Lithofacies properties, biostratigraphy, cyclicity and depositional environment of the Margala Hill Limestone, Hazara Basin, Northern Pakistan

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SUPERVISORY AND EXAMINING COMMITTEE

Aman Ullah, candidate for the degree of Master of Science in Geology, has presented a thesis titled, *Lithofacies properties, biostratigraphy, cyclicity and depositional environment of the Margala Hill Limestone, Hazara Basin, Northern Pakistan*, in an oral examination held on December 6, 2016. The following committee members have found the thesis acceptable in form and content, and that the candidate demonstrated satisfactory knowledge of the subject material.

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**Abstract**

The Margala Hill Limestone is a carbonate-dominated unit that occurs in the Kalla-Chitta, Hazara and Potwar basins in north Pakistan. This study addresses the lithofacies attributes, depositional setting, cyclicity, biostratigraphy and, sequence stratigraphy of the Margala Hill Limestone in the Hazara Basin. In the study area, the formation has an average thickness of 80 m; it conformably overlies the Paleocene-Eocene Patala Formation and is conformably overlain by the Early Eocene Chorgali Formation. The Margala Hill Limestone consists of bioclastic limestone lithofacies with subordinate gray to brownish gray, thin marl interbeds. The limestones are commonly grey, weathering pale grey, fine-to medium-grained, nodular, thinly to thickly bedded and rarely massive in nature. Four stratigraphic sections at, Goragali, Bharyan, Nathiagali and Kozagali, were studied in detail. Field data and petrographic analysis were used to create nine lithofacies (Mf1-Mf9) from the studied sections. These lithofacies includes miliolid Mudstone (Mf1), Algal-miliolid wackestone-packstone (Mf2), Bioclastic Packstone (Mf3), *Nummulites-Assilina* packstone-wackestone (Mf4), *Nummulites-Discocyclina* wackestone-packstone (Mf5), elongated Benthic Foraminifera wackestone (Mf6), Planktonic Foraminifera mudstone (Mf7), Bioclastic Marl Lithofacies (Mf8) and unfossiliferous Marl Lithofacies (Mf9). The Margala Hill Limestone was deposited in a quiet to moderately agitated ramp setting where lithofacies Mf1, Mf2 & Mf3 represents inner ramp, lithofacies Mf4, Mf5 & Mf8 represents middle ramp and lithofacies Mf6, Mf7 & Mf9 are outer ramp deposits. The vertical arrangements of these lithofacies suggest recurring subtidal shallowing-upward cycles (A, B and-C). Absence of intertidal
and supratidal signatures further suggest a subtidal setting. The cycles range from 10-20 meters in thickness. The index fossils *Nummulites atacicus, Nummulites globulus* and *Assilina laminosa* indicates a the Middle Ilerdian 2/SBZ8 (54Ma-52.8Ma) age for the formation. Portion of Patala Formation, Margala Hill Limestone and Chorgali Formation were deposited as a single supercycle (the PMC supercycle). The supercycle is comprised of two 3rd-order Transgressive-Regressive depositional sequences (TR-1 & TR-2). The Margala Hill Limestone makes the middle part of the PMC supercycle and is comprised of seven, 4th-5th-order shallowing-upward cycles.
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Chapter One

1.0 Introduction

1.1 Preface

The Eocene rocks are widely spread and extensively developed in Pakistan. They extend from the Himalayas in the north to the Arabian Sea in the south (Figure 1.1). The thickness of the Eocene strata ranges from a few hundred meters (Northern sub-basins) to about 4000 meters (Axial belt). Carbonates dominate the lithology of the Eocene strata in Pakistan. However, localized evaporites and marine shales are also reported from northern sub-basins (Kadri, 1995).

The Eocene rocks hold the highest percent of the hydrocarbons in Pakistan (Kadri, 1995). The country's largest gas field (Sui Field) in the Lower Indus basin produces gas from Eocene Sui Upper Limestone and Sui Main Limestone. The gas field is producing 24 million cubic meters gas per day (Qadeer and Saddique, 1998). Similarly, the Eocene Sakesar and the Chorgali Formations are excellent reservoirs and produce hydrocarbons in the largest oil fields of Upper Indus Basin (Kadri, 1995). The Thar Coalfield (Southern Pakistan) has reserves of 9.715 billion tons (Shah, 1977).

In the Upper Indus Basin, the Eocene strata are present in the Kohat, Potwar, and Hazara sub-basins. The Kohat Basin was isolated during the Eocene Epoch resulting in deposition of salt and gypsum. The Eocene strata in the Kohat Basin is comprised of 1) Bahadur Khel Salt, 2) Jatta Gypsum, 3) Kuldana Formation, and 4) Kohat Formation.
The first two formations produce the economically important rock salt and gypsum (Shah, 1977).

The Eocene strata in Potwar Basin contains the Nammal, Sakesar, Chorgali, and Kuldana formations. Except for the Kuldana Formation, all of the strata are dominated by carbonates (Bender and Raza, 1995). The Sakesar and Chorgali formations are excellent reservoirs in the Adhi and Pindori oil fields. The production of these oil fields in 2002-2003 was 2,071,298/yr and 116,311/yr barrels respectively (Shah, 1977).

The Hazara Basin lies north of the Potwar Basin and is the least explored. The Eocene strata in the Hazara Basin is comprised of 1) Patala, 2) Margala Hill Limestone, 3) Chorgali, and 4) Kuldana formations (Shah, 1977). The Margala Hill Limestone is the subject of this thesis.
Figure 1.1: Pakistan Geological Map. The Eocene strata (Brown strip), are exposed along the Axial Belt and in the Himalayas. The study area (blue box) is near Islamabad (the capital city of Pakistan). The arrow indicates the geographic north. (Modified from Shah, 1977).
1.2 Purpose of Study

Despite its high economic importance, the Eocene strata are poorly explored in the Hazara Basin (Northern Pakistan). Complex structural geology, dense vegetation cover, and limited accessibility account for the barely-investigated Eocene rocks in the area. The previous studies were limited to basic mapping, paleontologic reconnaissances and general description of the various lithofacies (Latif, 1970; Bhatti, 1972; Shah, 1977; Akhter and Butt 1999; Swati et al., 2013). This thesis intends to examine the Lower Eocene Margala Hill Limestone in the Hazara area (Figure 1.2). This study involves a detailed field investigation coupled with detailed petrography for a better understanding of the lithological content of the formation, as well as its biostratigraphic attributes for the purpose of age determination and correlation, both locally and regionally. The results of this thesis are expected to provide a solid understanding of the sedimentologic, biostratigraphic and sequence stratigraphic attributes of the formation. The details of objectives, various methodology involved and selected stratigraphic sections are given below.

1.3 Objectives

- Record the lithofacies of the Margala Hill Limestone form key stratigraphic sections.
- Perform a detailed petrographic study and microfacies analysis attributes of the formation of the collected samples.
- Identify the diagnostic fossils for biostratigraphic dating and paleoenvironmental analysis.
- Establish a depositional model for the formation (Using both field and petrographic investigation).
➢ Explain the significance of cyclicity and sea level changes and compare with the regional and global sea level curves.

➢ Perform a sequence stratigraphic analysis on the formation.

1.4 Methodology

This project includes fieldwork, laboratory work, and literature review.

1.4.1 Fieldwork

Four Margala Hill Limestone sections were described along Murree-Abbottabad Road in the Hazara Area during July-August (2014) (Figure 1.2). Field area was revisited in August (2015). The objectives of the fieldwork were: 1) to measure the total thickness of the formation and the thickness of various lithofacies, 2) to record the sedimentary structures, fossils, and nature of the contact, 3) to collect samples for petrography, 4) to identify marine flooding surfaces and cyclicity within the formation 5) to acquire field photographs and sketches. The four stratigraphic sections (1-4) near Hazara were selected (Figure 1.2). The selection of these sections is based on accessibility, minimum structural deformation and the presence of the upper and/or lower contacts of the formation. These sections include: 1) Nathiagali, 2) Kozagali, 3) Bharryan, and 4) Goragali sections. The first two stratigraphic sections have the complete Margala Hill Limestone including upper and lower conformable contacts. The lower contact is with the Paleocene-Eocene Patala Formation while the upper contact is with the Eocene Chorgali Formation. The Margala Hill Limestone in sections 3 & 4 has a faulted lower and conformable upper contacts. All four of these sections are exposed along road cuts.
Figure 1.2: Geologic map of the Hazara Area. Showing exposure of Margala Hill Limestone along with other Cambrian-Quaternary strata. The yellow stars show stratigraphic sections (1-4) on the Murree to Abbottabad Road (Modified from Latif, 1970).
1.4.1.1 Nathiagali Section (Section 1)

The Nathiagali section is exposed on the Nathiagali-Abbottabad Road, at a distance of 2 kilometers from the main Nathiagali bazaar. The coordinated of the section are 73°23'23.82” E and 34°4.17'70N.” Various formations of Paleogene age are exposed along this section. These formations are; 1) Middle Paleocene Lockart Formation, 2) Late Paleocene-Early Eocene Patala Formation, 3) Early Eocene Margala Hill Limestone and Early Eocene Chorgali Formation. The dominant lithologies of this succession are carbonate, except the Patla Formation, which is dominated by deep marine shales. In this section, the Margala Hill Limestone lies over Patala Formation while overlain by Chorgali Formation. Both lower and upper contacts are conformable (Figure 1.3). The total thickness of the Margala Hill Limestone is reported as 79 meters. For the petrographic and paleontologic analysis, 16 samples have been collected from the formation.
Figure 1.3: Geological map of the Nathiagali section. Showing exposed Paleogene Formations. The yellow square marks the studied section. The Margala Hill Limestone lies over the Patala Formation and is overlain by Chorgali Formation. The formation is preserved in this section (Modified from Latif, 1970).
1.4.1.2 Kozagali Section (Section 2)

The geographic coordinates of this section are 33°57'54.96"N and 73°23'20.88" E. This section is present on the Nathiagali-Murree Road, near Khaira gali village. The Paleocene Lockhart Formation, Paleocene-Eocene Patala Formation, Eocene Margala Hill Limestone and Eocene Chorgali Formation are exposed along this section. The Margala Hill Limestone is 86 meters thick and is present with both conformable contacts: lower with the Patala Formation and upper with the Chorgali Formation (Figure 1.4). 31 samples were collected for paleoenvironmental and biostratigraphic analysis.
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1.4.1.3 Bharryan Section (Section 3)

This section is located on the Nathiagali-Murree Road, near Bharryan village. The coordinates of this section are 33°59'1.38"N and 73°23'49.56" E. The formations exposed along this section are Early Eocene Margala Hill Limestone, Early Eocene Chorgali Formation, Early-Middle Eocene Kuldana Formation and Miocene Murree Formation. These formations are exposed along the road cuts. In this section, the Margala Hill Limestone is having with both upper and lower contacts with the Chorgali Formation. The former being conformable while the latter is a faulted contact (Figure 1.5). The Margala Hill Limestone has examined in details in this section. The Margala Hill Limestone is 62 meters thick. 17 samples were collected for petrographic and paleontologic studies.
**Figure 1.5**: The geologic map of the Bharyan Section. In addition to the Margala Hill Limestone, several other formations are also exposed in this section, including the Chorgali Formation, Kuldana Formation, and Murree Formation. Yellow square shows the studied section. The Margala Hill Limestone has a faulted lower contact with younger Chorgali Formation and is represented by a red line on the map while the upper conformable contact is also with Chorgali Formation. Several other faults are also present and is represented by a red line (Modified from Latif, 1970).
1.4.1.4 Goragali Section (Section 4)

This section is situated on the Goragali-Murree Road, near Goragali village. The geographic coordinates of this section are 33°53'2.64"N and 73°19'45.54" E. In this stratigraphic section, various formations are present. These formations include Lower Eocene Margala Hill Limestone, Lower Eocene Chorgali Formation, Middle-Upper Eocene Kuldana Formation and Miocene Murree Formation. These formations are exposed along the road cuts. In this section, the Margala Hill Limestone have a faulted lower contact with younger Miocene Murree Formation and a conformable upper contact with the Eocene Chorgali Formation (Figure 1.6). 28 samples have been collected from the formation during the field excursion.
Figure 1.6: Geologic map of the Goragali section. Various formations such as Margala Hill Limestone, Chorgali Formation, Kuldana Formation and Murree Formation are present in this section. The yellow square shows the studied section. The Margala Hill Limestone has a lower faulted contact with the younger Murree Formation. However, the upper contact is conformable with the Chorgali Formation. The red lines on the map show several other faults (Modified from Latif, 1970).
1.4.2 Laboratory Work

For the petrographic studies, 102 thin sections were prepared from the collected samples in the Department of Geology, University of Peshawar, Pakistan. These thin sections were examined, using a polarizing microscope, in the Department of Geology, University of Regina, Canada. During this study, the thin sections were described in detail. The study involved characterizing the framework grains, textural classification of the samples, identification of diagenetic features, and taking photomicrographs. The identification and classification of microfossils were also a fundamental part of this study. These fossils were further used for paleoenvironmental analysis and biostratigraphic dating of the formation.

1.5 Previous work

The Margala Hill Limestone is composed of bioclastic limestone, and marls. It lies over the Patala Formation and is overlain by the Chorgali Formation. Both upper and lower contacts are conformable. The formation is well exposed and well developed in the Hazara area (Latif, 1970; Shah, 1977). The bioclasts include foraminifera, mollusks, algae and echinoids (Raza, 1967; Cheema, 1968; Latif, 1970). The larger benthic foraminifera dominate the allochemical content of the formation. Cheema (1968) and Latif (1970) have recorded various species of *Nummulites*, *Alveolina*, *Lockhartia*, *Discocyclina*, and *Ranikothalia* from the formation. The occurrence of the larger benthic foraminifera in the Margala Hill Limestone indicated a shallow marine depositional environment in a carbonate platform setting (Akhter and Butt, 1999). Swati et al., (2013) have sorted the biostratigraphy of the formation and have recognized three microfacies in Kohala Bala section, Southeastern Hazara. The formation was correlated to the Eocene Sakesar Formation of Potwar basin by Abeer et al., (2013).
Swati et al. (2013) missed the upper contact, as well as a covered 40-meter thick portion of the middle part of the formation. The previous studies on the formation are also very general and lack a detail investigation for the depositional modeling, biostratigraphy and cyclicity. No one has attempted to perform sequence stratigraphic analysis of the formation. Therefore, the present study is aimed to investigate the formation lithologically and biostratigraphically in order to interpret its depositional setting and cyclostratigraphic properties.
Chapter 2

2.0 Regional Geology

2.1 Regional Tectonic Framework

2.1.1 Introduction

The collision of the Indo-Pakistan plate with the Kohistan Island Arc and the Eurasian plate resulted in the closure of the Tethys Ocean and the development of the Himalayan orogeny. The resultant mountain range is 3500 Km long and is stretching from Nepal to Afghanistan (Bender and Raza, 1995). This mountain belt in Pakistan is known as NW-Himalayas Fold-Thrust Belt (Shah, 1977). Due to the collision, a variety of Igneous, Sedimentary and Metamorphic thrust up to the surface in the form of elevated mountain peaks. These rocks successions are intensively folded and faulted. The intensity of deformation increases northward in the Himalayas. The age of these rocks ranges from Precambrian to Recent (Shah, 1977; Bender and Raza, 1995).

2.1.2 Divisions of Himalayas

The Himalayas Mountain range has been divided into three main parts (Sub-Himalayas, Lesser Himalayas, and Higher Himalayas). These subdivisions are based on the type of rock associations and the bounding thrust faults (SRT, MBT, MCT, MMT) in the NW-Himalayas Fold- Thrust Belt (Figure 2.1).
Figure 2.1: The tectonic map of Northern Pakistan. Shows the subdivisions of Himalayas (SH: Sub-Himalayas, LH: Lesser Himalayas, and UH Higher Himalayas), the Kohistan Island Arch (KIA) and Karakoram Block (KB). Various major thrust faults divide these geologic entities. These Major faults are (Main Boundary Thrust (MBT), Main Central Thrust (MCT), Main Mantle Thrust (MMT) and Main Karakoram Thrust (MKT). Blue box shows the study area. It is present in the Lesser Himalayas and is exposed by Main Boundary Thrust (Modified after Shah, 1977).
The lowermost part of the Himalayas is Sub-Himalayas. It is bounded by MBT (Main boundary thrust) in the north and the SRT (The Salt Range thrust) in the south. This part of Himalayas is primarily composed of sedimentary rocks that ranges in age from Precambrian-Recent. North of the Sub-Himalayas is the Lesser Himalayas which is capped by the MCT (Main central thrust) in the north and MBT (Main boundary thrust) in the south. Sedimentary and metamorphic rocks, ranging from Cambrian to Miocene, make this part of Himalayas. The northernmost Himalayas are the Higher Himalayas. They are bounded by Main Central Thrust (MCT) to the southward and Main Mantle Thrust (MMT) to the northward. This part of the Himalayas mainly composed of PrecambrianCambrian Igneous rocks and Cambrian metasedimentary rocks (Shah, 1977; Bender and Raza, 1995).

During the collision, the Kohistan Island Arc was sandwiched between Indian and Eurasian plates. This Island Arc is present above the Higher Himalayas and composed of metavolcanic and plutonic rocks. The Main Karakoram Thrust (MKT) separates Kohistan Island Arc from the Karakoram Block to the north (Shah, 1977).

2.1.3 Structural Geology of the Study Area

The study area has a very complex structural and historical geology. Numerous thrust faults have stacked older rocks on top of younger one. Various microscopic to mesoscopic folds and faults have shuffled the sedimentary successions of the area and created a rugged topography.

Geologically, the study area lies in the southern part of Lesser Himalayas and is known as Hazara Fold-Thrust Belt. The Margala Hill Limestone along with other
Cambrian-Miocene rocks are exposed along this belt. The Hazara Fold-Thrust Belt is capped by the Mansehra crystalline zone to the north, and Potwar Basin to the south. Similarly, the Hazara Fold-Thrust belt is bounded by Kashmir Basin and Peshawar Basin from eastern and western sides, respectively (Figure 2.2). The thrust faults that define the limits of the Hazara Fold-Thrust Belt are the Khairabad fault (northwards and westwards) and the Main Boundary Thrust (southwards and eastwards).
Figure 2.2: Tectonic map of the Lesser Himalayas. Showing various geological provinces and the boundaries of Hazara Fold-Thrust Belt. The blue arrow shows north. The Red square shows the study Area (Modified from Shah, 1977). The blue arrow shows the geographical north.
2.2 Paleogene Geology of the Study Area

2.2.1 Depositional history

The Cenozoic in Pakistan was the era of mountain building and the closure of the Tethys Ocean. During this time, the overall sedimentary system shifted from carbonate dominated marine deposits to siliciclastic dominated mollasse deposits; this was accompanied by the appearance of spectacular land life, especially mammals (Shah, 1977).

The Cenozoic rocks of the Indian subcontinent were deposited in a broad shelf of Tethys Sea. With the passage of time, this sea narrowed down and retreated southward until it reached its current position as the Arabian Sea (Shah, 1977; Bender and Raza 1995). Due to active tectonics concomitant with sedimentation, the rocks of the Cenozoic Era are variable in thickness and lithology in a regional scale. During the Paleogene Period, the Indo-Pakistani plate collided with the southeastern margin of the Afghan microplate (Warwick and Wardlaw, 1992). This collision resulted in the formation of a depression followed by the deposition of a thick succession dominated by carbonates and calcareous shales (Figure 2.3). Excellent outcrops of these rocks can be seen in the Kala-Chitta mountain ranges, Margala-Hills, and Salt-Range.
Figure 2.3: The Paleogeographic map showing the position of Indo-Pakistan plate during the Paleogene Epoch. The depositional trough formed due to the collision of Indo-Pakistan plate with the Afghan microplate is also shown. The star shows the study area (Modified from Warwick and Wardlaw, 1992).
2.3 Paleogene Stratigraphy of the Study Area

During the Paleogene Period, the Hazara Basin was a site of both clastic and carbonate deposition. The sedimentary succession of Hangu, Lockhart, Patala, Margala Hill, Chorgali, and Kuldana formations represents the Paleocene-Eocene series of the basin (Figure 2.4). The Early Paleocene Hangu Formation is formed by paralic deposits dominated by sandstone, shales, and localized coals. The Lockhart Formation lies conformably over the Hangu Formation. The former has a variety of bioclastic limestone, marl, and shales. During Late Paleocene to Early Eocene time, the overall pattern of sedimentation in the basin changed from carbonate-dominated to a siliciclastic-dominated shelf environment. These conditions lead to the deposition of the Patala Formation. Shales, marl, and limestone are the prominent lithologies of the Patala Formation. Later in the Early Eocene (Ypresian Stage), the carbonate factory was restored, leading to the deposition of the bioclastic rich Margala Hill Limestone. The formation lies conformably over the Patala Formation and is overlain conformably by the Chorgali Formation. The overall thickness and the lithofacies attributes of the Margala Hill Limestone vary within the basin. This formation grades upward into the late Early Eocene Chorgali Formation. The later is dominated by lagoonal shales, limestone, evaporites and dolomites. Siliciclastic dominated Kuldana Formation and/or Murree Formation disconformably overlie the Chorgali Formation. The deposition of Kuldana Formation marks the closure of the Eocene carbonate factory of the Hazara Basin; this is followed by the closure of Tethys Ocean and the major rise of the Himalayas. The Miocene recycled sediments (Molasse) of the Himalayas have an erosional lower contact with the Kuldana Formation and/or Chorgali Formation. The generalized stratigraphic
column of the Paleocene and Eocene stratigraphy of the study area is shown in Figure 2.4, followed by the brief description of each formation.
**Figure 2.4:** Stratigraphic column showing the Paleogene stratigraphy of the study area (Modified from Shah, 1977).
2.3.1 Hangu Formation

Davies (1930) termed the Lower Paleocene siliciclastic unit of Kohat area as "Hangu Shale and Hangu Sandstone". This name encompasses the "Dhak pass beds" of Davies and Pinfold (1937), the "Dhak Pass Formation" of the Danilchik and Shah (1987), and the basal part of the "Mari Limestone" of Latif (1970). The Fort Lockhart section (33° 33'40"N and 71° 03'E) and Dhak Pass section (32° 40' N and 71° 44'E) have been designated as the types section and reference section of the formation respectively. In the Hazara area, the formation is 35 meters thick and is dominated by sandstone, siltstone and shale lithofacies (Cheema et al., 1977). The Formation lies unconformably over the Mesozoic strata and is overlain unconformably by Paleocene Lockhart Formation. The biota of the formation is dominated by foraminifera, gastropods, and bivalves (Davies and Pinfold, 1937; Haque, 1956; Iqbal, 1972). Various species of Larger Benthic Foraminifera such as; Operculina, Miscellanea, Lockhartia, and Lepidocycma have been recorded by Davies and Pinfold (1937). On the basis of these fossils, the age of the formation is assigned as Early Paleocene in age. In the Eastern part of the Salt Range, the formation has the economical coal deposits. However, in the Hazara area, localized iron rich facies are present.

2.3.2 Lockhart Formation

Various names were given to Lockhart Formation by different authors. This includes the lower part of the "Hill Limestone" by Wynne (1873), the "Nummulitic series" by Middlemiss (1896), the "Khairabad Limestone" by Gee (1934), "Tarkhobi Limestone" by Eames (1952), and "Mari Limestone" by Latif (1970). The Fort Lockhart section (33 26'N and 70 30'E) has been designated as the type section of the formation (Shah. 1977). In the Hazara Area, the formation is 90-242 meters thick and
is comprised by nodular limestone, marl and shale lithofacies. The formation has conformable contacts with the underlying Hangu Formation and overlying Patala Formation. The Lockhart Formation has a rich association of foraminifera, corals, mollusks, echinoids, and algae. Various authors worked on the paleontology of the formation (Raza, 1967; Cheema, 1968; Latif 1970). Upper Thanetian age has been assigned to the formation on the basis of various species of *Lockhartia, Miscellanea*, and *Operculina*.

### 2.3.3 Patala Formation

The term Patala Formation was established by the Stratigraphic Committee of Pakistan. This name encompasses the middle part of the "Nummulitic Formation” of Waagen and Wynne (1872), the middle part of the "Hill Limestone” of Wynne (1873), the middle part of the "Nummulitic series” of Middlemiss (1896), and the "Kuzagali Shale” of Latif (1970). The Patala Nala Section (32 40' N and 71 49' E) has been designated as type section of the formation.

In the Hazara Basin, the formation is 60 m to 182 m thick and is comprised of green shale and interbedded brown nodular limestone. The Patala Formation conformably overlies the Lockhart Formation and is conformably overlain by the Margala Hill Limestone. Various species of *Nummulites, Oloboratalia, Globigerina, Rotalia, Assilina, Discocyclina Lockhartia*, and *Sakesaria* have been recorded from the formation by (Haque, 1956). The upper boundary of the formation is diachronous becoming younger towards northeast (Hazara area).

### 2.3.4 Margala Hill Limestone

The term Margala Hill Limestone was introduced by Latif (1970). This name was later formally recognized by the Stratigraphy Committee of Pakistan in 1973.
Various other names were given to the Early Eocene strata of the Hazara, Potwar, and Kohat basins. These names include the *Nummulitic* Formation by Waagen and Wynne (1872), the upper part of the "Hill Limestone" by Wynne (1873), and the "*Nummulitic Series*" by Middlemiss (1896). The Shahdara Section (33°48' N and 73°10' E) in the southeastern Hazara is assigned as the type section of the formation. Various facies of bioclastic limestone, and marls. The limestone is gray to pale-gray, nodular, fine to-medium grained, rarely massive, and medium to-thick bedded. The marls are gray to brownish gray. The unit is well-developed in the Kalachitta, Hazara, parts of Potwar and Eastern Kohat. It is 80m-100 m thick in the Hazara Area. The formation lies over the Patala Formation and is underlain by the Chorgali Formation, both with conformable contacts. The bioclasts are dominated by Foraminifera, mollusks, and echinoids. (Raza, 1967; Cheema, 1968; Latif, 1970) have recorded a variety of larger benthic foraminifera from the formation. The recognized species include *Assilina granulosa, A.laminosa, A.papillata, A. spinosa, Discocyclina ranikotensis, Fasciolites delicatissima, F. elliptica, Lepidocyclina (l'oylepidina) punjabensis, Lockhartia conditi, L. hunti, L. tipperi, Nummulites atacicus, N. globulus, Operculina iiwani, O. patolensis and Rotalia trochidiormis*. The reported fossils indicate an Early Eocene age for the formation (Shah, 1977).

### 2.3.5 Chorgali Formation

The term Chorgali beds were used for the first time by Pascoe (1920) for the Upper Eocene thinly bedded unit. The term Chorgali Formation encompasses the "Passage beds" of Pinfold (1918), the "Badhrar beds" of Gee (1934), and the Lora Formation of Latif (1970).

The type section of the formation is located in the Khair-e-Murat Range (33° 26' N and 72° 41' E). The thickness of the formation is 40-45meters in the Hazara
area. The formation represents a shallowing-upward trend. The lower part of the formation is dominated by bioclastic medium bedded limestone interbedded with marl. This open marine strata grades upwards into finely crystalline dolomites, limemudstone, anhydrite and localized paleosols (Benchilla et al., 2002). The foraminifera, molluscs, and algae dominate the allochems of the formation (Pinfold, 1918; Eames, 1952; Gill, 1953; Latif, 1970). The reported larger benthic foraminifers include Assilina granulosa, A. spinosa, A. leymeriei, A. daviesi, Globigerina prolata, Flosculina globosa, Globorotalia reissi, G. wilcoxensis, Lockhartia hunti, L. conditi, Nummulites atacicus, N. mamilla, Orbitolites complanatus and Rotalia crookshankiana. The reported fossils indicate the Early Eocene age for the formation (Shah, 1977).

2.3.6 Kuldana Formation

The "Kuldana beds" of Wynne (1873), "Kuldana series" of Middlemiss (1896), "Variegated Shales" of Pinfold (1918), Mami Khel Clay" of Meissner et al., (1968) and "Kuldana Formation" of Latif (1970) has been formalized as Kuldana Formation by Stratigraphic Committee of Pakistan (Shah, 1977).

The type section of the formation is located near the Kuldana Village, Hazara District (33° 56' and 73°27' E). Dolomite, marl and shale lithologies dominate the lower part of the formation. However, the upper part is more of sandstone, shale, and conglomerates lithofacies. In the Hazara area, the formation comprises of varied colored marl and shale. The formation is 150-200 meters thick in the Hazara area. It lies disconformably over the Chorgali Formation and is disconformably overlain by the Miocene Murree Formation. The lower part of the formation has some foraminifers, gastropods, and bivalves. Vertebrate bones have also been reported from the upper part of the formation by Pinfold (1918), Dehm et al., (1958), Meissner et al.,
(1968) and Latif (1970). The reported fossils suggest Middle Eocene age of the Formation (Shah, 1977)
3.1. General description

The lithofacies analysis of the Margala Hill Limestone has been carried out by thoroughly investigating the outcrop sections in the field and the petrographic examining the collected samples.

A detailed field investigation has been conducted along Murree-Abbottabad road (Figure 1.2). During the outcrop study, useful information such as sedimentary structures, sedimentary textures, fossil content, digenetic features, contacts of various lithofacies and the nature of the depositional surfaces were recorded. The thickness of the formation from the different location and the thickness of the various lithofacies units were measured. Recognition of marker beds to tie among the various sections of the formation was given a major consideration. The recognized marker beds were useful for correlation among the sections and to analyze any lateral and vertical variation of the formation as it occurs in the different sections. Sampling and photography were also an integral part of the field excursion. Microscopic details such as textural attributes, identification of significant fossil genera and species were aided by the petrographic study of the collected samples.

The outcrop and petrographic studies allowed identification of nine lithofacies units (Mf1-Mf9) to constitute the Margala Hill Limestone. These lithofacies units include: miliolid Mudstone (Mf1), Algal-miliolid Wackestone-packstone (Mf2), Bioclastic Packstone (Mf3), Nummulites-Assilina Packstone-Wackestone (Mf4),
*Nummulites-Discocyclina* Wackestone-Packstone (Mf5), Elongated Benthic Foraminifera Wackestone (Mf6), Planktonic Foraminifera Mudstone (Mf7), Bioclastic Marl Lithofacies (Mf8) and unfossiliferous Marl Lithofacies (Mf9). The descriptions of the lithofacies are summarized in Table 3.1, followed by the detailed characteristics, depositional environment energy and environment of each lithofacies.
<table>
<thead>
<tr>
<th>#</th>
<th>Lithofacies</th>
<th>Description</th>
<th>Sedimentary Structures</th>
<th>Depositional Energy and Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mf1</td>
<td>Miliolid Mudstone</td>
<td>Sparsely nodular, light grey lime mudstone.</td>
<td><em>Thalassinoides</em>, Thickly-to medium bedded.</td>
<td>Semi-protected to protected environment and low depositional energy</td>
</tr>
<tr>
<td>Mf3</td>
<td>Bioclastic Packstone</td>
<td>Non-nodular, light grey, bioclastic packstone.</td>
<td><em>Skolithos</em>, <em>Ophiomorpha</em>, Grain imbrications, Thickly-to medium bedded</td>
<td>Open marine and relatively high depositional energy</td>
</tr>
<tr>
<td>Mf4</td>
<td><em>Nummulites-Assilina</em> Packstone-Wackestone</td>
<td>Sparsely nodular, light grey, packstone-wackestone.</td>
<td>Scours, Graded bedding. Medium-to thinly bedded</td>
<td>Open marine and fluctuating energy</td>
</tr>
<tr>
<td>Mf5</td>
<td><em>Nummulites-Discocyclina</em> Wackestone-Packstone</td>
<td>Nodular, light grey, wackestone-packstone.</td>
<td>Nodular, thin to medium bedded</td>
<td>Open Marine-Deep marine and low depositional energy</td>
</tr>
<tr>
<td>Mf6</td>
<td>Elongated Benthic Foraminifera Wackestone</td>
<td>Highly nodular bioclastic wackestone.</td>
<td>Nodular, thin bedded</td>
<td>Deep marine and low depositional energy</td>
</tr>
<tr>
<td>Mf7</td>
<td>Planktonic Foraminifera Mudstone</td>
<td>Highly nodular, light grey, lime mudstone.</td>
<td>Nodular, thin bedded</td>
<td>Deep marine and low depositional energy</td>
</tr>
<tr>
<td>Mf8</td>
<td>Bioclastic Marl</td>
<td>Black, bioclastic marl</td>
<td>Semi-vertical burrows. Thinly bedded</td>
<td>Open-deep marine and low depositional energy</td>
</tr>
<tr>
<td>Mf9</td>
<td>Unfossiliferous Marl</td>
<td>Brown, unfossiliferous marl.</td>
<td>Massive</td>
<td>Deep marine and low depositional energy</td>
</tr>
</tbody>
</table>

**Table 3.1:** Summary of the lithofacies units that constitute the Margala Hill Limestone in the study area, including the level of water agitation (energy) and depositional environments.
3.1.1. Miliolid Mudstone Lithofacies (Mf1)

**Description:** In outcrop, this lithofacies is comprised of a thickly-to medium-bedded, light-to dark grey, sparsely nodular lime mudstone (Figure 3.1a). This lithofacies is mostly present in the middle and upper parts of the formation. Due to high bioturbation, the original texture of this lithofacies has been destroyed (Figure 3.1b). The identifiable trace fossils include *Thalassinoides* (Figure 3.1c).

The petrographic study suggests that this lithofacies has a mudstone depositional texture. The framework grains are composed of poorly sorted and moderately-to well-preserved miliolids, Ostracods and other thin-walled bioclasts. The abundance of these bioclasts ranges from 5%-10% of the overall volume. The micrite matrix surrounds the allochems. Calcite cement fills the chambers of the miliolids and ostracods (Figure 3.2.).

**Interpretation:** The occurrence of miliolids suggests a soft substrate, nutrient rich, low turbulence and restricted/semi-restricted depositional setting (Geel, 2000). The presence of *Thalassinoides* trace fossils and mudstone depositional texture further underscore the deposition in a low energy, nutrient rich and semi-restricted settings (Tucker and Wright, 1990; James and Dalrymple, 2010). Based on the textural attributes, faunal content, and sedimentary structures this lithofacies has been interpreted as a lagoonal environment (Tucker and Wright, 1990; Geel, 2000; James and Dalrymple, 2010).
Figure 3.1: Field photographs of Mf1 lithofacies. (a) Shows Mf1 lithofacies and underlying Mf3 (bioclastic packstone lithofacies). The Mf1 lithofacies is highly bioturbated [Br as indicated in (b)]. Recognizable burrows include *Thalassinoideas* [shown in (c)]. The stratigraphic top is shown by the head of the green arrow [Nathiagali Section].
Figure 3.2: Photomicrographs of Mf1 lithofacies. This lithofacies has a mudstone depositional texture. The allochems of this lithofacies include miliolids [Mi in (a) & (b)], Ostracods [Os in (a)], and other thin walled bioclasts [Twb in (b)]. Other features like pyrite crystals [Py in (a)], and calcite veins [Cv in (b)] are also present. Note the chamber of the bioclasts are filled with white spar.
3.1.2. Algal-Miliolid Wackestone-packstone Lithofacies (Mf2)

**Description:** In the outcrops, this lithofacies is represented by medium-to thickly bedded, grey, and non-nodular wackestone (Figure 3.3a). This lithofacies is mostly present in the upper and middle part of the formation. Intense bioturbation has destroyed the original fabric of the facies, and no sedimentary structure are present. The fresh surface of this lithofacies gives petroliferous odor. Thin streaks of marls and broken fragments of bivalves are present in this lithofacies (Figure 3.2b). In some places, the original wall material of the bivalves has been replaced by calcite spar (Figure 3.2c).

The microscopic study of this lithofacies reveals a wackestone-packstone depositional texture. The framework grains are mainly composed of Dasycladacean algae and miliolid shells. However, thin-walled bivalves and gastropods are also present in some samples. The framework grains are moderately sorted. The abundance of the framework grains ranges from 50-75% of the overall volume. Micritic matrix surrounds the allochems. (Figure 3.3.1).

**Interpretation:** The association of Dasycladacean algae and miliolid foraminifera suggests deposition in warmer water, nutrient rich and shallower water depth (10-15 meter) (Heckel, 1972; Flügel 1982). The wackestone depositional texture further indicates deposition in low to slightly energy environment (Tucker and Wright, 1990; James and Dalrymple, 2010). The occurrence of both hypersaline (miliolid) and open marine fauna (Dasycladacean algae) indicates deposition in a transition zone between a sand shoal and a lagoonal environment (Racey, 1994).
Figure 3.3: Field photographs of Mf2 lithofacies. The lithofacies is composed of thick to medium bedded packstone (a). Thin Marl lamination [M in (b)] interbedded with Mf2 lithofacies. Fragmented shells of bivalves [Bv in (b) & (c)] are also present. The green arrow shows the stratigraphic top. Green arrow shows the stratigraphic top [Bharyan section]. Note: White calcite cement has replaced the original wall material of bivalves [Bv in (b)].
Figure 3.3.1: Microscopic view of Mf2 lithofacies. The miliolid [Mi in (a) & (b)], and Dasycladean algae [Ag in (a) and (b)] dominate the allochemical content of this lithofacies. Note: Different cuts of the Algae are present.
3.1.3 Bioclastic Packstone Lithofacies (Mf3)

**Description:** This is a very typical lithofacies in the Margala Hill Limestone and makes the bulk of the formation along with Mf4 lithofacies. In outcrop, it is a thickly-to-medium-bedded, sparsely nodular, cream color to light grey packstone (Figure 3.4a). This lithofacies is moderately bioturbated. Most of the burrows are semi-vertical to vertical in shape. The identifiable trace fossils include *skolithos* and *ophiomorpha* (Figure 3.4b). Various bioclasts are present in the outcrops (Figure 3.4c). The identifiable fossil includes *Nummulites* and bivalves. In some places, the tests of *Nummulites* and other elongated grains shows imbrications (Figure 3.5).

The microscopic study of this Mf3 shows packstone depositional texture. A variety of bioclastic grains including *Alveolina*, *Nummulites*, Dasycladacean algae and bivalves, make the framework of this lithofacies (Figure 3.6). The foraminifera occurs in this lithofacies are globular and ornamented in shape. The outer surface of some forams are bored, and some grains are partly micritized. The bivalves are mostly broken and fragmented. Sparry calcite cement has replaced the original wall material of the bivalve’s shells. The framework grains of this lithofacies are poorly sorted. The volumetric abundance of the allochems ranges from 85-90% of the overall volume. The micritic matrix surrounds the framework grains. Other features like stylolite and calcite veins also occur in this lithofacies.

**Interpretation:** The abundance of thick walled, ornamented globular bioclasts and the packstone depositional texture suggest a moderate to slightly high depositional energy (Flügel, 1982; Tucker and Wright, 1990; James and Dalrymple, 2010). Sedimentary structures like *ophiomorpha*, *skolithos*, and imbrications of elongated grains
further underscore deposition in a relatively higher energy environment (Racey, 1994; Tucker, and Wright, 1990; James and Dalrymple, 2010). So, based on the textural attributes and sedimentary structures, this lithofacies is interpreted to be deposited as a carbonate sand shoal/barrier depositional environment. The absence of exposure surface in Mf3 suggests subtidal setting (Flügel, 1982).
Figure 3.4: Field characteristics of Mf3 lithofacies: (a) showing the sparsely nodular Mf3 lithofacies. Traces of \textit{Ophiomorpha} [Op in (b)] and \textit{Skolithos} [Sk in (b)] are also present. (c) shows a closeup view of the Mf3 lithofacies. The bioclasts of Mf3 lithofacies can be seen in Figure (c). Note: Green arrow shows the stratigraphic top [Nathiagali section].
Figure 3.5: Photographs showing sedimentary structures in Mf3 lithofacies. Vertical bores [Br in (a)] and grain imbrications [Gi in (a) & (b)] are present. These sedimentary structures indicate higher energy of the depositional environment. Occasional crinoids ossicles [Cr in (b)] are also present in this lithofacies [Bharian Section].
Figure 3.6: Photomicrographs of MF3 lithofacies. The Allochems of this lithofacies is dominated by Alveolina [Al in (a) and (c)], Algae [Ag in (a), (b) & (c)], Bivalves [Bv in (a)] and Nummulites [Nm in (b)]. Some of the bioclasts have microbores [Mb in (a)] on its outer surface. However, other are partially micritized [Pm in (b)]. Diagenetic features like Stylolite [St in (c)] and Calcite veins [Cv in (b)] are also present in this lithofacies.
3.1.4 *Nummulites-Assilina* Wackestone-Packstone Lithofacies (Mf4)

**Description:** This lithofacies commonly reoccurs throughout the Margala Hill Limestone. In outcrop, it is a sparsely nodular, light grey to-dark grey, bioclastic packstone-wackestone (Figure 3.7a). Bioclasts, such as crinoids, *Nummulites*, and *Assilina* can be seen in the field (Figure 3.7 b-c). The beds of the Mf4 lithofacies are characterized by erosional surfaces and normal grading from bioclastic packstone to bioclastic wackestone. The latter is capped by thin (0.5cm-3cm) bioturbated marls (Fig. 3.8a).

Petrographically, this lithofacies has wackestone to packstone depositional texture. The *Nummulites* and *Assilina* constitute the major framework grains of this lithofacies. The abundance of the framework grains ranges from 35-65%. Both megalospheric and microspheric forms of *Assilina* and *Nummulites* are present. The bioclasts are moderately to well-sorted, and moderately-to well-preserved. Partially-dolomitized micrite forms the matrix. (Figure 3.9).

**Interpretation:** The normal grading and the erosional surfaces suggest a deposition site dominated by storms. Thus, these facies are interpreted as a tempestite layers that accumulated below the fair weather wave base (FWWB) but above the storm wave-base (Flügel, 1982). The marl/mudstone that cap the tempestite layers were most likely deposited during inter-storm episodes (Tucker and Wright, 1990; James and Dalrymple, 2010). The close association of *Nummulites* and *Assilina* further indicates that deposition took place below the FWWB (Racey, 1994).
Figure 3.7: Photographs showing the field characteristic of Mf4 lithofacies. (a) Mf4 lithofacies has an occasional sharp contact with the miliolid rich lithofacies (Mf1). (b) shows various bioclasts like Crinoid ossicels, Assilina and Nummulites can also be seen [as shown in (b) and (c)] [Kozgali section].
Figure 3.8. The triangles A, B, and C, represent the tempestite beds in Mf4 lithofacies. Due to the nodular nature of the lithofacies, these beds are deformed. The base of each bed is erosive [Es in (a) & (b)] and has coarse grain bioclasts in the base [CB in (a) & (b)] that grades upward into marl [M in (a)] or lime mudstone [Lm in (b)]. The Marl is bioturbated [Bt in (a)] in some places [Kozagali section].
Figure 3.9: Thin section photos of Mf4 lithofacies. Bioclasts such as *Nummulites* [Nm in (a), (b) & (c)] and *Assilina* [As in (a), (b) & (c)] dominate the allochemical content. The Megalospheric test of *Assilina* and *Nummulites* is also present [Nm and As in (b)]. These tests have a large and round initial chamber (proloculus). Diagenetic features like Dolomite crystals [Dl in (a)] are also present in this lithofacies.
3.1.5 *Nummulites-Discocyclina* Wackestone-Packstone Lithofacies (Mf5)

**Description:** This lithofacies reoccurs throughout the formation. In outcrop, it is represented by medium-bedded, light grey to dark grey, sparsely nodular wackestone to packstone (Figure 3.10). Thin-bedded marl lithofacies (Mf8) is also interbedded with this lithofacies.

The thin section study reveals a packstone-wackestone depositional texture. The framework grains are mainly *Assilina, Nummulites* and *Discocyclina* (Figure 3.11). These bioclasts are flat-discoidal in shape. Recognizable species include *Nummulites atacicus, Assilina laminosa, A.spinosa, Discocyclina ranikothesis* and *D. sendesis*. These grains have moderate sorting and constitute 70-75% of the overall volume. Micritic mud forms the matrix. The volume of the matrix ranges from 25-30% of the overall volume.

**Interpretation:** The flat and discoidal allochems of this lithofacies along with the interbedded marl lithofacies suggest a low energy depositional environment. The intact flat and discoidal larger benthic foraminifera test cannot survive in the high-energy depositional environment but rather prefer to live in a quieter realm (Anketell and Miriheel, 2000; Racey, 1994).
Figure 3.10: Field characteristics of MF5 lithofacies. This unit is composed of thin-medium bedded wackestone-packstone. Note: This unit is interbedded with brown-black marl (MF9). A green arrow shows the stratigraphic top [Nathiagali section].
Figure 3.11: Microscopic pictures of Mf5 lithofacies. The allochems this lithofacies is composed of Nummulites [Nm in (a) & (c)], Discocyclina [Ds in (a), (b) & (c)] and Assilina [As in (b) & (c)]. Crinoids (Cr) are also present in some samples.
3.1.6 Elongated Benthic Foraminifera Wackestone (Mf6)

**Description:** This lithofacies is mostly present in the lower and middle parts of the Margala Hill Limestone. In outcrop, it is characterized by thin-bedded, highly nodular, grey to brown, bioclastic wackestone (Figure 3.12a). Occasionally, thin beds of brown marl (Mf9) are also interbedded with this lithofacies.

In thin section, it has a wackestone depositional texture. A variety of larger benthic foraminifera makes the framework of this lithofacies. The recognizable fossils are intact, elongated to-discoidal *Discocyclina*, *Assilina*, and *Ranikothalia* (Figure 3.12b & c). In some samples, planktonic forams are also present. The framework grains are well-preserved, thin and discoidal in shape. The abundance of the allochems ranges from 20-30% of the overall volume. Chemical compaction features such as stylolite are also present (Figure 3.12c).

**Interpretation:** Thin and elongated tests of the larger benthic foraminifera, as well as planktonic foraminifera, suggest low energy and deeper water depositional realm (Todd, 1964; Flügel, 1982). The assemblage of *Discocyclina* *sp*, *Assilina* *sp*, and *Ranikothalia* *sp* further underscores the relatively deeper, normal marine, quite condition for the deposition of the lithofacies. (Racey, 1994)
Figure 3.12: (a) Field photograph is showing the highly nodular Mf6 lithofacies on top of miliolid Mudstone Lithofacies (Mf1). (b) Photomicrograph showing the allochems of Mf6 lithofacies. Species of *Ranikothalia* (Rn), *Discocyclina* (Ds) and Planktonic forams are present. (c) Photomicrograph showing *Assilina* (As) and stylolite (St) in Mf6 lithofacies [Bharian section].
3.1.7 Planktonic Foraminifera Mudstone Lithofacies (Mf7)

**Description:** This lithofacies is mostly present in the lower part of the Margala Hill Limestone. In outcrop, it is composed of thin-bedded, highly nodular, light grey lime mudstone (Figure 3.13). Irregular, thin (>1 cm) marl thin marl layers separate between the mudstone nodule of this lithofacies (Figure 3.13 b).

Petrographic study of this lithofacies shows a mudstone depositional texture. Planktonic foraminifera and other thin walled bioclasts (broken bivalve fragments) dominate the allochemical content. In some samples, smaller size *Nummulites* also occur. The allochems are scattered and poorly sorted. These bioclastic are sand to fine silt size and volumetrically range from 5-10% of the overall amount of the thin sections. Micritic matrix makes the bulk of this lithofacies. Other features like stylolite are also present in this lithofacies (Figure 3.14).

**Interpretation:** The mudstone depositional texture indicates low energy depositional environment (Tucker and Wright, 1990; James and Dalrymple, 2010). The occurrence of planktonic foraminifera and thin-walled organisms suggest open, relatively deep marine, depositional environment (Todd, 1964). The nodular aspect of the lithofacies and thin irregular marls are due to diagenetic modifications (Moller and Kvingan, 1998). The depositional surface was undulating with ups and downs. The marls were deposited on troughs of the depositional surface. Compaction effects have later enhanced the nodularity of the strata and irregularity of the inter-nodule marls (Figure 3.13b).
Figure 3.13: Field photographs of Mf7 lithofacies. (a) Highly nodular lime mudstone (Mf7) overlying the thick bedded Mf4 lithofacies. (b) This photo shows thin marl [M] interbedded with Mf7 lithofacies. The green arrow shows the stratigraphic top [Kozagali section].
Figure 3.14: The allochems of Mf7 lithofacies are characterized by planktonic foraminifera [Pk in (a), (b) & (c)] and thin wall bioclasts [Twb in (b)]. Smaller test of Nummulites [SF in (b)] also occurs in some samples. Other features like stylolite [Sty in (a)] are common in this lithofacies.
3.1.8 Bioclastic Marl Lithofacies (Mf8)

**Description:** This lithofacies is present throughout in the Margala Hill Limestone of the study area. In outcrop, it is composed of bioclastic, grey to-black, thinly bedded marl (Figure 3.15). The thickness of beds ranges from a few centimeters to 0.5 meters. The recognizable bioclasts include fragmented bivalves (Figure 3.15a) and occasional larger benthic foraminifera. This lithofacies is highly bioturbated, and bioturbation has destroyed the primary sedimentary structures. Most of the burrows are semi-vertical to vertical (*Skolithos* or *Ophiomorpha*) (Figure 3.15c). The fresh surface of this lithofacies gives a petroliferous odor. This lithofacies is interbedded with *Nummulites-Assilina* Packstone-Wackestone (Mf4) and occasionally with *Nummulites-Discocyclina* Wackestone-Packstone (Mf5) lithofacies.

**Interpretation:** The association of this lithofacies with the *Nummulites-Assilina* Packstone-Wackestone (Mf4) and *Nummulites-Discocyclina* Wackestone-packstone (Mf5) lithofacies suggests open marine depositional environment. The occurrence of the bivalves and occasional larger benthic foraminifera further underscore open marine subtidal depositional environment (Racey, 1994).
Figure 3.15: (a) Photograph showing bioclastic marl lithofacies [Mf8] interbedded with *Nummulitic-Assilina* wackestone lithofacies [Mf4]. Broken bioclastic fragments such as Bivalves [Bv] can be seen. (b) Close up photograph of Mf8 lithofacies showing various fragmented bioclasts. (c) Field photograph showing the interbedded Mf8 and Mf4 lithofacies. Obvious vertical bores [Vb] *skolithos/ophiomorpha* can be seen in this photo. Note: The stratigraphic top is shown by the head of a green arrow [Goragali section].
3.1.9 Unfossiliferous Marl Lithofacies (Mf 9)

**Description:** This lithofacies occurs mostly in the lower part of the Margala Hill Limestone. In outcrop, it is composed of light to-dark brown-black, non-bioclastic and fissile marl (Figure 3.16). The bed thickness of this lithofacies ranges from few centimeters to 0.5 meters. This lithofacies in associated with the planktonic mudstone lithofacies (Mf7). No physical or biological sedimentary structure can be seen in this lithofacies. Small iron oxide nodules have also associated this lithofacies.

**Interpretation:** The association of this lithofacies with the deep marine facies such as planktonic mudstone lithofacies (Mf7) and occasionally with the elongated benthic foraminiferal wackestones (Mf6) suggests a deep marine environment. The absence of biota and finer grain size further underscore the low depositional energy and deeper depositional environment (Tucker and Wright, 1990; James and Dalrymple, 2010).
Figure 3.16: (a) Unfossiliferous marl lithofacies [Mf9] associated with planktonic foraminiferal mudstone lithofacies [Mf7]. (b) Unfossiliferous marl lithofacies interbedded with the nodular planktonic mudstone lithofacies [Mf7]. The head of the green arrow shows the stratigraphic top [Goragali section].
3.2 Depositional environment of the Margala Hill Limestone

The lithologic attributes and fossil content of the Margala Hill Limestone indicate deposition on a shallow marine carbonate platform within a tropical pale-geographic location. This Eocene platform was located on the northwestern edge of the Indian paleocontinent before adjoining the Asian Plate (Figure 3.17). Carbonate platforms that are attached to the mainland can be either a ramp type or a rimmed one. The former is characterized by a gentle slope (<1°) basin-wards to the shelf. The near-shore environments are characterized by a relatively higher energy environment that grade basin-wards into a variety of low energy environments. The shallower part of the platform is complex and has continuous to the discrete barrier (Bioclastic/carbonate shoals). The barrier makes smaller scale protected environments (lagoon/ponds) landwards of the basin. The rimmed platforms are characterized by a pronounced lime-sand shoals and/or a reef seaward on the shelf. The barrier absorbs the high-energy waves and makes a lower energy depositional environment landwards. Seawards to the shoal/barrier is a steep-to gentle slope, characterized by debris flow, fans, and other gravity-driven deposits (Tucker and Wright, 1990; James and Dalrymple, 2010).

Based on the lithofacies attributes, fossil content and lithofacies associations of the Margala Hill Limestone, it is suggested that the formation accumulated in a homoclinal ramp system (Figure 3.18). The fair-weather wavebase (FWWB) and storm wavebase (SWB) divide the ramp into an inner ramp, middle ramp and an outer ramp (Burchette and Wright, 1992). No subaerial exposures were identified, although shallowing-upward cycles were recognized (Section 5.2) No supratidal deposits were identified throughout the formation. This underscores that the formation accumulated
mainly under subtidal (to possibly intertidal) conditions. The details of the subenvironments of the Margala Hill Limestone are explained below.

3.2.1 Inner ramp

The inner ramp depositional site is the shallowest part of the ramp and lies above the fair weather wave base (FWWB). This part of the platform consisted of three sub-depositional environments (lagoonal environment, the transition zone, and the bioclastic sand shoal) (Burchette and Wright, 1992).

In the studied formation, the miliolid mudstone lithofacies (Mf1) represents the lagoonal sub environment. The high miliolid content and high bioturbation index including *Thalassinooides* support the lagoonal interpretation (Racey, 1994; James and Dalrymple, 2010). This lithofacies has a mudstone depositional texture and is composed of miliolids and other thin walled bioclasts. The Mf1 is highly bioturbated. The recognizable traces are *Thalassinooides*. The lagoon is formed due to the accumulation of bioclastic packstone (Mf3) seewards to the Mf1 lithofacies. The globular bioclasts, *Skolithos, Ophiomorpha*, and imbricated grains suggest the relatively higher energy of Mf3 lithofacies (Burchette and Wright, 1992). The Algal-Miliolid wackestone-packstone lithofacies (Mf2) represents the transition zone between the lagoon (Mf1) and the barrier (Mf3) subenvironments. The sedimentary process of the adjacent subenvironments (Mf1 and Mf3) affected the Mf2 lithofacies.
Figure 3.17: The Eocene paleogeographic map. The red dot indicate the location of the study area (Paleogeographic map is from Scotese et al., 2010).
3.2.2 Mid ramp

The mid ramp lies below the fair weather wave-base (FWWB) and above the storm wave-base (SWB). Storm waves frequently rework the sediments in this part (Burchette and Wright, 1992). In the studied formation, the *Nummulites-Assilina* wackestone-packstone lithofacies (Mf4), *Nummulites-Discocyclina* Wackestone-Packstone lithofacies (Mf5), and Bioclastic marl lithofacies (MF8) represent the mid ramp settings.

The MF4 lithofacies shows proximal, mid ramp and is composed of *Nummulites* and *Assilina* rich packstone-wackestone. Tempestite beds represent the storm events in this lithofacies (Burchette and Wright, 1992). The occurrence of *Assilina* and *Nummulites* in Mf4 further supports the interpretation (Racey, 1994). Distal-mid ramp, seawards to the Mf4, is represented by Mf5 lithofacies. This lithofacies has various species of discoidal *Discocyclina, Assilina*, and *Nummulites*. The association of distal tempestite in Mf5 shows less stirring by storm waves and currents. The bioturbated Marl lithofacies (Mf8) which is interbedded with both Mf4 and Mf5 lithofacies indicates quiet, inter-storm accumulations (Burchette and Wright, 1992). Basinwards, the thickness of the marl (Mf8) and the degree of bioturbation increase.

3.2.3 Outer ramp

The outer ramp lies below the storm weather wave base (SWB) (Tucker and Wright, 1990). The sediment accumulation occurs due to the deposition of thin and elongated bioclasts, pelagic mud and planktonic foraminifera (James and Dalrymple, 2010; Racey, 1994). In the Margala Hill Limestone, the Elongated benthic foraminifera
wackestone (Mf6), Planktonic foraminiferal mudstone (Mf7) and unfossiliferous marl (Mf9) lithofacies represents the outer ramp depositional environment (Todd, 1964).

The MF6 lithofacies is composed thinly bedded bioclastic wackestone. This lithofacies has well preserved thin bioclasts and occasional planktonic foraminifera. The fossil content of the Mf6 lithofacies suggests deposition in very low energy and deeper water setting (Racey, 1994). The absence of physical sedimentary structure in Mf6 indicates deposition below the storm weather wave base (SWB). However, the planktonic foraminiferal mudstone lithofacies (Mf7) represents deposition in a distal outer ramp setting (Todd, 1964). The non-fossiliferous and non-bioturbated marl (Mf9) is also interbedded with Mf6 and Mf7 lithofacies and represents deeper water settings.

3.3 Lithostratigraphic Correlation

The Margala Hill Limestone has been correlated in the studied sections. Two of the sections are present with both conformable contacts and total thickness is achieved. However, two sections are present with a lower faulted contact. The correlation is based on the presence of common lithofacies present in all four sections (Figure 3.19). The lower part of the formation in all four section has same lithofacies. However the facies in the middle and upper part of the formation in various section varies. The difference in the lithofacies is because of differential tectonics in the basin.
Figure 3.18: The hypothetical depositional model of the Margala Hill Limestone. Various lithofacies making different components of the ramp are shown. The light blue polygon shows the depositional energy while the light green bar illustrates the flatness of larger benthic foraminifera. The distal inner ramp has higher energy (H) and globular bioclasts (G). Seawards and landwards from the MF3, the energy decreases (L), and bioclasts become more flat and thin (T).
Figure 3.19: Lithostratigraphic correlation of the Margala Hill Limestone in the studied four sections.
Chapter Four

4.0 Biostratigraphy of the Margala Hill Limestone

4.1 Introduction

The Eocene succession of the study area is highly fossiliferous and contains abundant and moderately to well preserved larger benthic foraminifera (LBF). These fossils are very useful for both paleoenvironmental interpretation and biostratigraphic dating. Various species of *Alveolina, Assilina, Nummulites, Operculina, Lockhartia, Discocyclina*, and *Ranikothalia* have been reported from the Eocene strata of the study area by Raza (1967), Cheema (1968), Latif (1970) and Swati et al., (2013). The biostratigraphic application of these species is given below.

4.2 Biostratigraphy Using Larger Benthic Foraminifera (LBF)

For the Tertiary rocks of Tethys ocean, several biostratigraphic zonal schemes have been developed by Hottinger (1960), Blondaeau (1972) and Schaub (1981). Index species including *Alveolinids, Nummulitids, and Assilinids*, were used in these biozones to mark the boundaries between various epochs and stages of the Cenozoic Era. These schemes have been further classified into the Shallow Benthic Zones (SBZ) by Serra Kiel et al., (1998). The validity of these biozones has been tested by several authors (Racey, 1994; Ahmad, 2010 and Swati et al., 2013). The tertiary rocks of Oman were successfully dated by Racey (1994) using these biozonal schemes. Similarly, Ahmad (2010) used these biozones to date the Paleogene rocks of Kohat and Potwar Basins, Northwestern
Pakistan. Moreover, the Margala Hill Limestone of the Southwestern Hazara has been dated by Swati et al., (2013) using the above-mentioned biozonation scheme.

### 4.3 Present study

Swati et al., (2013) have worked on the Margala Hill Limestone of the Kohala Bala Area, Southwestern Hazara, Pakistan. However, there are two problems with this study: (1) the uppermost part of the formation is missing from Swati et al’s (2013) Kohala-Bala section and (2) about 40 meters (in the central part of the formation) is covered. Thus, the formation still needs a refined biostratigraphy to ensure the age of both upper and lower boundaries of the formation.

In this study, 4 stratigraphic sections have been selected for lithostratigraphic and biostratigraphic study of the Margala Hill Limestone in the Hazara Basin. For this purpose, more than one hundred samples have been collected from the logged sections. A thorough petrographic analysis (microfacies and biofacies) of the samples has been carried out. Sixteen LBF species were recognized and identified. These species are grouped together into a biozone (MHF). It is observed that the overall formation lies in one biozone. A comparison of the biozone (MHF) to the standard biozones of Schaub (1981) and Serra Kiel et al., (1998) have been performed. This comparison suggests the resemblance of MHF biozone to the Assilina leymerie/Nummulites globulus biozone of Schaub (1981) and SBZ 8 biozone of Serra Kiel et al., (1998). This study suggests the Middle Ilerdian 2 (Early Eocene Epoch)/SBZ 8 age of the formation.
4.4 Description of Species

The morphological description of various LBF occur in the formation are given below.

4.4.1 Nummulites

The test of *Nummulites* is lenticular-globular in shape. The initial whorls are tightly coiled that grades to lose coiling in the whorls away from the nucleus. The septa divide the coiling into numerous chambers. The size the test ranges from 1 mm to 6 mm. The geologic range of *Nummulites* is from Early Eocene to Early Oligocene (Hottinger, 1960; Blondaeau, 1972; Schaub, 1981; Serra Kiel et al., 1998). Various species of *Nummulites* reported from the formation are given below.

4.4.1.1 Nummulites globulus

**Remarks:** This species is present throughout the formation. The test is highly biconvex and globular. The walls of each chamber are relatively thick as compared to other species. The development of pillars is poor and is present in the central part of the test. The proloculus (Initial chamber) is small as compared to the overall test and in many representatives, it is absent. The size of the test ranges up to 3 mm in the studied (Figure 4.1 a &b).

4.4.1.2 Nummulites mammillatus

**Remarks:** This species has a lenticular-globular test. A prominent radial shape proloculus is also present in the central part of the test. The pillars are not developed. The degree of coiling varies from loose to-tight. The walls are thick. The size of the test ranges up to 2 mm in the formation (Figure 4.1 c &d).
4.4.1.3 *Nummulites atacicus*

**Remarks:** This species is abundant in the lower and upper part of the formation. It has a lenticular test. The walls are thin as compared to other species. The Umbilical pillars are well developed and is present in the central part of the test. The size of the proloculus is smaller. The size of the test ranges up to 3 mm. The whorls close to the proloculus are tightly coiled and away from the proloculus are loosely coiled (Figure 4.1 e &f).
Figure 4.1: Species of Nummulites. The Nummulites Globulus has a Globular test [(a) & (b)]. The proloculas is small as compared to the overall size of test or either it is absent. The Nummulites mamalitus [(c) & (d)] has a thick chamber and a prominent larger size of proloculas. The Nummulites atacicus [(e) & (f)] has a lenticular test. The species has prominent pillars in the central part of the shell.
4.4.2 Assilina

The test of the Assilina ranges from planispiral to lenticular in shape. Some species has a central depression that leads to the enveloping of the chamber over one another. Proloculas is present in many species. The coiling is tight in most species. The geologic range of Assilina is from Late Paleocene to Middle Eocene (Hottinger, 1960; Blondaeau, 1972; Schaub, 1981; Serra Kiel et al., 1998). The details of the reported species of Assilina is given below.

4.4.2.1 Assilina granulosa

Remarks: The test of this species is long, flat, and thin in shape. The margins of the test are sharp. Small scattered ridges and granules are also present on the surface of the test. The proloculus is absent in this species. The size of the test ranges up to 4 mm in many species (Figure 4.2 a &b).

4.4.2.2 Assilina laminosa

Remarks: The shape of this species is lenticular, and is characterized by sharp edges. The walls are thick. The proloculus is poorly developed to absent in many species. No pillars have been reported in this species of Assilina. The outer surface is smooth and barely granulated. The size of the test ranges up to 2 mm (Figure 4.2 c &d).

4.4.2.3 Assilina subspinosa

Remarks: The test of this species is lenticular-to-flat in shape. The outer surface of the test is characterized by thick, prominent and concentrated ridges. Edges of the test are sharp in most representatives. The walls are thick. The proloculus is barely developed. This species is present throughout the formation. The size of the test ranges up to 3 mm (Figure 4.2 e).
4.4.2.4 Assilina spinosa

Remark: The shape of the test is lenticular. This species also has a well-ornamented surface. The test of this species has a central depression leading to shorter size of granules in the central part. The proloculas is well developed in this species. The size of the test ranges up to 2 mm (Figure 4.2 f).
Figure 4.2: Various species of Assilina. The Assilina granulosa [(a) & (b)] has a long and elongated test. The Assilina laminosa [(c) & (d)] is highly lenticular in shape and has a smooth outer surface. The A. Spinosa (e) also has a lenticular shape, ornamented outer surface, and a prominent proloculus. The A. subspinosa (F) has scattered, well-developed spines on its outer surface and larger size of the test.
4.4.3 Discocyclina

Discocyclina has a discoidal and a flat test with numerous small chambers. Some species have a bulge in the central part. The thin flanks radiate from the central bulge. The geologic range of Discocyclina is from Middle Paleocene to Late Eocene (Hottinger, 1960; Blondaieu, 1972; Schaub, 1981; Serra Kiel et al, 1998). Two species of Discocyclina has been recognized from the Margala Hill Limestone. The description of these species is given below.

4.4.3.1 Discocyclina dispensa

Remarks: The test of this species is round, biconvex, and globular in the center (Figure 4.3 a&b). The flat, thin and discoidal flanks radiate from the central part of the test. In the studied samples, most species have broken flanks. The test is characterized by numerous chambers of various size. Due to the high micrite content in the samples, the delicate coiling, and internal structure is poorly preserved. The size of the species ranges up to 3 mm in the formation.

4.4.3.2 Discocyclina ranikothesis

Remarks: Unlike Discocyclina Dispensa, this species is very flat, elongated and thin in shape (Figure 4.3 c). The central part has a very gentle, and small biconvex bulge. This species is also characterized by chambers. The outer surface of the test has scattered granules. The size of the species ranges up to 4 mm.

4.4.4 Lockhartia

This species of LBF has a conical to lenticular test. The test has numerous chambers. Thin to thick pillar are present in the central part of most representatives. Micritization have deformed most of the representative of this species in the Margala Hill Limestone. The recognizable species includes Lokhartia conditi.
4.4.4.1 *Lockhartia conditi*

**Remarks:** This species has an ornamented shell. Thick and well prominent pillars are present in the central part of the test. *Lockhartia conditi* is present mostly in the middle and upper part of Margala Hills Limestone. The size of the test ranges up to 3 mm (Figure d &e).
Figure 4.3: Various species of Larger Benthic Foraminifera. The *Dicocyclina dispensa* [(a) & (b)] has a rounded budge in its central part, and the thin flanks radiate out of it. The *Discocyclina ranikothesis* (c) has a long, thin and a flat test. The *Lockhartia condotii* (d) has a conical test with prominent pillars in its central part (d). The internal features of *L.Sp* (e) is not very clear.
4.4.5 Alveolina sp.

These species reoccur throughout the formation in all four sections studied here. The test is spherical to-globular. Pillar and proloculus are absent (Figure 4.4a & b). The first few coils are loose while the outer whorls are tightly coiled. Straight to curved septa divide the coiling into various chambers. The size of the chambers varies across the species. The size of the species ranges up to 3 mm (Figure 4.4 a &b).

4.4.6 Operculina sp.

The test of Operculina sp. is planspiral, flat and elongated (Figure 4.4c & d). The pillars and proloculus are absent. Some representatives in the formation have grooves and ridges on their outer surfaces. This species is mostly present in the lower part of the formation. The size of the test ranges up to 3 mm (Figure 4.4 c &d).

4.4.7 Ranikothalia sp.

The test of Ranikothalia Sp. is thin, and flat-lenticular in shape (Figure 4.4e). The edges of the test have a bulge. The coiling of the test varies from loose to-tight in various species. The size of the species ranges up to 6 mm (Figure 4.4 e).
Figure 4.4: The *Alveolina* Sp [(a) & (b)] has a globular, robust and thick shell. The curved semi curved septa divide the coiling into various chambers. The *Operculina* sp [(c) & (d)] has a thin and planispiral test. The test is barely granulated. The *Ranikothalia* sp (d) has a long and thin test. The edges of the test have a rounded bulge.
4.5 The age range of the Margala Hill Limestone

The Margala Hill Limestone in Hazara Area lies conformably over the Paleocene-Eocene Patala Formation and is conformably overlain by the Eocene Chorgali Formation. The middle and lower part of the Patala Formation is Upper Paleocene. Whereas the upper part is Early Eocene in age (Shah, 1977). The occurrence of Miscellanea miscella in the lower and middle part and Nummulites sp and Assilina laminosa in the upper part confirm these age designations given to the Patala Formation (Sameeni et al., 2014). The extinction of the Miscellanea miscella marks the upper boundary of the Paleocene Epoch, whereas the first appearance of the Nummulites mamillatus marks the start of the Early Eocene Epoch in Pakistan (Sameeni et al., 2014).

As shown, the Margala Hill Limestone is a carbonate-dominated unit which contains a variety of LBF species. The age diagnostic fossils species that occur in the formation are Nummulites globulus, N.atacicus, N.mamillitus, N.sp., Assilina granulosa, A.subspinosa, A. spinosa, A. laminosa, Lockhartia conditi, L.sp, Alveolina sp., Discocyclina ranikothesis, D.dispensa, Ranikothalia sp., and Operculina sp. (Latif, 1970; Shah, 1977; Swati et al., 2013, and this study). The age of these species ranges from the Lower Paleocene to the Lower Eocene (Serra Kiel et al., 1998). Figure 4.5 shows the exact biostratigraphic age range of each species that occur within the studied formation. Among these fossils, the age range of the Nummulites globulus, N.atacicus, and Assilina laminosa is relatively small. It starts from the lower boundary of the SBZ 8/Middle Ilerdian 2 and ends at the upper limit of SBZ 8/Middle Ilerdian 2 (Schaub 1981; Serra Kiel et al., 1998). For that reason, these fossils are considered as the most significant index fossils for the formation and indicate a SBZ 8/Middle Ilerdian 2 stage of the Early
Eocene Epoch (Fig 4.5). In the studied sections, these species are recorded from the lower, middle and upper part of the formation. Hence, it is concluded that the Margala Hill Limestone lies within SBZ 8 stage of Serra Keil et al., 1998 and Middle Ilerdian 2 stage of Schaub (1981). It is also observed that the Margala Hill Limestone (both boundaries) has similar age in all studied sections.

The lithology of overlying Chorgali Formation is dominated by bioclastic limestone, dolomite, marl and shale lithofacies. The formation consists of well-preserved species of larger benthic foraminifera (Shah, 1977; Sameeni et al., 2014). The occurrence of the Alveolina indicatrix suggests the SBZ 9/ Upper Ilerdian age for the formation (Sameeni et al., 2014). The SBZ 9/Upper Ilerdian age of the overlying Chorgali Formation further confirms the SBZ 8/ Middle Ilerdian 2 for the upper boundary of the Margala Hill Limestone (Sameeni et al., 2014).

The distribution of the various species of LBF which are recognized from the Margala Hill Limestone in four studied sections are given below in figure 4.6, 4.7, 4.8 and 4.9.
Figure 4.5: Showing age range of various LBF occur in the Margala Hill Limestone. The red lines show the age range of index fossils while the blue line shows the age range of other associated longer range faunae. Note: The index fossils suggest the age of the MHF 1 as Middle Ilerdian 2/SBZ 8 (Early Eocene) (Modified from Schaub 1981 and Serra Kiel et al., 1998)

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Figure 4.6: Biostratigraphic chart of the Nathiyagali section (Section 1) showing the distribution of various larger benthic foraminifera in the formation.
**Figure 4.7**: Biostratigraphic chart of the Bharyan Section (Section 2) showing the distribution of various larger benthic foraminifera in the formation.
Figure 4.8: Biostratigraphy chart of Kozagali Section (Section 3) showing the distribution of various larger benthic foraminifera in the formation.
Figure 4.9: Biostratigraphic Chart of the Goragali section (Section 4) showing the distribution of various larger benthic foraminifera in the formation.
4.6 Biostratigraphic Correlation

The Early Eocene limestones of the majority of Neotethys contain a good record of Larger Benthic Foraminifera (Bellen et al., 1959; Schaub, 1981; Hottinger, 1971; Rahaghi, 1980; Sengor, 1984; White, 1994; Racey, 1994; Serra Kiel et al., 1998; Karim and Baziany, 2007; Sameeni et al., 2014 and Ahmad, 2010). These fossils are very useful for the biostratigraphic dating and biostratigraphic correlation. In this section, the Margala Hill Limestone is correlated with the Early Eocene strata of Pakistan, and with the Early Eocene strata of the India, Oman, Saudia Arabia, and Iraq. The correlation is carried out by using the age diagnostic index fossils such as *Nummulites atacicus*, *N. globulus*, *Assilina laminosa* and *Lockhartia teperie*. The details of the local and regional correlation of the Margala Hill Limestone with other Early Eocene units are given below.

4.6.1 Local biostratigraphic correlation of the Margala Hill Limestone

The Early Eocene strata of Pakistan is dominated by carbonates, localized shales, and evaporites. The carbonates of these rocks are highly fossiliferous and contain a variety of Larger Benthic Foraminifera (Shah, 1977). These fossils are used by various authors for the biostratigraphic dating of the Eocene strata in Pakistan (Shah, 1977; Swati., et al., 2013; Ahmad, 2010; Sameeni et al., 2014; and Alizai et al., 2016). In this study, the Margala Hill Limestone of the Hazara Area has been correlated with its equivalent succession of the adjacent basins in Pakistan. These basins include Kohat Basin, Potwar Basin, Salt Range (Upper Indus Basin), and Lower Indus Basin. The correlation has been performed by using the index fossils such as *Nummulites atacicus*, *N. globulus* and *A. laminosa* (Figure 4.10).
The Early Eocene rocks of the Kohat Basin is comprised of Panona Formation and Shekhan Formation (Shah, 1977). The Shekhan Formation is composed of interbedded limestone and shale. The limestone is thin bedded and nodular while the shale is gypsiferous (Cheema et al., 1977). The index fossils occur in the lower part of the Shekhan Formation are Assilina pustolosa, Alveolina vrendenburgi, and Discocyclina sella. The central part of the formation contain Nummulites atacicus, N.globulus, and N. mamalitus. However, the age diagnostic species of the upper part of the formation are Nummulites palnulatus, Assilina laxispira, and Alveolina rotundata. Based on these age diagnostic fossils, it is concluded that the lower part of the formation is Lower Ilerdian2-Middle Ilerdian 1, the central part is Middle Ilerdian 2 and the top portion is Upper Ilerdian to Cuisian in age (Alizai et al., 2016).

Similarly, The Early Eocene strata of Potwar basin and Saltrange is comprised of Nammal Formation, Sakesar Formation and Chorgali Formation (Shah, 1977). The Nammal Formation and Sakesar Formation are primarily composed of bioclastic limestones, shale, and marl. Both formations have a well-preserved species of Nummulites atacicus, N.globulas, and Assilina laminosa. Based on these age diagnostic foraminifera, these formations are biostratigraphically dated as Middle Ilerdian 2/SBZ 8 (Ahmad, 2010).

The Ghazij Group represents the Early Eocene strata of the Axial Belt and Lower Indus Basin. The unit composed of shale, arenaceous limestone, and localized coal. The upper fossils content of the group suggests the Lower Eocene age of the Group (Shah, 1977).
It is concluded that the biostratigraphically equivalent units of the Margala Hill Limestone in Pakistan include middle part of the Shekhan Formation (Kohat), Nammal Formation, Sakesar Formation (Potwar Basin and the Salt Range), and Ghazij Group (Lower Indus Basin/Axial Belt). Correlation of these strata with the Margala Hill Limestone is shown in Figure 4.10.
Figure 4.10: The biostratigraphic correlation of the various Early Eocene units in Pakistan. The Margala Hill Limestone of the study area is equivalent to the middle part of the Shekhan Formation, Nammal Formation, Sakesar Formation and Ghazij Group.
4.6.2 Regional Correlation Of The Margala Hill Limestone.

The Tethys Ocean existed between the Laurasia and Gondwana during most of the Mesozoic Era. Scotese et al., (2010) divided the Tethys Ocean into Northern (Paleothetys) and Southern (Neo-Tethys) parts. The present geographical entities of the Eastern Neo-Tethys are Pakistan, Indonesia, India and the Indian Ocean while Saudi Arabia, Oman, Yemen, Lebanon, Iraq, United Arab Emirates, and Iran covered the area once occupied by the central Neo-Tethys. However, the Aral Sea, the Caspian Sea, and the Black Sea are located in the area once covered by the Western Neo-Tethys (Stampfli, 2000). The Paleogene strata of the Neo-Tethys contain well-preserved species of LBF. Species of *Nummulites, Assilina* and *Aleolina* have been reported and compared from the Neo-Tethys by several authors (Bellen et al.,1959; Schaub, 1981; Hottinger, 1971; Rahaghi, 1980; Sengor, 1984; White, 1994; Racey, 1995; Serra-Kiel et al.,1998; Karim and Baziany, 2007; Sameeni et al., 2014 and Ahmad, 2010). In this study, the Early Eocene Margla Hill Limestone is correlated with its equivalent strata of the other parts of the Neo-Tethys (Figure 4.11 and 4.12). The Index fossils *Nummulites atacicus*, *N. globolus*, and *Lockhartia teperie* have been used for the correlation.
Figure 4.11: The Paleogeographic map of the Eocene Epoch. Showing the study area and its equivalent units across the Neo-Tethys ocean. Various localities across the Neo-Tethys are presented with the numbers [1 (Iraq), 2 (Saudia Arabia), 3 (Oman), 4 (Study Area), 5 (India)] (Modified from Blakey, 1988).
4.6.2.1 Pakistan

The Early Eocene strata of the Pakistan is dominated by carbonates and contain abundant and moderately to well preserved LBF. These fossils include *Nummulites atacicus*, *N. globulus*, *N. mamalitus*, *Assilina leymeri*, *A. granulosa*, *A. spinosa*, *A. subspinosa*, *A. laminosa*, *Alveolina sp*, *Lockhartia condoti*, *L. tapierie*, *Discocyclina dispensa*, *D. ranikothesis*, *Ranikothalia sp.*, and *Operculinasp*. The *Nummulites atacicus*, *N.globulus*, *N. mamalitus*, *Assilisa leymerie* and *A. laminosa* among them are index fossils and have been used for the biostratigraphic dating of the Early Eocene units of Pakistan (Latif, 1970; Shah, 1977; Ahmad, 2010; Swati., et al., 2013; Sameeni et al., 2014; and Alizai et al., 2016).

4.6.2.2 India

The Sylhet Limestone Group of the South Shillong Plateau contain an excellent association of the Larger Benthic Foraminifera (Evans, 1932; Ghosh, 1940; Nagappa, 1959; Murty, 1983). The Sylhet Limestone Group is composed of three carbonate-bearing formations separated by the sandstone lithofacies. These formations are Lakadong Formation (Lower), Umlatdoh Formation (Middle), and Prang Formation(Upper). The lower part of the Umlatdoh Formation contain a well-preserved species of *Ranikothalia nuttalli*, *Daviesina ruida*, and *Nummulites sp*. These fossils suggest the SBZ 5, SBZ 6 and SBZ 7 age for the lower part of the Formation. The middle part of the formation has species of *N.cf*, *N.atacicus*, and *Aleveolina sp* suggesting the SBZ 8 age for the middle part of the Formation. However, the top of the formation is SBZ 9 in age and contain *Alveolina schwageri*, *A.aeff.* and *A. sp.* (Jauhri and Agarwal, 2011).
4.6.2.3 Oman

The Paleogene strata of the central Oman is comprised of Jafnayn Formation, Rusayl Formation, Seeb Formation and Mahm Formation. The Jafnayn Formation is an Early Paleogene carbonate unit (Al-Sayigh and Salad Hersi, 2008). The lower member of the formation is composed of a variety of carbonate lithofacies and contain age diagnostic fossils such as *Lockhartia diiversa*, *Daviesina persica*, *Kathina sp* and *Nummulitoides margaretae*. Based on the fossils content the lower member of the formation is biostratigraphically dated as Upper Paleocene (Thanetian). However, the upper part of the formation is composed of relatively high energy carbonates lithofacies such as Coral facies, Red-algal facies, and grainstone lithofacies. Based on the presence of *Nummulites globulus*, *Sakesaria cotteri*, *Heterosteginaruid* in the upper part of the Jafnayn Formation, it is dated as Middle Eocene to Early Eocene (Ypresian) (Al-Sayigh and Salad Hersi, 2008).

4.6.2.4 Iraq

The Early Eocene Naopurdan Group is a carbonate-dominated unit in Iraq. This group extends westwards into Iran and eastwards into Turkey. This group contains various facies of bioclastic limtstones. The age diagnostic species of Larger Benthic Foraminifera in the group includes *Nummulites atacicus*, *N. aturicus*, *Alveolina oblonga*, *Alveolina sp.* and *Assilina sp.* Based on these fossils assemblages the group is dated as Early Eocene (Jassim and Goff, 2006).

4.6.2.5 Saudi Arabia

The Umm er Radhuma Formation represents the Early Paleogene strata of the Saudi Arabia. The unit is primarily composed of bioclastic limestone, dolomite, and
localized chert. The lowermost section of the formation contains well-preserved species of *Anamolina, dorri, Bulimina semicostata, Aragonesis, Siphogenerina eleganta and Loxostoma applinae*. These fossils reveal the Upper Paleocene age for lower part of the formation. However, the *Sakesaria cotteri, Lockhartia tipperi, and Lockhartia huntii* in the top of the formation suggests a Lower Eocene age for the Upper part of the Formation (Powers et al., 1963).

Based on the similar age diagnostic fossils, it is concluded that the Margala Hill Limestone of the study area is equivalent to various Early Eocene formations of the Neo-Tethys domain. These age equivalent of the studied formation include the Umlatdoh Formation (India), the upper part of Jafnayn Formation (Oman), the Naopurdan Group (Iraq), and the upper part of the Umm er Radhuma Formation (Saudi Arabia) (Figure 4.12).
Figure 4.12: Showing the correlation of the Margala Hill Limestone with its equivalent units in Oman, India, Iraq and Saudi Arabia
Chapter Five

5.0 Cyclicity and Sequence Stratigraphy of the Margala Hill Limestone.

5.1 General introduction

The Margala Hill Limestone, along with the upper part of the Patala Formation and the overlying Chorgali Formation, represents deposition in a large scale, Late Paleocene to Early Eocene shallowing-upward supercycle named here as, Patala-Margala Hill-Chorgali supercycle (or PMC supercycle, Figure 5.1). The supercycle is further comprised of shallowing-upward cycles of various scales; it is the purpose of this chapter to present and discuss the different cycles that constitute the Margala Hill Limestone and their position within the large PMC supercycle.

5.2 The PMC supercycle

The Patala Formation which lies conformably under the Margala Hill Limestone consists of lower, middle and upper parts that accumulated in different depositional settings. The lower part of the Patala Formation is dominated by thinly bedded limemudstone interbedded with planktonic foraminiferal-rich shale. The middle part is comprised of medium-thick bedded bioclastic packstone to wackestone, marl and thinly bedded shale. The upper part of the formation is comprised of brown-grey shale. Planktonic foraminifera and other smaller benthic foraminifera are the main faunal constituent of the shale, reflecting deposition in a deep marine pelagic environment (Shah, 1977; Ahmad, 2010; Afzal, 2011). This pelagic unit grades upward into the outer
ramp to inner ramp carbonate facies of the Margala Hill Limestone. The middle part of
the PMC supercycle is formed by the Margala Hill Limestone. The Chorgali Formation
conformably lies on top of the Margala Hill Limestone (Shah, 1977). The Chorgali
Formation consists of dolomite, shales, limestone and marl lithofacies. The depositional
environment of the Chorgali Formation is lagoonal to-intertidal (Shah, 1977). These
marginal marine strata mark the upper part of the PMC supercycle. A disconformable
surface characterizes the top of the PMC supercycle with erosional contact with the
overlying Kuldana Formation, in some places or molasse deposits of the Silwalik Group,
in elsewhere (Shah, 1977). The end of the PMC supercycle preserves the closure of the
Tethys Ocean in the study area (Shah, 1977; Bender and Raza, 1995). The age of the
strata that constitute the PMC supercycle ranges from Paleocene (SBZ 6/ Lower Ilerdian
2) to Eocene (SBZ 9/Upper Ilerdian). The lower boundary of the SBZ 6/Lower Ilerdian 2
is 55.5Ma while the upper boundary of the SBZ 9/Upper Ilerdian is 52.5 Ma. Hence the
overall time span of the PMC supercycle is approxiamtly 3Ma (Sera Kiel et al., 1998).
Figure 5.1: Litholog showing the various types of shallowing-upward cycles. The PMC supercycle is shown by the blue arrow. It consists of the upper part of the Patala Formation (deep marine shale with planktonic organisms), Margala Hill Limestone (Mainly inner to outer shelf carbonates) and the Chorgali Formation (mainly inner shelfal limestone, dolostone and, shale with some evaporites and paleosols). It has a lower contact with the inner ramp lithofaces of middle Patala Formation while its upper contact is unconformable with the siliciclastic Murree Formation or Kuldana Formation. The Margala Hill Limestone makes the middle part of the PMC supercycle; it is characterized by smaller scale shallowing-upward rhythmic successions.
5.3 Cyclicity within the Margala Hill Limestone

Due to the recurring nature of the lithofacies, three types (A, B &-C) of cycles have been identified from the formation (Figure 5.2). Each cycle consists of genetically-related and conformable lithofacies and is bounded by marine flooding surfaces. The flooding surface is marked by an abrupt lithofacies change from shallower facies to deeper facies (Figure 5.3). Each cycle is characterized by a basal-deeper lithofacies which grades upward into the shallower lithofacies. The thicknesses of these cycles in the Margala Hill Limestone range from 5 meters to 15 meters. The absence of exposure surfaces in the formation underscores a subtidal (to possibly intertidal) deposition realm as the main depositional system of the formation. Thus, recognition of cycles is not as evident as in conditions where intertidal to supratidal environments (or tidal flats) are prominent. From the Margala Hill Limestone, seven (1-7) meter scale shallowing-upwards cycles have been identified in this study. The vertical lithofacies arrangement of the cycles varies and can be grouped into three types (A, B and C).

Type A cycles: Mudstone-packstone cycle: This type of cycles has a planktonic foraminiferal mudstone (Mf7) at its base and grades upward into Nummulitic-Assilina rich wackestone (Mf4) and ends up to bioclastic packstone lithofacies (Mf3) (Figure 5.4 A). These types of cycles are present in the lower 20-25 meters of the formation (Figure 5.6).

Type B cycles: Wackestone-packstone cycle: elongated benthic foraminifera lithofacies (Mf6) or Nummulites/Discocyclina packstone-wackestone (Mf5) marks the base of this cycle. This grades upward into Nummulitic-Assilina rich wackestone (Mf4) through bioclastic packstone lithofacies (Mf3) to miliolid-algal wackestone-packstone
lithofacies MF2 (Figure 5.4 B). These kinds of cycles are present in the middle and upper part of the formation (Figure 5.6).

Type C cycles: Packstone-Mudstone Cycle: These type of cycles are defined by *Nummulites-Assilina* rich packstone/wackestone lithofacies (Mf4) at its the base, grading upward into the bioclastic-rich packstone lithofacies (Mf3) and algal wackestone-packstone lithofacies (Mf2). The *Miliolid* rich mudstone (Mf1) marks the top of this cycle in some locations (Figure 5.5). These types of cycles are present in the upper and middle part of the formation (Figure 5.6).

The vertical stacking of these cycles represents an overall shallowing-upward nature of the formation (Figure 5.6).
Figure 5.2: Lithologic characteristics, lithofacies association and interpretation of the three types of shallowing-upward cycles (A, B & C) that constitute the Margala Hill Limestone of the study area.
Figure 5.3: Field photographs showing the flooding surfaces. The red line shows the marine flooding surfaces. A) The planktonic mudstone facies (Mf7) is an outer ramp deposit lying on the top of shallower inner ramp facies (Mf2) B) The planktonic mudstone Mf7 lies on top of mid ramp (Mf4) deposits. The red arrow shows the stratigraphic top. Both photos show the base of the Type A cycle. [A:(Bhariyan) (B:Kozagali section)]
Figure 5.4: Showing various types of cyclicity in the Margala Hill Limestone. The red line shows the boundaries among different lithofacies while the yellow line shows marine flooding surfaces. A) The Type A cycle starting from Mf7 lithofacies and is capped by Mf4 lithofacies. B) The Type B-cycle is starting from the Mf6 lithofacies and is capped by the Mf3 lithofacies. The red arrow shows the stratigraphic top [(A: Kozagali section) (B: Bharyan section)]
Figure 5.5: Showing top and base of the Type C cycle in the Margala Hill Limestone. The red line shows the boundaries between various lithofacies while the yellow line shows marine flooding surfaces. A): The top of Type C cycle. The Mf1/Mf2 facies mark the Top. B): The base of Type C cycle. The picture shows the Mf4 lithofacies (middle ramp) lies over the shallower Mf3 lithofacies (Inner ramp). The red arrow shows the stratigraphic top [(A: Nathiagali section) (B: Goragali section)].
Figure 5.6: Litholog showing the Stratigraphic column of the Margala Hill Limestone and recognized shallowing-upward cycles that constitute the formation. Besides the cyclic nature of the formation, the figure also depicts the sedimentary structures, bioclastic framework grains and interpreted depositional environments of the various lithofacies. The lower 20-25 meters of the formation is comprised of Type A cycle. The Middle 40-46 meters are composed of Type B-cycle while the uppermost 25 meters is represented by Type C cycles [Nathiyagali section].
5.4 Sequence Stratigraphy of the Margala Hill Limestone

5.4.1 Introduction

The Early Paleogene collision of the Eastern part of the Indo-Pakistani plate with the Western part of Afghanistan micro-plate created a depression between the two plates (Figure 2.3). The depression was later filled with the Paleogene sediments. The active tectonics created complex depositional settings in the area where several basins, such as Potwar, Hazara, and Kohat basins were formed (Shah, 1977). The Potwar and Hazara basins were open marine-deep marine settings during most of the Paleogene Epoch. The Kohat Basin was open marine-deep marine in the Paleocene and restricted evaporites dominated setting in the Eocene (Wells, 1984; Warwick and Wardlaw, 1992).

In this section, the Early Eocene Margala Hill Limestone of the Hazara Basin has been discussed regarding relative sea-level changes and their effects on the depositional pattern. As mentioned in section 5.1, the Margala Hill Limestone is part of the larger scale transgressive-regressive system (PMC supercycle) which started with the underlying Late Paleocene-Early Eocene Patala Formation and ended up with the overlying Early Eocene (SBZ 9) Chorgali Formation (Shah, 1977). The stratigraphic position of the Margala Hill Limestone within this large scale transgressive-regressive cycle is the focus of this section by applying a sequence stratigraphic approach.

5.4.2 Depositional sequences

A sequence is a succession of genetically related strata bounded by unconformities or their correlative conformities (Vail et al., 1977). It is a product of the
episodic sea-level changes, subsidence and the sediment input to the depositional system (Emery and Myer, 1996, Catuneanu, 2006). The sea-level changes (Local/Eustatic) plus subsidence, play a role in the creation and distortion of accommodation space. The accommodation space is the room available for the sediments to be deposited (Vail et al., 1977). The variation of the accommodation space and sediment supply to the system produce a variety of facies architecture: retrogradation, aggradation, and progradation (Emry and Myer, 1996, Catuneanu, 2006). The retrogradation is the movement of the facies belt landwards. This is the product of low sediment production in the depositional system and high sea level rise. The vertical stacking pattern of such depositional setting shows a deepening upward trend (Wilgus et al., 1988; Emery and Meyer, 1996). The aggradation occurs when the rate of sediment supply and creation of the accommodation space remain same (Wilgus et al., 1988; Emery and Myer 1996). In the aggradation, the strata build up vertically without major changes in the movement of the facies belt. The progradation is the movement of the facies belt basin-wards. This type of deposition occurs when the sediment supply is higher than the creation of the accommodation space. In the progradation, the facies belt migrate basin-wards. The vertical stacking pattern of the prograding facies has an overall shallowing-upward trend (Emery and Myer 1996; Wilgus et al., 1988). These different types of depositional patterns make a depositional sequence. To describe the depositional sequence, a variety of models have been introduced by various authors (Figure 5.7). The Transgressive-Regressive (T-R) sequence model of Embry and Johannessen (1992) has been applied to the Margala Hill Limestone. The T-R sequence is bounded above and below by sub-areal unconformities, the basin-wards correlative conformity, and the transgressive surface. The transgressive surface is a
regional stratigraphic surface that shows a shift in a basin from regression to transgression. In most cases, there is a clear lithological contrast above and below the transgressive surface. The Maximum Flooding Surface (MFS) divides the T-R sequence into two system tracts: transgressive system tract and regressive system tract. The system tracts are internally made by meter-scale parasequences (Embry and Johannessen, 1992). A parasequence is a cycle of genetically-related beds bounded by marine flooding surfaces (Van Wagoner et al., 1988).
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**Figure 5.7**: A summarized classification of the system tracts (from Embry and Johannessen, 1992).
5.4.3 Transgressive-Regressive Cycle #1 (TR-1 cycle)

The upper part of the Patala Formation and, the lower and-middle part of the Margala Hill Limestone represent deposition in one Transgressive-Regressive cycle (TR-1). The pelagic sediments of the Upper Patala Formation and the limemudstone facies of the lower Margala Hill Limestone suggest a depositional setting within an outer to middle ramp realm under relative sea level rise (i.e. Transgression). The middle part of the Margala Hill Limestone is dominated by inner ramp shallow-marine facies and suggest deposition in a regressive phase of sea-level (Figure 5.8). Due to the active tectonics during the deposition of the PMC supercycle, it does not respond exactly to the global sea level curve. However, the PMC supercycle does follow the overall shallowing-upward trend of the global sea-level curve.

The planktonic mudstone lithofacies in the lower part of the Patala Formation represents the deposition in the deeper mid-outter ramp settings. The middle parts of the Patala Formation are comprised bioclastic wackestone-packstone facies representing depositions in the shallower subtidal environments. However, the top of the formation consists of deep marine pelagic shales (Ahmad, 2010). The lower part of the Patala Formation records a transgression which is followed by a regression in the middle part. However, the upper part of the Patala Formation records a transgression of the Neo-Tethys Sea (Ahmad, 2010). The occurrence of deep marine facies in the upper part of the Patala Formation over the shallower facies of middle Patala Formation indicates the existence of a Transgressive Surface (TS-1) within the formation. This TS-1 marks the start of the TR-1 depositional cycle. The transgression that deposited the upper part of the Patala Formation continued during the deposition of the lower part of the Margala Hill
Limestone. In the Margala Hill Limestone, the continuity of the transgressive system is represented by the Type A cycles (cycle 1 &-2, Fig. 5.8). These types of cycles are common in the lower part of the formation and, are generally deeper than type B and type C cycles. The Type-B cycles (cycles 3 &-4, Fig.5.8) in the middle part of the Margala Hill Limestone represent deposition in a transition phase of TR-1 cycle. These type of cycles are overlain by the Type C cycle (cycle 5, Fig.5.8). The Type-C cycles are dominated by shallower lithofacies and represent the regression of the sea-level. In the upper part of the formation, the Type-C cycle (cycle 5, Fig.5.8) is overlain by a relatively deeper Type B cycle (cycle 6, Fig 5.8). The surface separating the cycle 5 and cycle 6 is marked as the Transgressive Surface (TS-2) for the TR-2 depositional cycle. While, the Maximum Flooding Surface (MFS-1) in the TR-1 cycle is marked by the highest planktonic foraminiferal lithofacies in cycle 2 of the Margala Hill Limestone.

5.4.4 Transgressive-Regressive cycle #2 (TR-2 Cycle)

The uppermost part of the Margala Hill Limestone (20-25 m) and the overlying Chorgali Formation represent deposition in TR-2 depositional cycle.

The occurrence of the Type B cycle over the Type C cycle in the middle-upper part of the Margala Hill Limestone suggests a transgression. This transgression marks the start of the TR-2 cycle and leads to the deposition of the Type B cycles in the upper part of the Margala Hill Limestone. The Maximum Flooding Surface (MFS-2) of the TR-2 cycle is marked by the upper surface of the wackestone lithofacies (MF6) rich in elongated benthic foraminifera (cycle 5\textsuperscript{th}, Figure 5.8). The upper most 10-12 meters of the Margala Hill Limestone represent deposition in a transition phase of TR-2 cycle followed by a regression. The Chorgali Formation lies conformably over the Margala Hill.
Limestone. It is comprised of bioclastic wackestone-packstone, marl, dolomite and shale.

The Chorgali formation is deposited in a marginal marine settings and represents
deposition in the regressive phase of the TR-2 depositional cycle. The top of the TR-2
cycle is marked by deposition of siliciclastic dominated Kuldana Formation or Molasse
deposits of the Murree Formation.

As mentioned earlier, the age span of the PMC supercycle is about 3 m years. As
depicted in Figure 5.8, a little less than half of this time span is covered by the Margala
Hill Limestone which ranges from 54 Ma to 52.8 Ma. Thus, the time span of the
formation becomes 1.2 million years. By considering the time span for the formation, it
can be simplified that the average age span of the 7 cycles within the Margala Hill
Limestone is 1.2 Ma/7 cycles=171,429 years per cycle. These cycles are considered to be
due to Milankovitch cyclicity since their time span is within the range of such kind of
cycles (19,000-400,000 years, Boggs, 2006). Using this cycle average, the TR-1 cycle,
which contains 5 smaller cycles (Figure 5.8), becomes 5x171,429=857,145 years
(Approximately 0.86 Ma.) And the remaining 0.34 Ma is for the TR-2 cycle. The time
span for TR-1 is higher than those recognized for the fourth- to fifth-order Milankovitch
cycles. Thus, the TR-1 is envisaged to be a 3rd-order cycle. The Margala Hill Limestone
portion of the TR-2 time span is close to the upper level time span of the Milankovitch
cycles. However, by considering its continuation into the overlying Chorgali Formation,
its age is expected to be higher than the calculated amount. Thus, the TR-2 is also
interpreted as a 3rd-order cycle

Thus, it is concluded that the Margala Hill Limestone, along with the upper part
of the underlying Patala Formation and overlying Chorgali Formation, represents
deposition in a supercycle PMC. This supercycle is further made-up of two 3rd order Transgressive-Regressive (TR-1 and TR-2 depositional cycles). The Margala Hill Limestone makes the middle part of the PMC supercycle. The bottom of the formation is comprised of deeper facies grading upwards into the shallower one. Internally, the Margala Hill Limestone is composed seven (1-7) 4th-5th order shallowing-upward cycles.
Figure 5.8: Litholog showing the cyclicity in the Margala Hill Limestone and the PMC supercycle (Red Arrow). It starts from the upper part of the Patala Formation, goes through Margala Hill Limestone and ends at the top of the Chorgali Formation. Blue arrows (TR1-TR2) indicate 3rd order cycles within the PMC supercycle. The Margala Hill Limestone forms the middle part of the PMC supercycle. Internally, the formation is comprised of seven (1-7) 4th-5th order smaller scale cycles (See text for further discussion.).
Chapter 6

6.0 Conclusions

The study area lies in the south-eastern part of the Hazara Fold-Thrust Belt. Due to the Himalayan collision, the study area is deformed, and most of the strata are tectonically folded and faulted. The degree of the deformation increases northwards. The Eocene strata in the Hazara Basin is comprised of the upper part of the Patala Formation, Margala Hill Limestone, Chorgali Formation, and the Kuldana Formation.

The Margala Hill Limestone consists of a variety of limestone lithofacies with subordinate marl layers. The formation is Early Eocene in age and lies conformably over the earliest Eocene (SBZ-6-7), upper part of the Patala Formation and is overlain by Early Eocene (SBZ 9) Chorgali Formation. Due to thrust tectonics in the study area, the formation is not present with both upper and lower contacts in many stratigraphic sections. The Margala Hill Limestone has an average thickness of 80 meters in the Hazara Area.

The outcrop investigation incorporated with the petrographic analysis allows the recognition of nine lithofacies units (Mf1-Mf9). These lithofacies units are: i) Miliolid mudstone (Mf1), ii) Algal-Miliolid wackestone/packstone (Mf2), iii) Bioclastic packstone (Mf3), iv) Nummulites-Assilina wackestone/packstone (Mf4), v) Nummulites-Discocyclina wackestone/ packstone (Mf5), vi) Elongated benthic foraminifera wackestone (Mf6), vii) Planktonic foraminiferal mudstone (Mf7), viii) Bioclastic Marl (Mf8), and unfossiliferous marl (Mf9). The sedimentary structures, sedimentary textures,
the fossil associations of these lithofacies suggest deposition in a homoclinal carbonate ramp setting. The inner part of the ramp was comprised of three sub depositional environments: 1) Lagoon, 2) Transitional and 3) a bioclastic barrier. The MF1 lithofacies represents deposition in a semi restricted-restricted lagoonal environment. The MF2 lithofacies represents the transitional zone while the MF3 lithofacies represents a bioclastic barrier depositional environment. The mid ramp (Below FWWB) is represented by MF4, MF5 and MF8 lithofacies. These facies are characterized by tempestite beds which underscore the deposition below the FWWB. The deepest part of the ramp (outer ramp) is represented by the elongated benthic foraminifera wackestone (MF6), Planktonic rich mudstone (MF7) and unfossiliferous marl (MF9) lithofacies units.

The vertical stacking nature of these lithofacies suggests cyclic deposition. Three types of cycles (A, B, and C) have been identified from the formation.

A) Mudstone-Packstone Cycle: This type of cycles have a planktonic foraminiferal mudstone in the base and grades upwards into Nummulitic-Assilina rich wackestone and culminates into bioclastic packstone lithofacies. These types of cycles are present in the lower 20m-25m of the formation.

B) Wackestone-Packstone Cycle: elongated benthic foraminifera lithofacies (MF5) marks the base of this cycle and grades upward into MF4, MF3 and ends up into MF2 lithofacies. These kinds of cycles are present in the middle 40m-45m of the formation.

C) Packstone-Mudstone Cycle: These types of cycles have Nummulites rich packstone in the base (MF4), grading upward into the bioclastic and algal packstone
lithofacies (Mf3/Mf2). The miliolid rich mudstone (Mf1) marks the top of this cycle in some locations. These types of cycles are mostly present in the upper 20m-25m of the formation.

The absence of supratidal signature and exposure surfaces suggests a subtidal depositional setting of these cycles. The vertical stacking of the cycle A, B and C suggests an overall shallowing-upward nature of the formation.

The larger benthic foraminifera (LBF) dominates the allochemical content of the formation. These fossils have been thoroughly analyzed in this study. The identified index species are *Nummulites globulus, N.atacicus, N.mamillatus, N.sp, Assilina granulosa, A.spinosa, A. supspinosa, A.laminosa, A.sp*. Other associated LBF are *Lockhartia conditi, L.Sp, Discocyclina dispensa, D. ranikotensis, Operculina sp.* and *Ranikothalia*. In this study, these fossils have been grouped into a biozone (MHF1). The comparison of the MHF1 biozone with the standard biozonation schemes of the tertiary rocks suggests the Middle Ilerdian 2/SBZ8 age of the Formation. The lower boundary of the Middle Ilerdian 2/ SBZ8 is (54 Ma) while the upper boundary of SBZ 8 is (52.8) in age. So it is concluded that the formation is deposited in a time span of 1.2 Ma.

The Margala Hill Limestone (SBZ8) along with the upper part of the Patala Formation (SBZ6-7) and Chorgali Formation (SBZ9) suggests deposition in one supercycle, named here as PMC supercycle. The lower boundary of the SBZ 6 is (55.5Ma) while the upper limit of the SBZ 9 is (52.5). Thus, the biostratigraphy suggests 3 Ma for the PMC supercycle. The PMC supercycle is further comprised of two 3rd-order Transgressive cycles. These cycles are named here as TR-1 and TR-2. The upper part of the Patala Formation and the lower-middle part of the Margala Hill Limestone is
represented by TR-1. Whereas, the upper part of the Margala Hill Limestone and the overlying Chorgali Formation are represented by TR-2 cycle. The Margala Hill Limestone makes the middle part of the PMC supercycle. The formation is internally comprised of 7 parasequences. These cycles are $4^{th}$-$5^{th}$ order in nature.
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