Journal of Himalayan Earth Sciences Volume 47, No. 2, 2014, pp. 99-114

Microfacies analysis and diagenetic fabric of Lockhart Limestone exposed along Nathiagali-Murree Road, District Abbottabad, Pakistan

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Abstract

The microfacies analysis and digenetic fabric of the Lockhart Limestone (Paleocene age) are studied at two different geological field sections. The study is based on field and laboratory observations. The formation is predominantly comprised of medium to thick bedded, nodular and occasionally brecciated, highly fossiliferous, limestone with thin interbeds of clay/marl.

Four carbonate microfacies are, 1) Algal Foraminiferal Packstone microfacies of inner shelf, 2) Mixed Bioclastic Wacke-Packstone microfacies of middle shelf, 3) Benthic Foraminiferal Wacke-Packstone microfacies of middle-outer shelf and 4) Planktic-Benthic Foraminiferal Wacke-Packstone microfacies of outer shelf. While the diagenetic history is characterized by several diagenetic features of aragonite to calcite transformation, compaction, pressure dissolution (microstylolites), calcite-filled microfractures, development of microspar, micritization and nodularity.

Keywords: Microfacies; Lockhart Limestone; Diagenetic fabric; Depositional fabric.

1. Introduction

The field sections were measured at Touhidabad and Changagali, both the sections are located in the southern part of Abbottabad District (between Latitudes 34°3′N to 34°8′N and longitudes 73°17′E to 73°26′E, and is covered by survey of Pakistan topographic sheet no. 43 F/8), Pakistan (Fig. 1).

The stratigraphic sections in study area are comprised of Cretaceous-Eocene succession including Kawagarh Formation, Hangu Formation, Lockhart Limestone, Patala Formation, Margala Hill Limestone, Chorgali Formation, Kuldana Formation and Plio-Miocene succession of Murree Formation in ascending order.

The noteworthy pioneer work on southern Hazara include the work of Middlemiss (1869), Waagen and Wynne (1872), Gardezi and Ghazanfar (1965), Latif (1973), Calkins and Offield (1975), Coward et al. (1987), Schnellmann and Gnehm (1999). However, the present is aimed to study the skeletal components of Lockhart Limestone, recognize various textural types, and identify microfacies and to study the diagenetic fabric. The petrographic and field data is used to interpret the depositional environments of the Lockhart Limestone.

2. Material and methods

The Lockhart Limestone is mainly composed of limestone of gray color, hard, compact, medium to thick bedded, nodular in nature and marl/shales interbeds. In Touhidabad Section, the lower contact of Lockhart Limestone is conformable with Hangu Formation and the upper contact is not exposed (Fig. 2), while in Changlagali Section both upper and lower contacts are not exposed (Fig. 3).

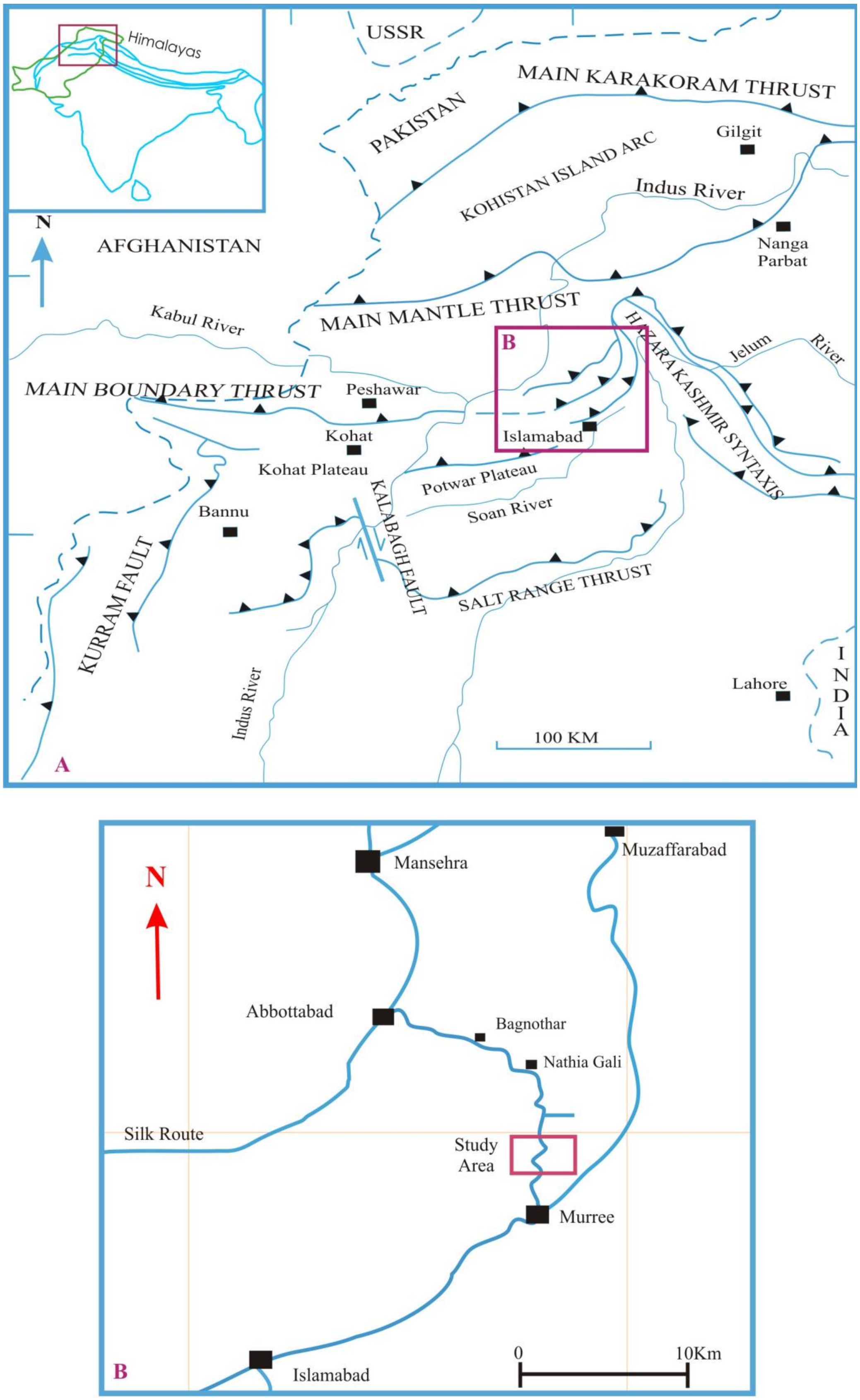


Fig. 1. Location map of studied sections exposed in Abbottabad district.

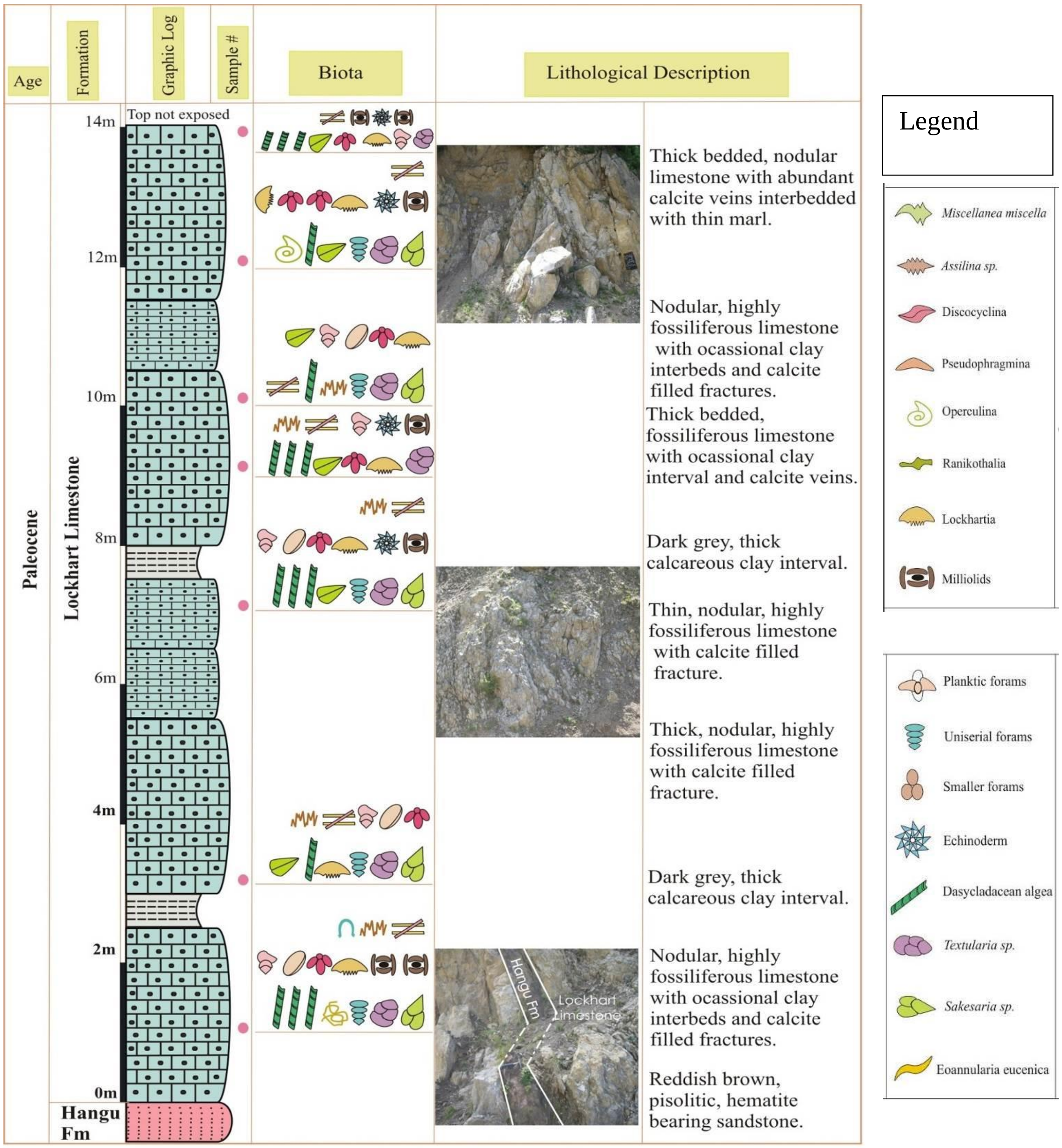


Fig. 2. Detailed stratigraphic column of Lockhart Limestone at Touhidabad section.

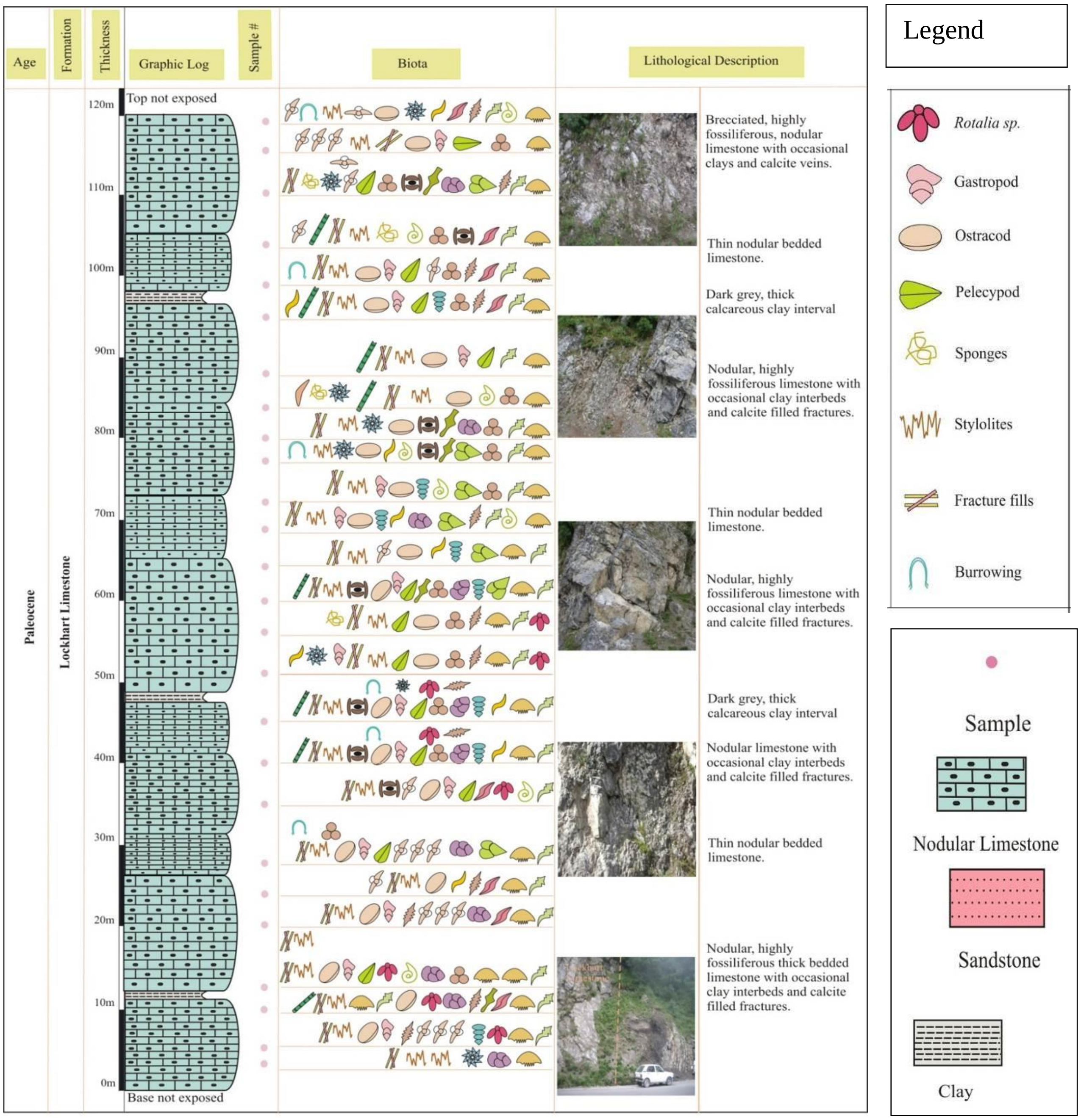


Fig. 3. Detailed stratigraphic column of Lockhart Limestone at Changlagali section.

The Lockhart Limestone is logged and only the limestone samples were thin sectioned for petrographical analysis, shale/marls samples were not analyzed in the present study. Field analysis included measurement of stratigraphic section of Lockhart Limestone and sampling of the key horizons. Thin sections were prepared and photomicrographs were taken of selected samples. The petrographic study was conducted by using standard polarizing microscope in Department of Geology, University of Peshawar. The allochemical constituents were identified and classified with the help of Folk (1962), Dunham (1962) and Flügel (1982). Microfacies are named according to Dunham (1962) classification which is compared with the Ramp

Microfacies (SMF) of Wilson (1975) and Flügel (2004) for the interpretation of depositional environment.

3. Results and discussion

3.1.1. Algal foraminiferal packstone microfacies (LMF-1)

Description

The Algal-Foram Packstone Microfacies is comprised of dark grey, thin bedded, nodular limestone with minor clay/marl interbeds. This microfacies is represented by four thin sections at Touhidabad and one thin section at Changlagali. The total thickness of the microfacies is 6m in Touhidabad and is repeated three times from the base at 3m, 9m and 14m heights respectively. In Changlagali this microfacies is 4m thick. The percentage of this microfacies is 43% in Touhidabad and 4% in Changlagali, with an average of 23.5%. It is characterized by larger and smaller benthic foraminifera mixed with dasycladacean algae, mollusks, gastropods and ostracodes with rare echinoderms and planktic foraminifera. The dasycladacean algae vary from 10-15%. The benthic foraminifera constitute 20-25% of the skeletal constituents and include milliolids, *Lockhartia* sp., *Rotalia* sp., agglutinated foraminifera Textularia and *Sakesaria* sp., *Miscellanea* sp. and *Assilina* sp. The allochems to micrite ratio is generally 3:1 with dominant lime mud matrix as compared to other microfacies. Burrowing is common and is displayed by disoriented textural elements of the microfacies (Plate 1A) (Figs. 4 and 5).

Interpretation

The microfacies are characterized by moderate diversity of faunal and floral constituents with dominant benthic foraminifera and dasycladacean algae. Dasycladacean algae is reported to occur in warm water, not more than few meters deep and are more common between depths of 12-15 meters of restricted circulation (Heckel, 1972; Wilson, 1975; Wray, 1977) while the presence of dasycladacean algae along with gastropods, indicate a general shallowing upward trend marked by onset of near shore, inner-shelf conditions of deposition. The wide variety of benthic foraminifera include milliolids and agglutinated foraminifera which indicates a protected muddy inner platform (Flügel, 2004). So based on restricted faunal assemblage this microfacies is interpreted to have been deposited in a shallow subtidal lagoonal environment of the inner shelf. This microfacies is similar to SMF-8 of Wilson (1975) and Flügel (2004).

3.1.2. Benthic foraminiferal wacke-packstone microfacies (LMF-2)

Description

The rocks of this microfacies is represented by dark grey to black, nodular limestone with thin clay interbeds which is represented by one thin section at Touhidabad and three thin sections from Changlagali sections. Total thickness is 2m at Touhidabad and 14m at Changlagali which is repeated twice from the base at 10 meters and 24 meters. The percentage of this microfacies is 14% at Touhidabad and 11% at Changlagali, with an average of 12.5%. The microfacies is characterized by skeletal allochems which are the only allochemical constituents marked by moderate diversity of organisms with allochem to micrite ratio of 7:3. Skeletal allochems include; larger benthic foraminifera, gastropods, pelecypods, ostracods, echinoderms and rare dasycladacean algae. The benthic foraminifera constitute 20-45% of skeletal constituents and include milliolids, *Lockhartia* sp., *Ranikothalia* sp, *Miscellinae* sp, *Assilina* sp., *Discocyclina* sp, Operculina and pseudophragmina. Other skeletal allochems including planktic foraminifera is less than 10%. The lime mud matrix constitutes 40-45% in this microfacies. The textural type recognized in this microfacies is wacke-packstone fabric according to Dunham (1962) and poorly-washed, biomicrite according to Folk (1959). The microfacies display poor sorting of constituents marked by size and shape variations. Lack of current oriented fabric imply below wave base conditions of deposition (Plate 1B) (Figs. 4 and 5).

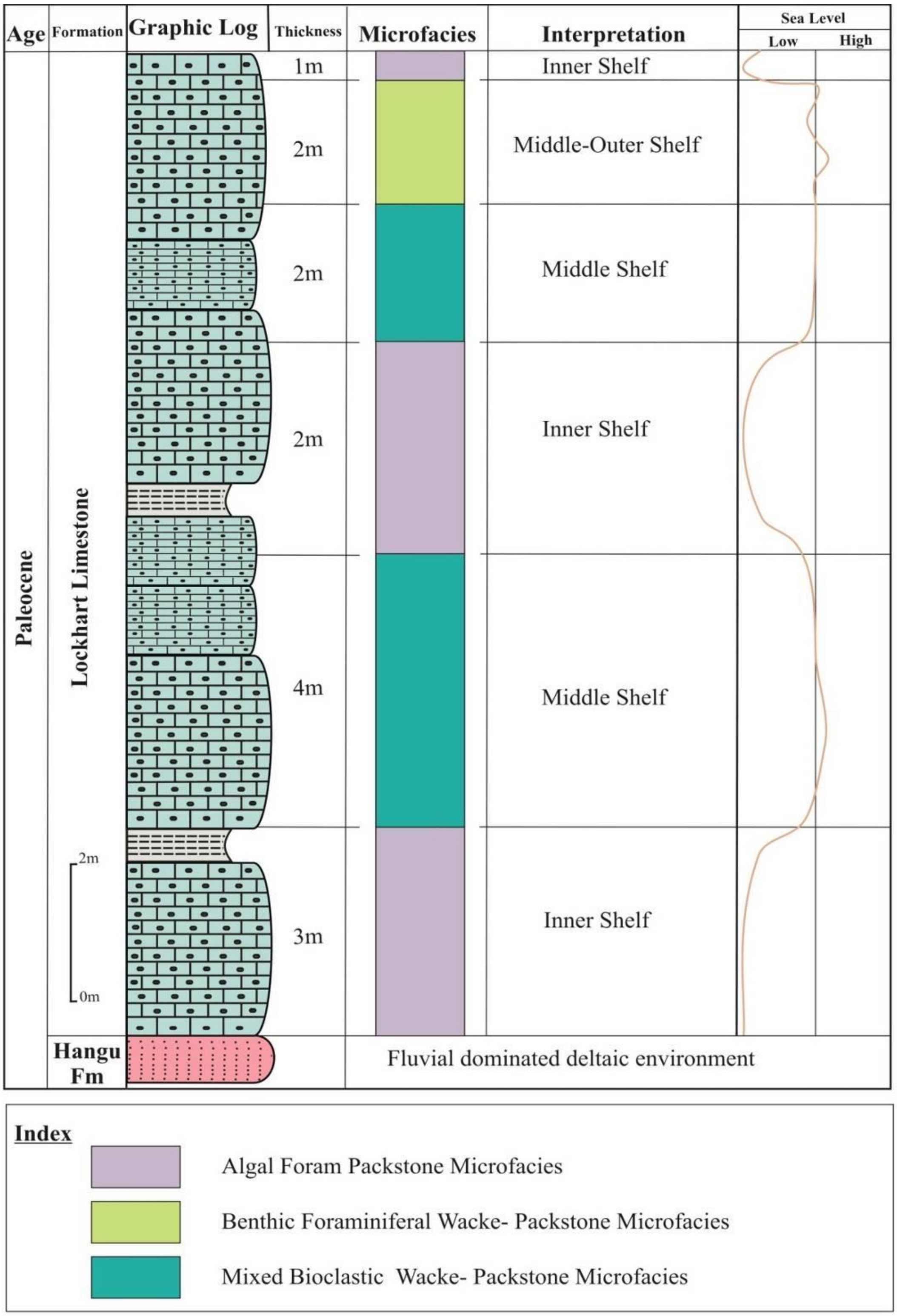


Fig. 4. Detailed stratigraphic column of Lockhart Limestone at Touhidabad section showing microfacies, depositional environments and sea level curve.

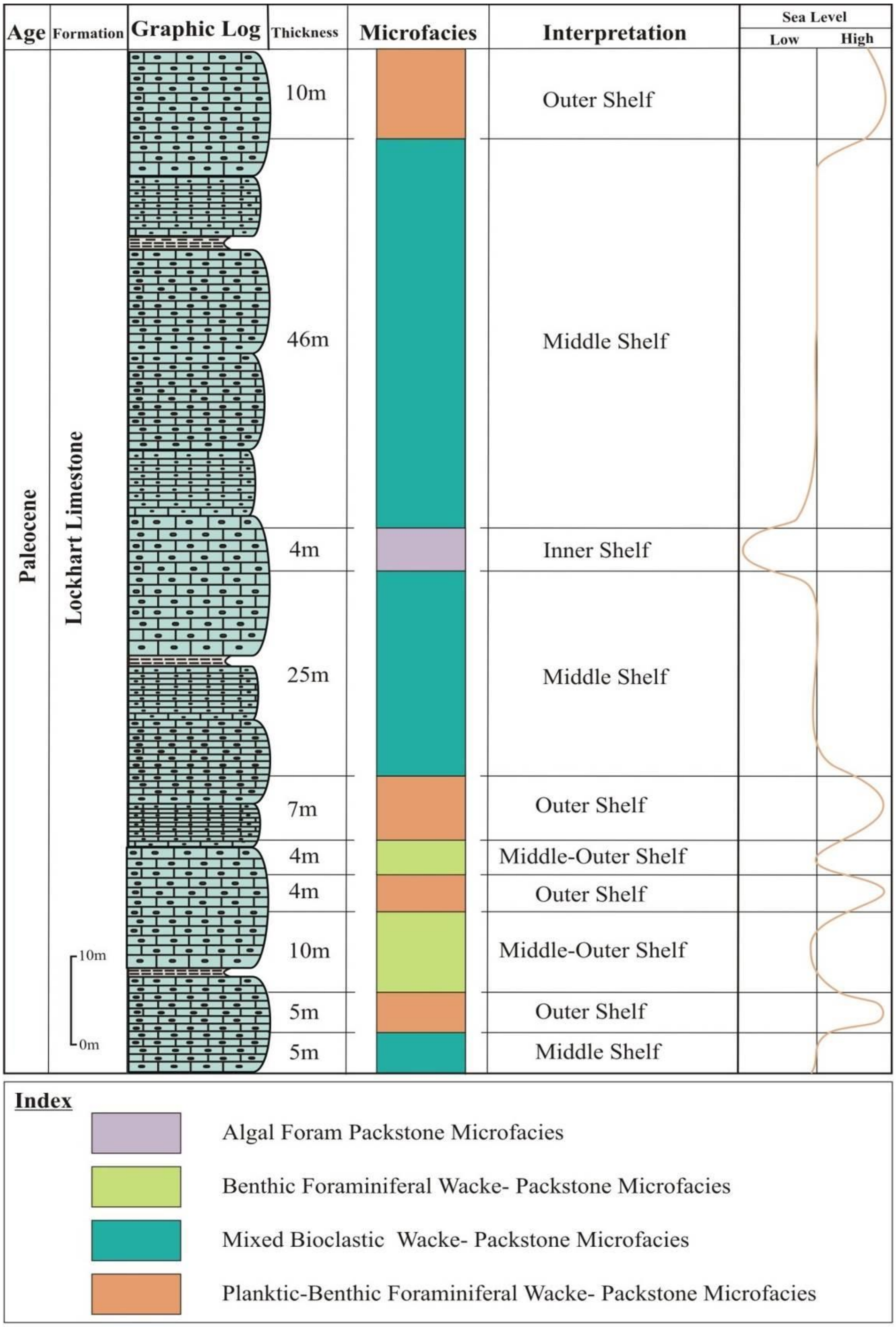


Fig. 5. Detailed stratigraphic column of Lockhart Limestone at Changlagali section showing microfacies, depositional environments and sea level curve.

Plate 1

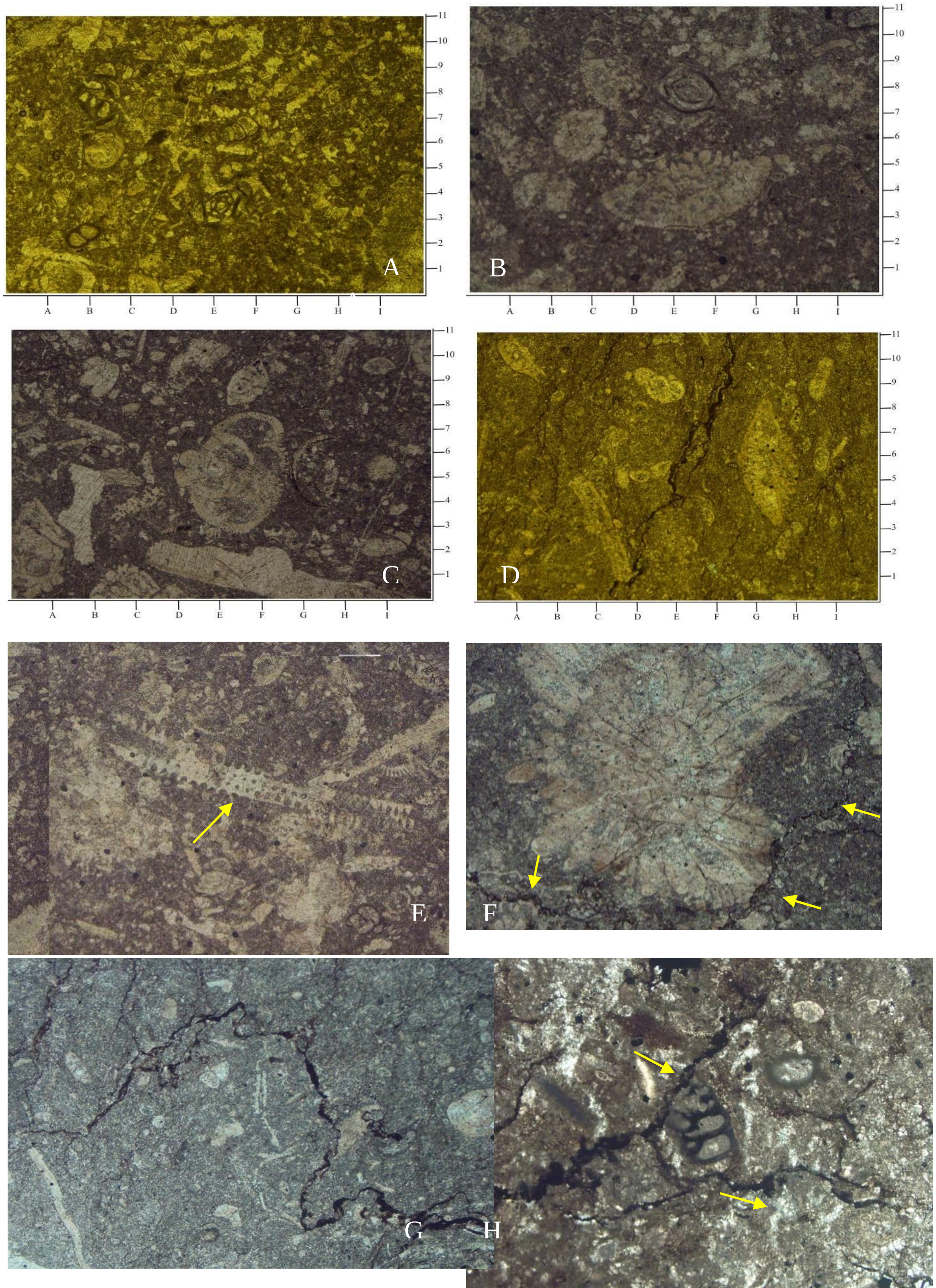


Fig. A. Photomicrographs of algal foraminifera packstone microfacies (LMF 1) displaying dasycladacean green algae (E-10), milliolids (E-4), and uniserials foraminifera (EF-7).

Fig. B. Photomicrographs of bentic foraminiferal wack-packstone microfacies (LMF 2) displaying *Lockartia hamiei* (DG-35) and millioids foraminifera (E-8).

Fig. C. Photomicrographs of mixed bioclastic wack-packstone microfacies (LMF 3) displaying echinioderms (AB-35, DH-2) and rotalia (EF-5), debris of benthic foraminifera, dasycladacean algae dasycladecan algae and other bioclasts.

Fig. D. Photomicrographs of mixed planktic-benthic foraminiferal wack-packstone microfacies (LMF 4) displaying lockartia hamiei (GH-48) and globorotalids (F-4). Besides it also shows pressure dissolution seams and neomorphic microspar.

Fig. E. Photomicrograph displaying aragonite transformation to low Mg calcite. The dasycladacean algae (arrow) originally aragonitic in composition have been replaced by coarse, sparry calcite (PPL. Mag. x4).

Fig. F. Photomicrograph displaying distorted, fractured foraminiferal test resulting from mechanical compaction at shallow depth followed by pressure dissolution (stylolites) at deep burial (PPL. Mag. x10).

Fig. G. High amplitude microstylolite characterized by truncation of shell debris across the boundary (PPL. Mag. x4).

Fig. H. Irregular non-sutured stylolite partially overriding foraminiferal test in microsparry fabric bearing limestone. Dissolution along such surfaces accounts for considerable volume loss in carbonate rocks (PPL. Mag. x4).

Interpretation

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, echinoderms, ostracods, bivalves and rare dasycladacean algae. The presence of echinoderms and diverse foraminiferal assemblages indicate open conditions of normal marine salinity. Micrite matrix is evident for deposition under low energy conditions. The microfacies are therefore interpreted to be deposited in relatively deeper, middle to outer shelf area. This microfacies is similar to SMF-2 of Wilson (1975) and Flügel (2004).

3.1.3. Mixed bioclastic wacke-packstone microfacies (LMF-3)

Description

This microfacies is characterized by brown to light grey, thin to thick bedded limestone with pronounced nodules varying in size, enhanced by solution cavities and weathering. This microfacies is represented by two thin sections at Touhidabad and sixteen thin sections at Changlagali. This microfacies is 6 meters thick at Touhidabad and is repeated twice at 3m and 10m while the thickness of this microfacies at Changlagali is 76m and is repeated three times at 3m, 35m and 64m. The percentage of this microfacies is 43% at Touhidabad and 63% at Changlagali, with an average of 53%. The allochemical constituents are exclusively skeletal fragments displaying Wacke-Packstone depositional fabric according to Dunham (1962) and poorly washed biomicrite according to Folk (1959). All the rocks are characterized by micrite matrix which ranges from 15-30% resulting in close packing in some sections. The microfacies is characterized by wide diversity of benthic foraminifera with other skeletal allochems including dasycladacean algae, bivalve, gastropods, ostracods, echinoderms, sponges and planktic foraminifera. The planktic foraminifera constitute less than 10% of the microfacies. The benthic foraminifera include *Lockhartia* sp., *Rotalia* sp., *Operculina* sp, *Discocyclina* sp, *Miscellanea* sp, *Assilina* sp., Textularia, *Sakesaria* sp. and rare milliolids. The dasycladacean algae gradually decrease up-section. The average percentage of the allochems ranges from 15-35%. The unidentified skeletal debris is less than 5% (Plate 1C) (Figs. 4 and 5).

Interpretation

This microfacies is characterized by moderate diversity of fauna and flora and is interpreted to represent deposition in a low energy, below wave base, middle shelf setting. The gradual upward decrease in dasycladacean algae and increase in echinoderms, increase in diversity of benthic foraminifera and other skeletal allochems support this interpretation. The presence of lime mud matrix indicates low energy, no turbulence and calm conditions of the middle shelf. The alternating/cyclic interbeds of fine clastics in the microfacies is attributed to rare offshore directed storm surges that are gradually prevalent on the middle shelf setting

(Tucker and Wright, 1990). The input of planktic foraminifera mixed with benthic foraminifera indicates offshore conditions of middle shelf. This microfacies is similar to SMF-7 of Wilson (1975) and Flügel (2004).

3.1.4. Planktic-Benthic Foraminiferal Wacke-Packstone (LMF-4)

Description

The rocks of this microfacies are light to dark grey, medium bedded to massive with pronounced nodules of various sizes. This microfacies is not reported at Touhidabad and is represented by six thin sections at Changlagali. The total thickness of this microfacies is 26 meters and is repeated four times at 5m, 20m, 28m and 110m. The percentage of this microfacies is 21% at Changlagali with an average of 10.5%. This microfacies is characterized by the presence of common planktic foraminifera, benthic foraminifera and lime mud as matrix with an allochem to matrix ratio of 7:3. The allochemical constituents are exclusively skeletal fragments marked by wide diversity of organisms. The benthic foraminifera of this microfacies include; *Miscellanea* sp, *Assilina* sp, milliolids, agglutinated Textularia and *Sakesaria* sp., *Lockhartia* sp, *Ranikothalia* sp., and *Discocyclina* sp.. The planktic foraminifera include; globorotallids, morozovella and planorotalites. Along with planktic foraminifera other skeletal allochems of this microfacies include; ostracods, gastropods, pelecypods and dasycladacean algae. This microfacies contains 30-45% lime mud matrix, 8-12% planktic foraminifera and 15-35% other skeletal allochems including benthic foraminifera. The unidentified skeletal material is up to 5%.The textural type recognized in this microfacies is wacke-packstone according to Dunham (1962) and poorly- washed, biomicrite according to Folk (1959) (Plate 1D) (Fig. 5).

Interpretation

This microfacies is dominated by benthic and planktic foraminiferal assemblage with subordinate ostracods, pelecypods, gastropods and dasycladacean algae.

Although other microfacies criteria are similar to Mixed Bioclastic Wacke-Packstone Microfacies, this microfacies is specifically dominated by relative abundance of planktic foraminifera and is interpreted to represent deposition in outer shelf conditions.

4. Depositional Settings of Lockhart Limestone

Based on carbonate microfacies identification and interpretation, the Lockhart Limestone represents deposition under clastic free shallow shelf conditions. Presence of wide variety of fauna, predominantly wackstone to Packstone fabric of rocks and nodular nature support the above interpretation. The sub-environments include inner, middle and outer shelf, where four major types of microfacies including 1) Algal Foraminiferal Packstone Microfacies, 2) Benthic Foraminiferal Wacke-Packstone Microfacies, 3) Mixed Bioclastic wacke-Packstone Microfacies and 4) Planktic-Benthic foraminiferal Wacke-Packstone Microfacies were deposited (Fig. 6).

5. Diagenetic fabric of Lockart limestone

5.1. Aragonite to calcite transformation

The Lockhart Limestone predominantly displays wack-packstone textural types with an appreciable amount of lime mud matrix and a total absence of intergranular spar cement. The microfacies of the inner shelf specifically contain chlorophyta, represented by dasycladacean algae and mollusk skeletal fragment with original mineralogy of aragonite. As is the case with ancient limestone, all the skeletal constituents of dasycladacean algae and mollusk shell fragments with unstable mineralogy have been replaced to low Mg calcite (Plate 1 E).

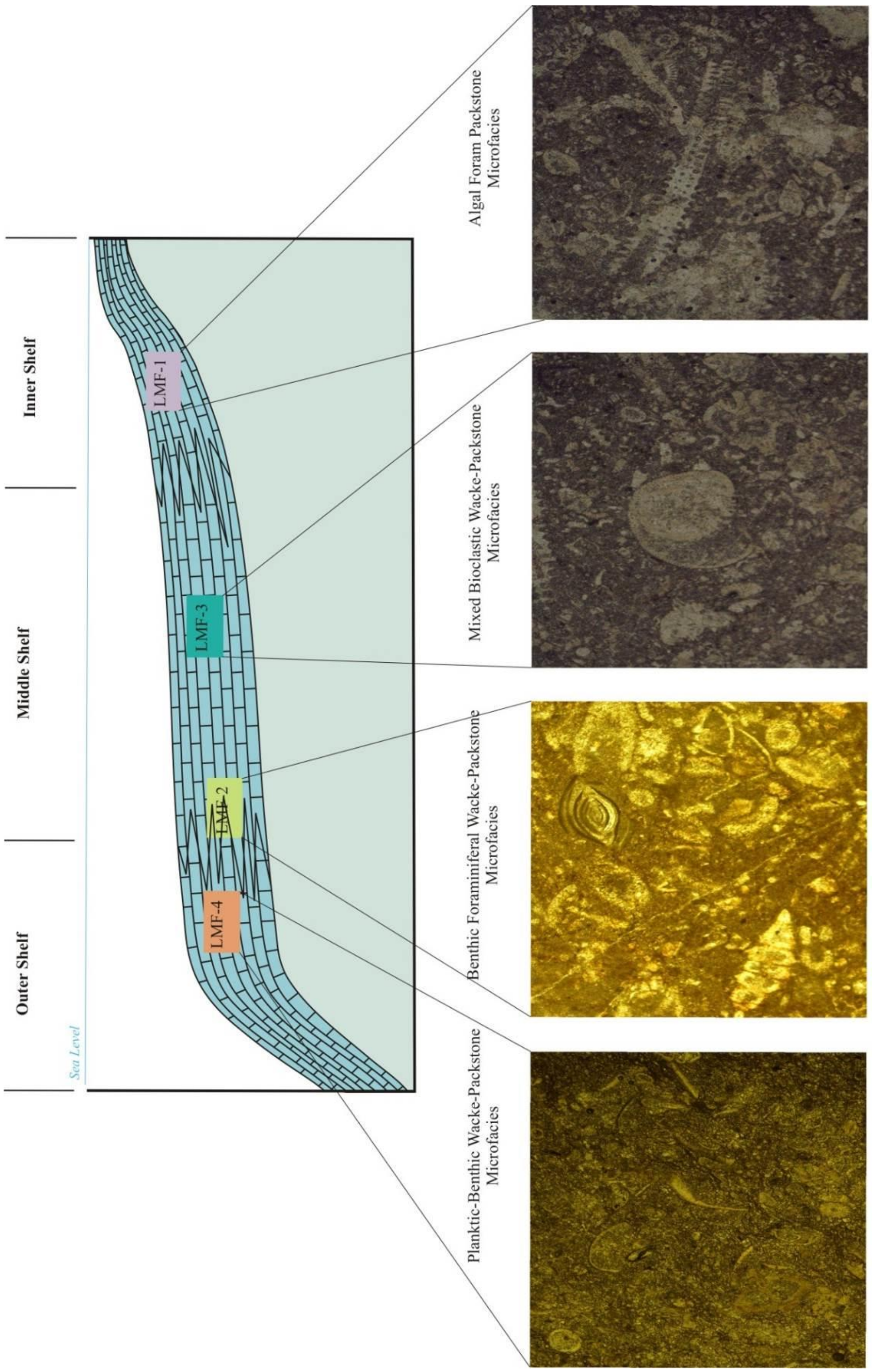


Fig. 6. Depositional model of Lockhart Limestone based on both field sections.

Compaction

The compaction refers to changes in original fabric of the rocks under shallow to deep burial conditions as a result of overburden pressures. The fabric changes involve either physical breakdown of constituent grains or chemical dissolution at and along grain boundaries. The compaction results in reduction of porosity, fracturing of constituent grains and overall changes in the stratigraphic thickness of strata. The compaction features recognized in the Lockhart Limestone include the followings:

1) In-situ brecciation of allochemical constituents

This type of fabric is typically associated with larger foraminifera (Plate 1F) and involves localized fracturing without any appreciable dislocation along closely associated fractures. Crushed foraminiferal test is generally the victim of physical compaction caused by bioclast to matrix contact. Differences in rigidity of bioclast and matrix caused breakage of test associated with relatively shallow burial.

2) Pressure dissolution fabric

The chemical compaction is exemplified by pressure dissolution fabric resulting in the formation of various types of stylolites and solution seams developed under deep burial conditions. These planes are usually, but not always, characterized by the accumulation of relatively insoluble residues or authigenic minerals along them, which form the stylolite seam. The composition of this material is infact a function of host rock (Park and Schot, 1968).

In the Lockhart Limestone a number of pressure-dissolution induced features have been recognized. The features include:

1) Sutured seams (swarms, grain contact, and multi grain to nodule bounding) solution seams are isolated or swarm-like partings characterized by thin seams, often with accumulations of insoluble residues. In case of Lockhart Limestone the concentration of insoluble residue along stylolite surfaces is iron oxide (Plate 1G and 1 H).
2) Stylo-brecciated fabric
   The stylo-brecciated fabric is a type of fabric also referred to as condensed fabric (Logan and Semenjuk, 1976). The fabric develops by the intersection of multiple sets of low amplitude stylolites in three dimensional frameworks enclosing a relatively rigid grain. The resulting feature called as iden is densely packed and bounded by irregular to anastomising microstylolites. In the Lockhart Limestone, these idens are large tests of foraminifera and other skeletal allochems which have undergone partial dissolution along microstylolites (Plate 2A).
3) Stylo-laminated fabric
   The stylo-laminated fabric is characterized by a set of closely spaced, straight, low amplitude, stylolites separated by seams of reactant, the iron oxide residue. In the Lockhart Limestone, this type of fabric seems to be the result of continuous dissolution of texturally homogenous limestone with appreciable quantity of uniformly distributed, clay minerals or iron oxide insoluble residue (Plate 2 B).
4) Stylo-nodular fabric
   The stylonodular fabric, result from swarms of stylolites, enclosing relatively rigid, residual idens. The size of the nodules varies from submicroscopic to macroscopic while the shape of the nodules varies from highly irregular to round to ellipsoidal or lenticular. In the Lockhart Limestone, this type of fabric is the most common one and occurs throughout the stratigraphic section (Plate 2C).

5.2. Nature and origin of calcite-filled microfractures

Many carbonate rocks display millimeter to centimeter-sized, mineral-filled (often calcite-filled) microfractures (veins and veinlets). Fractures are discrete breaks within a rock mass and comprise microfractures, joints and faults.

Fracture system in carbonate rocks form in various stages of sedimentation and diagenesis, but most calcite veins are due to brittle failure and tectonic fracturing of lithified carbonate rocks caused by stress and shear displacement, as is the case with limestone of the studied area. Extensional movements and natural hydraulic fracturing is also responsible for the formation of microfractures (Sibson, 1975). A wide variety of calcite veins and veinlet are present in Lockhart Limestone. These include, single to multiple, intersecting, large to small veins displaying a wide range of thicknesses from several cm to few mm

(Plate 2D and 2E). Detailed studies of fractures are important in deciphering tectonic history, fluid migrations, diagenetic history, reservoir potential and the mechanical properties of carbonate rocks.

Micritization

The term micritization refers to conversion of allochemical constituents of the carbonate rocks into micrite or lime mud through boring activity of endolithic algae (Flügel, 1982). The micritization of carbonate grains, a slow process, generally takes place in a low energy, restricted, environments. The process of conversion varies from partial to complete obliteration of original depositional fabric. The micritized fabric, identified in the Lockhart Limestone is restricted to shell fragments of benthic organisms specifically gastropods and larger foraminifera. The presence of micrite matrix in all the facies types, indicate low energy, subtidal conditions of deposition (Plate 2F).

Microspar

The term refers to fine grained calcite matrix, characterized by rather uniformly sized and generally loaf-shaped, subhedral and euhedral calcite crystals ranging from 5 to more than 20µm in diameter (Folk, 1959). The formation of microspar has been attributed to aggrading neomorphism (Folk, 1965).

In the Lockhart Limestone, conversion of micrite to microspar is a common phenomenon and is characterized by the development of isolated, patches of inequi-granular microspar selectively converting high magnesium calcite (micrite) into low magnesium calcite with heterogeneous texture (Plate 2G, 2H and 1H).

5.3. Carbonate nodularity

The Lockhart Limestone is typically characterized by nodularity in the studied section as well as elsewhere (Kohat and Salt Ranges). The individual nodules are highly irregular and represent a wide range of size variations.

The most typical nodularity of Lockhart Limestone is attributed to chemical compaction of an alternating sequence of thin bedded limestone and marl. The abundant bedding parallel, high amplitude stylolites and solution seams in limestone strongly support this interpretation.

Origin

Detailed petrography of the Lockhart limestone indicates two mechanism of nodularity.

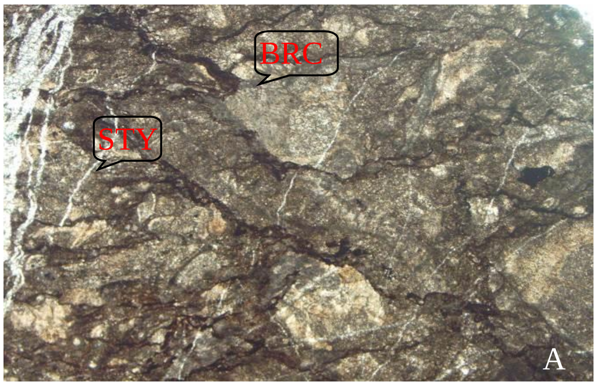
1. Organic burrowing within the soft, mud supported substrate of the Lockhart limestone manifested in the form of jumbles and homogenized fabric in most of the rocks pointing towards organic activity as a probable cause of nodularity.
2. Presence of swarms of stylolites with iron oxide residue giving brownish color to the rocks is regarded as the predominant phenomena.

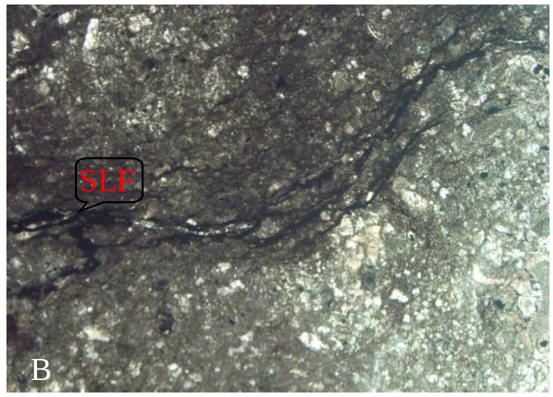
Nodularity is most commonly associated with deeper water pelagic limestones which are bounded by hard grounds and omission surfaces (Fischer and Garrison, 1967).

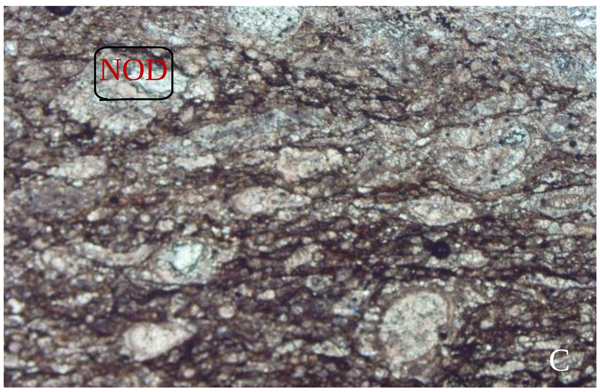
But in case of Lockhart Limestone which is dominated by shallow water benthic fauna and flora with low input of planktics, restricted to some facies, the development of nodularity is mostly attributed to pressure dissolution related to deep burial.

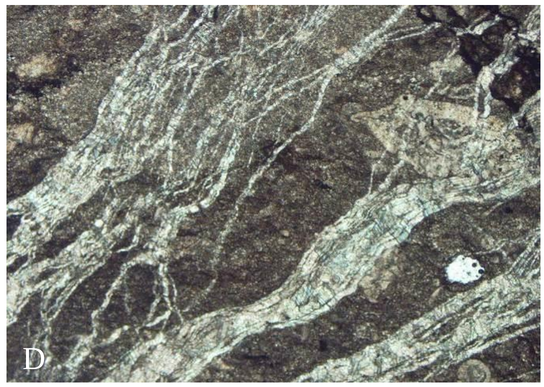
The presence of abundant secondary porosity due to possible subsurface dissolution potential of predominantly aragonitic and high magnesium calcite skeletal constituents and tectonic deformation (indeed fracture porosity) of Galiat area, the Lockhart Limestone can serve as a good reservoir for hydrocarbons. However the impact of pressure dissolution and development of abundant microstylolites with insoluble residue (permeability barrier) may have negative effects.

Plate 2









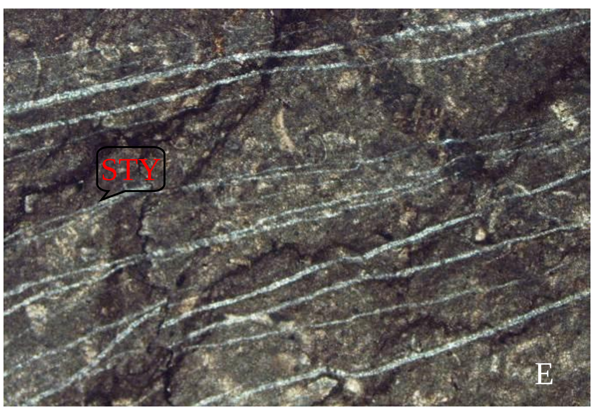


Fig. A. Stylobreccia (BRC) formed by sutured multi-grains fabric of Wanless (1979) or condensed fabric of Logan and Semeniuk (1976). Idens (bodies that behave as homogeneous entities under physical or chemical conditions) are densely packed and bounded by irregular to anastomising microstylolites (STY). Note partial elimination of foraminiferal shell (PPL. Mag. x4).

Fig. B. Sutured wispy parallel sets of dissolution seams producing locally stylolaminated fabric (SLF), normally associated with clayey limestones. (PPL. Mag. x4).

Fig. C. Stylonodular fabric formed by nodules (NOD) and lenses of limestone idens separated by stylolite (STY) swarms (PPL. Mag. x4).

Fig. D. A parallel sets of calcite-filled microfracture (CFF) swarms intersecting *Lockhartia sp*.(top right) These calcite-filled microfracture swarms seem to be the result of hydraulic fracturing of Lockhart Limestone (PPL. Mag. x4).

Fig. E. Parallel to sub-parallel hairline calcite-filled fractures (CFF) offset by microstylolites (STY). Note the association of these microstylolites with small scale calcite-filled microfracture sets can be used as paleostress indicators (PPL. Mag. x4).

Fig. F. Photomicrograph displaying partial micritization (MIC) of gastropod along shell boundaries (PPL. Mag. x10).

Fig. G. Photomicrograph displaying neomorphic development of microspar (MSP) characterized by irregular, patchy occurrences of in equigranular crystals (PPL. Mag. x4).

Fig. H. Photomicrograph displaying two sets of intersecting, closely bound, parallel sets of low amplitude, microstylolites (STY) (post-dating) within coarse sparry calcite-filled microfracture (PPL. Mag. x10).

6. Conclusions

1. The Lockhart Limestone logged and sampled at studied sections comprises of light to dark grey nodular limestone with marls/ shale interbeds.
2. Faunal assemblage of Lockhart Limestone include benthic and planktic foraminifera, dasycladacean algae, echinoderms, ostracods, gastropods, pelecypods, bivalves and sponges. The foraminifera include; *Lockhartia* sp., *Ranikothalia* sp., *Miscellanea* sp., *Assilina* sp., *Discocyclina* sp., *Sakesaria* sp., *Texularia* sp., *Operculina salsa*, *Operculina subsalsa*. Pseudophragmina, Planorotalites, Morozovella and *Pseudohatigerina* sp..
3. Four microfacies include; 1) Algal Foraminiferal Packstone Microfacies, 2) Benthic Foraminiferal Wacke-Packstone Microfacies, 3) Mixed Bioclastic Wacke-Packstone Microfacies, 4) Planktic-Benthic Foraminiferal Wacke-Packstone Microfacies.
4. On the basis of microfacies interpretation the Lockhart Limestone is interpreted to have been deposited in a shallow shelf area.
5. The presence of several diagenetic features indicates that it has been subjected to various post-depositional alterations which include; aragonite to calcite transformation, compaction, pressure dissolution, calcite-filled microfractures, carbonates nodularity, micritization and development of microspar.
6. Lockhart Limestone can serve as a good reservoir for hydrocarbons because of abundant secondary porosity.

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