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Integrated paleoenvironmental, bio- and sequence-stratigraphic analysis of the late Thanetian Lockhart Limestone in the Nammal Gorge section, western Salt Range, Pakistan

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Abstract

The paleodepositional system dynamics of the Lockhart Limestone are elucidated in the Western Salt Range with the help of microfacies analysis. Three facies associations are recognised in downslope, along a distally steepened carbonate ramp platform. These facies associations correspond to inner ramp, middle ramp and ramp slope settings. The age-diagnostic foraminiferal species recognized consisted of *Miscellanea miscella*, *Ranikothalia sindensis*, *Discocyclina ranikotensis*, *Alveolina vredenburgi* and *Assilina dandotica*. Based on this larger foraminiferal assemblage a Late Thanetian age has been assigned to the Lockhart Limestone. The biostratigraphy implies that ramp carbonates were deposited in a single third order depositional cycles in a high stand systems tract.

Keywords: Thanetian; Lockhart limestone; Carbonate ramp; Salt Range; Foraminifera.

1. Introduction

Davies (1930) used the term “Lockhart Limestone” for the Paleocene limestone unit in the Kohat area and has been extended by the Stratigraphic Committee of Pakistan to similar units in other parts of the Potwar and the Hazara areas. This unit thus represents the “Nummulitic Series” of Middlemiss (1896), the “Khairabad Limestone” of Gee (1934) has been well-studied for the local biostratigrahic and sedimentolgical investigations (Sameeni and Butt, 1992; Afzal et al., 2011; Hanif et al., 2013; Imraz et al., 2013). However, the unit lacks integration of the biostratigraphical and sedimentological data for sequence stratigraphic analysis. The use of microfacies analysis aided with the outcrop and constituent fossils assemblages in the Lockhart Limestone yielded sufficient information about paleoenviroments, sea level changes and construction of sequence stratigraphic framework.

2. Tectonic setting of the Salt Range

The under thrusting of the Indian Plate beneath the Eurasian Plate gave rise to many conspicuous tectonic features around the northern and northwestern peripheries of the Indian Plate. As a result of this under thrusting, spectacular mountain ranges of the Himalaya and a succession of foreland fold-and-thrust belts were created (Kazmi and Jan, 1997). The northward under thrusting of the Indian Plate constitutes the major tectonic fabric of north Pakistan that includes the Main Karakorum Thrust (MKT), Main Mantle Thrust (MMT), Main Boundary Thrust (MBT) and the Salt Ranges Thrust (SRT) (Fig.1). The SRT is the southernmost thrust zone along the foothills of Salt and Trans-Indus Ranges and is largely covered by the Quaternary alluvium and conglomerates (Kazmi and Jan, 1997). However, in places the thrust is exposed and shows the Palaeozoic rocks overlying Neogene or Quaternary deposits of the Jhelum Plain (Gee, 1945).

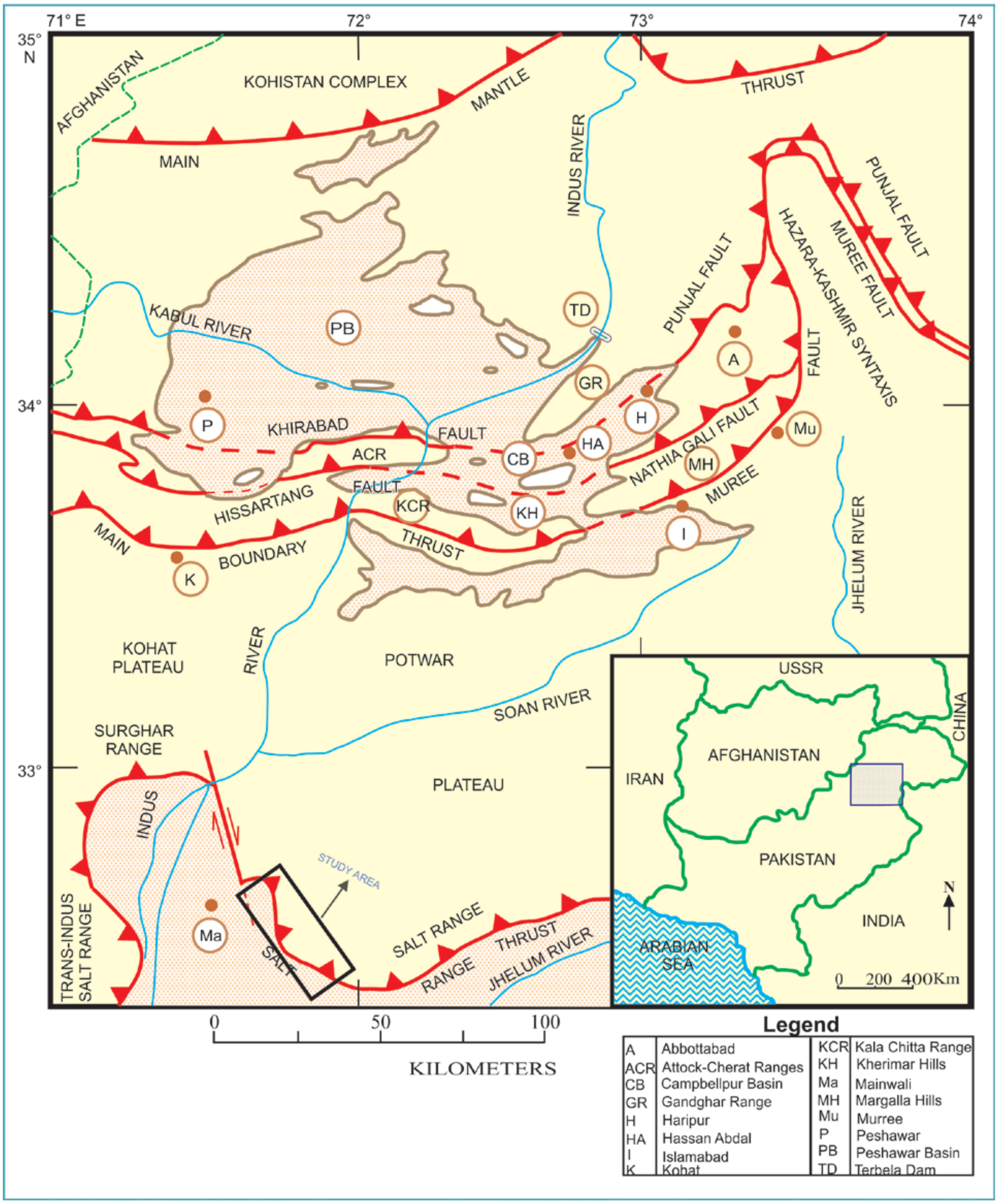


Fig. 1. Tectonic map of northern Pakistan, showing major structural boundaries, plateaus and geomorphological features, inset shows the study area (modified after Halland et al., 1988).

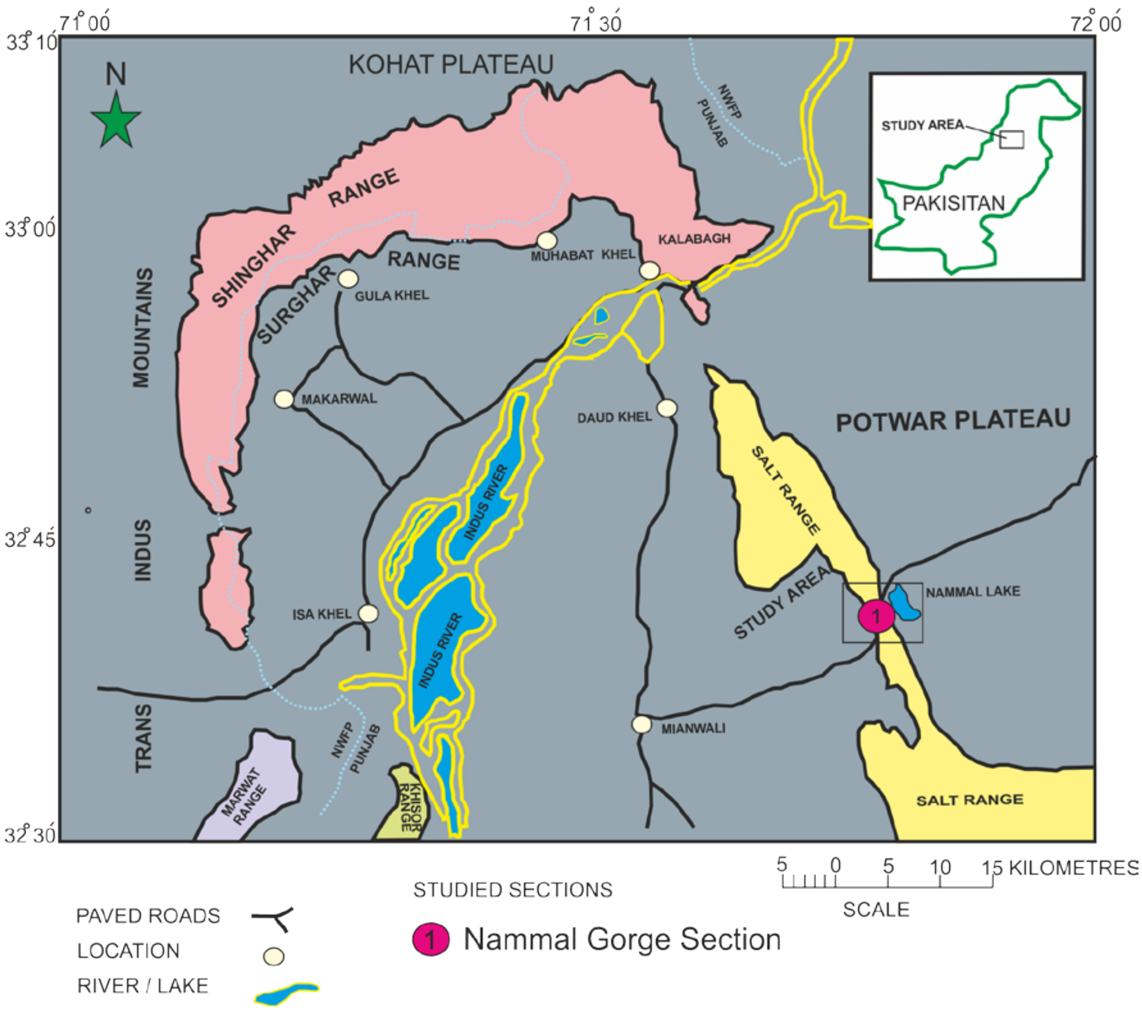


Fig. 2. Location map of the Nammal Gorge Section, Western Salt Range, Pakistan (modified after Ahmad, 2010).

3. Material and methods

The study area includes the Nammal Gorge Section in the Western Salt Range (Fig. 2). The stratigraphic thickness of the Lockhart Limestone was measured and 10 rock samples were collected for biostratigraphic and microfacies analysis. The rock thin sections were prepared for microfacies analysis and individual fossils tests/shells identification. The first and last occurrences of the age diagnostic species of foraminifera were used to establish biozonal boundaries. The microfacies analysis represents the allochem types, matrix, textural features and fossils content. The abundance, type, size and paleoecology of the foraminifera, brachiopods, bivalves, gastropods, echinoids, ostracodes, algae and non-skeletal components (peloids and intraclasts), provided valuable information for the interpretation of depositional environments. The limestone calssification scheme of Dunham (1962) was practiced because of its practical and easy to use nature (Table 1). The integration of outcrop, paleoenvironmental and biostratigraphical data was used to establish sequence stratigraphic framework of the Lockhart Limestone.

4. Results

4.1. Facies and paleoenvironments

The microfacies of the Lockhart Limestone in this study are abbreviated as LKF 1 to LKF 4 (LK stands for the Lockhart Limestone, F stands for microfacies and 1-4 are various types of the recorded microfacies). The three facies associations and their constituent microfacies are explained as follows;

4.1.1. Inner ramp facies

Algal foraminiferal wackestone-packstone microfacies (LKF 1)

The LKF 1 microfacies is represented by grey colour limestone in the lower part of the Lockhart Limestone. Under microscope, the LKF 1 microfacies is characterized by wackestone-packstone texture. The biogenic content is well preserved. The allochemical constituent ranges in abundance from 40-80 %, with an average of 60%. The microfloral components are dominated by calcareous green algae with an abundance that ranges from 40-60 % of the total allochems. The micritic matrix dominates and its abundance ranges from 25-45 % with an average of 30 %. The identified algal flora includes *Ovulites arabica*, *Ovulites margaritula* and *Ovulites elongata*. Mass accumulations of the algal thali segments show partial to complete internal micritization (Fig. 3A). Well preserved foraminiferal species of *Miscellanea miscella*, *Alveolina vredenburgi* (Fig. 3B), *Nummulites deserti* (Fig. 3C), *Assilina spinosa*, *Alveolina globula* and *Lockhartia haimei* are identified. Subordinate occurrence of bioclastic invertebrate fauna includes brachiopods (1-3 mm size range), ostracodes (2-3 mm size range), and small boring gastropods (< 2 mm size). Most of the grains have poor- to moderate-sorting and do not show any preferred orientation. The diagenetic fabric is characterized by microbial micritization, neomorphic alteration and presence of micro fractures, filled with sparry calcite (Fig. 3A). The LKF1 microfacies is characterized by intergranular, moldic and fracture type porosities.

Table 1. The petrographic constituents of the Lockhart Limestone exposed in the Nammal Gorge Section.

Thin section #	Miscellanea %	Algae %	Lockhartia %	Milliolid %	Discocyclina %	Ranikothalia %	Assilina %	Operculina %	Bioclasts %	Gastropods %	Echinoderms %	Orbititadea %	Uniserial+Biserial %	Bivalves %	Grain %	Matrix %	Grain : Matrix	Classification	
																		Folks (1962)	Dunham (1962)
NG 02	05	05	03	-	-	-	-	-	35	-	-	-	-	-	48	52	1:1	Biomicrite	Wacke-Packstone
NG 03	06	15	05	02	01	-	-	-	22	-	-	-	01	01	53	47	1:1	Biomicrite	Packstone
NG 04	07	09	08	02	03	01	02	-	20	-	-	-	02	02	56	44	1:1	Biomicrite	Packstone
NG 05	10	12	03	01	02	-	-	02	20	-	-	-	04	03	57	43	1:1	Biomicrite	Packstone
NG 06	12	09	02	-	01	-	-	-	08	-	-	-	01	03	36	64	1:2	Biomicrite	Wackestone
NG 07	06	04	03	01	-	01	-	02	17	-	-	-	-	03	37	63	1:2	Biomicrite	Wackestone
NG 08	10	14	05	02	02	-	01	-	18	02	01	-	02	02	59	41	1:1	Biomicrite	Packstone
NG 09	14	11	06	01	01	-	02	-	10	-	-	-	01	02	48	52	1:1	Biomicrite	Packstone
NG 10	07	12	03	-	01	-	03	-	20	-	-	-	01	05	52	48	1:1	Biomicrite	Packstone
NG 11	12	05	04	-	-	-	04	01	19	-	01	-	01	05	54	46	1:1	Biomicrite	Packstone

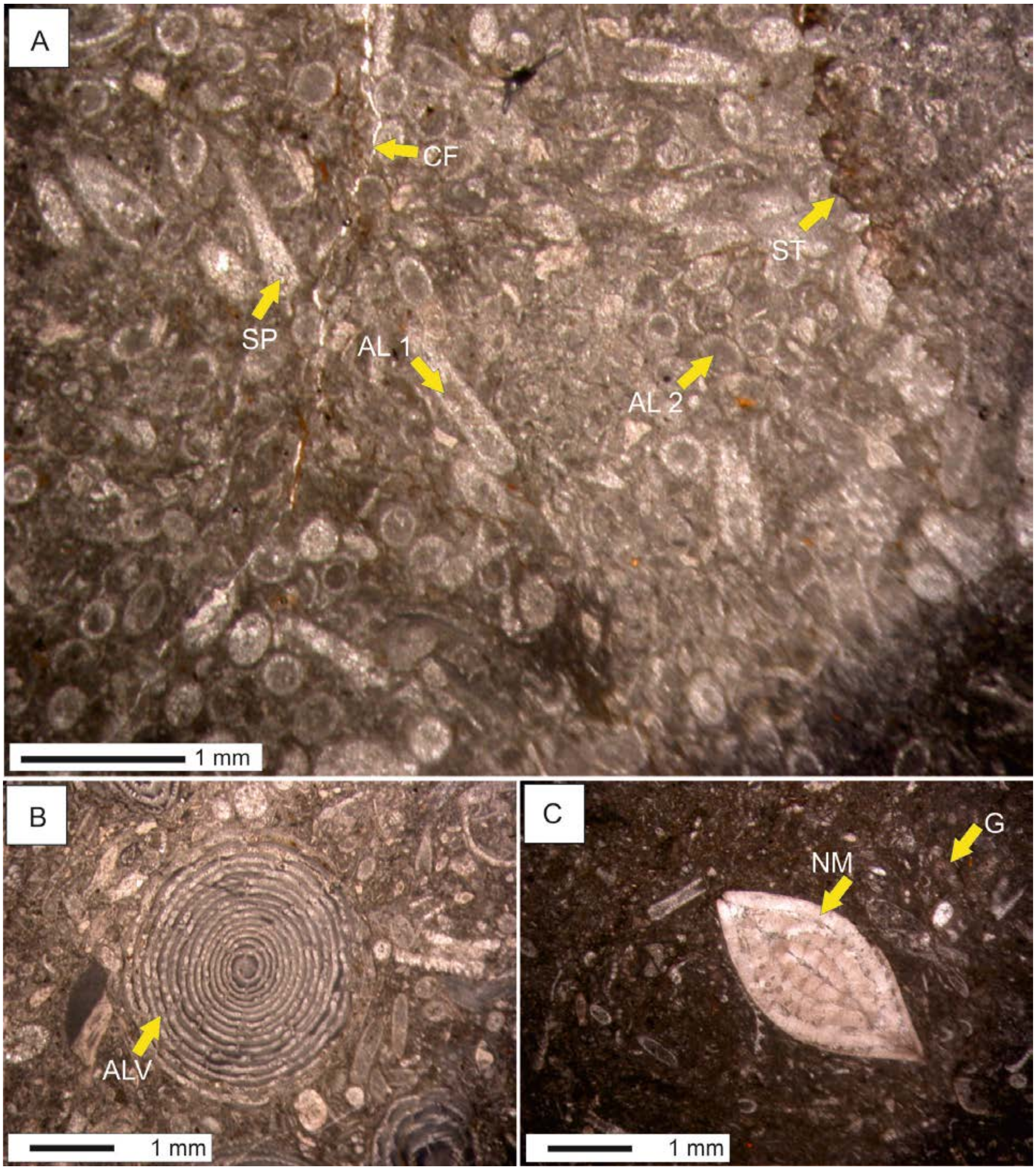


Fig. 3. Algal foraminiferal wackestone-packstone Microfacies (LKF 1): The allochems are represented by Algae include *Ovulites arabica* (AL1, AL2), Alveolina ALV, *Nummulites* (NM) and small gastropods (G). The diagenetic fabric is shown by stylolites (ST), and coarse spar formed by aggrading neomorphism within calcite filled fracture (CF).

Depositional environment

The LKF 1 microfacies show moderate floral and faunal diversity. The *Dasycladacean* algae is reported to occur in warm water, not more than few meters deep and is more common between depths of 12-15 meters of restricted circulation. In the fossil record, Alveolina is found in association with Nummulites and Orbitolites in the Eocene Jdeir Formation of offshore Libya, representing a back ramp environment (Anketell and Mirheel, 2000).

The impoverished assemblage of the gastropods is responsible for the mixing of sediments (Flügel, 2004). The presence of lime mud matrix indicates low energy conditions.

Based on textural relationship, paleoecology and restricted faunal assemblage this microfacies is interpreted to have been deposited in a shallow subtidal environment of the distal inner ramp setting.

Alveolina rich bioclastic wackestone-packstone microfacies (LKF 2)

The LKF 2 microfacies is represented by grey to yellowish grey colour fossiliferous limestone. Under the microscope, the LKF 2 microfacies is characterized by a wackestone-packstone texture, having abundant allochems ranging in abundance from 40-70 %, with an average of 55 %. Among the allochems alveolinid foraminifera dominate with good biogenic preservation (Fig. 4A). Other foraminiferal species include milliolids (Fig. 4B) and Lockhartia *pustulosa* (Fig. 4D). The foraminiferal tests show partial to complete micritization (Fig. 4E) and silicification of the internal chambers. Gastropods are the second most abundant allochems ranging in size from 0.5 - 2 mm with burrowing and boring modes (Figs. 4A-4B). The grains are poorly sorted and do not show preferred orientation. The micritic matrix ranges in abundance from 20-50 %, with an average of 30 %. Sparry cement fills the intergranular spaces (Fig. 4A). The diagenetic fabric is characterized by neomorphism, chemical compaction, calcite- filled fractures and stylonodular fabric. The LKF 2 microfacies shows intergranular, vuggy, moldic and fracture type porosity (Figs. 4A-4C and 4E).

Depositional environment

The Alveolina is reported from the shallow shelf between 5 - 75 m water depth range in the Sesoko Island, Japan (Hohenegger et al., 1999) and at 3 – 50 m depth range from the reef base on hard substrate in the SW Sulawesi, Indonesia (Renema and Troelstra, 2001). It is also reported associated with milliolids and Orbitolites from the shallow protected inner ramp settings of the Pyrenean Basin (Luterbacher, 1998). Species of milliolids prefer low turbulence and soft substrate and their high abundance indicates saline to hypersaline, nutrient rich back reefs/ramps and restricted lagoonal setting. Their abundance also indicates connection to the open ocean shallow lagoons and fore reef. The co-occurrence of abundant *Alveolina* sp., milliolid and gastropods in the LKF 2 microfacies reflects deposition in the shallow-water, low-energy restricted conditions of the proximal inner ramp settings.

4.1.2. Middle ramp facies

Diverse benthic foraminiferal wackestone-packstone microfacies (LKF 3)

In the study area, the LKF 3 microfacies is represented by grey colour nodular limestone. Under the microscope, the LKF 3 microfacies is characterized by wackestone-packstone texture. The biogenic content is well-preserved having a rich allochemical constituent of larger benthic foraminifera ranging in abundance from 50-70 %, with an average of 55 %. The identified foraminiferal species are *Discocyclina ranikotensis*, *Miscellanea miscella*, *Operculina salsa*, *Lockhartia haimei*, *Nummulites pinfoldi*, *Ranikothalia sindensis*, *Assilina spinosa* and *Alveolina globula* (Figs. 5A-5E). The size of these foraminiferal bioclasts ranges from 2 - 5 mm. The micritic matrix abundance ranges from 30-60 %, with an average of 45 %.

The matrix has shown evidence of bioturbation and burrowing of small gastropods. The brachiopod bioclasts (~ 5 mm in size) show partial to complete internal micritization and only the outline were preserved forming a ghost structure (Fig. 5E). The diagenetic fabric is characterized by chemical compaction that resulted in the stylonodular fabric (Fig. 5C), neomorphic alteration and spar -filled fractures (Fig. 5D). The LKF 3 microfacies is characterized by the moldic, intergranular, fracture and intragranular porosities (Figs. 5A-5E).

Depositional environment

Nummulites live in shallow waters both in the inner and outer platform or ramp settings (Flügel, 2004) and occur at a depth of 20-130 m (Reiss, 1977). *Miscellanea miscella* indicates a warm shallow water environment (Levin, 1957). The Discocyclina represents normal marine conditions, found slightly deeper than *Assilina* but shallower than *Operculina.* When it is found associated with *Alveolina* and milliolids this represents the back reef environment. This microfacies is characterized by the presence of diverse fauna and lime mud as a matrix. A variety of fauna displayed by this microfacies include foraminifera, bivalves and rare dasycladacean algae. The presence of diverse foraminiferal assemblages indicates open conditions of normal marine salinity. Micritic matrix is evident for deposition under low energy conditions. The paleoecology of the foraminifera, absence of restricted marine fauna and matrix supported rock fabric suggest that the LKF 3 microfacies was deposited in distal middle ramp settings.

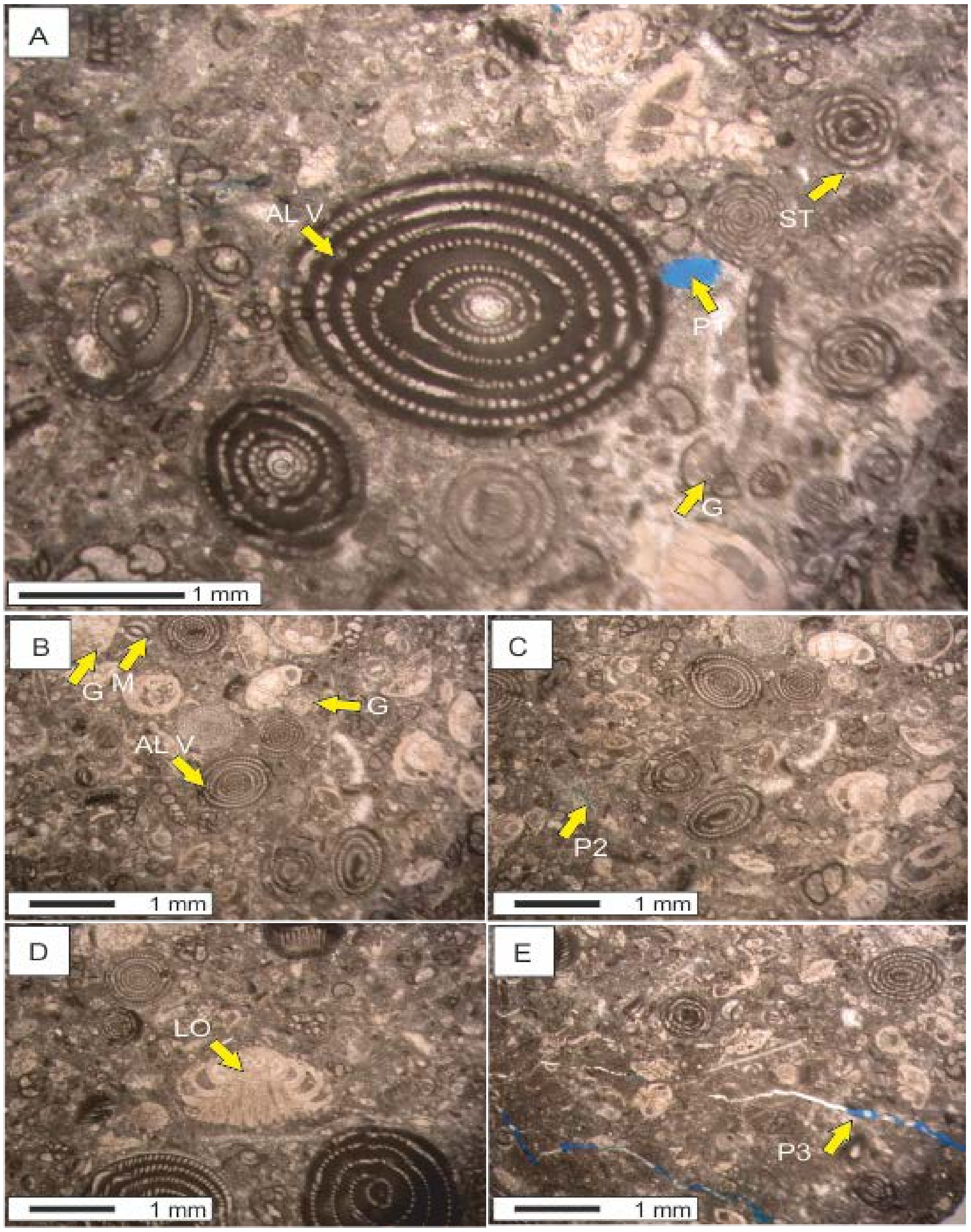


Fig. 4. Alveolina rich bioclastic wackestone-packstone Microfacies (LKF 2): The allochems of LKF 2 include larger benthic foraminiferal species of *Alveolina globula* (ALV), Lockhartia (LO), milliolid (M), and gastropods (G) in micritic matrix. The diagenetic fabric shows low amplitude stylolites (ST), and coarse sparry cement. The P1-P3 porosities are also shown.

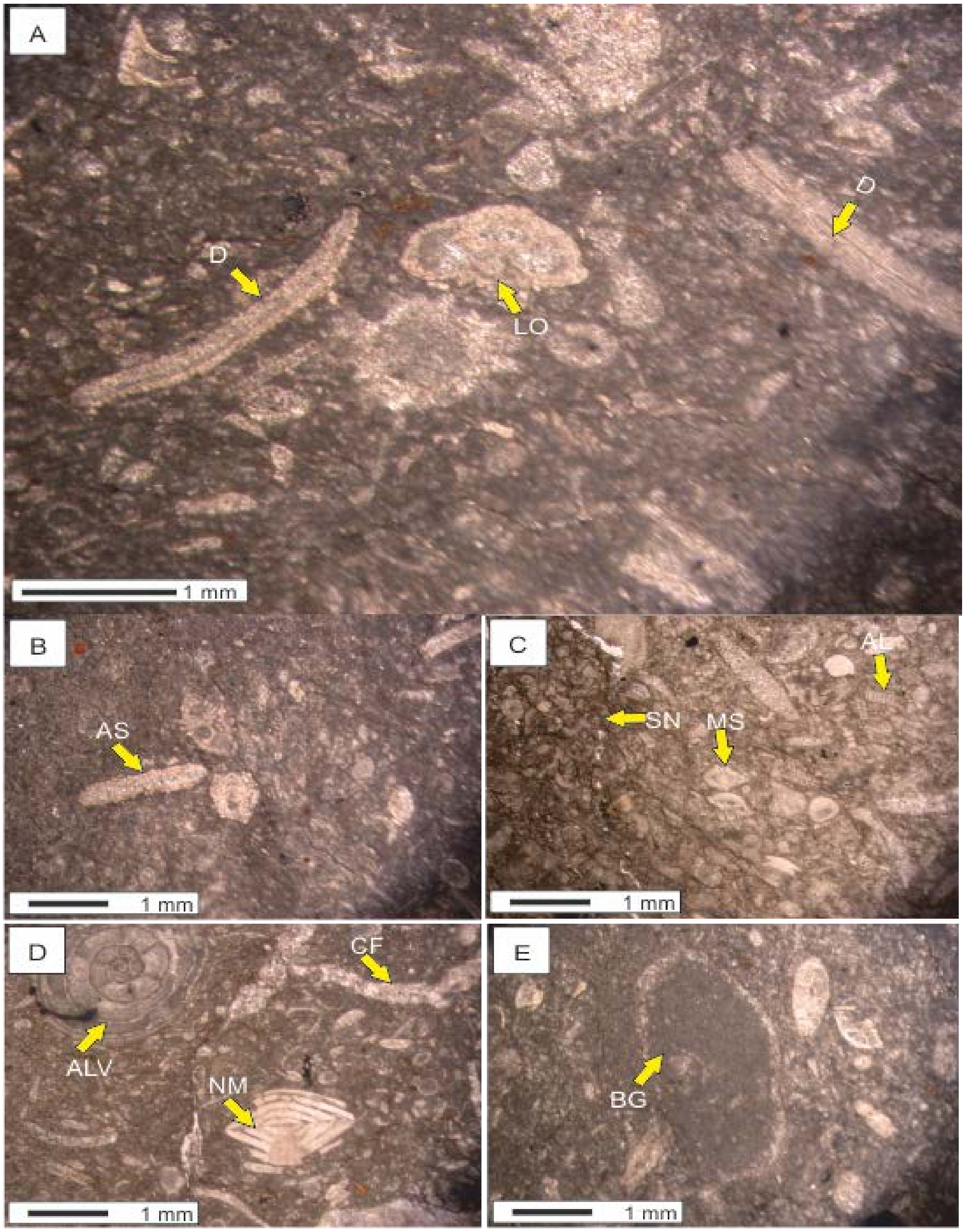


Fig. 5. Diverse benthic foraminiferal wackestone-packstone Microfacies (LKF 3): The allochems of the LKF 3 microfacies include *Discocyclina ranikotensis* (D) Lockhartia (LO), *Assilina spinosa* (AS), *Miscellanea stampi* (MS), *Nummulites pinfoldi* (NM), *Alveolina globula* (ALV) and Algae (AL). The diagenetic fabric is characterized by the stylonodular fabric (SN), complete internal micritization of brachiopod shell forming ghost structure (BG), post depositional spar filled fractures (CF) and neomorphic spar replacement of bioclasts (LO and AS).

4.1.3. Ramp slope facies

Planktic-benthic mixed foraminiferal lime mudstone-wackestone microfacies (LKF 4)

In the study area, the LKF 4 microfacies is represented by thin-bedded, grey nodular limestone. Under the microscope, the LKF 4 microfacies is characterized by a lime mudstone-wackestone depositional textures. A well-preserved biogenic content is seen, containing both planktic and benthic foraminifera. The abundance of the allochems ranges from 10–30%, with an average of 18%. Species of the larger benthic foraminifera include *Ranikothalia sahini* (Fig. 6B), *Operculina salsa*, *Miscellanea miscella* and *Discocyclina ranikotensis*, having an abundance range of 30-45% of the total allochems. The planktic foraminifera include genera of *Globorotalia*, *Globigerina* and *Planorotalites* and their abundance ranges from 10 to 20 % of the total allochems. Some planktic foraminiferal tests show silicification and internal micritization of the chambers (Fig. 6A). The micritic matrix dominates and ranges in abundance from 60-90 %, with an average of 75%. The diagenetic fabric is characterized by neomorphic alteration, planer to wavy grain contacts, stylolites with iron oxide residue and calcite filled fractures showing post depositional deformation (Fig. 6C). The LKF 4 microfacies has intragranular and fracture type porosities.

Depositional environment

Larger benthic foraminifera have been the major constituents of shallow marine shelf carbonates formed in warm waters since the late Paleozoic time (Flügel, 2004). Planktic foraminifera are the dwellers of upper 400m column of open ocean waters and in modern marine settings they become more abundant seaward (Tucker and Wright, 1990) and their greatest abundance occurs in depths > 200m. During normal conditions planktic to benthic ratio increases as the water depth increases (Murray, 1973). The productivity of planktic foraminifera is higher in open pelagic waters and that of benthic foraminifera is higher in shallow neritic environment (Van der Zwann, 1982; Van Morkhoven et al., 1986). Globigerinids are more resistant to solution and can survive at a depth of >500m (Parker, 1971; Milliman, 1974). The matrix of this microfacies is composed of micrite which indicates generally low energy sub-tidal environment below fair-weather wave base conditions (Flügel, 2004). On the basis of faunal paleoecology and presence of micrite matrix and the depositional texture of this microfacies, it is interpreted that LKF 4 microfacies was deposited in a low energy ramp slope-outer ramp settings.

4.2. Depositional model, bio- and sequence stratigraphy

The facies analysis of the Lockhart Limestone indicates that the proximal inner ramp settings were dominated by algal meadows, milliolid foraminifera and small gastropods, resulting in algal-foraminiferal mixed bioclastic wackestones and packstones. The Alveolina rich algal-foraminiferal wackestone-packstone facies representing the proximal inner ramp changes to the bioclastic wackestone-packstones facies of the distal inner ramp in the offshore direction. The proximal middle ramp was essentially covered by diverse assemblages of larger benthic foraminifera (*Ranikothalia* sp., *Alveolina* sp. and *Assilina* sp.) and invertebrate fauna (brachiopods and gastropods). The diversity of the foraminifera is further increased in the distal middle ramp setting, where *Discocyclina*,*Operculina* and *Ranikothalia* species dominate. The upper slope facies consists of planktic-benthic mixed foraminiferal wackestones-packstones with evidence of slumping and turbidity movements. Resedimented *Discocyclina* tests are found in the planktic foraminiferal mudstones-wackstones. An ecologically distinct fauna is encountered in the middle slope setting and includes ostracodes, bivalves and those foraminifera having middle ramp affinity. Hanif et al. (2013) proposed a homoclinal ramp model for the Lockhart Limestone in the Nammal Gorge, but the absence of continuous reefal build ups, scarcity of reef forming organisms and presence of slope facies within the Lockhart Limestone (Fig. 7) is consistent with the distally steepend carbonate ramp models of Burchette and Wright (1992) and Flügel (2004).

In the Upper Indus Basin, Afzal et al. (2011) and Hanif et al. (2013) have identified SBZ 3 Biozone within the Lockhart Limestone however in this detailed study local biozones BF1 is recognized (Fig. 8) which corresponds to SBZ4 and SBZ5 of Serra-Kiel et al. (1998) and representing younger age. The base of BF 1 Biozone is taken at the first occurrence of *Ranikothalia sindensis* and the top is taken at the synchronous first occurrences of *Assilina dandotica* and *Discocyclina despensa.* Age of this biozone is Late Paleocene (Serra Kiel, 1998) (Late Thanetian).

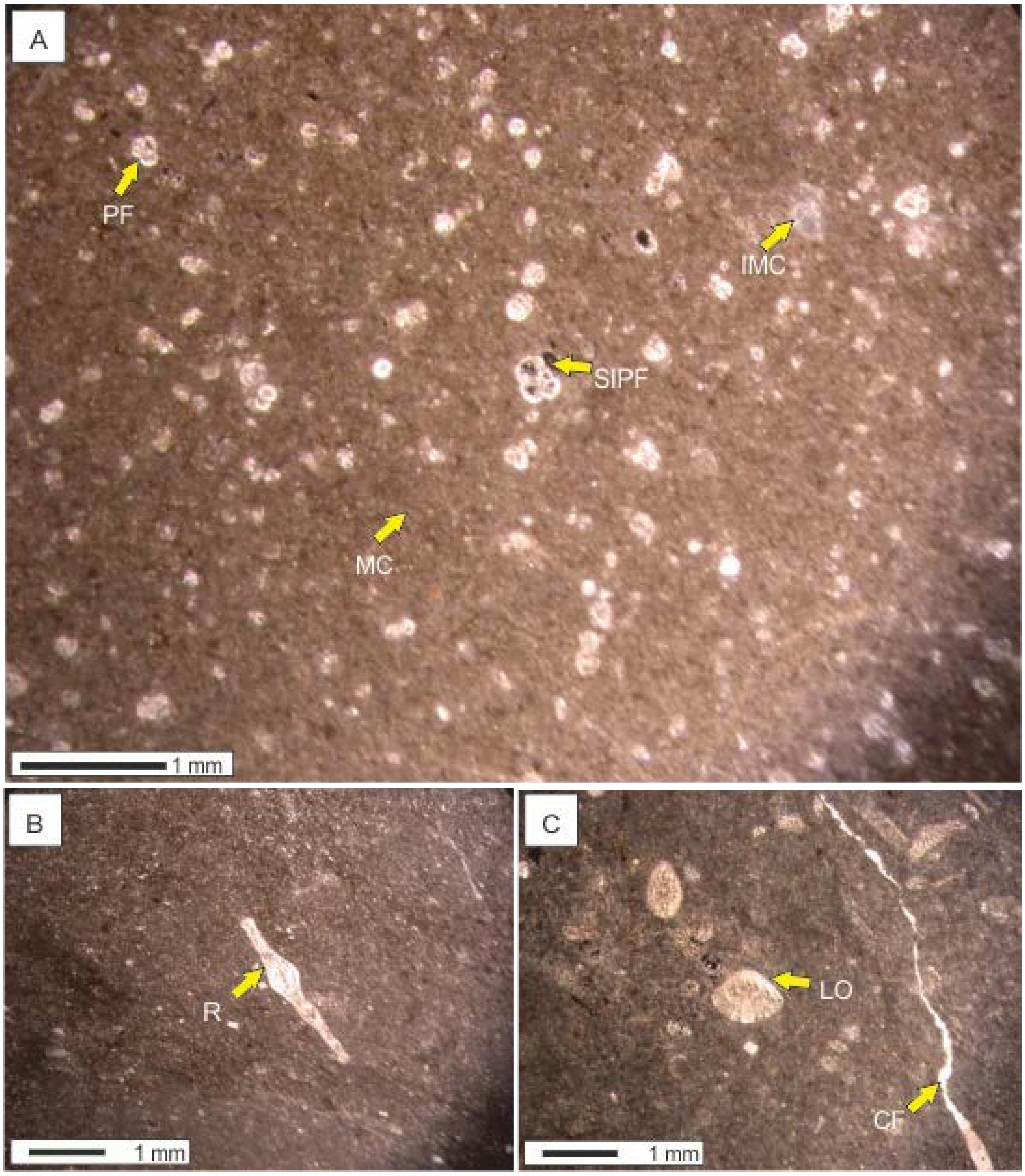


Fig. 6. Planktic-benthic mixed foraminiferal lime mudstone-wackestone microfacies (LKF 4): The allochems of the LKF 4 microfacies include planktic foraminifera (PF), benthic foraminifera i.e. *Ranikothalia sahini* (R) and *Lockhartia conditi* (LO). The diagenetic fabric is characterized by complete internal micritization (IMC) and silicification (SIPF) of the planktic foraminiferal test and spar filled fractures (CF).

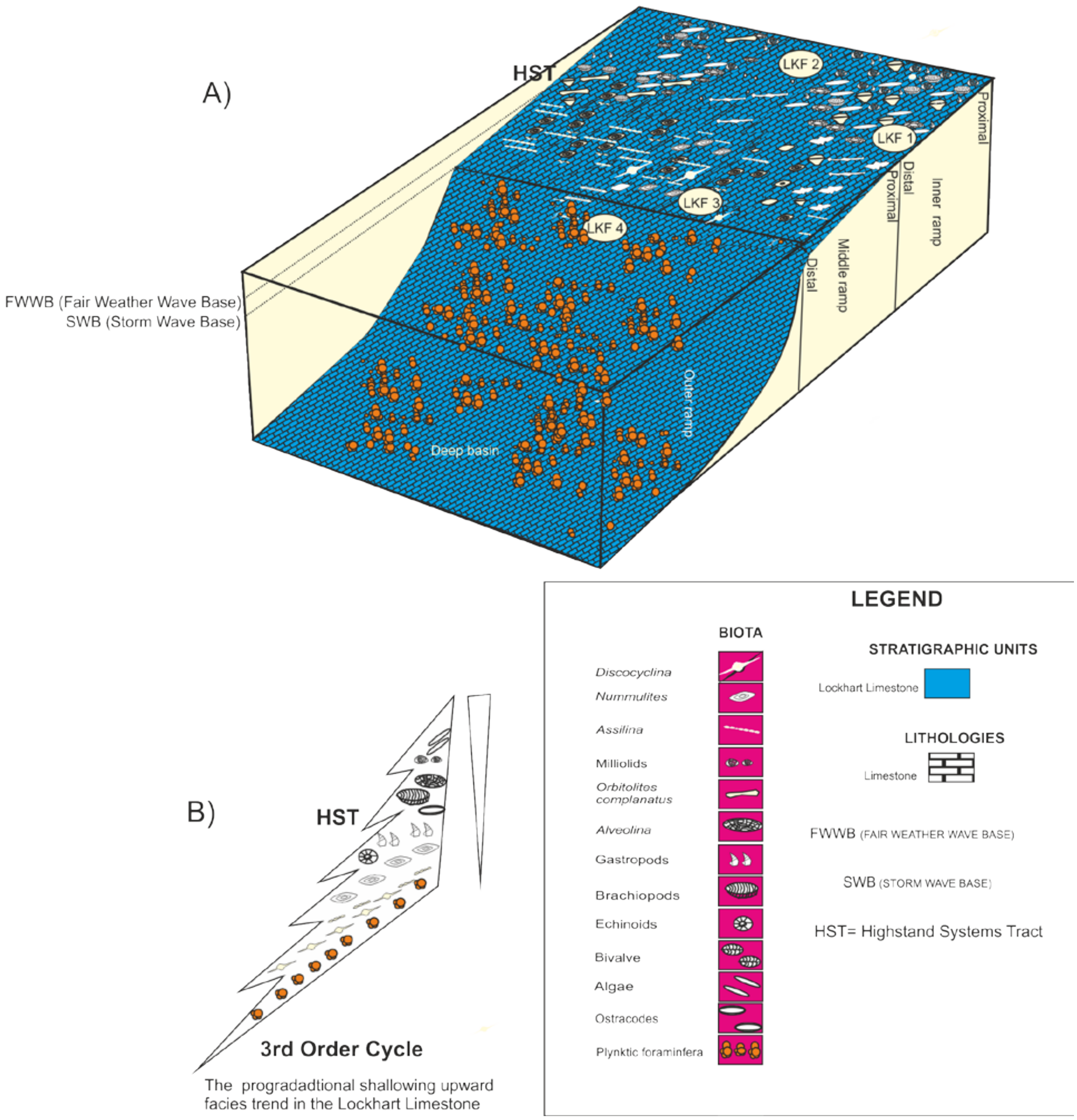


Fig. 7. A) The depositional setting of the Lockhart Limestone is consistent with the ramp platform showing the paleoecology of the fauna and the distribution of the LKF1-4 facies deposited in a Highstand Systems Tract (HST). B) The 3rd order depositional cycle is marked on the basis of biostratigraphy and the shallowing upward facies signature is based on the diagnostic paleoecology of the foraminifera and associated invertebrate fauna (Legend shows the symbols used).

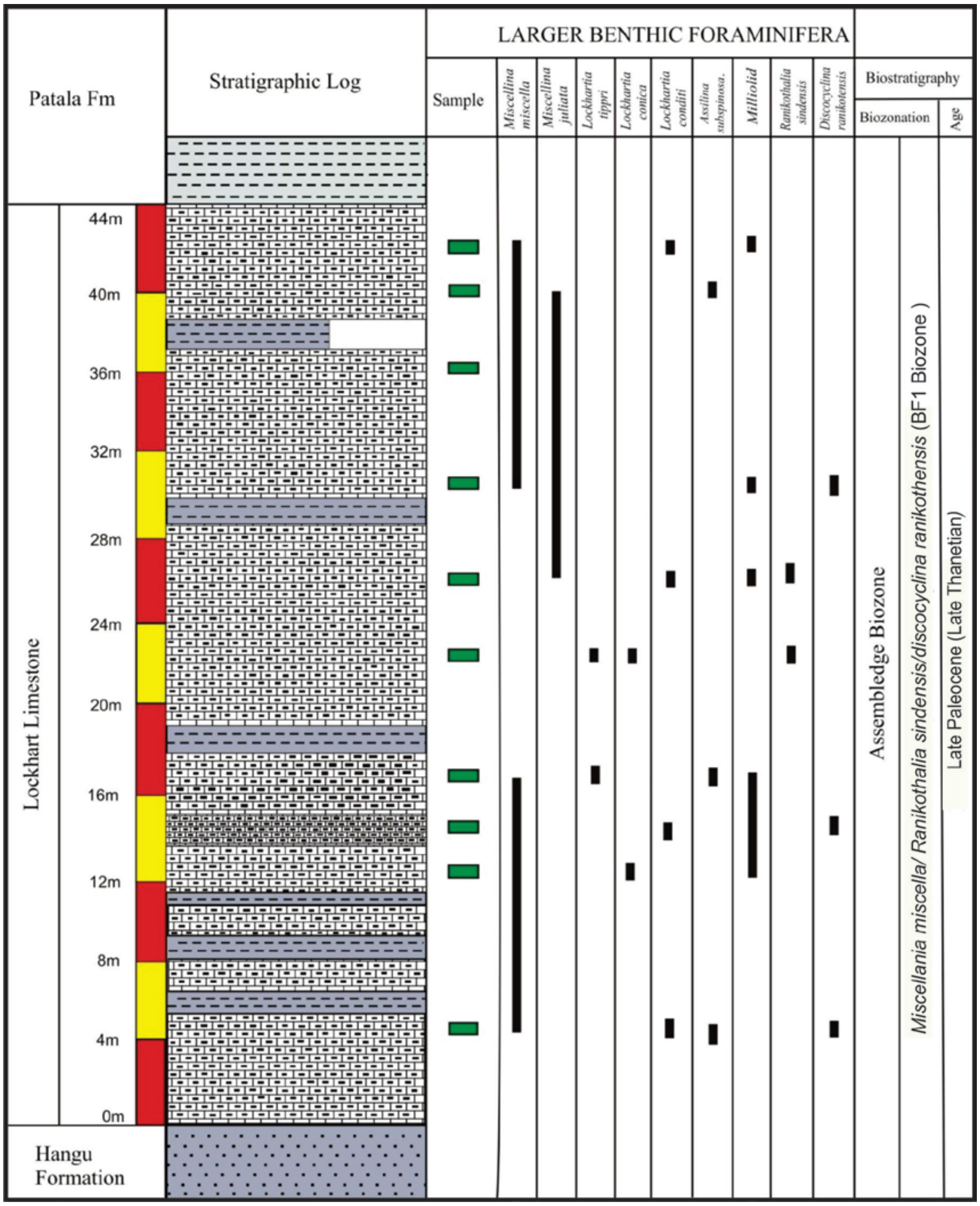
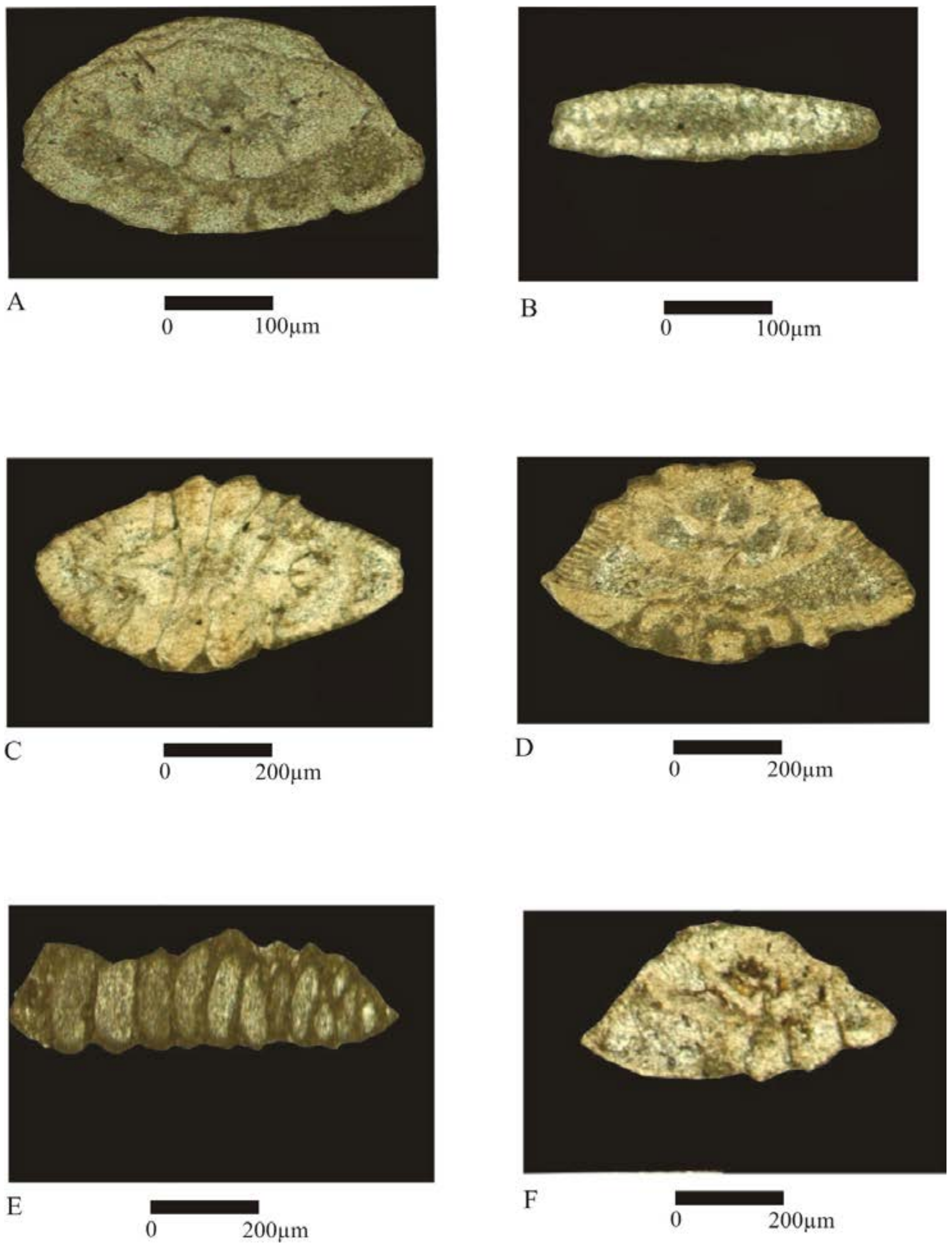


Fig. 8. Schematic columnar section, vertical range distribution of selected larger benthic foraminifera and biozonation of the Lockhart Limestone exposed in the Nammal Gorge Section.

The elaborated sequence stratigraphic model in present study details the systems tract with emphasis on its sedimentological and paleontological characterization. The biostratigraphy implies that deposition of the Lockhart Limestone in the study area span in a third order depositional sequence comprising of a highstand systems tract (Figs. 7A-7B). A diverse age and depth diagnostic foraminiferal fauna that characterizes the topsets of the HST includes *Ranikothalia sindensis*, *Ranikothali nuttali*, *Miscellanea miscella*, *Lockhartia*, *Miscellanea stampi*, *Operculina salsa*, *Operculina subsalsa*, *Discocyclina ranikotensis*, *Discocyclina*

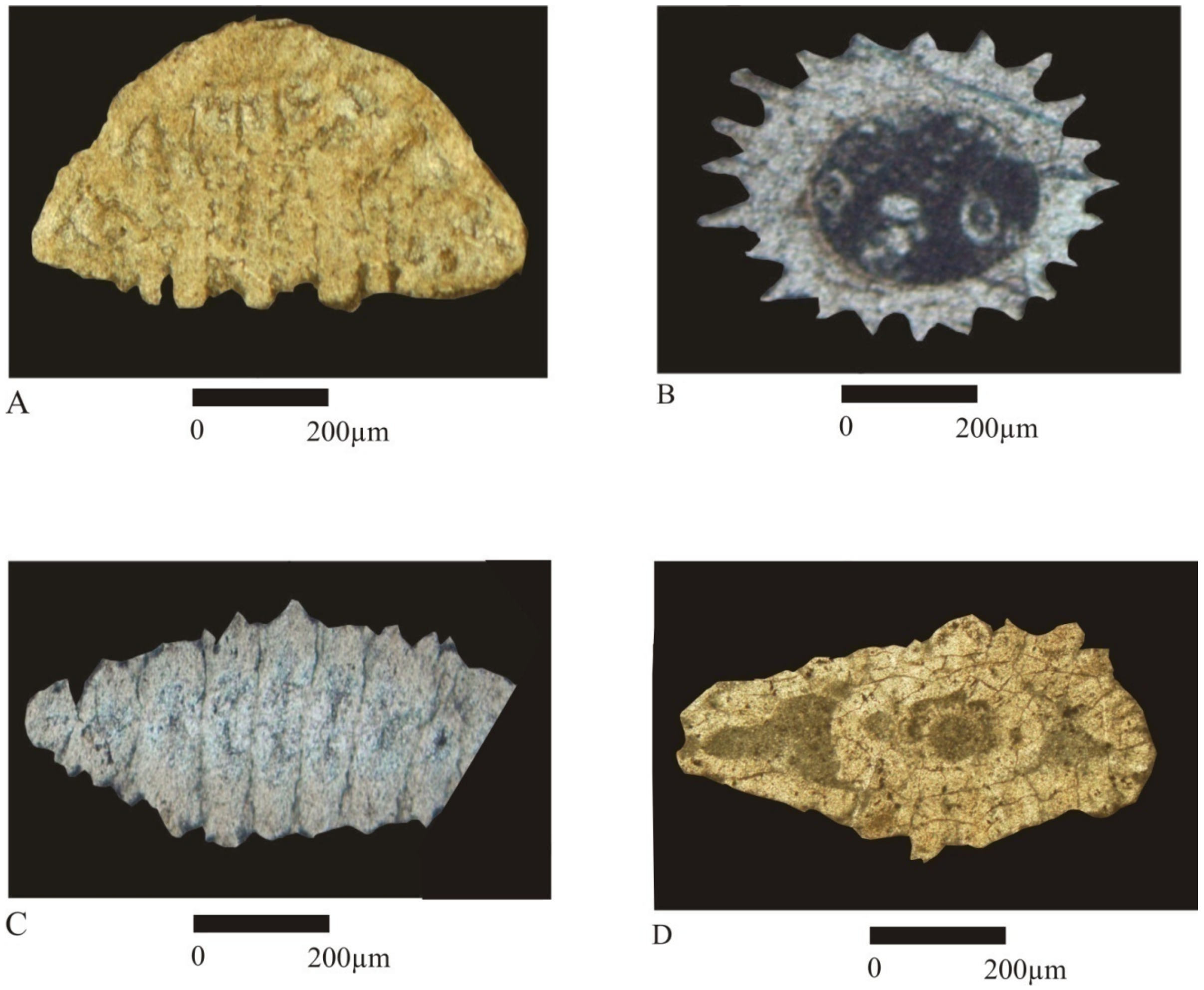
Seunesi, *Operculina petalensis*, *Assilina spinosa, Nummulites lahiri*, *Nummulites thalicus*, *Nummulites pinfoldi*, *Alveolina vredenburgi*, *Alveolina pasticlata*, *Alveolina conradi* and *Alveolina globula* (Fig. 7A). The shallow-marine rampal invertebrate fauna (gastropods, pelecypods, brachiopods) and flora (green algae) also accompanied the foraminiferal fauna. The planktic-benthic mixed foraminifera indicate progradation of the shallow benthic formaniniferal fauna in the subtidal, open marine settings of the upper slope environment.

Plate 1



A: Axial view of the *Lockhartia conica*
B: A view of the algae
C: Axial view of the *Miscellanea juliata*
D: Axial view of the *Lockhartia conditi*
E: A view of the uniserial foraminifera
F: Axial view of the *Lockhartia conditi*

Plate 2



A: Axial view of the *Lockhartia tippri*
B: A view of the algae
C: Axial view the *Assilina subspinosa*
D: Axial view of the *Miscellanea miscella*

5. Conclusions

The microfacies, bio- and sequence stratigraphic analysis of the Late Palaeocene (Late Thanetian) Lockhart Limestone at the Nammal Gorge Section in the Western Salt Range, Pakistan resulted in the following interpretations:

1. The Lockhart Limestone predominantly consists of nodular limestone which is dominated by small and large benthic foraminifera with some planktics, gastropods, mollusks and dasycladacean algae.
2. On the basis of detailed petrographic study, four microfacies with distinct textures, allochem type, fossil contents and sedimentary structures are identified
3. Three facies associations are identified which shows deposition in the inner ramp, middle ramp and ramp slope setting of a distally steepened carbonate ramp.
4. Based on *Miscellanea miscella/ Ranikothalia sindensis/Discocyclina ranikotensis* an assembledge biozone BF1 is defined and the Lockhart Limestone is dated as Late Paleocene (Late Thanetian).
5. Based on the biostratigraphy a third order depositional cycle is recognized with a distinctive Highstand Systems Tract (HST) deposition.

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