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ORIGINAL ARTICLE

Sedimentology, diagenesis and sequence stratigraphy of the Early–Middle Eocene Chorgali Formation in the Hazara sub-Basin, Northwest Himalayas, Pakistan

Emad Ullah Khan[1] · Shadab Khan[1] · Syed Muhammad Wasim Sajjad[2] · Maryam Saleem[3] · Muhammad Ilyas[4] · Saif Ullah Khan[5]

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Abstract

Carbonate rocks are the most important sedimentary rocks since they hold almost 60% of the world's oil reserves. Therefore, it is very important to evaluate the factors that control the formation and deposition of these rocks. The current study aimed to better understand the depositional facies and sequence stratigraphy of Eocene Chorgali Formation from Barian and Nathia Gali Sections of Hazara Basin, NW Himalayas, Pakistan. The field observation shows that the formation comprises of grey to pale grey compacted limestone, argillaceous limestone, and greenish grey shale. From microscopic observations, eight and nine microfacies were constructed form both Barian and Nathia Gali section respectively. The formation is also rich from benthic foraminifera. The constructed microfacies and foraminiferal assemblage shows that the carbonates of Chorgali Formation were most likely deposited in the inner ramp to proximal middle ramp setting. Frequent variations in the microfacies reveals that the Eocene Chorgali Formation was deposited in a 3rd order cycle representing several second order system tracts. Transgressive Systems Tracts (TSTs) and High Stand System Tracts (HSTs) based on sea level variations derived from microfacies in the vertical section. The sea-level curve of the present study deviates from the established global scheme, indicating the influence of intense local tectonics. The carbonate unit of the Chorgali Formation also represents various diagenetic alteration like micritization, bioturbation, dissolution, cementation, compaction and dolomitization. Overall, processes like fracturing, dissolution, and dolomitization enhanced the reservoir quality while cementation infills the available pore spaces and significantly reducing the reservoir quality.

Keywords Depositional environment · Diagenesis · Microfacies · Paleontology · Reservoir characterization · Sequence stratigraphy

Introduction

Recently, the carbonate rocks became popular among researchers because they hold almost 60% of the world oil reserves (Azerêdo et al. 2020; Kargarpour et al. 2020; Saleem et al. 2022; Bilal et al. 2024). Many researchers interprets that the deposition of carbonate facies is controlled by factor like water depth, their chemistry and temperature, diagenetic processes, and wide biological activities (Scholle and Ulmer-Scholle 2003; Flugel 2010). The depositional environment also governs the initial porosity of carbonate rocks by defining the packing, sorting, and grain size of the rock (Bilal et al. 2022a, b, c; Khan et al. 2022). The basic mineralogical framework of carbonate rocks is within the control of their depositional environment which affect the generation of secondary porosity by subsequent diagenetic

✉ Emad Ullah Khan
emadgeo@awkum.edu.pk

1 Department of Geology, Abdul Wali Khan University Mardan, Mardan, Pakistan

2 Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, Parma, Italy

3 Department of Earth and Environmental Sciences, Bahria University, Islamabad, Pakistan

4 Petroservices GMBH, Islamabad, Pakistan

5 Department of Geology, Bacha Khan University, Charsada, Pakistan

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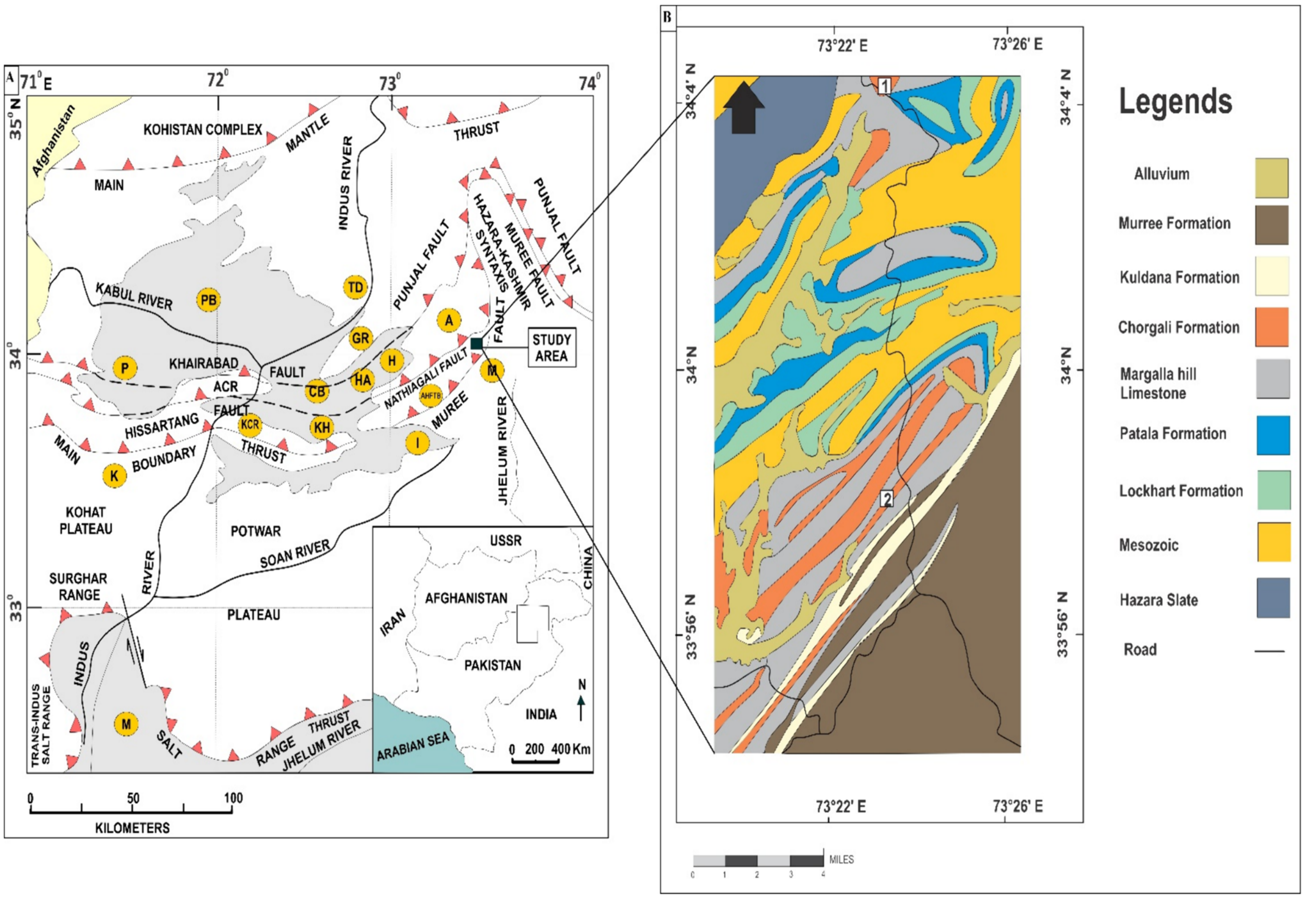


Fig. 1 In the above figure **A** depicts Tectonic map of Northwestern Himalayan, its evident structural boundaries and **B** depicts the geological map of the study area with the location of outcrop sections, where (1) shows Nathia gali section and (2) shows Barian section. *P* Peshawar, *PB* Peshawar Basin, *TD* Terbela Dam, *A* Abbottabad, *M* Muree, *I* Islamabad, *MH* Margalla Hills, *H* Haripur, *GR* Gandghar Range, *HA* Hasan Abdal, *KH* Kherimar Hills, *CB* Cambellpore Basin, *ACR* Attock-Cherat Range, *KCR* Kala Chitta Range, *AHFTB* Attock Hazara fold and thrust belt, *K* Kohat, *M* Mianwali (modified after Latif 1970)

alteration (Khan et al. 2022). This diagenetic modification either enhance or reduce the reservoir characteristic by defining the pore shape and size distribution (Amel et al. 2015; Afife et al. 2017; Khan et al. 2022, 2024). (Morad et al. 2000; Flügel 2004) develops a strong correlation between sea level fluctuations and the evolution of porosity in carbonate rocks. During regression, porosity decreases as tends to occlude by heavy cementation of large-size pore systems. Conversely, during transgression, the primary porosities is preserved during the deposition of matrix-supported lithologies. Similar studies are also carried out by (Read 1994; Tucker 1993; Flügel 2004; Khan et al. 2024).

The development of carbonate microfacies requires a good understanding of contemporary carbonates as well as a thorough understanding of the biological and geological changes that occur throughout the process. Previously, different classification schemes were proposed for limestone emphasizing the color, size, composition, texture, and fabric of the rock. But the most used classification for limestone is the (Dunham 1962) and (Folk 1959) classification, which is based on the grain size and fabric of the rock. The Folk's classification provides more information about the morphology and limited knowledge of grain deposition, energy levels, and movement. Therefore, people only took into account the skeleton and non-skeleton grains, micrite, sparry, and crystalline calcite cementation for this classification. However, Dunham's classification, which is based on fabric, separated the carbonate rocks into two categories: those that were supported by grain and those that were contained within a carbonate filler. Hence for this study Dunham's (1962) classification is used.

Several researchers have recently focused their attention on the Chorgali Formation. Swati et al. (2013) carried out the biostratigraphy from Kala Chitta Ranges. Bilal et al. (2022a, b, c) conducted a comprehensive sedimentological and diagenetic study of Early – Middle Eocene carbonates from the eastern margin of Upper Indus Basin. In the Salt Range,

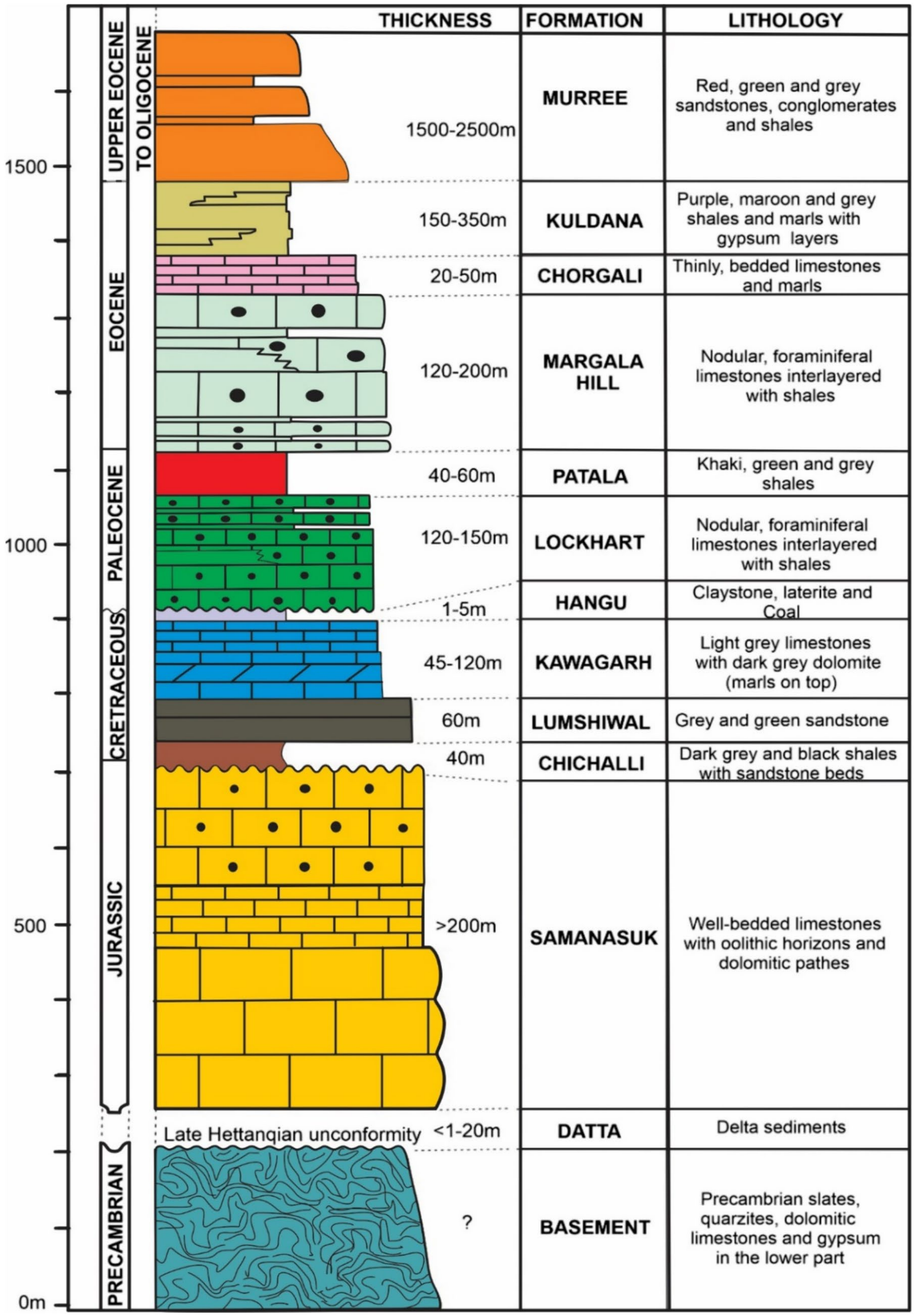


Fig. 2 Stratigraphic column of south-eastern Hazara sub-Basin (modified after Latif 1970)

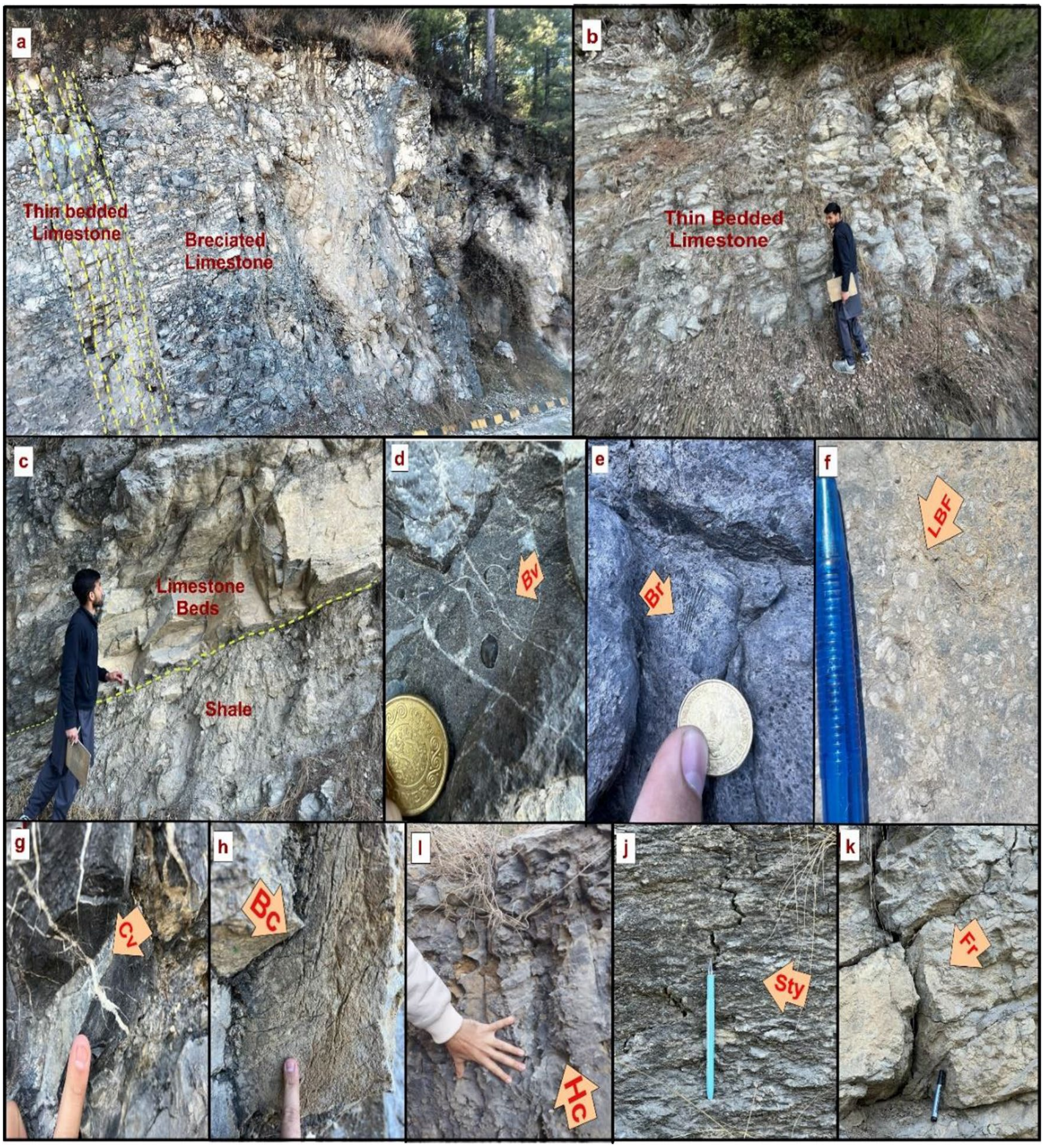


Fig. 3 Field photographs of Barian and Nathia Gali section. **a** Barian section, light grey thin bedded limestone alternate with dark grey brecciated limestone. **b** Nathia Gali Section, light grey thin bedded limestone. **c** Nathia Gali section, contact between shale and light grey limestone. **d** Fragmented shell of bivalve (Bv), **e** Fragmented shell of brachiopod (Br), **f** Larger Benthic Foraminifera (LBF), **g** Calcite veins (Cv), **h** Butcherchop weathering (Bc), **i** Honeycomb weathering (Hc), **j** Stylolite (Sty), **k** Fracture porosity (Fr)

Ghazi et al. (2014) briefly documented the sedimentological characteristics, while Jamal et al. (2015) investigated the stratigraphic and diagenetic alteration within the Salt Range, specifically from central Salt Range, (Mirza et al. 2022) carried out a detail study on Chorgali Formation and paid their attention to biostratigraphy, paleo-environment and sequence stratigraphy from Pail, Wanhar and Sarkalan sections. From the Yaadgar Section of Muzaffar Abad area, Khawaj et al. (2018) decoding the depositional environment of Chorgali Formation by integrating the biostratigraphy and microfacies analysis. In the Hazara Basin, a thick carbonate unit of Chorgali Formation is lacking any kind of comprehensive study to unveil their untapped potential. For this reason, the current study is carried out to documents the sedimentological characteristic and unravel the depositional environment of Chorgali Formation by integrating the microfacies, biostratigraphy and sequence stratigraphic analysis from the Hazara Sub-Basin, Northwestern Himalayas, Pakistan.

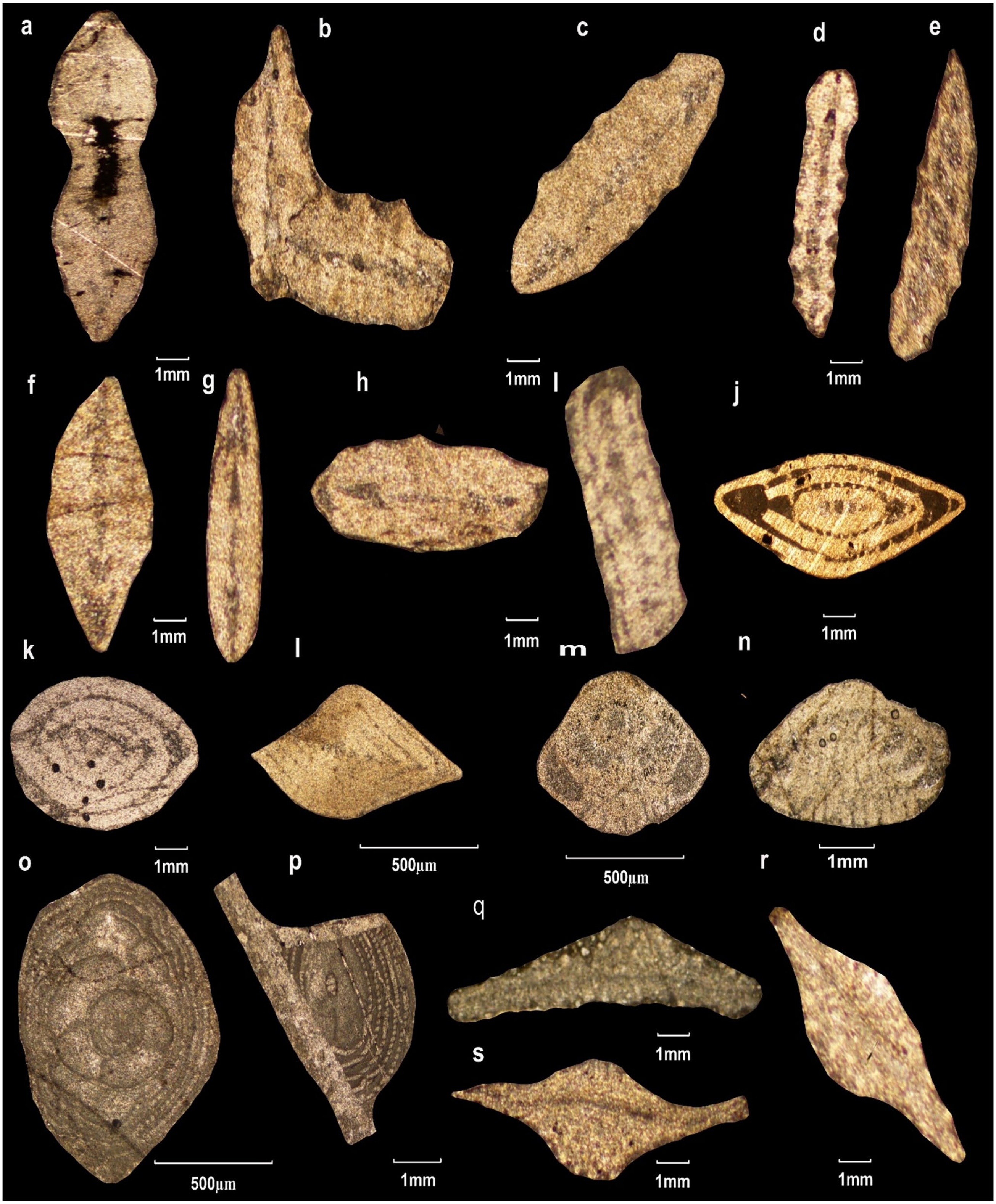


Fig. 4 The above plate documents all fossils which we encountered in Chorgali Formation. **a** Assilina spionsa, (**b** and **c**) Assilina subspinosa, (**d** and **e**) Assilina granulusa, (**f** and **g**) Assilina laminose, (**h** and **i**) Assilina Placentula, **j** Nummulite aticacus, **k** Nummulite Globulus, **i** Nummulite mammilatus, **m** Lockhartia conditi, **n** Lockhartia tipper, **o** Alveolina citrea, **p** Alveolina sp, **q** Discocyclina sp 2, **r** Discocyclina dispensa, **s** Discocyclina sp 1

Geological setting

The Attock-Hazara fold and thrust belt (AHFTB) of Pakistan, which forms the northern margin of the oil-producing Kohat-Potwar basin, is a sheet of crumpled sedimentary successions driven southward. The thrusting, which was followed by twisting and decollement, resulted in the stacking of stratigraphic sections (Ghazanfar et al. 1990; Khan et al. 2024). This folded belt, particularly its southern flank, is of certain significance for petroleum exploration because to its proximity with the oil-producing Kohat-Potwar depression (Munir Ghazanfar et al. 1990). The Eocene epoch in south-eastern Hazara sub-Basin is located in Attock-Hazara fold and thrust belt (Fig. 1a), which delimited in the north and south by Panjal-Khairabad fault, which is also known as western continuation of Main central thrust in Pakistan and Murree fault, respectfully. The Indus Basin is Pakistan's most notable sedimentary basin, surrounded by three tectonic plates: Asian, Arabian, and Indian (Khan et al. 2023). The Paleocene-Eocene sequence of Pakistan's Indus Basin reflects the Indian Plate's north-western continental shelf boundary setting (Afzal et al. 2009, 2011). The Indian-Asian collision has had a significant impact on the Paleocene-Eocene strata of Pakistan's Indus Basin (Hanif et al. 2021; Khan et al. 2023). The Himalayas were raised during the Eocene collision of the Indian and Eurasian plates, which also produced a number of thrust faults in Pakistan, namely the Main Karakoram Thrust (MKT), the Main Mantle Thrust (MMT), the Main Boundary Thrust (MBT), and the Salt Range Thrust (SRT), which run from north to south (Powell 1979; Coward et al. 1986). The subsequent thrust (i.e., MBT) in the research region lesser Himalayan exposes the Chorgali Formation out of all these thrusts. Tectonically, the Panjal-Khairabad fault, often referred to as the western extension of the Main Central Thrust in Pakistan and the Main Boundary Thrust or Murree fault, respectively, delimits the carbonates of the Eocene epoch in the southeastern Hazara sub-Basin located in Attock Hazara fold and thrust belt (AHFTB) (Fig. 1a). The research region in the Upper Indus Basin is heavily buckled, with diverse phases of tectonic activity complicating the geology and structure of the northern Indus Basin in contrasts to the southern sections. Several thrust faults have formed, which thrust over the older rocks over younger ones. Multiple smaller and larger folds and faults have altered the sedimentary sequences in the area. (Baker et al. 1988; Bender and Raza 1995). The study area is situated in the Lesser Himalayas, in the Hazara sub-Basin, based on structural geology. The Panjal fault and the Murree fault (Calkins et al. 1975) and its lateral equivalents bordering the Atock-Hazara fold and thrust belt to the north and south, respectively (Fig. 1a). The two faults move closer together to the east and then north, eventually merging near Hassa, north of Garhi Habibullah. According to the geologic map of southeast Hazara (Latif 1970), the mega synclinorium of the Attock-Hazara fold and thrust belt along the Murree-Abbottabad road is divisible into at least two synclinoria: the Nawashahr synclinorial complex towards Abbottabad and the much larger Kuza Gali synclinorial complex towards Murree. The study area is situated in Kuza Gali Synclinorial Complex and is delimited in the northwest by Nathia Gali fault or Hazara fault against the Hazara slates and in the south by MBT (Murree fault).

The region in southeast Hazara is stratigraphically a component of the considerably larger Kohat-Potwar Basin. Along with a few other minor disconformities, it displays a reasonably full geological succession from the Eocene-Cambrian to the Miocene, with the Middle and Upper Paleozoic sequences conspicuously absent. Carbonate deposition is dominating the Eocene Epoch in the Hazara sub-Basin. One of these carbonate sequences is the Chorgali Formation, which neatly covers the Early Eocene Margala Hill Limestone and is neatly overlain by the late middle Eocene Kuldana Formation (Khan et al. 2017; Bilal et al. 2022a, b, c) (Fig. 2). Two sections, the Barian and Nathia Gali of the Early Eocene Chorgali Formation were considered for the current study (Fig. 1b). In the south-eastern Hazara Sub-Basin's, the Chorgali Formation is exposed along the main Murree to Abbotabad road and is dominantly composed of light to pale grey limestone and marls that are weathered to light yellow and cream hues. The rocks have a distinctly platy look and are often sparsely bedded, the formation lacks the typical strong nodularity of Lockhart and Margala Hill limestones.

Methodology

The current study employed multiple approaches encompassing the comprehensive field works and microscopic observations. During the field, the 60 m and 54 m thick Barian and Nathia Gali sections were measured, logged and sampled respectively. The depositional sedimentary features and later diagenetic features were observed and noted. Overall, 76 samples were collected from the carbonate portion of the Chorgali Formation at regular intervals as well as from diagenetically altered portion. The collected samples were cut and marked the desire portion for thin section preparation which were later studied under the Polarizing Nikon Eclipse Microscope (LV100N POL) attached with Nikon digital camera in the petrographic lab of National Center of Excellence in Geology (NCEG), University of Peshawar. From petrographic study, microfacies were constructed by using the Dunham

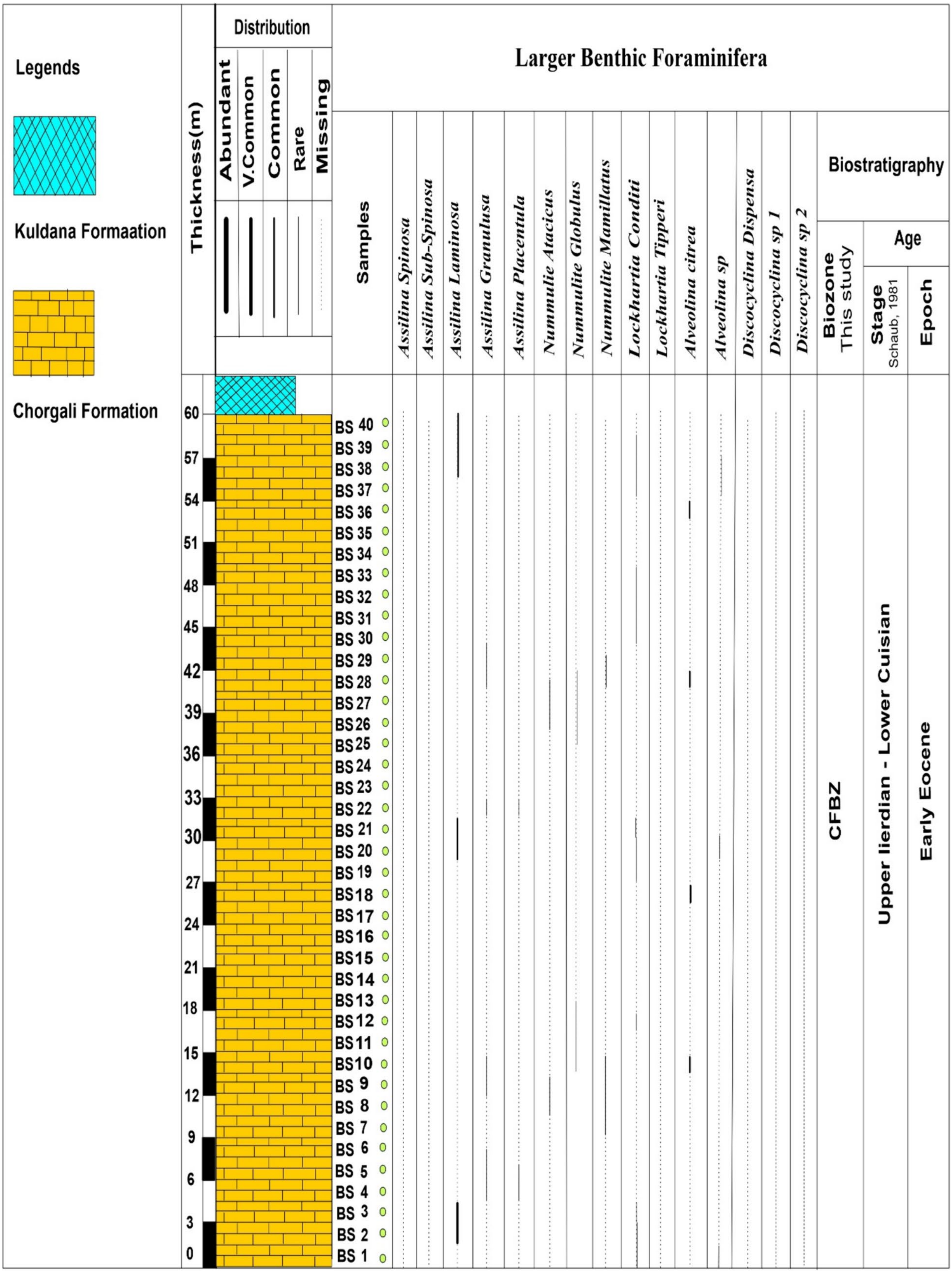


Fig. 5 The distribution of the Larger Benthic Foraminifera (LBF) of the Chorgali Formation at Barian section is listed in the above Bio-stratigraphic log

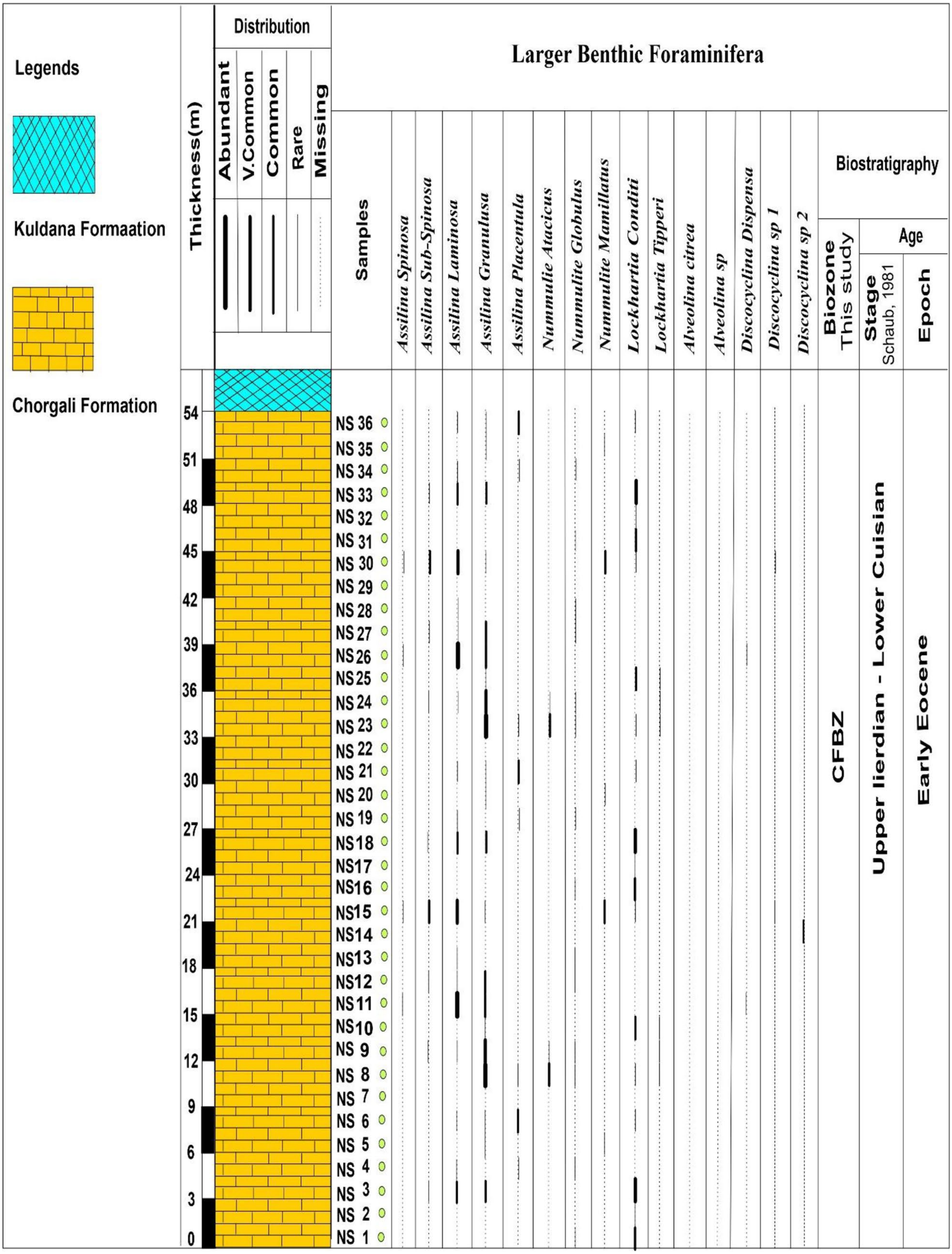


Fig. 6 The distribution of the Larger Benthic Foraminifera (LBF) of the Chorgali Formation at Nathia Gali section is depicted in the above Biostratigraphic log

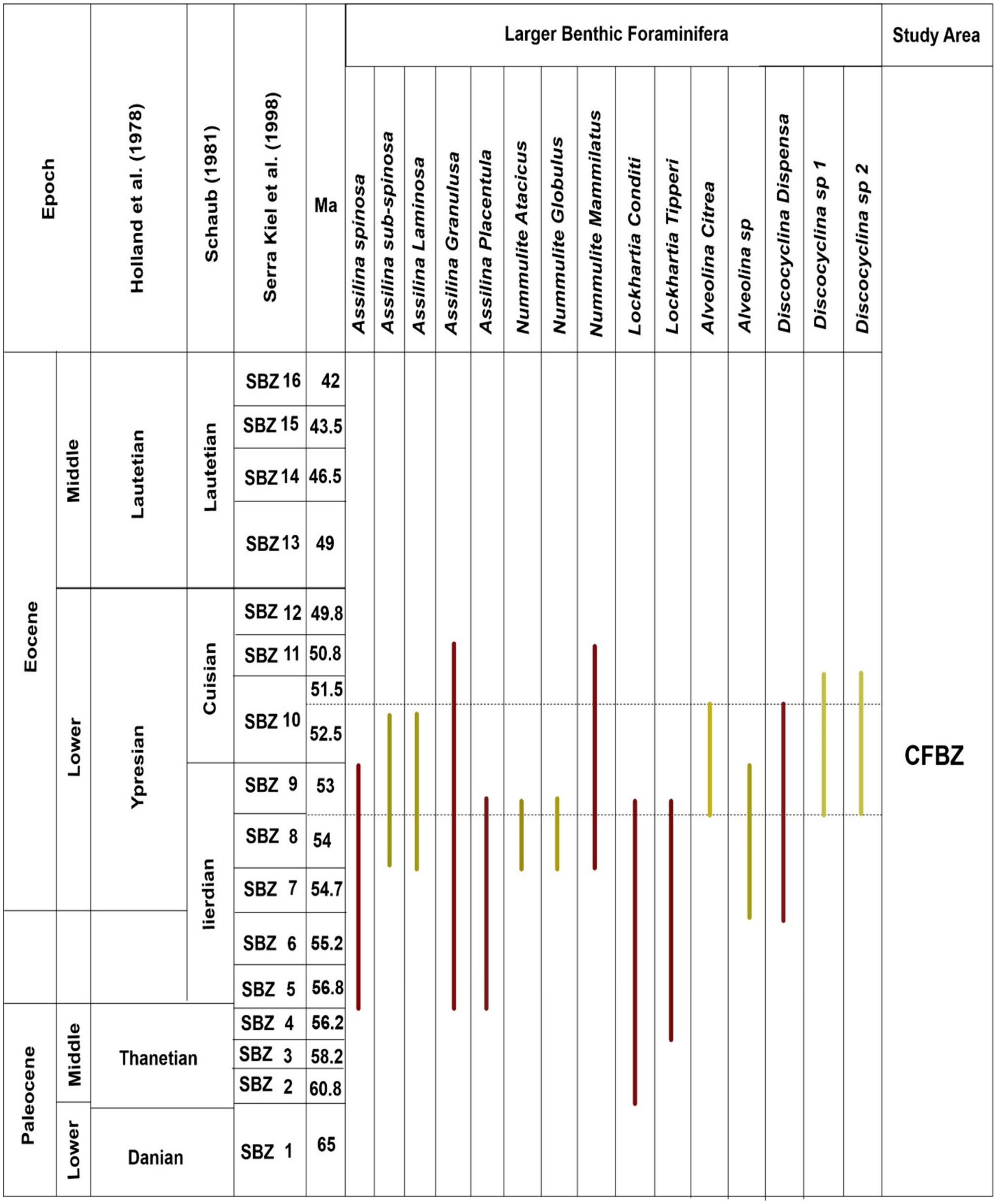


Fig. 7 Age distribution of various Larger Benthic Foraminifera (LBF) in the Chorgali Formation. In comparison to the red lines, the yellow lines represent relatively limited age ranges of the diagnostic fossils. "(CFBZ.)" represents the Chorgali Formation Biozone. It ranges in age from Late Ilerdian/ SBZ9 (53 Ma) to Lower Cuisian/ SBZ10 (51.5 Ma) (modified from Schaub 1981; Serra-Kiel et al. 1998; Zhang et al. 2013)

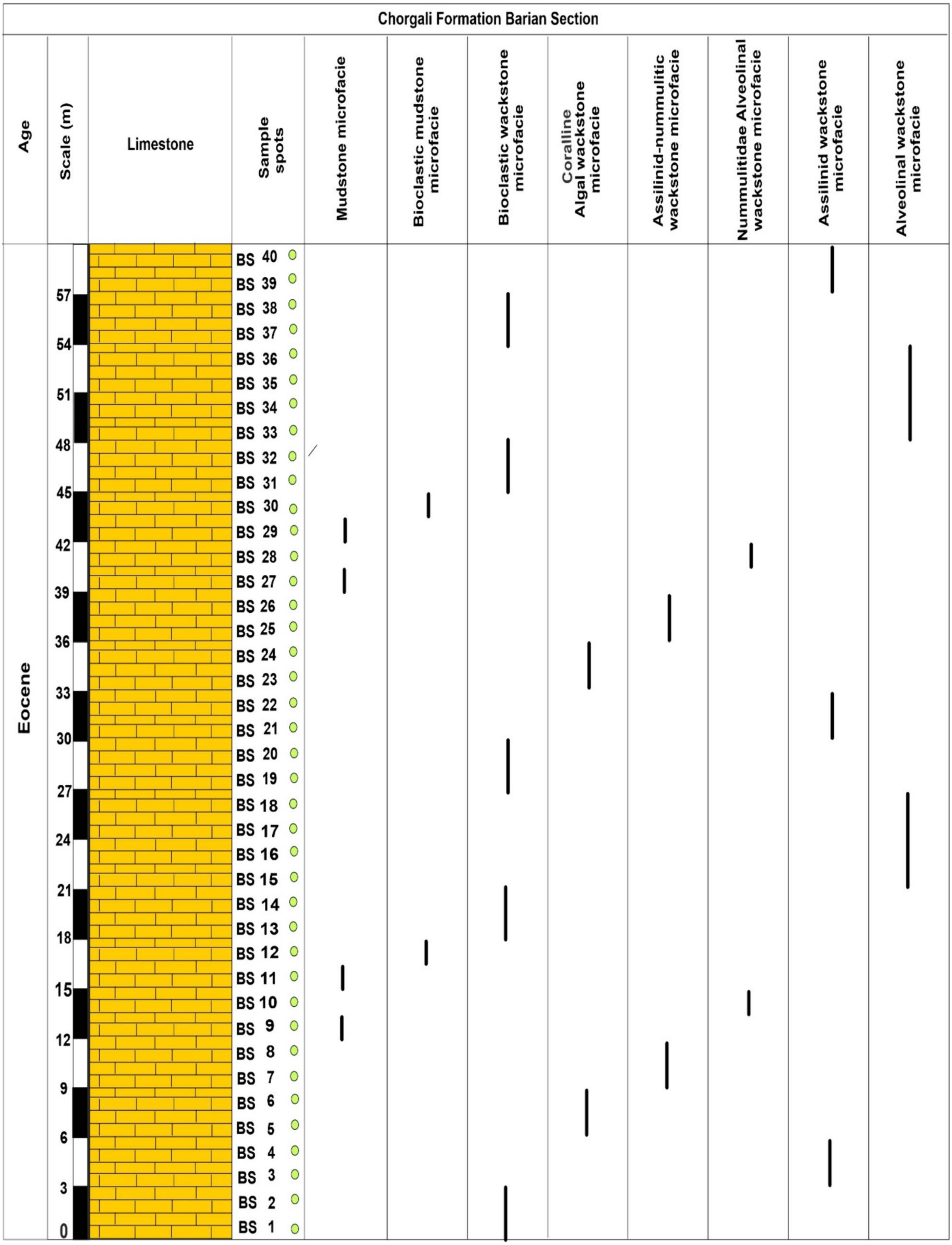


Fig. 8 Microfacies chart of Chorgali Formation, Barian section

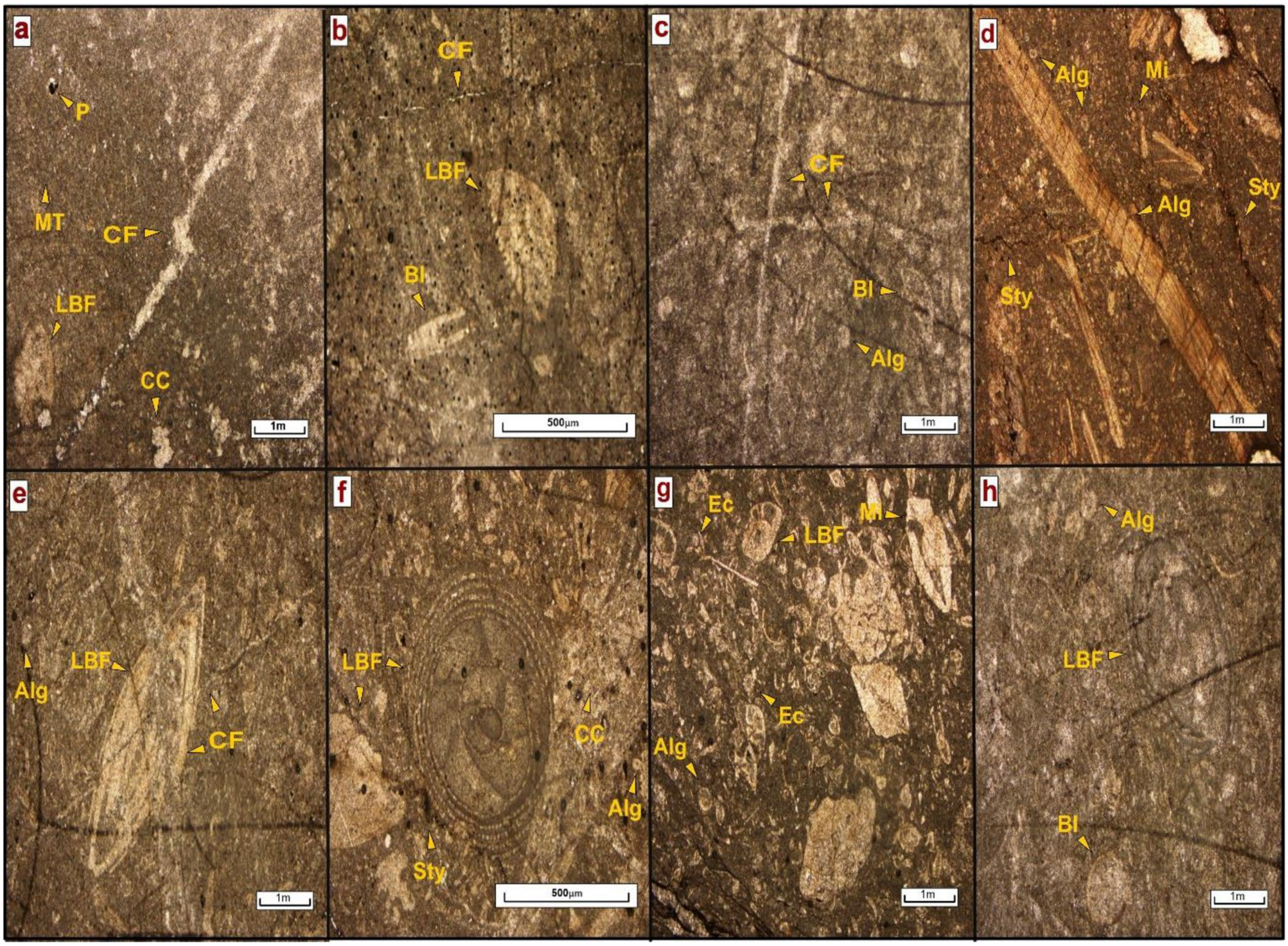


Fig. 9 Photomicrographs of constructed microfacies from Barian section, Chorgali Formation **a** Mudstone microfacies, **b** Bioclastic mudstone microfacies, **c** Bioclastic wackstone microfacies, **d** Algal wackstone microfacies, **e** Assilinid Nummulitic wackstone microfacies, **f** Nummulitidae Alveolinal wackstone microfacies, **g** Assilinid wackstone microfacies, **h** Alveolinid wackstone microfacies. *P* Porosity, *MT* Matrix, *CF* Calcite filled fracture, *LBF* Larger benthic foraminifera, *CC* Calcite cement, *BI* Bioclast, *Alg* Algae, *MI* Miliolid, *Sty* Stylolite, *EC* Echinoid

(1962) classification while (Haq et al. 1987; Emery and Myers 1996) were followed for sequence stratigraphic interpretation.

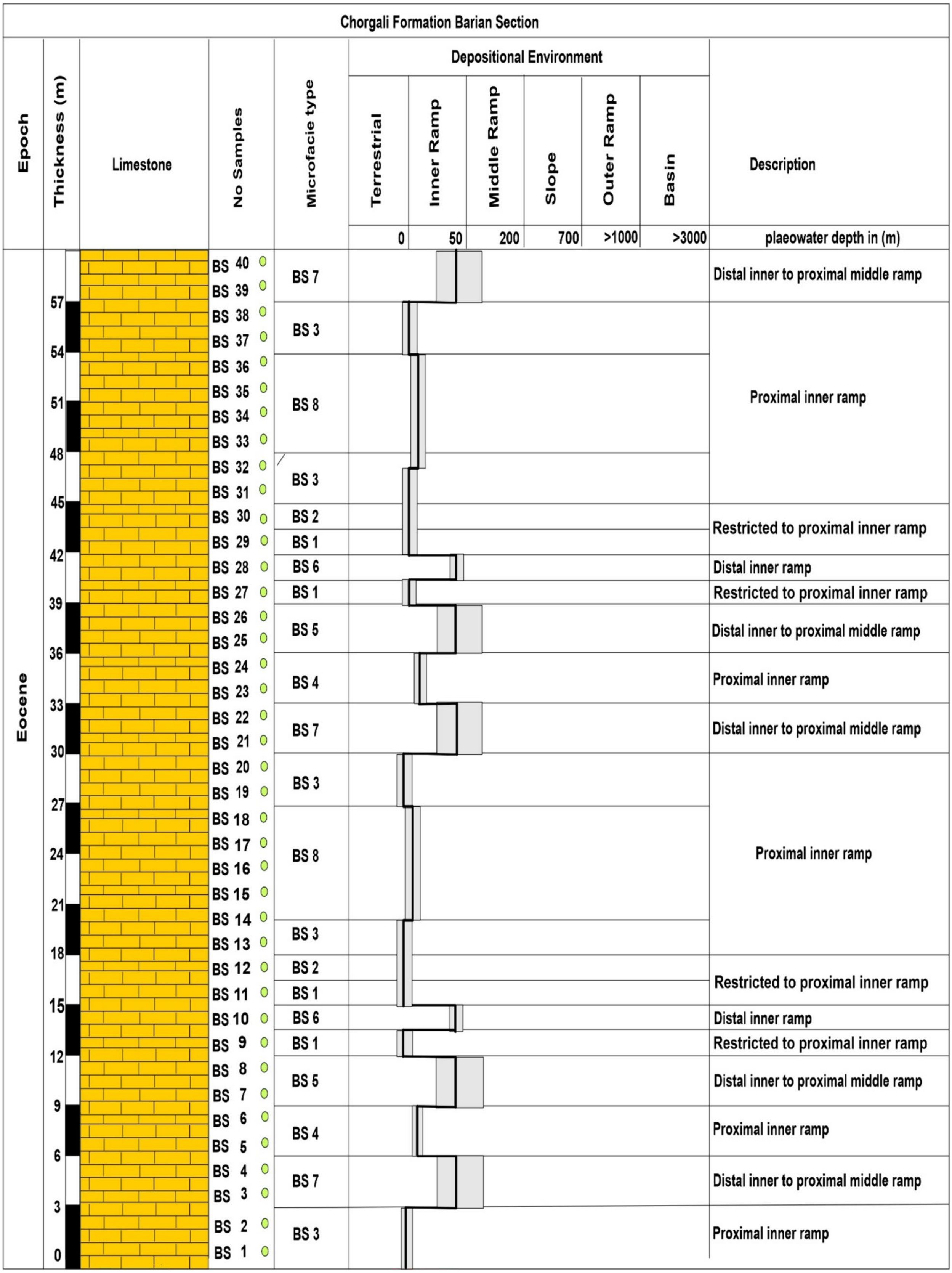
Results

Field observation

During the field, Nathia Gali and Barian sections were assessed (Fig. 1b). The geographic (latitude and longitude) coordinates of the studied sections are (330 57′ 50″ N 730 23′ 21.44″ E, 340 4′ 23.00″ N 730 23′ 16.37″ E). The formation comprises of light grey thin bedded limestone which alternates into dark grey brecciated limestone (Fig. 3a, b). The limestone shows a sharp contact with the underlying shale (Fig. 3c). The limestone is crosscut by multiple calcite veins and hold fragmented shells of bivalves and brachiopods (Fig. 3d, e) on macroscopic scale, larger benthic foraminifera were also observed (Fig. 3f). Numerous calcite veins were also observed on outcrop scale (Fig. 3g). The formation also comprises of brown-grey dolomite having diagnostic butcher-chop weathering (Fig. 3h). Dissolution in the form of Honeycomb weathering is also observed (Fig. 3i). The low amplitude jig-saw stylolite and mechanical fracturing is also observed (Fig. 3j, k).

Systematic paleontology

During the microscopic observations, predominantly larger benthic foraminifers were observed in the Chorgali


Chorgali Formation Barian Section
Epoch
Thickness (m)
Limestone
No Samples
Microfacie type
Depositional Environment
Terrestrial
Inner Ramp
Middle Ramp
Slope
Outer Ramp
Basin
Description
0
50
200
700
>1000
>3000
plaeowater depth in (m)
Eocene
BS 40
BS 39
BS 38
BS 37
BS 36
BS 35
BS 34
BS 33
BS 32
BS 31
BS 30
BS 29
BS 28
BS 27
BS 26
BS 25
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57
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BS 7
BS 3
Distal inner to proximal middle ramp
Proximal inner ramp
Restricted to proximal inner ramp
Distal inner ramp
Restricted to proximal inner ramp
Distal inner to proximal middle ramp
Proximal inner ramp
Distal inner to proximal middle ramp
Proximal inner ramp
Restricted to proximal inner ramp
Distal inner ramp
Restricted to proximal inner ramp
Distal inner to proximal middle ramp
Proximal inner ramp
Distal inner to proximal middle ramp
Proximal inner ramp

◂**Fig. 10** Microfacies distribution, depositional environments, and a mean relative sea level curve inferred from the faunal paleoecology (Racey 1994) and facies criteria (Flügel 2004) of the Chorgali Formation exposed in the Barian section, South-Eastern Hazara sub-Basin. (The shaded area represents the range of variation in the depositional environment)

Formation. These foraminifers are useful for Bio-stratigraphic age. Foraminifera also provide a clue for carbonate biozonation in the shallow and deep marine environment (Wadia 1930). From Chorgali Formation, fifteen diagnostic larger benthic foraminiferal species were observed.

Assilina Spinosa (Davies and Pinfold 1937)

This specie is of Genus Assilina (d'Orbigny 1826) of Early Eocene age shows biconvex morphology and is mature. It features a depression that causes the granules in the center of the test to become smaller in size (Fig. 4a). This species has a stratigraphic age range of lower Ilerdian/ SBZ5 to upper Ilerdian/ SBZ9 (Ahmad 2011; Zhang et al. 2013) and can be easily differentiated from Assilina subspinosa by its central depression.

Assilina subspinosa (Davies and Pinfold 1937)

This sub-specie generally shows a biconvex to flat shell. The test's external surface is distinguished by wide crowded crinkles. Majority of them shows sharp test edges with poorly developed proloculus (Fig. 4b, c). This sub-specie is also characterized by thick walls. The stratigraphic age extends from the middle Ilerdian/ SBZ8 to the lower Cusian/ SBZ10 (Ahmad 2011; Sameeni et al. 2013; Zhang et al. 2013). The lack of a central depression of Assilina subspinosa mark it a different species from Assilina spinosa. The stratigraphic ranges can also be used as a tool to differentiate them.

Assilina granulosa (d'Archiac 1850)

Assilina granulosa of Eocene age is characterized by plane, lengthy, and high-pitched edges. It has crinkles with granules on the test's external surface (Fig. 4d, e). The proloculus is absent. This species' age ranges from lower Ilerdian/SBZ5 to higher Cusian/SBZ11 (Ahmad 2011).

Assilina laminosa (Gill 1953)

This species of Early Eocene age represents a biconvex form, honed edges and wide walls. The proloculus is either lacking or poorly developed. Many representatives lack pillars. The outside surface is even, and the granules are scarcely developed (Fig. 4f, g). The stratigraphic age lies with in middle Ilerdian/ SBZ8 to lower Cusian/ SBZ10 (Ahmad 2011; Sameeni et al. 2013; Zhang et al. 2013).

Assilina placentula (Deshayes 1838)

This species of Early Eocene age shows wide walls that are biconvex in shape and have even boundaries. In few species, the proloculus is not apparent or may not be well established. They show a smooth outside surface and scarcely granular (Fig. 4h, i). The stratigraphic age ranges from lower Ilerdian/ SBZ5 to late middle Ilerdian/ SBZ9 (Ahmad 2011; Zhang et al. 2013).

Nummulites atacicus (Leymerie 1846a)

This specie is of Nummulites (Lamarck 1801) of Eocene age. It has a biconvex form and show a tinny test wall with respect to other Nummulites species. The umbilical pillars are deep-rooted and are presents at the center of the test. The proloculus is quite tiny. These coils at the proloculus are tightly wrapped. The coils are loosely curled away from the proloculus (Fig. 4j). This class represents middle Lllerdian/ SBZ8 biozone (Sameeni et al. 2013; Zhang et al. 2013).

Nummulites Globulas (Leymerie 1846b)

It has thick chambers, biconvex to spherical form having weak pillars within the center of the test. The primary chamber (proluculus) is insignificant in comparison to the complete exam (Fig. 4k). They show intermediate llerdian/ SBZ8 zone (Middle to upper Eocene). (Ahmad 2011; Sameeni et al. 2013).

Nummulites mamillatus (Fichtel & Moll 1798).

It has thick walls and a globular to lenticular form. A noticeable radial form proloculus is observed in the center of the shell. Its pillars have yet to be created. The curls are generally tight towards the proloculus (Fig. 4l). The age ranges from Lower to Middle Eocene which is middle llerdian/ SBZ8 to upper Cusian/SBZ10.

Lockhartia Conditi (Nuttall 1926)

This specie is of Lockhartia (Davies 1932) having age of Upper Paleocene-Early Eocene is distinguished by mature and wide pillars in the core of the test (Fig. 4m). This class is most typically found in the lower and middle Chorgali Formation. The stratigraphic range extends from Lower Thanetian/SBZ2 to late middle llerdian/SBZ9 (Ahmad 2011; Zhang et al. 2013).

Lockhartia tipperi (Davies 1932)

This species shell is low trochospiral, fairly convex, and has curved edges. The umbilicus has become clogged with pillars (Fig. 4n). This species' geological age extends from the late Paleocene to the early Eocene. This species' stratigraphic range extends from upper Thanetian/SBZ4 to late middle llerdian/SBZ9 (Ahmad 2011; Zhang et al. 2013).

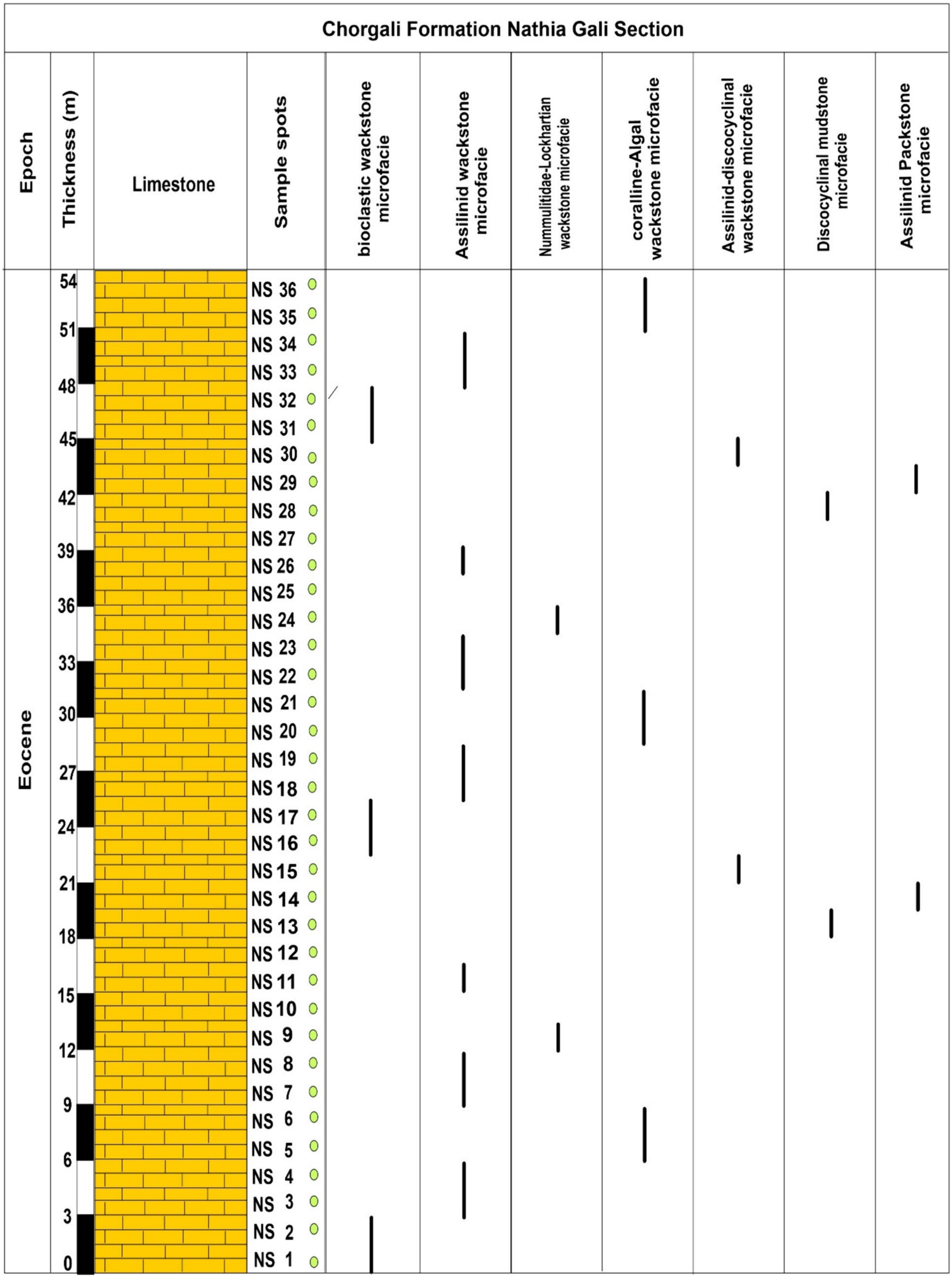


Fig. 11 Microfacies chart of Chorgali Formation, Nathia Gali section

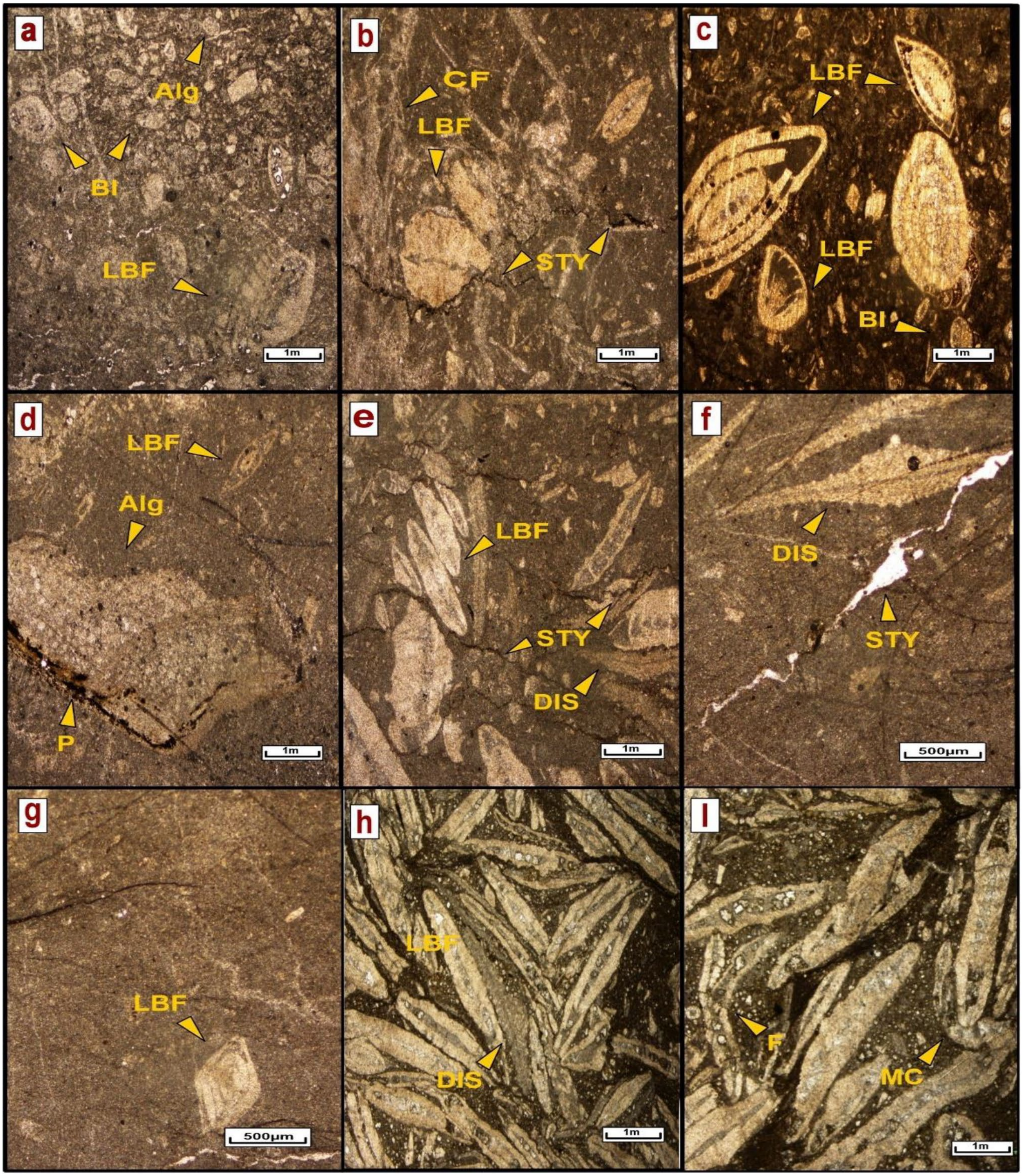
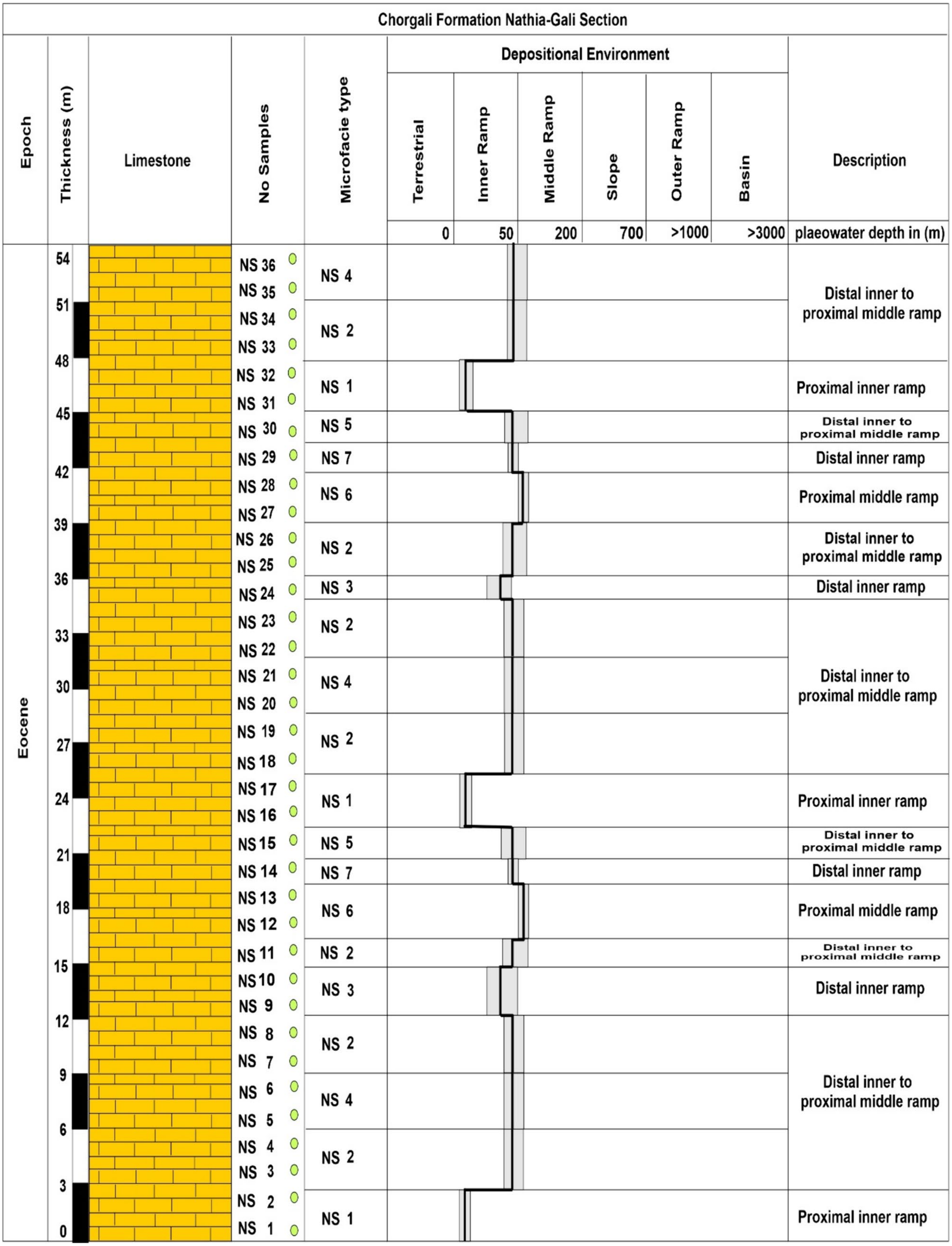


Fig. 12 Photomicrographs showing microfacies of Chorgali Formation, Nathia Gali section. **a** Bioclastic wackstone microfacies, **b** Assilinid wackstone microfacies, **c** Nummulitidae – Lockhartian wackstone microfacies, **d** Algal-Assilinal wackstone microfacies, **e** Assilinid – Discocyclinal wackstone microfacies, **f** and **g** Discocyclinal mudstone microfacies, **h** and **i** Assilinid packstone microfacies. *P* Porosity, *CF* Calcite filled fracture, *LBF* Larger benthic foraminifera, *CC* Calcite cement, *BI* Bioclast, *Alg* Algae, *Sty* Stylolite, *Dis* Discocyclina, *MC* mechanical compaction, *F* Fractures


Chorgali Formation Nathia-Gali Section
Epoch
Thickness (m)
Limestone
No Samples
Microfacie type
Depositional Environment
Terrestrial
Inner Ramp
Middle Ramp
Slope
Outer Ramp
Basin
Description
0
50
200
700
>1000
>3000
plaeowater depth in (m)
Eocene
54
51
48
45
42
39
36
33
30
27
24
21
18
15
12
9
6
3
0
NS 36
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Distal inner to proximal middle ramp
Proximal inner ramp
Distal inner to proximal middle ramp
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Distal inner ramp
Distal inner to proximal middle ramp
Proximal inner ramp

◂**Fig. 13** Microfacies distribution, depositional environments, and a mean relative sea level curve inferred from the faunal paleoecology (Racey 1994) and facies criteria (Flügel 2004) of the Chorgali Formation exposed in the Nathia Gali section, South-Eastern Hazara sub-Basin. (The shaded area depicts the range of variation in the deposition environment)

Alveolina citrea (Drobne 1977)

This is characterized by oval test with truncated poles and sometime rounded of Early Eocene. Proloculus is round. It has four to five looser coils and up to five moderately tight coils (Fig. 4o). The stratigraphic range of is SBZ-9 (Serra-Kiel et al. 1998).

Alveolina sp, (Drobne 1977)

This species is observed both in lower and upper part of Chorgali Formation (Fig. 4p). The stratigraphic range of this species is from SBZ-7 to SBZ-9 of Early Eocene (Zhang et al. 2013).

Discocyclina Sp. 2 (Zhang et al. 2013)

This specie is of Genus Discocyclina of Early Eocene age is mostly recorded in Nathia-Gali section and represents lower and upper part of Chorgali Formation (Fig. 4q). The stratigraphic range of this species is upper part of SBZ-9 to lower part of SBZ-11 (Zhang et al. 2013).

Discocyclina dispansa (Sowerby 1840)

This class represents spherical, convexo-convex tests, and spherical in the center. The even, tinny, and disc-shaped edges radiate from the test's core. Th majority of the species examined had fractured flanks (Fig. 4r). The test is distinguished by a huge amount of variable size chambers. The exquisite coiling and internal structure of the samples is poorly preserved due to the high micrite content. The stratigraphic range of this species is upper part of SBZ-6 to SBZ-10.

Discocyclina Sp. 1 (Zhang et al. 2013)

It also shows spherical, convexo-convex tests and spherical in the center (Fig. 4s). The plane, tinny, and disc-shaped edges radiate from the test's centre (Zhang et al. 2013). The stratigraphic range of this species is upper part of SBZ-9 to lower part of SBZ-11 (Figs. 5, 6, 7).

Microfacies analysis

Barian section

After detail microscopic observations, eight microfacies were identified in the Barian Section. These facies are comparable with the standard facies model for ramp (Mondello Sicily et al. 2002). The constructed microfacies are summarized in (Fig. 8). These are coded as BS1-BS8, where BS stands for Barian section and 1–8 are the several types of reported microfacies.

(1) Mudstone microfacies BS1

This facie represents micritic limestone, which contains nearly 2% allochems in a 93% micritic ground mass. The biogenic content is not well retained. The facies are also crosscut by sparry calcite (5%) filled veins (Fig. 9A). The dominant allochems consist of benthic foraminifera and Miliolid traces.

Interpretation

This facie is characterized by carbonate mud and traces of miliolids, which indicates a warm water, low-agitated, and restricted/partially restricted depositional environment (Geel 2000). The occurrence of mudstone depositional texture emphasizes the deposition in low energy and semi-restricted environments (Tucker and Wright 1990). This microfacies has been characterized as a lagoonal environment or inner proximal ramp environment based on textural features and faunal composition (Fig. 16a; Tucker and Wright 1990; Geel 2000). It has a correlation with RMF-19 (Flugel 2010).

(2) Bioclastic mudstone microfacies BS2

This facie is micritic limestone, with 9% grains and 85% matrix. Green algae and larger benthic foraminifera, such as Nummulite and Lockhartia, are the major allochems. There are 6% vissible calcite veins and some miliolid traces were also present (Fig. 9b). The facies contain opaque mineral like pyrite framboids and siliciclastic grains in the form quartz.

Interpretation

This facie is characterized by abundant carbonate mud, miliolids traces and low organism diversity which direct its deposition inner ramp lagoon environment. In such cases, the alteration of water salinity and its temperature is severe and indicate stressful environmental conditions (Kakemem et al. 2016; Jafarian et al. 2017). In general, the facies represents a warm water, low-agitated, near shore shallow,subtidal to intertidal confined depositional habitat. The presence of muddy matrix, limited biota, and fine silty quartz suggests a low energy lagoon with little circulation (Fig. 16a; Rasser et al. 2005; Bachmann and Hirsch 2006). The facie is show resemblance to RMF-19 of (Flugel 2010).

(3) Bioclastic wackstone microfacies BS3

This facie contains 15–25% bioclasts, with an average of 18%. There is a 60–80% matrix present, with an average of 70%. This facie is also characterized by similar frequency of miliolids and dasyclad green algae. The foraminiferal bioclastic assemblages specify low to moderate density and diversity. The bioclasts contain mollusks,

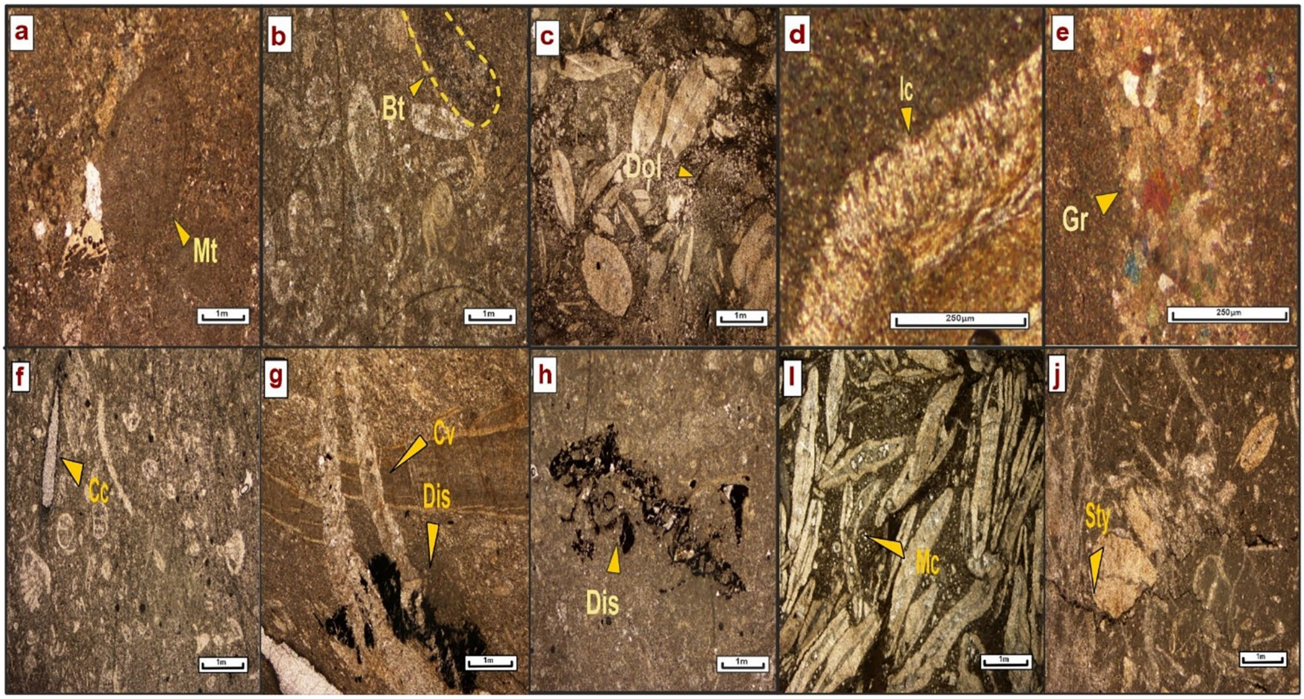


Fig. 14 Photomicrographs of the observed diagenetic features **a** micritized Alveolina, **b** Bioturbation, **c** Seclective dolomitization, **d–f** different generation of calcite cementsfilling the pores, veins and vugs, **g** and **h** Dissolution infills by opaque minerals like pyrite framboids, **i** Mechanical compaction and **j** Chemical compaction (Stylolite)

echinoderms, and shattered fragments of Nummulites, Alveolina, and Lockhartia. The facie is crosscut by a later diagenetic secondary veins and fractures which is infills by micro spar calcite cements (Fig. 9c).

Interpretation

The presence of limited biota, such as milliolids, green algae, gastropods and larger benthic foraminifers along with micritized bioclasts, indicate a lagoonal environment with slow sedimentation (Fig. 16a; Wilson 1975; Flugel 2010). The micritized bioclasts with in the micritic texture represents shallow water inner ramp lagoonal environments with a relative abundant microbial activity (Rasser et al. 2005; Tomás et al. 2016). This facie is consistent with RMF-20 of (Flugel 2010). The co-occurrence of alveolina with miliolids point out a back-shoal depositional environment (Boudaugher-Fadel 2018).

(4) Coralline algal wackstone microfacies BS4

This facie contains 25–30% allochems, with an average of 28% allochems and 63% matrix. This facie contains abundant coralline red algaes along with moderate amounts of dasyclad green algae. The facies are crosscut by low amplitude stylolite filled with framboids that account almost (9%) of the facie (Fig. 9d).

Interpretation

This microfacies have a considerable number of allochems, plentiful coralline red algae, and a little amount of dasycladalean green algae. Dasyclad green algae suggest deposition in warmer water at shallower depths (Heckel 1972; Flügel 1982). The depositional texture of wackestone designates additional deposition in a low to somewhat energetic environment (Tucker and Wright 1990). The depositional texture of the wackstone and the presence of dasyclad green algae imply deposition in a transition zone between a sand shoal and inner proximal ramp setting (Racey 1994). The occurrence of these algae along larger benthic foraminifera like miliolids in a relatively rich lime mud matrix represents inner ramp lagoonal environment characterized by low energy, warm water and restricted circulations (Adabi et al. 2016; Jafarianet al. 2017). It has a correlation with RMF-20 (Flugel 2010).

(5) Assilinid nummulitic wackstone microfacies BS 5

This microfacie is made up of 30% allochem and 57% micrite. The allochemical components are predominantly composed Assilina and Nummulite, which form the primary skeletal framework grain. It also contains 13% sparry calcite veins (Fig. 9e).

Interpretation

This microfacies is characterized by wackestone depositional texture where assilina and nummulites accounts for primary framework grains. Nummulites have been found in a variety of open marine setting. Assilina and nummulites are known to inhabit soft carbonate substrates in open marine environments characterized by low-energy conditions and medium light levels, typically occurring in the oligophotic zone below the fair-weather wave base (FWWB) but above the storm wave base (SWB) (Beavington-Penney and Racey 2004; Kakemem et al. 2023). Such conditions provide the optimal balance of available light and hydrodynamic energy for their growth and survival. The tight relationship of Nummulites and Assilina suggests that deposition occurred in distal inner to proximal middle ramp setting below the FWWB (Racey 1994). It has a correlation with RMF-13 (Flugel 2010).

(6) Nummulitidae alveolinal wackstone microfacies BS6

This microfacies is primarily composed of allochems in micrite matrix. The allochem accounts for 38% while the remaining matrix contain 55% micrite, and 7% sparry calcite veins. The abundant allochems in this facie are nummulite and alveolina, with a small proportion of lockhartia (Fig. 9f).

Interpretation

The abundance of nummulites, alveolina and lockhartia indicates that it is deposited in shallow water, under low to moderate energy setting, distal inner ramp (Fig. 16a). It has a correlation with RMF-13 (Flugel 2010). The presence of normal marine benthic foraminifera like nummulites and lockhartia and its association with protected marine alveolinids suggests that the BS6 microfacies are deposited in mid-ramp depositional environments linked with photic to the oligophotic zone (Pomar et al. 2014; Kakemem et al. 2016). This accumulation resulted by a combine in-situ production of open marine environment and from transport of inner platform biota by means of waves and currents.

(7) Assilinid wackstone microfacies BS7

This microfacies is characterized by a mud supported fabric which contain 60% micrite and 36% allochem. The allochems of this microfacies are predominantly assilina, echinoids embedded in the carbonate matrix. It also contains relatively low proportion of nummulite, lockhartia and discocyclina. Moreover, 4% stylolites were observed (Fig. 9g).

Interpretation

The presence of abundant assilina, echinoids and comparatively small amount of lockhartia, nummulite and discocylina suggested that this microfacies deposited in distal inner to proximal middle ramp setting (Fig. 16a) (Racey 1994). The depositional texture of wackestone designates additional deposition in a low to somewhat energetic environment (Tucker and Wright 1990). This microfacies is deposited in a low-energy, open marine environment, lies within the oligophotic zone below the fair-weather wave base but above the storm wave base, which favored the growth and accumulation of assilina and other foraminifers (Beavington-Penney and Racey 2004). Such microfacies suggests a relatively quiet depositional setting with minimal hydraulic energy and thus allowing the preservation of the mud-supported fabric and the original growth of the larger benthic foraminifera. It has a correlation with RMF-13 (Flugel 2010).

(8) Alveolinal wackstone microfacies BS8

This microfacies has 35% allochem and 50–65% micrite. The allochemical components are mostly Alveolina and a relatively small amount of nummulite, lockhartia, and 3–5% green algae (Fig. 9h).

Interpretation

This microfacies is characterized by benthic foraminifers of shallow-water specially the alveolinids. The alveonilids occur in an association with micritized skeletal grains with in a micritic matrix such condition is favored by protected shallow water inner ramp-lagoonal environments with abundant microbial activities (Rasser et al. 2005; Tomás et al. 2016). The back-shoal environment is favourible for Alveolina deposition (Boudaugher-Fadel 2018). The presence of dasyclad green algae imply deposition in a transition zone between a sand shoal and inner proximal ramp setting (Racey 1994). The wackestone texture represents low to somewhat energetic depositional environment (Tucker and Wright 1990). It has a correlation with RMF-17 (Flugel 2010) (Fig. 10).

Nathia Gali section

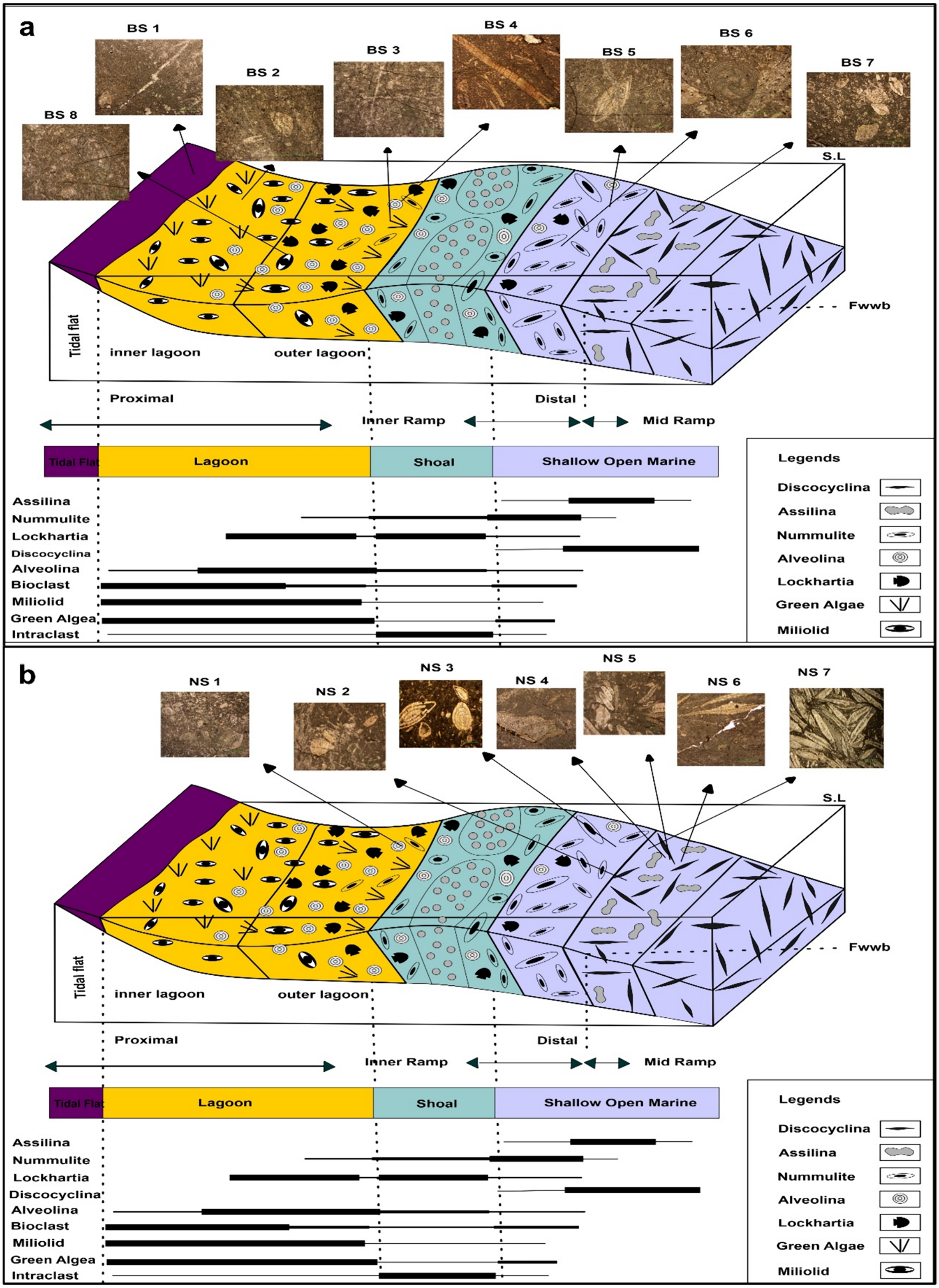
The organized microfacies from the Nathia Gali section are listed in (Fig. 11). These are described as NS1-NS7, where NS stands for Nathia Gali section and 1–7 are the reported microfacies.

(1) Bioclastic wackstone microfacies NS 1

This facie contains 35–45% bioclasts embedded in 55% micrite matrix. The facies contain abundant of opaque minerals like framboids in disseminated form. The bioclast contain fragments of algaes, millolids, lockhartia and rare amount of nummulite (Fig. 12a).

Interpretation

The depositional pattern of wackestone suggests that this microfacie was deposited in a low to moderately active environment (Tucker and Wright 1990). The presence of both dasycladean and miliolid algae suggests that deposition occurred in warmer shallower water (Heckel 1972; Flügel 1982) and represents a zone between sand shoal


a
BS 1
BS 2
BS 3
BS 4
BS 5
BS 6
BS 7
BS 8
S.L
Fwwb
Tidal flat
inner lagoon
outer lagoon
Proximal
Distal
Inner Ramp
Mid Ramp
Tidal Flat
Lagoon
Shoal
Shallow Open Marine
Assilina
Nummulite
Lockhartia
Discocyclina
Alveolina
Bioclast
Miliolid
Green Algea
Intraclast
Legends
Discocyclina
Assilina
Nummulite
Alveolina
Lockhartia
Green Algae
Miliolid
b
NS 1
NS 2
NS 3
NS 4
NS 5
NS 6
NS 7
S.L
Fwwb
Tidal flat
inner lagoon
outer lagoon
Proximal
Distal
Inner Ramp
Mid Ramp
Tidal Flat
Lagoon
Shoal
Shallow Open Marine
Assilina
Nummulite
Lockhartia
Discocyclina
Alveolina
Bioclast
Miliolid
Green Algea
Intraclast
Legends
Discocyclina
Assilina
Nummulite
Alveolina
Lockhartia
Green Algae
Miliolid

◂**Fig. 15** **a** Facies depositional model of a carbonate ramp showing the temporal distribution of the Eocene facies of the Chorgali Formation, South-Eastern Hazara sub-Basin at Barian section. **b** Facies depositional model of a carbonate ramp showing the temporal distribution of the Eocene facies of the Chorgali Formation, South-Eastern Hazara sub-Basin at Nathia Gali section

and inner proximal ramp environment (Fig. 7b) (Racey 1994). The richness of miliolids, and the low diversity of other foraminiferal community may suggest that the marine environment was characterized by saline or even hypersaline conditions, which are typical of shallow water settings (Geel 2000). The occurrence of miliolids in a mud supported matrix indicate its deposition in low-energy, shallow marine i.e., lagoonal environments (Flügel 2004; Vaziri-Moghaddam et al. 2006; Brandano et al. 2009). The facie is identical to RMF-20 of (Flugel 2010).

(2) Assilinid wackstone microfacies NS 2

This microfacies is characterized by 26% allochem and 65–70% micrite. This microfacies contain various species of larger benthic foraminifera with abundant Assilina and relatively low proportion of nummulite, lockhartia and algae. The facies also contain 10% unidentified bioclast fragments (Fig. 12b).

Interpretation

The wackestone microfacies suggests low to moderately active depositional environment (Tucker and Wright 1990). The abundance of Assilina and scare Nummulite and Lockhartia indicated that this microfacies were deposited in the distal inner to proximal middle ramp setting below the FWWB (Fig. 16b) (Racey 1994). It correlates with RMF-13 (Flugel 2010).

(3) Nummulitidae-Lockhartian wackstone microfacies NS 3

This microfacies comprises of 36% allochems, and 54% matrix. The dominant allochems are the larger benthic foraminifera including Nummulites and Lockhartia with relatively small amount of Assilina. Nine percent bioclasts were observed which includes broken fragments of nummulite, lockhartia and algae, which is also crosscut by low amplitude stylolite (Fig. 12c).

Interpretation

The occurrence of abundant Nummulites and lockhartia, with a low concentration of assilina and wackestone depositional texture indicates a low to moderate energy environment (Tucker and Wright 1990). The nummulites are characterized by robust to ovate test and thick shelled and indicates its presence in low energy shallow marine conditions with intense light penetration and sufficient nutrients (Beavington-Penney and Racey 2004; Barattolo et al. 2007). The abundant carbonate mud without any faunal biodiversity may also suggests shallow water setting with low to moderate energy conditions (Khatibi et al. 2014). The presence of Nummulites suggests sedimentation rates of Mid ram setting while Lockhartia indicates inner to middle ramp setting (Racey 1994). Based on its texture and faunal composition, this microfacies has been classified as a distal inner ramp environment (Fig. 16b). It has a correlation with RMF-13 (Flugel 2010).

(4) Coralline Algal wackstone microfacies NS 4

This microfacies comprises of 35–40% allochems, with the average of 36% and 60% matrix. The texture is micritic wackestone with symmetric and oriented fabric. The dominant allochems are coralline algae. Assilina, Nummulites, Discocyclina and green algae are the subordinate facies components. Apart from that 4% bioclast were observed which includes broken fragments of algae, assilina, along with some shells (Fig. 12d). The foraminifers are affected by micritization and is rimmed around by micritic envelope.

Interpretation

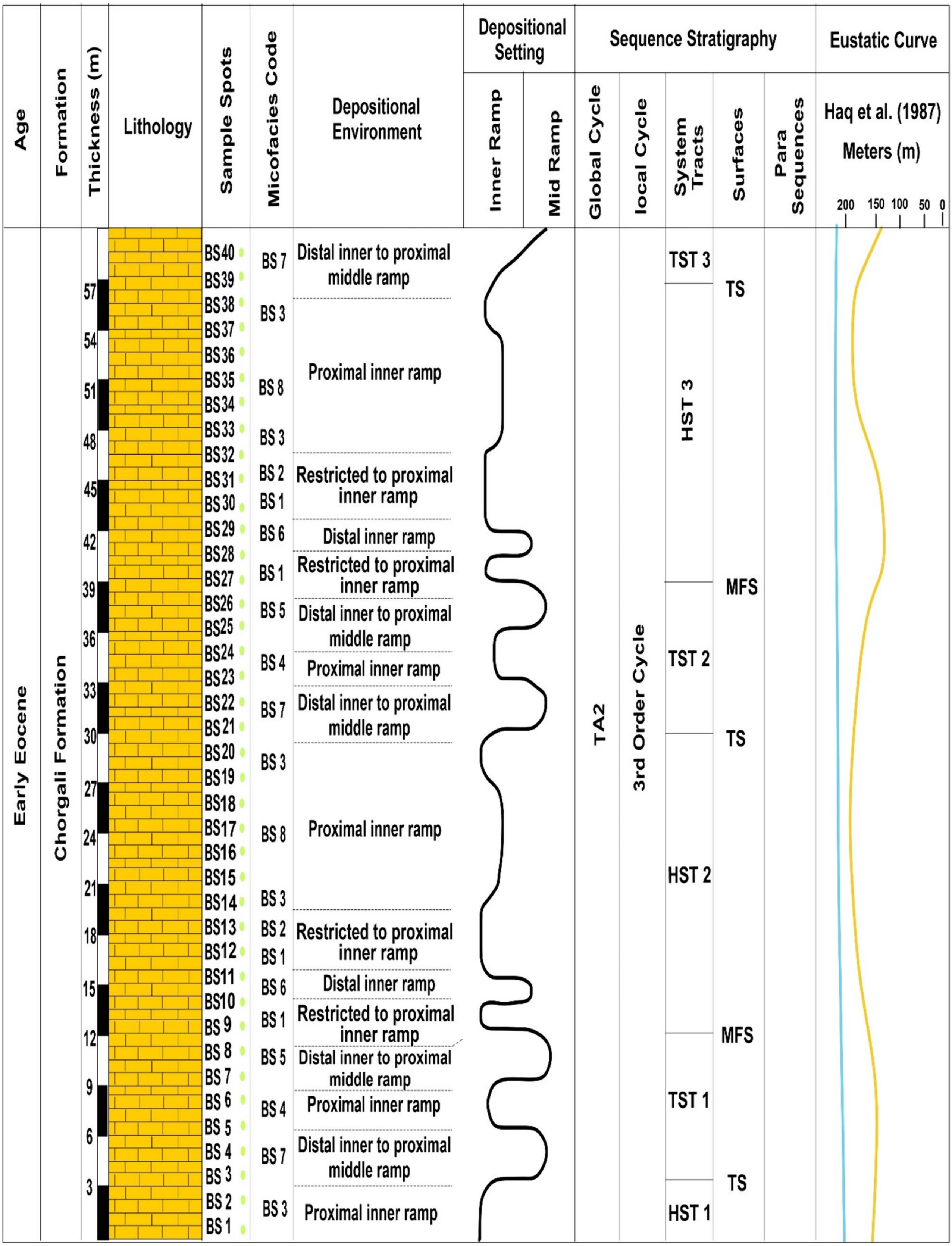
This microfacies is found in both sections with similar characteristics. The mud supported matrix and abundant coralline algae represents low energy conditions possibly very near or marginally below the FWWB (Nebelsick et al. 2013). Such amount of carbonate mud may prevent the dominance of coralline algae (Barattolo et al. 2007). According to (Heckel 1972; Adams and Mackenzie 1998), coralline algae can be found at low energy levels on the inner ramp and intermediate to high energy settings on the middle ramp. The dominant allochems suggests distal inner to proximal mid ramp settings (Fig. 16b). It has a correlation with RMF-13 (Flugel 2010).

(5) Assilinid-Discocyclinal wackstone microfacies NS 5

This microfacies is 30% allochem and 50% micrite. It contains various species of larger benthic foraminifera like Assilina, discocyclina and relatively low proportion of nummulite, 11% bioclast were observed which include fragments of assilina and planktonic foraminifera. Stylolites covers 9% of the facie (Fig. 12e).

Interpretation

The wackestone depositional texture suggests deposition in a low to moderate energy setting (Tucker and Wright 1990). It is rich in assilina and discocyclina, with a relatively modest concentration of nummulites. This microfacies has been characterized as a distal inner to proximal mid ramp environment according to its texture and faunal composition (Fig. 16b). It correlates with RMF-13 (Flugel 2010).


Age
Formation
Thickness (m)
Lithology
Sample Spots
Micofacies Code
Depositional Environment
Depositional Setting
Inner Ramp
Mid Ramp
Sequence Stratigraphy
Global Cycle
local Cycle
System Tracts
Surfaces
Para Sequences
Eustatic Curve
Haq et al. (1987)
Meters (m)
200 150 100 50 0
Early Eocene
Chorgali Formation
57
54
51
48
45
42
39
36
33
30
27
24
21
18
15
12
9
6
3
BS40
BS39
BS38
BS37
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BS16
BS15
BS14
BS13
BS12
BS11
BS10
BS 9
BS 8
BS 7
BS 6
BS 5
BS 4
BS 3
BS 2
BS 1
BS 7
Distal inner to proximal middle ramp
BS 3
Proximal inner ramp
BS 8
BS 3
BS 2
Restricted to proximal inner ramp
BS 1
BS 6
Distal inner ramp
BS 1
Restricted to proximal inner ramp
BS 5
Distal inner to proximal middle ramp
BS 4
Proximal inner ramp
BS 7
Distal inner to proximal middle ramp
BS 3
Proximal inner ramp
BS 8
BS 3
BS 2
Restricted to proximal inner ramp
BS 1
BS 6
Distal inner ramp
BS 1
Restricted to proximal inner ramp
BS 5
Distal inner to proximal middle ramp
BS 4
Proximal inner ramp
BS 7
Distal inner to proximal middle ramp
BS 3
Proximal inner ramp
TA2
3rd Order Cycle
TST 3
HST 3
TST 2
HST 2
TST 1
HST 1
TS
MFS
TS
MFS
TS

◂**Fig. 16** Stratigraphic log of Barian section highlighting variable lithology, microfacies distribution, depositional environments, sequence stratigraphy, and eustatic curve. Blue color line shows long term global eustatic changes and dark yellow color line shows short term global eustatic changes. *HST* High Stand System Tract, *TST* Transgressive System Tract, *MFS* Maximum Flooding Surface, *TS* Transgressive Surface

(6) Discocyclinal mudstone microfacies NS 6

This facie represents micritic limestone, which contains nearly 6% allochems in a 76% micrite. It contains modest concentration of larger benthic foraminifera including discocyclina and assilina, 3% unidentified bioclast and 11% sparry calcite filled veins were observed (Fig. 12f, g).

Interpretation

The intimate relationship between discocyclina and assilina supports its deposition in the proximal mid ramp below the FWWB (Fig. 16b) (Racey 1994). Further, the mudstone depositional texture of this microfacies shows that it is deposited in a calm environment. Based on depositional texture and faunal paleoecology, this microfacies deposited in the proximal middle ramp setting. It has a correlation with RMF 2 (Flugel 2010).

(7) Assilinid packstone microfacies NS 7

This microfacies is 72% allochem and 25% micrite. It contains various species of larger benthic foraminifera with abundant Assilina and relatively low proportion of discocyclina. 3% unidentified bioclasts were observed (Fig. 12h, i).

Interpretation

This microfacies is made up of abundant Assilina with subordinate discocyclina with a packstone depositional texture, indicating its deposition in a moderate to high energy environment based on depositional texture and faunal paleoecology. This microfacie indicates its deposition in the distal inner ramp environment (Fig. 16b). It has a correlation with RMF 13 (Flugel 2010) (Fig. 13).

Diagenesis

Several diagenetic events like micritization, bioturbation, cementation, dissolution, compaction, and dolomitization were also observed. Micritization is found as a micritized rim around the allochems (Fig. 14a) and represents shallow marine environment (Bathurst 1975; Read 1985). Digger organisms also cause bioturbation (Fig. 14b). Fine grain subhedral to anhedral dolomites were also observed representing selective dolomitization (Fig. 14c). Microcrystalline and blocky calcite cement typically clogged the allochems and pores, destroying reservoir characteristics (Fig. 14d, e). The carbonates in (Fig. 14f, g, h) have a slight dissolving impact; nevertheless, the dissolved vugs are largely filled by later-stage diagenetic cements (Fig. 14f). Calcite-cemented veins are also apparent (Fig. 14g). Both mechanical compaction in the form of cracks and bent grains (Fig. 14i) and chemical compaction in the form stylolite is also evident (Fig. 14j).

Discussion

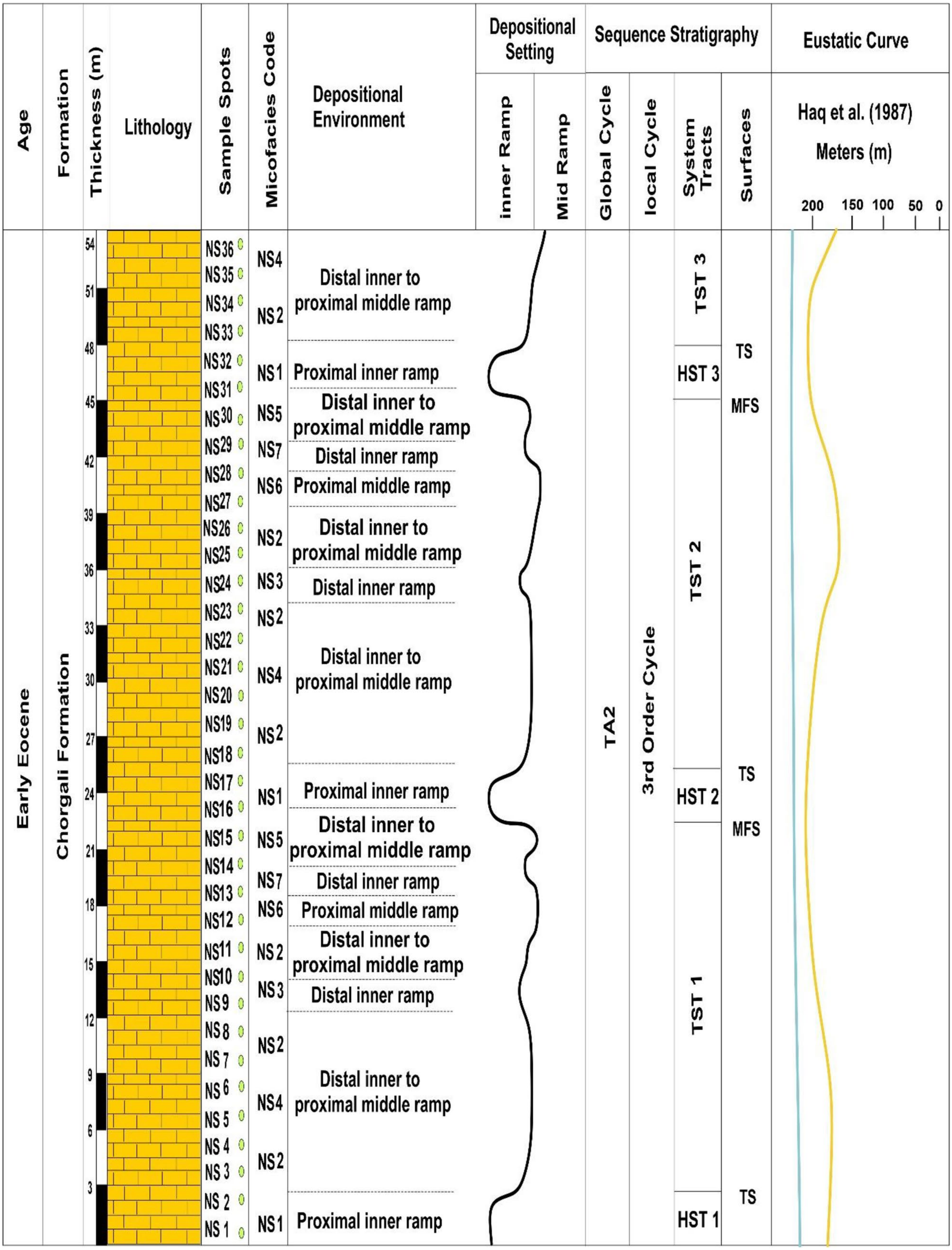
Bio-stratigraphic age range of Chorgali Formation

The carbonate unit of Chorgali Formation contains high concentration of Larger Benthic Foraminifera (LBF), which are considered for precise age determination. Assilina spinosa, Assilina sub-spinosa, Assilina laminosa, Assilina granulusa, Assilina placentula, Nummulites atacicus, Nummulites globolus, Nummulites mamillatus, Lockhartia conditi, Lockhartia tipperi, and Alveolina citrea are examples of index fossils (Shah 1977; Swati et al. 2013) These species range in age from the late Paleocene to the Early Eocene (Schaub 1981); Serra-Kiel et al. 1998). The comprehensive biostratigraphic age range of these species from the current study are described in (Fig. 7). The age ranges of Assilina sub-spinosa, A. laminosa, Nummulites atacicus, N. globulus, Alveolina citrea, Alveolina sp, discocyclina sp 1 and discocyclina sp 2 are the shortest among these species. The ages span is from the Lower Ilerdian/ SBZ5 to the Upper Cuisian/(SBZ11). The age range of the Alveolina indicatrix species ranges from Late Ilerdian (SBZ9) to Lower Cuisian (SBZ10) (Schaub 1981; Serra-Kiel et al. 1998).

The age ranges of these index fossils as well as the formation's stratigraphic position (i.e., between the middle Ilerdian Sakesar Formation/Margala Hill Limestone and the Upper Cuisian Kuldana Formation), the Chorgali Formation can be dated as Late Ilerdian/SBZ9 (53 Ma) to Lower Cuisian/ SBZ10 (51.5 Ma) (Ahmad et al. 2011; Sameeni et al. 2013). The identified LBF species and their precise age are comprehensively described in (Figs. 5, 6, 7).

Depositional model of Chorgali Formation

Tucker (1992) proposed five different carbonate depositional environments which includes rimmed, non-rimmed, ramps, epeiric, and isolated platforms. All these are differentiated from one another through different diagnostic features. In the current study, from macroscopic to microscopic observations, the Chorgali Formation is completely barren from any kind of reef deposits, moderate transported deposits, widespread reworking materials, and as well as the geometry of the basin suggests a ramp like profile for the deposition of these Chorgali Carbonates. The persistent open marine condition of Early Eocene resulted into the deposition of Eocene strata (Ghazi et al. 2014; Fahad et al. 2021) which is evident


Age
Formation
Thickness (m)
Lithology
Sample Spots
Micofacies Code
Depositional Environment
Depositional Setting
inner Ramp
Mid Ramp
Sequence Stratigraphy
Global Cycle
local Cycle
System Tracts
Surfaces
Eustatic Curve
Haq et al. (1987)
Meters (m)
200 150 100 50 0
Early Eocene
Chorgali Formation
TA2
3rd Order Cycle
TST 3
HST 3
TST 2
HST 2
TST 1
HST 1
TS
MFS
TS
MFS
TS
Distal inner to proximal middle ramp
Proximal inner ramp
Distal inner ramp
Proximal middle ramp
NS1
NS2
NS3
NS4
NS5
NS6
NS7

◀**Fig. 17** Stratigraphic log of Nathia Gali section displaying variable lithology, microfacies distribution, depositional environments, sequence stratigraphy, and eustatic curve. Blue color line shows long term global eustatic changes and dark yellow colour line shows short term global eustatic changes. *HST* High Stand System Tract, *TST* Transgressive System Tract, *MFS* Maximum Flooding Surface, *TS* Transgressive Surface

from the Eocene deposits of Salt Range (Hussain et al. 2021; Fahad et al. 2021). In Potwar and adjacent Kohat areas, during the Early Eocene, the open continental shelfal condition transitioned into a shallow marine setting which triggered the western part of the Potwar Basin into sabkha while toward east shallow water carbonate was deposited. Based on the constructed microfacies and abundant allochemical components, the Chorgali Formation represents deposition in proximal inner ramp to proximal mid ramp (Fig. 15) which signifies the foraminiferal dominated carbonate ramp model of (Read et al. 1985). LBFs are considered as a tool to demonstrate the models of paleo-environments linked with shallow warm water environment (Geel 2000) and can be used as a proxy for facies interpretations (Rasser et al. 2005). The Paleogene preserved abundant of LBFs of carbonate platforms (Banerjee et al. 2018). The middle ramp environment support Nummulites accumulation with significant sediment productions (Pomar 2001; Barattolo et al. 2007). The occurrence of Lockhartia specify inner to middle ramp enviroment (Racey 1994). The significant Assilina platforms strongly match into the deeper photic zone (Racey 1994; Zamagni et al. 2008). The carbonate depositional model of Chorgali Formation is barren from any kind of high-energy facies (Khatibi Mehr and Adabi 2014; Hussain et al. 2021). The abundant of LBF like Assilina, Nummulites, Lockhartia, Alveolina, Discocyclina and the completely absence planktonic foraminifera represent their deposition in shallow environment as these planktonic foraminifers characterizes open marine pelagic water conditions (Zwaan 1982; Berggren 1986). The coexistence of Nummulites and Assilina show their deposition in deeper inner to middle ramp environment (Buxton and Pedley 1989; Racey 2001; Beavington-Penney and Racey 2004; Vaziri-Moghaddam et al. 2006; Adabi et al. 2008; Payros et al. 2010). In both sections, the occurrence of LBFs reveals tropical to subtropical climate conditions at the time of deposition of Chorgali Formation conversely to other Tethyan carbonate ramps (Buxton and Pedley 1989). As the mud stone is deposited with lots of micrite as cementing material, low energy quiet water environment would be indicated, whereas the wackestone and packstone exhibited a moderate energy environment (Tucker and Wright 1990; Flügel 2004). There is no evidence of a large break in the slope, sand shoals, sedimentation, and no deep-water breccia. Based on the constructed microfacies, ramp setting for the deposition of Chorgali Formation is proposed which supported by the presence of abundant micrite matrix, the absence grainstone facies, complete lack of reef building organisms, re-sedimentation, and slump structures (Khatibi Mehr and Adabi 2014).

Sequence stratigraphy

Sequence stratigraphy is commonly characterized as the "geological history of Stratified rocks" (Emery and Myers 1996). Sequence stratigraphy bridges tectonics, sedimentation, and eustasy (Vail 1987). These factors finally deposit strata in discrete packets known as sequences. Normally, sequences are advanced partitioned into system tracts based on the principle of the bounding sequence stratigraphic surfaces, para-sequence set distributions, and their corresponding location in the framework sequences (Wagoner et al. 1995). A "systems tract" is a link between modern depositional systems, according to (L. F. Brown Jr 1977). In the clastic system, these sequence stratigraphic inherited components are (1) Transgressive-Systems Tract (TST), (2) Low Stand System Tract (LST), and (3) High Stand System Tract (HST) (Emery and Myers 1996; Catuneanu et al. 2009). While Regressive Systems Tract (RST) and Transgressive Systems Tract (TST) are employed for carbonate systems confined on each side by sequence stratigraphic surfaces (Embry and Johannessen 2017). The sequence stratigraphic technique is usually useful for gaining a better understanding of how facies tracts, stratigraphic units, and deposition components interact in the basin interior over time and space. The uses of sequence stratigraphy range from indicating and exploring for economic placer deposits, coal deposits, and petroleum system finding to gaining a better understanding of the earth's geological record from regional to global changes.

Carbonate deposits are more reactive than clastic sediments, hence slight sea level changes caused changes in the chemistry of pore trapped water (Morad et al. 2013). As a result, such sea level variations are undoubtedly related with the distribution of diagenetic modification of carbonate rocks as opposed to clastic rocks (Tucker 1993; McCarthy et al. 1998; Morad et al. 2000). With microfacies analysis and outcrop data, this chapter tries to establish the general framework sequence stratigraphy of Early Eocene Chorgali Formation.

Sequence stratigraphy of Chorgali formation

Two stratigraphic sections (Barian and Nathia Gali) are used in this study to create a framework of sequence stratigraphy for the early Eocene Chorgali Formation in the Hazara sub-basin, NW Himalayan, Pakistan. The sea level curve of the Chorgali Formation is identified by the interpretation of microfacies and outcrop features. The Chorgali Formation was deposited over a 1.5 Ma time range (Muhammad et al. 2022). According to (Embry and Johannessen 2017) the Chorgali Formation is overall located in one 3rd order local cycle and has recorded many 2nd order transgressive and regressive sequences. By comparing the 3rd order local cycle to the (Haq et al. 1987) curve, the 3rd order local cycle can be correlated with TA2.

The Chorgali Formation in the study area has recorded second-order system tracts. In Barian section three Transgressive Systems Tracts (TSTs) and three Regressive Systems Tracts (RSTs) have been identified using microfacies-based depositional environment (Fig. 16). Individual HSTs are significantly thicker than TSTs, and the overall thickness of HST strata is greater than that of TST strata, implying that regressive events and overall sea-level decline last longer than transgression. While in Nathia Gali section the petrographic and outcrop-based research indicated three Transgressive System Tracts (TSTs) and three High Stand System Tracts (HSTs) delimited by maximum flooding surfaces and transgressive surfaces (Fig. 17). Individual TSTS are thicker than individual HSTs.

Correlation with global eustatic curve

The Chorgali Formation was deposited over a period of 1.5 million years (Muhammad et al. 2022). The correlation eustatic curves in (Figs. 16, 17) shows that the sequence stratigraphic model of the Early Eocene Chorgali Formation does not share the same architecture as the global sequence TA2 from (Haq et al. 1987). Local intensive tectonics in the region could explain the mismatch with the global curve. Local tectonics is also supported by the geological features like highly fractured outcrops along with the presence of vertical stylolites.

Conclusion

In the current study, the sedimentological characteristics of carbonate deposits of Eocene Chorgali Formation from Hazara Basin, NW Himalayas, Pakistan were examined and have identified several key findings. The formation represents thin to bedded limestone light grey and dark grey brecciated limestone, intercalated shales, and a brown-grey dolomite unit. The dolomite unit shows butcher chop weathering. On outcrop scale, the observations of veins and fracture filled calcite veins, honeycomb weathering and low to high amplitude stylolite indicates that the formation has undergone through multiple diagenetic stages. The microscopic observations show the occurrences of Larger Benthic Foraminifera, bioclast in the form broken shells of brachiopods and bivalves, framboid and siliciclastic quartz grains. The Larger benthic foraminifera include fifteen age diagnostic species: N. mamillatus, N. atacicus Leymerie, Nummulite Globulus, A. spinosa Davies and Pinfold, A. subspinosa Davies and Pinfold, A. laminose Gill, A. granulosa (d'Archiac), L. tipper Davies, Lockhartia conditi, Alveolina Citrea, Alveolina Sp, Discocyclina Dispensa, Discocyclina Sp 1 and Discocyclina Sp 2. Th identified microfacies represents the occurrence of mainly wackstone facies along with packstone and mudstone facies. Based on these constructed microfacies and the absence of grainstone facies and the complete lack of reef building organisms, re-sedimentation, and slump suggests that the Chorgali Formation is deposited in deeper inner to middle ramp environment. The presence of shallow water and larger benthic foraminifera also supports the early Eocene Chorgali Formation's get deposited in lagoon to open marine environment. The identified microfacies in the vertical sections suggests that the Chorgali Formation is in 3rd order local cycle and has recorded many 2nd-order transgressive and regressive cycles based on sea level variations. The current sea-level curve deviates from the established global scheme, indicating the influence of intense local tectonics. From both field observations and microscopic analysis, it is evident that diagenetic process like dissolution, dolomitization, and fracturing enhance reservoir quality, while dissolution and fracturing following by calcite cementation calcite cementation reduced porosity and permeability.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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