilina granulosa, Assilina laminosa, Discocyclina dispansa, Alveolina dolioliformis, Alveolina pasticillata, Alveolina globula, Lockhartia tipperi,* and *Lockhartia conditi.* Stable carbon and oxygen isotopic signatures of the Nammal Formation designate shallow marine depositional environment. During Eocene a carbonate sequence developed in the Salt Range, lower boundary of which is marked as SB-II at the base of the Nammal Formation overlying the Palaeocene Patala Formation. The Nammal Formation presents the retrogradational facies suggesting the transgressive system tracts. The Sakesar Limestone shows agradational to progradational pattern of facies, which developed in highstand system tracts. The Chor Gali Formation possesses shallowing-upward trend by forming progradational shift of facies, and represents the falling stage system tracts. Early Eocene carbonate sequence is terminated by a regional sub-aerial unconformity SB-I marked between marine carbonate sequence of the Chor Gali Formation and the overlying non-marine clastic Miocene Kamlial Formation. Overall, the Nammal Formation presents shallow water neritic carbonate deposits containing larger benthic foraminifers.

Keywords: sedimentology, stratigraphic evolution, palaeontology, shallow water, Early Eocene, Nammal Formation, Salt Range, Pakistan

DOI: 10.1134/S0869593820070047

INTRODUCTION

The Salt Range is the southernmost and recent expression of the Himalayan Frontal Fold and Thrust Belt that originated as a result of continent to continent collision between northward drifting of the Indo-Pak Plate and southward drifting of the Eurasian Plate (Agard et al., 2005; Baker et al., 1988; Ghazi and Mountney, 2009; Grelaud et al., 2002; Hughes et al., 2019; Najman, 2006). The east-west trending Salt Range is bounded on the east by the Jhelum River, on the west by the Indus River (Ghazi et al., 2015; Hughes et al., 2019), and on the north and south, by the hydrocarbon-bearing Potwar Basin (Riaz et al., 2018, 2019) and Punjab Plains (Sameeni, 2009), respectively (Fig. 1). The Eocene succession of the Salt Range consists of the Nammal Formation, Sakesar Limestone and Chor Gali Formation deposited in shallow water neritic environments (Ghazi et al., 2015). The present study focusses on the facies development, sequence and depositional history of the Early Eocene Nammal Formation. The name Nammal Formation has been formalized by the Stratigraphic Committee of Pakistan (Fatmi, 1973) for the Nammal Limestone and shale of Davies and Pinfold (1937) from its type locality in the Nammal Gorge, Salt Range. The Nammal Formation predominantly is composed of an alternation of nodular limestone,

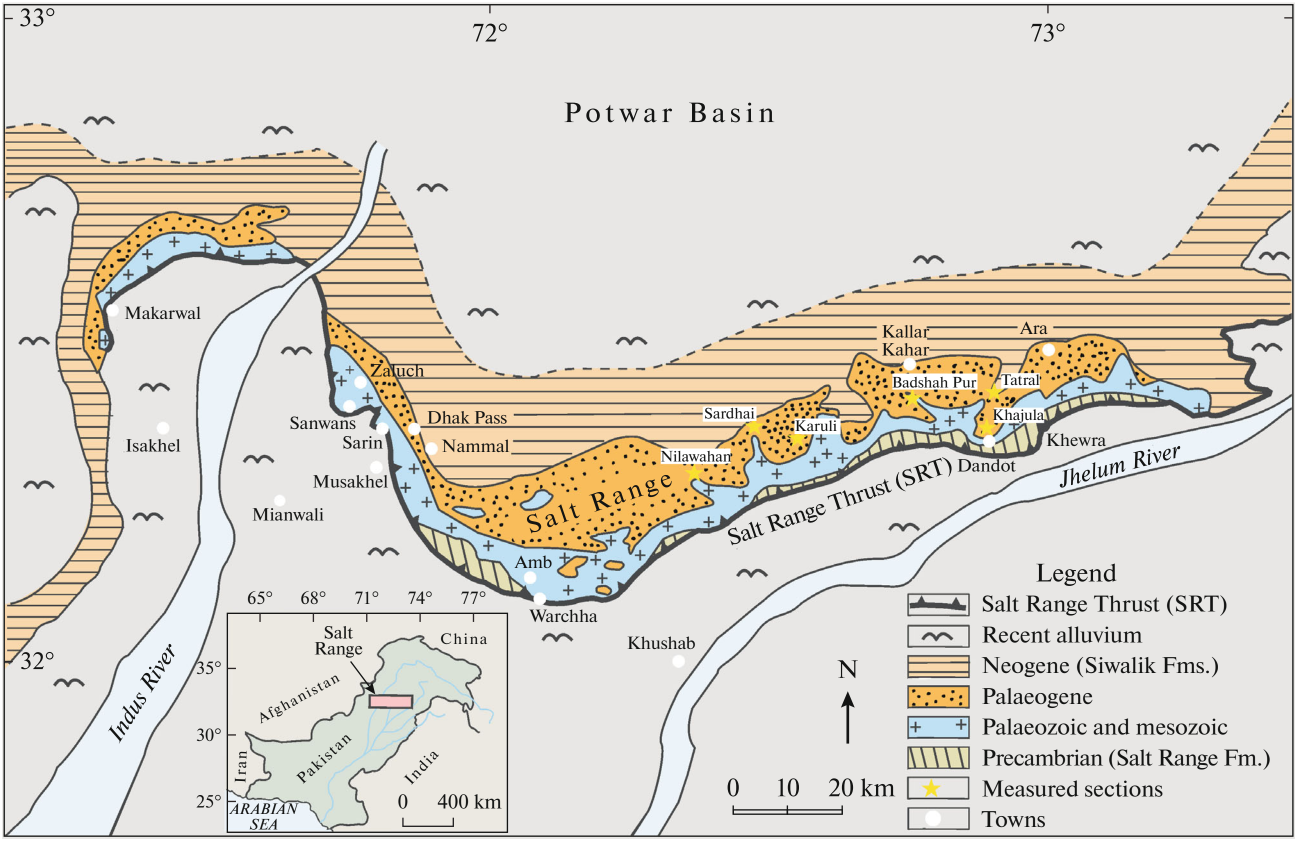

Fig. 1. Location map of the study area, showing measured sections of the Nammal Formation, Salt Range, Pakistan (modified after Ghazi et al., 2015; Hughes et al., 2019).

shale and marl. This formation is fossiliferous, and especially the marly part is highly fossiliferous in various sections of the Salt Range.

The Nammal Formation has been studied previously by many authors including Davies and Pinfold (1937) who worked as pioneer on the foraminiferal biostratigraphy of the marine Lower Tertiary succession in the Salt Range. Gill (1953) reported different species of *Assilina* in the Nammal Formation from the Salt Range. Boustani and Khawaja (1997) described the microfacies of the Eocene strata, Salt Range. Afzal and Butt (2000) studied the planktonic biostratigraphy of the Lower Tertiary. Later on Ghazi et al. (2004) studied the Nammal Formation for its microfacies analysis and foraminiferal assemblage from the Nilawahan Gorge, Salt Range. However, no detailed sedimentological study of the Nammal Formation and its stratigraphic evolution has been carried out.

The present research represents the lithostratigraphic analysis and stratigraphic evolution of the Nammal Formation during the Early Eocene in the Salt Range region. Depositional environment of the Nammal Formation was inferred from litho- and biofacies, predominantly based on the benthic foraminiferal studies. The Nammal Formation records fluctuating relative sea level and in response a basin-wide accumulation of carbonate sediments, marking the Palaeocene–Eocene boundary. The aims of this paper are (1) to provide for the first time a detailed facies analyses, and (2) to reconstruct stratigraphic evolution of the Nammal Formation within Early Eocene framework on the basis of facies assemblages and microfacies variations.

MATERIALS AND METHODS

The detailed sedimentological analysis of the Nammal Formation is carried out from six stratigraphically important sections (Nilawahan, Sardhai, Karuli, Badshah Pur, Tatral and Kahjula) from Salt Range (Fig. 1). A total of 70 thin sections were prepared and examined for composition, texture and microfossil assemblages. Microfacies scheme is established based on the classification proposed by Dunham (1962). A total of sixteen microfacies were identified, the most prominent being mudstone, wackestone, packstone, wackestone to packstone, dolomitic limestone and grainstone. Furthermore, eleven samples of carbonate were collected from the Nilawahan and the Badshah Pur sections, starting from the lower

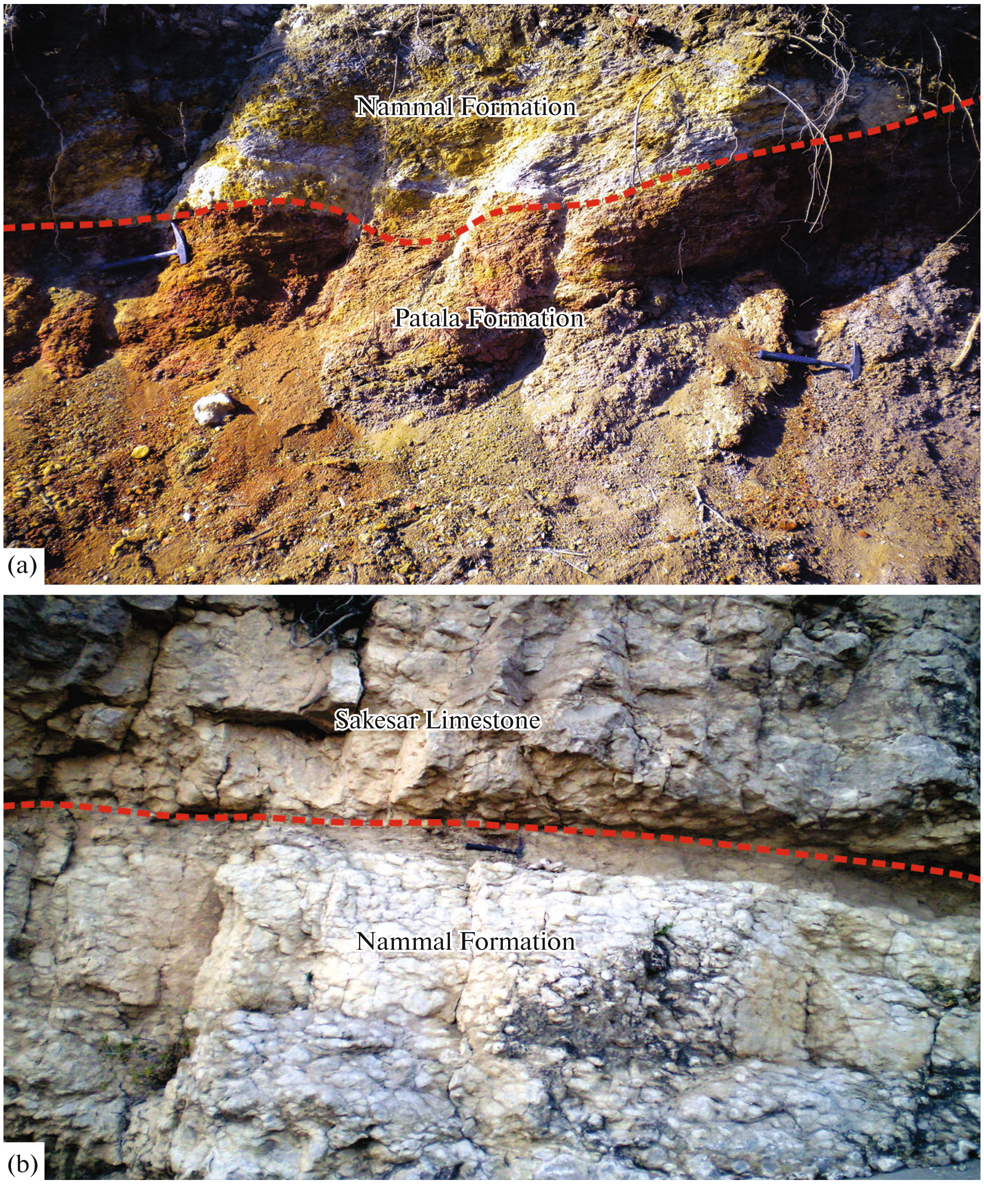

Fig. 2. Outcrop exposure of the Nammal Formation, Salt Range, Pakistan, showing: (a) lower contact with the Patala Formation; (b) upper contact with the Sakesar Limestone.

contact of the Nammal Formation with Patala Formation (Palaeocene–Eocene boundary) up to the top of the Nammal Formation near its contact with Sakesar Limestone for the purpose of ^{13}C and ^{18}O analysis. Samples were analyzed at the Cornel University (New York, USA), Isotope Laboratory at Thermo Delta V isotope ratio mass-spectrometer (IRMS) interfaced with a Temperature Conversion Element Analyzer (TC/EA). The $\delta^{13}C$ values are measured against a primary reference Vienna Pee Dee Belemnite (VPDB) and $\delta^{18}O$ values are measured against a primary reference Vienna Standard Mean Oceanic Water (VSMOW). The isotopic values are expressed in parts per million (‰) with an accuracy of 0.31‰.

LITHOSTRATIGRAPHY

Nature of Contacts

The Nammal Formation was deposited above the Palaeocene Patala Formation and marks regionally the Palaeocene–Eocene boundary in the Salt Range and Potwar Basin. The lower contact of the Nammal Formation with the underlying Patala Formation is exposed in few places and is generally recorded in coal mines, and is represented by grey to dark-grey siltstone, olive-grey to greenish-grey marl with light- to medium-grey carbonaceous shale of the underlying Patala Formation (Fig. 2a). The upper contact is sharp and wavy and grades into massive thick-bedded

Fig. 3. Outcrop exposures of the Nammal Formation showing development of nodule into five stages, Salt Range, Pakistan: (a) example of stage 1 characterized by alternate marl and limestone unit; (b) example of stage 2 initiated by the fracturing of limestone; (c) example of stage 3 characterized by marl rounding limestone; (d, e) examples of stage 4 characterized by the rounding of the limestone material and accommodation compensated by marl; (f) example of stage 5 of final nodule development.

Sakesar Limestone. It is marked by about 25 cm thick layer of light-grey to grey nodular limestone embedded in greenish grey shale (Fig. 2b).

Lithological Variations

The Nammal Formation is composed of nodular limestone, shale, and marl in six measured sections in

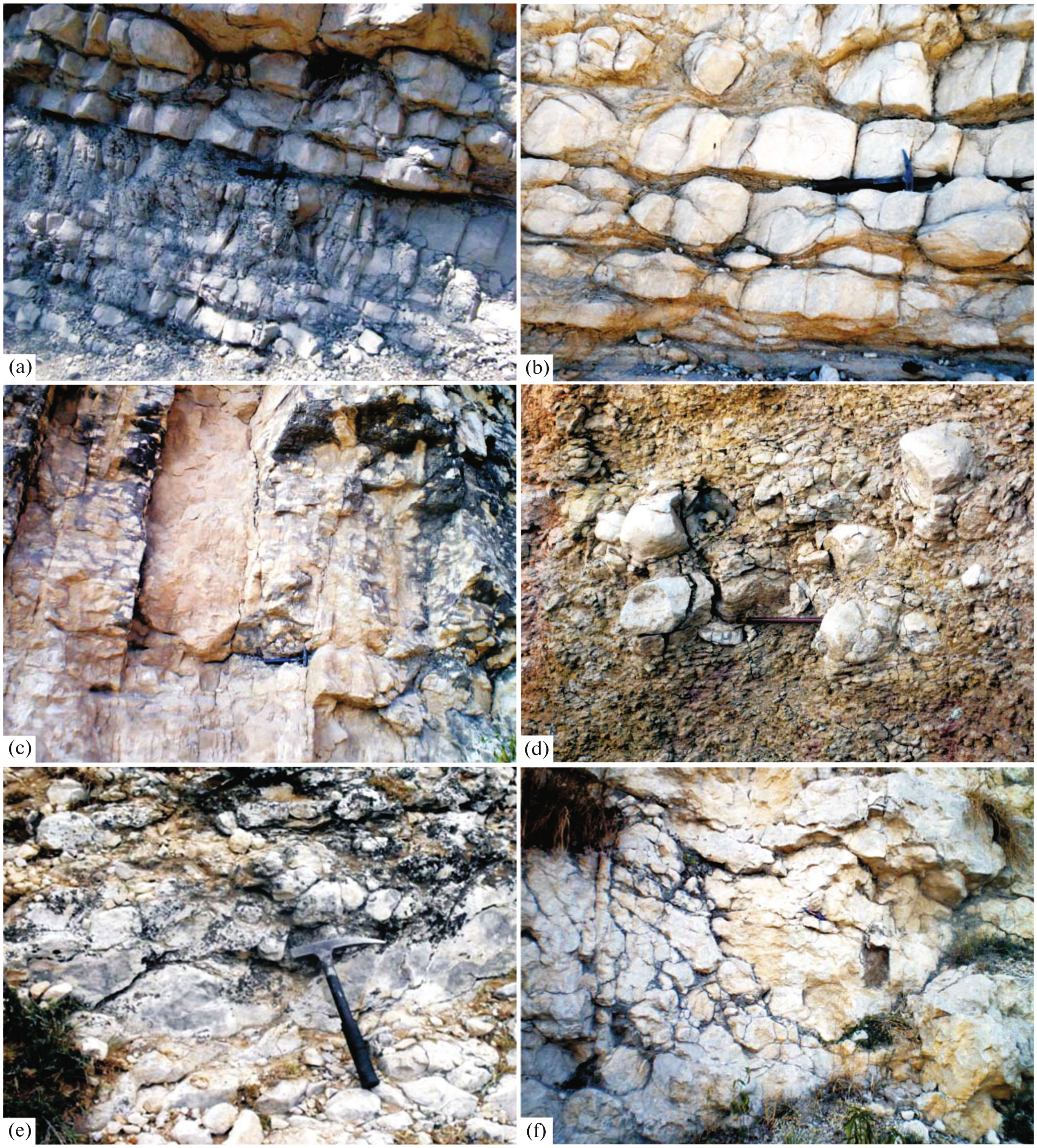

Fig. 4. Outcrop exposures of the lithostratigraphic units of the Nammal Formation, Salt Range, Pakistan: (a, b) examples of alternate marl and limestone unit; (c) example of well-bedded nodular limestone with chert nodules unit; (d) example of limestone interbedded with shale unit; (e, f) examples of dolomitic limestone unit.

the Salt Range. The limestone and marl are light-grey to bluish in color, while the shale is grey to olive-green in color. The size of the nodules of limestone is 10–12 cm in diameter and at places 16–20 cm. The Nammal Formation is predominantly composed of well-bedded nodular limestone interbedded with marl showing cyclic deposition. Minor lithologies include dolomite, shaly limestone, chert and iron concretions. Several sedimentary structures are recorded, which are mainly associated with solution crack and seal

Table 1. Chronostratigraphy of the Lower Eocene strata based on Alveolinids, Salt Range, Pakistan (modified after Sameeni and Butt, 2004)

Chrono-stratigraphy, age			Biostratigraphy Alveolinids zonation	Shallow benthic biozones	Lithostratigraphy	
					Salt Range	Trans Indus Range
Lower Eocene	Ypresian	Cuisian	Dainellii	SB 11	Chor Gali Formation	
			Oblonga	SB 10		
			Trempina	SB 9		
		Ilerdiani	Corbarica	SB 8	Sakesar Limestone	Sakesar Limestone
			Moussoulensis	SB 7		
			Ellipsoidalis	SB 6	Nammal Formation	Nammal Formation
			Vredenburgi	SB 5	▨	Patala Formation
Upper Paleocene	Thanetian		Levis	SB 4	Patala Formation	
			Pimaeva	SB 3	Lockhart Limestone Hangu Formation	Lockhart Limestone Hangu Formation

structures. Stylolites are the most abundant features, amplitude of stylolites varies greatly. Nodularity in limestones is a characteristic feature in the Nammal Formation. These nodules are generally rounded to sub-rounded and elongated in shape having diagenetic origin (Ghazi et al., 2004). These nodules development went through five noticeable stages, recorded at many places (Figs. 3a–3f). Mostly marly matrix surrounds the limestone nodules in core. Stylolites and nodularity show compaction effect on the formation during diagenesis (Flügel, 2010; Ghazi et al., 2006). Calcite veins fill the cracks/fractures, formed during the deformation of the Nammal Formation. Replacement of fossil shells by spar is most common features of these deposits. Both nodular and embedded chert and iron concretions are recorded in the middle and upper parts of this formation. The chert nodules recorded in the Nammal Formation are smaller in size than those from the overlying Sakesar Limestone (Ghazi et al., 2004). On the basis of lithological variation the Nammal Formation is divided into four distinct units as follows.

(a) Alternate marl and limestone. The limestone in this unit is thin-bedded, nodular and fossiliferous. The color of the limestone is yellowish, off white to light-grey on the weathered surface and light-brown to light-grey on the fresh surface. The beds of limestone are 15–20 cm thick and interbedded with marl. The marl is off white to light-grey in color and 10–12 cm thick. The limestone is highly fossiliferous and interbedded with marl (Figs. 4a, 4b). The bedding surface shows broken shells of fossils, and the thin-bedded ones are often wavy to nodular.

(b) Well bedded limestone with chert nodules. The limestone in this portion is light-brown, yellowish on the weathered surface and olive-grey to greenish grey on the fresh surface. The limestone of this part is hard, and chert nodules developed in it. The size of the chert nodules is 16–20 cm in diameter. The 1.5 m thick dolomitic limestone is present at few places in the middle part of this unit. It is light-brown on the weathered surface and light-grey on the fresh surface. The limestone gives petroliferous odour when broken due to presence of organic matter (Fig. 4c).

(c) Limestone interbedded with shale. The limestone of this part is grey to light- grey, light-brown on the weathered surface and light-grey to light-blue on the fresh surface. Limestone is thin-bedded and interbedded with shale and marl. Beds of limestone are at least 6–8 cm thick. The shale is greenish-grey, olive-

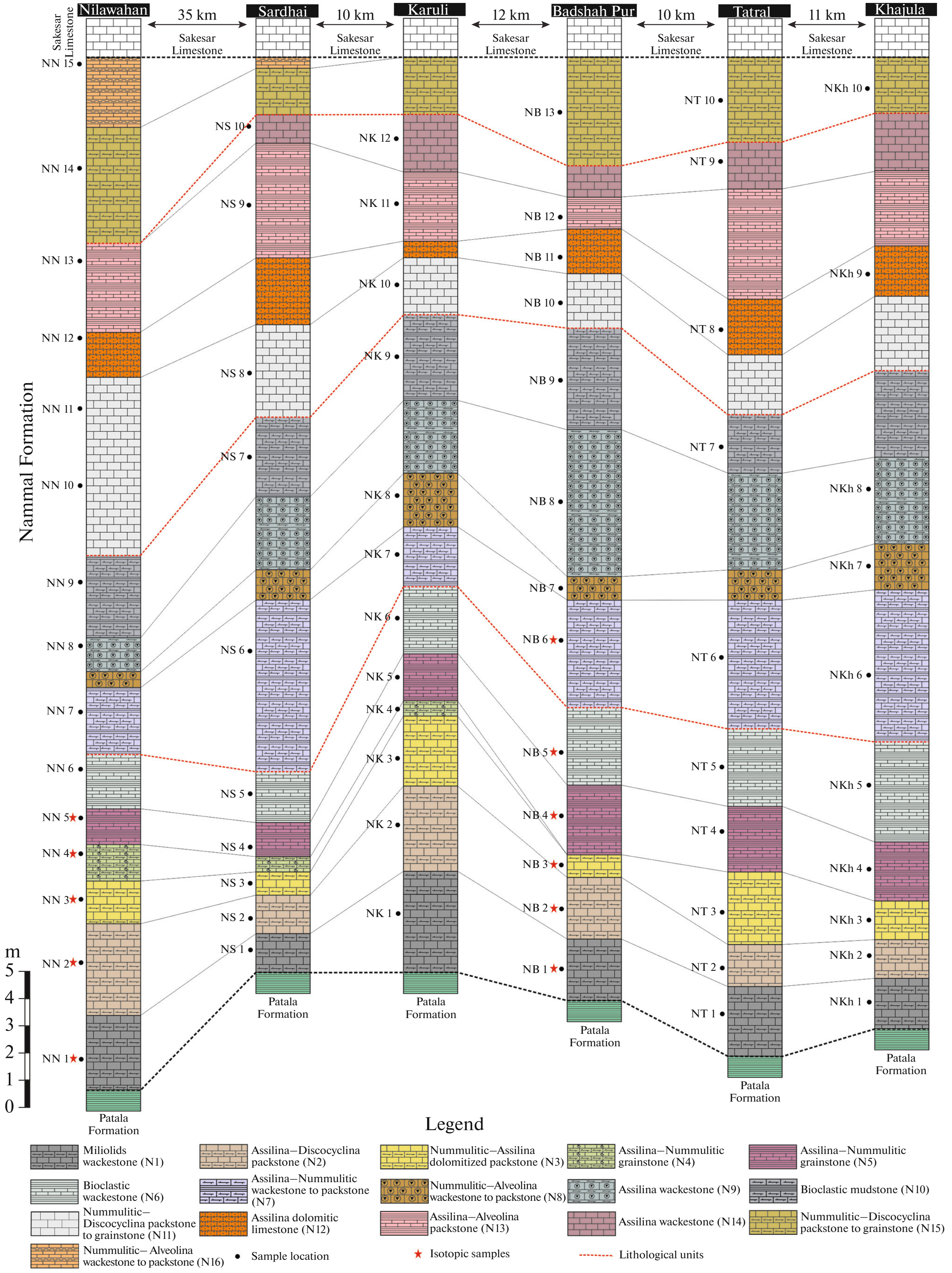

Fig. 5. Measured sections showing the vertical relationship of facies of the Nammal Formation, Salt Range, Pakistan.

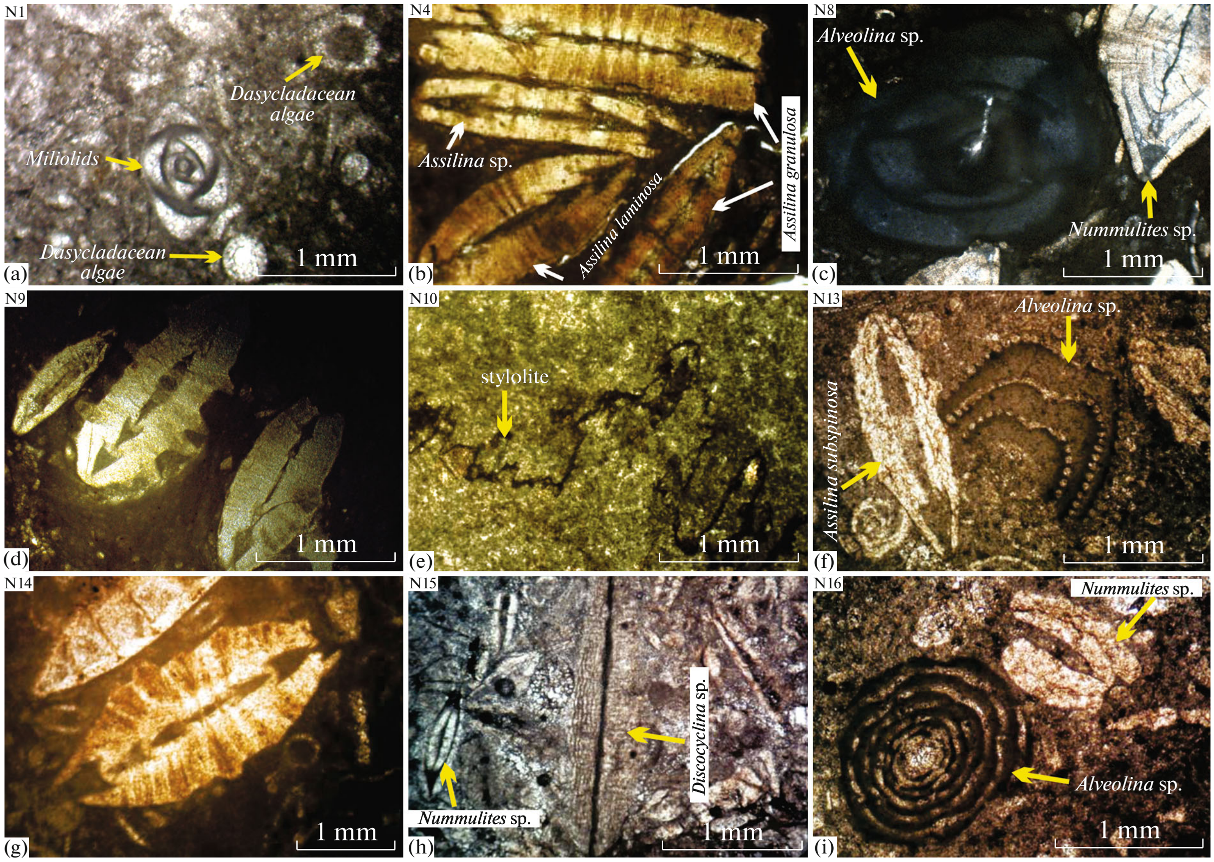

Fig. 6. Photomicrographs showing microfacies of the Nammal Formation, Salt Range, Pakistan: (a) Miliolids wackestone representing N1, with prominent bioclasts of *Miliolids;* (b) Assilina grainstone representing N4, with prominent bioclasts of *Assilina granulosa* (d'Archiac), *Assilina laminosa* Gill, and *Assilina* sp.; (c) Nummulitic–Alveolina wackestone to packstone representing N8, with prominent bioclasts of *Nummulites* sp. and *Alveolina* sp.; (d) Assilina wackestone representing N9, with prominent bioclasts of *Assilina subspinosa* Davies and Pinfold; (e) bioclastic mudstone representing N10, with stylolites of moderate to high amplitude; (f) Assilina–Alveolina packstone representing N13, with prominent bioclasts of *Assilina subspinosa* Davies and Pinfold and *Alveolina* sp.; (g) Assilina wackestone representing N14, with prominent bioclasts of *Assilina subspinosa* Davies and Pinfold; (h) Nummulitic–Discocyclina packstone to grainstone representing N15, with prominent bioclasts of *Nummulites* sp. and *Discocyclina* sp.; (i) Nummulitic–Alveolina wackestone to packstone representing N16, with prominent bioclasts of *Nummulites* sp. and *Alveolina* sp.

green to black in color. The shale is at least 10–15 cm thick and contains organic matter (Fig. 4d).

(d) Dolomitic limestone. Light-pink colored dolomitic limestone is recorded in the upper part of this formation. However, this dolomite is absent in the western parts of the studied area (Figs. 4e, 4f).

Age and Thickness

A number of age diagnostic larger foraminifera were reported from the Nammal Formation by previous workers. Davies and Pinfold (1937) recorded *Nummulites atacicus* Leymerie, *Nummulites irregularis* Deshayes, *Nummulites subirregularis* De la Harpe, and *Assilina granulosa* (d'Archiac) in the Salt Range. Gill (1953) reported *Assilina granulosa* (d'Archiac), *Assilina laminosa* Gill, *Assilina daviesi* de Cizancourt, and *Assilina sublaminosa* Gill from Jaba area in the western Salt Range. Ghazi et al. (2004) also identified different species of *Assilina* and *Alveolina* which include *Assilina spinosa* Davies and Pinfold, *Assilina granulosa* (d'Archiac), and *Alveolina globosa* Leymerie from the Nilawahan Gorge in the Salt Range. On the basis of microfossils assemblage, the Early Eocene (Ypresian) age is assigned to the Nammal Formation (Table 1). The thickness of the Nammal Formation does not show much variation: the maximum thickness of 36 m is recorded at the Nilawahan area while the minimum thickness of 32 m is recorded at Sardhai area (Fig. 5).

RESULTS AND DISCUSSION

Microfacies Analysis

A total of 16 microfacies were identified from bottom to top followed by classification scheme of Dunham (1962). The Nammal Formation is characterized

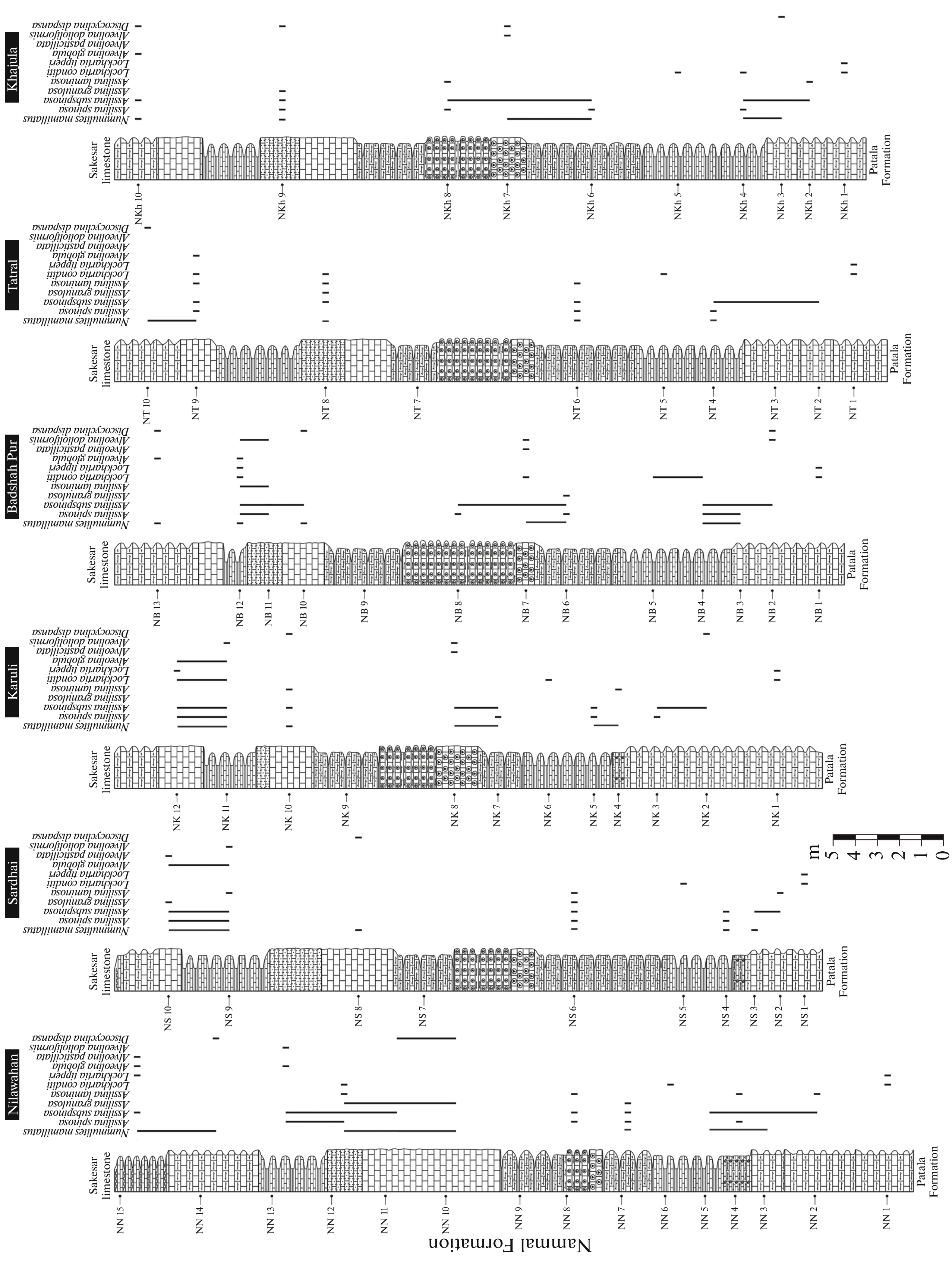

Fig. 7. Distribution chart of the larger benthic foraminifera found in the Early Eocene Nammal Formation in the Salt Range, Pakistan.

Table 2. Summary of microfacies recorded in six measured section of the Nammal Formation, Salt Range, Pakistan

Facies	Code	Description	Interpretation
Miliolids wackestone	**N1**	It is 1.5 to 3.5 m thick, contributes 7% of total rock volume, comprised 20% bioclasts floating in 80% micrite matrix. The bioclasts are *Miliolids* 15% and *Dasycladacean algae* 5% (Fig. 6a). The bioclast grains are filled with micrite but some of the grains are partly or completely replaced by microsparite.	*Miliolids*, *Dasycladacean algae,* and abundance of micrite matrix indicates the deposition in shallow marine quiet water conditions (Ghazi et al., 2004; Taheri et al., 2008).
Assilina–Discocyclina packstone	**N2**	It is 1 to 3 m thick, contributes 6% of total rock volume, composed of 55% foraminiferas and 45% micrite matrix, contains *Assilina subspinosa* (Davies and Pinfold) 20%, *Assilina laminosa* (Gill) 10%, *Discocyclina dispansa* (Sowerby) 10%, *Nummulites* sp., crustose coralline algae and broken shell fragments contribute 15% (Fig. 5). The micrite matrix is partially recrystallized into microspars (5%).	Low micrite and abundant of *Assilina* with *Discocyclina* indicates moderate energy, neritic conditions with moderately agitated waters (Ghazi et al., 2004, 2006). It represents sufficient nutrient supply and moderate salinity and suitable pH values (Al-Wosabi and Al-Aydrus, 2011; Afghah and Farhoudi, 2012).
Nummulitic–Assilina dolomitized packstone	**N3**	It is 0.75 to 2.5 m thick, contributes 5% to total rock volume, moderately dolomitized with prominent dolomite rhombs, comprises 35% micrite matrix and 65% bioclasts; *Nummulites mamillatus* (Fichtel and Moll) 30%, *Assilina subspinosa* (Davies and Pinfold) 15%, *Assilina spinosa* (Davies and Pinfold) 7% and *Assilina laminosa* (Gill) 5%, *Discocyclina dispansa* (Sowerby) 3% and broken shell fragments 5% (Fig. 5).	*Nummulites* with *Assilina* occur in both low and high energy conditions of shallow shelf (Beavington-Penney and Racey, 2004; Flügel, 2010). The dolomitization indicates fluid circulation through the sediments (Friedman, 1995; Strasser et al., 2012).
Assilina grainstone	**N4**	It is 0.5 to 1 m thick, contributes 1% of total rock volume. Foraminiferal contents 80%, mud matrix 15% and spar replacement 5%. *Assilina granulosa* (d'Archiac) contributes 30%, *Assilina laminosa* (Gill) 25%, *Assilina* sp. 15% (Fig. 6b), *Nummulites mamillatus* (Fichtel and Moll) 3%, *Lockhartia tipperi* (Davies) 2%, and other broken shell fragments 5%.	Agitated waters i.e. grain supported texture and features pointing to quiet-water conditions i.e. infiltration of mud in the grains (Shinn and Robbin, 1983), presence of *Assilina* and *Nummulites suggests* shallow marine environment (Nichols, 2009; Rafi et al., 2012).
Nummulitic–Assilina packstone	**N5**	It is 1 to 2 m thick, contributes 5% of total rock volume, comprises 60% larger benthic foraminifera in a micrite matrix of 35%. Bioclastic assemblage contributed by *Nummulites mamillatus* (Fichtel and Moll) 25%, *Assilina subspinosa* (Davies and Pinfold) 13% and *Assilina spinosa* (Davies and Pinfold) 10%. *Lockhartia conditi* (Nuttall) 2%, algae 3% and broken shell fragments contribute 7% (Fig. 5). Minor replacement of matrix and shell fragments with sparry calcite 5%.	*Nummulites* with low % age of *Assilina* having original morphology and mineralogy of their shells represent the relatively moderate energy conditions below fair weather wave base (Flügel, 2010). Shallow shelf conditions with high degree of sunlight penetration providing conducive environment for flourishing fauna and high level of nutrients availability (Afghah and Farhoudi, 2012).
Bioclastic wackestone	**N6**	It is 2 to 6 m thick, contributes 8% of total rock volume. Shell fragments of *Lockhartia conditi* (Nuttall) 15% and *Miliolids 10%* surrounded by homogeneous lime mud matrix. Shell fragments are largely replaced by microsparite due to recrystallization during diagenesis (Fig. 5).	Abundance of micrite matrix, *Lockhartia* and *Miliolids* represents the deposition in high salinity, low energy shallow shelf environments (Ghazi et al., 2004, 2006).
Assilina-Nummulitic wackestone to packstone	**N7**	It is 2 to 6 m thick, represents 12% of total rock volume. Whole to fragmented bioclasts (35-40%) dispersed in the micrite matrix (57-60%). *Assilina subspinosa* (Davies and Pinfold) contributes 10%, *Assilina spinosa* (Davies and Pinfold) 5%, *Assilina laminosa* (Gill) 2%, *Assilina granulosa* (d'Archiac) 3%, *Nummulites mamillatus* (Fichtel and Moll) 9%, and broken shell fragments 5-10%. Some of the bioclasts have chambers filled with sparite 2-5% (Fig. 5).	Whole and fragmented forms of *Assilina* and *Nummulites* indicating reworking by current activity in moderately high energy conditions (Flügel, 2010) under shallow marine open shelf environment (Taheri et al., 2008; Flügel, 2010)
Nummulitic–Alveolina wackestone to packstone	**N8**	It is 1 to 2 m thick having 3% of total rock volume, consists of 35% whole to broken skeletal grains; *Nummulites* sp. 17%, *Alveolina* sp. 12% (Fig. 6c) and other less common biota is *Assilina subspinosa* (Davies and Pinfold) 2%, *Lockhartia conditi* (Nuttall) 1% and broken shell fragments 3%, embedded in lime mud matrix. The chambers of some fossils are filled with spar due to recrystallization.	Presence of the whole and broken shells of larger benthic foraminifera like *Nummulites* and *Alveolina* presents the deposition in moderately agitated water in shallow marine open shelf environment (Flügel, 2010).

Table 2. (Contd.)

Facies	Code	Description	Interpretation
Assilina wackestone	**N9**	It is 1 to 5.25 m thick and represents 9% of total rock volume. Skeletal grains (25%) distributed in the homogeneous micrite matrix (65%). *Assilina subspinosa* (Davies and Pinfold) contributes 12% (Fig. 6d), *Assilina spinoa* (Davies and Pinfold) 3%, *Assilina laminosa* (Gill) 2%, *Miliolids* 3%, helimida 0.5%, green algae 1%, some planktonic forams 1% and broken shell fragments are 2.5% (Fig. 5). Some grains chambers replaced with sparite (5%).	*Assilina* along with *Miliolids*, green algae and planktons reflects deposition under low energy quite water conditions with restricted circulation in shallow shelf environments (Boggs, 2006; Ghazi et al., 2006; Flügel, 2010).
Bioclastic mudstone	**N10**	It is 2 to 3.5 m thick, contributes 8.5% of total rock volume. Mud 95% and low content of biota. Diagenetic features including microfractures, pressure solutioning and stylolites of low and high amplitude can also be observed (Fig. 6e).	High proportion of mud matrix along with few benthonic and planktonic forams indicate slow rate of sedimentation in relatively deeper water conditions of open shelf environment (Taheri et al., 2008; Flügel, 2010; Strasser et al., 2012).
Nummulitic–Discocyclina packstone to grainstone	**N11**	It is 2 to 6 m thick, contributes 8.5% of total rock volume. Skeletal grains are 75%; *Nummulites mamillatus* (Fichtel and Moll) contributes 28%, *Discocyclina dispansa* (Sowerby) 27%, *Assilina subspinosa* (Davies and Pinfold) 6%, *Assilina laminosa* (Gill) 2%, *Assilina granulosa* (d'Archiac) 2%, and broken shell fragments are 10%. The shells are highly fractured and fragmented (Fig. 5).	Abundant *Nummulites* and *Discocyclina* and lack of micrite matrix indicates shallow shelf inter-tidal environment in high energy conditions that resulted in reworking of shells and winnowing out of fine matrix (Flügel, 2010; Afghah and Farhoudi, 2012; Strasser et al., 2012).
Assilina dolomitic limestone	**N12**	It is 0.5 to 2 m thick, comprises 5% of total rock volume. Highly dolomitized with fine to coarse-grained euhedral rhombs of dolomite that replaced the shell fragments. Bioclasts 20 %; *Assilina subspinosa* (Davies and Pinfold) 8%, *Assilina spinosa* (Davies and Pinfold) 4%, *Assilina laminosa* (Gill) 3%, *Assilina granulosa* (d'Archiac) 2%, *Nummulites mamillatus* (Fichtel and Moll) 2%, and *Lockhartia conditi* (Nuttall) 1% (Fig. 5).	Presence of larger benthic foraminifera mainly of *Assilina* with less common *Nummulites* represents deposition under shallow shelf neritic conditions (Ghazi et al., 2004, 2006).
Assilina–Alveolina packstone	**N13**	It is 1 to 4 m thick, comprises of 8% of total rock volume. Abundant *Assilina* associated with *Alveolina* (Fig. 6f); *Assilina subspinosa* (Davies and Pinfold) contributes 20%, *Assilina spinosa* (Davies and Pinfold) 10%, *Assilina laminosa* (Gill) 5%, *Alveolina globula* (Hottinger) 8%, *Alveolina dolioliformis* (Schwager) 8%, *Nummulites mamillatus* (Fichtel and Moll) 4%, *Lockhartia tipperi* (Davies) 1%, *Lockhartia conditi* (Nuttall) 1%, *Miliolids* 1% and shell fragments7%. The micrite matrix is 28% and sparry calcite that replaced some micrite is 5-6%. Calcite veins are 1-2% which cut across the shells	The presence of larger benthic foraminifera mainly *Assilina* and *Alveolina* with less abundance of mud matrix represents the deposition under normal marine conditions in shallow shelf inner-neritic environment (Ghazi et al., 2004, 2006; Flügel, 2010).
Assilina wackestone	**N14**	It is 1 to 4 m thick, contributes 6% of total rock volume, comprises of 20-25% bioclasts, 70-75% micrite matrix and 5% sparite. *Assilina subspinosa* (Davies and Pinfold) 8% (Fig. 6g), *Assilina spinosa* (Davies and Pinfold) 5-7%, *Assilina laminosa* (Gill) 1%, *Nummulites mamillatus* (Fichtel and Moll) 1%, *Alveolina pasticillata* (Schwager) 0.5%, *Alveolina globula* (Hottinger) 1%, *Lockhartia tipperi* (Davies) 0.5%, *Lockhartia conditi* (Nuttall) 1%, and foraminiferal shell debris is 2-5%. Some grain chambers are replaced with sparite.	Less abundant grains as compared to micrite matrix with dominant fauna of larger benthic foraminifera mainly *Assilina* suggests shallow shelf inner-neritic environment with low energy conditions (Ghazi et al., 2004, 2006; Flügel, 2010; Al-Wosabi and Al-Aydrus, 2011).
Nummulitic–Discocyclina packstone to grainstone	**N15**	It is 2 to 4 m thick, contributes 6% of total rock volume. Skeletal grains 70-75%; *Nummulites mamillatus* (Fichtel and Moll) 35%, and *Discocyclina dispansa* (Sowerby) 27% along with *Assilina subspinosa* (Davies and Pinfold) 1%, *Alveolina globula* (Hottinger) 2%, green algae 1%, and broken shell fragments are 4-9%. The micrite matrix is 10-15% recrystalized into spar 10% and chambers of some grains are also replaced with spar (Fig. 6h).	Skeletal grains mainly of *Nummulites* and *Discocyclina* suggests the deposition under high energy conditions capable of winnowing out the shell debris. Deposition in agitated water conditions of shallow shelf environment (Ghazi et al., 2004; Flügel, 2010; Al-Wosabi and Al-Aydrus, 2011).
Nummulitic–Alveolina wackestone to packstone	**N16**	It is 0.25 to 3 m thick, contributes 2% of total rock volume. Bioclastic grains 35-40% (Fig. 6i); *Nummulites mamillatus* (Fichtel and Moll) 15%, *Alveolina globula* (Hottinger) 9% and *Alveolina pasticillata* (Schwager) 5%, *Assilina subspinosa* (Davies and Pinfold) 2%, *Lockhartia tipperi* (Davies) 1%, and fragmented shells 3-8%. The micrite matrix 55-60%, recrystallized into sparite 5% .	Presence of larger benthic foraminifers like *Nummulites* and *Alveolina* suggests deposition in moderate to high energy conditions of shallow shelf environment (Ghazi et al., 2004; Taheri et al., 2008; Flügel, 2010).

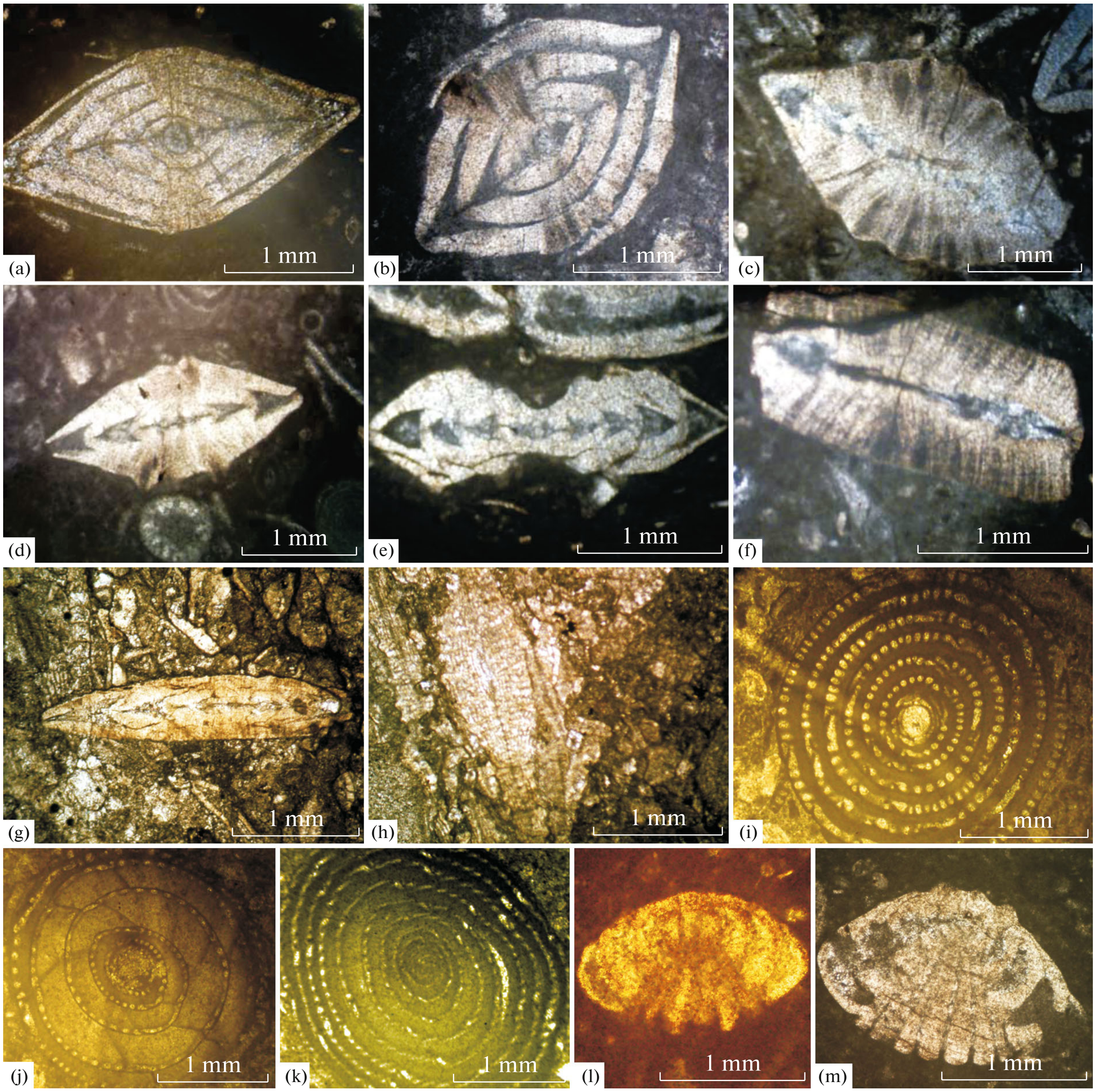

Fig. 8. Photomicrographs of foraminifers in the Nammal Formation, Salt Range, Pakistan: (a, b) *Nummulites mamillatus* Fichtel and Moll; (c, d) *Assilina subspinosa* Davies and Pinfold; (e) *Assilina spinosa* Davies and Pinfold, which is similar to *Assilina lacunata* Cizancourt; (f) *Assilina laminose* Gill; (g) *Assilina laminosa* Gill; (h) *Discocyclina dispansa* Sowerby; (i) *Alveolina dolioliformis* Schwager; (j) *Alveolina pasticillata* Schwager; (k) *Alveolina globula* Hottinger; (l) *Lockhartia tipperi* Davies; (m) *Lockhartia conditi* Nuttall.

on the basis of lateral and vertical variation in lithology and biota. The differences are indicated by different degrees of size, sorting and roundness of grains; type and frequency of fossils associations and substrate. The Nammal Formation is composed of wackestone, packstone and grainstone facies with minor contribution of mudstone (Figs. 5, 6; Table 2).

Palaeontological Analysis

Mainly larger benthic foraminifers that include age indicator species belonging to *Nummulites*, *Alveolina*, *Lockhartia*, *and Discocyclina,* have been recorded throughout the Nammal Formation. The foraminiferal frequency distribution of larger benthic species has been established (Fig. 7). The prominent foraminifers include *Nummulites mamillatus* (Fichtel and Moll) (Figs. 8a, 8b), *Assilina subspinosa* Davies and Pinfold (Figs. 8c, 8d), *Assilina spinosa* Davies and Pinfold that looks like *Assilina lacunata* Cizancourt (Kaever, 1964) (Fig. 8e), *Assilina laminose* Gill (Fig. 8f), *Assilina laminosa* Gill (Fig. 8g), *Discocyclina dispansa* Sowerby (Fig. 8h), *Alveolina dolioliformis* Schwager (Fig. 8i), *Alveolina pasticillata* Schwager (Fig. 8j), *Alveolina globula* Hottinger (Fig. 8k), *Lockhartia tipperi* Davies (Fig. 8l), *Lockhartia conditi* Nuttall (Fig. 8m), *Miliolids*, *Textularia* sp., *Nodosaria* sp., and gastropods are also found.

A brief review of foraminifera that are found in the Nammal Formation is given.

Miliolids. They are rarely found having few occurrences in the lower parts of the formation. Because of the difficulties of identifying the different species of *Miliolids*, they are not further described. These are relatively small (0.3 to 0.5 mm) and difficult to recognize in the field also. In the Nammal Formation, the presence of *Miliolids* in association with *Lockhartia* shows low agitation and normal marine conditions of a shallow shelf environment (cf. Geel, 2000).

Nummulites. Both microspheric and megalospheric *Nummulites*, predominantly *Nummulites mamillatus* (Fichtel and Moll) are present throughout the formation. They range from 2 to 3 mm in diameter and are generally lenticular in shape. *Nummulites* in the Nammal Formation show their association with *Alveolina*, *Assilina* and *Discocyclina* representing accumulation of biota in shallow shelf conditions (cf. Beavington-Penney and Racey, 2004; Geel, 2000; Racey, 2001).

Alveolinids. Rounded to elongated forms of *Alveolinids*, predominantly *Aveolina dolioliformis* Schwager, *Alveolina globula* Hottinger and *Alveolina pasticillata* Schwager are abundant in the upper parts of the formation. They vary from 2 to 3 mm in diameter.

Assilina. A number of species were recognized including *Assilina subspinosa* Davies and Pinfold, *Assilina spinosa* Davies and Pinfold, *Assilina granulosa* (d'Archiac) and *Assilina laminosa* Gill present throughout the formation. Their size ranges from 2.5 to 3 mm.

Discocyclina. Both flat and lens shaped (about 3 mm in lengths) *Discocyclina*, predominantly *Discocyclina dispansa* (Sowerby) is present at different levels through the formation. In the Nammal Formation, *Discocyclina* in association with *Assilina* and *Nummulites* represents relatively deeper water conditions in a shallow shelf (cf. Beavington-Penney and Racey, 2004; Geel, 2000; Racey, 2001).

Algae. Rarely green algae are recorded in the thin sections indicating low energy environment.

Carbon 13 and Oxygen 18 Isotope Record

The stable isotope chemostratigraphy of the Nammal Formation was studied for its $\delta^{13}C$ and $\delta^{18}O$ concentration for palaeoclimate conditions in the Tethys Sea and impact of global Palaeocene-Eocene thermal maxima on deposition of the Early Eocene in eastern Tethys. The samples were taken from two different locations (Nilawahan section and Badshah Pur section) starting from the lower boundary of Nammal Formation to the upper contact with Sakesar Limestone. The variations in isotopic values from the analyzed samples are shown in Fig. 9.

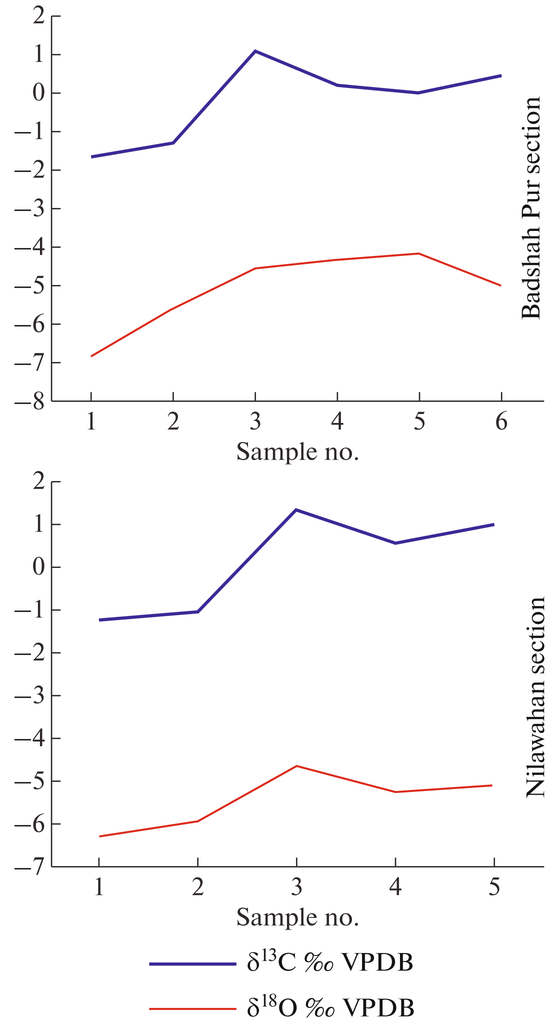

Fig. 9. Curves for the measured $\delta^{18}O$ and $\delta^{13}C$ isotopic values in the Nammal Formation.

The isotopic results are plotted in a $\delta^{13}C$ versus $\delta^{18}O$ (Fig. 10) cross plot diagram (Hudson, 1977) in which the Nammal Formation samples fall in marine limestones and represent a shallow marine environment. The $\delta^{18}O$ values of a carbonate precipitated from water depending mainly on salinity and temperature of water (Nagarajan et al., 2008; Strasser et al., 2012). More negative values of the $\delta^{18}O$ are indicative of decreasing salinity and increasing temperature (Hudson, 1977). Lighter values of $\delta^{18}O$ with its most negative value of −6.85‰ PDB indicate tropical environment at time of deposition of the Nammal Formation. Likewise in many tropical carbonate deposits, in this study the range of $\delta^{18}O$ values in all samples is sup-

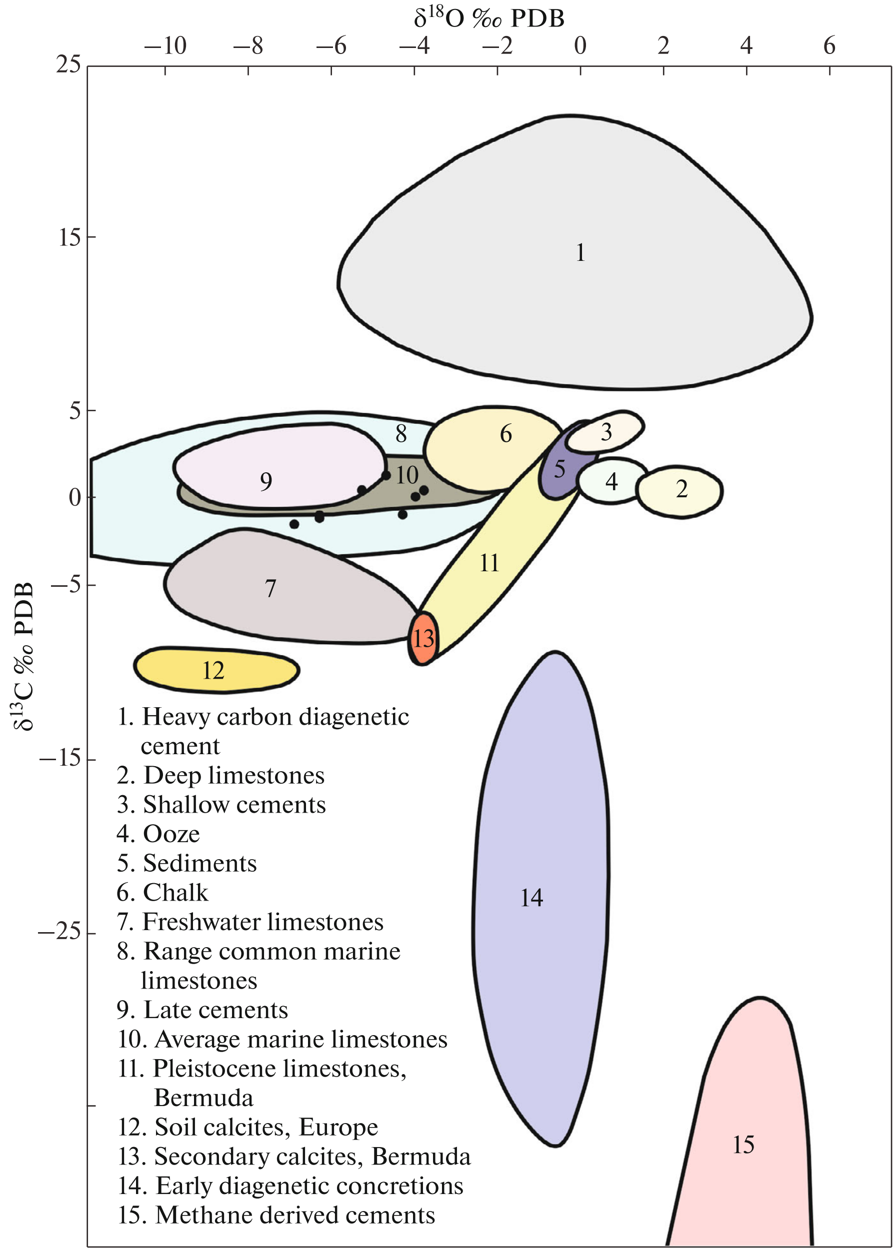

Fig. 10. Plot of $\delta^{13}C$ verses $\delta^{18}O$ for the Nammal Formation along the different carbonate rocks proposed by Hudson (1977).

portive of cementation under marine environments (cf. Nagarajan et al., 2008).

Stratigraphic Evolution of the Nammal Formation

The Early Eocene in the Salt Range is recognized as a carbonate sequence bounded above and below by sequence boundaries. The whole sequence is classified into three system tracts: Nammal Formation as transgressive system tracts (TST), Sakesar Limestone as highstand system tracts (HST) and Chor Gali Formation as falling stage system tracts (FSST).

During the Early Eocene gradually increasing eustatic sea-level in present Salt Range region generated transgressive systems tracts in shallow marine environment (Fig. 11; cf. Wardlaw et al., 2007). The Nammal Formation is lowermost unit of Early Eocene carbonate sequence in the Salt Range, composed of alternate marl and limestone. The facies distribution in lower and middle parts of the Nammal Formation predominantly comprises larger benthic foraminifera

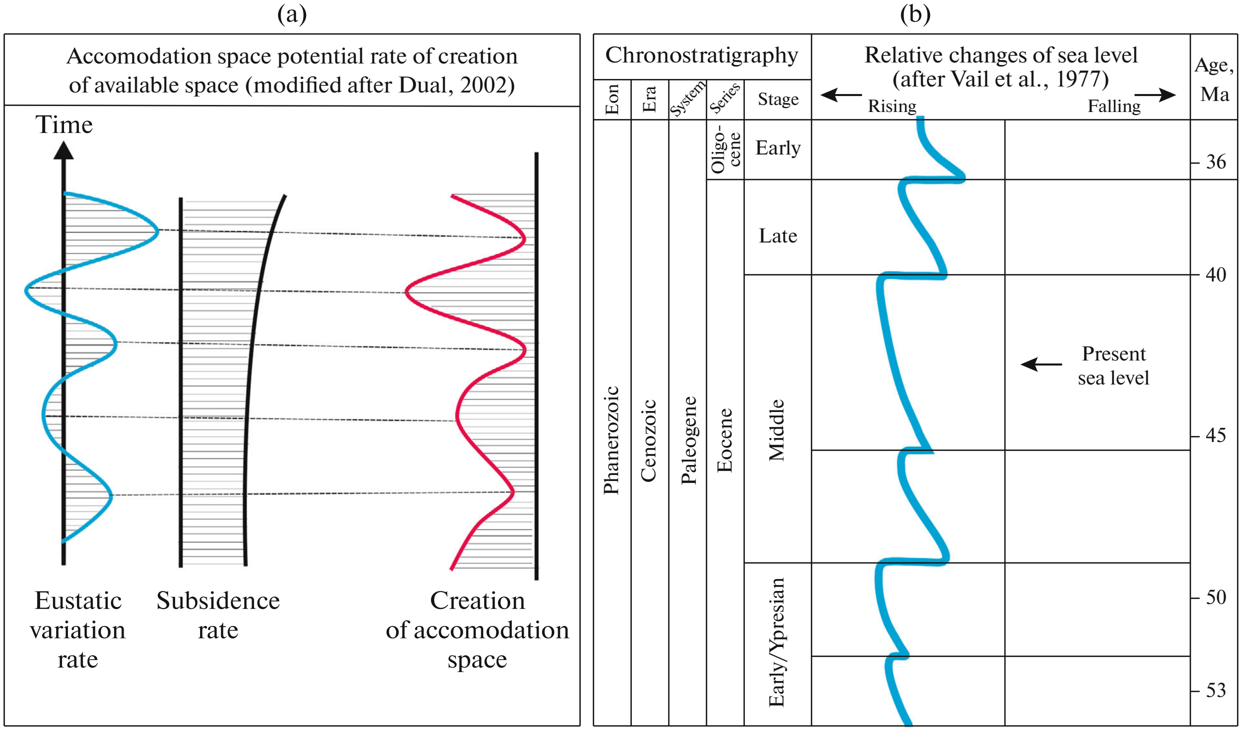

Fig. 11. (a) Relationship between accommodation space and eustatic sea level change; (b) eustatic sea level change in Eocene.

such as Nummulitids (*Nummulites* and *Assilina*) and Discocyclinids with rare Alveolinids representing fining-upward or deepening upward sequence. The packstone to grainstone facies (N11) with abundance of biota like Nummulitic-Discocyclina is marked as condensed section in middle parts of the formation overlain by the dolomitic limestone facies (N12) (Fig. 5). The upper parts of the formation represent shallowing up sequence due to presence of Nummulitids (*Nummulites* and *Assilina*) and Alveolinids with rare Discocyclinids. The lower boundary of the Nammal Formation with the Patala Formation is marked as the Sequence Boundary SB-II (Fig. 12a) represented by siltstone, marl and carbonaceous shale of the Patala Formation. The Patala Formation is predominantly composed of alternate limestone and marl with dominant fauna of Miscellanids and Ranikothalids (Akhtar and Butt, 1999, 2001). Above this boundary, base of the Nammal Formation represents rise in sea-level dominated by shallow shelf facies over tidal marshy facies of the Patala Formation (cf. Wardlaw et al., 2007).

The Sakesar Limestone is the middle unit of Early Eocene carbonate sequence, is composed of thick-bedded limestone and suggests increase in sedimentation rate, that overcome the rate of base-level rise during normal regression. The Sakesar Limestone is identified as highstand systems tracts (HST) forming an agradational to progradational pattern with regressive surface at the top (Fig. 13; Hanif, 2013).

The Chor Gali Formation represents the top unit of Early Eocene carbonate. It is predominantly composed of thinly bedded limestone interbedded with shale. The Chor Gali Formation deposited during falling stage systems tracts (FSST), showing a progradational pattern and basinward shift of facies during regression (Fig. 13; Hanif, 2013). The continuing fall in sea-level and development of regressive facies are related to closure of Neo-Tethys.

The whole Early Eocene carbonate sequence in the Salt Range is terminated and capped by a thick pile of Miocene molasse sediments marking the upper sequence boundary SB-I (Fig. 12b). The middle-upper parts of Eocene and Oligocene sediments are absent throughout the Salt Range and mark event of erosion/non-deposition. The presence of 50 cm to 2 m thick conglomerates at the top of the Early Eocene Chor Gali Formation derived mainly from Nammal and Sakesar formations indicate the period of erosion (Hanif, 2013).

Depositional Settings

In the Salt Range, during the Early Eocene a nearly 80 to 90 m thick sedimentary sequence of carbonates deposited as Nammal Formation, Sakesar Limestone

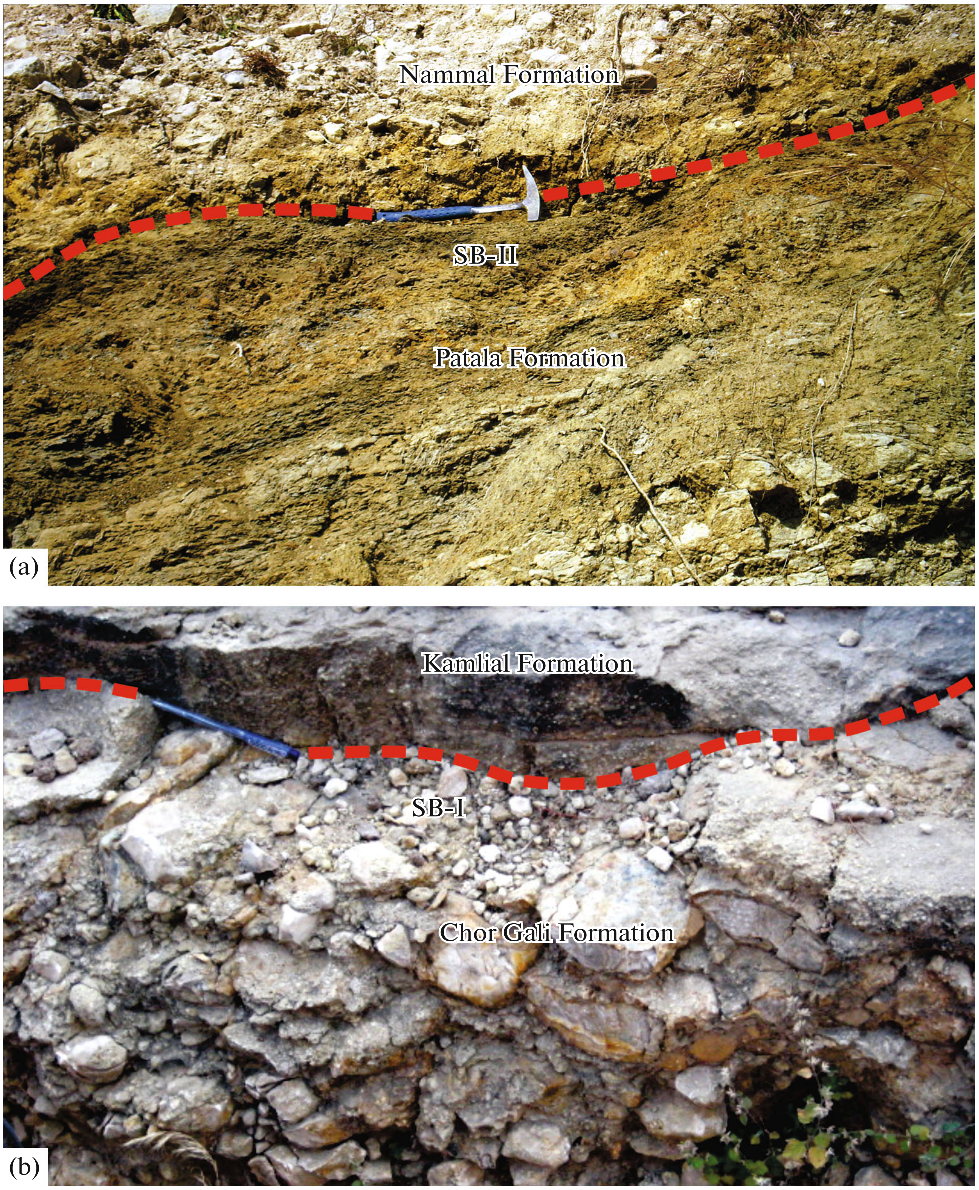

Fig. 12. (a) Outcrop exposure of the SB-II between the Nammal Formation and Patala Formation, Salt Range, Pakistan; (b) outcrop exposure of the SB-I between the Chor Gali Formation and Kamlial Formation, Salt Range, Pakistan.

and Chor Gali Formation, near equatorial setting at a palaeolatitude of about 10° N (Gaetani and Garzanti, 1991). Microfacies analysis of the Nammal Formation indicates that much of the carbonate sediments are composed of larger benthic foraminifera with lesser amounts of smaller benthic foraminifera, planktonic foraminifera and mollusks (gastropods). The presence of larger benthic foraminifera in the Nammal Formation shows the constancy of an equatorial climate throughout the deposition of the formation (cf. Zhang et al., 2013).

Larger foraminifera are excellent indicators used as valuable tools to reconstruct palaeoenvironmental models in warm, shallow marine environments in carbonate platform successions (Flügel, 2010; Geel, 2000). On the basis of the paleobathymetric distribution of larger foraminifera, Nummulitids (*Nummulites, Assilina, Operculina*) are mainly present in the middle part of the platform/open shoal and Discocyclinids are mainly present in the offshore part of the carbonate platform (e.g., Buxton and Pedley, 1989). With the arrival of the Early Eocene in the Salt Range the platform underwent retrogradation and genera of Nummulitids, Alveolinids and Discocyclinids dominate over Miscellanids and Ranikothalids due the short term effects of the Palaeocene–Eocene Thermal

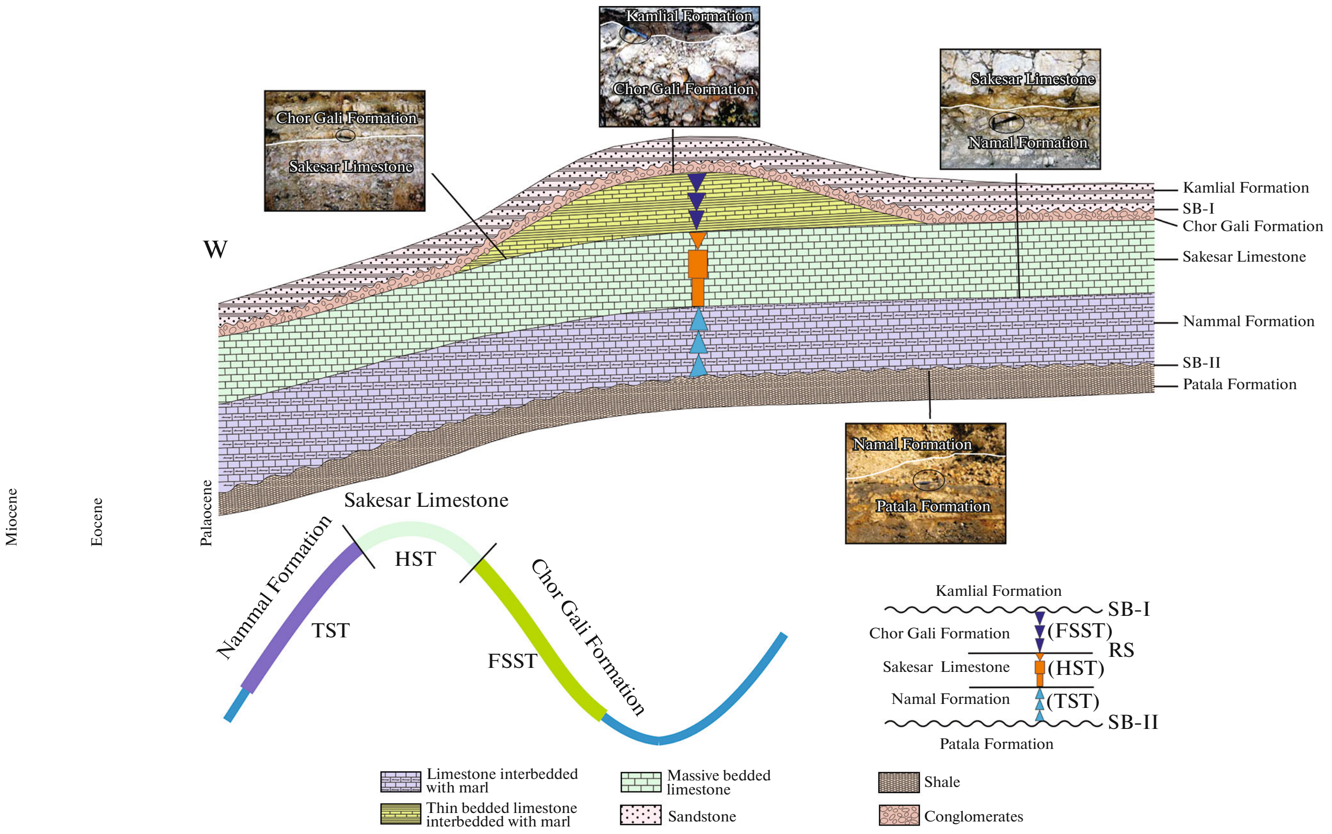

Fig. 13. Generalized depositional model for the Early Eocene succession based on the sequence stratigraphic framework.

Maximum (temperature increase, eutrophication) during the platform stage III of Tethyan realm (cf. Akhtar and Butt, 1999; Scheibner and Speijer, 2008). These foraminifera belong to Tertiary and are present in the entire studied Nammal Formation belonging to Early Eocene (Barattolo et al., 2007; Ćosović et al., 2004; Hottinger, 1988; Wardlaw et al., 2007). As the Nummulitids, Alveolinids and Discocyclinids occur at the same time in the sections, it can be assumed that there was no barrier at the time of deposition (Rafi et al., 2012). Based on the results of the facies interpretation, palaeoecology, distribution of larger foraminifera and isotopic analysis, it is interpreted that deposition took place in shallow water above fair weather wave base representing shallow marine open shelf environments present in all studied sections where open shelf settings are dominated by Nummulitids, Alveolinids and Discocyclinids. Middle and outer shelf facies were not recognized (Fig. 14).

CONCLUSIONS

The Early Eocene (Ypresian) Nammal Formation represents shallow shelf carbonate sedimentation in the Salt Range. A total of sixteen microfacies were identified which are mainly mudstone, wackestone, packstone, wackestone to packstone, dolomitic limestone and grainstone indicating the inner-neritic shelf environment. In the microfacies, the benthic larger foraminifera are abundant belonging to the genera *Assilina*, *Nummulites*, *Alveolina*, *Discocyclina* and *Lockhartia* characteristic of shallow shelf environments. The Nammal Formation represents the cyclic deposition with predominant lithology of interbedded limestone and marl. Oxygen and carbon isotope signatures from the Nammal Formation indicate the carbonate deposition under warm water conditions of shallow marine environments.

The Early Eocene succession is identified as a depositional sequence with three system tracts bounded above and below by unconformable surfaces represented by sequence boundaries. Sequence Boundary-II is marked at the base of the Nammal Formation with the Patala Formation. The east-west depositional trend of the Nammal Formation shows retrogradational pattern. The Nammal Formation is overall placed in transgressive systems tracts (TST). Further, the overlying Sakesar Limestone marks the highstand systems tracts (HST) indicating agradational to progradational pattern. In comparison, the Chor Gali

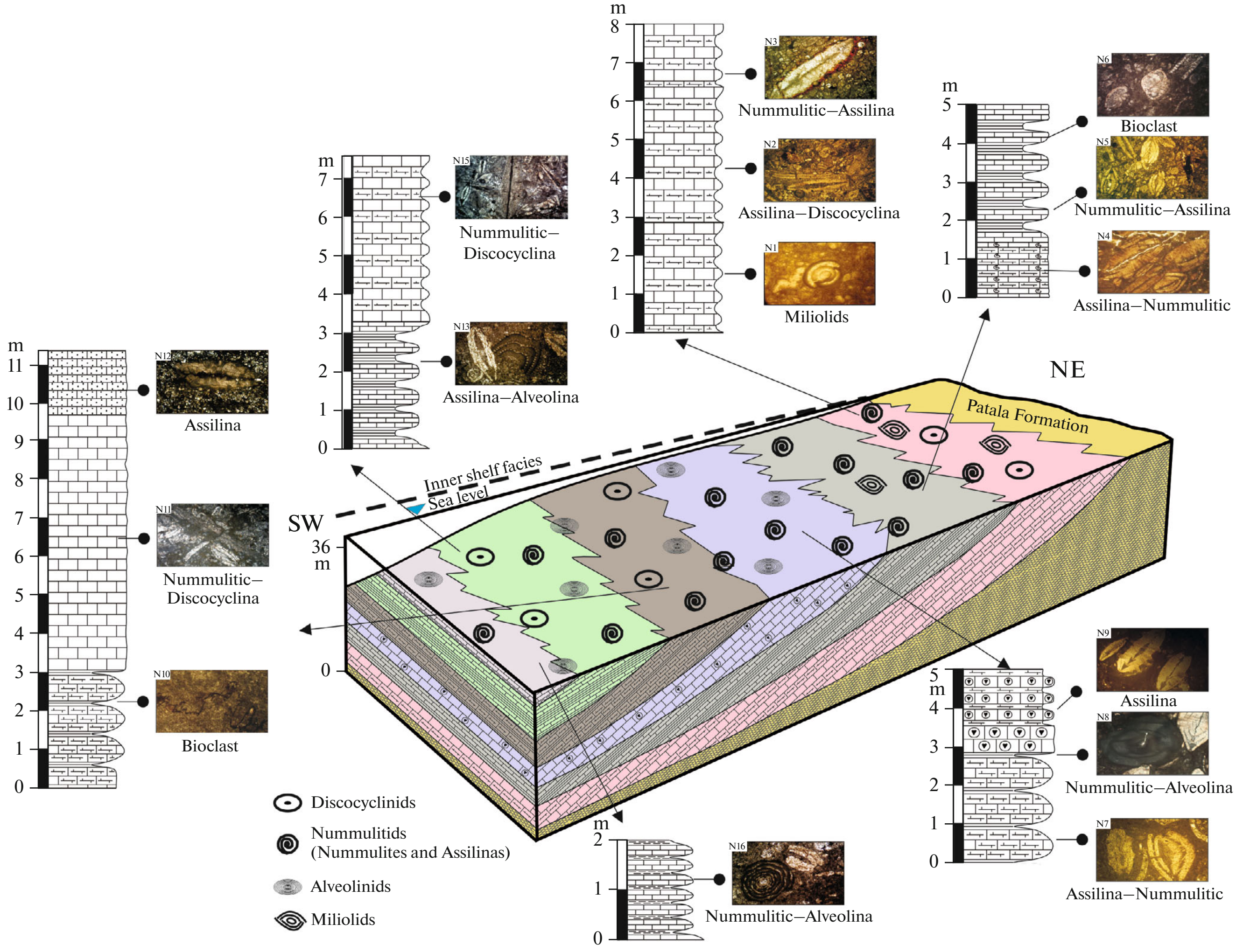

Fig. 14. Depositional model of the Early Eocene Nammal Formation showing microfacies along with distribution of selected biota in a shallow shelf carbonate setting.

Formation depicts progradational pattern and deposited during falling stage systems tracts (FSST). Based on sequence stratigraphic analysis, we conclude that the Sequence Boundary-I can be marked at the top of Chor Gali Formation with Kamlial Formation.

ACKNOWLEDGMENTS

This study benefited from the Pakistan University of the Punjab, Lahore Pakistan grant. The authors wish to express their thanks to Institute of Geology, University of the Punjab. This study benefited from suggestions given by Maurice Tucker, Aftab Ahmad Butt and Kaleem Akhtar Qureshi and their insights are greatly appreciated. The authors also thank Dr. E.V. Yakovishina (Moscow State University) and Dr. E.Yu. Zakrevskaya (Vernadsky State Geological Museum, Moscow) for reviewing the manuscript.

Reviewers A.S. Alekseev, E.V. Yakovishina, and E.Yu. Zakrevskaya

REFERENCES

Afghah, M. and Farhoudi, G., Boundary between Upper Cretaceous and Lower Paleocene in the Zagros Mountain Ranges of Southwestern Iran, *Acta. Geol. Sin. (Engl.)*, 2012, vol. 86, no. 2, pp. 325–338.

Afzal, J. and Butt, A.A., Lower Tertiary planktonic biostratigraphy of the Salt Range, Northern Pakistan, *N. Jb. Geol. Palaont. Mh.*, 2000, vol. 12, pp. 721–747.

Agard, P., Omrani, J., Jolivet, L., and Mouthereau, F., Convergence history across Zagros (Iran): constraints from collisional and earlier deformation, *Int. J. Earth Sci.*, 2005, vol. 94, no. 3, pp. 401–419.

Akhtar, M. and Butt, A.A., Lower Tertiary biostratigraphy of the Kala Chitta Range, northern Pakistan, *Rev. Paleobiol.*, 1999, vol. 18, no. 1, pp. 123–146.

Akhtar, M. and Butt, A.A., The Paleocene of the Kala Chitta Range, northern Pakisan, *N. Jb. Geol. Palaont. Mh.*, 2001, vol. 1, pp. 43–55.

Al-Wosabi, M. and Al-Aydrus, A.A., Microfacies analysis and depositional environments of Tertiary carbonate sequences in Socotra Island, Yemen, *Türkiye Jeol. Bül.,* 2011, vol. 54, no. 12, pp. 57–80.

Baker, D.M., Lillie, R.J., Yeats, R.S., Johnson, G.D., Yousuf, M., and Zamin, A.S.H., Development of the Himalayan frontal thrust zone: Salt Range, Pakistan, *Geology*, 1988, vol. 16, no. 1, pp. 3–7.

Barattolo, F., Bassi, D., and Romano, R., Upper Eocene larger foraminiferal–coralline algal facies from the Klokova Mountain (southern continental Greece), *Facies*, 2007, vol. 53, no. 3, pp. 361–375.

Beavington-Penney, S.J. and Racey, A., Ecology of extant nummulitids and other larger benthic foraminifera: applications in palaeoenvironmental analysis, *Earth Sci. Rev*., 2004, vol. 67, nos. 3–4, pp. 219–265.

Boggs, S.J., *Principles of Sedimentology and Stratigraphy,* 4th ed., New Jersey: Pearson Prentice Hall, Upper Saddle River, 2006.

Boustani, M. and Khawaja A.M., Microfacies studies of the Sakesar Limestone, Central Salt Range, Pakistan, *Geol. Bull. Univ. Peshavar*, 1997, vol. 30, pp. 131–142.

Buxton, M.W.N. and Pedley, H.M., Short Paper: A standardized model for Tethyan Tertiary carbonate ramps, *J. Geol. Soc.*, 1989, vol. 146, no. 5, pp. 746–748.

Ćosović, V., Drobne, K., and Moro, A., Paleoenvironmental model for Eocene foraminiferal limestones of the Adriatic carbonate platform (Istrian Peninsula), *Facies*, 2004, vol. 50, no. 1, pp. 61–75.

Davies, L.M. and Pinfold, E.S., *The* Eocene beds of the Punjab Salt Range, *Geol. Surv. India, Mem., Palaeontol. Indica, New Ser*., 1937, vol. 24.

Dunham, R.J., Classification of carbonate rocks according to depositional texture, *AAPG Mem*., 1962, vol. 1, pp. 108–121.

Fatmi, A.N., Lithostratigraphic units of the Kohat-Potwar Province, Indus Basin, Pakistan, *Geol. Surv. Pakistan Mem.*, 1973, vol. 10.

Flügel, E., *Microfacies of Carbonate Rocks: Analysis, Interpretation and Application,* 2nd ed., Berlin, New York: Springer-Verlag, 2010.

Friedman, G., The arid peritidal complex of Abu Dhabi: A historical perspective, *Carbonates Evaporites*, 1995, vol. 10, no. 1, pp. 2–7.

Gaetani, M. and Garzanti, E., Multicyclic history of the northern India continental margin (northwestern Himalaya), *AAPG Bull*., 1991, vol. 75, no. 9, pp. 1427–1446.

Geel, T., Recognition of stratigraphic sequences in carbonate platform and slope deposits: empirical models based on microfacies analysis of Palaeogene deposits in southeastern Spain, *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 2000, vol. 155, nos. 3–4, pp. 211–238.

Ghazi, S., and Mountney, N.P., Facies and architectural element analysis of a meandering fluvial succession: The Permian Warchha Sandstone, Salt Range, Pakistan, *Sediment. Geol.*, 2009, vol. 221, nos. 1–4, pp. 99–126.

Ghazi, S., Butt, A.A., and Khan, K.A., Microfacies and foraminiferal assemblage of the Lower Eocene Nammal Formation, Nilawahan Gorge, Salt Range, Pakistan, *Geol. Bull. Punjab Univ.*, 2004, vol. 39, pp. 75–85.

Ghazi, S., Butt, A.A., and Ashraf, M., Microfacies analysis and diagenesis of the Lower Eocene Sakesar Limestone, Nilawahan Gorge, Salt Range, Pakistan, *J. Nepal Geol. Soc.,* 2006, vol. 33, pp. 23–32.

Ghazi, S., Sharif, S., Hanif, T., Ahmad, S., Aziz, T., and Riaz, M., Micropaleontological analysis of the Early Eocene Sakesar Limestone, Central Salt Range, Pakistan, *Pakistan J. Sci*., 2015, vol. 67, no. 2, pp. 150–158.

Gill, W.D., The genus *Assilina* in the Laki Series (Lower Eocene) of the Kohat-Potwar Basin, Northwest Pakistan, *Contrib. Cushman Found. Foraminifer. Res*., 1953, vol. 4, no. 2, pp. 76–86.

Grelaud, S., Sassi, W., de Lamotte, D.F., Jaswal, T., and Roure, F., Kinematics of eastern Salt Range and South Potwar Basin (Pakistan): A new scenario, *Mar. Petrol. Geol.*, 2002, vol. 19, no. 9, pp. 1127–1139.

Hanif, T., Sedimentology and stratigraphic evolution of the Early Eocene succession, Central Salt Range, Pakistan, *M. Phil. Thesis (unpublished)*, Inst. Geol., Univ. Punjab, Lahore, Pakistan, 2013.

Hottinger, L., Shallow benthic foraminifera at the Paleocene–Eocene boundary, *Strata*, 1998, vol. 9, pp. 61–64.

Hudson, J.D., Stable isotopes and limestone lithification, *J. Geol. Soc. London*, 1977, vol. 133, pp. 637–660.

Hughes, N.C., Myrow, P.M., Ghazi, S., McKenzie, N.R., Stockli, D.F., and DiPietro, J.A., Cambrian geology of the Salt Range of Pakistan: Linking the Himalayan margin to the Indian craton, *Geol. Soc. Am. Bull.*, 2019, vol. 131, nos. 7–8, pp. 1095–1114.

Kaever, M., Über Assilina lacunata CIZANCOURT, aus dem Unter-Eozän, Afghanistans, *Geol. Jb.*, 1964, vol. 82, pp. 131–142.

Nagarajan, R., Sial, A.N., Armstrong-Altrin, J.S., Madhavaraju, J., and Nagendra, R., Carbon and oxygen isotope geochemistry of Neoproterozoic limestones of the Shahabad Formation, Bhima basin, Karnataka, southern India, *Rev. Mex. Cienc. Geol.*, 2008, vol. 25, no. 2, pp. 225–235.

Najman, Y., The detrital record of orogenesis: A review of approaches and techniques used in the Himalayan sedimentary basins, *Earth Sci. Rev*., 2006, vol. 74, nos. 1–2, pp. 1–72.

Nichols, G., *Sedimentology and Stratigraphy*, Oxford, London: Blackwell, 2009.

Racey, A., A review of Eocene nummulite accumulations: structure, formation and reservoir potential, *J. Petrol. Geol.*, 2001, vol. 24, no. 1, pp. 79–100.

Rafi, R., Khursheed, S.H., and Mohsin, S.I., Microfaunal assemblage of the Sui Main Limestone from Sui Gas Field, Pakistan, *J. Basic Appl. Sci*., 2012, vol. 8, no. 1, pp. 85–90.

Riaz, M., Pimentel, N., Ghazi, S., Zafar, T., Alam, A., and Ariser S., Lithostratigraphic analysis of the Eocene reservoir units of Meyal Area, Potwar Basin, Pakistan, *Himal. Geol.*, 2018, vol. 39, no. 2, pp. 161–170.

Riaz, M., Pimentel, N., Zafar, T., and Ghazi, S., 2D seismic interpretation of Meyal Area, northern Potwar Deform Zone (NPDZ), Potwar Basin, Pakistan, *Open Geosci.,* 2019, vol. 11, pp. 1–16.

Sameeni, S.J. and Butt, A.A., Alveolinid biostratigraphy of the Salt Range succession, Northern Pakistan, *Rev. Paléobiol., Genéve*, 2004, vol. 23, no. 2, pp. 505–527.

Sameeni, S.J., The Salt Range, in *PaleoParks: The Protection and Conservation of Fossil Sites Worldwide*, Univ. Bretagne Occidentale, Départment Sci. Terre, 2009, pp. 65–73.

Scheibner, C. and Speijer, R.P., Late Paleocene—early Eocene Tethyan carbonate platform evolution—A response to long- and short-term paleoclimatic change, *Earth Sci. Rev.*, 2008, vol. 90, nos. 3–4, pp. 71–102.

Shinn, E.A. and Robbin, D.M., Mechanical and chemical compaction in fine-grained shallow-water limestones, *J. Sediment. Res.*, 1983, vol. 53, no. 2, pp. 595–618.

Strasser, A., Védrine, S., and Stienne, N., Rate and synchronicity of environmental changes on a shallow carbonate platform (Late Oxfordian, Swiss Jura Mountains), *Sedimentology*, 2012, vol. 59, no. 1, pp. 185–211.

Taheri, A., Vaziri-Moghaddam, H., and Seyrafian, A., Relationships between foraminiferal assemblages and depositional sequences in Jahrum Formation, Ardal area (Zagros Basin, SW Iran), *Hist. Biol.*, 2008, vol. 20, no. 3, pp. 191–201.

Vail, P.R., Mitchum, Jr., R.M., and Thompson III, S., Seismic stratigraphy and global changes of sea level, Part 3: Relative changes of sea level from coastal onlap, in: *Seismic Stratigraphy—Applications to Hydrocarbon Exploration*, Payton, C.E., Ed., *AAPG Mem.,* 1977, vol. 26, pp. 63–81.

Wardlaw, B.P., Martin, W.E., and Haydri, I.H., Stratigraphic analysis of Palaeocene and Lower Eocene rocks adjacent to the Potwar Plateau, Northern Pakistan, in *Regional Studies of the Potwar Plateau Area, Northern Pakistan,* Warwick, P.D., and Wardlaw, B.P., Eds., *U.S. Geol. Surv. Bull.,* 2007, vol. 2078, pp. 1–18.

Zhang, Q., Willems, H., and Ding, L., Evolution of the Paleocene—Early Eocene larger benthic foraminifera in the Tethyan Himalaya of Tibet, China, *Int. J. Earth Sci.*, 2013, vol. 102, pp. 1427–1445.