GENESIS OF LIMESTONE-MARL ALTERNATIONS IN CARBONATE SEQUENCE OF EOCENE SALT RANGE-POTWAR PLATEAU, PAKISTAN

BY

FAIZAN SABIR

A thesis submitted for the degree of Master of Philosophy

Department of Earth Sciences

Quaid-i-Azam University, Islamabad

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ACKNOWLEDGEMENT

I would like to express my sincere gratitude to the Almighty God for granting me the strength, knowledge, and wisdom to complete this thesis. I am truly grateful for His guidance and blessings throughout this journey.

I am deeply grateful to my teacher, Dr Abbas Ali Nassem, for his unwavering support, guidance, and encouragement throughout the research process. His invaluable insights, constructive criticisms, and belief in me have been instrumental in shaping this thesis into its present form. I want to thank him for being an inspiration and a mentor and for providing me with an enriching academic experience.

I would also like to acknowledge Ms Beenish Rashid, Deputy Collector Pakistan Customs, for providing me with invaluable support in my research. Her help is greatly appreciated.

I would also like to thank Dr Salman, my friend and colleague, for his support, encouragement, and motivation throughout the journey. His guidance and advice have been instrumental in helping me stay focused and on track, and I am genuinely grateful for his friendship and support.

I thank Ms Humaira Hafeez for her support in formatting, proofreading, and editing my thesis.

I would like to thank my family and friends for their love, support, and encouragement during the entire journey of completing this thesis. Their encouragement and motivation have been a source of great inspiration for me. Their unwavering support has been a source of strength and comfort throughout this challenging process.

I also thank Mr Zubair Ahmad for his help and support in the fieldwork. His assistance and cooperation have been greatly appreciated, and I am genuinely grateful for his contributions.

At last, I want to extend my appreciation to all those who have contributed in some way to the completion of this thesis. Their support, help, and encouragement have been greatly appreciated and will always be remembered.

Thank you, everyone!

ABSTRACT

The thesis focus on the genesis of limestone marl alternations in the Carbonates sequence of the Eocene Salt Range-Potowar Plateau in Pakistan. Three sections were studied: the Nammal Dam section, the Chal Abdal section, and the Tatryal-Sethi section. The study used microfacies analysis of limestone and SEM images of marl and limestone samples. This research investigated the processes responsible for forming alternations in carbonate sequences. The study analyses twenty-four thin sections of limestone samples under the microscope. Four samples of limestone-marl alternations are studied using a scanning electron microscope. The study results show that cementation, dissolution and neomorphism significantly formed limestone marl alternations. The alternations were formed due to differential diagenesis in a shallow marine environment. The SEM images revealed that the limestone samples were characterized by a high concentration of micrite, microspar cementation, and altered nano fossils, indicating early cementation and compaction in marl; well-preserved fossils refer to lithification in limestone samples. On the other hand, the marl samples showed evidence of dissolution and neomorphism, resulting in the formation of fine-grained sediments. The complex reciprocity of diagenetic processes responsible for the formation of alternations in Eocene carbonates of the Salt Range emphasizes the importance of differential diagenesis in the formation of limestone marl alternation.

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CHAPTER 01 INTRODUCTION

1.1 Introduction to Limestone Marl Alternations

Carbonate rocks often take the form of limestone-marl alternations, which can range from nodular patterns to well-defined layers (Einsele, 1991; Einsele & Ricken, 1991). Limestone Marl alternations are often present in the outcrop stacked vertically in a regular sequence of limestone and marl. This pattern of distinct and visible layers presents a sharp boundary between the two, showing the different origins of each layer. Limestone-marl layers result from complex geological processes in various environments, including marginal marine areas and shallow and deep marine settings. These layers can have different bedding styles, such as nodular or wavy, and can be composed of either carbonate or marl (Westphal, Munnecke, Böhm, et al., 2008). The layers appear to be formed in isolation from one another at different periods. In literature, this type of sequence has different names; Calcareous rhythms, couplets, limestone-marl alternations and nodular limestone. Sometimes, marly material is surrounded by a limestone layer showing nodular texture. Limestone-marl typically alternates between $CaCO_3$-rich limestone and less $CaCO_3$-rich marl, regardless of their absolute $CaCO_3$ content. These formations originate from a mixture of terrigenous material (quartz and clay), biogenic calcium carbonate (calcite or aragonite), and organic matter (Nohl et al., 2021).

Limestones in these alternations commonly have a symmetrical structure, with the highest carbonate concentration in the middle. They also do not experience significant compaction, unlike marls, which are usually much thinner. This lack of compaction in the limestones suggests that they solidified at an early stage (Kent, 1936), (Illies, 1950), (Seibold, 1962), (Noble & Howells, 1974), (Bathurst, 1980), (Walther, 1982), (Ricken, 1986, 1992), (Moller & Kvingan, 1988) the lack of any compaction in the limestones suggests that they lithified early on (Kent, 1936), (Weller, 1959), (Pray, 1960), (Seibold, 1962), (Henningsmoen, 1974), (Noble & Howells, 1974), (Jones et al., 1979), (Eder, 1982), (Lasemi et al., 1990). The majority of nodules contain more carbonate than the sediments surrounding them. While some researchers have suggested that nodules in carbonate form during the later stages of diagenesis (Bjorlykke, 1973), others have argued that an early diagenetic origin is more common (Jenkyns, 1975); (Mullins et al., 1980); (Moller & Kvingan, 1988).

Limestone is compact, rigid and stratified, while marl is composed of loose and fragile material distributed in sharp and visible layers. Nodules formed early on due to excess fringe-cement, which prevented compaction and led to the development of a large amount of calcite cement. Differences in sediment were further emphasized during later stages of diagenesis with less compaction and more cementation in nodules compared to host rocks and during recent weathering (Molenaar & Martinius, 1990). Because of this reason, limestone marl alternations are easily recognized in the field. Limestone-marl and limestone-shale alternations and nodular limestones are less easily interpreted in paleoclimate because they may contain fewer fossil remains. This might explain why no studies about the global distribution of such rhythmites have been published (Westphal & Munnecke, 2003). The reason for the formation of limestone-marl alternations in shallow water depositional carbonates sequences is challenging to find because there are no modern analogues for such alternations (Munnecke & Samtleben, 1996).

The microfacies of rock provide essential information about a sedimentary environment and its mineralogy. They are essential in the interpretation of sedimentary rocks, particularly carbonates. Microfacies of carbonates can reveal important details about rocks' deposition and diagenetic processes. This study investigates the processes and mechanisms responsible for forming limestone-marl alternations and why they are common in certain regions. Limestone Marl alternations are formed in the carbonate sequence of Early Eocene deposited in the Salt Range-Potwar Plateau. The study relates the field observation with the results of microfacies and ultra-facies obtained from sedimentological analysis of Nammal, Sakesar and Chorgali Formations Early Eocene.

1.2 Tectonics /Regional Geology of Study Area

The Salt Range is a mountain range in the Punjab province of Pakistan. It is rich in mineral deposits, particularly salt and gypsum. The range extends from the Jhelum River to the Indus River, spanning an area of about 300 km. The Salt Range is a mountain range located south of the Himalayas that has been formed because of the ongoing collision between the Indian and Eurasian tectonic plates. This fold-and-thrust belt is well-described and comprises sedimentary rocks with salt deposits. The collision also led to several other ranges in this area, including the Margalla Range, Potwar Plateau, and Sulaiman Range. The Salt Range is the youngest fold-and-thrust belt created to the south of the Himalayas due to the collision of the Indian and Eurasian plates (Baker et al., 1988; Jaumé & Lillie, 1988). It lies between the Trans-Indus Ranges and the Himalayan Arc and is spread over approximately 27,000 km^2 of land. The region between the Punjab plain and the main boundary thrust (MBT) is called the Potowar Plateau. The first petroleum discovery occurred in 1915. Since then, intense petroleum exploration has been carried out in the Potwar region, and extensive geophysical and geological data is available for analysis (Grelaud et al., 2002). East-West extended; long Salt Range Trust marks the southern boundary of Salt Ranges. The region is confined between two strike-slip faults on both sides and is divided into four major parts: Eastern, Central, Western and the Surghar Ranges. The eastern strike-slip fault is the Jhelum fault, while the western fault is the Kalabagh strike-slip fault, separating the Surghar range from the main salt range. Thrusting due to Indo-Eurasian plate collision has progressively proliferated towards the south, and as a result of this collision Salt Range is formed, which is considered to be the youngest compressional structure within the Himalayan foreland in the south (Gansser, 1964; Grelaud et al., 2002; Molnar & Tapponnier, 1975; Powell & Conaghan, 1973). The study area consists of east-west laterally extended salt ranges with a geologically wide range of sediments deposited. The base of the region is composed of pre-Cambrian Salt Range Formation following the deposition of Cambrian to Eocene rock formations along with four significant hiatus periods, first in the Permian, second in the Late Cretaceous, third in Oligocene and fourth after Miocene. Eocene marks the top sequence in the salt range; however, Miocene clastic sediments make unconformable contact with Eocene carbonates at the western flank of Salt Range (Shah, 1977a).

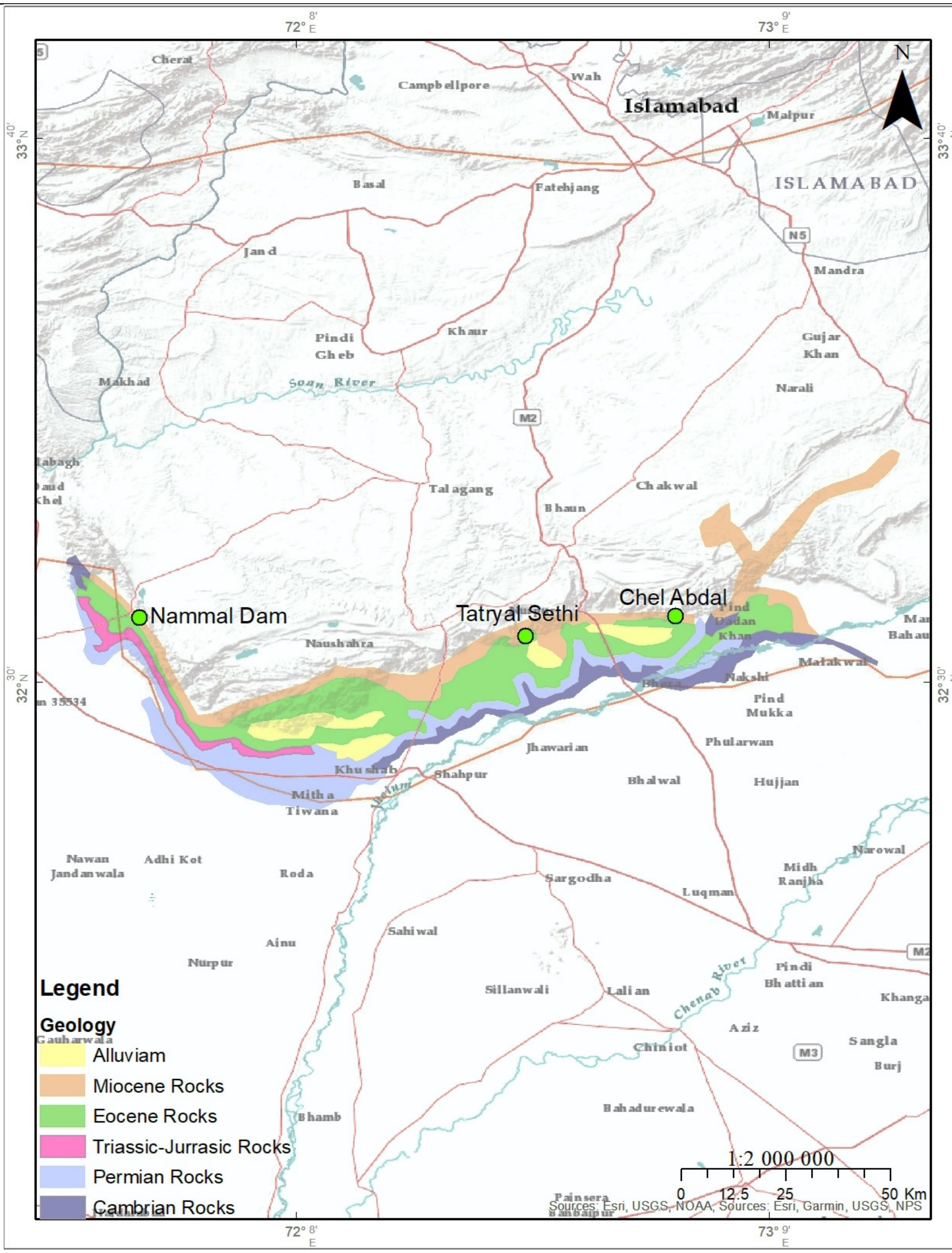


Figure 1 Regional Geology map of Salt Range, red indicates Eocene carbonate sequence exposed from East to West. Green points are the section studied in the present research (Geological Map of Pakistan, 1964).

1.3 Stratigraphy of Study Area

The average elevation of the Salt Range is about 670 m, and the highest peak, Mount Sakesar (32°40′30″N 72°47′35″E), is 1,522 m high. At peaks, carbonates from Early Eocene or Tertiary clastic sediments are exposed in some places. The majestic Salt Range is an excellent 180-km-long, 85-km-wide ridge of hills in the Potwar Basin, located just 70 km away south of the Himalayan Mountains. The geological exposure offers stunning views and a unique geological landscape that captivates visitors worldwide. Elphinston, a British envoy to the court of Kabul, first used the name Salt Range. He visited this territory (1808–1815) and noticed substantial salt deposits in the Salt Range(Ghazi et al., 2015). Apart from the easily accessible geological sections, some gorges cutting through the formations provide excellent sites to understand the depositional history of salt ranges; Khewra, Nammal, and Chichali gorges are famous among all. The central salt range is the broadest of the other two parts, the western and eastern salt ranges, with rock sequences exposed from Eo-Cambrian to the recent era (Table 1). The geology of the Salt range experienced four significant hiatus periods in geological time scales from Cambrian to Pleistocene (Ghazi et al., 2012).

Age	Group and Formation	Lithology	Environment
Recent	Alluvium	Alluvial deposits, boulder fan.	
Middle Pleistocene	Kalabagh Conglomerates	Brown and grey conglomerates with sandstone and clay interbed.	Glacio-fluvial deposits.
		Angular Unconformity	
Pliocene - Pleistocene	Soan Formation	Conglomerate with subordinate sandstone, siltstone and clay.	Fluviatile (coarse fan deposits).
Early to Middle Pliocene	Dhok Pathan Formation	Interbedded grey to brown sandstone and brown to red clays. Lenses of conglomerate	Fluviatile (coarse fan deposits) and lacustrine.
Early Pliocene	Nagri Formation	Greenish-grey sandstones with subordinate clays and conglomerates.	Fluviatile - meandering and braided rivers.
Late Miocene	Chingi Formation	Bright red clays with subordinate brownish sandstone.	Fluviatile with ponded conditions.
Middle to Late Miocene	Kamlial Formation	Grey to red brick sandstone with subordinate interbeds of purple shale and minor intraformational conglomerate.	Fluviatile and lacustrine.
Early Miocene	Murree Formation	Dark red and purple clay and purple to greenish grey sandstone—shales, basal conglomerate.	Fluviatile lacustrine.
		Major Unconformity	
Early Eocene	Chorgali Formation	Greenish grey marl with thin interbeds of limestones followed upwards with dolomitized limestone.	Indicate low energy, tidal flat environment.
	Sakesar Limestone	Medium to thick, massive and nodular limestones with a minor amount of marl	Mostly lagoon.

Age	Group and Formation	Lithology	Environment
	Nammal Formation	Mostly light grey limestone with alternations of grey or greenish marl.	Low energy shallow marine conditions.
Paleocene	Patala Formation	Green to dark grey shales with thin interbeds of limestone: thin beds of sandstones in the upper part. Coal in the eastern Salt Range.	Lacustrine/organic-rich lagoon to the restricted marine environment.
	Lockhart Formation	Grey, Nodular limestone with thin marly beds in the lower part.	Low energy marginal marine environment.
	Hangu Formation	Variegated sandstones and sandy carbonaceous shales with some intercalation of limestone, laterite at the base and siltstone or marl at to	Terrestrial conditions for the basal part to shallow marine conditions elsewhere.
Major Unconformity			
Early Cretaceous	Lumshiwal Formation	Grey feldspathic to ferruginous sandstones with thin carbonaceous and glauconitic shale bands at the base.	Manne environments in the lower part, swamps, flood plain and deltaic in the rest of the unit.
Early Cretaceous - Late Jurassic	Chichali Formation	Dark green to black glauconitic shales and sandstones.	Shallow marine.
Unconformity			
Middle Jurassic	Samana Suk Formation	Grey and purple limestones with shale interbeds.	Neritic to the littoral environment.
Middle to Early Jurassic	Shinawari Formation	Alternating grey limestone. Shale and sandstone; siltstone at top.	Littoral environment,
Early Jurassic	Datta Formation	Variegated sandstones with limestones, carbonaceous shales and lateritic zones.	Alternating shallow marine, estuarine and terrestrial/mostly
	Unconformity		
Late Triassic	Kingriali Formation	Massive light-coloured fine dolomite and dolomitic limestones with few interbeds of shale and marl in the upper part. Sandstones at the base.	Shallow marine.
Middle Triassic	Tredian Formation	The lower part is thin to thickly bedded variegated micaceous sandstone interbedded with shale. The upper part is white, thick to massive sandstone.	Non-marine/deltaic to shallow marine environments.
Early Triassic	Mianwali Formation	Olive-green and grey shales with thin grey to yellowish-brown flaggy limestones, sandstones, siltstones and dolomites.	Shallow marine.
Paraconformity			
Late to Early Permian	Chidru Formation	Grey to Green shale at the base, alternations of calcareous sandstones, marls and arenaceous limestones.	Marginal marine, estuarine or lagoon environment.
	Wargal Formation	Medium to massive grey arenaceous limestones and dolomite with few intercalations of black shales. Chert in the upper part.	Mostly shallow marine conditions. Some horizons are believed to be storm deposits.
	Amb Formation	Brownish grey calcareous sandstone alternating with light grey or creamish yellow arenaceous limestone; some carbonaceous shale interbeds	Mostly shallow marine with periods of paralic or lacustrine conditions.
Early Permian	Sardhai Formation	Bluish grey, purple and lavender clays with subordinate sandy shales and glauconitic sandstone interbedded with clays.	Lacustrine to lagoon environment.
	Warchha Formation	Purple, red, white, reddish thick to massive arkosic sandstones; occasionally interbeds of grey shales and pebbly sandstones. Sometimes thin seams of coal at the base.	Fluvial to localized lagoon environment, alluvial flats.

Age	Group and Formation	Lithology	Environment
	Dandot Formation	Olive-greenish shales and siltstone intercalated with sandstones. The shales are carbonaceous in (the central Salt Range.	Marine in the east to tidal flat in the west.
	Tobra Formation	Complex facies of tillites mixed with sandstone and shale	Glacio-fluvial environment.
Major Unconformity			
Middle and Late Cambrian	Baghanwa-la/Khisor Formation	Reddish brown shales and flaggy sandstones with salt pseudomorphs.	Lagoon environment under evaporitic conditions.
	Jutana Formation	Massive light-coloured sandy dolomite and dolomitic sandstone with few intercalations of shales.	Shallow marine conditions.
Middle and Early Cambrian	Kussak Formation	Grey, silty and sandy glauconitic shales with some sandstone intercalations. A conglomerate at the base.	It is restricted to arid lagoon environments.
	Khewra Sandstone	Massive maroon fine textured sandstones, with maroon shales and flagstones in the lower part.	Changing conditions predominantly fluvial to lacustrine.
Precambrian	Salt Range Formation	Red gypseous marl with rock salt; gypsum dolomite above; occasionally oil shale	Intertidal-supratidal environment /enclosed basin arid conditions.

Table 1 General Stratigraphy of Salt Range (Shah, 1977a).

Cherat Group

Stratigraphic Committed of Pakistan formalized the Cherat Series (Pinfold, 1918) as the Cherat Group after the Chharat Village in Attock District, Punjab Province. In the Potwar, the Salt Range and Trans-Indus ranges, the Kuldana Formation, Chorgali Formation, Sakesar Limestone and Nammal Formation are included in the Chharat Group (Shah, 1977b). The group's base contains grey to bluish-grey marl, limestone and shale (Nammal Formation), followed by nodular, massive and cherty limestone in the south.

Nammal Formation

The Stratigraphic Committee of Pakistan has accepted the "Nammal Formation" as the formal name for the "Nammal Limestone and Shale" of Gee (Fermor, 1935) and "Nammal Marl" of (Danilchik & Shah, 1967)occurring in the Salt and Trans-Indus ranges, named after the Nammal Dam due to its best exposure in the western Salt Range (Malkani & Mahmood, 2017). It is equivalent to the Laki Group and Ghazij Group of southern Kirthar and Sulaiman basins, respectively (Shah, 1977b).

The formation extends throughout the Salt Range in the Punjab region. The rocks alternate between shale and limestone, with marl in between. The formation is well-developed in the Salt and Surghar ranges but thins to 60 meters at Khairabad. It is around 35 meters thick in the

Khewra-Choa Saidan Shah Road section of the eastern Salt Range. The lower contact with the Patala Formation and upper contact with the Sakesar Limestone are transitional.

(Khan, 1968) reported the discovery of abundant fossils, mainly foraminifers and molluscs, in the formation; Fasciolites oblonga, Nummulites lahirii, Assilina granulosa, Operculina, Nummulitoides, Assilina laminosa, Assilina spinosa, Lockhartia tipperi, Lockhartia hunti, Lockhartia conditi, Discocyclina ranikotensis, and Nummulites atacicus. (Haque, 1956) found many small foraminiferans in the type section and noted that they included Textularia crookshanki and Quinqueloculina gapperi. Based on the fauna, the age of the Nammal Formation is assumed to be Early Eocene.

Sakesar Limestone:

Gee named the Sakesar Limestone for the Sakesar peak in the Salt Range (Fermor, 1935) (Malkani & Mahmood, 2017). The rock unit is limestone with subordinate marl layers. The limestone is cream-coloured and massive, with chert developing at the top. In the western Salt Range, limestone grades into gypsum and massive lenses increase in number and size. The formation is widespread in the Salt Range and Surghar Range. The thickness varies between 70 m and 150 m, with 220 m at Chichali Pass and 300 m in the Surghar Range. The eastern Salt Range's lower contact with the Nammal Formation is conformable. However, an upper contact with Chorgali Formation is also conformable. The Rawalpindi or Siwalik Group unconformably overlies it everywhere else. The Margalla Hill limestone has been considered a time equivalent of the Sakesar Limestone because of the same facies, faunal assemblage and depositional basin.

The formation provides evidence of the Early Eocene period, as revealed by its rich assemblage of foraminifers, Molluscs and Echinoids (Cheema et al., 1977) (Malkani & Mahmood, 2017). Some important ones are Assilina leymeriei, A. laminosa, Flosculina globose, Fasciolites oblonga, Lockhartia conditi, Sakesaria cotteri, Lockhartia hunti, Operculina, Nummulitoides, Orbitolites complanatus and Rotalia trochidiformis.

Age	Salt Range	Lithology	Time Equivalent *Margalla/Kalachita Range*
Early Eocene	Chorgali Formation	Nodular Limestone, Marl	*Chorgali Formation*
	Sakesar Limestone	Nodular Limestone	
	Nammal Formation	Nodular Limestone, with marl	*Maraglla Hill Limestone*

Table 2 Comparison of Stratigraphy of Eocene, Salt range with adjacent mountain ranges (Shah, 1977a).

Chorgali Formation:

In 1920, Pascoe named a formation as ‘’Chorgali beds’’ after the Chorgali Pass in the Khair-e-Murat range. The formation is also known as the "Badhrar beds" of Gee and Evans (Davies, 1926) (Pinfold, 1937). The name "Chorgali beds", coined by (Pascoe, 1920) has been formalized later as Chorgali Formation by the Stratigraphic Committee of Pakistan (Shah, 1977b)

It is made up of shale, marl and limestone from the Early Eocene period. It is exposed in the eastern Salt, Kala-Chitta, Khair-e-Murat Ranges, and Hazara region. In the Salt Range, the formation can be divided into two parts. The lower part consists of greenish-grey or buff shale/marl and limestone; the upper part is mainly limestone. The most striking feature of the lower part is a porcelaneous limestone band in the middle of the unit near Kallar Kahar, which gradually thickens westward. The top limestone bed is slightly nodular, and the middle bed contains minor chert lenses. The Chorgali Formation's contact with Sakesar limestone is conformable, and its contact with Kuldana in the Murree, Hazara and Kohat areas is conformable. However, its contact with Murree formation in some parts of Salt Range is disconformable.

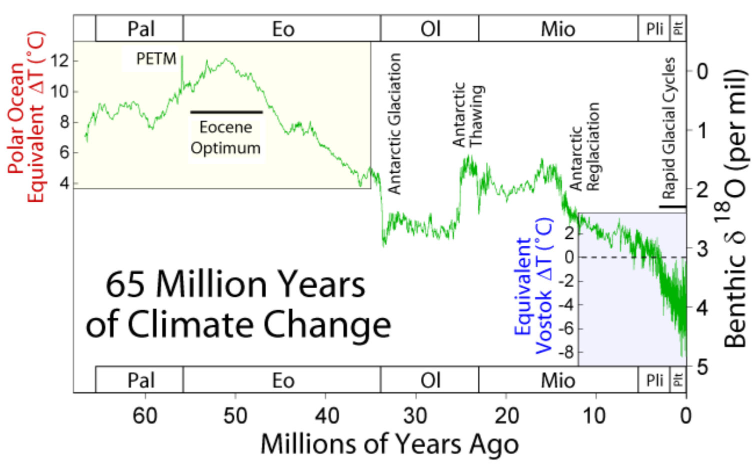
A rich assemblage of fossils has been reported by (Davies, 1926; Pinfold, 1918), (Eames, 1952), (Gill, 1951) and (Latif, 1970). Among them are Asslina spinosa, Asslina. granulose, Asslina daviesi, Asslina leymeriei, Globorotalia reissi, Flosculina globose, Globigerina prolata, Lockhartia hunti, Lockhartia tipperi and Lockhartia conditi, Nummulites atacicus, Nummulites mamilla, Orbitolites complanatus and Rotalia crookshankiana. The age of Chorgali Formation is declared Early Eocene age by (Shah, 1977b) and late Early-Middle Eocene by (Malkani & Mahmood, 2017).

1.4 Paleogeography and paleoclimate in Eocene Indian plate context

Palaeogeography is the study climate of past environments, locations and landforms. The Eocene Epoch, a period of geologic time, spanned from 55.8 to 34.6 million years ago. The Eocene contains two stages: the Early Eocene and Ypresian stage (55.8–47.8 mya), which includes the uplift of mountain ranges in many areas of the world as India started to collide with Eurasia during this period. Part of this collision included the formation of a new ocean basin called Tethys Ocean, which eventually closed after 20 million years, and Late Eocene (34.6–33 mya), which includes a cooler climate and drier conditions in many parts of the world. The initial explosion in the diversity of placental lineages in the Eocene Epoch coincided with rapid global warming that encouraged the spread of forests worldwide.

In addition to climate and geography, there were significant changes in flora and fauna during this period. For example, large numbers of plants colonized on newly exposed lands around rivers due to increased rainfall; this event is called an "ecological revolution" because it changed how ecosystems functioned across entire continents at once. Establishing an abiotic corridor between India and Asia in the Early and Middle Eocene enabled hordes of Asian vertebrates to sweep into India, including turtles, crocodiles, marsupials, and placental mammals (Chatterjee et al., 2013).

While the Indian plate has been moving northward for millions of years, it is only recently that the subcontinent's climate has started to change. The Eocene Epoch was a time when Indian plate was experiencing warming, with an increase in temperature and sea level (Scotese, 2001). During this time, Indian plate experienced significant climatic changes that had an impact on its ecosystems and geography:



1. Sea levels rose by about 20 m (about 65 ft) from present-day levels.
2. Temperatures increased by about 3 degrees centigrade.
3. The amount of precipitation increased from about 90% to 100%.

Figure 2 Temperature trend during the Eocene epoch (Rohde, 2023).

Warmth events which occurred during Paleocene-Eocene Thermal Maximum (PETM), had a significant impact on the carbonate rocks of the Indian plate. The Paleocene-Eocene Thermal Maximum (PETM) was a brief interval of extreme warmth that disrupted marine and terrestrial ecosystems on a global scale. The Paleocene-Eocene Thermal Maximum (PETM) was an event that occurred at the end of the Paleocene and into the beginning of the Eocene Epoch. It was a period of extreme global warmth, coinciding with a massive carbon release to the ocean-atmosphere system. At the onset of the PETM, land abruptly shifted from an open marine setting with less terrestrial and freshwater input to a depletion environment with increased terrestrial and freshwater input. Changes in microfossil biota suggest stratification of the water column and low-oxygen bottom water conditions in the earliest Eocene (Self-Trail et al., 2017). The paleoclimate of the Salt Range is a product of its location and geological history. The region is located in the central part of Pakistan, and the Indus River borders it on the west and northwest, the Jhelum River on the east and northeast. The salt range mountains are composed of Mesozoic sedimentary rocks that have been folded into complex fault blocks.

The climate of this area changes dramatically from north to south. While there are some rain-shadowed locations in this region, most areas are arid or semiarid, with annual precipitation between 100 mm and 400 mm. The average annual temperature ranges from about 20°C (68°F) in northern areas to about 10 °C (50°F) at higher altitudes. The mean annual temperature is lowest in February and highest in August; there are also significant differences in rainfall during these months, which can fluctuate significantly from year to year depending on local topography and monsoon patterns.

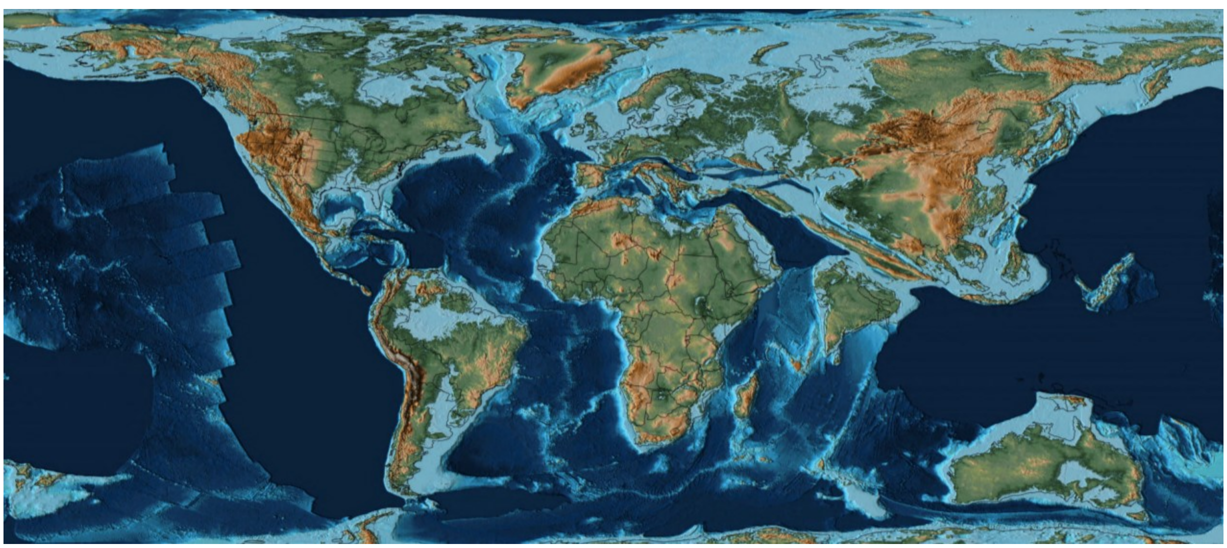


Figure 3 Paleogeographic map of Eocene showing the location of the Indian Plate in Early Eocene (Scotese, 2001).

Carbonates of the Early Eocene were deposited in various environments e.g., shallow-marine, reef and logoons. Skeletal grains are often abundant in carbonate rocks and are produced due to the compaction of organic matter under pressure (Jurgen et al., 1988). The interpretation of depositional environments indicates that the Eocene carbonates formed during an early stage of sea level rise on a ramp-like slope. This is consistent with the interpretation (Mujtaba, 2001), who proposed that Potwar and Kohat areas were changed from an open continental shelf to a shallow sea during this period. This change caused the widespread development of shallow water carbonate platforms throughout what is now Pakistan's Salt Range province.

CHAPTER 02 LITERATURE REVIEW

2.1 Previous Work

International researchers have worked extensively on the genesis and processes responsible for nodule formation. Some worked on the processes of nodule formation and described the associated changes; however, A. Munnecke, H. Westphal and T. Nohl studied and worked on Limestone-marl alternations extensively conducted in-depth work and provided the reasons behind the genesis and their effects on the overall fabric of rock. Details of the work carried out by all these researchers are studied in detail. At the national level, no study focuses on forming Limestone-marl alternations or explains a rationale. However, extensive literature confirms the presence of nodules in these formations. Notable researchers who reported and worked on nodule-bearing formations are Ghazi et al., Hanif et al., Abbas et al., Hottinger et al., Mirza et al., Butt et al. and many others.

(Hildebrand, 1929) (Schindewolf, 1925) (Kukal, 1975)

Concretional growth due to diagenetic differentiation of carbonate and argillaceous material.

(Hollman, 1962)

Sub-solution during deposition at the sedimentary interface.

(Grundel & Rosler, 1963)

Microbial decomposition of organic matter.

(Garrision & Fischer, 1969) (Jenkyns, 1971)

In situ submarine cementation during early diagenesis.

(Dvorak, 1972)

Late burial diagenesis is sometimes in connection with pressure-solution.

(Deelman, 1974) (Born, 1921) (Nichols, 1966)

Structural boudinage, differential compaction, and mechanical rearrangement of particles in sediment mixtures.

(Seyfried, 1980)

Alternation of periods of sedimentation (associated with the formation of soft bottoms) and of non-sedimentation (associated with the formation of hard bottom and solution hard bottoms. A slumping of these variously lithified layers may produce the nodular texture.

(Moller & Kvingan, 1988)

Nodules in nodular limestones have been studied from the Lower Chasmops Shale (Middle Ordovician) and the Rytteráker Formation (Lower Silurian). Nodules are formed by ferroan/non-ferroan calcite cement variations that help explain the role of precipitation, dissolution and redistribution of carbonate. The forms of nodular limestones depend on environmental conditions such as carbonate/clay ratio, grain size distribution and bioturbation.

(Munnecke & Samtleben, 1996)

The study of Limestone marl-alternations in Silurian, Gotland Sweden, revealed that it could result from early marine diagenesis, in which aragonite dissolution occurred because of diagenesis and compaction caused by overburden and not from pressure dissolution. The other case for forming regular marl-limestone alternations could be climate-induced changes known as Milankovitch cycles. Pitted micro spar is the evidence of the original aragonite dissolution, and well-preserved fossils in limestone refer to early lithification and, with marl, mechanical compaction caused the deformation of dinoflagellates or even flat species when seen through a scanning electron microscope.

(Munnecke et al., 1997)

Pliocene sediments from the Bahamas indicate that early marine diagenesis caused the formation of microspar that leads to mechanical lithification when compared with the results of sediments from Silurian Gotland, Sweden. The results lead to the same conclusion despite the difference between the sediments and geological age. A model is proposed for the formation of microspar cementation from aragonite mud. Unconsolidated mud caused the precipitation of microspar that forms aragonite needles and the dissolution of needles, leaving the pitted microspar behind and recrystallization. However, the opinion on microspar formation contradicts the previous concept of microspar production from lithified micrite.

(Westphal & Munnecke, 1997)

The author highlighted the difference between early cemented and mechanically compacted limestones with the help of preserved microfossils. The fossils preserved in both limestones were spherical and flattened, respectively.

(Akhtar & Butt, 1999)

The differential compaction or the concretional growth due to the diagenetic differentiation of carbonate can be a more plausible explanation for the origin of nodularity in Limestone.

(Westphal et al., 2000)

According to the author, limestone marl alternations are produced due to Rhythmic diagenesis, and mechanical compaction and early cementation are employed to be responsible for these alternations. Cementation occurred in an early phase, and subsequent overburden caused the sediment to be compacted mechanically. Based on petrographic observations author concluded that cementation is coming from compacted layers to uncompacted layers, and overall sedimentary input is uniform, but the diagenetic changes from the beginning are also diverged and not linked between two different layers.

(Munnecke et al., 2001)

The author prepared a model of early diagenesis by studying limestone-marl alternations from Silurian in Gotland, Sweden. It is assumed that early diagenesis of precursor sediments with minor differences can lead to limestone-marl alternations forming. Redistribution of aragonite in the system may occur, forming the calcite cement in the limestone bed. In the paper, the author attempted quantitative analysis by employing mathematical equations and calculated the quantity of aragonite dissolution and calcite precipitation during diagenesis. For testing the model, data on limestone marl alternations from Sweden, France, Germany and North America were collected; ratios of marl-limestone thickness and carbonate contents from both layers are used in the calculation. The model successfully marks the difference between the layers and whether depositional changes occurred.

(Westphal & Munnecke, 2003)

The articles suggest some strong assumptions on the available data of limestone marl alterations formation from the Cambrian to Cretaceous and overview the depositional environments in different geological times concerning differential diagenesis. Aragonite is vital in LMAs, which are abundant in warm seas. LMAs formed in shelf environments differ in diagenesis from those formed in cretaceous rhythmites formed in deep pelagic seas where little or no aragonite is present but abundant calcite.

(Mujtaba et al., 2004)

While analysing well-core samples from the Sakesar Limestone (Early Eocene), the author suggests that chemical compaction (pressure solution) is responsible for developing nodular structure during diagenesis. Limestone nodules contain preserved features of depositional origins, such as the scattered distribution of skeletal grains. These features indicate that the limestone nodules remained unaffected by principal volume reduction.

(Westphal et al., 2004)

Employing a multiproxy approach (independent biotic, sedimentary and geochemical parameters) to study the palaeo-environmental signal recorded in Early Cretaceous limestone–marl alternations from Bahama Basin unravel that differential diagenesis may overprint primary signs that hamper the original factors responsible for rhythmic alternation. Well-preserved microfossils in interlayers make the source of aragonite mud or late calcite cement for limestone cementation unclear. Therefore, careful analysis of diagenetically inert parameters is needed to interpret palaeo-environmental signals from calcareous rhythmites.

(Westphal, 2006)

The review article provides an in-depth analysis of research by authors and reflects the experience gained from previous studies. The author suggests new techniques and revision of a few methods on different regions of varying Limestone-marl alternations worldwide. However, the paper also emphasized re-evaluating results obtained from diagenetically inert parameters applied in studying rhythmic successions with enhanced care.

(Munnecke et al., 2008)

In this paper, flinz and faule alternating bedding in Upper Jurassic south Germany has been studied, and differences are marked using high-resolution microscopy. Pitted microspar, micrite, well-cemented calci-spheres, and deformed fossils indicate the role of differential diagenesis in flinz beds (>high carbonate content or pure limestone) faule beds (< low carbonate content or soft interlayers), sediments. However, the primary origin of rhythm remains unresolved.

(Westphal, Munnecke, & Brandano, 2008)

In the paper, two different sections of Neogene's alternations have been considered. The author found one section reflecting primary signals, while in the other section, the origin of alternations remained unclear due to diagenetic overprints by differential diagenesis. The astrochronological technique is applied in this paper, but it was only sometimes emphatic in interpreting the original sediments in limestone-marl alternations.

(Westphal, Munnecke, Böhm, et al., 2008)

In another study of limestone–marl alternations in Epeiric sea settings, the author concluded pure diagenetic origin of alternations rater environmental changes. The box model simulations conclude that effects of differential diagenesis redistribute calcium carbonate after aragonite export from interlayers and control cementation in limestone beds, in overwriting or sometimes generating rhythmic successions, thus distorting primary signals.

(Tucker & Wright, 2009)

Combination of early lithification and burial diagenesis (compaction and pressure solution).

(Westphal et al., 2010)

In a critical review paper, the author suggests using high-resolution chronostratigraphic and astrochronological methods based on Milankovitch cycles to study calcareous rhythmites. Study couplets with utmost care if reflecting any primary signals; however, investigating and matching these couplets with orbital curves could give exciting results. If the origin of the couplet is missing or reflects no primary signals, the high-resolution analysis must be avoided because it can lead to misinterpretation of their origin.

(Behl, 2011)

Physical properties, deformational style and oxygen-isotopic composition of chert spheroids indicate early diagenesis.

(Westphal et al., 2015)

The paper emphasises using Global Stratotype Sections and Points (GSSPs) only if primary signals are reflected in the lithology; otherwise, the interpretation of couplets might be misleading. The author demonstrated that differential diagenesis could produce calcareous rhythmites without a link to any primary signal. The geometry of layers influenced by the anisotropic arrangement of beds gives an impression of interlayers in Miocene rocks.

(Amberg et al., 2016)

Amberg et al., 2016 studied Limestone-marl alternations in the Ordovician rocks of the Oslo-Asker District, Norway. The study is conducted to reveal whether the alternations are purely diagenetic or formed during primary glacio-eustasy. Tests on two different sections employing geochemical XRF data and palynology data revealed ta palynological assemblages are the same in both limestone and marl, with minor exceptions at the species level. In contrast, geochemical data suggest good correlations of insoluble elements (diagenetically inert) data suggesting similar compositions of precursor sediments in both limestone-marl alternation layers. The results, however, refer to rather a diagenetic scenario than a glacio-eustatic imbalance, but the complete origin may not necessarily be diagenetic.

(Kahsnitz & Willems, 2017)

Autochthonous processes: pre-compactional cementation followed by mechanical and chemical compaction and variable clay contents in carbonate rocks are assumed responsible for the nodule fabrics' genesis.

(Ishaq et al., 2018)

This study investigates Early Eocene Sakesar Limestone microfacies and sedimentology at two outcrop sections from the central and eastern Salt Range, Potwar Plateau. This work examines and evaluates reservoir quality through depositional and diagenetic fabrics.

According to the author, Sakesar Limestone is affected by various diagenetic processes; micritization, cementation, dissolution, neomorphism, nodularity, silicification, and mechanical and chemical compaction. Based on the abundance of biota and the presence of a micrite matrix in the Sakesar Limestone, the depositional environment is interpreted as the inner ramp to the middle ramp.

(Nohl & Munnecke, 2019)

The author suggested the presence of a large number of aragonite fossils and their subsequent dissolution provide the excessive mud required in calcium carbonate redistribution during the formation of Limestone-marl alternations. Alteration in Halysites coral structures indicates that differential diagenesis can strongly distort primary environmental signals. The author further suggested the study of cyclo-stratigraphy to completely correlate the features information, especially form marl layers, to diagnose Limestone-marl alternations formation because some of the information might get ignored during the tin section study process, which is a nightmare in the case of marl layers.

The same year, the author applied a taphonomic approach to limestone-marl alternations in Upper Ordovician sediments. The applied differential diagenesis model results conclude that the pressure dissolution assumption is not the primary driver during the limestone-marl alternations formation and suggest that the primary aragonite mud plays a role in calcium carbonate redistribution resulting in the formation of rhythmic lithology.

(Ghazi et al., 2020)

In a publication, model of Nammal marl formation, five stages are identified: Stage 1—is characterized by alternating marl and limestone units; Stage 2—is initiated by the fracturing of limestone; Stage 3—is characterized by rounding of such material and accommodation compensated by marl; Stage 4—characterized by rounded marl material, which accommodates the developing nodule in last stage. However, ideal patterns of concretions are found in some rock formations described above. Maybe those nodules are continuously evolving and will be in an adequately rounded nodule (Stage 5) later in the future. The reported size of the nodules of limestone varies from 3–12 cm. However, the researcher has not concluded the nodule genesis and the presence of marl around them.

(Nohl et al., 2020)

In the research conducted in 2020, the author has concluded that alternating lithologies are formed due to carbonate redistribution within the formation during early diagenesis. Nevertheless, another interesting point made by the author is that the primary changes in the rock have been detected. However, these changes are not related to the change in overall lithology. Furthermore, the Limestone-marl alternations are not driven by external factors.

(Nohl et al., 2021)

The author has conducted a complex analysis using the geochemical results and tried to find the original mineral components in limestone-marl alternations using a novel vector technique.

CHAPTER 03 MATERIAL AND METHODS

3.1 Field Work and Sampling

The study studied tree rock formations Nammal Formation, Sakesar Limestone and Chorgali Formation of Early Eocene at three different locations in Salt Range. Geological fieldwork is conducted in three sections; Tatryal village, Chal abdal and Nammal Dam, distributed in Eastern, Central and Western Salt Range. Geological fieldwork helps to collect vital field information such as bedding thickness, physical characteristics of rock such as colour, grain size, fossils, the structural orientation of rock, and sedimentary structures were noted. It also includes section measurement that helps collect the samples evenly from top to bottom of each exposure. Limestone-marl alternations are present in the Chorgali Formation Tatryal village, while in the Chal Abdal Section, the Nammal formation is nodular and surrounded by fragile marl around it. In the Nammal Dam Section, the Sakesar Limestone has well-developed limestone nodules, and abundant chert nodules are also present.

3.1.1 Geological Section Measurement

In order to accurately measure a rock section, the site was accurately prepared. The first step involved ensuring that all exposed layers were easily accessible, thereby facilitating precise measurements. The thickness of each layer was then measured in meters at a section perpendicular to the dips of the bed. To conduct these measurements, a ruler or tape measure was utilized. Care was taken to measure near the middle of each layer, although not necessarily at the exact midpoint between exposures. To avoid overlapping measurements from different exposures, any parts where one exposure transitioned into another were excluded. It is important to note that measurements encompassed any portions that were obscured by vegetation or other obstructions. These field procedures were diligently carried out for the purpose of my research.
Geological section measurements were carried out in the following formations in the Salt Range.

1. Nammal Formation
2. Sakesar Limestone
3. Chorgali Formation

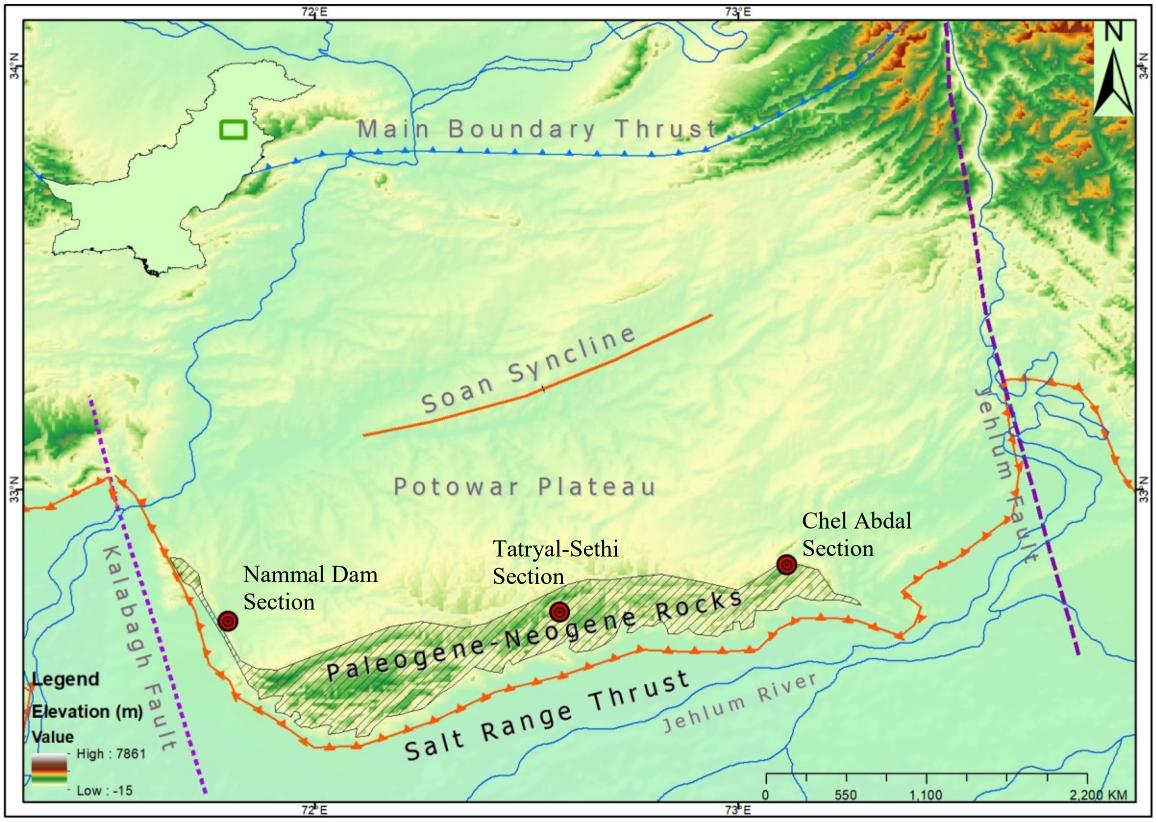


Figure 4 Location of study sections shown in a red circle; Chal Abdal Section, Tatryal Section and Nammal Dam Section in the Salt range (right to left); Inset map shows the location of the study area.

3.1.2. Samples Collection

Samples are collected from each formation in systematic order according to the rock exposure. From the Chorgali Formation vertical outcrop of limestone, marl alternations provided ease to collect samples from the centre of the exposure from top to bottom. Nine samples of marl/limestones are collected at the Tatryal-Sethi Section (location: 32° 40′ 58″ N, 72° 34′ 44″ E). In the Nammal Dam Section, Sakesar Limestone is near vertical exposure of nodular and uniform bedded limestones. Nine samples are collected systematically at intervals of 3 meters. The total thickness of the formation is 27 meters at the dam site (location: 32° 39' 53" E, 71° 48' 9.5"). The Nammal formation is sampled at the Chal Abdal Section near Ara Basharat, Kallar Kahar and seven samples are collected (location: 32° 49′ 22″ N, 73° 07′ 10″ E). Samples are collected from top to bottom after identifying the upper and lower contacts of the Nammal Formation with Sakesar Limestone and the Patala Formation, respectively. Seven samples were collected, including Nodular and non-nodular beds. Marl sample was collected from the base of the Nammal Formation in this section.

3.2 Microfacies Analysis

In the lab, I selected a suitable rock sample and cut a small piece. After grinding the sample to a uniform thickness using abrasives, water, and grit powder, I mounted it on a glass slide using epoxy resin. The edges were polished using fine abrasives and compounds. Using a specialized machine with a diamond blade or wire saw, I cut a thin section approximately 30 microns thick. The thin section was carefully placed on a glass slide and covered with a glass cover slip for protection. Relevant information was labeled on the slide. This prepared thin section can now be examined under a petrographic microscope to analyze mineralogy, texture, and geological features.

3.3 Scanning Electron Microscopy

SEM provides three-dimensional information about a material's surface and internal microstructure, especially features and defects in the micrometer range. It operates based on the emission and detection of secondary electrons (SEs) when high-energy electrons bombard the material's surface. SEs can pass through the objective lens without deflection, allowing their detection. SEM image resolution depends on the accelerating voltage and sample thickness, with higher values leading to lower resolution.

In preparing the microscope for SEM analysis, the sample was prepared as follows: A small square of rock was cut and carefully polished to ensure a smooth surface. The polished sample was then mounted onto a carbon tape or epoxy, which served as a mounting medium, providing secure attachment and good electron conductivity. To facilitate easy handling and stability during analysis, the sample was mounted onto a specimen holder, which was later attached to the microscope stage. Subsequently, the sample underwent grinding and etching for approximately 40 seconds using a 0.1 standard HCl solution, followed by a brief immersion in an ultrasonic bath for 2 seconds. To enhance the conductivity of the sample and minimize charging effects, it was sputter coated with a thin layer of gold. Finally, the prepared sample was investigated using the SEM, including capturing photographs for analysis.

CHAPTER 04 RESULTS

In this chapter, results of field work, petrography and scanning electron microscope have been discussed after a careful observation correlation of field to micro and ultra-micro scale is established.

4.1 Field Observations

Nammal Formation (Early Eocene) Chal Abdal Section near Basharat, Chakwal

This section is visible along the Chal Abdal-Basharat road. It lies adjacent to a village known as Ara Basharat. A contact was identified Nammal Formation and the underlying Patala Formation, which is currently being mined for coal. The upper part of the Nammal Formation is dark grey limestone covered with vegetation. The lower part is composed of oxidized Marl. The total thickness of this formation was 16.1 meters, with nine different lithofacies (LF) found top to bottom.

LF1: This lithofacies is thick-bedded and massive, with nodularity at the edges of limestone beds. Small to intermediate size nodules were found in this bed. Nodules have specific round shapes embedded in an egg tray surrounded by Marl. Bedding vertical fractures are found in this unit, filled with botryoidal yellow calcite cementation. Chert nodules of small size are present. The dark grey colour of this top bed represents weathering, but the fresh colour of this unit is pale yellow, off-white and creamy. The bed is fossiliferous overall; however, the nodules have low fossil content. The size of the chert nodules is small, wrapped in a pale yellow calcite envelope, and black from the inside rest of the beds look greyish. The thickness of this unit is 7.8 meters (23 feet).

LF2: The limestone bed is highly compacted but fractured and partially covered in soil debris. The fresh colour is a light pale yellow, and its weathered colour is dark grey. It has medium to small-sized Chert nodules in places. Its thickness in the field is measured as 3.2 m.

LF3: The third unit in the lithofacies is massive limestone with a light to dark grey appearance. This bed has diagenetic cavities and vugs caused by dissolution. Crystal replacement botryoidal calcite, black quartz vein and fracture networks are also found during the fieldwork. Its thickness is 2.1 m

LF4: The bottom Marl bed is oxidized pale yellow to brownish, making contact with the overlying limestone layer and marking contact with the underlying Patala Formation. Small fossils are visible in some places, and the bed shows a shaly appearance due to the effects of meteoric water and other physical and chemical weathering processes. Its thickness is 3 meters measured in the field.

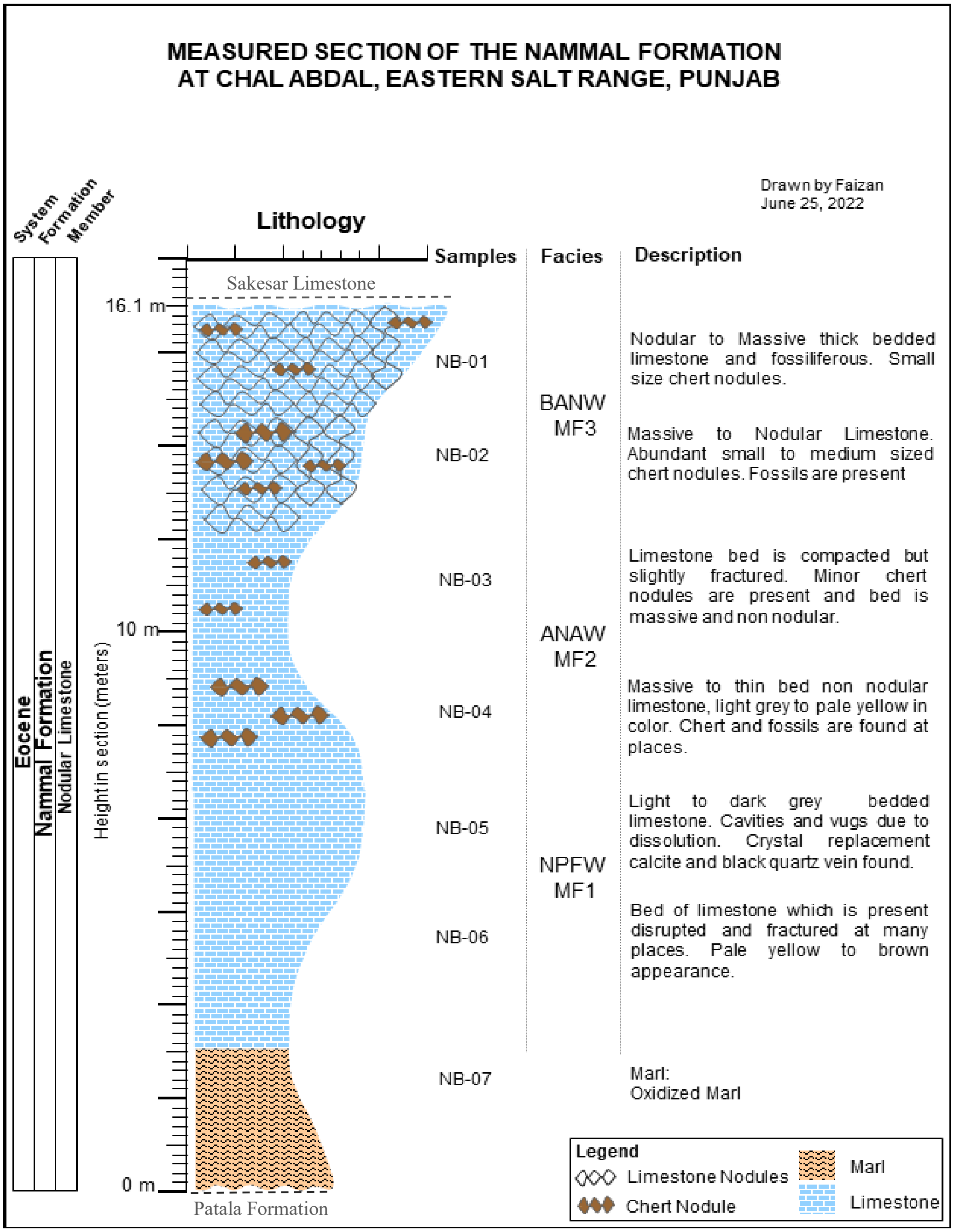


Figure 5 Lithological log of the Nammal Formation (Early Eocene) Chal Abdal section. BANW: Bioclastic Assilina Nummulitic Wackestone, ANAW: Alveolina Nummulitic Assilina Wackestone, NPFW: Nummulitic Planktonic Foraminiferal Wackestone.

Sakesar Limestone (Early Eocene) Nammal Dam Section (NGS) Musakhel.

Sakesar limestone is exposed on the left and right sides of the Nammal Dam crest in the Nammal Gorge, Musakhel. These limestone beds are nodular, have chert nodules, and well-developed calcite concretions with up to 27 meters of thickness. It has medium to thick beds but is uniform in size, features, and orientation. Systematic sampling was carried out at intervals of three meters. Nine samples were collected from bottom to top: creamy-to-light brown fresh colour; dull light brown weathered colour with black spots at crevices and fractures; overall colour a dull off-white. The unique feature distinguishing this formation from the underlying Nammal Formation is its large-sized calcite concretions. When viewed from a distance, it appears as layers of stack balls. Chert nodules are abundant and look diagenetic, dispersed at irregular intervals. Various sizes and shapes have been observed in chert nodules from 2 cm to 12 cm in length. The shape of all nodules was different—some were round, subrounded elongated or angular. All nodules were covered by calcite like an eggshell and black from the inside, with microcrystalline quartz.

The youngest of the top beds are diagenetic, fragile in breaking and contain several veins filled with secondary fluids. These layers are divided into the following units (bottom to top). At the bottom near the dam, bulging in the rock formation is observed due to stress. The arrangement of nodules also appears disturbed. A few chert nodules are stretched mainly because of tectonic activity. Calcite concretions are common features found near fractures and veins of calcite.

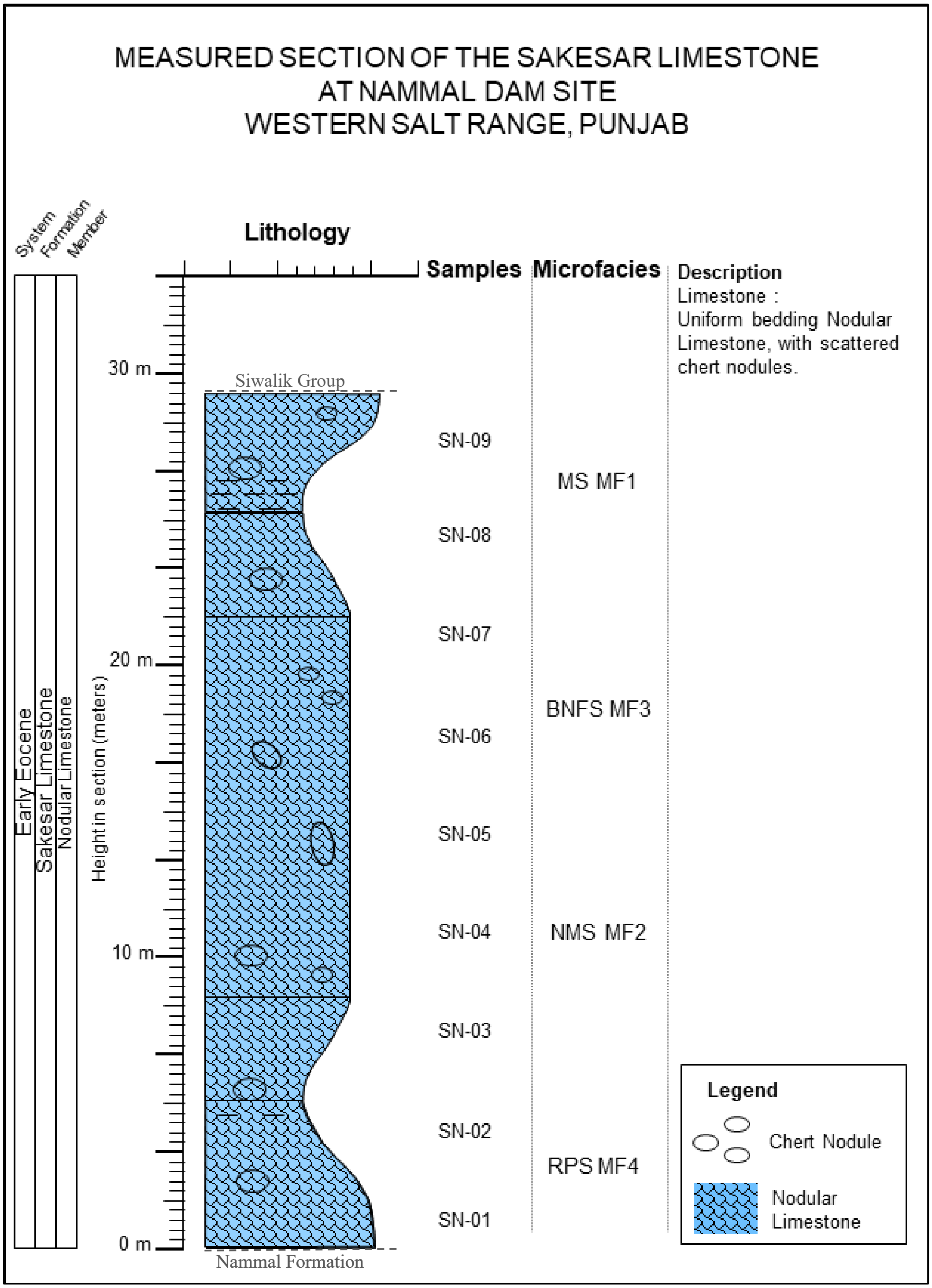


Figure 6 Lithological log of the Sakesar Limestone (Early Eocene) Nammal Dam Section. RPS: Radiolarians Packstone, BNF: Bioclastic Nummulitic – floatstone, NM: Nummulitic Mudstone, MS: Mudstone.

Chorgali Formation (Early Eocene) Tatryal section, Noorpur Sethi, Chakwal:

This section of the road is cut along its length. It lies on the way to Tatryal village in Noorpur-Sethi. Beyond the road, recent excavation has exposed an entire portion of the Chorgali Formation, cutting it from the centre of one side to another. The bedding in this unit consists of dark grey limestone covered with vegetation; its lower contact is with the Sakesar Limestone exposed at the study site. At the same time, no deposition was found on top of this formation. The total thickness of this studied formation is 17.9 meters, with nine different lithofacies (LF).

The lithofacies LF1 is massive and thick bedded, though nodularity is found in the middle and lower portions of the limestone beds. The size of these nodules ranges from 2-16 cm on average but varies in size and shape. Nodules have different shapes; rounded, half rounded and elongated. The dark colour of this top bed represents weathering; the fresh colour of this unit is a pale yellow to creamy white or off-white. Fresh surfaces show no or few fossils that appeared primarily as micritic features in this lithofacies. Nodules are surrounded by unidentified comparatively softer material. The thickness of this unit is 7 meters.

LF-2: A thick bed of limestone marked as the second lithofacies that lacks fossils. Few fossils were discovered in one or two regions of this whole bed, with an average thickness of 0.8 m approx. The weathered colour is brownish yellow, while its fresh surface is light grey. A nodule and a limestone piece are sampled from this part marked as CS-2.

The third unit in the formation is Marl, which is marked as lithofacies LF-3. Its fresh colour is yellow and highly compacted. The outer surface is shaly in appearance, but close examination and digging prove it to be compacted Marl due to the overburden of the limestone bed. Its thickness in the field is 2.8 meters.

LF-4: This is an alternative bed of limestone found between marly layers. The limestones of this bed have fossils in them. Its fresh colour is grey and brown, while its weathered appearance is a pale yellow and dark brown. Its thickness is 0.4 m or less.

LF-5: The lithofacies LF-5 is Marl, which has a pale-yellow appearance and an average thickness of 0.5 m. This bed is also compacted due to the overlying and underlying layers of beds. It has sharp contacts with above and below lithofacies units.

LF-6 consists of a single limestone bed, which is in the repetition of the previous LF-4. Small calcite nodules are found in this limestone bed with fractures. Its fresh colour is light to dark grey and has an exact thickness of 0.6 meters.

LF-7 Unlike the above limestone layers, this marl bed is a different colour and has sharp contact with the limestone bed. Its colour is green to light green. Visible fossils are present in small chunks on Marl. The outer surface of this bed shows some characteristics of shaly action mainly because of meteoric water and other physical and chemical weathering effects, but further digging with a hammer revealed the original scenario; compacted soft green mud was distinct from shale. Its thickness is about 0.7 m.

LF-8: This thick-bedded biomicritic limestone has been diagenetically altered at some places showing oxidized, filled pore material. Its weathered colour is pale yellow, while its fresh colour is grey. This unit is fossiliferous with minor fractures, and its exact thickness is about 0.9m.

LF-9: The base of the Chorgali Formation is a bed of Marl. Its upper contact is sharp with a limestone bed. The lower contact of the Chorgali Formation is conformable with the Sakesar Limestone, which is exposed and visible half a meter on the surface.

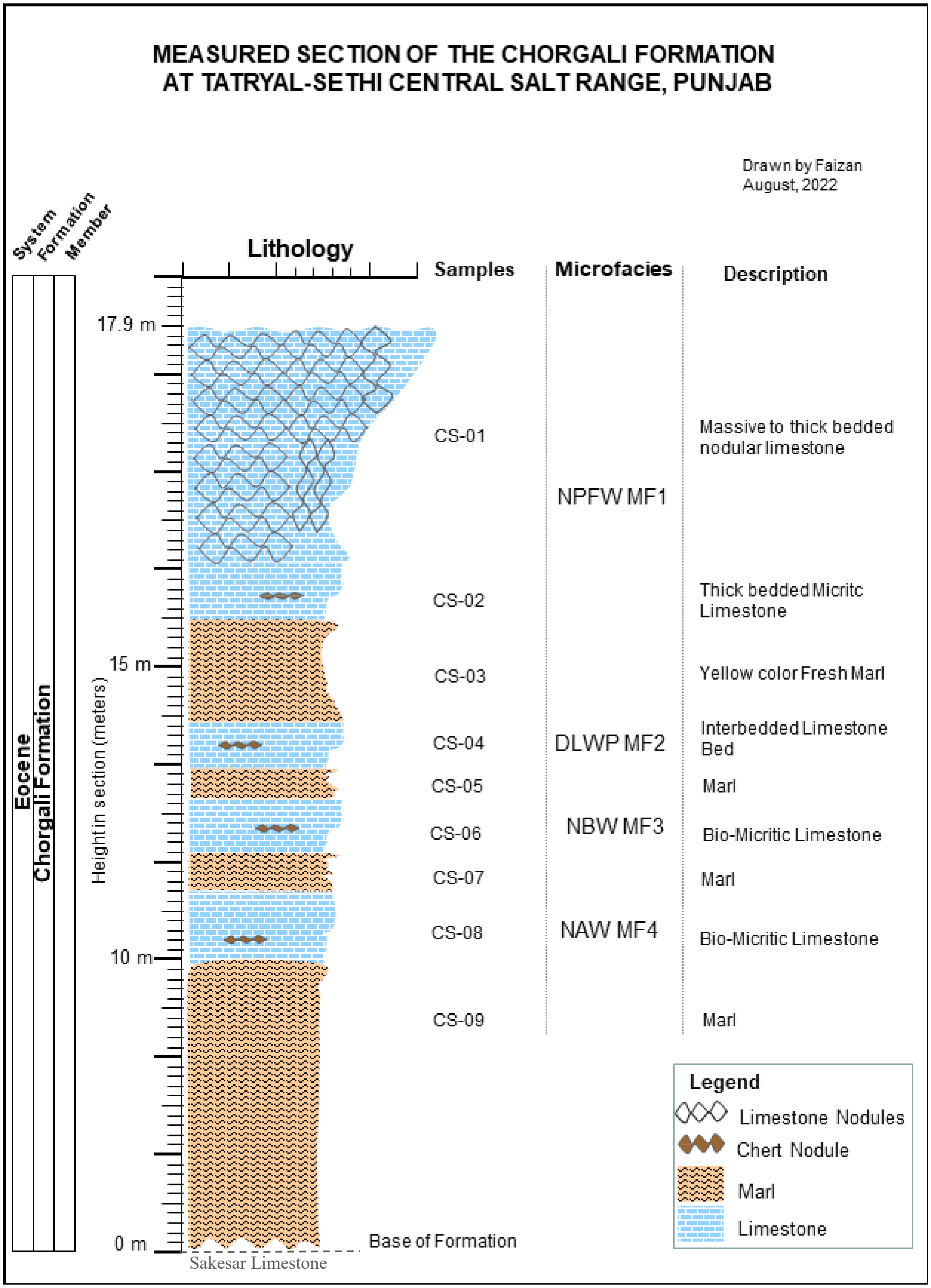


Figure 7 Lithological log of Chorgali Formation (Early Eocene) Tatryal-Sethi section. NPFW: Nummulitic Planktonic Foraminiferal Wackestone, DLWP: Discocyclina Lokchartia Wackestone to Packstone, NBW: Nummulitic Bioclastic Wackestone, NAW: Nummulitic Assilina Wackestone.

Figure 8 Field Pictures

Direction is shown by yellow north arrow.

A: Nodular limestone with marl, Nammal Formation, Chal Abdal Section.

B: Brachiopod shell in Nammal Formation, Chal Abdal Section.

C: Caverns dissolution in Nammal Formation, Ara Basharat.

D: Stylolite in Nammal Formation, Ara Basharat.

E: Bioturbation in Nammal Fomation, Chal Abdal Section.

F: Gastropod and Chert nodule in Nammal Formation, Chal Abdal Section.

G: Contact of Sakesar Limestone (left) and Nammal Formation (right), right side of Nammal dam from Nammal gorge.

H: Spade Chert Nodule Sakesar Limestone, Nammal dam section.

I: Deformed Chert Nodule Sakesar Limestone, Nammal dam section.

J: Small chert in limestone beds of Chorgali Formation, Tatryal-Sethi section.

4.2 Microfacies

The study of rock under the microscope is called micro-facies analysis. Microfacies analysis is used to classify rock using information seen in a microscope. The subject of carbonate classification has also been a matter of debate amongst various workers throughout the globe. Many workers have proposed different categories of limestone based on various parameters. Among these classifications, Folk and Dunham are the most widely accepted.

In his classical work (Dunham, 1962), he emphasized the depositional texture of the carbonate grains. Dunham's classification is widely accepted because of its simplicity and accessible applications in the field and laboratory. Dunham used the terms like mudstone, wackestone, packstone, grainstone, and boundstone for different carbonate rocks depending upon the relative abundance of the carbonate grains in the depositional framework. Microfacies of rock provide information about its depositional environment, sedimentary structures, and mineralogy. They are essential in the interpretation of sedimentary rocks, particularly carbonates. Carbonates can reveal important details about a rock's environment and diagenetic processes.

(Dunham, 1962) classification of carbonate rocks is used to describe and classify them based on their macroscopic textures and structures. The Dunham's classification is based on the principle that the texture of a carbonate rock reflects the depositional environment and the type of sediment present. The category comprises six main types: mudstone, wackestone, packstone, grainstone, boundstone, and floatstone. A mudstone is a rock composed of primarily mud-sized particles with little to no skeletal material. This rock is deposited in quiet, deeper water environments like lagoons and basins.

Wackestone is a rock composed of mud-sized and skeletal particles with no significant grain-supported fabric. This rock is deposited in shallow waters, such as reef flats and shallows.

Packstone is a rock composed of well-sorted, grain-supported particles with no significant matrix. This type of rock is deposited in high-energy environments, such as tidal channels and shallow subtidal areas. Grainstone is a rock composed of well-sorted, grain-supported particles with little to no matrix. This type of rock is accumulated in high-energy environments, such as tidal channels and shallow subtidal areas. Boundstone is a rock composed of firmly cemented skeletal material, such as corals and bryozoans. This rock is frequently deposited in shallow water environments, such as reef flats and shallows. Floatstone is a rock composed of floating skeletal material, such as bioclasts and peloids. This type of rock deposits in shallow water environments, such as lagoonal areas and shallow subtidal habitats.

(Folk, 1959, 1962) classification is based on the relative abundance of carbonate grains versus matrix, whereas Dunham focuses on the constituent grains' textural framework. Examination of thin sections under the petrographic microscope is considered a core study of any carbonate rock by which the type and texture of constituent grain/crystal of carbonates can be identified. Our understanding of carbonate rocks is based on the studies of their microscopic sections. The Dunham classification is widely used in the study of carbonate rocks and has been modified and refined over the years to better reflect the complexities of carbonate depositional environments. For example, the recognition of micrite, a fine-grained carbonate matrix often present in carbonate rocks, has led to the developing a modified classification system that includes micrite as a separate component.

Bioclasts

Skeletal grains (whole and broken) are the major allochemical constituents, with foraminifera predominating. Other fossil forms observed in decreasing order of abundance are Ostracods, Red Algae, Pelecypods, Echinoids, Green Algae, Gastropods and Corals. The fossils consist mainly of shallow marine benthonic Forams such as Miliolidae, Soritidae, Alveolinidae, smaller Rotaliidae and larger Rotaliidae such as Nummulites, Assilina, and Lockhartia (Plate-1, 2, 3). The shell debris almost exclusively represents Echinoids and Ostracods with sparse Pelecypods, Brachiopods and Gastropods. Green and red algae are sporadically distributed (Plates 1 and 2). Some bioclasts are represented mainly by moulds (open or filled); the filled ones mostly contain sparry calcite (Plate-1).

Foraminifera

Foraminifera is the abundant allochemical constituent of the Early Eocene carbonate rock formations. A wide variety of Large Benthic foraminifers predominate over planktonic foraminifers.

Those identified include representatives of the families; Nummulidae, Rotalidae (larger), Alveolinidae, Miliolidae, Soritidae and Textularidae.

Cementation

Cementation is a process by which cementing materials fill in the pore spaces of sediments. The cementing material in carbonate sediments is commonly calcite. The fracture is filled with calcite cement (Plate-3).

4.2.1 Scope of Microfacies

Microfacies are the total of all the paleontological and sedimentological criteria classified in the thin sections, peels and polished slabs" (Flügel, 2013). The present study aims to examine the texture of rock components, focusing on how diagenetic changes affect their appearance. The content also includes a discussion of how limestone-marl alternations form. Evidence collected through a sedimentological point of view helps scientists identify any post-depositional changes that occurred in precursor sediments of couplets. Nammal Formation, Sakesar Limestone and Chorgali Formation, a carbonate rock sequence of Early Eocene exposed in different regions in the Salt range, are analyzed for sedimentological analysis. For this study, 24 samples were collected for detailed petrographic analysis. Important petrographic features, such as types of bioclasts and intraclasts, are recorded during microfacies analysis. Microfacies in each studied section are described below.

4.3 Interpretation

Microfacies

Carbonate to tidal deposits flats is traditionally associated with expansive marine environments characterized by three main types; deep marine, shallow marine and tidal flats. Deep marine or pelagic refers to open marine deposits on oceanic crust, such as a seismic ridge, submerged Plateaus, mid-oceanic ridges and abyssal plains. There are varieties of biogenic and non-biogenic components in most pelagic sediments. The dominant presence of Planktonic foraminifers, radiolarians, or other groups of plankton or nekton characterizes these environments. Benthonic foraminifers' open or restricted circulation and abundance characterize shallow marine environments. Wackestone to boundstone Microfacies is found in this environment. Continental shelf, fore-slope, back-slope, shoal, and lagoons are the typical environmental parts of shallow marine environments. Tidal flat environments are characterized by three main types; subtidal, intertidal and supratidal zones. Subtidal and intertidal are included in the shallow marine environment. The subtidal zone is the permanently submerged area, seaward of the tidal flats.

This zone is mainly associated with protected low-energy lagoons and restricted bays but is sometimes also affected by intense wave action and tidal currents. The intertidal zone lies between the normal low and high tide levels and is alternately flooded by marine water and exposed. The area is subaerially exposed, and burrowing organisms are commonly present. The supratidal zone lies above the normal high tide and occasionally floods during spring tides or under storm conditions. It can be extensive on low relief prograding coastlines and characterized by prolonged exposure.

4.3.1 Microfacies Analysis of the Nammal Formation

Chal Abdal Section

At the Chal Abdal Section, the following three microfacies were observed from top to bottom in Nammal Formation in total exposure of 16.1 m:

4.3.1.1 Nummulitic Planktonic Foraminiferal Wackestone MF1

Description

The Benthic Foraminiferal wackestone to grainstone includes extinct Alveolina in planispiral arrangement, ostracods, and brachiopod shell fragments. Nummulites spp with abundant Planktonic forams and biodebris are found in these microfacies. It has a total thickness of about 2 meters and comprises the lower part of Nammal Formations. This microfacies has a total thickness of about 2 meters and comprises the lower part of Nammal Formation, sparse Pelecypods and intraclasts (Plate-1 Figure A-B).

Interpretation

Various depositional models described Nummulites accumulations as banks, bars or low-relief banks, sometimes related to palaeo-highs. The behaviour of Nummulites could explain the diversity of such depositional models. Depending on local hydrodynamic conditions, autochthonous Nummulite deposits can be preserved as in situ winnowed bioaccumulation or accumulated offshore, onshore or alongshore, away from the original biotope (Jorry et al., 2006). Planktonic foraminiferal wackestone with high planktonic forams (35–40%) indicates an open deep marine (outer shelf) environment with low energy conditions (Flügel, 2010). In the current study, the low percentage of planktonic foraminifera indicates the depositional environment restricted tidal to the Lagoon and overall peritidal environment (Tucker & Wright, 2009; Wanas, 2008). Moreover, the lime muddy texture further signifies low energy restricted tidal flat to lagoonal (Wilson, 1975).

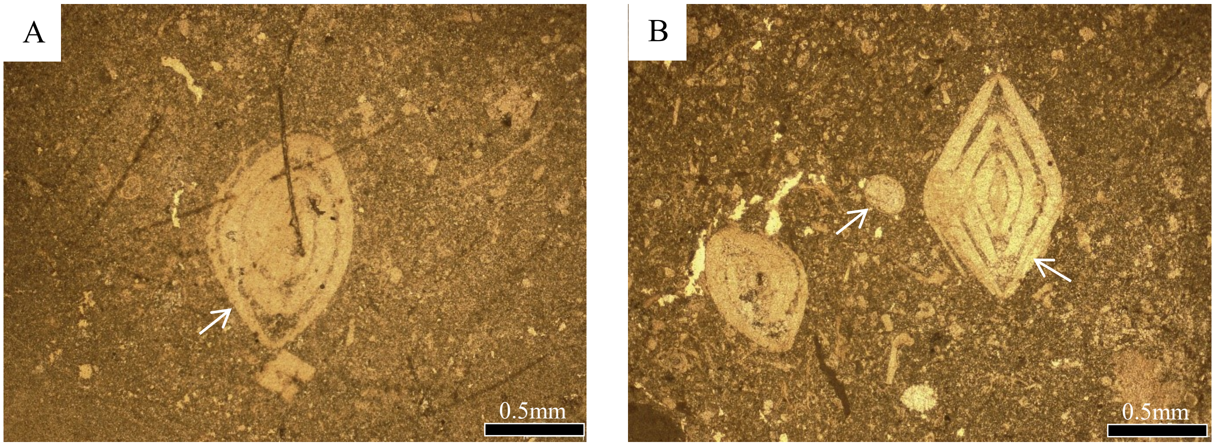


PLATE 1: Photomicrographs scale: 0.5 mm (Plane polarized light)

Sample ID: NB-6

A: Nummulites sp with abundant planktonic forams.

B: Numulities sp, Ostracods and bioclasts.

4.3.1.2Alveolina Nummulitic Assilina Wackestone MF2

Description

Large Benthic Forams include Assilina spinosa, Alveolina sp, small Miliolid, Nummuities Atacicus, and Rotospirella conica. However, Miliolidae is small in size biodebris, and Planktonic forams are present. Echinids include sea urchin spine, and Molluscs include brachiopods, pelecypods and ostracods. However, the structure is preserved by cementing the internal structure of LBFs in chambers. The first microfacies found in the rock include brachiopod shells, large benthic forams, and bioclasts. Sparse soritoidae and green algae are also present, along with ostracods. The first facies have a total thickness of about 3 meters (Plate-2 Figure A-D).

Interpretation

Large benthic foraminifers like Nummulites and Alveolina suggest deposition in a shallow-shelf environment with moderate to high energy conditions. Miliolids and micrite matrix abundance indicate deposition in shallow marine quiet water conditions (Ghazi et al., 2004; (Taheri et al., 2008). Open Lagoon to Backreef shelf deposits (Boudaugher-Fadel, 2018).

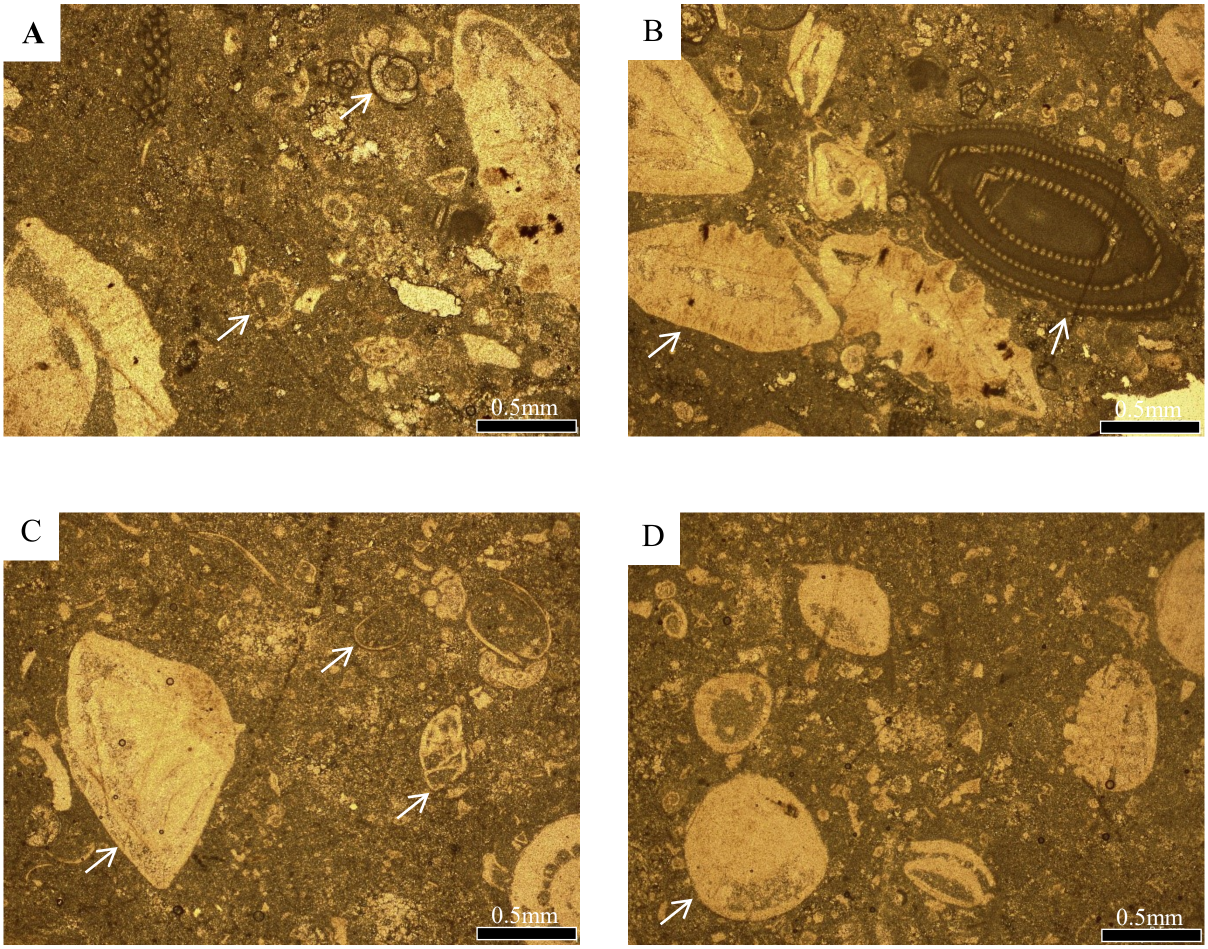


PLATE 2: Photomicrographs scale: 0.5 mm (Plane polarized light)

Sample ID:
NB-1
A: Millioids, Sea urchin spine, and large benthic foraminifers.
B: Assilina sp, Alveolina sp, Assilina spinose, and bioclasts.
NB-2
C: Nummuities sp, Ostracod, Rotospirella conica, and fossil shell fragraments.
D: Large Benthic foraminifers; internal structure of large benthic foraminifers is cemented.

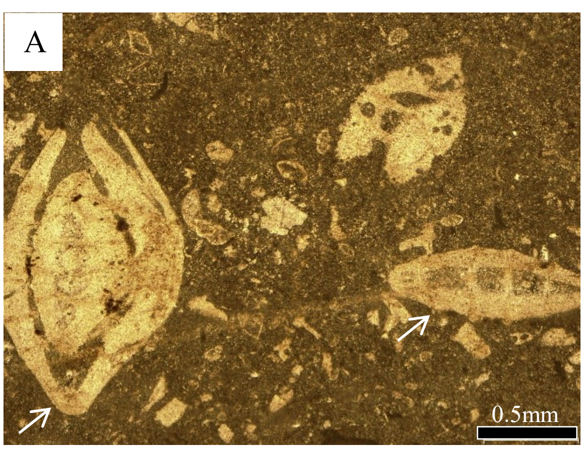
4.3.1.3 Bioclastic Assilina Nummulitic Wackestone MF3

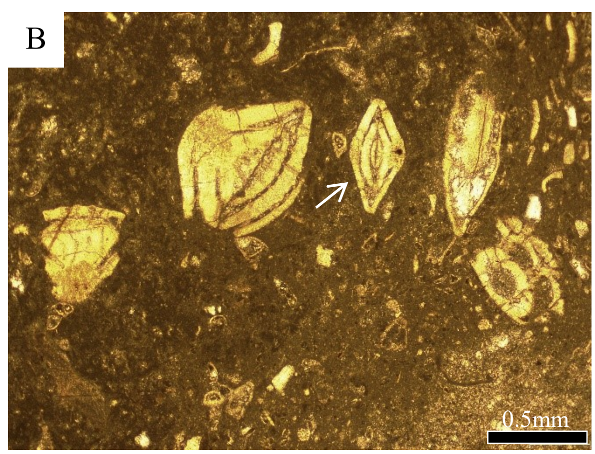
Description

Benthic Foraminiferal wackestone MF2 contains, Nummulites, Alveolina, Assilina and abundant large and small plankton foraminifers. Species include Nummulites sp and Assilina laminosa. A broken fragment of the brachiopod is filled with silica and calcite cement. Broken larger foraminifers and abundant debris are present. Ostracod-Planktonic foraminifers are calcite and internal structure is not visible. This microfacies has a total thickness of about 8.8 meters and comprises the middle part of the Nammal Formation. (Plate-3 Figure A-D).

Interpretation

Nummulites with a low percentage of Assilina having original morphology and mineralogy of their shells represent the relatively moderate energy conditions below fair weather wave base (Flügel, 2013). Shallow shelf conditions with high sunlight penetration provide a conducive environment for flourishing fauna and high nutrient availability (Afghah & Farhoudi, 2012). In the proximal fore-reef shelf, the most dominant foraminifera are cycloclypids, lepidocyclinids, operculinids, Amphistegina and Heterosteginids associated with scattered alga and coral and cemented by sparite and micrite (Boudaugher-Fadel, 2018). In the present study the Amphistigina, along with the other benthic foraminifera and their relative percentage, support the proximal part of the forereef shelf (Asis & Jasin, 2015).





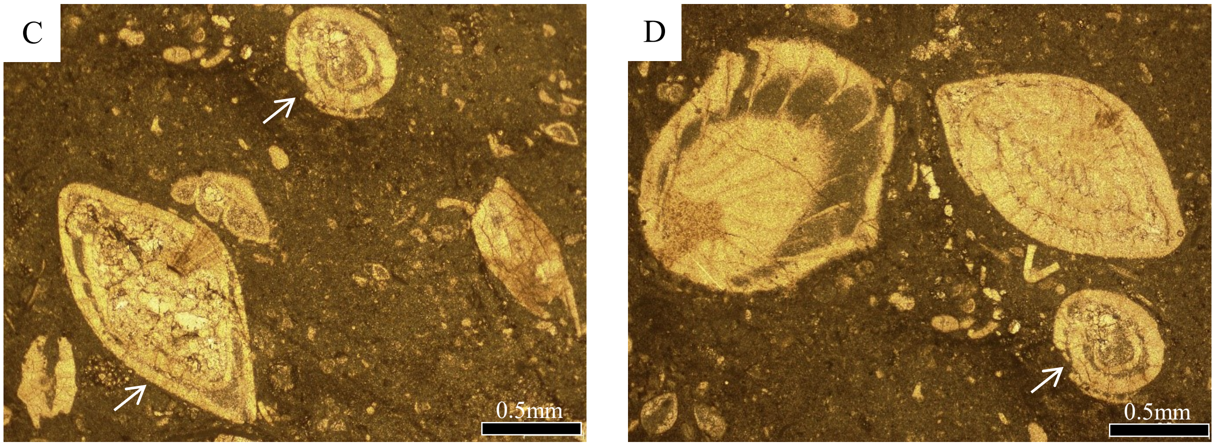


PLATE 3: Photomicrographs scale: 0.5 mm (Plane polarized light)

Sample ID: NB-3

A: Nummulites sp, Assilina sp with abundant planktonic foraminifers.

B: Nummulities atcicus.

NB-4

C: Nummulites sp. filled with calcite cement.

D: Nummulites sp axial and planispiral arrangement.

Depositional Environment of Nammal Formation

Nammal Formation reflects the deepest stage of the Lower Eocene Carbonate facies (Jurgen et al., 1988). The Formation is mostly wackestone, where the top is characterized by Benthic foraminiferal rich in Miliolidae, Nummulitdae, Assilindae and Alveolinadae. In the middle part, the benthic foraminiferal wackestone facies implies to Nummulitdae-Assilinadae and other unidentified pelagics. At the base, it contains sparse pelagic foraminifers, benthonic foraminifers such as sparse Nummulites and sparse remains of ostracods. The Nammal Formation consists of thin-bedded, slightly argillaceous rocks and a high percentage of silt-sized bioclasts. The depositional environment of the Nammal Formation is some shallow marine facies of Lagoon, fore and backreef shelf setting of inner shelf depositional environment.

4.3.2 Microfacies Analysis of Sakesar Limestone

Nammal Dam Section

At the Nammal Dam section, four microfacies in the Sakesar limestone Early Eocene are present. These are from lower contact to formation top in vertical beds.

4.3.2.1 Mudstone Facie MF1

Description

A fossilized brachiopod shell is filled with blocky and authigenic silica cement. Micritized gastropod fossils show Neomorphism. Radiolarian's calcified original structure is absent, and sparse to abundant faecal pellets are present. The thickness of the microfacies zone is 6 meters, comprised of the upper part of the Sakesar Limestone. This limestone contains abundant radiolarians and calcite cementation (Plate-1, Figure A-B).

Interpretation

The percentage of allochem relative to the matrix is negatable and reflects pure mud content appears as the bulk of lime matrix, the nonexistence of faunal contents, and no lamination represent the low energy environment of deposition in lagoonal setting (Flügel, 2013; Hussein et al., 2017; Wilson, 1975). The less diversity of fauna in succession implies a restricted subtidal lagoons environment of deposition under low energy and high salinity (Flügel, 2013). The facies can be correlated with those defined by (Alqattan & Budd, 2017; Hughes, 2009; Wanas, 2008)

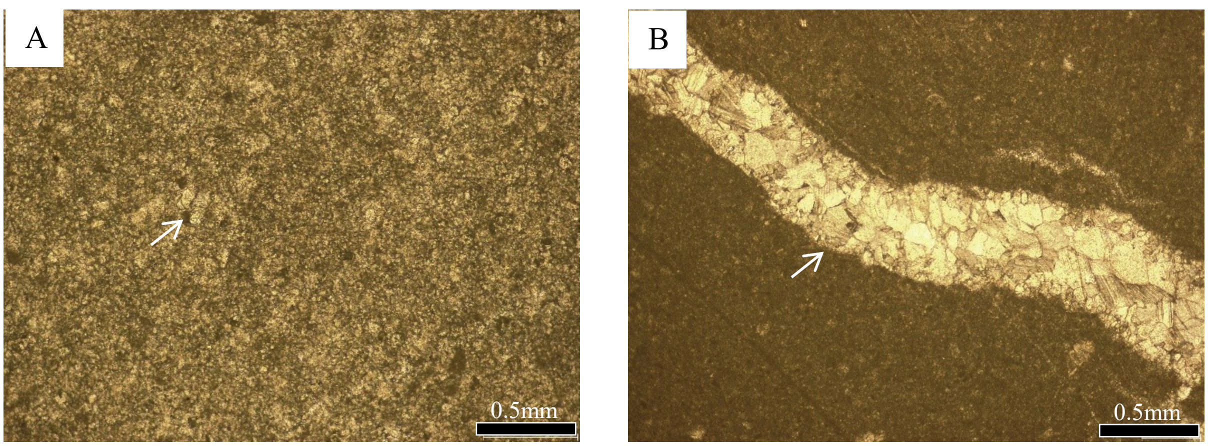


PLATE 1: Photomicrographs scale: 0.5 mm (Plane polarized light)

Sample ID: SN-8, SN-9
A: Micrite and microsparite and sparse Fecal pellets.
B: Microfracture filled with calcite (blocky cement).

4.3.2.2 Nummulitic Mudstone MF2

Description

The facies' large part is mudstone, mostly covered with micrite mud, and sparse benthic foraminifers found include Nummulites and Assilina species. A large brachiopod shell is filled with blocky calcite cement preserving the structure. The thickness of these facies is 12 meters. (Plate-2, Figure A-B).

Interpretation

The well-preserved nummulites indicate calm energy hydrodynamics, which is further supported by the bioturbations burrows and fecal pellets; however, the debris with micritic matrix indicates extensive transportation and reworking from high to low energy conditions (Dunham, 1962). Large Nummuilites with pelecypod indicate a typical back reef environment (back-bank facie) of the inner ramp on an inner shelf of a carbonate platform (Ćosović et al., 2004; Pomar, 2001).

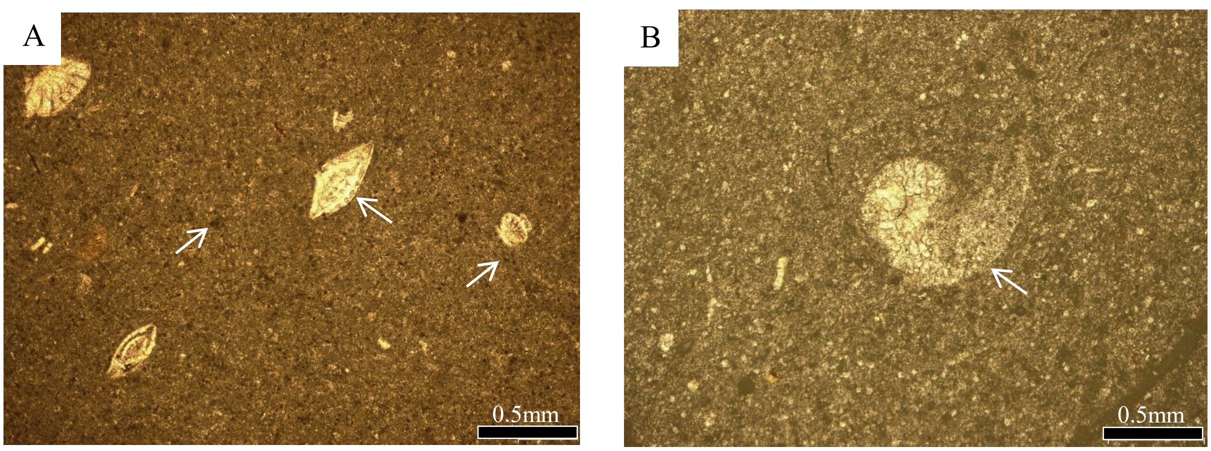


PLATE 2: Photomicrographs scale: 0.5 mm (Plane polarized light)

Sample ID:
SN-3
A: Nummulites, fecal pellets.
SN-5
B: Calcified Gastropod fossil in a mudstone.

4.3.2.3 Bioclastic Nummulitic – Floatstone MF3

Description

Large benthic foraminifers exist in these facies, including Nummulites and Assilina species. However, a large broken Assilina fossil is found. A Gastropod shell is calcified, and the outer structure is preserved. Species include Nummulites Globulus sparse brachiopod fragments and small ostracod, sparse planktonic foraminifers, and biodebris. This microfacies comprises the end of Sakesar Limestone and is about 3 meters thick. In addition, broken parts of green algae are also present but not common. (Plate-3, Figure A-B).

Interpretation

Nummulites with Assilina occur in both low and high-energy conditions of shallow shelves (Beavington-Penney & Racey, 2004; Flügel, 2013). The association of Nummulites debris with micritic matrix indicates extensive transportation and reworking from high to low energy conditions (Dunham, 1962). Large Nummulites with Assilina fore reef setting on an inner shelf setting (Wanas, 2008). Furthermore, the broken Assilina fragments also support high energy conditions, most probably the outer ramp proximal part of the fore-reef setting.

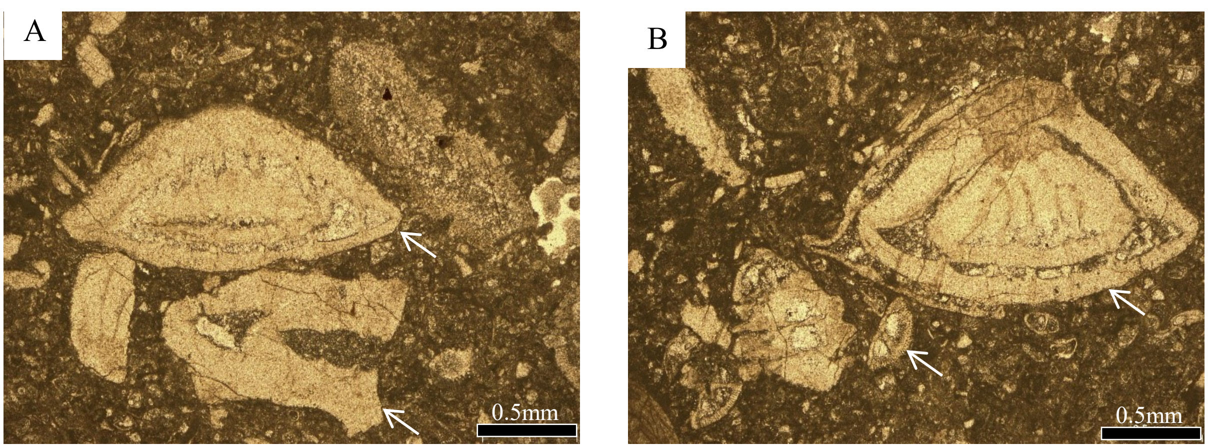


PLATE 3: Photomicrographs scale: 0.5 mm (Plane polarized light)

Sample ID: SN-6
A: Nummulites sp, broken Assilina fossil and abundant bioclasts.
B: Nummulities sp, plantonic forams with broken fossil fragments.

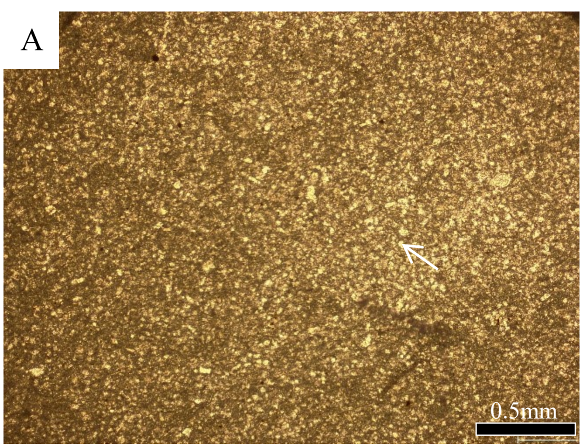
4.3.2.4 Radiolarians Packstone MF4

Description

Abundant radiolarians and planktonic foraminifers are present in micrite mud. Sparse benthic foraminifers are unidentified due to their micritization of internal structures and cement filling. A large broken sell fragment is filled and replaced by calcite cement, but the original structure is preserved. The fracture is filled with blocky calcite cement and authigenic quartz. This microfacies is 6 meters thick and contains faecal pellets and biodebris (Plate-4, Figure A-B).

Interpretation

Radiolarian is believed to be an exclusively marine organism (Flügel, 2013). Similarly, the study of (Emery & Myers, 1996) and (Abdula et al., 2015) suggested that planktonic foraminifera and Radiolarians are generally common in deep-water environments. The Calcispheres are usually restricted in cherty limestone and associated with calcified radiolarians. (Bishop, 1972) maintains that calcispheres indicate deep open sea. Based on (Masters & Scott, 1978) calcisphere can be found in shallow and deep water deposits. Additionally, the high abundances of poorly preserved radiolarians and moderately well-preserved planktonic foraminifers suggest a transgression and eutrophication of the upper water column (Heldt et al., 2008). The presence of Radiolarians signifies the oligophotic zone of the integrated outer ramp proposed by (Boudaugher-Fadel, 2018) of the distal part of the fore-reef setting to an open shelf environment.



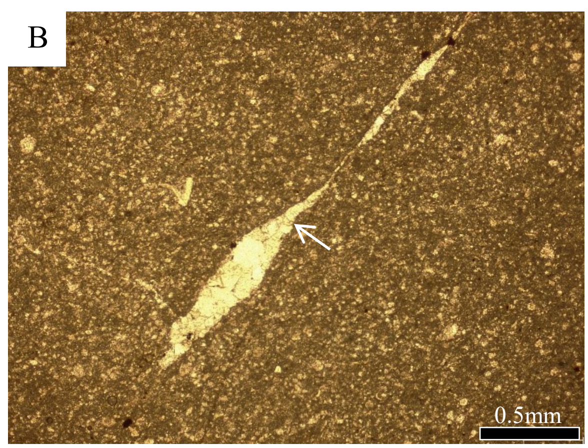


PLATE 4: Photomicrographs scale: 0.5 mm (Plane polarized light)

Sample ID: SN-1, SN-2

A: Radiolarians; original structure is replaced by calcite cement.

B: Radiolarians, sparse planktonic foraminifers; fracture is filled with blocky calcite cement.

Depositional Environment of the Sakesar Limestone

The depositional environment of Sakesar Limestone in studied sections concerning microfacies is given as follows:

Nummulites, Radiolarians, gastropods, sparse gastropods, and fecal pellets are found in this section of Sakesar Limestone. Ostracods live in both fresh and marine water. Modern forms live chiefly in the uppermost few cm of fine-grained sediments on the shallow seabed (Scoffin, 1987). The association of ostracods with other microfossils indicates subtidal to lower intertidal environments. These microfacies are believed to have been deposited in the subtidal Lagoon to lower intertidal habitats. These microfacies contain sparse to common Nummulites from bottom to top in this formation. The percentage of Nummulites increases in the middle portion of the Sakesar Limestone. Nummulitids species are believed to have been bottom dwellers throughout their life, living within a few cm of the soft bottom mud in non-turbid marine water of normal salinity (Lemann, 1970) from near wave base to low tidal level, 20 to 130 meters (Lee et al., 1994) has been inferred.

The Sakesar Limestone is an entirely marine, shallow water deposit (Jurgen et al., 1988). The composition of the rock and its large extent suggests accumulation on a very gently dipping carbonate ramp in a shallow-water, inner to middle shelves with some part in the outer shelf and lagoon environment (Boudaugher-Fadel, 2018).

4.3.3 Microfacies Analysis of the Chorgali Formation

Tatryal-Sethi section

At this location, the following four microfacies from bottom to top of the Chorgali Formation (Early Eocene) were observed.

4.3.3.1 Nummulitic Planktonic Foraminiferal Wackestone MF1

Description

MF1 belongs to the upper part of the Chorgali Formation, which is sparsely populated with planktonic foraminifera, benthic foraminifera, and micritized broken fragments of Molluscs—fossils identified as planktonic Globorotalia spp. Large benthic foraminifers include Nummulites mamillatus, Miliolids spp., and Molluscs, including Brachiopods shell fragments, Ostracods, Palycepod and planispiral Gastropod with cement-filled shells. The spine of sea-urchin represents echinoids in image C. MF1 has a total thickness of 7.8 meters (Plate-1, Figure A-D).

Interpretation

Nummulites has various proposed depositional models, and most of them described Nummulites accumulations as banks, bars or low-relief banks, sometimes related to palaeo- highs. The behaviour of Nummulites could explain the diversity of such depositional models. Depending on local hydrodynamic conditions, autochthonous Nummulite deposits can be preserved as in situ winnowed bioaccumulation or accumulated offshore, onshore or alongshore, away from the original biotope (Jorry et al., 2006). The occurrence of Nummulites with Asstrotrlina, Planktonic foraminifers and bivalves is a typical indication of an open Lagoon to backreef shelf of the Inner ramp (Boudaugher-Fadel, 2018).

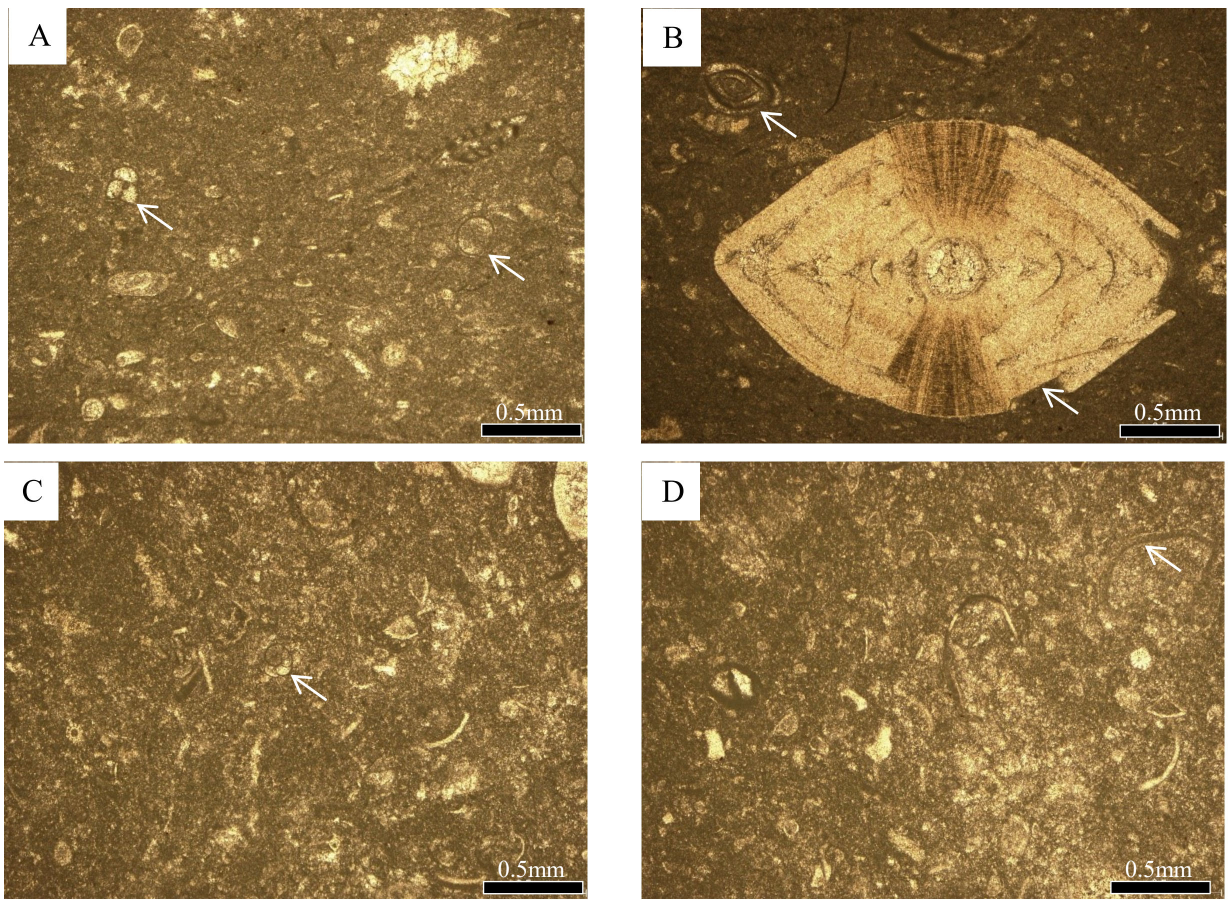


PLATE 1: Photomicrographs scale: 0.5 mm (Plane polarized light)
Sample ID: CS-1
A: Globorotalia, Ostracod, Gastropod and biodebris.
B: Nummulities sp, and Miliolid.
CS-2
C: Gastropod planispiral shell in center, fragments of brachiopods, spine of sea urchin-echinoid.
D: Brachiopods fragments filled with cement, bio debris.

4.3.3.2 Discocyclina Lokchartia Wackestone to Packstone MF2

Description

The Benthic foraminiferal packstone microfacie is found in the middle of the Chorgali Formation, has a thickness of 0.4 meters. Common large benthic foraminifers, Molluscs and biodebris are found. Identified species include Nummulites atacicus, Lockartia Tipperi and brachiopods shell fragments. This fossil bed contains whole to fragmented ostracods, sparse echinids and shells of pelecypods. (Plate-2, E-F).

Interpretation

The Lokhartia signify typical shallow conditions (Adabi & Rao, 1996; Beavington-Penney & Racey, 2004). The large, well-preserved Discocyclina has a wide range of carbonate platform settings. The presence of Nummulites and Discocyclina indicates a shallow shelf environment in high energy conditions that resulted in the reworking of shells and winnowing out of fine matrix (Afghah & Farhoudi, 2012; Flügel, 2013; Strasser et al., 2012). Overall, this facie reflects low to high energy on the shallow proximal part of the back bank setting of the inner ramp (Boudaugher-Fadel, 2018).

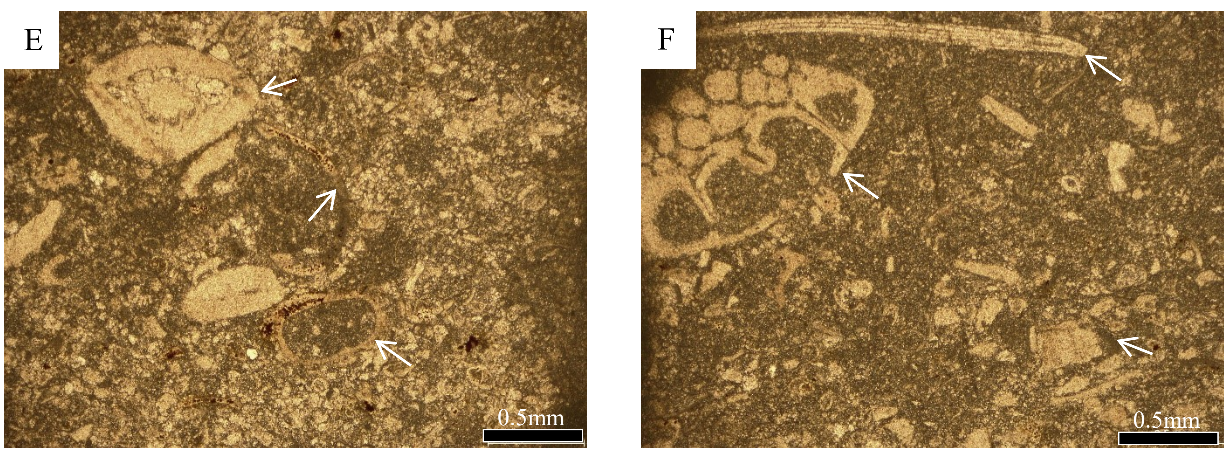


PLATE 2: Photomicrographs scale: 0.5 mm (Plane polarized light)

Sample ID: CS-4

E: Nummulities, brachiopods shell fragments, Ostracod.

F: Lochartia praehaimei, and biodebris.

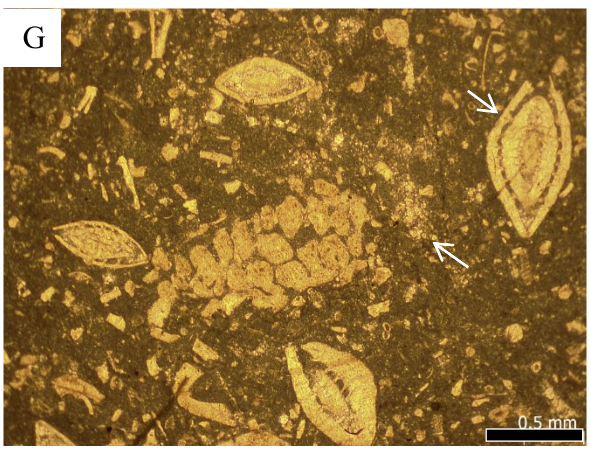
4.3.3.3 Nummulitic Bioclastic Wackestone MF3

Description

Benthic foraminiferal wackestone MF3 contains large benthic foraminifers, molluscs, sparse planktonic forms and broken fossils fragments. Common fossils are Nummilities atacicus axial section, Nummilities globulus (broken), brachiopod shell fragments. Ostracods also appear in this microfacie. It has a thickness of about 0.6 meters and comprises the middle part of the Chorgali Formation (Plate-3, Figure G-H).

Interpretation

The association of nummulite debris with the micritic matrix indicates extensive transportation and reworking from high to low energy conditions (Dunham, 1962). The presence of large nummulites tests bivalves and echinoid shell fragments represents a fore reef facies of outer ramp on the inner shelf (Ćosović et al., 2004; Pomar, 2001).



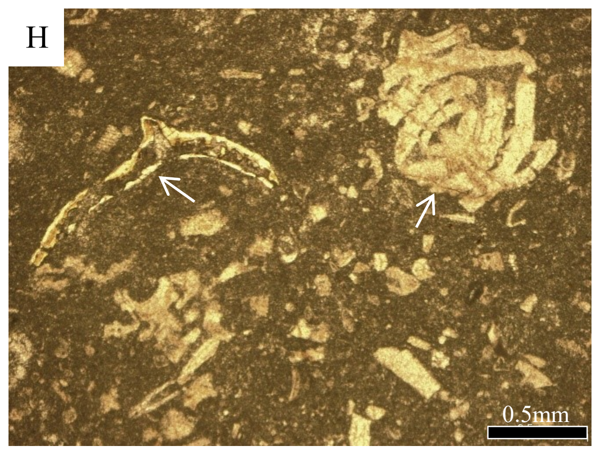


PLATE 3: Photomicrographs scale: 0.5 mm (Plane polarized light)

Sample ID: CS-6

G: Nummulities sp and biodebris.

H: Nummilities globlus (broken), brachiopod shell, with bioclasts.

4.3.3.4 Nummulitic Assilina Wackestone MF4

Description

Benthic foraminiferal Wackestone MF4 comprises small and large benthic foraminifera, including Nummulites globulus, Assilina spinosa, and small Miliolids. In addition, Soritidae sparse planktonic foraminifers and green algae were also found. This microfacies has a total thickness of about 0.9 meters and comprises the lower part of the Chorgali Formation. (Plate-4, Figure I-J).

Interpretation

Whole and fragmented forms of Assilina and Nummulites indicate reworking by current activity in moderately high energy conditions (Flügel, 2013). This facie is deposited under shallow outer ramp fore reef setting(Taheri et al., 2008).

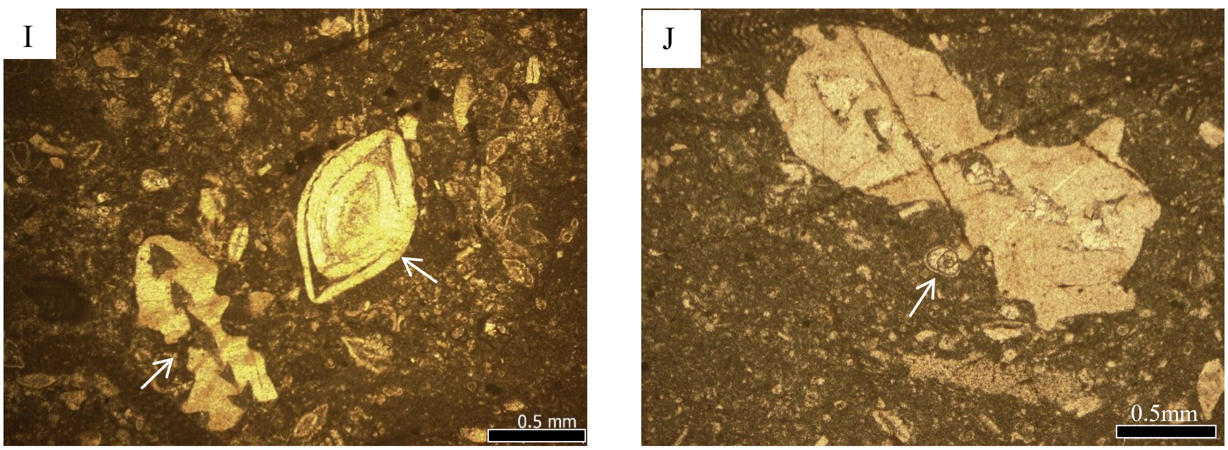


PLATE 4: Photomicrographs scale: 0.5 mm (Plane polarized light)

Sample ID: CS-8

I: Nummulites and Assilina sp

J: Assilina sp, small Miliolid.

Depositional Environment of the Chorgali Formation

A depositional model can be developed based on the identified facies within the Chorgali Formation. The Chorgali Formation was likely deposited in a shallow marine environment near a continental shelf or a carbonate platform with a moderate to high energy level.

The Nummulitic planktonic foraminiferal wackestone (MF1) facies suggests a shallow marine environment with moderate energy. The deposition of these facies may have occurred in a shallow back reef shelf setting. The Discocyclina Lokchartia wackestone to packstone (MF2) facies suggests a protected environment with a lower energy level than MF1. The deposition of these facies may have occurred in a protected environment such as a lagoon or a back reef shelf (Boudaugher-Fadel, 2018). The Nummulitic bioclastic wackestone (MF3) facies suggests a higher input of skeletal debris, likely due to increased input from nearby reefs or bioclastic sediment sources. The deposition of these facies may have occurred in a shallow marine environment near a carbonate platform in fore reef shelf. The Nummulitic Assilina wackestone (MF4) facies suggests a higher energy environment than MF1 and MF3, possibly due to the influence of nearby currents or waves. The deposition of these facies may have occurred in a shallow marine environment near a coastline.

In summary, the Chorgali Formation was likely deposited in a shallow marine environment with a range of energy levels from moderate to high. Changes in the local environment are indicated by the different facies present, likely due to fluctuations in sea level, tectonic activity, or sediment supply. The deposition of the different facies may have occurred in different environments, such as near a continental shelf, a carbonate platform, a lagoon, a barrier reef, or a shoal.

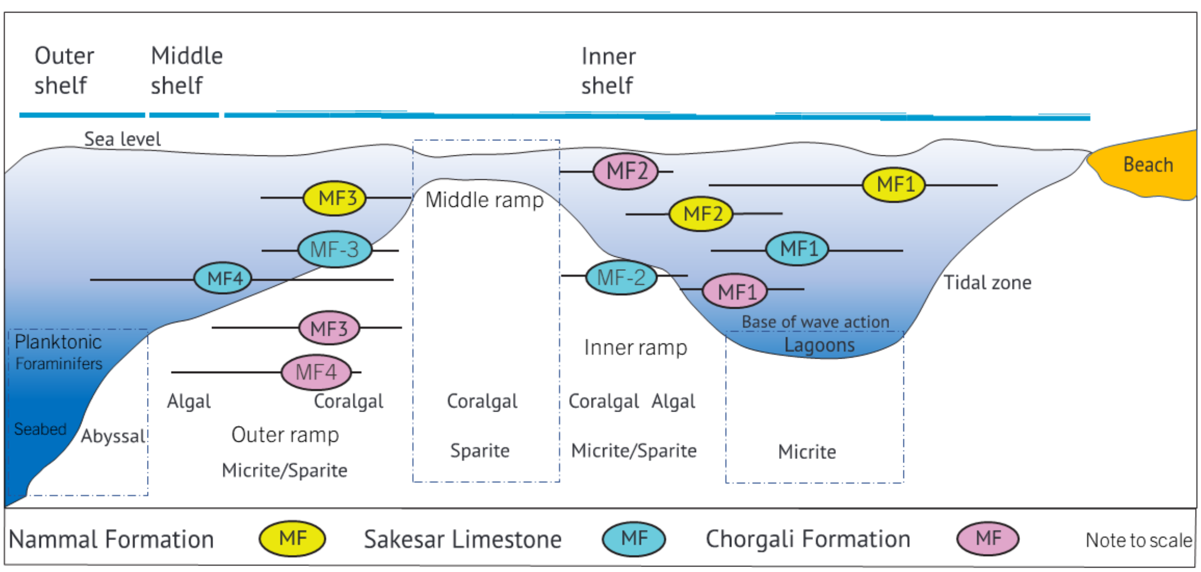
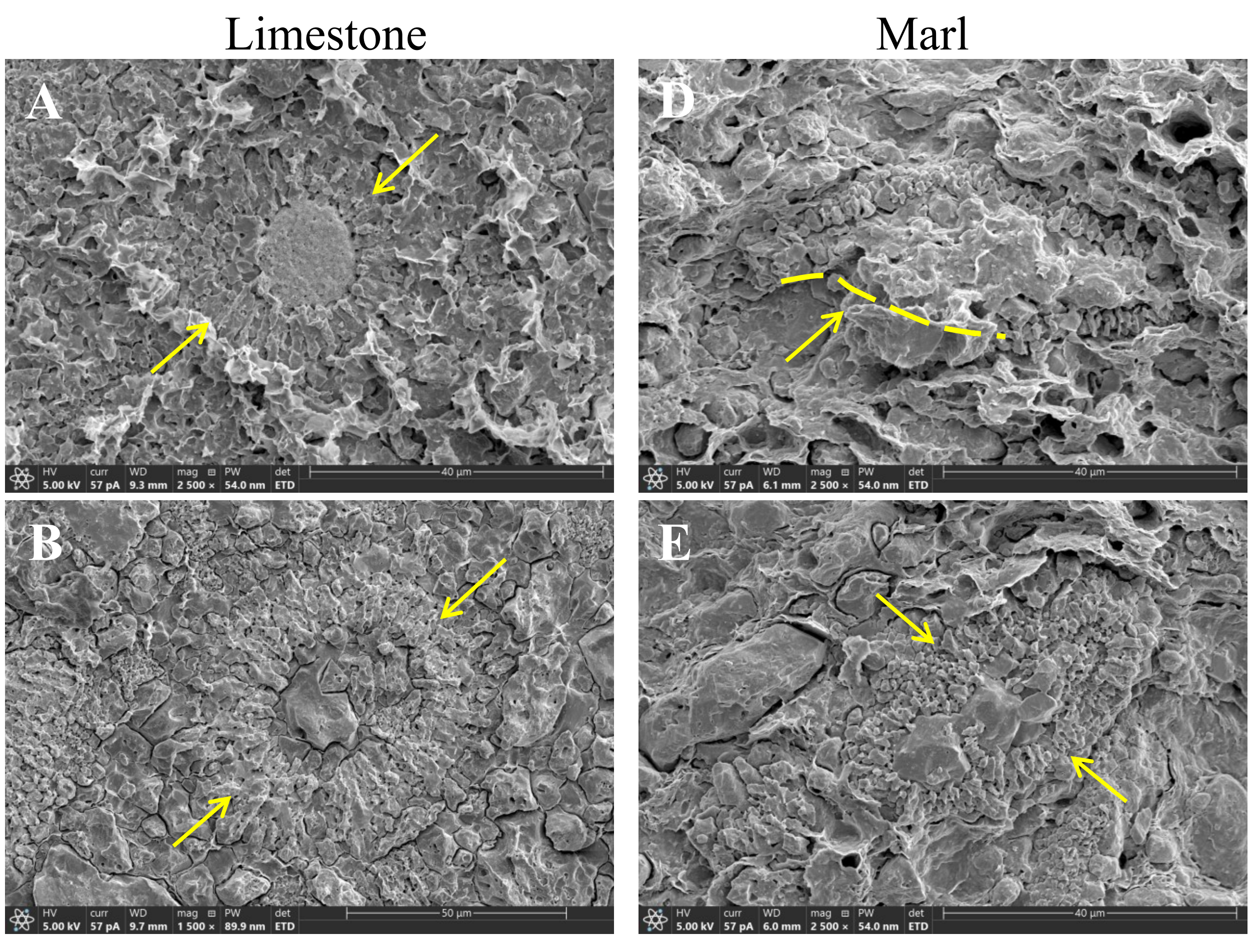


Figure 9 Deposition model of carbonate deposits of Early Eocene, Salt Range.

4.4 Scanning Electron Microscopy

SEM analysis is conducted on samples from limestone-marl alternations of the Chorgali Formation exposed in the Tatryal-Sethi section, Kallar Kahar. Preparing a marl sample for the thin section is a challenging and laborious task, and ordinary microscopic results may not be effective for the present study because, at low resolution, it is not worthwhile to study the effects of differential diagenesis. Therefore, we conducted high-resolution analysis through scanning electron microscopy. Despite difficulties associated with the sample preparation process and SEM preparation procedures, the results from both layers are auspicious. Calcareous nano fossils are detected in alternations providing visible evidence of differential diagenesis—the composition of precursor sediments altered by the action of diagenetic factors such as dissolution, mechanical compaction and cementation. Limestone sample images are arranged on the left, and images from the marl samples are on the right (Plate 1).



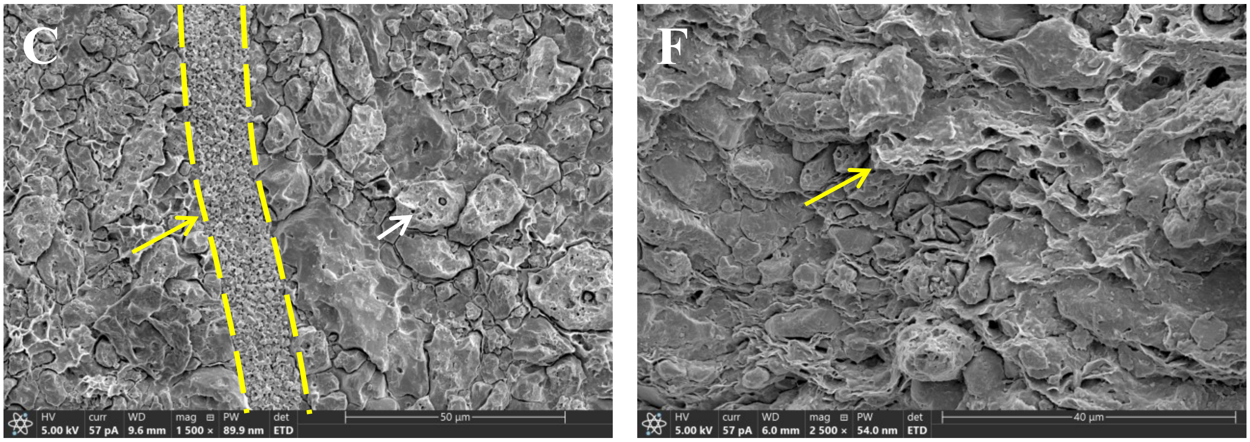


Plate 1 Scanning electron micrographs of samples of limestone-marl alternations from the Chorgali Formation, Tatryal-Sethi section. All the samples are polished and slightly etched with Hcl before gold coating. The left images are from limestone sample (CS-04), and the right side images are from the marl layer sample (CS-09). A: Micro-fossil is preserved in limestone surrounded with dog-tooth cementation in yellow colour (40 µm). B: Micro-fossil is filled with blocky calcite cement, and the structure is preserved by dog-tooth cement crystals (50 µm). C: Ostracod shell fragment boundary is preserved and fixed into microspar crystals (50 µm). D: Shell of calcareous micro-fossil is deformed and partly dissolved due to initial aragonite dissolution (40 µm). E: Shell of calcareous nano-fossil is deformed due to mechanical compaction in marl layers (40 µm). F: Deformed shell of coccolith wrapped in clay (yellow) (40 µm).

Clay content in marl is higher and arranged in a bedding orientation perpendicular to stress, while limestone experience less compaction having low clay content compared to marl and random distribution (Plate 1, Figure A, F). Fossils are aligned in different directions following the pattern of compaction in marl, but in limestone, significantly less compaction occurs, and nano-fossils are not disturbed or deformed. Limestone layers take calcium carbonate and are known as importers; on the other hand, marl layers export calcium carbonates and become deficient and, therefore, more affected by compaction than limestone. Aggrading neomorphism caused blocky mud microspar is produced and preserved in the fossil's centre, and the shell's original boundary is preserved. (Plate 1, Figure B).

4.4.1 Results of Scanning Electron Microscopy

Cementation is a process commonly observed in limestone layer, according to the model of differential diagenesis (Munnecke & Samtleben, 1996) during deposition, at the initial stages, early cementation caused the preservation of nano fossil structures (see Plates 1, A and B). Aragonite dissolution provides excessive calcite cement that preserves the structure of fossils and helps limestone layers to lithify into solid layers.

Compaction is a process in which fossil shells deform and cannot retain their original structure without changing their composition, showing no signs of chemical compaction in limestone layers. According to (Westphal & Munnecke, 1997), in the marl layers, the mechanical compaction of marls produces deformed calcareous microfossils. Moreover, due to overburden pressure, some of these fossils' shells are flat and oriented horizontally, possibly due to the direction of external forces applied to the bedding.

Dissolution is the primary process that is responsible for the formation of limestone-marl alternations. It is widely accepted that the calcium carbonate cementing the limestones in limestone-marl alternations comes from dissolution within these interbeds (Bathurst, 1972); (Ricken, 1986). During differential diagenesis, large-scale dissolution occurs in the marl layer of a couplet. Marl becomes exporting agent during the whole process of differential diagenesis (Westphal et al., 2000)**,** and limestone becomes an importer of cement at a large scale, causing cementation that retains the outer boundary of Dissolved aragonite fossils. Differential diagenesis caused the dissolution of precursor sediments, thus exporting aragonite from marl layers. A partially dissolved shell of the fossil is found in the marl layer. The fossil shell is deformed, and in the left portion, the outer boundary is dissolved partially (see Plate 1, D). Mostly the aragonite fossils and dissolved and calcite cementation filled the internal structures with blocky or equant cement, indicating diagenesis in marine burial (Melim, L.A., Westphal et al., 2002). Aragonite skeletal grains are often neomorphosed to pale yellow blocky calcite and primary and secondary pores are nearly complete occluded by blocky calcite spar reducing porosity.

4.5 Discussion

The interpreted depositional environments of Early Eocene carbonate show that they are shallowing upward sequence from deep marine to supratidal settings. The lateral thickness variation of Early carbonates of Salt Range shows that the sea was deep in the western portion. The Nammal Formation belongs to the shallow environment in fore to backreef and lagoon region, Sakesar Limestone is deposited in shallow marine environments (inner shelf) with restricted circulation, and the Chorgali Formations belongs to upper intertidal to supratidal environments (Jurgen et al., 1988). During the Early Eocene, the Potwar and Kohat areas were changed from open continental shelves to shallow sea. During Early Eocene, the Potwar and Kohat areas were transformed from open continental shelves to shallow sea, which led to widespread carbonate platforms (Mujtaba, 2001). Trace fossils, organic-walled microfossils, and delicate calcareous tests are undeformed in limestones. In contrast, marly interbeds are firmly compacted, and trace fossils, organic-walled microfossils, and calcareous tests are deformed (Westphal & Munnecke, 2003). In SEM (Plate 1 Figure A-B), micro-fossils have lithified slightly deformed structure, and in marl layers, shape of the shell is completely deformed due to compaction. The standard model (Ricken, 1986, 1987) holds that calcium carbonate redistribution is driven by calcite pressure dissolution. A problem with this model is that limestones are typically uncompacted (Bathurst, 1970); (Shinn, 1977), which limits their cementation depth. The depth difference between the loci required for pressure dissolution in interbeds on one side and for pre-compactional cementation of limestone beds on the other side is not easily explained. A new model offers a possible solution for this enigma. The theory assumes that aragonite in the interlayer layers is a source of calcium carbonate cement in the limestones (aragonite in the limestone layers recrystallizes to calcite) (Munnecke & Samtleben, 1996); (Westphal, 1998); (Munnecke et al., 2001). The latter approach seems to be valid in our case for three reasons; (i) the presence of aragonite fossils can cause the dissolution of unstable aragonite, and later blocky cementation of calcite in microfracture can be found in (Plate 1 Figure B SN-9). (ii) Small and large fractures are filled by secondary cementation. (iii) Preserved outer boundary of nano fossils and microspar development in the core can be seen in the ultra-facies (Plate 1 Figure B). Neomorphism is also observed in microfacies and ultra-facies of limestone samples; the thin boundary of nano fossil indicates the aggrading neomorphism with surrounding microspar crystals. The microspar crystals are growing in the internal part of gastropod shell, and outer structures is preserved, indicating that the microspar is developed according to the (Munnecke et al., 1997) approach (Plate 2, Figure B). Pitted microspar in SEM (Plate1, Figure C) suggests the aragonite dissolution and re-precipitation as calcite is probably caused by differential diagenesis (Munnecke et al., 1997).

CONCLUSION AND RECOMMENDATIONS

Limestone-marl alternations in Early Eocene carbonates are developed due to differential diagenesis. Evidence from SEM results showed that carbonates have gone through the cycle of aragonite dissolution and calcite precipitation in alternative layers of limestone and marl. Dissolved aragonite fossils and linear arrangement of shells depict the mechanical compaction in marls. However, carbonates have undergone cementation in the early phase after deposition in the marine environment. In the Nammal Formation, the presence of calcite nodules surroundings by marl is evidence marked in the field.

Moreover, limited fossils content in the nodules supports the argument of aragonite dissolution and calcite deposition in limestone layers. Fossil shells are preserved, but their aragonite content is replaced by dissolution in limestone layers and the shells are surrounded by micro spars formed from micrite. Petrography results revealed micritic fossils filled with calcite blocky cementation. Carbonates of Eocene deposited in the deep marine-shallow marine-restricted environment. During the Early Eocene, the Potwar and Kohat areas were changed from open continental shelves to shallow sea which led to widespread carbonate platforms. Environmental changes occurred due to the Indian Plate movement and the closure of the Neo-Tethys Sea at the end of the Early Eocene. A large clastic influx was deposited in the Miocene, which marks the contact with the carbonate sequence, and mid to late Eocene marks the period of non-deposition. Correlation of Field observations with microscopic results revealed that Limestone-Marl alternations are formed mainly by differential diagenesis, but the effects of climate cannot be ruled out completely. However, the detailed geochemical analysis may help access the samples for climate and astronomical proxies. Deposition on the Indian Plate drastically changes with time during the long drift from Gondwana to the great Himalayas uplifting. Therefore, it is imperative to carefully examine rocks from this region by employing multiple overlapping techniques to find the exact reason behind such occurred in the geological past.

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