# MICROFACIES ANALYSIS AND DEPOSITIONAL ENVIRONMENT OF JURASSIC SAMANA SUK FORMATION, TOWNSHIP SECTION ABBOTTABAD, PAKISTAN


**By**

**Abid Ullah**

**(01-262212-002)**

**Department of Earth and Environmental Sciences**

**Bahria University, Islamabad Pakistan**


**2023**

**MICROFACIES ANALYSIS AND DEPOSITIONAL ENVIRONMENT OF JURASSIC SAMANA SUK FORMATION, TOWNSHIP SECTION ABBOTTABAD, PAKISTAN**

A thesis submitted to Bahria University, Islamabad in partial fulfillment of the requirement for the degree of MS in Geology


**Abid Ullah**

**(01-262212-002)**

**Department of Earth and Environmental Sciences**

**Bahria University, Islamabad Pakistan**


**2023**

## APPROVAL OF EXAMINATION

Scholar Name: **Abid Ullah**, Registration No. **01-262212-002,** Program of Study: **Master of Science in Geology**, Thesis Title "**Microfacies analysis and depositional environment of Jurassic Samana Suk Formation, Township section Abbottabad, Pakistan"**

It is to certify that the above scholar's thesis has been completed to my satisfaction and, to my belief, its standard is appropriate for submission for examination. I have also conducted a plagiarism test of this thesis using HEC prescribed software and found a similarity index of 9% that is within the permissible limit set by the HEC for the MS degree thesis. I have also found the thesis in a format recognized by BU for the MS thesis**.**

Principal / Supervisor Signature: ______________________________

Date:

Name: **Dr Maryam Saleem**

# AUTHOR'S DECLARATION

I, **ABID ULLAH** hereby state that my MS/MPhil thesis titled Master of Science in Geology, Thesis Title "Microfacies analysis and depositional environment of Jurassic Samana Suk Formation, Township section Abbottabad, Pakistan"

" Is my own work and has not been submitted previously by me for taking any degree from **this university Bahria University Islamabad Campus** or anywhere else in the country/world. At any time if my statement is found to be incorrect even after my graduation, the University has the right to withdraw/cancel my MS degree.

Name of the scholar: Abid Ullah

Sign:

Date:

**PLAGIARISM UNDERTAKING**

I, solemnly declare that the research work presented in the thesis titled "Microfacies analysis and depositional environment of Jurassic Samana Suk Formation, Township section Abbottabad, Pakistan" is solely my research work with no significant contribution from any other person. Small contribution/help wherever taken has been duly acknowledged and that complete thesis has been written by me.

I understand the zero-tolerance policy of the HEC and Bahria University towards plagiarism. Therefore, I as an Author of the above-titled thesis declare that no portion of my thesis has been plagiarized and any material used as reference is properly referred to/ cited.

Scholar / Author's Sign:

Name of the scholar: Abid Ullah

# DEDICATIONS

I dedicated this whole effort to my beloved parents, family members and respected teachers whose love and full support made it easy to accomplish this work.

# ACKNOWLEDGEMENT

All glorification and reverence belong to ALLAH S.W.T and it is of utmost significance to bow my head before Allah almighty, who is the solitary provider of all erudition. The greatest of all, who refine my heart with enhanced perceptions and blessed me robustness to complete my research. I am core heartedly thankful to ALLAH Almighty, the most gracious and the most merciful, who gave me the ability and make me to achieve this goal. I am grateful to many people as without their help, guidance and most sincere assistance I could not have achieved my aim of study.

First of all, I would like to thank my supervisor Dr Maryam Saleem, Assistant Professor at the Department of Earth and Environmental sciences Bahria University, Islamabad, for supervising my thesis. Without her cooperation it was very far to achieve this goal. Her generosity, demonstrative guiding, sympathetic attitude and encouraging nature will always be appreciated. Also heartfelt thanks to my fellows who helped me a lot. Special thanks to Izaz Hassan and Saqlain Haidar for their useful suggestions and assistance. At last I would like a deepest thanks to my parents and teachers, for their heartiest prayers, encouragement and financial support throughout my education carrier. May Allah gave them lots of happiness, solve their problems, and bless them all. (AMEEN)

## ABSTRACT

The present study deals with the microfacies and depositional environment of Jurassic Samana Suk Formation Township section Abbottabad. The Samana Suk Formation is consisting of carbonate unit deposited in Attock-Hazara Fold and Thrust belt of north-western Himalayas, and represent a region with well-developed stratigraphic and structural geological exposure. Field observations demonstrate that Samana Suk Formation is widely distributed in the studied section with thin to thick bedded, oolitic, bioclastic, dolomitic limestone unit having skeletal and non-skeletal grains. The studied section that is Township section was logged and sampled in detail for the petrographic analyses in an attempt to reveal the microfacies analysis, depositional and diagenetic settings. Thirty-seven thin sections were prepared for microscopic analysis resulted in the identification of nine microfacies (MF1-MF9). These microfacies are Mudstone (MF1), Dolomudstone (MF2), Bioclastic peloidal wackestone (MF3), Peloidal packstone (MF4), Ooidal grainstone (MF5), Bioclastic ooidal grainstone (MF6), Peloidal grainstone (MF7), Bioclastic intraclastic grainstone (MF8) and Intraclastic bioclastic peloidal grainstone (MF9) that are deposited in different environmental settings. Diagenetic processes include Micritization, Bioturbation, Neomorphism, Compaction, Fractures and veins, Dissolution, Cementation, Dolomitization and Pyritization have been observed in the petrographic study of the samples. Based on the microfacies analysis, the Mudstone (MF1), Bioclastic peloidal wackestone (MF3) and Peloidal packstone (MF4) deposited in lagoonal while Ooidal grainstone (MF5), Bioclastic ooidal grainstone (MF6), Peloidal grainstone (MF7), Bioclastic intraclastic grainstone (MF8) and Intraclastic bioclastic peloidal grainstone (MF9) reveal deposition on carbonate shoal settings of inner ramp. The deposition of Dolomudstone (MF2) is directly belong to inner ramp. It is concluded that the Jurassic Samana suk Formation in the Studied section characterized by

nine microfacies reflected deposition in lagoon, shoal and inner ramp of homoclinal carbonate ramp affected by different digenetic events.

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# LIST OF ACRONYMS

| Acronyms | Explanation |
|---|---|
| **KIA** | Kohistan Island Arc |
| **MFT** | Main Frontal Thrust |
| **MKT** | Main Karakoram Thrust |
| **MMT** | Main Mantle Thrust |
| **MBT** | Main Boundary Thrust |
| **SRT** | Salt Range Thrust |
| **Km** | Kilometer |
| **m** | Meter |
| **Fig** | Figure |
| **Lat.** | Latitude |
| **Long.** | Longitude |
| **MF** | Microfacies |

# CHAPTER 1

# INTRODUCTION

## 1.1 General Introduction

Carbonate rocks make up approximately 19-22% of the worldwide sedimentary cover, representing a significant portion. These deposits consist of carbonate minerals and exhibit unique characteristics composed of various sizes and pore geometries; therefore, Dunham classification is used to describe the depositional textures in such a way that it can be linked to the pore geometries. Hence, it can be observed that the grain supported textures have a tendency of larger pore size than the mud supported matrix. These textures have different geometries in different depositional environments (Scholle et al., 1983). The carbonate rocks texture is extensively impact and recognized entirely by hydro-dynamical circumstances of depositional environments. While the presence and high proportion of bioclasts reflecting types and as well as used for interpretation of the depositional environments.

After deposition, major changes occur in the sediments or lithified rock fabric. During burial composition, porosity and mechanical strength occurs through diagenetic events as microbial micritization, neomorphism, compaction, cementation, dissolution, and finally mineral replacement (such as dolomitization) (Lapponi et al., 2014). Such diagenetic modifications destroy the original imprints and work in the near surface during initial marine, meteoric and late deep burial stages of diagenesis (Smith & Simo, 1997; Machel, 2005; Nichols, 2009). The correct interpretation of boundaries and the whole geometry of sedimentary deposited facies arrangement comprises in the play is the earliest and most important step in the evaluation of hydrocarbon prospects. Rock heterogeneities distribution is immensely controlled by lithofacies deposition, diagenetic history, and structural framework (Martín et al., 2013). The current study is a kind of aim to show these facies variations as well as, the link of these changes to depositional environment of the study area. Throughout the previous times microfacies has evolved and recognized as an essential portion for the study of carbonate rocks and the types of microfacies are important representations of sedimentary facies for carbonate platforms (Wilson, 1975; Flügel, 2010; Zhang et al., 2020). Therefore, it is necessary to be aware of diagenetic processes, facies distribution and its depositional system in order to identify heterogeneities.

Microfacies analyses give us detailed information about the constituent fabric, diagenetic features and depositional as well as diagenetic history of the rock. This information proceeds to the reconstruction of diagenetic processes and their sequence to give an overall picture of sedimentary and depositional history of the rock and reservoir. The identification of environmental condition and depositional history of a basin is depending upon the microfacies analysis and explaining variation in stratigraphic units. The microfacies and diagenetic processes have greatly influenced the quality of reservoir of carbonates (ullah khan, 2021).

However, more than 50% carbonate reservoirs hold a substantial portion of the globally recognized hydrocarbon reserves, emphasizing their importance in the industry of oil and gas, and also host a significant volume of ore resources. Jurassic carbonate formations are host to numerous significant oil and gas fields worldwide. Notable examples include the Abqaiq, Ghawar and Fereidoon-Margon oil fields in Saudi Arabia, the Arenque oil field in Mexico, while the Shilarghan gas field in Afghanistan. These carbonates of Jurassic period are widespread across the Indus Basin in Pakistan. The carbonate platform deposits of Jurassic period are well exposed in the Indus Basin of Pakistan and characterized by a mix of silici-clastic and carbonate lithologies. The Middle Jurassic period witnessed significant carbonate system activity, leading as the deposition of Samana Suk Formation within the Upper Indus Basin (Cheema, 2010). The distribution of Samana Suk Formation extends extensively across various regions, including the Samana Range, Trans Indus Ranges, western Salt Ranges, Kohat, Kala Chitta Ranges, and Hazara area. It is the predominant lithological package of carbonates (mostly limestone) with minor amount of marl and calcareous shales in the Mesozoic strata of these areas. Samana Suk Formation holds various grains and cements in the carbonates that provides it the distinctive appearance. Samana Suk Formation comprises skeletal and non-skeletal grains components which are previously not documented from other units of carbonate in Pakistan (Saboor et al., 2014).

The Hazara region, the tectono-stratigraphic basin in northern Pakistan, signifies a Jurassic platform deposits of Tethyan domain, almost make up of a carbonated Samana Suk Formation (Shah, 2009). The Jurassic Samana Suk Formation is widely distributed through different sections in Hazara area which is situated in the north-western part of Himalayas and characterized by a region with well-structured stratigraphic exposure and structural geological features. From Precambrian to Mesozoic, and Tertiary ages rocks exposed in the region. Samana Suk Formation requires a detail evaluation regarding microfacies and its depositional setting as well of diagenetic background in Hazara area. This thesis addresses major sedimentological aspects as microfacies and depositional environment of Samana Suk Formation in Township section Abbottabad, Hazara area situated in the Lesser Himalaya (northwestern Himalayas).

## 1.2 Location and Accessibility

Geographically, the study area is located in Township, district Abbottabad of Hazara, Khyber Pakhtunkhwa, northern Pakistan. Geologically, the study section lies in the Lesser Himalayan region of north-western Himalayas characterized by well-structured stratigraphic exposure and structural geological features of Samana Suk Formation. Geographic coordinates of study area are (lat. 34°, 11', 46"; long. 73°, 17', 16"). The location of study area is about 150 km north of Islamabad (Capital of Pakistan) and can be easily accessed through Karakoram Highway. The outcrop is accessible along Township road through a distance of 8 km from Abbottabad city. Figure (1.1) shows the direction and location of the study area.

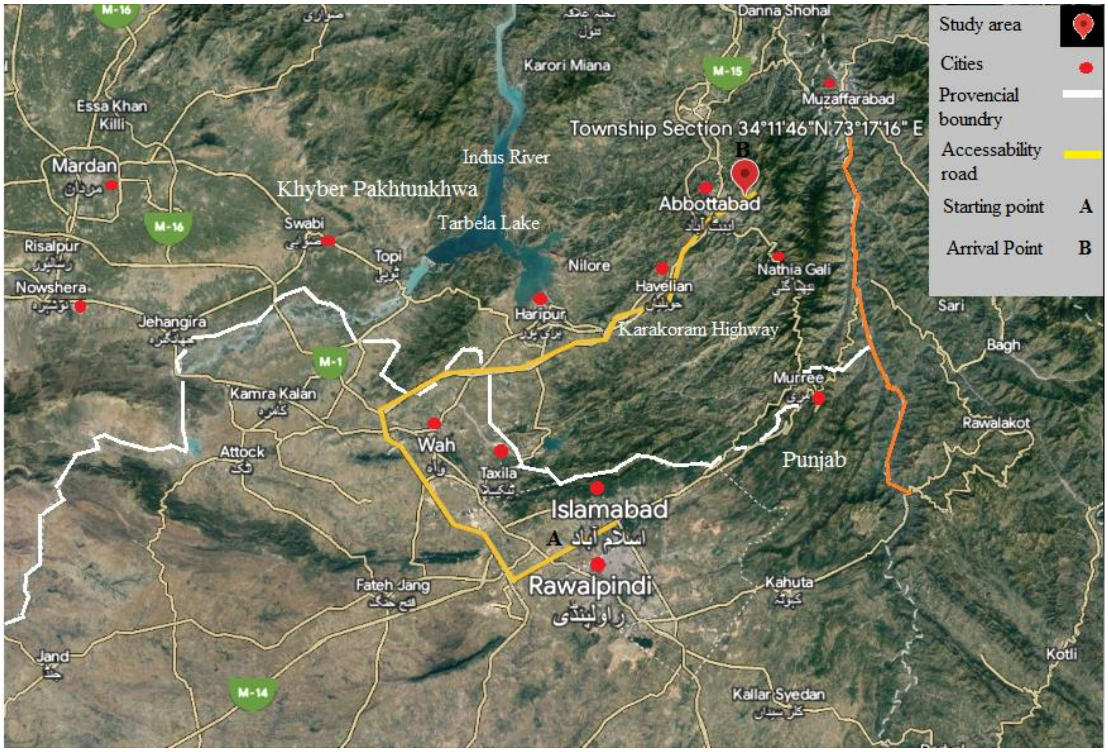


Figure 1.1. Google earth image showing the geographic location of the studied section.

## 1.3 Previous work

The microfacies and depositional environments of Samana Suk Formation vastly studied in various areas such as Salt Ranges, Kalachitta ranges and Trans Indus ranges, (Mensink et al., 1988; Fatmi et al., 1990; Qureshi et al., 2008; Nizami and Sheikh, 2009). Latif (1970) provided a description of the stratigraphy of southeast Hazara using a geological map scaled at 2.5 cm to 1.6 km, offering valuable insights into the region's geological composition. Butteler and Coward (1985) published a structural section along the Murre Abbottabad road, offering a comprehensive view of the geological structures in that area. Numerous researchers have dedicated their efforts to studying the geology of the Samana Suk Formation in Hazara and its surrounding regions. Their contributions have provided valuable insights into the characteristics and features of the Formation in the area. Researchers such as Waagen (1872), Middlemiss (1896), Latif (1970), and Butt (1989) have made significant contributions in elucidating the stratigraphic and structural aspects of the Hazara area as a whole. Their studies have shed light on the geological characteristics and formations present in the region, providing valuable insights into its geology. In the eastern portion of the area, particularly in proximity to the prominently curved mountain structure, Wadia (1931) referred to these formations as 'synthexis'. This nomenclature was used to describe the geological units present in that specific region. Gnehm and Schnellmann (1999) developed a dynamic and kinematic model to explain the deformation processes in the Hazara area and prepared a cross-section and geological map of the northwestern Himalayan fold and thrust belt, which includes Hazara. Their work provided insights into the geological structures and deformation patterns in the region. Additionally, Ghazanfer et al., (1990) conducted research on the Dunga Gali, Kuza Gali, and Ayubia areas, establishing the geology, structure, and various stratigraphic provinces in these specific locations. Their findings contributed to our understanding of the geological characteristics and stratigraphy in those areas.

Ahsan and Chaudry (1998) conducted a sedimentological examination of the Hazara Basin, focusing on the analysis of various Mesozoic and Tertiary formations' microfacies. Their study provided valuable insights into the sedimentary characteristics and depositional environments of these rock units. Furthermore, Chaudry et al. (1998) described the sedimentology of Jurassic to Eocene rocks in the Hazara Basin. Their research focused on detailing the sedimentary features and processes that shaped these geological formations. In the Hazara and its surrounding areas very limited work has been conducted on this formation concerned with sedimentological attributes within the different sections. Masood (1989) studied the sedimentological and diagenetic characteristics of Samana Suk Formation in the Hazara area, and the interpretation of microfacies and diagenetic features recommended shoal type environments. According to Rahim et al., (2020) in Muslim Abad section, the Samana Suk limestone is light grey to light-red in color, thin to medium bedded, comprises of different types of faunal assemblages and four microfacies have been identified in their interpretation, suggested the deposition of the formation in a carbonate inner shelf environment. Additionally, in the Sangar-gali section, they distinguished twelve different microfacies types, highlighting the diverse sedimentary characteristics and facies variations within the studied area. Samana Suk Formation have been identified that revealed four different environments as carbonate peri-tidal, lagoonal, shoal and open marine (Rahim et al., 2020).

In the Harnoi Section, Hussain et al., (2013) identified three microfacies and five sub-microfacies within the Formation. Based on their findings, they proposed an inner to mid ramp setting as the carbonate platform's depositional environment for the Formation in that area. Four microfacies identified by Naqib et al., (2016) in Lower Salhad section which reveal wave dominated inner ramp setting. Similarly, Afridi et al., (2010) examined the Formation along the Abbottabad-Nathiagali Road and documented four microfacies, eight sub-microfacies, and one lithofacies within it. Their research contributed to understanding the sedimentary characteristics and facies variations in the studied area. In Thandiani Section, five microfacies with seven sub microfacies identified by Rahim et al., (2020). These microfacies determined as inner to outer ramp environment of deposition and finally concluded that based on interpretation, the Samana suk Formation was to be deposited in a shallow shelf environment.

## 1.4 Objectives of the Research

This study is designed with the aim of pursuing and coming up with the first detailed sedimentological investigation of the Jurassic carbonate unit in the area. The primary objective of this study is to enhance our understanding of the Jurassic Samana Suk Formation within the research area. The study aims to achieve this goal by focusing on the following objectives:

i. To identify and analyze various microfacies of study area.
ii. To determine the depositional environment base on microfacies analysis.
iii. To study diagenetic features associated with microfacies and depositional environments.

# CHAPTER 2

# REGIONAL GEOLOGY AND TECTONICS

## 2.1 Paleotectonic

At the time of middle Paleozoic, northern and south America were the western portion of Gondwana domain, north-western Africa had moved toward subtropical latitudes from south polar, though Indo-Australian the eastern portion of the Gondwana domain stayed at comparatively low latitudes (Scotese et al., 1999). Indo-Australian, Antarctic portion of the Gondwana displaced rapidly toward the polar region from a subtropical region (Fig 2.1) and remained stationary throughout the Carboniferous-Triassic period (Blakey, 2008; Álvaro et al., 2010). Before late Triassic Indian plate was close to Australia and Antarctica after travelling of thousands of kilometers northward, now it is close to Iran, Afghanistan, Tibet and other micro-continents (Dietz & Holden, 1970; Chatterjee, 1992; Chatterjee & Scotese, 1999 & 2010; Rogers & Santosh, 2004). Moreover, the composite climatic situation represents wide geographic composition. The paleo depositional studies of the Indian plate show documentation of resemblances in stratigraphic records settled far away in opposite directions (Blakey, 2008; Álvaro et al., 2010).

The Eurasian plate comprises of initial Laurasian landmass of the Laurasian domain, “initial Laurasian landmass and former fragments of Gondwanaland” and the Gondwana domain, “the accumulated set of the terminal former fragments i.e. Indian & Arabian shields of Gondwanaland at the south of Tethyan domain (Kazmi & Jan, 1997). Laurasian domain is term as the Tethyan domain (Sengor et al., 1988). The Gondwana domain is described by the crystalline basement, the continental crust of Precambrian that developed into a platform type in Paleozoic. In the north and south, the Laurasia and Gondwana respectively, producing an oceanic expansion of paleo-pacific, which nowadays forms the Central Atlantic Ocean (Khan & Tewari, 2016).

As continental drift is a continuous process that occurs over geologic time. Afterward the late Devonian- Triassic, it results in the further splitting of Laurasia and Gondwana into seven major tectonic plates, micro plates, and sea landforms and ocean spaces. The present North American and Eurasian plate derived from Laurasia while the South American, African, Antarctica, Indian and Australian plates are derived from Gondwanaland. During the middle to late Paleozoic rifting and successive fragmentation of continental blocks from Gondwanaland started drifting northward and then its collision with Laurasian landmass result to Tethyan domain. Its evolution is connected with the opening and closing of numerous ocean spaces with different geologic events i.e. rifting, subduction and collision of crustal blocks (Chatterjee, 2013).

In the Middle Carboniferous, the Pangaea was intact and the earliest known ocean space between Gondwanaland and Laurasia was known as Paleo-Tethys. During the late Triassic, a significant collision occurred between most of the tectonic blocks and the supercontinent Laurasia. This collision led to the closure of the Paleo-Tethys Ocean in the early Jurassic. During the early Jurassic, Paleo-Tethys had closed while in late Jurassic the Neo-Tethys grows. The Neo-Tethys gets closed upon the collision of Indian plate with Eurasian plate resulted in creation of Kohistan island arc and orogenic uplifting of the Himalayas (Johnson et al., 1976; Coward et al., 1986). Indian Plate is still drifting underneath the Eurasian plate (Seeber et al., 1981). The uplifted orogenic mountain range is 3500 Km long which is extending from Nepal to Afghanistan in east-west direction, and this range is recognized as North-West Himalayas Fold and Thrust Belt in Pakistan. Igneous, sedimentary and metamorphic rocks ranges are obducted to the surface in the form of higher mountains. Due to collision, the rocks are extremely folded and faulted. deformations increase from the south to northward in the Himalayas and Precambrian to Recent age rocks are developed in this area (Shah, 1977a; Shah, 1977c; Bender and Raza, 1995).

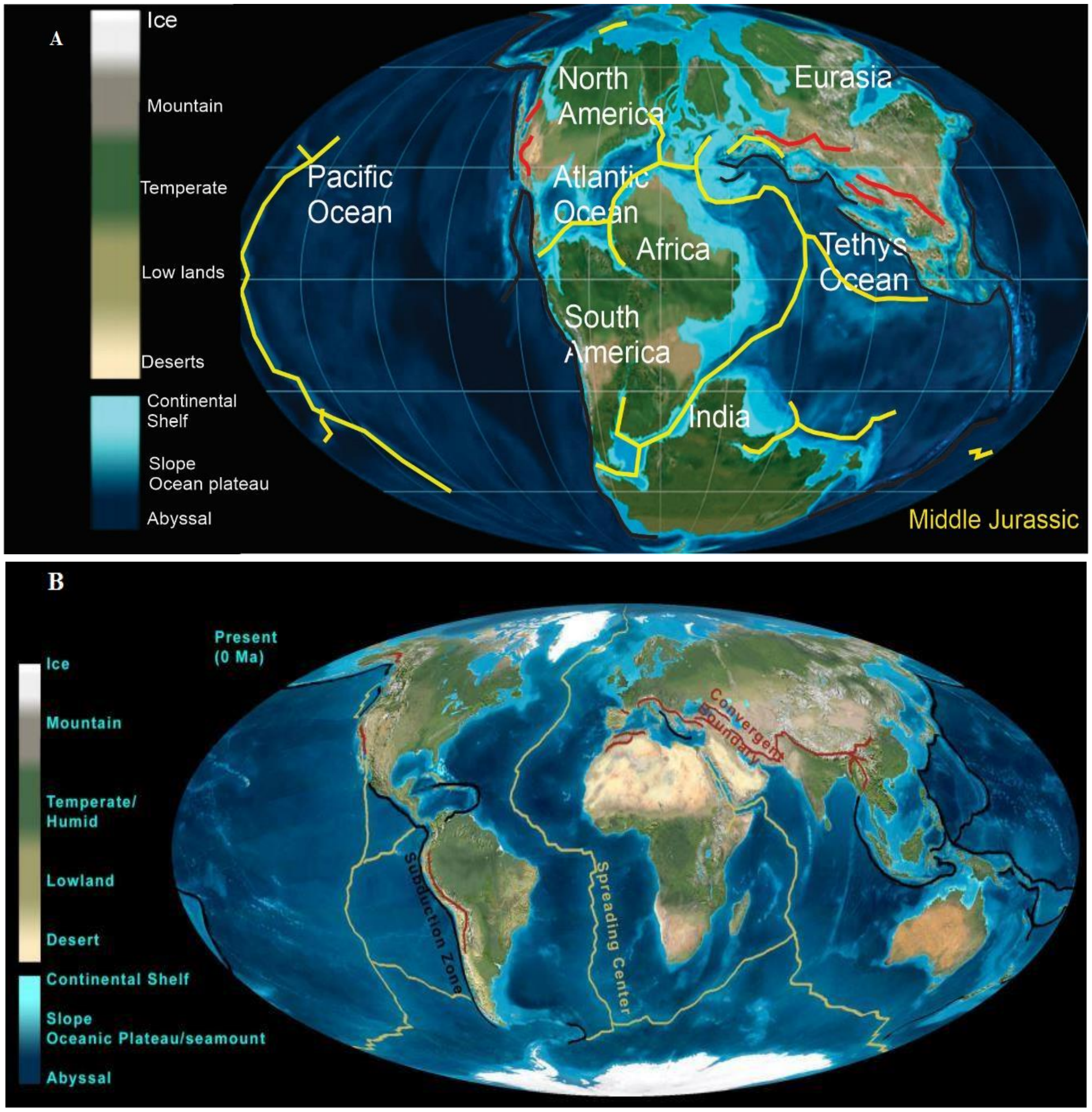


Figure 2.1. Paleogeographic reconstruction shows the location of Indian plate (A) location of Indian plate during Middle Jurassic time (after Chatterjee, 2013). (B) Location of Indian plate at present time.

## 2.2 Regional Tectonic Setting

The Himalayas are divided into Sub Himalayas, Lesser Himalayas and Higher Himalayas by various thrust faults which are interrelated with each other in North-West Himalayas Fold and thrust belt zone. These various bounding thrust faults are Salt Range Thrust (SRT), Main Boundary Thrust (MBT), Main Mantle Thrust (MMT) and Main Karakorum Thrust (MKT) as shown in (Fig 2.2).

The Sub Himalayan zone is lowermost part of the Himalayas and it is mostly covered by the Kohat and Potwar Plateaus. The Potwar Plateau is characterized by less deformation and 150 kilometers wide, extending from north to south direction (Kazmi and Rana, 1982). The Potwar plateau is bounded by Kala Chitta -Margalla Hill ranges in north and Salt Range thrust (SRT) in the south. The Sub Himalaya mainly consist red molass foredeep deposits of Murree Formation and Siwalik Group which have been dislocated at areas to formed upthrust structures such as Balakot - Muzafarabad and Salt Range. The northern part is higher tightly folded that includes the Poonch, Patehka areas of Azad Kashmir, Kwai (area of Kaghan Valley) and the Rawalpindi zone of Potwar plateau (Ghazanfar, 1993). The southern parts are less compressed as known as Sialkot zone in Azad Kashmir and Soan zone in Potwar region (Sokolove and Shah, 1966). The two zones are separated by the Muzafarabad and Jammu/Riasi zones of uplift in Kashmir and the Khairi Murat anticlinal zone in Potwar. The southern margin of the Salt Range serves as a significant boundary where Precambrian rocks have been thrust over Pleistocene fanglomerates along the Himalayan Frontal Thrust, as described by Lillie et al. (1987). The Sub Himalaya region, on the other hand, is primarily characterized by unmetamorphosed rocks and consists of a wide range of sedimentary formations spanning from Precambrian to Recent times.

Further to the north of the Sub Himalayas is the Lesser Himalayas zone, which is bounded by Main boundary thrust (MBT) to the south and Main Central thrust (MCT) in the north. This portion of Himalayas represents sedimentary and metamorphic rocks ranging from Cambrian to Miocene (Shah, 1977c; Bender and Raza, 1995). The Lesser Himalayan zone comprises non-fossiliferous, low-grade meta-sedimentary rocks that are overlain by Permian to Cretaceous strata of the Gondwana sequence, as described by LeFort (1975).

While the Lesser Himalayas share similarities with the Higher Himalayas in terms of lithology and structure, they have lower elevations, typically rising to heights of around 3500-4500 meters. On the basis of tectonic zonation, the Lesser Himalaya is divided from north to south into; Kohistan Island arc, MMT, Nanga Parbat Haramosh Massif, Southern Kohistan range, Peshawar and Campbellpur basin, Hill ranges, parts of Kohat-Potwar plateau, Salt range and Indian foreland (Yeats & Hussain, 1987).

The southern boundary of Lesser Himalaya with Sub Himalaya is the Main Boundary Thrust (MBT) depicted by the distinctive nature of the red Neogene molass deposits considered to lie south of the MBT. Bounded to the north by MCT and to the south by MBT, the Lesser Himalaya in northern Pakistan expands in the form of a thick slab covering the areas of Kashmir, Kaghan, Hazara and Swat. The width is decreases to the north of Hazara-Kashmir Syntaxis (Bossart et al., 1992; Ghazanfar, 1993). Generally, the Precambrian and Paleozoic sediments have suffered with low grade metamorphism and overlain by younger sediments in large basins of Peshawar Basin, Hazara Basin and Kashmir Basin and by high grade Precambrian metasediments and gneisses occurring as nappes eastwards in Shimla and Gharwal Himalaya. The mainly brittle deformations are indicated by tight to overturned folds and imbricate faults.

Moreover, Lesser Himalaya is broadly subdivided into two zones (Ghazanfar, 1993). The northern metamorphic zone comprises the terrain between Luat and Nauseri in Neelum Valley, between Batal and Tutan in Kaghan Valley, between Banna sequence and Panjal fault in northern Hazara and the whole of Peshawar basin including the area between Malakand and Attock-Cherat (Ghazanfar, 1993). The southern sedimentary zone known as Attock Hazara Fold and Thrust Belt extends around Nauseri in Neelum valley (Autochthonous Fold Belt), between Tutan and Paras in Kaghan valley, between Abbottabad and Murree in Hazara area and the Cherat Kalachitta and Kohat Ranges. Geologically, the area of northern Hazara extends from the Panjal Fault in the south up to MMT in the north and covered the area between Panjal Fault/MBT in the east and the Indus River on the west. This is the area where the Tanol sequence and Mansehra Granite outcrop exists and tectonically represented by East-W faults that bend northwards on the sides to merge into the N-S Panjal and Thakot

Fault. The arcuate trends of the Tanol region in Northern Hazara have been noted and Calkins et al. (1975) marked some faults during his work. Recent interpretations by Coward et al. (1988) and Treloar et al. (1989a, b) suggest that the Northern Hazara region can be interpreted as an imbricate thrust pile. These studies propose that the geological structures in the area exhibit a stacking of thrust sheets, indicative of multiple thrusting events and deformation along the tectonic boundaries. This interpretation provides insights into the complex structural history and tectonic processes that have influenced the formation of the Northern Hazara region.

The sedimentary zone of Southern Hazara consisting of a thick foreland sedimentary sequence is exposed as a wide belt to the south of the metamorphosed hinterland. The wide belt may be subdivided into a northern Cambrian to Eocene sequence between the Panjal Fault and the MBT and further to the southward a Miocene and younger foredeep molasses sequence between MBT and MFT (Main Frontal Thrust). This shelf sequence is an entirely part of the Lesser Himalaya that will be discussed here. The Lesser Himalaya shelf sequence covers the areas of Galiat, Margala Hills, Kalachitta, Attock-Cherat, Kohat and Parachinar in the form of a wide E-W trending belt which rotate northeastwards to converge and close off into the western limb of Hazara-Kashmir Syntaxis at Garhi Habibullah in the east. The Attock Hazara Fold-and-Thrust Belt (AHFTB) is a geological feature where the Hazara Basin is situated in the northeastern part (Ghazanfar et al., 1987, 1990). Within this belt, the rocks ranging from Precambrian to Eocene in age are organized into a synclinorium. These rocks have undergone deformation, resulting in the formation of tight to overturned folds. Furthermore, the geological layers within the synclinorium have been imbricated by a series of high-angle thrusts and normal faults. This complex tectonic setting has played a significant role in shaping the geological structure and architecture of the Attock Hazara Fold-and-Thrust Belt.

Furthermore, to the northern part of the Lesser Himalayas is the Higher Himalaya which is bounded by Main mantle thrust (MMT) in the north and Main central thrust (MCT) in the south. It is the northernmost part of upper Indus basin. The MCT forms the base of a massive 10-15 km thick slab of high-grade metamorphic rocks that overlie the Lesser

Himalayan sequence. This infracrustal thrust sheet of Precambrian Central Crystallines make up the high Himalayas and form the very core of the Himalayan Range. The basal part of the section is characterized by Precambrian gneisses with total rock ages of (1,500- 1,800 m.y). However, these ages mark still older metamorphic events (Kazmi & Jan, 1997). Medium grade metamorphism traces of an active fault, the Himalayan Frontal Fault (HFF) cut the alluvium in the foothill region. This portion of Himalayas contains Precambrian to Cambrian igneous rocks and Cambrian metasedimentary rocks (Shah, 1977b; Bender and Raza, 1995). In addition, due to the collision between Indian and Eurasian Plates, the Kohistan Island arc was formed in-between the two plates and lies above the Higher Himalayas. The Main Karakoram Thrust (MKT) separates the Kohistan Island Arc from the Karakoram Block in the north (Shah, 1977a).

## 2.3 Structural Geology of the Study Area

Geologically, the study area lies in the southern part of Lesser Himalayas and is known as Hazara Fold-Thrust Belt. The Samana Suk Formation along with other Cambrian-Miocene rocks is exposed along this belt. The Hazara Fold-Thrust Belt is confined by the Mansehra crystalline zone to the north and Potwar Basin in the south. Similarly, the Hazara Fold-Thrust belt is bounded by Kashmir Basin and Peshawar Basin from eastern and western sides, respectively (Fig 2.2). The thrust faults that define the limits of the Hazara Fold-Thrust Belt are the Panjal-Khairabad Fault (northwards and westwards) and the Main Boundary Thrust (southwards and eastwards) (Ullah, A., 2017).

The study area exhibits a complex structural and historical geology characterized by various thrust faults that have caused older rocks to be stacked on top of younger rocks. Additionally, the sedimentary successions in the area have been affected by microscopic to mesoscopic folds and faults, resulting in a rugged topography. The results of the Himalayan orogeny highlight the presence of significant geological structures such as thrust faults, anticlines, and synclines, which have contributed to the overall structural framework of the region. Being part of the Lesser Himalaya, the study area is characterized by the Main

Boundary Thrust (MBT), a prominent tectonic boundary where metasedimentary rocks are present. The MBT is a planar zone that appears to dip northward at an angle of 15 degrees and extends to a depth of approximately 10 to 20 kilometers (Seeber et al., 1981). The southern eastern Hazara area serves as a stratigraphic boundary separating the significant sedimentary Potwar Basin and Kohat Basin (Ghazanfar et al., 1990). In the southern side of the Hazara area, a thick foreland sequence consisting of extensive mountain chains can be observed, which lies to the south of the metamorphosed hinterland. This sequence spans from the north Cambrian to Eocene and is situated between the MBT and Panjal Thrust. Further to the southern side, between the Main Frontal Thrust (MFT) and MBT, a sequence of younger foredeep and Miocene molasses deposits is present (Ahsan, 2008). These geological features and boundaries contribute to the overall complexity of the study area's geological and tectonic history.

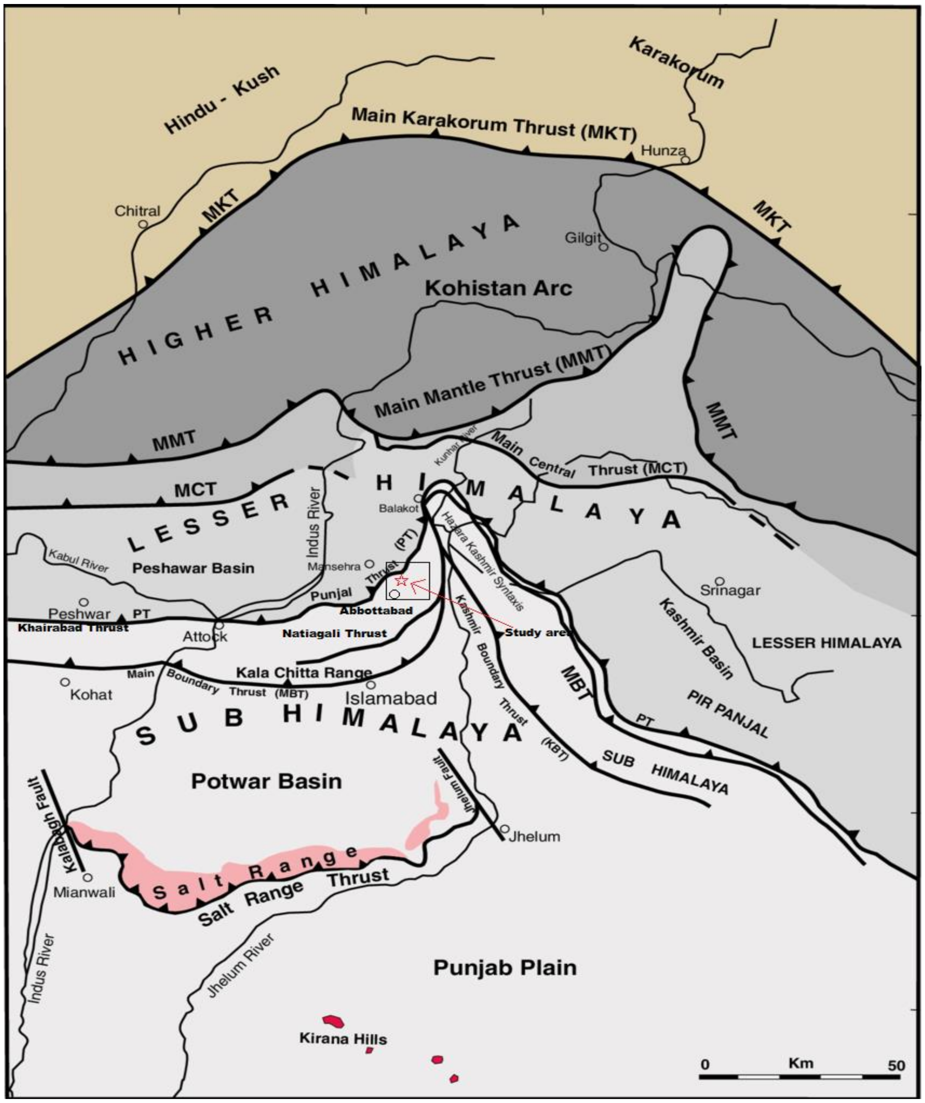


Figure 2.2. Generalized tectonic map of northern Pakistan, showing subdivisions of the Himalayan Mountains and within black rectangle red star shows the study area (after Kazmi and Rana, 1982).

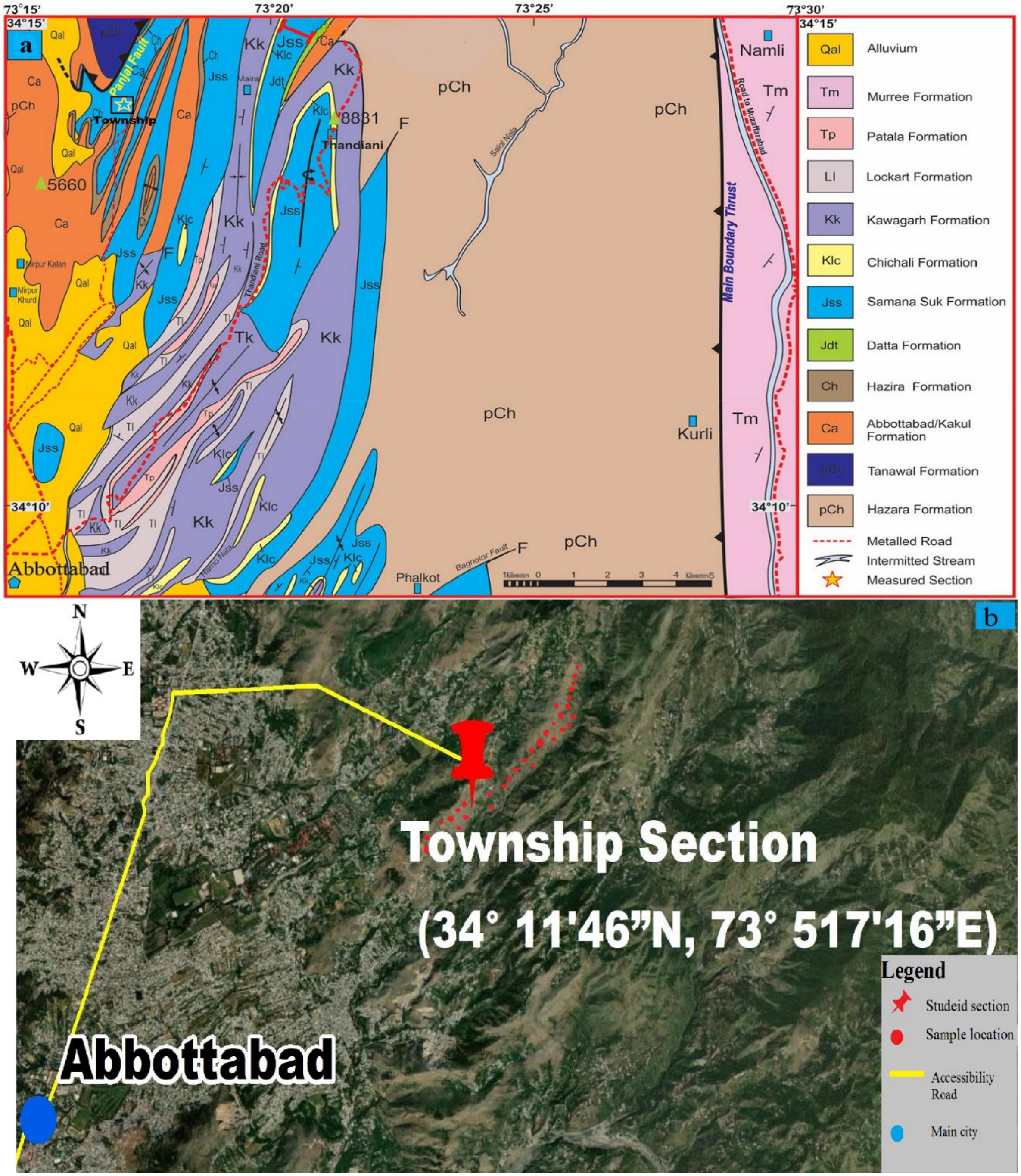


Figure 2.3. (**a**) Simplified geological map of the study area showing the location of studied section and distribution of formations (after Afridi, 2010). (**b**) Google earth image showing the samples location of study area.

## 2.4 Stratigraphy of study area

The study area shows good stratigraphic exposures ranging from Precambrian to Eocene time (Fig 2.3). The Precambrian rocks associated with Hazara and Tanawal Formations which are quartzites, slates, phyllites, shales with limestones. While the Cambrian rocks characterized by marble, dolostone and argillites of Abbottabad and Hazira Formations. This Cambrian succession is followed by Ordovician–Triassic gap of sedimentation though, the Mesozoic to Cenozoic platform successions directly overly the Cambrian rocks.

The area has preserved lower to Middle Jurassic succession of subordinate sandstones, shales and limestones of the Datta and Shinawari Formations but these formations are comparatively thin having thicknesses of 10 m and 25 m, respectively. Bulk of this Jurassic succession is composed of Tethyan oolitic platform carbonates of the Middle Jurassic Samana Suk Formation (maximum thickness of which is recorded as 65 m in the current study). The late Jurassic is absent and depicting a Jurassic–Cretaceous unconformity, thus the Cretaceous succession lies directly on Middle Jurassic strata. The Cretaceous succession includes a mix of lithologies (sandstones, shales, and sandy limestones) of the Chichali and Lumshiwal formations overlain by pelagic carbonates of the Kawagarh Formation. The Kawagarh Formation has an unconformable upper contact with the Tertiary strata that is marking the Cretaceous–Tertiary (K–T) Boundary (Kazmi and Jan, 1997). The Tertiary strata having Paleogene lithologies of shallow-marine sandstones, limestones and shales/marls of the Hangu Formation, Lockhart Limestone, Patala Formation, Margalla Hill Limestone and Chorgali Formation (Shah, 2009).

The generalized stratigraphic column of the Jurassic stratigraphy of study area is shown in Figure (2.3), followed by the brief description of Samana Suk formation given below.

### 2.4.1 Samana Suk Formation

The term "Samana Suk" was first introduced by Davies (1930), and its type locality was described by Fatmi (1973) near Shinawari (33 31' 13" N, 70 48' 06" E) in the western Samana Range. The distribution of the Samana Suk Formation is similar to that of the Shinawari Formation and comprises various lithologies. The dominant lithology is limestone, accompanied by marls, sandstone, clays, and minor amounts of dolomites. In the Hazara area, the Samana Suk limestone is mainly medium-grained and contains subordinate marls, shale, and sandstone. The limestone beds are well-bedded, medium to dark gray in color (on fresh surfaces), with yellow dolomitic patches (Ghazanfer et al., 1990). The maximum reported thickness of the Samana Suk Formation in the Hazara area, specifically in the Bagnotar section, is 366 meters. However, in the current study, a thickness of 65 meters was recorded in the Township section. The upper part of the Samana Suk Formation is fossiliferous and contains ammonites, brachiopods, pelecypods, gastropods, belemnites, and corals. The upper contact with the Chichali Formation is disconformable, indicating a period of erosion or non-deposition, while the lower contact with the Shinawari Formation is conformable.

However, near Abbottabad along the Hazara Trunk Road, the Samana Suk Formation directly overlies the Cambrian succession, and in some other places in the Hazara area, it overlies the Datta Formation (Latif, 1977; Ghazanfar et al., 1990). In the study area, the beds of the Samana Suk Formation are well-exposed, allowing for detailed examination from bottom to top. Although the base contact of the formation is not marked due to lack of exposure, the sequence of the formation can still be studied effectively.

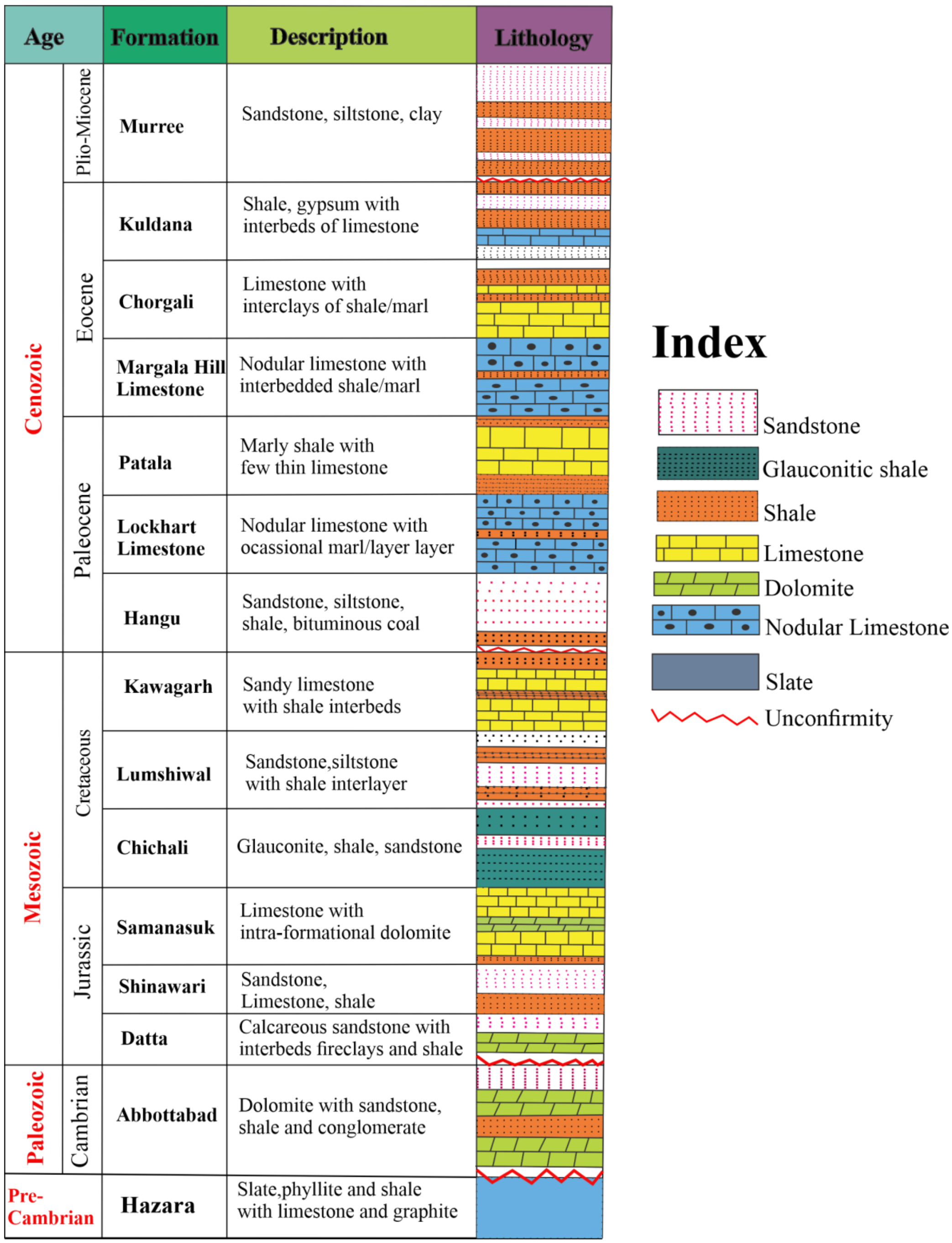


Figure 2.4. Showing generalized stratigraphic column of the study area in Hazara Basin (after Latif, 1970).

# CHAPTER 3

# METHODOLOGY

## 3.1 Introduction

The Jurassic Samana Suk Formation exposed in Township section was properly examined through detail literature review followed by a relevant geological map of the study area. Related literature was broadly studied to obtain knowledge about the microfacies with their depositional setting. Relevant published papers regarding microfacies analysis in several national and international journals were collected and systematically studied with a view to obtain meaningful idea of the work established till recent by the previous researchers. The section was selected where the outstanding exposures of rocks of the Samana Suk Formation present in the study area. The study area has also one quarry that is easily accessible. The standard techniques have been utilized which includes field work for section measurement, detailed systematic sampling, preparation of thin sections, petrographic microscopy and further observations. These techniques were carried out through the objectives of the study. Field plan was conducted according to requirements of field work for study area. Moreover, all the geological field equipments were checked before starting the field work. The field and laboratory work formed the base of this research. The method of study for this research is as follow.

## 3.2 Field work

For microfacies analysis, the outcrops should be studied according to lithology, texture, rock color, sedimentary features and diagenetic overprints etc. Detailed field work was conducted to the proposed study area. The location of section was traced by Global positioning system (GPS). The contacts of the Formation with the overlying and underlying formations were not exposed, while contacts of the strata were well exposed.

Thickness was measured using a measuring tape and recorded as 65 m from bottom to top. A diluted 10% Hydrochloric acid was used for verification of Limestone of the formation. The lithological distribution of limestone and dolomite of Samana Suk Formation weredifferentiated through 10% dilute HCl and other field features such as color contrast,hardness, butcher chop weathering etc. The Samana Suk Formation in the study area was identified by the presence of oolitic limestone which was clearly visible and is its diagnostic feature.

The measured section was covered by capturing field photographs through a camera which includes a general and close up view of different observed features, outcrop features and also an overall panoramic view of the type locality. These all photographs are categorized with detail descriptions in their respective chapter of study. The outcrop features were observed through hand lens and naked eyes which include bedding, lithology, sedimentary structures, texture and composition of grains along with its bioclastic contents were identified and recorded on the spot as well noted on the paper. Fresh samples were collected according to a specific plan of distribution at proper intervals from bottom to top of measured section.

The sampling specification is entirely based on different observed features and a systematic sampling of the section. A geological hammer was used for the samples collection. According to the requirements, forty (40) representative samples were collected from the measured section that covering all the facies variation of the entire Samana Suk Formation. The collected rock samples marked with sample number, lithology type and put into the sample bags. The collected rock samples were then carried to the Rock cutting lab for thin sections preparation and further sent to the respective departmental labs for detail analysis.

### 3.3 Laboratory work

Laboratory work includes thin sections preparation, petrographic study and photomicrography.

#### 3.3.1 Thin sections preparation

The collected rock samples were carried to the Rock cutting lab of Pakistan Museum ofNatural History, Islamabad for thin sections preparation. The rock samples were cut to prepare polished slabs and thin sections. In total of forty (40) samples, thirty-seven (37) samples were selected for preparation under clear observation of polished slabs of the total collected samples under hand lens for possible inference of textural facies. Hence, thirty-seven (37) thin sections were prepared according to requirements for petrographic studies.

#### 3.3.2 Petrography

The thin sections were studied through petrographic microscopic in the sedimentology Lab National Center of excellence in Geology, University of Peshawar. Photographic equipment associated with microscope was utilized to show low and high power magnification. Various rock constituents, structural grains, classification of textures of the samples, pore spaces, microfossils, diagenetic features identification and diagenetic products like cement, micro-fractures and many more are described using this microscopy. Petrographic data such as percentages of allochems, matrix and cements were produced and on the basis of such data the limestone was classified through the (Dunham, 1962) classification scheme (Fig 3.1). The percentage of each individually component is estimated by using visual charts with consideration of total grains as 100%. So, the demonstration of microfacies is based on this estimation of allochems and their types. The allochems type was farther identified to determine environments of deposition. Depositional environments were recognized through combining fieldwork observations, textures, sedimentary features, fossil contents, and other assemblages according to (Wilson, 1975).

After petrographic analysis photomicrographs were captured for the description of microfacies. The photomicrographs with their detail description are described in their respective chapters. For meaningful interpretation, all the lab work was accomplished in a systematic manner.

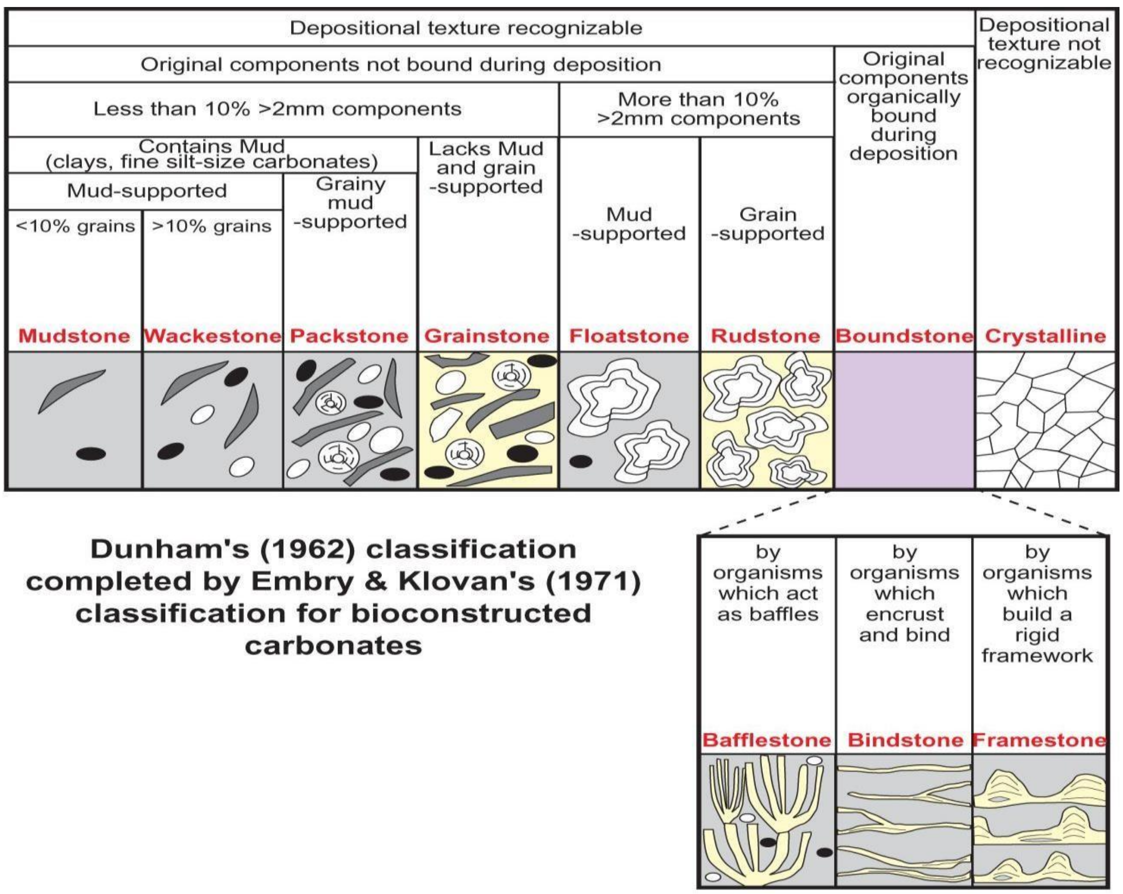


Figure 3.1. Dunham’s classification of limestone, further completed by Embry and Klovan’s (1971), classification of bioconstructed carbonates.

# CHAPTER 4

# FIELD OBSERVATIONS

## 4.1 Introduction

The fieldwork is conducted at the Township section of Abbottabad, Hazara area to observe and investigate the important field characteristics and collect samples for the microscopic analysis. Based on research objectives the samples were collected from 65 m thick carbonate unit of Samana Suk Formation (Fig 4.1 A). The Samana Suk Formation having well developed package of carbonate rocks in study area. This Formation comprised of variety of grains and cement which give it a unique identification. In Township section, the Formation is consisting of mainly limestone with light grey-dark, grayish color having brown to yellowish, rusty brown and grey to dark grey color dolomitic beds (Fig 4.1 B & C). The limestone is oolitic and thin to thick bedded. The thick oolitic beds of 1-2 m are repeated at multiple intervals (Fig 4.1 B). The bedding of limestone is parallel to sub parallel and as well in an irregular shape (Fig 4.1 C). Different limestones beds showing facies contrast and contacts (Fig 4.2 B-C & 4.3 B). Various skeletal and non-skeletal grains are present in these beds of limestone. The skeletal grains consist of bioclasts while the non-skeletal grains include peloides and ooids (Fig 4.4). It has also intraclasts and etxraclasts (Fig 4.5 F) and (Fig 4.6 C-D). The verities of cement and matrix are present in the Formation. The ripple marks (Fig 4.6 B) and bioturbation structures such as bores and burrows are also present (Fig 4.4 C & 4.5 E).

The section comprised of various types of dolomite beds which were differentiated from the limestone by color contrast and hardness etc and as well multiple phases of dolomites have been observed in the area (Fig 4.2 A). The diagenetic features such as stylolite, dolomite and calcite pitches, fractures and in addition that filled by calcite cementation, recrystallization, compaction etc were observed (Fig 4.5) and as well as described in their relevant chapter (6) in detail. The selected section consists of various microfacies. Though, these all are described in detail in petrographic section (chapter 5).


Figure 4.1. (**A**) Panoramic view of study area, (**B**) study area having alternating thin to thick beds and (**C**) shows close-up view of medium-thick beds of limestone of light grey to green color on fresh surface and yellowish color on weathered surface, (man for scale).

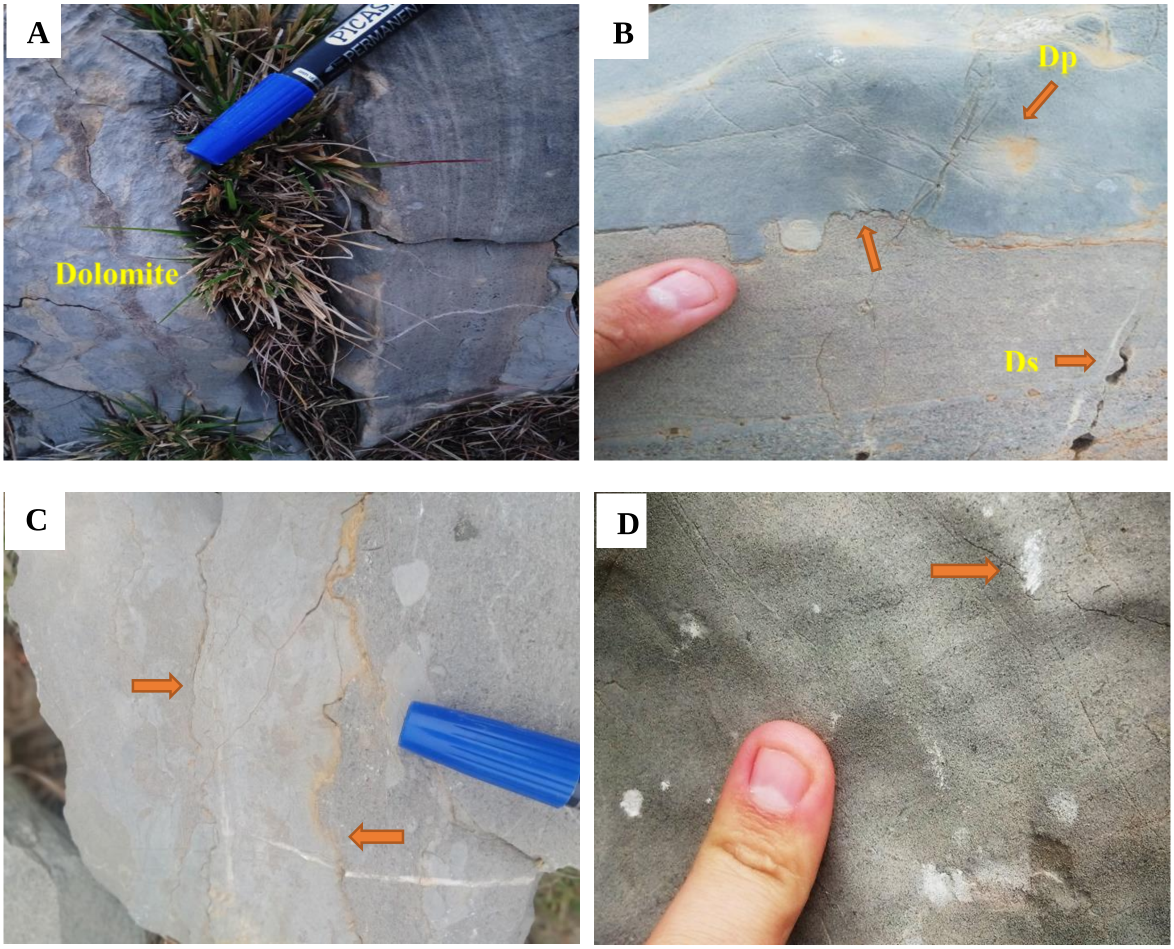


Figure 4.2. Field photographs: (**A**) Dolomite and limestone beds, (**B**) displaying two different facies of limestone sharply contacted by stylolite (St) along with dissolution features (Ds) and dolomitic patches (Dp). **(C**) Limestone beds representing facies variation with sharply contacts indicated by arrows and having stylolites. (**D**) Showing oolitic Grainstone bed of limestone with low amplitude stylolite (St).

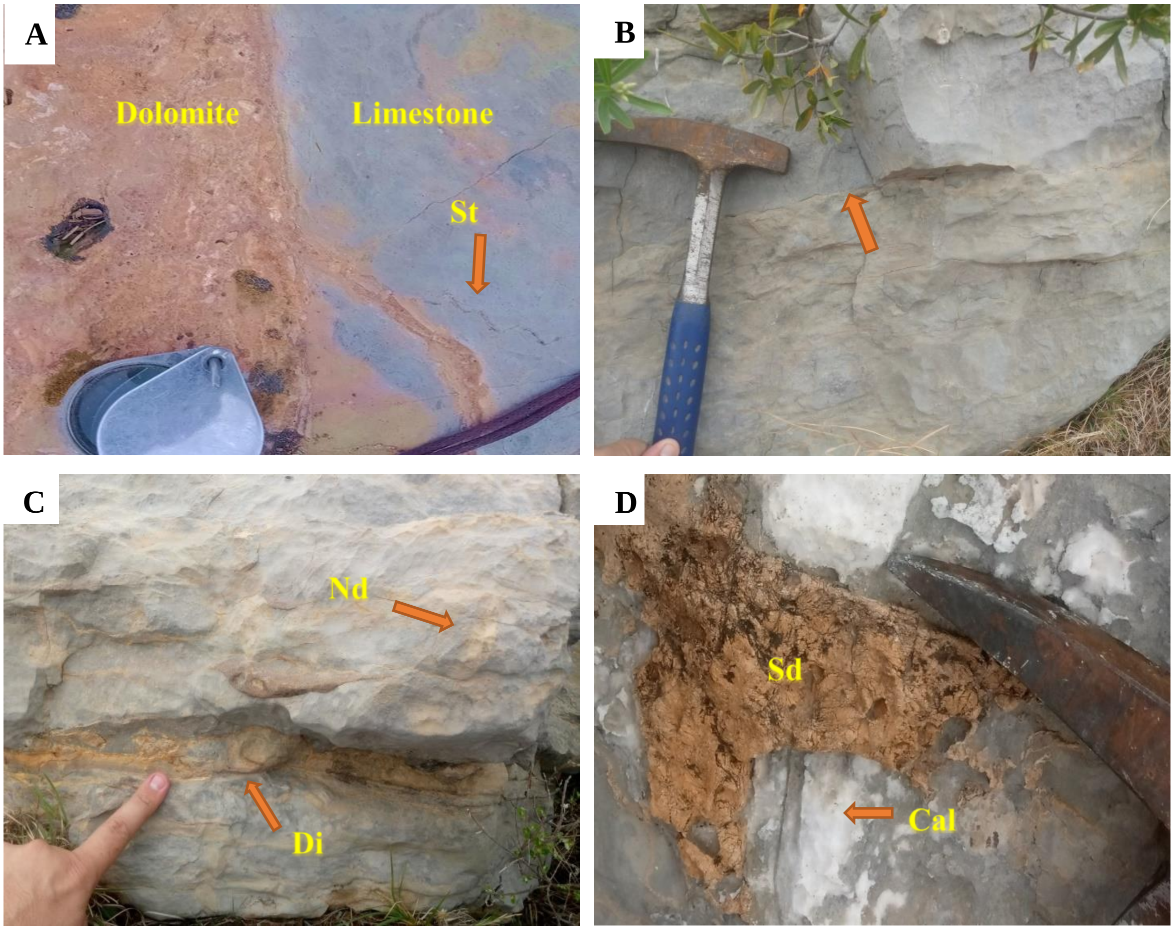


Figure 4.3. Field photographs: (**A**) displaying brown dolomite and limestone beds in which sharply contact can be seen. **(B**) Limestone bed representing facies variation with sharply contact indicated by arrows and having stylolites. (**C**) Showing the dolomitic intrusion (Di) in the form of thin bed existed in the limestone bed and bed probably indicating nodularity (Nd). (**D**) Saddle (Sd) and calcites (Cal) in the limestone.

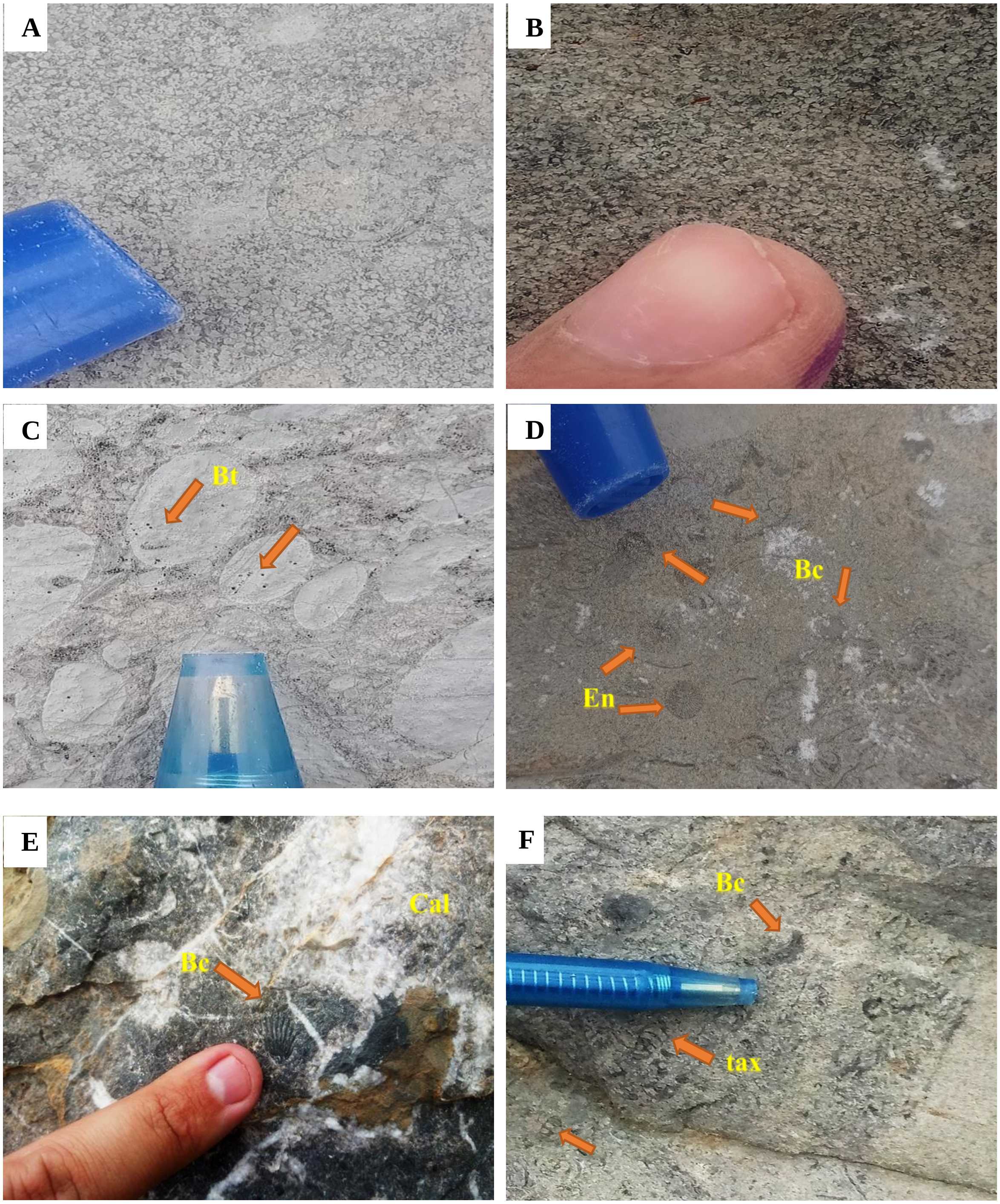


Figure 4.4. Field photographs: (**A** & **B**) showing ooides in the limestone of Samana Suk Formation. In (**C**) Small pores represented Bioturbation (Bt) within the large rounded intraclasts. (**D**, **E** & **F**) displaying different types of bioclasts (Bc) which are present in the limestone beds e.g Echinoderm (En), Taxtularia (tax) etc.

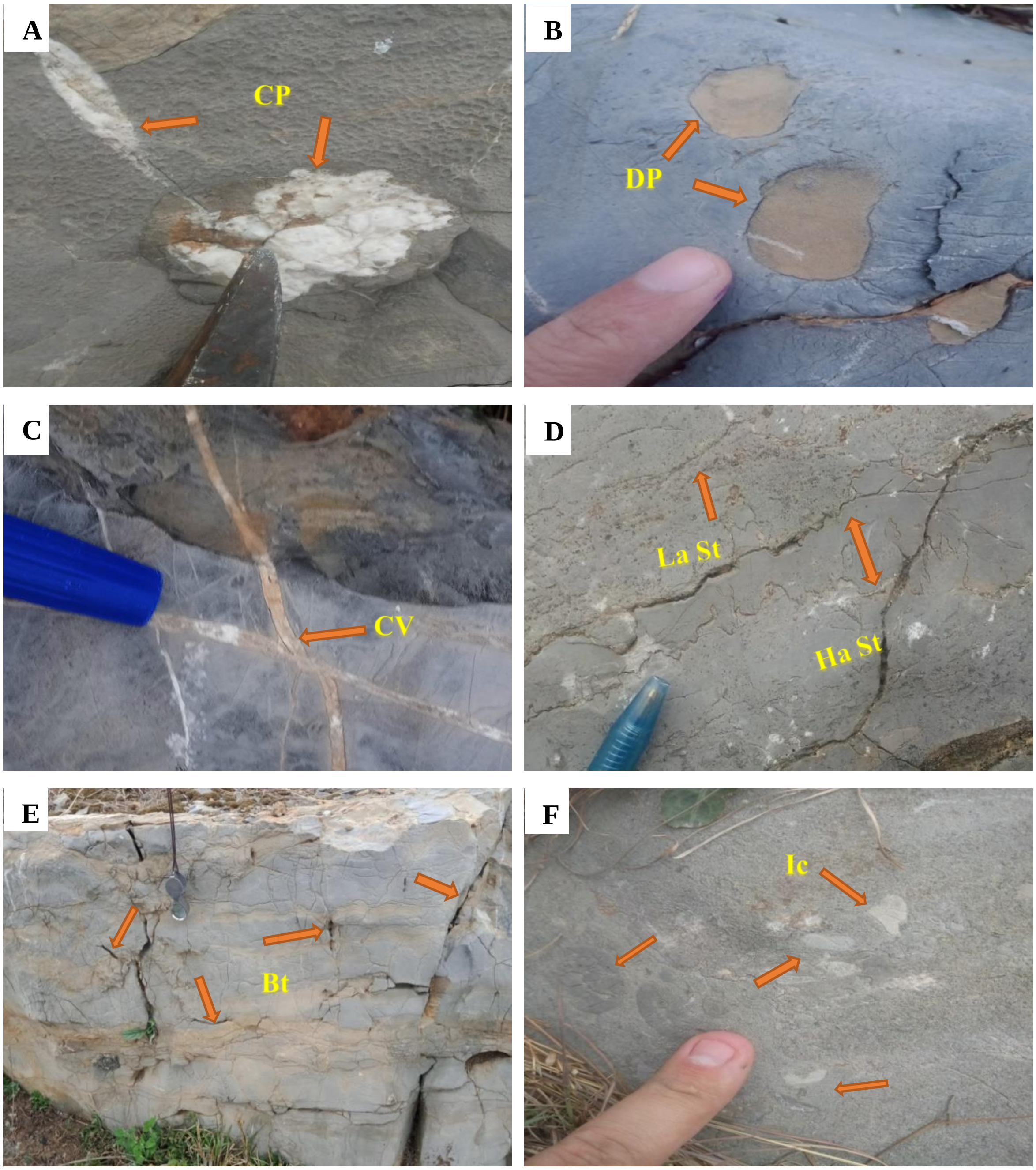


Figure 4.5. Field photographs (**A** & **B**) showing calcite patches (CP) and dolomite patches (DP) in the limestone of Samana Suk Formation respectively. In (C) calcite veins cross cutting each other. (**D**) Displaying low amplitude (La) and high amplitude (Ha) stylolites in the limestone bed. In (**E**) Fractures and small holes can be seen which are indicating

bioturbation (Bt) and mechanical compaction. (**F**) Showing intraclasts (Ic) as broken fragments of carbonate rocks in grainstone bed.

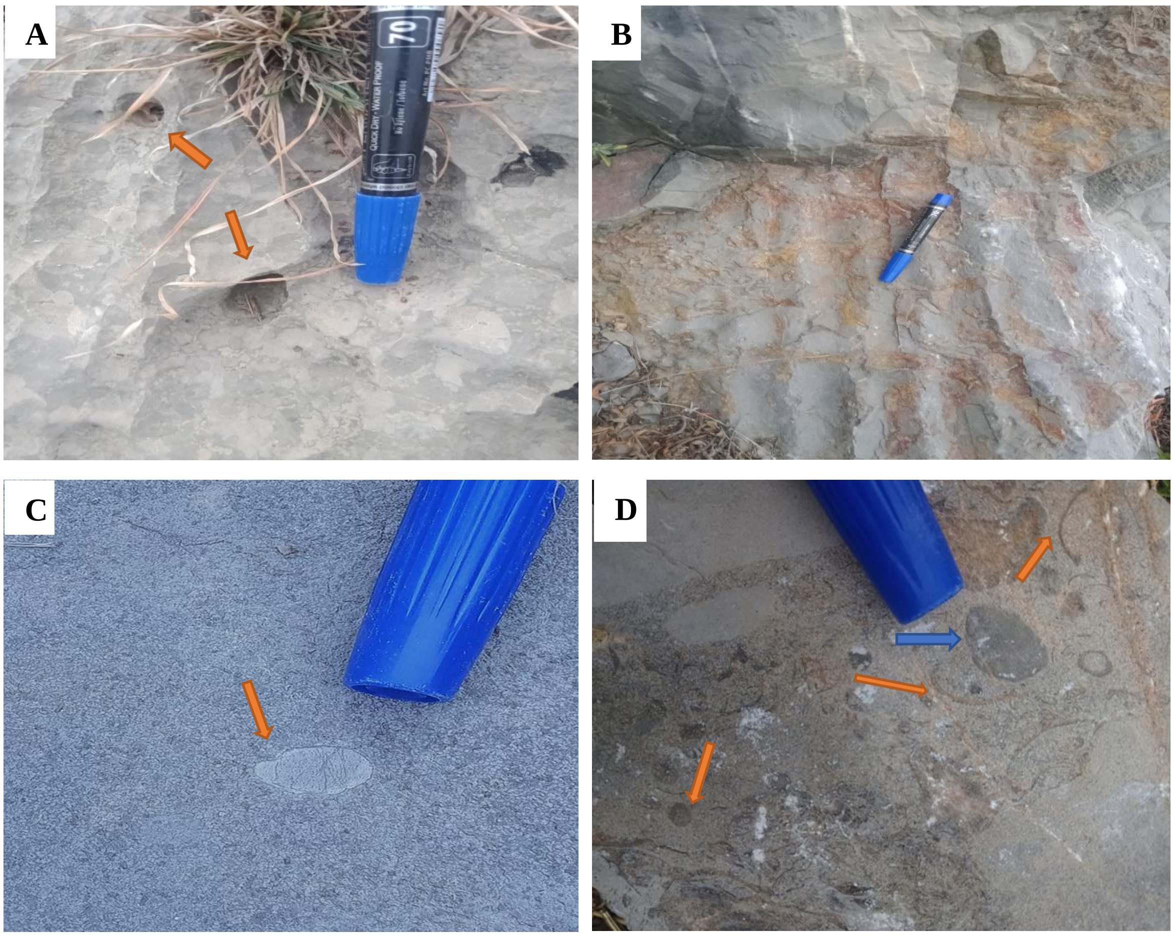


Figure 4.6. Field photographs: (**A**) Displaying vugs indicated by arrows which are formed due to dissolution in the limestone. (**B**) Showing ripple marks in the limestone bed. In (**C**) Intraclastic fragment is present in ooidel grainstone, while in (**D**) bioclasts are indicated by red arrows and Intraclastic is represented by blue arrow in the limestone bed. .

# CHAPTER 5

# MICROFACIES ANALYSIS

## 5.1 Introduction

The microfacies are demonstration of the paleontological and sedimentological data that they can be classified and described from thin sections and polished slabs of rock samples (Flugel, 2010). The type of microfacies determination from carbonate rock sample is carried out by using the classification of fossils, framework of limestone and the texture of that specific sample (Flugel, 2004). Wilson (1975) and Flugel (2004 & 2010) have presented different criterion for microfacies analysis and established 26 standard microfacies (SMF) types with distinguishing features (meso and micro) which are representative for certain marine environment. On the basis of thin-section studies microfacies further divides facies into units of same compositional characteristics that indicate specific depositional environments and controls. Microfacies identification and interpretation of their depositional environments can be done through petrographic data.

In this study, the classification system that was proposed by Robert Dunham (1962) has been followed. According to this classification scheme, the limestones are divided into two prominent groups. Limestone whose components were originally bound together in the time of deposition is called boundstone and limestone whose original components were bound together by grains or matrix. The limestone original components bound together by matrix or grains are further sub divided into mudstone, wackestone, packstone and grainstone. A limestone consists of 90% matrix (mud) and less than 10% of grains is called mudstone. The grain components are greater than 10% with less than 90% of mud is called wackestone. Grains supported limestone that containing lime mud is known as Packstone. The limestone which is grain supported and having no mud is called Grainstone. Mudstone, Wackestone are matrix supported while Grainstone and Packstone are grain supported. The name of different types of grains using as prefix with the rock names that display the abundance of that grain in rock, i.e. bioclastic wackestone, ooidal grainstone, peloidal mudstone, ooidal intraclastic grainstone etc.

## 5.2 Microfacies of Samana Suk Formation in the study area

The following nine (9) microfacies are identified in Samana Suk Formation at Township section. The description and interpretation of these microfacies with respect to depositional environment are described below.

### 5.2.1 Mudstone (MF1)

#### 5.2.1.1 Description

The MF1 microfacies consist of 90% mud and 1% grains which is represented by very fine size of peloides (Fig 5.1 A-B). The microfacies is overall homogeneous, non-laminated and having no skeletal grains and predominantly it is a pure mudstone. Very fine dolomitic crystallization is seen and stylolitization of low amplitude is present (Fig 5.1 A). Calcite filled large and small veins are also present.

#### 5.2.1.2 Interpretation

The nonexistence of skeletal contents, allochemical components, the percentage of allochems relative to the matrix, absence of lamination and the bulk of lime mud as a matrix, demonstrate the low energy environment of deposition in lagoons (Nizami, 2008; Hussein et al., 2017). The presence of pure micrite represents the lagoonal depositional environment (Wilson, 1975; Flügel, 2010). Mudstone microfacies can be comparable with standard microfacies, SMF-23 of Wilson (1975) and Flügel (1982; 2004).

### 5.2.2 Dolomudstone (MF2)

#### 5.2.2.1 Description

This microfacies dominantly consists of widespread dolomitic crystals of 70-80% while 15-20% matrix with minor amount of very small quartz crystals and too small peloidal grains. Well-developed fine to medium sized rhombs of dolomite are present. Porosity is also can be seen in dolomudstone. Bioclasts existence is absent and the extensive dolomitization is pervasive in nature (Fig 5.1 D). Multiple extensive calcite filled fractures as veins are present which are cross cutting each other (Fig 5.1 C-D). Microstylolites are also present.

#### 5.2.2.2 Interpretation

This microfacies consists of dolomitic mudstone. Well-developed rhombs of dolomite are present and dolomitization is pervasive in nature. Fine to medium grained dolomicrite and non-fossiliferous lime mudstone are sometimes deposited in saline and evaporative environment. The environment of deposition is inner ramp toward mid ramp

(Wilson, 1975; Flügel, 2004). This microfacies can be correlated with SMF-23 of Wilson (1975) and Flügel (2004).

### 5.2.3 Bioclastic peloidal wackestone (MF3)

#### 5.2.3.1 Description

Bioclasitic peloidal wackstone microfacies consist of 20-30% peloides, 5-10% bioclasts and ooides. The remaining portion is ragarded as matrix. Peloides and ooides are sorrounded by spars, while they are mud supported. The concentric liminations of ooides and bioclasts are replaced by spars (Fig 5.2 A). Some of the ooidal grains and bioclasts are micritized and micritization envelopes are present (Fig 5.2 B). MF3 is also having rare amount of dolomitic rhombs and calcite viens (Fig 5.2 A).

#### 5.2.3.2 Interpretation

The principle mud supported grains, low diversity of faunal assemblage and other bioclasts reveal that this microfacies was deposited in low to moderate energy condition, shallow subtidal and probably lagoonal environments. The microfacies is correlated to standard microfacies SMF-9 of Wilson (1975) and Flügel (2004).

### 5.2.4 Peloidal packstone (MF4)

#### 5.2.4.1 Description

In this microfacies 60-70% of peloides are widely distributed in packstone. The rare amount of skeletal grains and ooids of 1-3% are also present, while the rest of the portion is covered by spars and mud (Fig 5.2 C-D). The peloides are mostly fecal and having elliptical, rounded, or irregular shape. Pores filling between the grains are covered by calcites and lime mud. Peloidal packstone microfacies are also contains calcite filled veins (Fig 5.2 D).

#### 5.2.4.2 Interpretation

As this microfacies represents large amount of peloids with mud and very rare bioclasts shows deposition in calm condition, which reflects lagoonal setting. The bioclasts scarcity is because of semi-arid climate and limited circulation result in saline environment in lagoons (Flügel, 2010). The high proportion of peloids with rare bioclastic and skeletal grains represent a restricted subtidal lagoonal environment (ullah Khan et al., 2020). This microfacies can be correlated with described by (ullah Khan et al., 2020) and SMF-16 of Wilson (1975) for lagoonal settings.

### 5.2.5 Ooidal grainstone (MF5)

#### 5.2.5.1 Description

This microfacies dominantly comprises of 70-80% ooides, with rare amount of peloides and intraclasts. The ooids are concentric and well rounded, displaying dark and light color striped multi-laminae (Fig 5.3 A-B). The nuclei of ooidal grains are derived from pre-existing ooides and peliodes. Multiple dolomite crystals destroyed the structures of majority of ooidal grains, while the majority of ooides are partially micritized. The major calcite veins passing through ooidel grains (Fig 5.3 A-B). The pore spaces between the ooidal grains are filled by calcite cementation.

#### 5.2.5.2 Interpretation

The concentric, roundness and sortation of ooidal grains indicating relative high energy condition environment (Reolid et al., 2007). Relative high energy deposits are mostly related to shoals and bar environments which are near or on the seaward edge of carbonate platforms (Wilson, 1975; Flügel, 2010). According to (Harris, 1979; Hashmie et al., 2016), the abundance and well sortation of ooids and scarcity of micrite specify a high energy shoal environment above fair weather wave base (FWWB). Dolomitic influxes on grains indicate secondary diagenetic event. This microfacies can be correlated with standard microfacies SMF-15 C of Wilson (1975) and Flügel (2004).

### 5.2.6 Bioclastic ooidal grainstone (MF6)

#### 5.2.6.1 Description

This microfacie majorly characterized by ooides of 50-60% and 10-20% bioclasts in grainstone facie (Fig 5.3 C-D). The remaining grains include peloides and intraclasts of 10-15%. The ooides are very well rounded, radial and as well as concentric and exhibits mostly light colored multi-laminae. The cores of ooidal grains are derived from pre-existing ooides and peloides. The pore spacing between the grains are covered by spars and majority of the ooidal grains are closed to each other. Micritic envelops formed around the bioclasts and intraclasts, and mostly affected by neomorphism (Fig 5.3 D). Small calcite veins are present and passing through different grains. The intragranular porosity of blue color can also be seen which are mostly within the ooidal grains, while some quartz influxes also filled the porosity (Fig 5.3 C).

#### 5.2.6.2 Interpretation

The high percentage of ooids and bioclasts reveal that this microfacies is deposited in a barrier shoal environment. The ooids structures indicate deposition by waves and currents of moderate energy through little reworking. Shallow water depositional environment productivity is mostly in enough microbial encrusting (Buxton & Pedley, 1989). According to (Hussein et al., 2017) restricted lagoon to the back shoal environment of shallow water is generally interpreted by elongated peloidal grains and rounded to sub rounded ooides with shell fragments.

### 5.2.7 Peloidal grainstone (MF7)

#### 5.2.7.1 Description

Peloidal grainstone microfacies incorporate majorly 80-90% of peloides, with rare bioclasts and ooidal grains as a minor component (Fig 5.4 A-B). The peloidal grains are well sorted, randomly oriented and cemented through granular calcite cement and blocky cement.

#### 5.2.7.2 Interpretation

The abundance and well-sortation of peloidal grains, profusion of peloidal grains with few ooids indicate shoal depositional environment in high energy conditions (Scholle & Umer-Scholle, 2003). The shoal environment represents minimal association of mud low tidal and relative high wave energy (Lasemi et al., 2012). The peloids are indicated by the low circulation of warm water at shallow depth in shoal depositional environment (Jank et al., 2006). The Peloidal grainstone microfacies can be correlated with standard microfacies SMF-16 of Wilson (1975).

### 5.2.8 Bioclastic intraclastic grainstone (MF8)

#### 5.2.8.1 Description

This microfacies largely comprised of 40-60% intraclasts and 20-30% bioclasts fragments. These are probably sorted while some of these intraclasts closed to each other.

Neomorphism occurred in some of these intraclasts and bioclasts and micritic envelops are also present around of these clasts (Fig 5.4 C-D). Dolomite crystals (rhombs) indicated the selective dolomitization in Intraclasts (Fig 5.4 C).

#### 5.2.8.2 Interpretation

The abundance of peloides and intraclasts represent moderate to high energy condition and shallow subtidal-intertidal, bar/shoal environments. The biota which including common smaller benthic forams i.e. Taxtularia and other bioclastic fragments. The presence of various bioclastic fragments indicate toward the land portion of the ramp setting. So, these observations suggest that this microfacies could be deposited in the inner ramp shoals and carbonate dominant. This microfacies is comparable with standard microfacie SMF-16, 17 of Wilson (1975) and Flügel (2004).

### 5.2.9 Intraclastic bioclastic peloidal grainstone (MF9)

#### 5.2.9.1 Description

This microfacies is widespread consist of 20-30% peloides, 15-25% intraclasts 10-15% bioclasts i.e. Taxtularia etc and minor amount of ooidal grains (Fig 5.4 E-F). Some aggregate of peloidal grains are cemented by micrite as known as lumps and due to influence of micritization majority of the ooidal grains are converted into peloides (Fig 5.4 E-F).

### 5.2.9.2 Interpretation

The abundance of peloides and intraclasts suggests moderate to high energy and shallow subtidal to intertidal, shoal/bar environments. The biota which including common smaller benthic forams i.e. Taxtularia and other bioclastic fragments. The presence ofvarious bioclastic fragments indicate landward portion of the ramp setting. Based on these observations, this microfacies could be formed in the inner ramp shoals and carbonate dominant. This microfacies can be correlated with standard microfacie SMF-16, 17 of Wilson (1975) and Flügel (2004).

Approximately all of the microfacies characterized by numerous diagenetic characteristics and other structural fabrics associations. These associations represent certain impacts on the microfacies and their depositional environment. The overall details, features and characteristics of each individual microfacies and their respective depositional environments are summarized in Table 5.1.

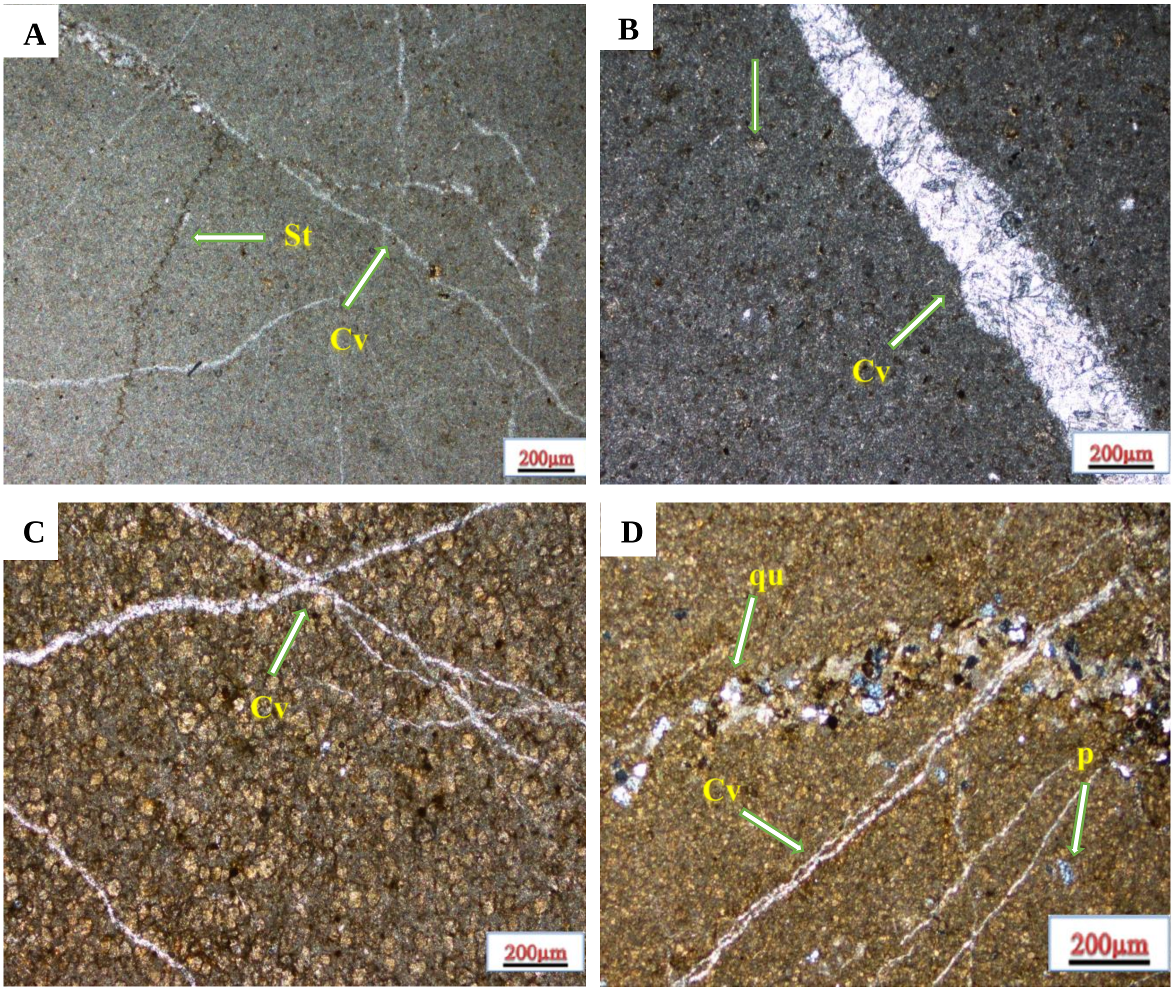


Figure 5.1. Photomicrographs; (**A-B)** representing the homogeneous mudstone microfacies which include calcite veins (Cv), stylolites (St), very fine dolomite crystals (Do) and rare peloides. (**C-D**) Dolomudstone microfacies showing fine to medium size Euhedral dolomite rhombs, cross cut calcite veins (Cv), quartz crystals (qu), porosity (p).

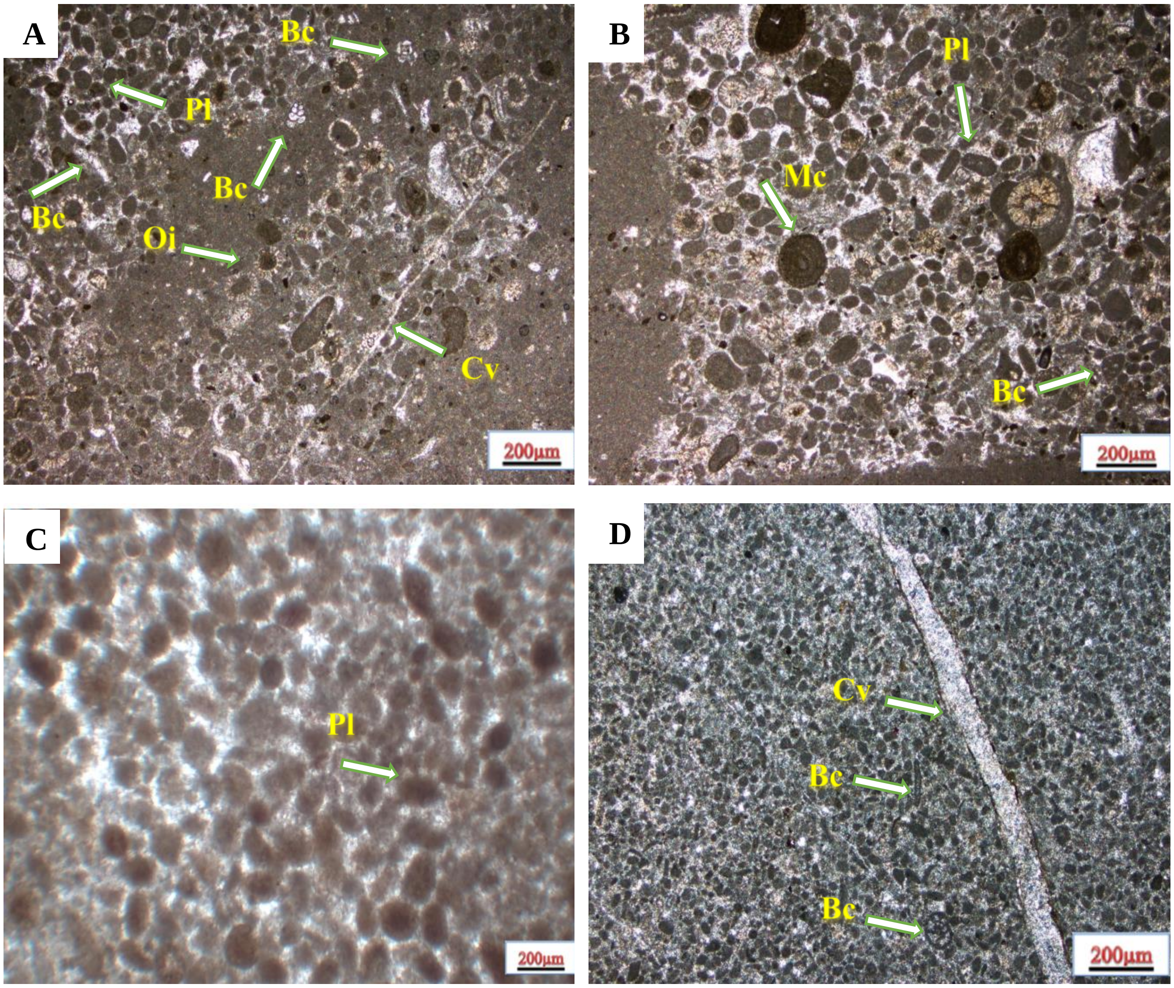


Figure 5.2. Photomicrographs; (**A-B**) Bioclastic peloidal wackestone having bioclasts (Bc), peloides (Pl), calcite vein (Cv), ooides (Oi) and micritization (Mc). (**C-D**) Peloidal packstone having abundance of peloides (Pl), bioclasts (Bc) and calcite vein (Cv).

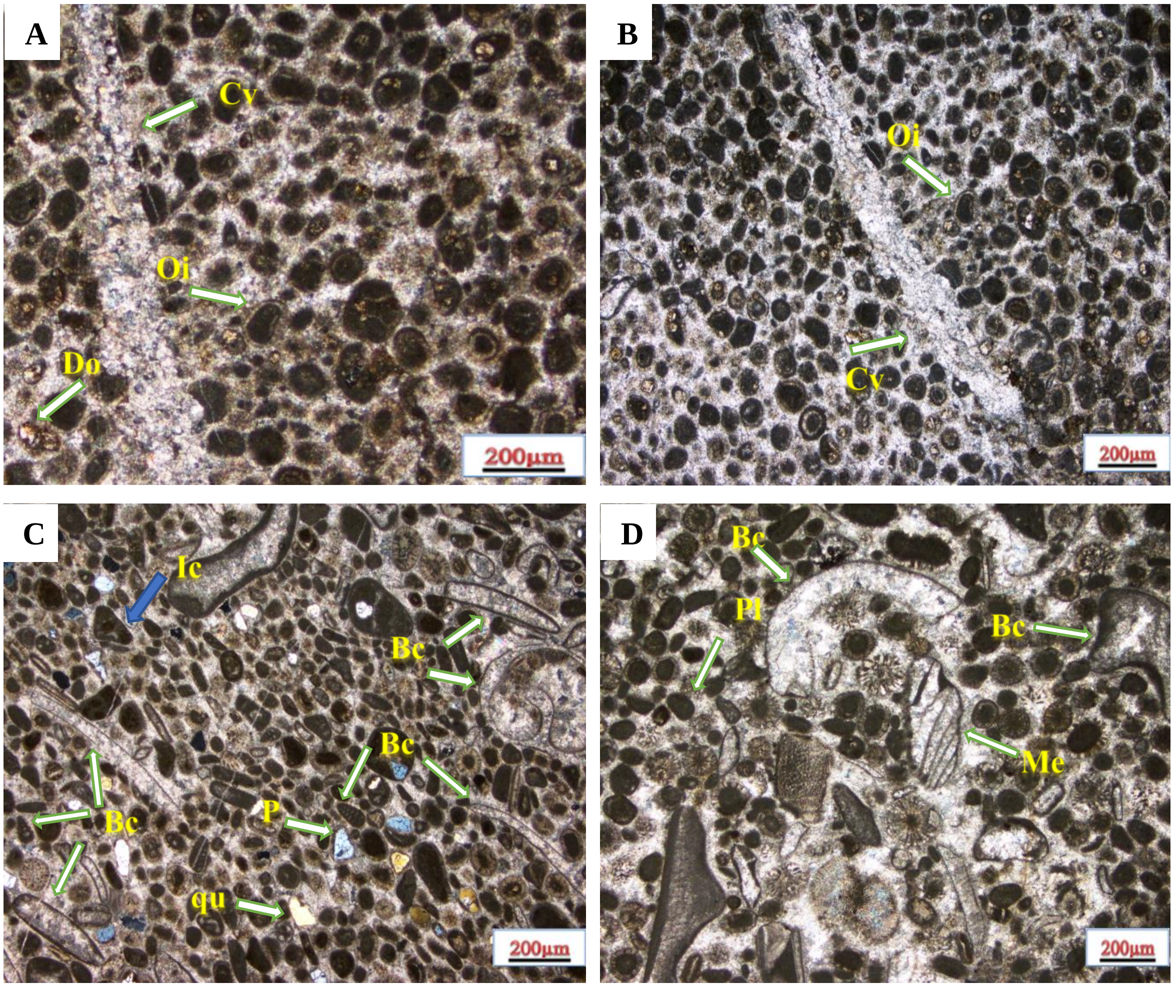


Figure 5.3. Photomicrographs; (**A-B**) Ooidal grainstone contain concentric ooides (Oi), dolomitic rhombs (Do) destroyed the ooides and cementation in the calcite vein (Cv). (**C-D**) Bioclastic ooidal grainstone represent bioclasts (BC), micritic envelops (Me), peloides (Pl), intraclasts (Ic), quartz (qu) and porosity (P).

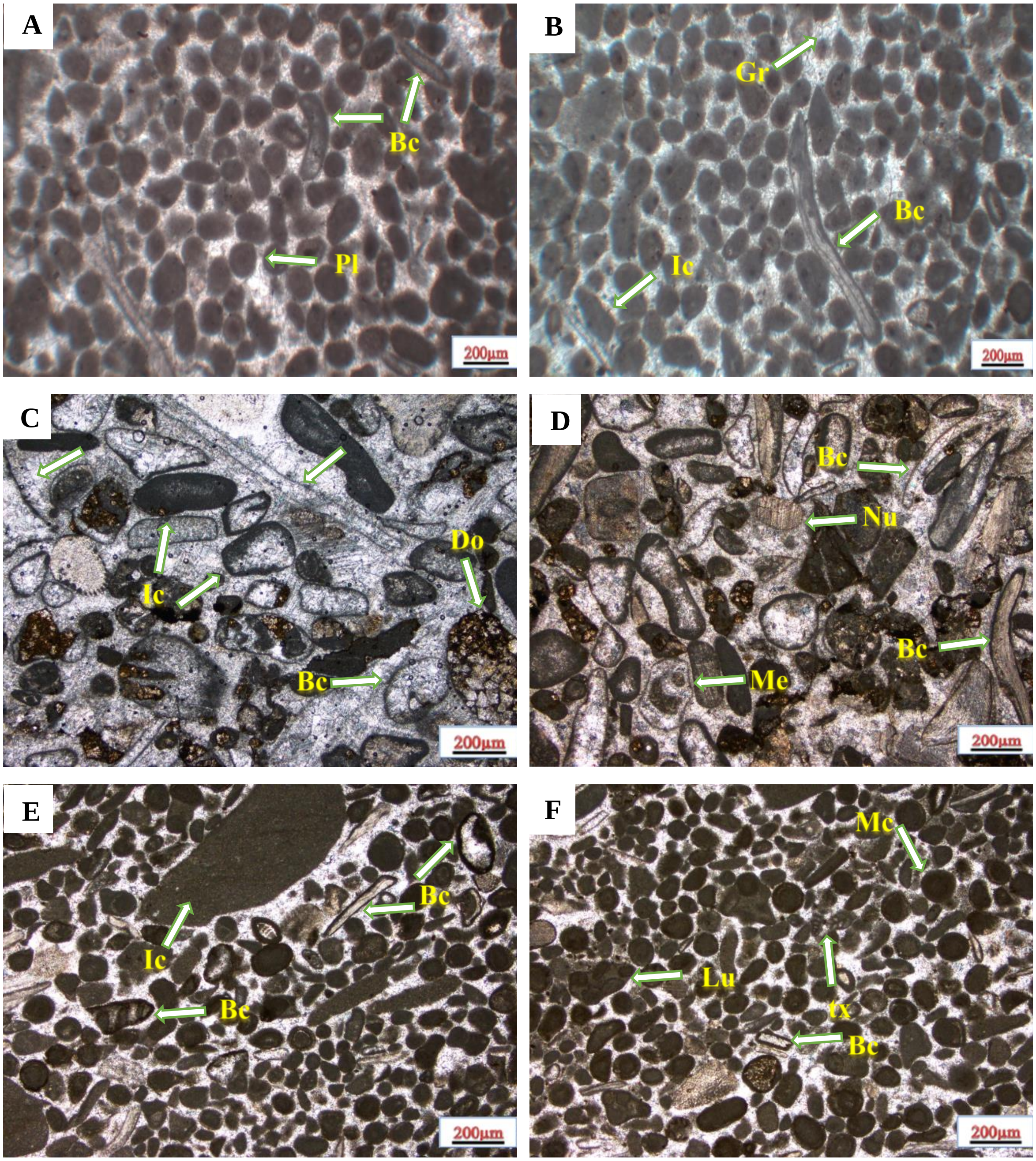


Figure 5.4. Photomicrographs; (**A-B**) Peloidal grainstone contains abundance of peloides (Pl) bioclasts (Bc), granular cements (Gr) and intraclasts (Ic). (**C-D**) Bioclastic intraclastic grainstone showing intraclasts (Ic) with bioclastic fragements (Bc) and Neomorphism (Nu), dolomite rhombs (Do),micritic envelops (Me). (**E-F**) Intraclastic bioclastic peloidal grainstone having intraclasts (Ic), bioclast (Bc), Taxtilaria (tx), Lumps (Lu) and micritization.

Table 5.1. Overall summary of microfacies of Samana Suk Formation at Township section.

| Facies | Microfacies types +code | Diagenetic features | Allochemical components | Depositional environment |
|---|---|---|---|---|
| Inner ramp | Dolomudstone (MF2) | Euhedral dolomite rhombs, calcite veins and stylolites | Dolomite rhombs (70-80%), rare quartz and peloides. | Low to moderate energy (evaporate+ saline) environment. (Inner ramp). SMF 23 |
| Lagoon | Mudstone (MF1) | Calcite veins, stylolites, fine dolomite crystals | Pure mudstone. Mud (90%) | Low energy lagoon environment (inner ramp). SMF 23 |
| | Bioclastic peloidal wackstone (MF3) | Micritization, dolomite rhombs and calcite veins | Peloides (20-30%), bioclasts and ooides (5-10%). | Low to moderate energy, shallow subtidal (inner ramp). SMF 9 |
| | Peloidal packstone (MF4) | Calcite veins, spars ,cements | Peloides (60-70%). Ooides and bioclasts (1-3%). | Subtidal lagoon environment. (inner ramp). SMF 16 |
| Shoals | Ooidal grainstone (MF5) | cements, dolomite rhombs, calcite vein, Micritization | Ooides (70-80%) | High energy shoal environment. (inner ramp). SMF 15C |
| | Bioclastic ooidal grainstone (MF6) | Micritic envelops, cements(spars), veins and neomorphism | Ooides (50-60%), bioclasts (10-20%). Peloides and intraclasts (10-15%). | Moderate to High energy shoal environment. (inner ramp). RMF 27 |
| | Peloidal grainstone(MF7) | Cements. | Peloides (80-90%) | High energy shoal environment. (inner ramp). SMF 16 |
| | Bioclastic intraclastic grainstone (MF8) | Micritic envelops, dolomite rhombs, neomorphism, cements | Intraclasts (40-60%), bioclasts (20-30%). | High energy subtidal to intertidal shoal environment. (inner ramp). SMF 17 |
| | Intraclastic bioclastic peloidal grainstone (MF9) | Micritization, cements | Peliodes (20-30%), bioclasts 15-25%, intraclasts 10-15%. | High energy subtidal-intertidal environment. (inner ramp). SMF 16,17 |

# CHAPTER 6

# DIAGENESIS

## 6.1 Introduction

Diagenesis starts during deposition or after deposition which consists of the chemical, physical and biological processes that affects the sedimentary rock before the metamorphism. The major diagenetic processes brought through diagenesis are micritization, neomorphism, bioturbation, mechanical and chemical compaction, fracturing, cementation, dissolution, dolomitization and pyritization (Tucker et al., 2007). The global carbonate reservoirs display an effective relationship to diagenesis. Various diagenetic specifications of the carbonate rocks from early micritization up to final stage can completely change the reservoir quality (Rosales et al., 2018). Carbonate diagenesis is a multi-faceted interconnection at depth burial (shallow to great) between both the mechanicaland chemical processes. Diagenesis brings alterations and break off the textures which formed at the time of deposition, later on produce a new secondary texture and as well the dissolution of fractures by pressure solution increases the reservoir capacity (Croizé et al., 2010).

## 6.2 Diagenesis of Samana Suk Formation in Township section

Diagenesis of Samana Suk Formation in Township section was carried out by petrographic studies (microscopic examination) and field observations as macro examination. The Samana Suk Formation has passed through different diagenetic alterations in the study area. The diagenetic characteristics in study area are micritization, bioturbation, neomorphism, compaction (mechanical and chemical), fractures and veins, dissolution, cementation, dolomitization and pyritization which are described in detail in this chapter.

### 6.2.1 Micritization

Micritization occur just after deposition during initial burial, where due to microbial activities micritic envelope is forming around the allochemical components. Micritization process occurs in two stages. In the early stage micritization is due to microbial activities while the late stage is generally related with stabilization of mineral constituent without microbial activities (Harris, 1979). Micritization is produce by different microorganisms such as endolithic algae and bacteria etc (Tucker and Wright, 1990). In the studied section micritization is commonly found in various facies. It resulted to the destruction of internal laminations of ooidal grains and mostly developed in the centers of ooids (Fig 6.1 A). Some of the grains formed micritic envelopes around them while some of the peloidal grains are derived from ooids due to the influence of micritization in majority of facies (Fig 6.1 B).

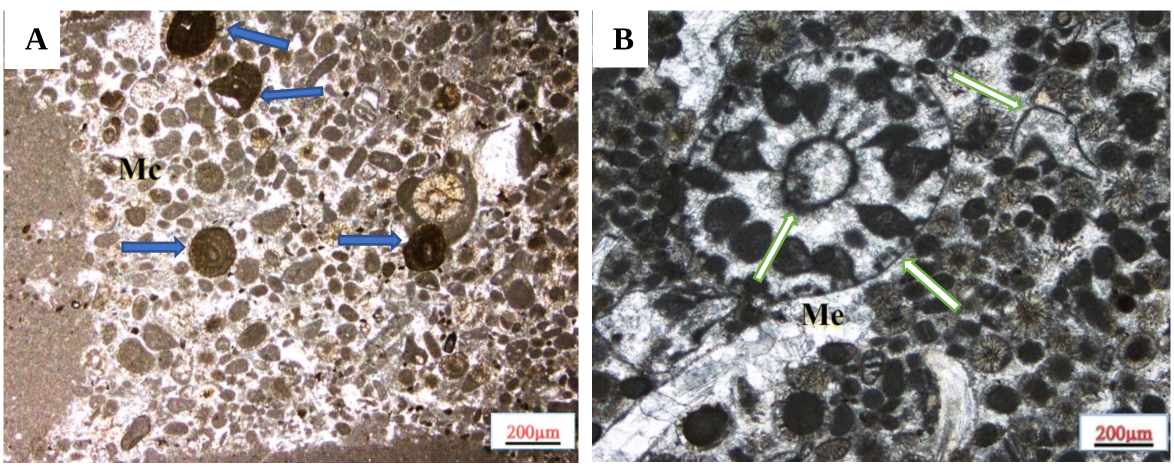


Figure 6.1. Photomicrographs: (**A**) showing micritization (Mc) of ooides and their internal laminations destruction indicated by blue arrows. (**B**) Micritic envelope (Me) around the grains and mostly the ooides are internally micritized, while the peloides are derived due to influence of micritization.

### 6.2.2 Bioturbation

Bioturbation is the process in which the reworking of sediments by organism activities resulted to destruction of texture and represented by burrow filling (Flügel, 2010). It is commonly seen in the bedding planes and few microfacies of the studied section (Fig 6.2 A-B).

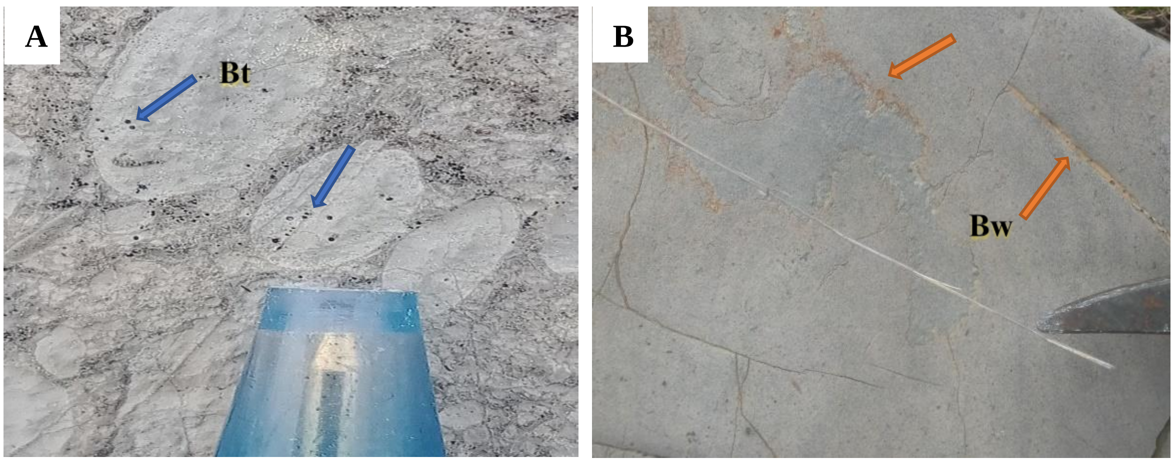


Figure 6.2. Field photographs: In (**A**) small pores showing bioturbation (Bt) within rounded intraclasts indicated by blue arrows. (**B**) Representing bioturbation with burrows filling (Bw) indicated by arrows.

### 6.2.3 Neomorphism

Neomorphism is recrystallization or replacement process in which one shape transfer to another, either in the crystal or as a polymorph that different from the previous crystallized shape. It occurs in the presence of moisture mostly in water through a process of dissolution and precipitation (Tucker and Wright, 1990). Neomorphism is present virtually in majority of samples of Samana Suk Formation in the study area (Fig 6.3 D).

### 6.2.4 Compaction

A compaction process is induced by friction during burial with increasing pressure and temperature, and by growing of overburden sediments (Tucker and Wright, 1990). It occurs as physical (mechanical) compaction and chemical compaction. The current studied section of Samana Suk Formation also shows both mechanical and chemical compaction.

#### 6.2.4.1 Mechanical compaction

The mechanical or physical compaction starts within a few meters of burial (Shinn & Robbin, 1983). The continuous deposition result to the formation of sediment layers and the layer's development causing overburden thickness. Due to overburden load, the rearrangement, dewatering and crushing of rocks occurs and result into physical compaction. It reduces porosity, permeability, sediments thickness and proceeds to distortion, breakage of grains and constructs compressed fabrics (Flügel, 1982). As a result of overlying deposition, the Samana Suk Formation in Township section has undergone through anomalous shallow to deep burial compaction. The mechanical compaction as a result of stress concentration at grains contact has caused point contacts and sutured contacts between the grains and broken deformed grains (Fig 6.3 A-B). Compaction produced calcite veins deformation and caused breakage of the veins (Fig 6.3 C).

#### 6.2.4.2 Chemical compaction

The chemical compaction is also known as pressure solution phenomena. It starts with overburden or tectonic stresses at different depths. It decreases porosity, permeability and sediments thickness. It is represented by formation of various types of stylolites and other pressure solution seams that form during the deep burial conditions (Carrozi and Bergen, 1987; Flügel, 2004). Chemical compaction is commonly observed phenomena and mostly dominated by stylolites in Samana Suk Formation in the studied area. It is observed in various phases i.e. sutured seams, pressure solution contacts, micro-stylolites and stylolites (Fig 6.4 A-C). Micro-stylolites are mostly filled with pyrite precipitation and cross cut the calcite veins (Fig 6.4 B).

### 6.2.5 Fractures and veins

Fractures are secondary features that are produced through mechanical compaction or developed by regional tectonic regime (Tucker and Wright, 1990). Fractures are common in Samana Suk Formation that is parallel and sub-parallel to bedding planes (Fig 6.5 A). The effects of physical compaction are mostly identified by presence of fractures which later on filled by calcite and known as calcite veins. These micro fractures (calcite veins) are small-large in size, single-multiple and straight to cross cutting (Fig 6.5 B-D). The calcite filled micro fractures are the most common seen digenetic features in the current study and found in all of microfacies, while mostly present in the mudstone microfacies.

### 6.2.6 Dissolution

Carbonate rocks dissolution mostly associated with saturation of pore fluid that result to dissolution of meta-stable carbonate grains and cements i.e. aragonite or high magnesium calcites. The dissolution may occur immediately after the deposition and or afterwards with the uplifting of rock. The majority of the grains have gone through reprecipitation and dissolution in the void spaces. Dissolution is very common secondary processes that produced different types of porosity in Samana Suk Formation of Township section i.e. inter-granular, intragranular, vuggy porosity etc (Fig 6.6 A-C). Dissolution has been identified in various facies of Samana Suk Formation in the studied section (Fig 6.6 B-D). Dissolution of some calcites is also has been observed in different bedding planes (Fig 6.6 D).

### 6.2.7 Cementation

It is a diagenetic process in which precipitation of minerals from fluids into void spaces takes place. The cementation commonly occurs, when diagenetic pore fluids are supersaturated relative to carbonate minerals (Flügel, 2010). It provides a well representative record of diagenetic environment and establishes the paragenetic sequence. Cementation is very common in Jurassic Samana Suk Formation of study area and different types of cements are observed i.e. Blocky cement, Granular mosaic cement, Isopachous Fibrous cement and Syntaxial overgrowth cements. The blocky cement has medium to coarse grained crystals without a specific inclination. This type of cement is consisting of various size crystals and display distinct crystal boundaries. This blocky cementation is mostly associated with peloidal and ooidal microfacies (Fig 6.7 A & D). The granular mosaic cement consists of fine grained pore filling calcite crystals of non-uniform size and without proper orientation. The granular mosaic cement is commonly present in peloidal grainstone microfacies (Fig 6.7 C). The isopachous fibrous cement include fibrous,bladed or microcrystalline calcite crystals that are mostly developed around grains as single or more equant rims (Fig 6.7 B). It mostly forms by consisting marine first generation cements (Wilson et al., 1992). Syntaxial overgrowth cement is characterized by overgrowth of calcite on host grain (Flügel, 2010), which observed mostly in peloidal and as well as in ooidal microfacies of Samana Suk Formation (Fig 6.7 A & C). It is overall less affected by mechanical compaction and it is an indication of early stage of cementation.

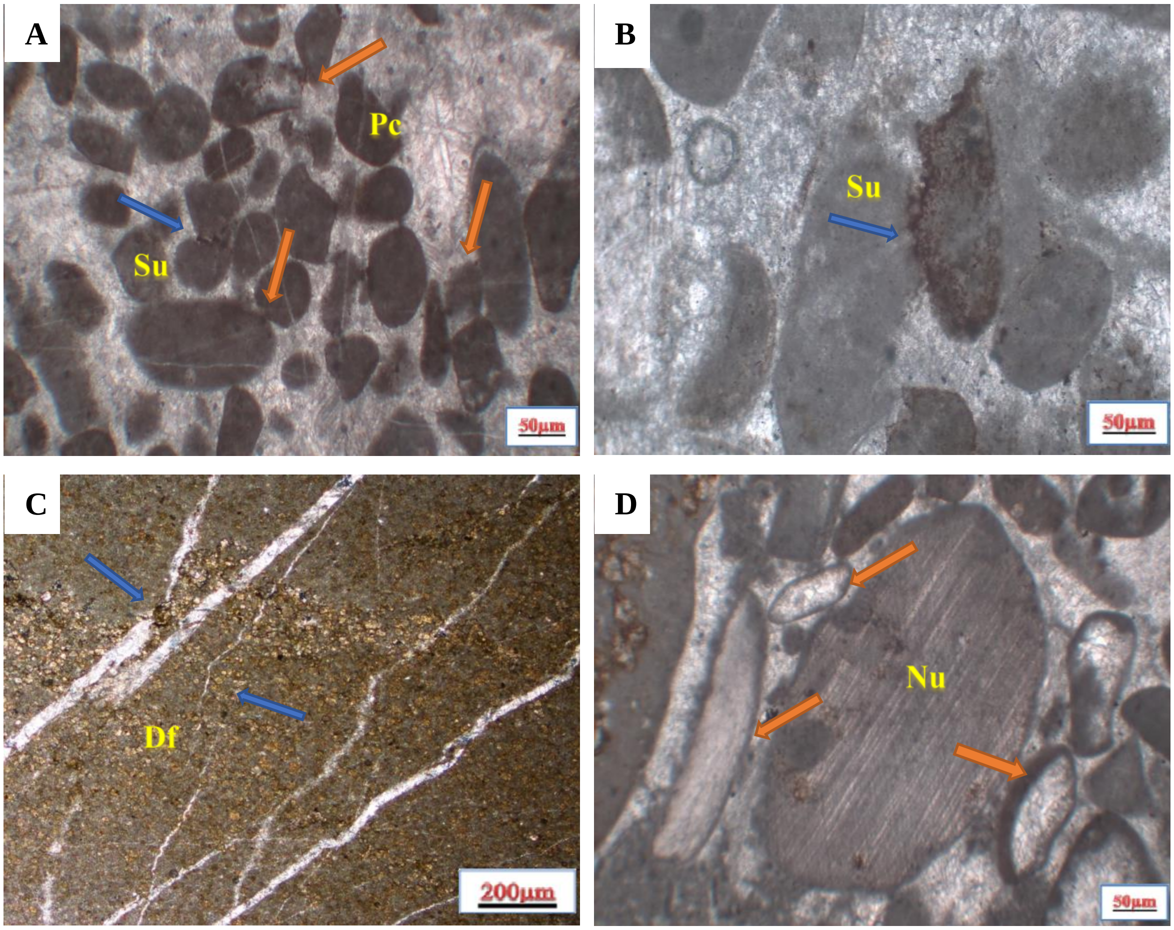


Figure 6.3. Photomicrographs: (**A-B**) representing mechanical compaction by point contact (Pc, red arrow) and suture contact (Su, blue arrow) between the different allochems and the allochems closeness to each other is due to compaction. (**C**) Showing deformation (Df) of calcite veins due to compaction indicated by arrows. Photomicrograph (**D**) representing neomorphism (Nu) by arrows.

### 6.2.8 Dolomitization

Dolomitization is the process in which calcium (Ca) replaces by magnesium (Mg) with in the calcite mineral result to the formation of dolomites. Then the resulted dolomite shows variation in volume and crystalline form from the precursor rock, while their porosity is also affected. As the ionic size of magnesium (Mg) as compare to calcium (Ca)is less, so their mineral volume reduces while the porosity is increases respectively (Weyl, 1960). The rock consists of more than 10% replacement dolomite mineral is known as dolomitization (Folk, 1959). Apart from the replacive nature, dolomite is also occurring in the form of dolomite cement but it occurred rarely while the replacive dolomite has been identified in sufficient amount all over the world. Dolomitization is extensively observed in Sammana Suk Formation of studied section and found in majority ofsamples. It has been occurred in various forms i.e. pervasive dolomitization and selective dolomitization etc. Dolomitization of selective nature is documented in some of microfacies in which the allochems components and primary texture is preserved within the dolomite crystals (Fig 6.8 B). Dolomitization of pervasive nature is a widespread dolomitization phenomenon in which the overall limestones become dolomitized. This type of dolomitization is non-texture selected and most commonly observed in mudstone microfacies (Fig 6.8 A).

### 6.2.9 Pyritization

The mostly sufficient iron sulfide mineral as pyrite is occur in carbonate sediments. Pyrite is an isometric mineral that appears in different forms i.e. cubic, octahedral and pyritohedral while also can be seen as a sphere in the form of small aggregate crystals (Scholle and Umer-Scholle, 2003). Pyritization is common in Sammanasuk Formation in the studied section and appears as dark brown iron oxides. It reduced porosity by filling into micro pores of micrite in the form patches, while precipitated and randomly distributed in mudstone and dolomudstone microfacies (Fig 6.8 C & D).

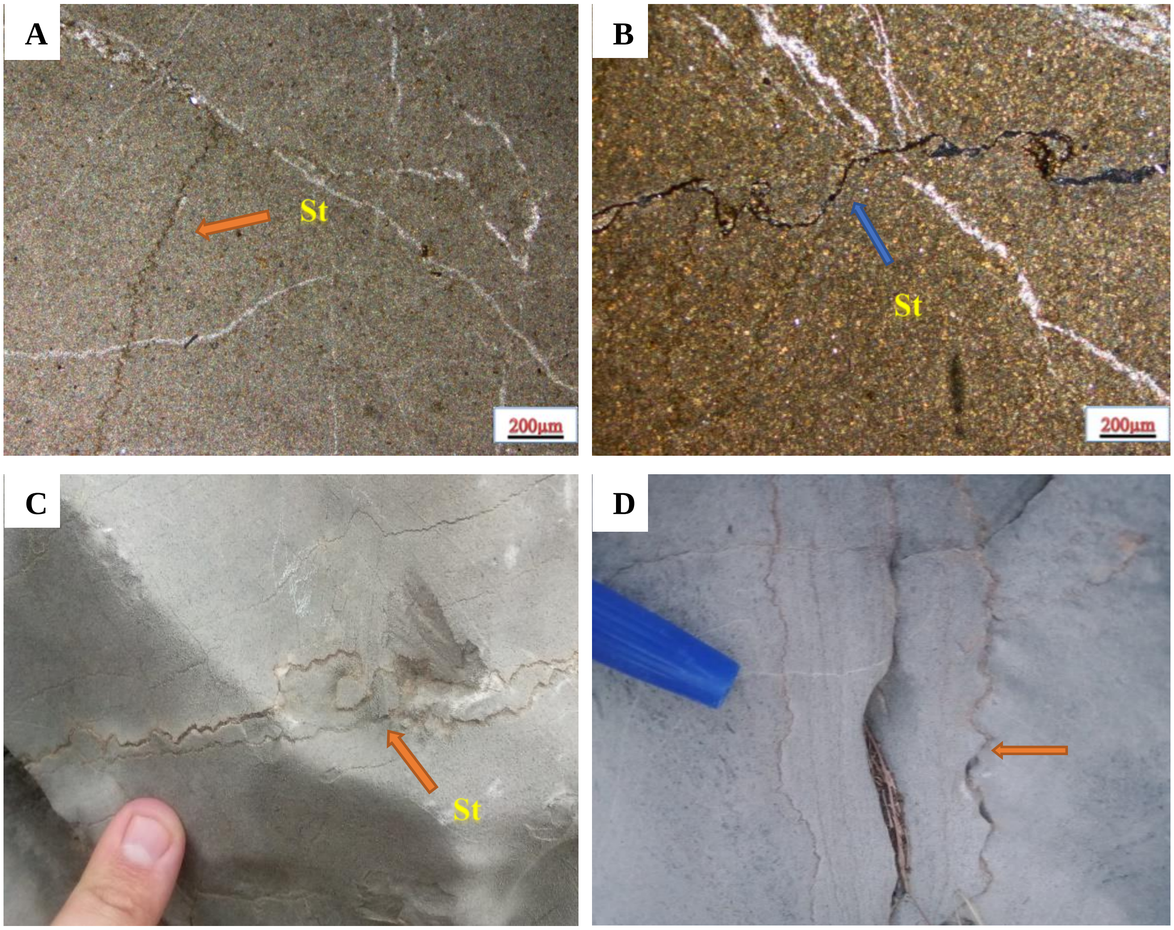


Figure 6.4. Photomicrographs: (**A**) displaying low amplitude stylolite (St) due to chemical compaction, while in (**B**) stylolite filled by pyrite precipitation. Field photographs (**C**) and (**D**) showing stylolites (St) running parallel to each other in the same direction.

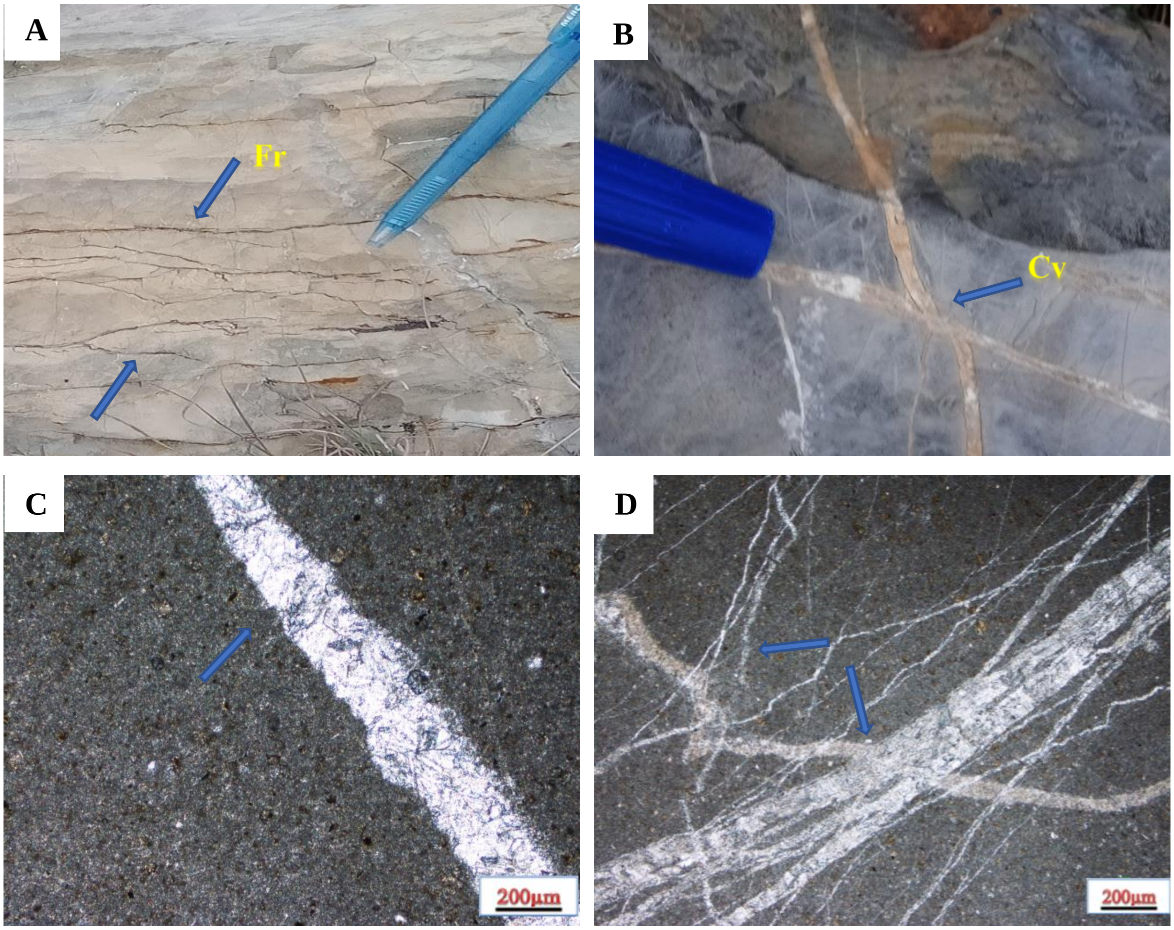


Figure 6.5. Field photographs: (**A**) Fractures (Fr) showing the effects of physical compaction due to stressess within the limestone bed and (**B**) indicating cross cutting fractures filled with calcite as representing calcite veins. Photomicrograph: (**C**) Single calcite filled micro fracture and (**D**) displaying multiple calcite filled micro fractures of small to large size which are cross cutting each other indicated by arrows.

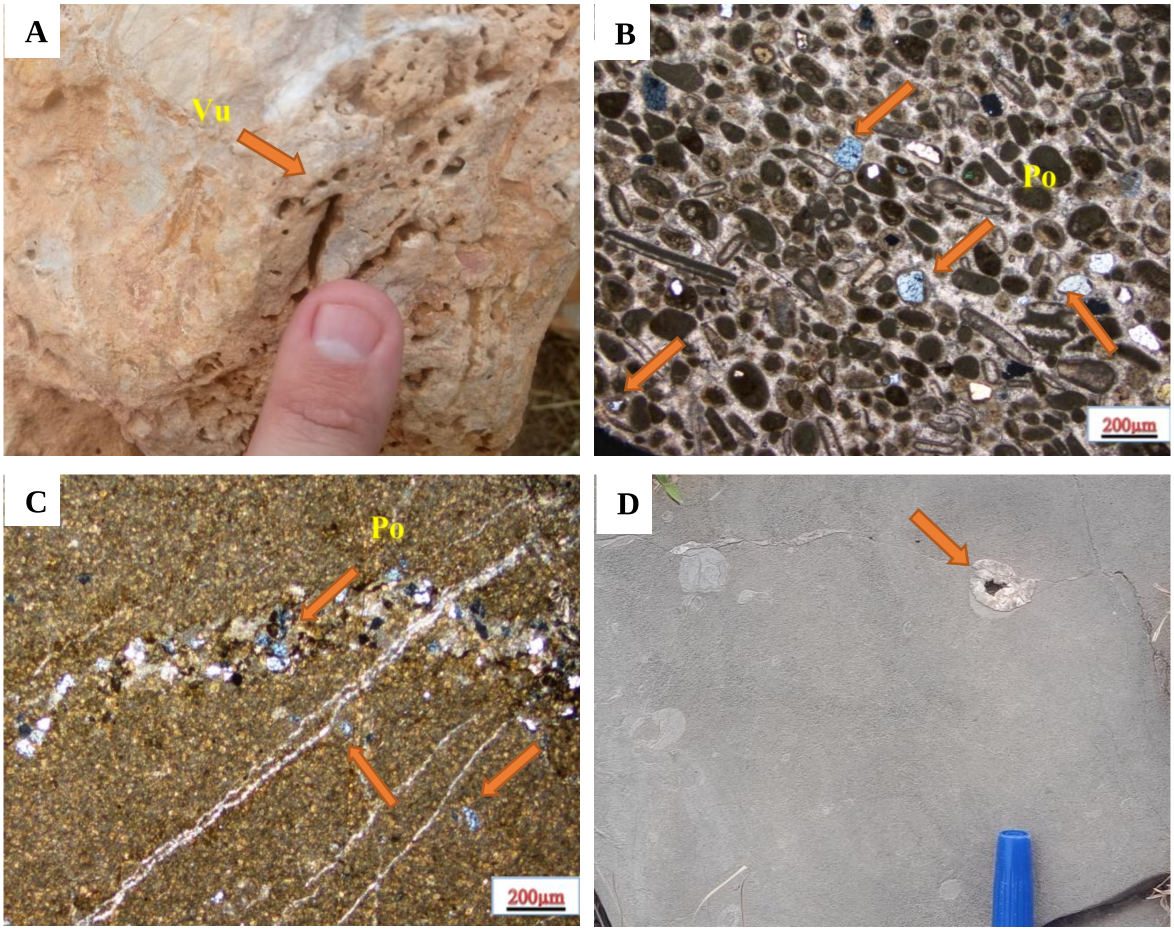


Figure 6.6. Field photograph (**A**) showing vuggy porosity (Vu) created due to dissolution. Photomicrographs (**B**) and (**C**) representing dissolution with intra-granular porosity (blue color) indicated by arrows. Field photograph (**D**) is dissolution within calcite patch indicated by arrow.

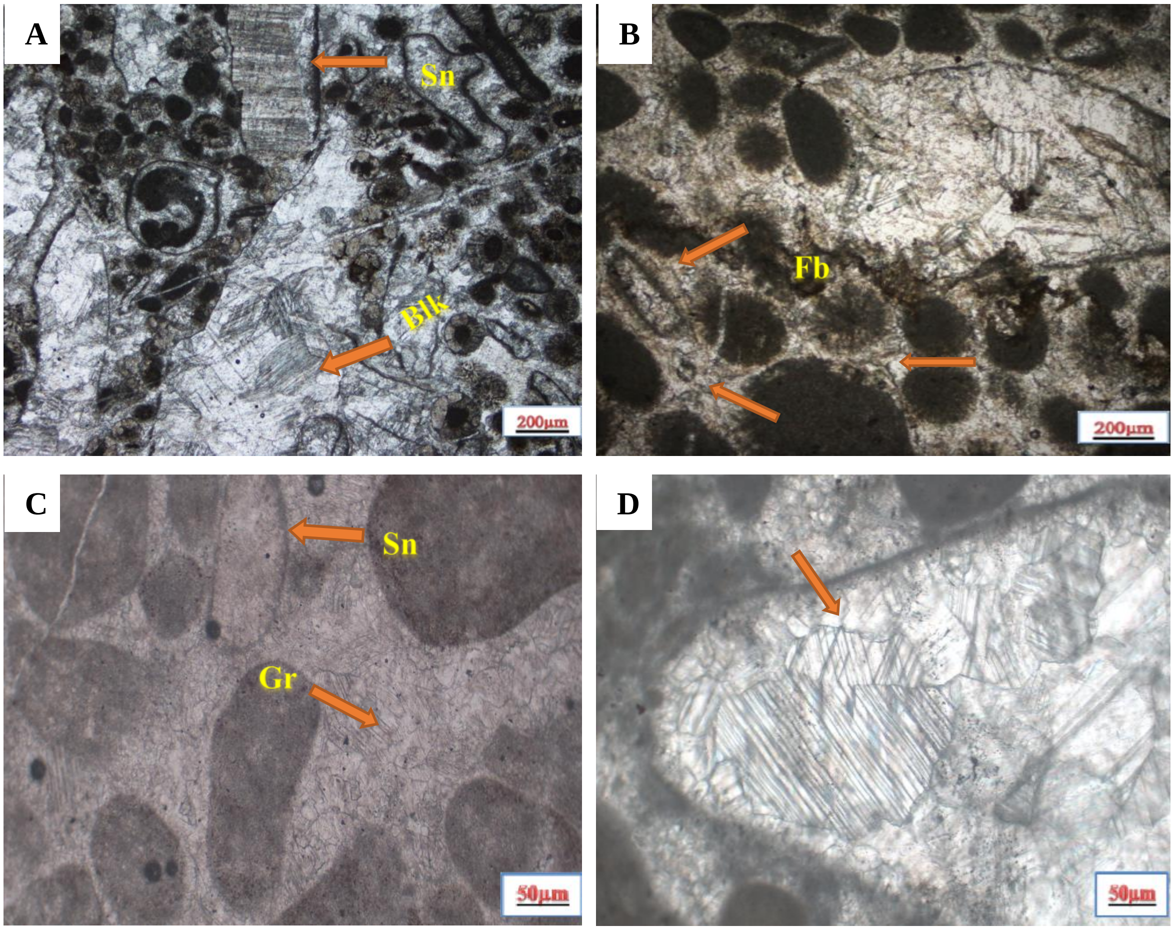


Figure 6.7. Photomicrographs: (**A**) Ooidal grainstone showing syntaxial overgrowth cementation (Sn) and blocky cementation (Blk), while (**B**) displaying isopachous fibrous cements (Fb) around the grains. (**C**) Peloidal grainstone showing granular cementation in the pore spaces between the grains and syntaxial overgrowth (Sn) cements. (**D**) Blocky cementation.

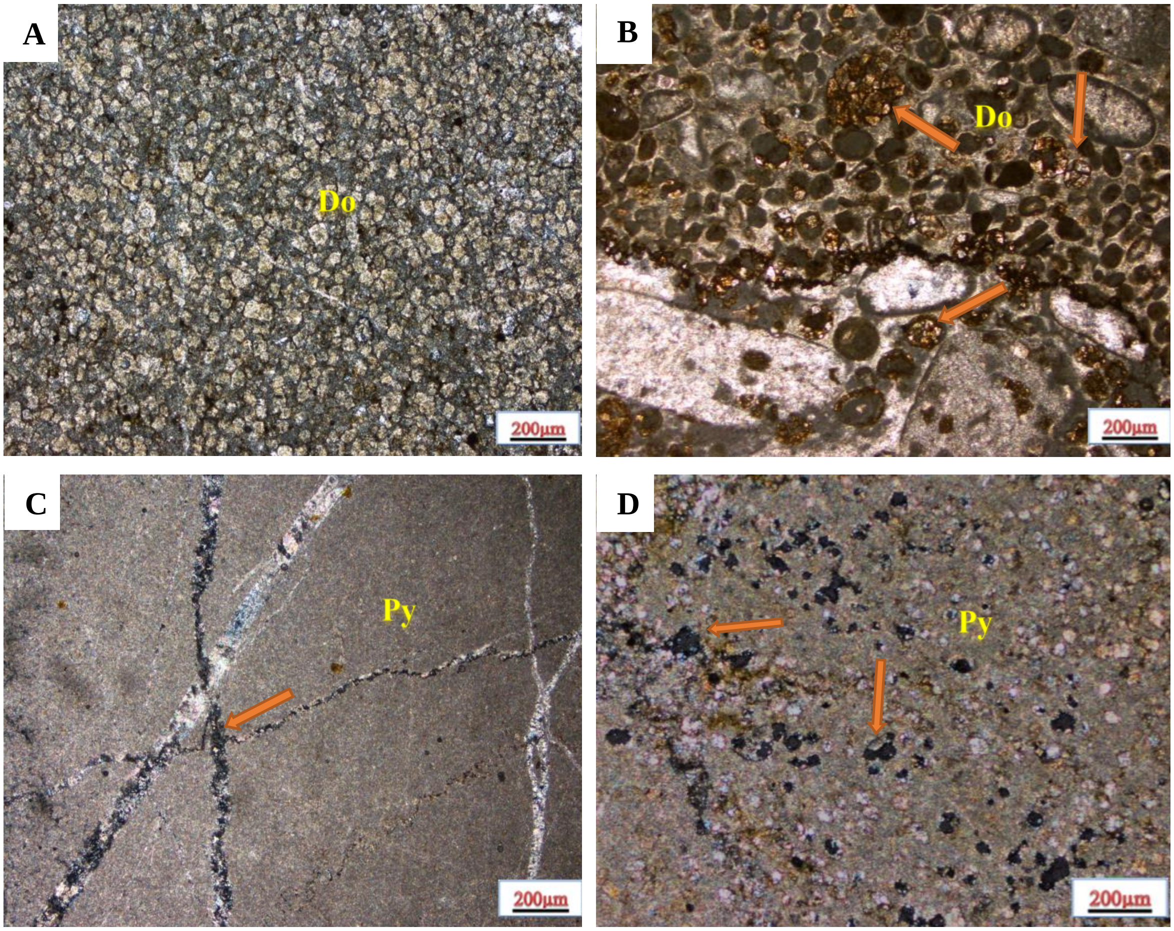


Figure 6.8. Photomicrographs: (**A**) Dolomudstone showing pervasive dolomitization (Do) with euhedral rhombs. (**B**) Peloidal grainstone representing selective dolomitization (Do) indicated by arrows. In mudstones (**C**) pyrite precipation (Py) occurred in the cacitic veins, while in (**D**) the pyrite precipated (Py) mostly within the dolomitc rhombs.

# CHAPTER 7

# DISSCUSSION

In the detailed petrographic studies of Samana Suk Formation at Township section, nine recognized microfacies (MF1-MF9) and other diagenetic characteristics discussed below.

## 7.1 Microfacies (MF1-MF9)

The mudstone (MF1) microfacies is overall homogeneous, non-laminated and having no skeletal grains and predominantly it is a pure mudstone. The diagenetic features include dolomitic crystallization, stylolitization of low amplitude and calcite filled large and small veins. The overall characteristics as absence of skeletal contents, allochemical components, and percentage of allochems relative to the matrix, lamination and the bulk of lime mud as a matrix, presence of pure micrite recognize the low energy environment of deposition in lagoons (inner ramp) for this microfacies. The absence of grains and grain productive organisms likely recognized unfavorable environmental conditions (Nizami, 2008; Hussein et al., 2017; Wilson, 1975; Flügel, 2010). This mudstone microfacies can be compared with standard microfacies SMF-23 of Wilson (1975) and Flügel (2004).

Dolomudstone (MF2) microfacies dominantly consist of widespread dolomitic crystals (well-developed fine to medium sized rhombs) with minor amount of very small quartz crystals and too small peloidal grains. Diagenetic characteristics as extensive dolomitization, multiple calcite filled fractures as veins, microstylolites are present in this microfacies. This microfacies consists of dolomitic mudstone (dolomicrite) and having no fossils contents. The non-existence of fossils contents represents the environmental condition of high salinity and non-favorable environment for survival (Karimi et al., 2015). According to (Wilson, 1975) and (Flügel, 2004) fine to medium grained dolomicrite and non-fossiliferous lime mudstone are deposited in saline and evaporative environment and probably represents deposition on inner ramp. The Dolomudstone microfacies is correlated with SMF-23 of Wilson (1975) and Flügel (2004).

Bioclastic peloidal wackestone (MF3) microfacies consist of peloides, bioclasts and ooides and high portion of matrix. The concentric laminations of ooides and bioclasts are replaced by spars. Diagenetic overprints as ooidal grains and bioclasts micritization, micritic envelopes, rare amount of dolomitic rhombs and calcite veins are present. The principle mud supported grains, low diversity of faunal assemblage and other bioclasts represent that this microfacies was formed in low to moderate energy condition and belongs to shallow subtidal, lagoonal environments (inner ramp) (Cheema, 2010). The abundance of matrix portion, the disarticulated and low concentration of bioclasts is the indications of deposition on the subtidal seafloor under low energy conditions (Sattler et al.,2005). The Bioclastic peloidal wackestone microfacies correspond to standard microfacies SMF-9 of Wilson (1975) and Flügel (2004).

In Peloidal packstone (MF4) microfacies peloides are widely distributed in packstone with rare amount of skeletal grains and ooids, while the rest of the portion is covered by spars and mud as well contains of calcite filled veins. Pores filling between the grains are coveredby calcites and lime mud. As this microfacies represents large amount of peloids with mud shows deposition in calm condition and bioclasts scarcity is because of semi-arid climate and limited circulation result in saline environment in lagoons (Flügel, 2010). The high proportion of peloids with rare bioclastic and skeletal grains represent a restricted subtidal lagoonal environment of inner ramp (ullah Khan et al., 2020). This microfacies can be correlated with described by (ullah Khan et al., 2020) and SMF-16 of Wilson (1975) for lagoonal settings.

Ooidal grainstone (MF5) microfacies dominantly consist of concentric and well rounded, dark and light color striped multi-laminae ooides, with rare amount of peloides and intraclasts. Multiple dolomitic influxes on grains indicate secondary diagenetic event, while the majority of ooides are partially micritized. The pore spaces between the ooidal grains are filled by calcite cementation and calcite veins are also present. The concentric, roundness and sortation of ooidal grains indicating relative high energy condition depositions that are mostly related to shoals and bar environments, which are near to the seaward edge of carbonate platforms (Wilson, 1975; Reolid et al., 2007; Flügel, 2010). The abundance and well sortation of ooids and scarcity of micrite specify a high energy shoal environment above fair weather wave base (FWWB) as inner ramp (Harris, 1979; Hashmie et al., 2016). This microfacies corresponds to standard microfacies SMF-15 C of Wilson (1975) and Flügel (2004).

Bioclastic ooidal grainstone (MF6) microfacie majorly characterized by very well rounded, radial and concentric ooides, and bioclasts in grainstone facie. The remaining grains includepeloides and intraclasts. The ooides are exhibits mostly light colored multi-laminae. The pore spacing between the grains is covered by spars. Diagenetic features as compaction, micritic envelops, neomorphism, intragranular porosity filled by quartz and small calcite veins are existed in this microfacies. The ooids structures indicate deposition by waves and currents of moderate energy through little reworking and high percentage of ooids and bioclasts reflecting that this microfacies is deposited in a barrier shoal environment of shallow water (inner ramp) (ullah Khan, 2021). Elongated peloidal grains and rounded to sub rounded ooides with shell fragments generally recognized restricted lagoon to the back shoal environment of shallow water (Hussein et al., 2017). This microfacies is comparable with RMF-27 of Wilson (1975) and Flügel (2010).

Peloidal grainstone (MF7) microfacies incorporate majorly of well sorted and randomly oriented peloides, with rare bioclasts and ooidal grains as a minor component. The peloidal grains are cemented through granular calcite cement and blocky cements. The high percentage of well-sorted peloidal grains, with few ooids indicate high energy conditions, while peloids are indicated by the low circulation of warm water at shallow depth in shoal depositional environment of inner ramp (Scholle & Umer-Scholle, 2003; Jank et al., 2006). The shoal environment represents minimal association of mud low tidal and relative high wave energy (Lasemi et al., 2012). This microfacies corresponds to standard microfacies SMF-16 of Wilson (1975).

Bioclastic intraclastic grainstone (MF8) microfacies largely comprised of probably sorted intraclasts with bioclasts fragments. Diagenetic processes include compaction, neomorphism, micritic envelops and selective dolomitization (dolomite rhombs) within the intraclasts are present. The profusion of sorted, coarse and very coarse grain size intraclasts reflecting that this microfacies deposited in high energy wave dominated condition, shallow subtidal to intertidal on shoal/bars (Cheema, 2010). The presence of various bioclastic fragments indicate landward portion of the ramp setting (Wilson, 1975; Flügel, 2004). Based on these observations, this microfacies could be formed in the inner ramp shoals and carbonate dominant. This microfacie is corresponds to SMF-17 of Wilson (1975) and Flügel (2004).

Intraclastic bioclastic peloidal grainstone (MF9) microfacies is widespread consist of peloides, intraclasts, bioclasts i.e. taxtularia etc and minor amount of ooidal grains. Aggregate of peloidal grains are cemented by micrite as lumps and influence of micritization are also present. The abundance of peloides and intraclasts suggests moderate to high energy and shallow subtidal to intertidal, shoal/bar environments (Cheema, 2010). The presence of various bioclastic fragments indicate landward portion of the ramp setting (Wilson, 1975; Flügel, 2004). Based on these observations, this microfacies could beformed in the inner ramp shoals and carbonate dominant. This microfacies can be correlated with standard microfacie SMF-16 and 17 of Wilson (1975) and Flügel (2004).

The lithological variations of the identified microfacies at different intervals to their depositional environments are given in Figure (7.1).

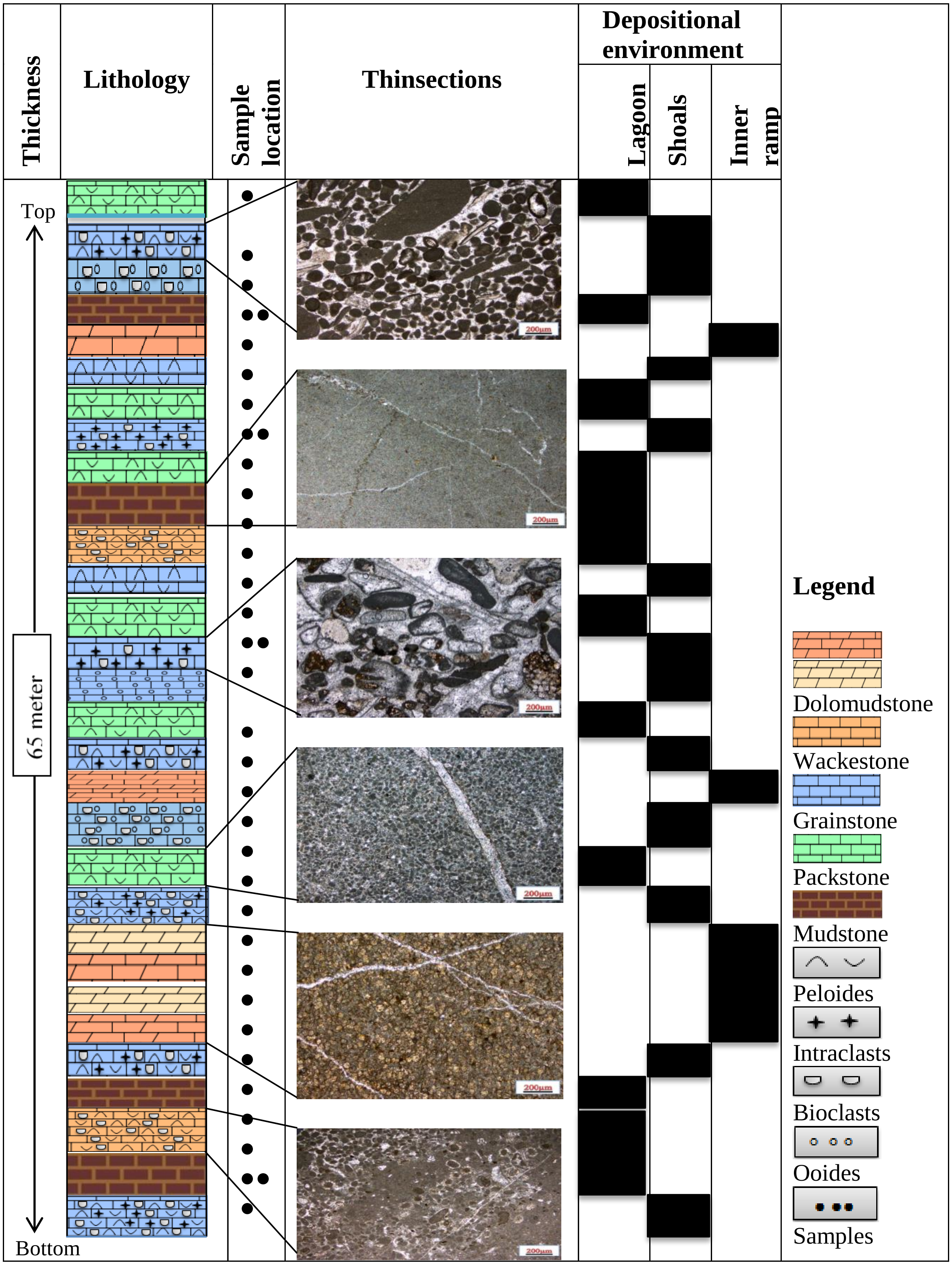
Thickness
Lithology
Sample location
Thinsections
Depositional environment
Lagoon
Shoals
Inner ramp
Top
65 meter
Bottom
200µm
Legend
Dolomudstone
Wackestone
Grainstone
Packstone
Mudstone
Peloides
Intraclasts
Bioclasts
Ooides
Samples

Figure 7.1. Detailed log of Samana Suk Formation showing lithology, photomicrographs of microfacies at various intervals and depositional environment in the Township section.

## 7.2 Depositional Environment

The substantial amount of skeletal grains and non-skeletal grains are generally used for the interpretation of depositional environment. Under petrographic studies 9 different types of microfacies (MF1-MF9) are identified which are characterized by different skeletal and non-skeletal components, petrographic features and other depositional textures. The relative proportion and abundance of the skeletal and non-skeletal grains, and base on lithology, the microfacies reveal mostly association with lagoons and carbonate shoals environments. The detailed investigations of the Samana Suk Formation provided us an idea of ramp type platform deposition as comprises of inner, mid and outer ramp. The inner ramp dominated by lagoonal facies and shoal facies. The lagoonal microfacies including MF1, MF3 and MF4 characterized by low energy and restricted circulation, and MF2 is directly belongs to inner ramp while the microfacies MF5-MF9 of the shoal environment are dominated by moderate to high energy environment. The microfacies of lagoonal environment have mostly non-laminated, unfossiliferous, homogeneous, and has an abundance of non-skeletal fragments, with low diversity of biota. The shoal environment microfacies are mostly represented by abundance of non-skeletal components as ooides, peloides and intraclasts with considerable amount of bioclasts.

The carbonate shoal microfacies reveal the dominancy in Samana Suk Formation in the type locality which are characterized of more than 50% of the total rock, followed by lagoonal microfacies (Fig 7.2). These microfacies of different environmental perspectives are separated from each other and interspersed throughout the stratigraphic thickness of the unit. These kinds of distribution of microfacies are recorded in the various units of Samana Suk Formation in the Upper Indus Basin (Saboor et al., 2020; ullah Khan et al., 2020, Ahmad et al., 2020). The non-existence of the Samana Suk Formation microfacies in the Eastern and Central Potwar, and its lower concentration nature in the western Salt Range, and then its expanded their thicknesses in the Hazara region represented that the shoreline of the ramp was located in northeast-southwest direction basin was deepening to the north and west in the region (Saboor et al., 2020).

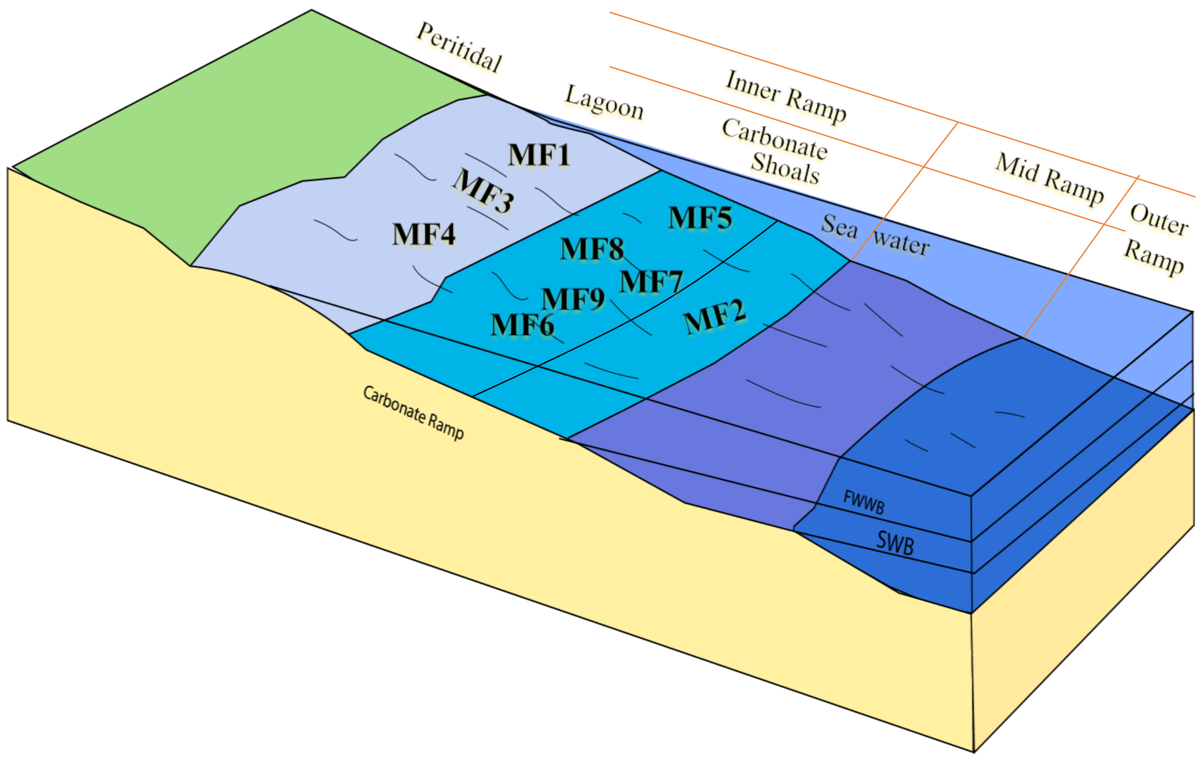


Figure 7.2. Depositional model for Jurassic Samana Suk Formation. FWWB (Fair weather wave base, SWB (Strom wave base).

## 7.3 Paragenetic Sequence of Samana Suk Formation in the study area

The extensive micritization in the Samana Suk Formation altered the primary depositional textures and suggest that the carbonates underwent marine phreatic environment at early stage of diagenesis. The reworking of organism i.e. burrows effected the limestone beds in low energy marine phreatic environment at early stage diagenesis in the Formation. Furthermore, early mechanical and chemical compaction as well as various types of cements i.e. syntaxial overgrowth calcites and isopachous fibrous cements represents the other marine diagenetic events, while neomorphism and blocky calcite cements in most of the samples indicating diagenesis in meteoric phreatic environment of early to late stage diagenesis (ullah Khan et al., 2020). Due to overburden, the mechanical and chemical compaction starts at shallow and deep burial at late stage of diagenesis. The mechanical compaction caused micro and macro fractures due to overburden load of strata and tectonic stresses. Similarly, the chemical compaction occurred due to overstrain load and causing fluids squeezed out resulted in the development of sutured seams, microstylolites and stylolites. The second generation cementation during diagenesis of the sediments includes blocky and granular mosaic cements, filling the inter-granular and intra-granular spaces (Flügel, 2010).

The dissolution phase shows meteoric phreatic environment and as well as the inflow of freshwater produced the dissolution of carbonate grains in shallow to deep burial of late stage diagenesis. Pyrite crystals in the form of patches as well as in dispersed form and dolomitization occur as a result of Mg-rich fluids through fractures indicating deep burial late stage diagenesis. The multiple fracturing and dolomite cementation phases in fractures and pore spaces represent the late stage of diagenesis (Fig 7.3). These fractures filled with calcite as calcite veins are more evident for late stage deep burial diagenesis (ullah Khan et al., 2020).

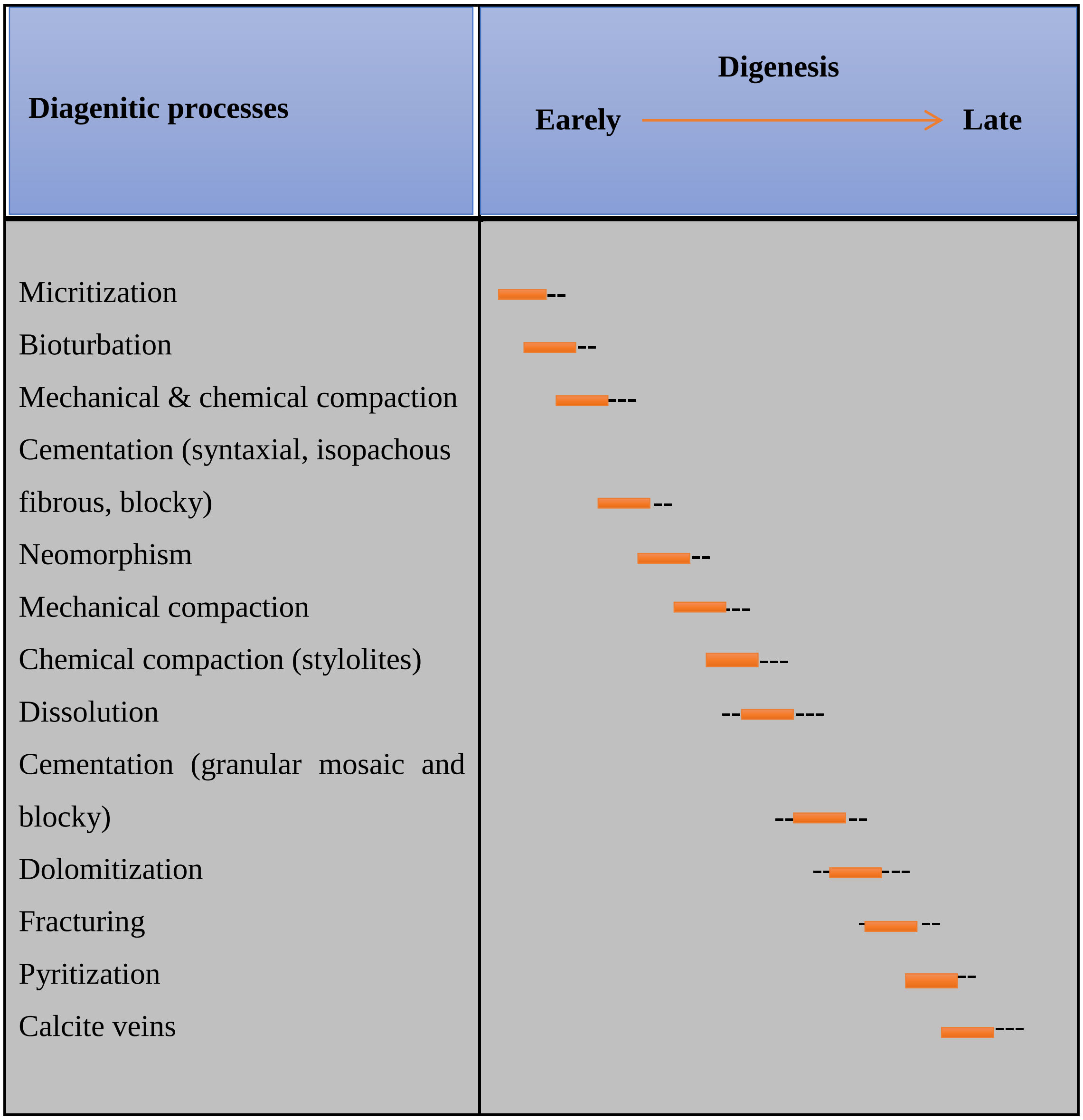


Figure 7.3. Proposed paragenetic sequence of Samana Suk Formation at Township section.

# CONCLUSIONS

- In the Samana Suk Formation the microfacies analyses were conducted based on field observations, grain composition, estimation of allochems and their types, sedimentary features and the fossil content in selected thin-sections resulting in the identification of nine different types of microfacies (MF1-MF9).
- The interpretations of these different types of microfacies suggested that Samana Suk Formation in the study area was deposited in different depositional settings which include lagoon and carbonate shoals that are developed on the inner part of a homoclinal carbonate ramp environment.
- The lagoonal carbonate comprises of mudstone, wackestone and packstone, while dolomudstone is directly belongs to inner ramp. The carbonate shoals are characterized by grainstone microfacies. Carbonate shoals facies represented dominancy which are more than 50% of the total rock, followed by lagoonal facies.
- The lithological log representing variations in lithology of microfacies from bottom to top across the thickness of outcrop.
- The diagenesis of Samana Suk Formation in the Township section was represented by using basic petrography complemented with outcrop data. Diagenetic processes include micritization, bioturbation, neomorphism, compaction, fractures and veins, cementation, dissolution and dolomitization.
- The diagenetic processes suggested that Samana Suk Formation was exposed to marine, meteoric and burial diagenetic settings.
- Based on various diagenetic features a detailed paragenetic sequence has been established for the Jurassic Samana Suk Formation. The early stage of diagenesis that extensively altered the primary depositional structures include

micritization, formation of the micritic envelopes, bioturbation i.e. burrows effected the limestone beds in low energy marine phreatic environment. Other marine diagenetic processes include early mechanical and chemical compactions followed by the cementation of sediments by syntaxial, isopachous fibrous calcite cement are indicative of early stage diagenesis in the Formation. Similarly, neomorphism and blocky calcite cements in most of the samples represented diagenesis in meteoric phreatic environment of early to late stage diagenesis.

- The mechanical and chemical compaction started due to overburden at shallow and deep burial in the late stage of diagenesis. The mechanical compaction caused micro and macro fractures, while chemical compaction caused fluids squeezed out resulted in the development of sutured seams, microstylolites and stylolites. Blocky and granular mosaic cements, filled the inter-granular and intra-granular spaces during the second generation of cementation of the sediments at late stage of diagenesis.
- The dissolution phase shows meteoric phreatic environment in shallow to deep burial of late stage diagenesis. Dolomitization occur as a result of Mg-rich fluids and pyrite crystals in the form of patches as well as in dispersed form indicated deep burial late stage diagenesis. Similarly, the multiple fracturing and dolomite cementation phases in fractures and pore spaces, fractures filled with calcite as calcite veins represented the late stage deep burial diagenesis.

## REFERENCES

Afridi, B. A., Saleem, A., Kibriya, G., Anwar, A., Khan, B. (2010). Microfacies analysis and diagenetic fabric of the Jurassic Samana Suk Formation along Abbottabad-Nathiagali road section, Hazara, Pakistan.

Ahmad, S., Wadood, B., Khan, S., Ahmed, S., Ali, F., & Saboor, A. (2020). Integrating the paleo-stratigraphy, petrography, X-ray diffraction and scanning electron microscopy data for evaluating hydrocarbon reservoir potential of Jurassic rocks in the Kala Chitta Range, Northwest Pakistan. Journal of Petroleum Exploration and Production Technology, 10(8), 3111-3123.

Ahsan, N., Ahmed, N., Nadeem, M., & Chaudhry, M. N. (1998). Sedimentological Studies of Chorgali Formation at Chahla Bandi on the western limb of Hazara Kashmir Syntaxial region in Azad Jammu and Kashmir. Pak. Jour. Geol, 8, 18-28.

Ahsan, N., Chaudhry, M. N., (2008). Geology of Hettangian to Middle Eocene rocks of Hazara and Kashmir Basins, northwest Lesser Himalayas, Pakistan. Geol. Bull. Punjab University, 43, 131-151.

Álvaro, J. J., Monceret, E., Monceret, S., Verraes, G., & Vizcaïno, D. (2010). Stratigraphic record and Paleogeographic context of the Cambrian Epoch 2 subtropical carbonate platforms and their basinal counterparts in SW Europe, West Gondwana. Bulletin of Geosciences, 85(4), 573-584.

Bandyopadhyay, S., Chatterjee, S., & Scotese, C. (2010). The wandering Indian plate and its changing biogeography during the Late Cretaceous-Early Tertiary period. New aspects of Mesozoic biodiversity, 105-126.

Bender, F. K., and Raza, M.R. (1995). Geology of Pakistan: Berlin, Germany, Tutte

Druckerei GmbH, 355p.

Blakey, R. C., Fielding, C. R., Frank, T. D., & Isbell, J. L. (2008). Gondwana paleogeography from assembly to breakup-A 500 my odyssey. Geological Society of America Special Papers, 441, 1-28.

Bossart, P., Chaudhry, M. N., Dietrich, D., Ghazanfar, M., Greco, A., Meir, A., & Wahrenberger, C. H. (1992). A review of the geology of the Northern Indian Plate, Kaghan Valley, NE Pakistan. In 7th Himalaya-Karakoram-Tibet Workshop, Abstracts, Oxford, England (Vol. 6).

Butt, A. (1989). An overview of the Hazara arc stratigraphy, northern Pakistan. Geol. Bull. Punjab Univ., 24, 1-11.

Buxton, M. W. N., Pedley, H. M. (1989). Short paper: a standardized model for Tethyan Tertiary carbonates ramps. Journal of the Geological Society, 146(5), 746-748.

Calkins, J. A., Tw, O., & Skm, A. (1975). Geology of The Southern Himalaya in Hazara, Pakistan and Adjacent Areas.

Carrozi, A. V., & Bergen, D. V. (1987). Stylolitic porosity in carbonates: a critical factor for deep hydrocarbon production. Journal of Petroleum Geology, 10(3), 267-282.

Chatterjee, S. (1992). A kinematic model for the evolution of the Indian plate since the Late Jurassic. New concepts in global tectonics, 33, 62.

Chatterjee, S., & Scotese, C. R. (1999). The breakup of Gondwana and the evolution and Biogeography of the Indian plate: Proceedings of the Indian National Science Academy, v. 65A.

Chatterjee, S., Goswami, A., Scotese, C. R. (2013). The longest voyage: Tectonic, magmatic, and paleo-climatic evolution of the Indian plate during its northward flight from Gondwana to Asia. Gondwana Research, 23(1), 238-267.

Chaudhry, M. N., Ghazanfar, M., Ahsan, N., & Masood, K. R. (1998). Age, Stratigraphic Position and Provenance of Murree Formation of North West Sub-Himalayas of Pakistan and Azad Kashmir. In Third Geosas Workshop on Siwalik GSP, Islamabad. Bull. Geol. Surv. Pak (pp. 81-91).

Cheema, A. H. (2010). Microfacies, diagenesis and depositional environments of Samana Suk Formation (middle Jurassic) Carbonates exposed in South East Hazara and Samana range. Ph.D. Thesis. University of the Punjab.

Coward, M. P., & Butler, R. W. H. (1985). Thrust tectonics and the deep structure of the Pakistan Himalaya. Geology, 13(6), 417-420.

Coward, M. P., Butler, R. W. H., Chambers, A. F., Graham, R. H., Izatt, C. N., Khan, M. A., & Williams, M. P. (1988). Folding and Imbrication of the Indian Crust during Himalayan Collision. Philosophical Transactions of the Royal Society of London Series A, 326(1589), 89 115.

Coward, M. P., Rex, D. C., Asif Khan, M., Windley, B. F., Broughton, R. D., Luff, I. W., & Pudsey, C. J. (1986). Collision tectonics in the NW Himalayas. Geological Society, London, Special Publications, 19(1), 203-219.

Croizé, D., Bjørlykke, K., Jahren, J., & Renard, F. (2010). Experimental mechanical and chemical compaction of carbonate sand. Journal of Geophysical Research: Solid Earth, 115(B11).

Davies, L. M. (1930). The fossil fauna of the Samana Range and some neighbouring areas. Part I: An Introductory Note, Geol. Survey India, Mem. Palaeont., NS, 15,

Dunham, R.J. (1962). Classification of carbonate rocks according to depositional textures.

Dietz, R. S., & Holden, J. C. (1970). The breakup of Pangaea. Scientific American, 223(4), 30 41.

Embry, A. F., & Klovan, J. E. (1971). A late Devonian reef tract on northeastern Banks Island, NWT. Bulletin of Canadian petroleum geology, 19(4), 730-781.

Fatmi, A. N. (1974). Lithostratigraphic units of the Kohat-Potwar province, Indus basin, Pakistan. Mem. Geol. Surv. Pakistan, 10, 1-80.

Fatmi, A. N., Hyderi, I., & Anwar, M. (1990). Occurrence of the Lower Jurassic Ammonoid genus Bouleiceras from the surghar range with a revised nomenclature of the Mesozoic Rocks of the Salt Range and Trans Indus Ranges (Upper Indus Basin). Geol. Bull. Punjab Univ, 25, 38-46.

Flügel, E., & Munnecke, A. (2010). Microfacies of carbonate rocks: analysis, interpretation and application (Vol. 976, p. 2004). Berlin: springer.

Flugel, E., 1982. Microfacies analysis of Limestone. Springer-Verlag, Berlin 442-445 pp.

Folk, R. L. (1959). Practical petrographic classification of limestones. AAPG bulletin, 43(1), 1-38.

Ghazanfar, M. (1993). Petro-tectonic elements and tectonic framework of northwest Himalaya. Ph.D. Thesis. University of Punjab.

Ghazanfar, M., Chaudhry, M. N., & Latif, M. A. (1987). Three stratigraphic provinces at Hazara- Kashmir Boundary, Pakistan. Kashmir Jour. Geol, 5, 65-74.

Ghazanfar, M., Chaudry, M. N., Pervaiz, K., Qayyum, M., & Ahmed, R. (1990). Geology and structure of Kuza-Dunga Gali-Ayubia area, Hazara-Potwar Basin with reference to hydrocarbon prospects of Attock Hazara Fold and thrust belt. Pakistan Journal of Hydrocarbon Research, 2(2), 43-55.

Harris, P. M. (1979). Facies anatomy and diagenesis of a Bahamian ooidal shoal (Vol. 7). Comparative Sedimentology Laboratory, Division of Marine Geology and Geophysics, University of Miami, Rosenstiel School of Marine & Atmospheric Science.

Hashmie, A., Rostamnejad, A., Nikbakht, F., Ghorbanie, M., Rezaie, P., & Gholamalian, H. (2016). Depositional environments and sequence stratigraphy of the Bahram Formation (middle–late Devonian) in north of Kerman, south-central Iran. Geoscience Frontiers, 7(5), 821-834.

Hussain, H. S., Fayaz, M., Haneef, M., Hanif, M., Jan, I. U., & Gul, B. (2013). Microfacies and diagenetic-fabric of the Samana Suk Formation at Harnoi Section, Abbottabad, Khyber Pakhtunkhwa, Pakistan. Journal of Himalayan Earth Sciences, 46(2), 79.

Hussein, D., Collier, R., Lawrence, J. A., Rashid, F., Glover, P. W. J., Lorinczi, P., & Baban, D. H. (2017). Stratigraphic correlation and paleo-environmental analysis of the hydrocarbon-bearing Early Miocene Euphrates and Jeribe formations in the Zagros folded-thrust belt. Arabian Journal of Geosciences, 10, 1-15.

Hussein, D., Collier, R., Lawrence, J. A., Rashid, F., Glover, P. W. J., Lorinczi, P., & Baban, D. H. (2017). Stratigraphic correlation and paleo-environmental analysis of the hydrocarbon bearing Early Miocene Euphrates and Jeribe formations in the Zagros folded-thrust belt. Arabian Journal of Geosciences, 10, 1-15.

Johnson, B. D., Powell, C. M., & Veevers, J. J. (1976). Spreading history of the eastern Indian Ocean and Greater India's northward flight from Antarctica and Australia. Geological Society of America Bulletin, 87(11), 1560-1566.

Karimi, H., Ghadimvand, N.K. and Kangazian, A. (2015). Sedimentary environment and Sequence stratigraphy of the Kangan formation in Kish gas field (Kish Well A1 Subsurface Section). Indian Journal of Science and Technology, 8(7), p.655.

Kazmi, A. H., & Jan, M. Q. (1997). Geology and tectonics of Pakistan. Karachi (Pakistan).

Kazmi, A. H., and Rana, R. A., (1982). Tectonic Map of Pakistan, 1: 1,000,000. Geological Survey of Pakistan Quetta, Pakistan.

Kazmi, A.H. and Jan, M.Q. (1997). Geology and tectonics of Pakistan. Graphic publishers.

Khan, E. U., Saleem, M., Naseem, A. A., Ahmad, W., Yaseen, M., & Khan, T. U. (2020). Microfacies analysis, diagenetic overprints, geochemistry, and reservoir quality of the Jurassic Samanasuk Formation at the Kahi Section, Nizampur Basin, NW Himalayas, Pakistan. Carbonates and Evaporites, 35, 1-17.

Khan, E. U. (2021). Unravelling the Depositional & Diagenetic Controls on Jurassic Samanasuk Formation along the MBT in Kohat and Attock-Cherat Ranges, NW Himalayas, Pakistan. Ph. D. Thesis, Quaid-e-Azam University, Islamabad.

Khan, S., Ahmad, S., Hanif, M., Jan, I. U., Swati, M. A. F., Khan, S., & Saboor, A. (2014). Lithofacies, paleo environments and sequence stratigraphic modelling of the Wargal Limestone: Implication for reservoir characterization in the Salt Range, northwest, Pakistan. Journal of Himalayan Earth Sciences, 47(1), 41.

Khan, Z. A., & Tewari, R. C. (2016). The concept of Gondwanaland and Pangaea: a reappraisal. Jour. Applied Geology and Geophysics, 4, 44-56.

Koehrer, B. S., Heymann, C., Prousa, F., & Aigner, T. (2010). Multiple-scale facies and reservoir quality variations within a dolomite body–outcrop analog study from the

Lapponi, F., Bechstaedt, T., Boni, M., Banks, D. A., & Schneider, J. (2014). Hydrothermal dolomitization in a complex geodynamic setting (Lower Palaeozoic, northern Spain). Sedimentology, 61(2), 411-443.

Lasemi, Y., Jahani, D., Amin-Rasouli, H., & Lasemi, Z. (2012). Ancient carbonate tidalites. Principles of tidal sedimentology, 567-607.

Latif, M. A. (1970). Explanatory notes on the geology of Southeastern Hazara, to accompany the revised geological map: Austria Geolgie, Bundesanstalt, Sonderban, v. 15, p. 5-20.

LeFort, P. (1975). Himalayas: the collided range. Present knowledge of the continental arc. American Journal of Science, 275(1), pp.1-44.

Lillie, R. J., Johnson, G. D., Yousuf, M., Zamin, A. S. H., & Yeats, R. S. (1987). Structural development Within the Himalayan Foreland Fold-And-Thrust Belt of Pakistan. Canadian Society of Petroleum Geologists, Memoir, 12, 379-392.

Lloyd, R. M. (1977). Porosity reduction by chemical compaction-stable-isotope model.

Machel, H. G. (2005). Investigations of burial diagenesis in carbonate hydrocarbon reservoir rocks. Geoscience Canada, 32(3), 103-128.

Martín-Martín, J. D., Gomez-Rivas, E., Bover-Arnal, T., Travé, A., Salas, R., Moreno-Bedmar, J. A., & Stafford, S. L. (2013). The Upper Aptian to Lower Albian syn-rift carbonate succession of the southern Maestrat Basin (Spain): Facies architecture and fault-controlled strata bound dolostone. Cretaceous Research, 41, 217-236.

Masood, H. (1989). Samana Suk Formation depositional and diagenetic history. Kashmir Journal of Geology, 6, 151-161.

Mensink, V.H., Mertmann, D., Bochum, D., Ahmad, S. (1988). Facies development during the Jurassic of the Trans Indus Ranges, Pakistan, Neues. Jahrb. Geological Paleontological memorial, Germany, 3, Pp. 153- 166.

Middlemiss, C. S. (1896). The geology of Hazara and the Black Mountain (Vol. 26). Geological Survey. Indian Geological Survey Memoir, 26, Pp. 1-302.

Moore, C. H., & Wade, W. J. (2013). Carbonate reservoirs: Porosity and diagenesis in a sequence stratigraphic framework. Newnes. Middle Triassic, SW German Basin. Marine and Petroleum Geology, 27(2), 386-411.

Muni, C., Chaudhry, M. N., Pervaiz, K., Qayyum, M., & Ahmed, R. (1990). Geology and structure of Kuza Gali-Dunga Gali-Ayubia area, Hazara-Potwar basin with a reference to hydrocarbon prospects of Attock-Hazara fold and thrust belt. Pakistan Journal of Hydrocarbon Research, 2(2), 43-55.

Nichols, G. (2009). Sedimentology and stratigraphy. John Wiley & Sons.

NIZAMI, A. R. (2008). Sedimentology of the middle Jurassic Samana Suk Formation in Trans Indus Ranges Pakistan (Doctoral dissertation, University of Punjab, Lahore).

Nizami, A. R. (2009). Microfacies analysis and diagenetic settings of the middle Jurassic Samana Suk Formation, Sheikh Badin Hill section, trans Indus Ranges-Pakistan. Geol. Bull. Punjab Univ, 44, 69-84.

Qureshi, M. K. A., Butt, A. A., & Ghazi, S. (2008). Shallow shelf sedimentation of the Jurassic Samana Suk Limestone, Kala Chitta Range, Lesser Himalayas, Pakistan. Geological Bulletin Punjab University, 43, 1-14.

Rahim, Y., Lia, Q., Jadoona, U. F., Lutfia, W., Khanb, J., & Akhtarc, S. (2020). Microfacies analysis of late Jurassic Samana Suk formation, Hazara basin lesser Himalaya north Pakistan. Earth Sciences Malaysia (ESMY), 4(2), 102-107.

Reolid, M., Gaillard, C., & Lathuilière, B. (2007). Microfacies, microtaphonomic traits and foraminiferal assemblages from Upper Jurassic oolitic–coral limestones: stratigraphic fluctuations in a shallowing-upward sequence (French Jura, Middle Oxfordian). Facies, 53, 553-574.

Rogers, J. J., & Santosh, M. (2004). Continents and supercontinents. Oxford University Press.

Rosales, I., Pomar, L., & Al-Awwad, S. F. (2018). Microfacies, diagenesis and oil emplacement of the Upper Jurassic Arab-D carbonate reservoir in an oil field in central Saudi Arabia (Khurais Complex). Marine and Petroleum Geology, 96, 551-576.

Saboor, A., Haneef, M., Hanif, M., & Swati, M. A. F. (2020). Sedimentological attributes of the Middle Jurassic peloids-dominated carbonates of eastern Tethys, lesser Himalayas, Pakistan. Carbonates and Evaporites, 35, 1-17.

Sattler, U. T. E., Immenhauser, A., HILLGÄRTNER, H., & Esteban, M. (2005). Characterization, lateral variability and lateral extent of discontinuity surfaces on a carbonate platform (Barremian to Lower Aptian, Oman). Sedimentology, 52(2), 339-361.

Schnellmann, M., Gnehm, F. (1999). A structural analysis of the NW Himalayan folds and thrust belt in Hazara, Pakistan. Unpublished Diploma thesis, Institute of Geology, ETH Zurich.

Scholle, P. A., & Ulmer-Scholle, D. S. (2003). A color guide to the petrography of carbonate rocks: grains, textures, porosity, diagenesis, AAPG Memoir 77 (Vol. 77). AAPG.

Scholle, P. A., Bebout, D. G., & Moore, C. H. (Eds.). (1983). Carbonate depositional environments: AAPG Memoir 33 (No. 33). AAPG.

Scotese, C. R., Boucot, A. J., & McKerrow, W. S. (1999). Gondwanan paleogeography and paleoclimatology. Journal of African Earth Sciences, 28(1), 99-114.

Seeber, L., Armbruster, J. G., & Quittmeyer, R. C. (1981). Seismicity and continental subduction in the Himalayan arc. Zagros Hindu Kush Himalaya Geodynamic Evolution, 3, 215-242.

Sengor, A. M. C., Altiner, D., Cin, A., Ustaomer, T., & Hsu, K. J. (1988). Origin and assembly of the Tethyside orogenic collage at the expense of Gondwana Land.

Shah SMI (2009) Stratigraphy of Pakistan. GSP Memoir 22:381

Shah, S. M. I. (1977). Stratigraphy of Pakistan: Geological Survey of Pakistan Memoirs 12, p. 1-138.

Shah, S.M. I. (1977a). Stratigraphy of Pakistan: Islamabad, Pakistan, Geological Survey of Pakistan, 355 p.

Shah, S. M. I. (1977b). Stratigraphy of Pakistan: Islamabad, Pakistan, Geological Survey of Pakistan, 254 p.

Shah, S. M. I. (1977c). Precambrian and Paleozoic of Pakistan. In Shah, S.M.I. (ed.) Stratigraphy of Pakistan. Memoir of Geological survey of Pakistan, 12, 1-5 p.

Shinn, E. A., & Robbin, D. M. (1983). Mechanical and chemical compaction in fine-grained shallow-water limestones. Journal of Sedimentary Research, 53(2), 595-618.

Singer, A., & Müller, G. (1979). Diagenesis in argillaceous sediments. In Developments in Sedimentology (Vol. 25, pp. 115-212). Elsevier.

Smith, G. L., & Simo, J. A. (1997). Carbonate diagenesis and dolomitization of the lower Ordovician Prairie du Chien Group. Geoscience Wisconsin, 16, 1-16.

Sokolove, B. A., & Shah, S. H. A. (1966). Major tectonic features of Pakistan, Part-I, Western Province. Jour. Sci. Ind. Res, 4-175.

Treloar, P. J., Broughton, R. D., Williams, M. P., Coward, M. P., & Windley, B. F. (1989). Deformation, metamorphism and imbrication of the Indian plate, south of the Main Mantle Thrust, north Pakistan. Journal of Metamorphic Geology, 7(1), 111-125.

Treloar, P. J., Rex, D. C., Guise, P. G., Coward, M. P., Searle, M. P., Windley, B. F., & Luff, I. W. (1989). K- Ar and Ar- Ar geochronology of the Himalayan collision in NW Pakistan: Constraints on the timing of suturing, deformation, metamorphism and uplift. Tectonics, 8(4), 881-909.

Tucker, D., Hildreth, W., Ullrich, T., & Friedman, R. (2007). Geology and complex collapse mechanisms of the 3.72 Ma Hannegan caldera, North Cascades, Washington, USA. Geological Society of America Bulletin, 119(3-4), 329-342.

Tucker, M. E., & Wright, V. P. (1990). Carbonate Sedimentology Blackwell (pp. 482).

Ullah, N., Saboor, A., Ahmad, W., Haneef, M., Hussain, M. S., Jalil, R., & Ullah, Z (2016). Microfacies, diagenetic fabric and depositional environment of Middle Jurassic Samana Suk Limestone, Lower Salhad, Abbottabad Pakistan.

Ullah, A. (2017). Lithofacies properties, biostratigraphy, cyclicity and depositional environment of the Margala Hill Limestone, Hazara Basin, Northern Pakistan. The University of Regina (Canada).

Waagen, W. (1872). Rough Section Showing the Relations of the Rocks Near Murree (Mari), Punjab.

Wadia, D. N. (1931). The Syntaxis of the northwest Himalaya: its rocks, tectonics and orogeny. Rec. Geol. Surv. India, 65(2), 189-220.

Weyl, P. K. (1960). Porosity through dolomitization--Conservation-of-mass requirements. Journal of Sedimentary Research, 30(1), 85-90.

Wilson, J. L. (1975). Carbonate Facies in Geologic History. Springer, Berlin, p. 471.

Wilson, M.A., Palmer, T.J., Guensburg, T.E., Finton, C.D. and Kaufman, L.E. (1992). The development of an Early Ordovician hard ground community in response to rapidsea-floor calcite precipitation. Lethaia, 25(1),19-34.

Yeats, R. S., & Hussain, A. (1987). Timing of structural events in the Himalayan foothills of northwestern Pakistan. Geological society of America bulletin, 99(2), 161-176.

Zhang, X., Pang, X., Jin, Z., Hu, T., Toyin, A., Wang, K. (2020). Depositional model for Mixed carbonate-clastic sediments in the middle Cambrian lower zhangxia formation xiaweidian, north China. Adv. Geo-Energy Research, 4 (1), 29-42.

**MICROFACIES ANALYSIS AND DEPOSITIONAL ENVIRONMENT OF JURASSIC SAMANASUK FORMATION, TOWNSHIP SECTION ABBOTTABAD, PAKISTAN**

ORIGINALITY REPORT

| 9% | 4% | 4% | 3% |
|---|---|---|---|
| SIMILARITY INDEX | INTERNET SOURCES | PUBLICATIONS | STUDENT PAPERS |

PRIMARY SOURCES

| | | |
|---|---|---|
| 1 | Submitted to Higher Education Commission Pakistan<br>Student Paper | 3% |
| 2 | link.springer.com<br>Internet Source | 3% |
| 3 | Emadullah KHAN, Abbas Ali NASEEM, Suleman KHAN, Bilal WADOOD et al. "Facies Analysis, Sequence Stratigraphy and Diagenetic Studies of the Jurassic Carbonates of the Kohat Basin, Northwest Pakistan: Reservoir Implications", Acta Geologica Sinica - English Edition, 2022<br>Publication | 1% |
| 4 | ourspace.uregina.ca<br>Internet Source | 1% |
| 5 | Bilal Wadood, Mansoor Aziz, Junaid Ali, Nasar | 1% |

Khan, Jamal Wadood, Ahmad Khan, Muhammad Shafiq, Mohib Ullah. "Depositional, diagenetic, and sequence stratigraphic constrains on reservoir characterization: a case study of middle Jurassic Samana Suk Formation, western Salt Range, Pakistan", Journal of Sedimentary Environments, 2021

Publication

| | | | |
|---|---|---|---|
| Exclude quotes | Off | Exclude matches | Off |
| Exclude bibliography | On | | |