DEPOSITIONAL SETTING OF THE DATTA FORMATION IN THE WESTERN SALT RANGE, PAKISTAN.

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Hasan Raza

(M. Phil Geology)

Abstract

The aim of the present work is to investigate the depositional setting of the Jurassic Datta Formation in the western Salt Range of Pakistan. In the western Salt Range, the Jurassic Datta Formation is comprised of quartz rich conglomerates, dolomite, shale, and coarse to fine sandstones of white, light and dark gray in colors having cross-bedding, ripple marks, bioturbation, mud cracks and plants remains are the common sedimentary structures. Based on field observation the Datta Formation in the studied section is divided into five lithofacies and three lithofacies associations. The channel belt lithofacies association predominates in the bottom portion of the lithological section, it consists of conglomerate lithofacies and medium to coarse grained sandstone lithofacies. It displays lenticular bedding with pinching behavior, having trough cross-bedding, illuminating sandstone deposition in a constrained environment. This association is overlain by channel margin and flood plain lithofacies association. The sandstone of this association is different from the channel belt facies association. Mud cracks, ripple marks, and bioturbation are the common feature which show low energy conditions than channel belt facies associations. Channel margin lithofacies association is overlain by lagoonal lithofacies associations, which is comprised of interbedded shale and dolomite with some minor sandstone/siltstone lithofacies. It has vertical and inclined burrows which show calm conditions. Moreover, the sedimentlogical feature of sandstone and siltstone of the studied area composed of dominantly cross-bedded sandstone reveal the flow direction of sediments in the north-northwest. The petrographic study shows that the sediments are sub-sorted to well sorted and contain more than 90% of quartz, other minerals such as feldspar and lithic fragments are also observed but they are minor. The geochemical data shows that the sediments are highly weathered and recycled and the sediments were deposited in passive margin setting. The combined lithofacies associations, petrographic studies and geochemistry data indicate that the Jurassic Datta Formation in the western Salt Range exists probably in fluvial-deltaic environment.

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CHAPTER-01

Introduction

1.1 Introduction and Research Questions

The preserved sedimentary rock sequence in the Salt Range of NW Pakistan ranges from Precambrian up to Recent (Kazmi and Jan 1997). The Mesozoic sediments of the Salt Range represent a perceptive sedimentary rock sequence in Pakistan, which were derived from the passive margin of the NW Indian Plate. The lower Jurassic Datta Formation is one of the most important formations in terms of hydrocarbon significance (Fazeel et al. 2010). The present work investigates in detail the Jurassic Datta Formation from two localities in the western Salt Range including Nammal Gorge and Zaluch Nala section to describe the lithofacies association and to address the questions like .in which setting the formation was deposited and what were the conditions of the globe at the time of deposition.

However, although being economically important, the strata have received very limited research attention in the study area, i.e., in the western Salt Range. Elsewhere, in the Salt Range and Trans-Indus Ranges

This study may thus help in establishing the position of the Datta Formation as an important horizon for regional and global correlation, following the Late Triassic disconformity. Depositional Environment of the Datta Formation in the western Salt Range, based on investigation in the field and petrographic studies in the laboratory. This study interprets the depositional environments of different lithofacies in the Datta Formation and establishes facies association for the formation. It further tries to present a tentative palaeodepositional model for the formation based on the interrelationship of the various lithofacies, and facies association.

1.2 Location and Accessibility

The Salt Range occupies the southern margin of the Kohat–Potwar Plateau which is a part of the foreland region of the Himalayan Fold and Thrust Belt (Iqbal et al., 2015). The Salt Range Thrust brings about the surface expression of the EW trending Salt Range (Kazmi and Jan 1997). The studied sections of the Datta Formation are exposed at, Zaluch Nala and Nammal Gorge which is in the western Salt Range. The selected sections of the Salt Range are easily accessible through Islamabad-Mianwali Road

Table 1.1Table of latitude and longitude of the studied sections.

S.No	Locality Name	Latitude	Longitude	Positions
1	Nammal Gorge	32°39/ 43.83//N	71°47/ 48.23//E	Starting
2	Zaluch Nala	32°47/ 14.95//N	71°39/ 11.67//E	Starting

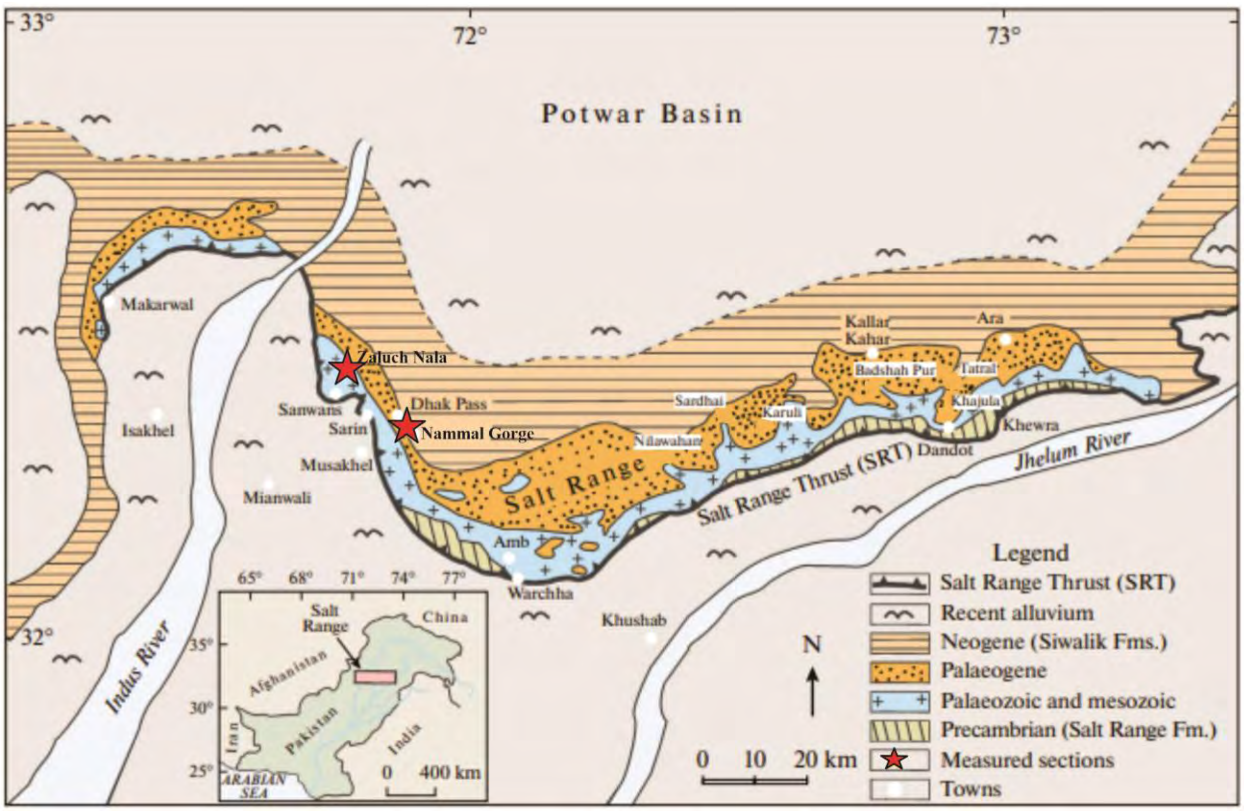

Figure 1.1 Location map of the study area, showing measured sections of the Datta Formation in the western salt range, Pakistan (Modified after Ghazi et al., 2015; Hughes et al., 2019).

1.3 Climate

The climate of the Datta Formation in the studied sections i.e. Nammal Gorge, and Zaluch Nala sections are continental and arid, changing from tropic to subtropic. Tropical air prevails during all seasons of the year except the cold winter months. Its average height is 2,200 feet, and its highest altitude, at Sakesar Mountain, is 4,992 feet (1,522 m). Temperature in summer is too hot in Salt Range, while moderate in winter season. The maximum temperature reached in summer season up to 48°C and low is 27 °C (Pak Met, 2015). The favorable weather for field Work to study the sections is winter especially from November to Mid-March. The hottest months of the year of the studied sections is June, and July, so in this season the field is so difficult.

1.4 Objectives

The present work investigates in detail the Jurassic Datta Formation from two localities in the western salt range including Nammal Gorge, Zaluch Nala

- To understand the depositional Environment of the Datta Formation in the western Salt Range, based on investigation in the field and petrographic studies in the laboratory.
- To established different lithofacies of the Datta Formation to determine the depositional environment of the formation.

1.5 Methodology

There are different methods that we used in our research.

1.5.1. Field work and Sampling

The Jurassic Datta Formation was studied in the Western Salt Range. Detailed sections were measured at, Nammal Gorge and Zaluch Nala. These two different sections were sampled. The sampling was based on lateral and vertical variations. The sections bed are measured and different sedimentological features are recorded. Total71 samples were collected covering all the lithological/facies variations of the Datta Formation in different parts of the area. The samples were properly labelledand archived (Selley, 2000; Boggs, 2009).

1.5.2 Petrographic Studies

Thin sections were made for all the siltstone, sandstone, conglomerates, and carbonates and evaporate samples. Total46 out of 71 thin sections were prepared at the Department of Earth Sciences, Sedimentology Lab, Quaid-i-Azam University, Islamabad. These thin sections were studied systematically using Leica DM2700 P microscope with Leica MC170 HD camera to find out the framework composition, Matrix, and cement types, depositional setting, and digenetic history of the Strata.

Point counting was performed (Appendix 1) for all the siltstones, sandstones, and conglomerates (Dickinson, 1970; Graham et al., 1976; Ingersoll et al., 1984; Pettijohn et. al., 1987). The data was then used in Quartz – Feldspars – Rock Fragments (QFR) plot (Dickinson and Suczek, 1979; Suttner and Dutta, 1986).

1.5.3 Bulk Mineralogy\XRF Analysis

On the Basis of fieldwork observations and petrographic analysis, 20 samples were selected for the bulk mineralogy using XRF from different parts of the sections covering all the lithological/facies variation in the strata. Powder XRF was used for the determination of the bulk mineralogical composition of the selected samples (Iqbal et al.,2021)XRF analysis was conducted using PAN alytical X'Pert Pro diffract meter (CuKα- radiation (40 kV, 40 mA), step size 0.0167, 5 s per step) at the Department of Earth Sciences, Sedimentology Lab, Quaid e Azam University, Islamabad.

1.5.4Bulk Geochemistry

For these methods we prepared 20 Samples.The bulk rock geochemistry analyses were conducted in Acme Analytical Laboratories Ltd. Canada (now Bureau Veritas) using Inductively Coupled Plasma Emission Spectroscopy/Mass Spectrometry (ICP- ES/MS). The analyses include oxides, major, minor, trace and rare earth elements.

1.6 Previous work

The name Datta Formation was first introduced by Danilchik and Shah (1967), this name has also been extended to the Kala Chitta range and adjoining areas by the Stratigraphic Committee of Pakistan (Fatmi 1973). There are many authors to work on the Datta Formation on different aspects few of them are mentioned as Follows

Guideline to explored Datta Formation in the western salt range and in the tras-indus ranges toward the west published by Shahid., et al., 2015. They worked on the paleoenvironmaents and sequence stratigraphy on the Jurassic Datta Formation and also on the lathiofacies in Kasanwala and Kaowaali sections. They also worked on the responce of sliciclastic system to fluctuating sea-level.

The organic geochemical and palynofacies studies showed that the coal and OM-rich shale intervals in the Datta Formation have good-to-excellent source rock potential in the study area, whereas the grey shale intervals have poor potential as source rocks Khan et al., 2021. The Datta Formation has tentatively been correlated with the stratigraphically equivalent Lathi Formation in the Jaisalmer Basin, India Khan et al., 2021.

The western Salt Range and adjoining Trans–Indus ranges of Pakistan, a thick and laterally persistent dolomite of the Kingriali Formation represents the Upper Triassic platform carbonates Iqbal et al., 2021. The overlying predominantly siliciclastic rich strata of the Datta Formation represents the Lower Jurassic fluvial-deltaic system in the area. The overall succession provides ideal sections for the Triassic–Jurassic transition from the tropical southeastern margin of the Pangaea supercontinent facing western Tethys (northwestern margin of the Indian Plate) Iqbal et al., 2021.

CHAPTER-02

General Geology

This chapter contains information on the general geology of the study area, including tectonics, structural geology, and stratigraphy. A detailed overview of the regional tectonic setting of Pakistan, the tectonics framework, and sections are presented. In addition, the structural and tectonic map of the study area is also shown. Furthermore, this chapter also includes the stratigraphic framework of the Datta Formation in the western Salt Range along with their stratigraphic chart.

2.1 Regional tectonic setting

During the Early Mesozoic the supercontinent Pangaea split into the northern Laurasiaand the southern Gondwana with an intervening ocean called as the Tethys Ocean (Kazmi and Jan 1997; Rees et al. 2000; Ali and Aitchison, 2008). During most part of the Mesozoic, the Indian Plate remained part of Gondwana Land (Kazmi and Abbasi, 2008). The Indian Plate separated from Gondwanaland in the Early Cretaceous Period and started a northward drifting which resulted to the subduction of the Neo-Tethys under the Eurasian Plate and collision with remnant Kohistan–Ladakh Arc (Kazmi and Jan, 1997). The northward drift continued where eventually the Indian Plate having Kohistan-Island Arc on its leading edge collided with the Eurasian Plate (about 52 Ma). As a consequence of the northward movement of Indian Plate, the marine sediments were compressed and creased and then squeezed up to form the Himalayas Mountains (Baker et al., 1988).

The Salt Range marks the southernmost part of the western Himalayan ranges of Pakistan where the study area lies in the western part of Salt Range. Structurally, the Salt Range is the result of tectonic forces imposed during the later phases of the Himalayan Orogeny during Late Cenozoic and represents the southern periphery of the Himalayan Fold-and-Thrust Belt (HFTB) in Pakistan (Gee and Gee 1989; Kazmi and Jan,1997). The Indian and Eurasian Plates collision during Eocene has uplifted the Himalayas and then generated several thrust faults in Pakistan including MKT (Main Karakoram Thrust), MMT (Main Mantle Thrust), MBT (Main Boundary

Thrust), and SRT (Salt Range Thrust) from the north towards the south (Coward et al. 1988) The study area is bounded by Hill Ranges in the north, Punjab Foreland in the south, and Jhelum River in the East whereas westward, the Kalabagh Fault separates the Salt Range from Trans Indus ranges (McDougall and Khan, 1990; Kazmi and Jan, 1997). Tectonically, it is bounded by the Main Boundary Thrust (MBT) in the north and SRT in the south (Kadri, 1995)(Fig 2.1)

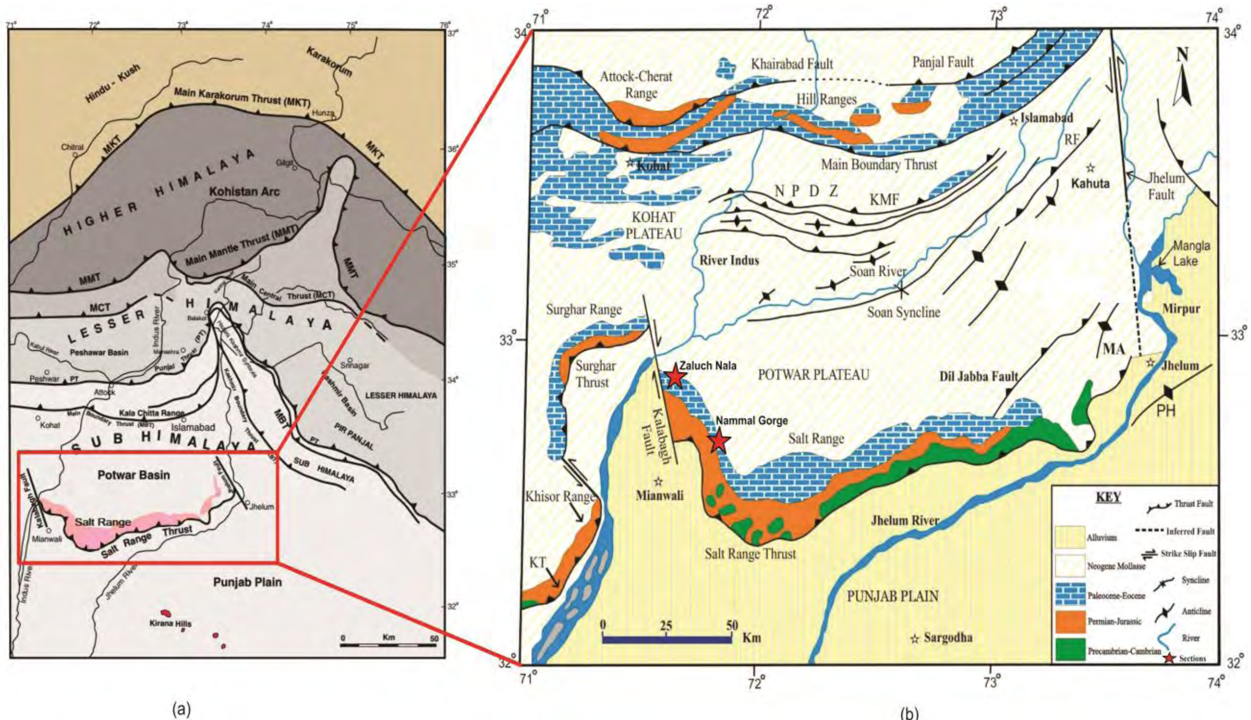

Figure 2.1 (a) Geological map of Pakistan. (b) Map showing the stratigraphy present in study area in the western Salt Range. (Modified after Safi et al, 2021)

2.2 Stratigraphy

The stratigraphy of Salt Range ranges from Precambrian age up to Recent (Fig. 2.2) with a mark absence of Ordovician, Silurian, Devonian, and Carboniferous strata throughout the region. The stratigraphic sequence of the Salt Range pinches out laterally to the point of vanishing like the well-developed Mesozoic succession of the Western Salt Range and Trans Indus Ranges which were completely like Cretaceous sequence or partly like Triassic strata are absent in the Central and Eastern Salt Range (Shah, 1977).

The older exposed Precambrian Salt Range Formation in the area is composed of clays, marls, gypsum, dolomite, and rock salt. The base of the Formation in unexposed in the area but is only known from the Karampur well where it overlies the metamorphic rocks, presumably of Precambrian age (Fatmi, 1973). The upper contact is with the overlying Khewra Sandstone

(Table 2.1) which is generally normal and conformable. The Paleozoic rocks exposed in the Salt Range include the Khewra Sandstone, Kussak, Jutana, and Baghanwala Formations of the Cambrian age which are placed in the Jhelum Group. The Khewra Sandstone conformably overlies the Salt Range Formation and underlies the Kussak Formation. The Kussak Formation has conformable upper contact with the Jutana Dolomite which in turn conformably underlies the Baghanwala Formation. The younger Paleozoic rocks of the Lower Permian age include the Nilawahan Group which comprises the Tobra Formation,the Dandot Formation,the Warchha Sandstone, and the Sardhai Formation. The Permo-Cambrian unconformity is marked between the Baghanwala Formation of the Jhelum Group and the Tobra Formation of the Nilawahan Group. The Upper Permian, Zaluch Group is composed of marine siliciclastic-carbonate mixed lithofacies of the Amb Formation,the Wargal Limestone, and the Chhidru Formation respectively (Shah, 1977). The Permo-Triassic Boundary is marked between the Chhidru Formation and the overlying Mianwali Formation of the Musa Khel Group. The Triassic rocks of the Salt Range include the Mianwali Formation,the Tredian Formation, and the Kingriali Formation of the Musakhel Group. The overlying Jurassic rocks include the fluvio-deltaic, shallow marine, and deep marine rocks of the Datta Formation,the Shinawari Formation, and theSamana Suk Formation of the Surghar Group. The Makarwal Group comprised of the Hangu Formation, the Lockhart Limestone, and the Patala Formation. The overlying the Nammal Formation, the Sakesar Limestone, and the Chorgali Formation constitute the Cherat Group of the Eocene age. The Miocene Murree and Kamlial Formations of the Rawalpindi Group and the younger fluvial/alluvial sediments of the Chinji, Nagri, Dhok Pathan, and Soan Formations constitute the molasses sedimentation of the Siwalik Group.

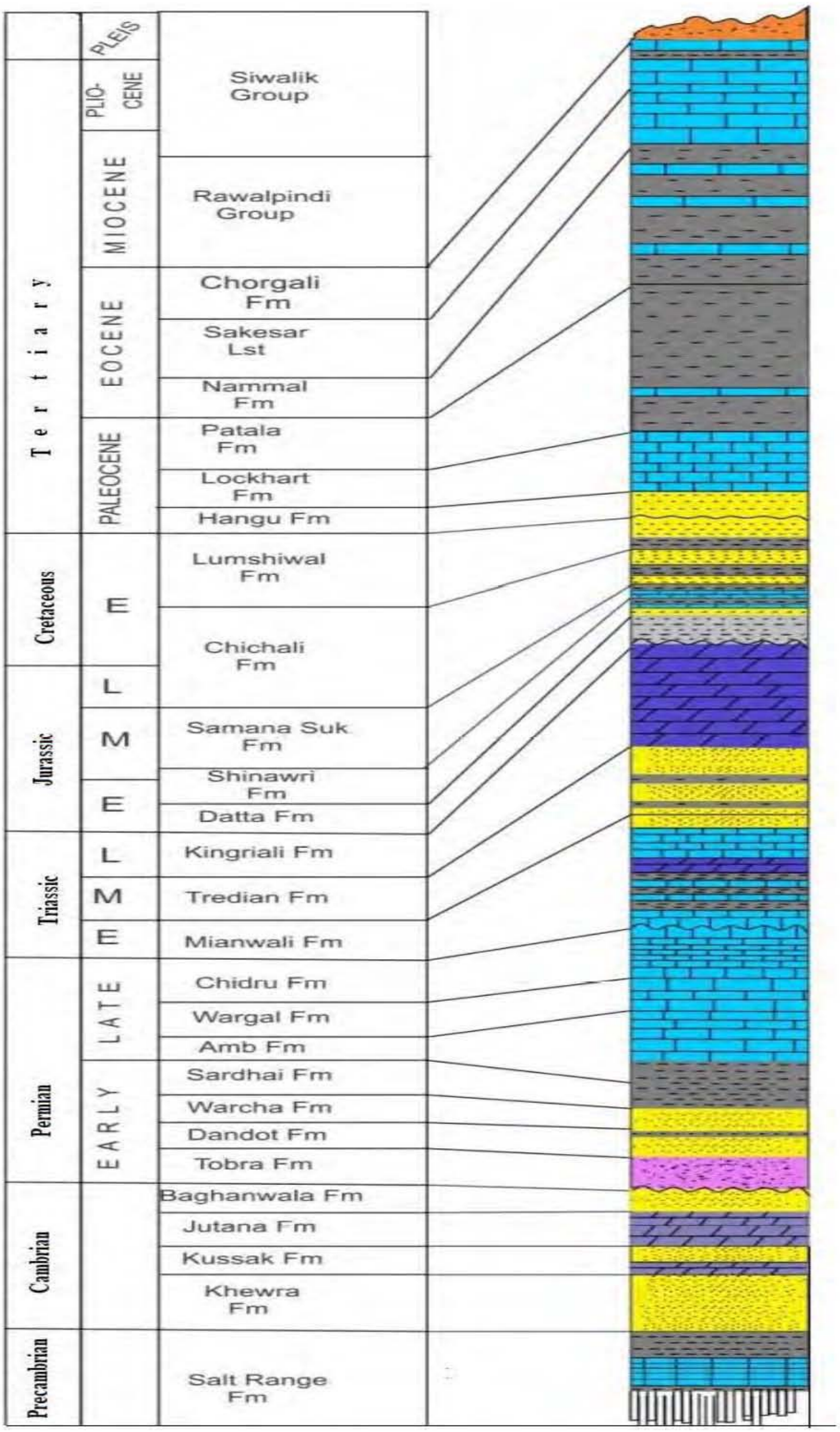

Figure 2.2 Generalized Stratigraphic Chart of Salt Range.(Modified after khan et al, 2014)

2.3 Structures

The Salt Range is a large allochthonous block that has been thrusted and differentially rotated along a decollement within or at the base of, an incompetent, evaporite-bearing sequence that directly overlies a metamorphic basement (Wadia, 1957; Gansser, 1964; Crawford, 1974; Seeber and Armbruster, 1979; Yeats et al., 1984). The Pre-Cambrian Salt Range Formation is an evaporitic-clastic unit that has been interpreted as the decollement zone responsible for the irregular rotation of the Salt Range relative to the Himalayan trend (Seeber et al., 1981). Infrequent and low-magnitude seismicity in the area (Quittmeyer et al., 1979; Yeats et al., 1984), along with the fact that strata in the western and central Potwar Plateau have been transported with so little internal deformation, can also be attributed to the decoupling properties of the evaporites. The Salt Range is a pronounced topographic ridge representing the uplifted edge of the thrust block, but the topographically subdued Potwar "Plateau" is a well-defined structural depression.

North of the axis of the Soan Syncline lies the Northern Potwar Deformed Zone (NPDZ), (Fig 2.1). representing considerable shortening in a zone of imbricate faults. Bounding the NPDZ to the north are the Hill Ranges, a series of thrust imbricates that displace a Cretaceous to lower Tertiary sequence over the Rawalpindi Molasse of the northern Potwar Plateau (Pinfold, 1918,).

Towards the west, the Salt Range/Potwar Plateau thrust block appears to be abruptly truncated by the Kalabagh transpressional fault system (Fig 2.1). This fault extends 20 km north of the Indus River before bending to the west along several north-dipping reverse faults (McDougall, 1985). Northward in the Kohat Plateau, severe thinning, or lithologic change in the Salt Range Formation., coupled with the existence of a shallower Eocene age evaporite sequence, results in anticlines cored by salt and shale, underlain by blind thrusts that verge southward (Khan et al., 1986). In the eastern Potwar Plateau, however, displacement along the SRT dies out, and shortening is distributed along a segmented, range-bounding thrust system, and a par autochthonous en echelon fold system, which may be only partially decoupled from the basement. Although displacement relative to the Salt Range and Potwar Plateau can be measured only along the Kalabagh Fault.

Seventy kilometers south of the Salt Range, near the town of Sargodha are the low-lying Kirana Hills, the largest group of the metamorphic and metasedimentary basement of the Indian

Plate in the Pakistan foreland (Davies and Crawford, 1971; Shah, 1977). These outcrops are a portion of the crest of the Sargodha Ridge, and correspond to positive gravity anomalies along a northwestern line of discontinuous gravity "highs" (e.g., the Delhi-Lahore Ridge; Aithal et al., 1964; Farah et al., 1977), which eventually merge with the northeast-trending basement exposures of the Aravalli Range in India (Datta et al., 1964). The Sargodha Ridge described as a broad, gentle basement uplift, represents a reversal in basement dip from south-southwesterly on its southwest flank to northward dip across the axis of the ridge (Datta et al., 1964).

2.4 Datta Formation

The formation was described as variegated beds by Wynne (1878, 1879); Kioto Limestone by Middlemiss (1896) and Cotter (1933). Cox et al., (1930) introduced the term “Samana beds” in the Kohat area. Later on, it was named as variegated stage (Gee, 1945) and Maira formation (Davies and Gardezi, 1965). Danilchik, (1961) and Danilchik and Shah, (1967) introduced the name Datta Formation. The name was formalized by the Stratigraphic Committee of Pakistan after the locality of Datta Nala (lat. $33^{O}00^{/}$N: long. $71^{O}19^{/}$E) in the Surghar Range. In the western Salt Range and Trans–Indus ranges the formation consists of conglomerates, sandstones, siltstones, shale, dolomite, and laterite horizons.

2.4.1 Nammal Gorge Section

In Nammal Gorge the lower part of Datta Formation is comprised of 2 m thick red, white, light gray fine to medium grained quartz-rich sandstone and overlying 3.2 m light gray, dark gray and brown shale. The rest of the succession is similar to that observed in the eastern section. The only difference is the increase in thickness and frequency of carbonaceous shales. The uppermost part of the formation at the Nammal Gorge also has much thicker, coarse-grained, trough cross-bedded sandstone and has more plant remains than anywhere else in the formation. Another marked difference is the absence of kaolinite mining in Nammal Gorge.

2.4.2 Zaluch Nala Section

The Zaluch Nala section display similar lithofacies architecture to the Nammal Gorge section. The lower white, red, and brown sandstones and shales reappear at the Zaluch Nala after the disappearance in the Nammal Gorge section. Kaolinite is mined in the area and the formation is thicker than the eastern section

2.4.3 Contacts

In both sections i.e Nammal Goarge and Zaluch Nala section, the lower contact of the formation in conformable with the Kingriali Formation and the upper contact is conformable with the Samana Suk Formation.

2.4.4 Age

The literature that is currently in circulation disputes the existence of age-diagnostic fossils in the formation, and a Pre-Toarcian age is determined based on the stratigraphic position beneath the Shinawari Formation, which has produced lower Toarcian ammonites in its lower part.

CHAPTER-03

Results

To understand the depositional settings of the Datta Formation in the western Salt Range, Pakistan detailed section measurement and sampling from two sections were conducted which covered lateral and vertical facies variations. The sections beds were measured, and different sedimentological features were recorded. Sampling was conducted for sediment petrography and geochemistry. The description of methods, which have been used for present work and the results are presented in the following lines.

3.1 Field Observations

Nammal Gorge and Zaluch Nala sections are part of the western Salt Range, east of the Kalabagh Fault. In Nammal Gorge, upper Permian, Mesozoic, and Cenozoic rocks are well exposed while good exposures of Permian to Eocene rocks are present in Zaluch Nala. The studied formation i.e., The Datta Formation is a part of Baroch Group present in both cited sections. The lithology of the Datta Formation has shale, sandstone, conglomerate, fireclay and some carbonaceous material representing continental and shallow water marine environment (Shah, 2009).

3.1.1 Nammal Gorge

In the Nammal Gorge section the thickness of the Datta Formation is 135 m (Fig 3.1). The lower contact of the Datta Formation is conformable with the Kingriali Formation. This contact is marked by a conglomerate bed which is consist of angular to sub angular and well-rounded pebbles of Quartz, Chert and Rock Fragment.The Datta Formation consist of fine to medium grained white, light gray, pink, red to brown sandstone and interbedded red, brown, yellowish-brown shale (Fig. 3.1). This is overlain by thick, dark red, purple laterite/bauxite interval. Quartz rich oligomictic conglomerates and pebbly sandstones of white, light and dark gray in colours. Overlie the interval in Nammal Gorge. These conglomerates and pebbly sandstones are pink and red at places and are overlain by red, brown fine to medium grained sandstone. Trough cross bedding, normal graded bedding (Fig. 3.2A) and clasts alignment are the common sedimentary structures. Plant remains (Fig. 3.2B) and coal patches are common.

Ripple marks, mud cracks, Raindrop imprints, and bioturbation are the common sedimentary structures. Light gray, brown and rusty brown shalesoverlie the succession (Fig. 3.2C). This succession is overlain by interbedded sandstones, siltstones, shales and carbonates. The sandstones are fine to medium grained and compositionally quartz arenites. At places calcareous sandstones occur. Cross bedding, ripple marks, bioturbation and paleosol horizons are common. The shales are dark gray, brown and black in color. Carbonaceous horizons occur and yellow color due to sulphur can be observed with these horizons. The carbonates are yellowish orange and light brown in color and include both pure and arenaceous dolomites. Planar and wavy bedding planes occur, and ripple marks are also observed. The upper contact of the Formation is conformable with Samana Suk Formation.

3.1.2 Zaluch Nala

The Datta Formation in the Zaluch Nala section has 130 m thickness, and displays similar lithology to the Nammal Gorge section(Fig. 3.1) but in the Zaluch Nala section the lower white, red, brown sandstones and shale reappear after the disappearance in the Nammal Gorge. This section having mainly, interbedded sandstone (Fig. 3.3 A), interbedded sandstone and dolomite (Fig. 3.3 B), white sandstone, maroon shale (Fig. 3.3 C) and fossiliferious dolomite (Fig. 3.3 D). The Formation having both coarser and fine sandstone with abundant sedimentary structure i.e. Bioturbation, cross bedding, rain imprints and ripple marks. Kaolinite are present in the area and the formation is thicker than the Nammal Gorge .In this section the lower contact of the formation is conformable with the kingriali Formation, but the upper contact is conformable with the Samana Suk Formation.

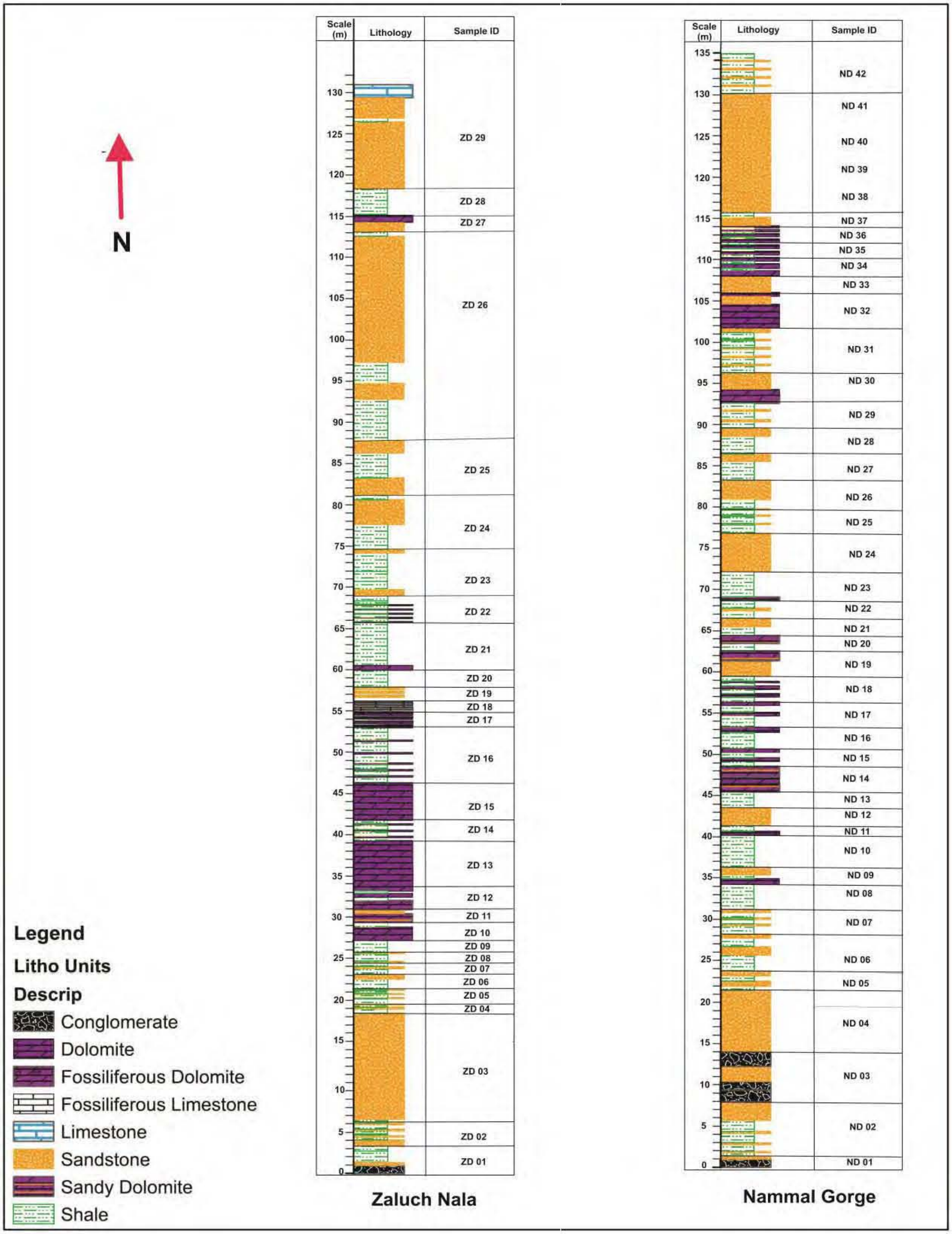

Figure 3.1 Lithological logs of the Datta Formation at Zaluch Nala and Nammal Gorge sections Western Salt Range Pakistan.

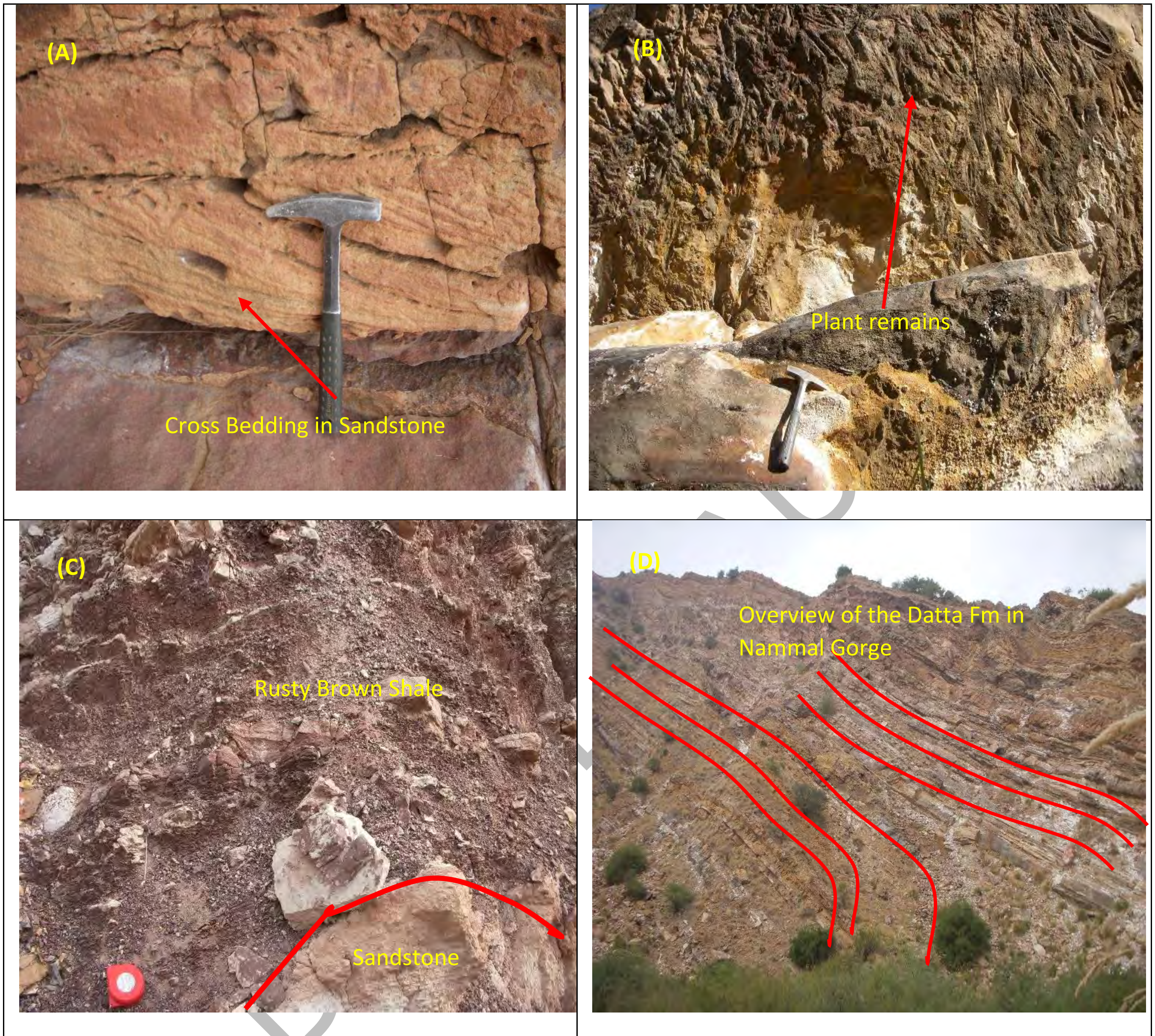

Figure 3.2.Field photographs of the Datta Formation in Nammal Gorge. (A) Cross bedding in sandstone, hammer is used as a scale. (B)Arrowhead is toward plants remains). (C) Contact between sandstone and rusty brown shale. (D) Overview of the Datta Formation in Nammal Gorge.

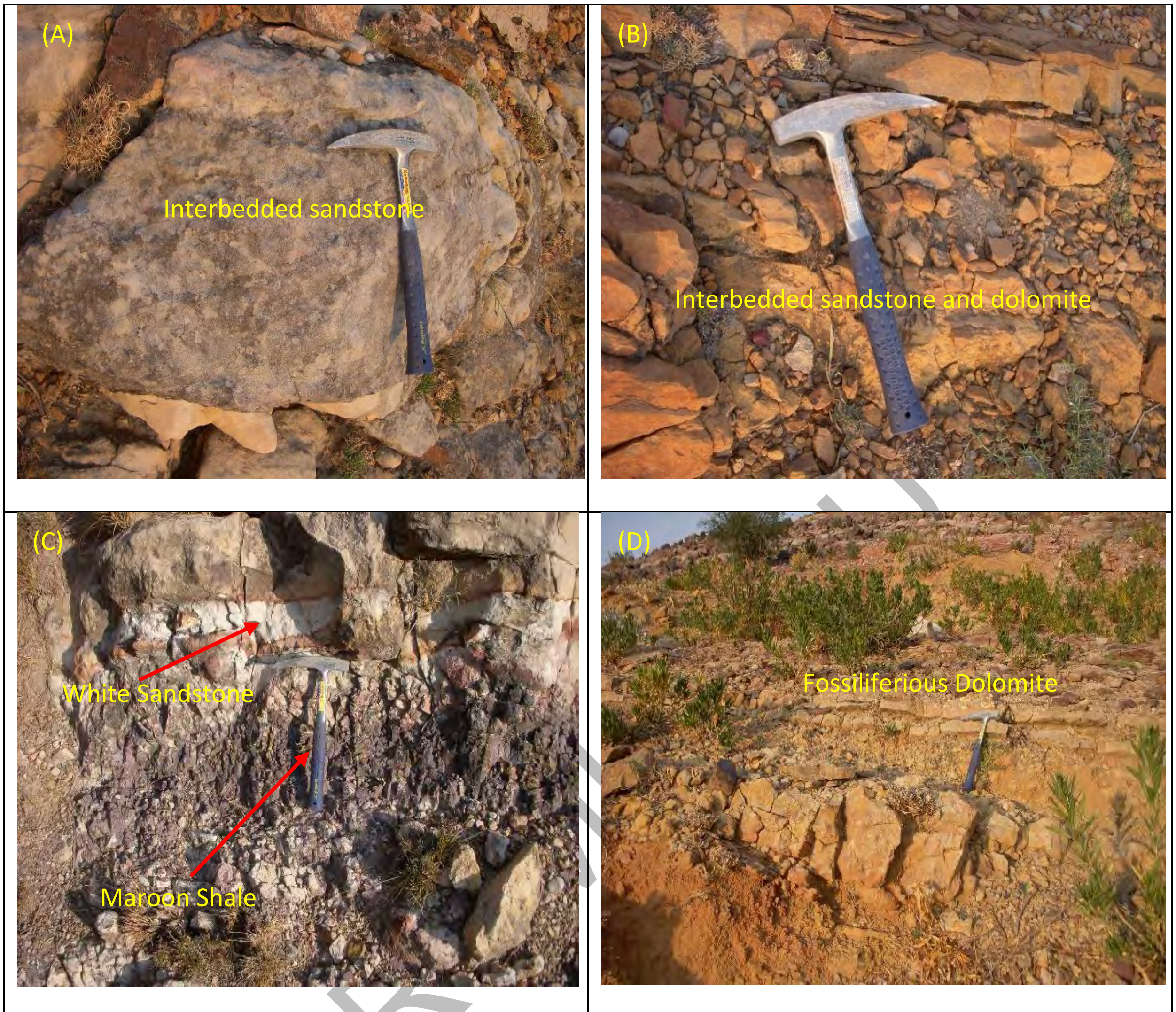

Figure 3.3.Field photographs of the Datta Formation in Zaluch Nala section (A) Interbedded Sandstone. (B)Interbedded sandstone and dolomite. (C) White sandstone and maroon shale beds. (D) Fossiliferous Dolomite in the Datta Formation.

3.2 Petrographic Studies

46 out of 71 samples are selected for thin sections analysis from different lithology's such is, sandstone, siltstone, and carbonate rocks from both Nammal Gorge and Zaluch Nala sections. All thin sections were studied using Leica DM2700 P microscope with Leica MC170 HD camera in petrographic laboratory Earth Sciences Department, Quaid-i-Azam University Islamabad.

3.2.1 Pointing Counting Methods

For point counting analysis Image J software was used. Dickinson (1970), Graham et al. (1976), Ingersoll (1978), and Ingersoll and Suczek (1979) discuss the parameters and criteria for identifying the mineral composition. To obtain more information three microphotograph of each thin section were taken from bottom to top. After we import the microphotograph to image J, where automated grid was applied to each image. When the grid was in the middle of grain, it is counted is one, when the grid is on the edge, so it is counted 0.5. A total 400 points were counted for each thin section, using maximum grid spacing that covered the whole photo.

3.2.1.1 Petrography of Nammal Gorge Section

According to the petrographic study quartz is the major constituents in Nammal Gorge section. Quartz is divided into maonocrystalline and polycrystalline. The monocrystalline is further subdivided into monocrystalline with unit extinction ($Q_{mue)}$ and undoluse extension ($Q_{muu)}$. The polycrystalline quartz is also subdivided into two types, polycrystalline quartz with two to three(Q_{P2-3}) and polycrystalline quartz greater than three($Q_{P>3}$). The monocrystalline quartz are sub-rounded to sub angular, while the polycrystalline quartz are sub-angular to angular. The contact between grain to grain are mostly straight to suture. Two types of feldspars plagioclase and K-feldspars have also been identified in petrographic study, (Table 3.1).Quartz is the most common component in Sandstones. In Nammal Gorge section the total Quartz (Q_{total}) averages 96% of the framework components. Q_{mue} is averaging 72.9% followed by Q_{muu} (15.8%), whereas $Q_{pq\ (2-3)}$ content averages 4.4% and $Q_{pq>3}$ averages 2.9% of the total framework composition. The total feldspar (F_{total}) average is only 0.19% having Alkali Feldspar (A) is 0.13% and Plagioclase (P) is 0.01% of the total framework. The total lithic fragments average is 1.5%. (L_{total}) is the combination of volcanic-hypabysssal (L_v) averages 0.4%. Metamorphic (L_m) averages 0.4% and sedimentary lithic (L_s) averages 0.5%.The average of polyslicates mineral (M), heavy mineral (D) and unidentified mineral (O) is 0.2%, 1.5% and 0.3% respectively.

3.2.1.2 Petrography of Zaluch Nala Section

In Zaluch Nala Section ,Quartz is also the most common component in Sandstones(Table 3.2).The average of total Quartz (Q_{total}) is 97.9% of the framework components which is greater than (Q_{total}) of the Nammal Gorge Section. Q_{mue} is averaging 91.9% followed by Q_{muu} (4.2%).The average of $Q_{pq\ (2-3)}$ is 1.5%and $Q_{pq>3}$ averages 0.38% of the total framework composition. The total feldspar (F_{total}) average is only 0.15% having the Alkali Feldsper (A) is

0.15% and plagioclase (P) is 0.0% of the total framework. The total lithic (L_{Total}) fragments average is 0.2% having volcanic-hypabysssal (L_v) averages 0.01%. metamorphic (L_m)averages 0.0% and sedimentary lithics (L_s) averages 0.1% .The average of polyslicates mineral (M), heavy mineral (D) and unidentified mineral (O) is 0.06%,0.5% and 1.1% respectively.

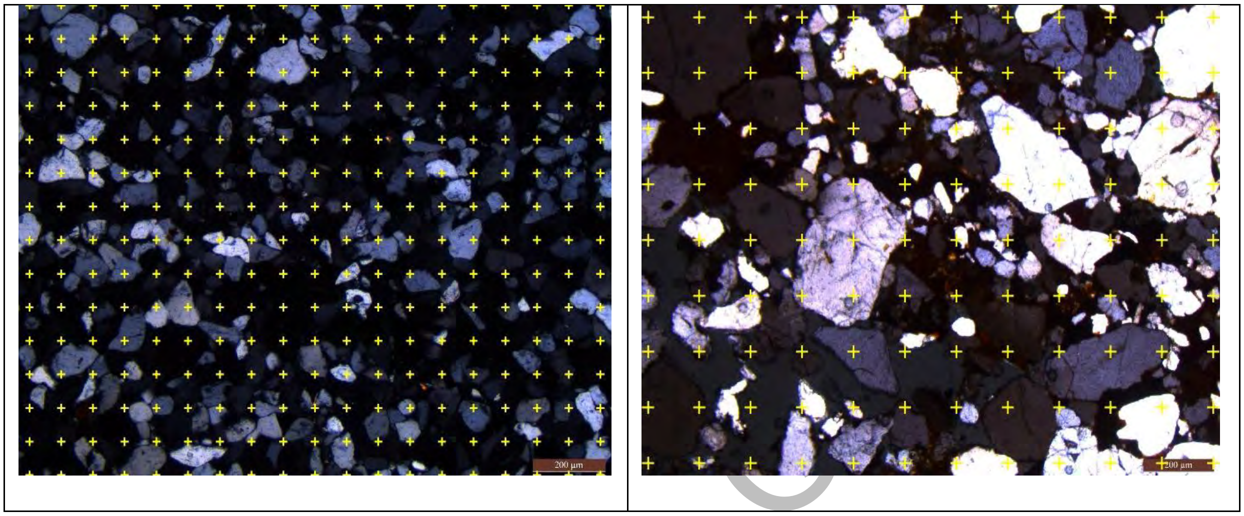

Figure 3.4. The photo micrograph showing the point counting procedure and grid spacing

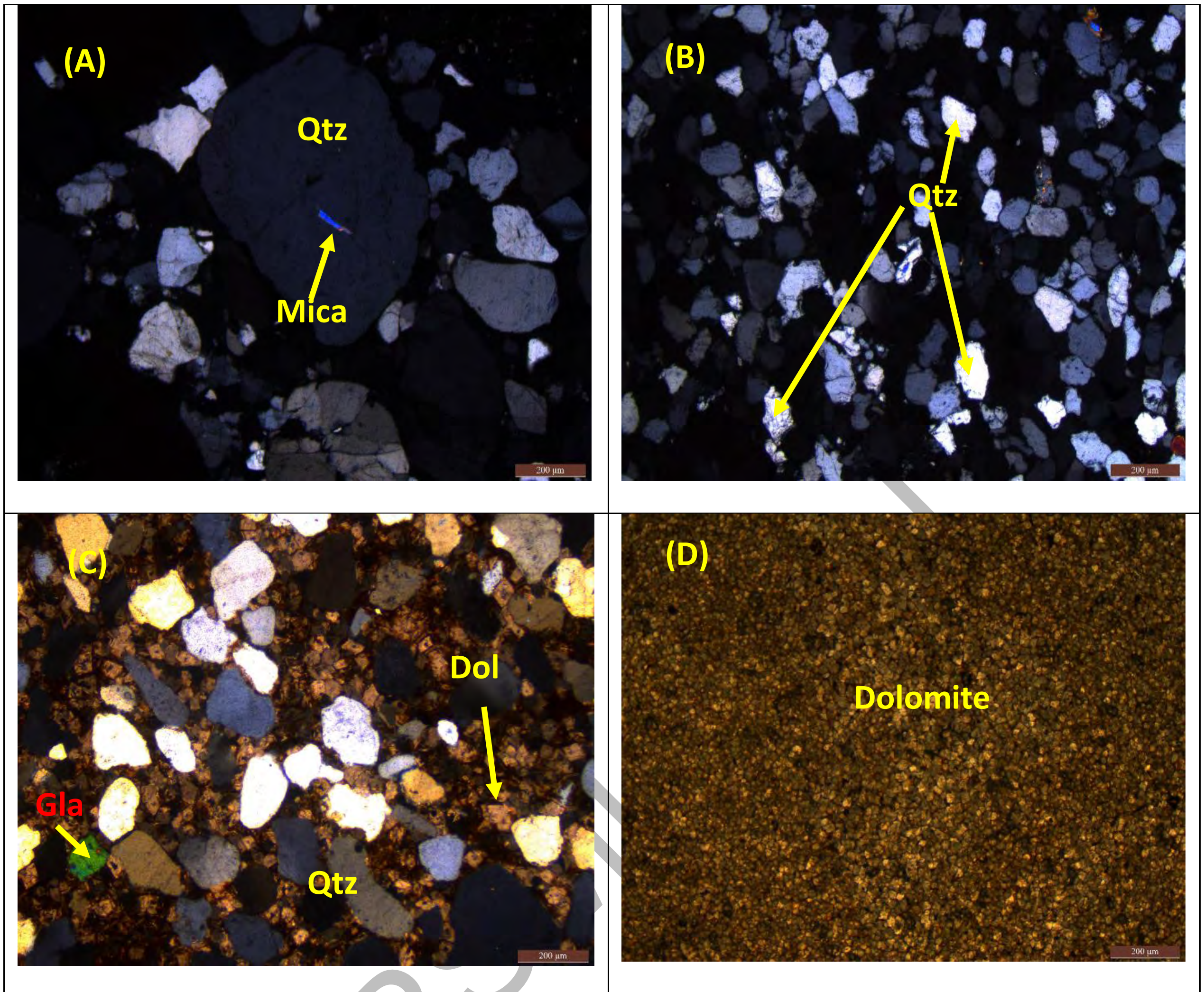

Figure 3.5. Petrographic study of the Datta Formation of Nammal Gorge (A) Monocrystalline, polycrystalline Quartz and mica flakes. (B) Monocrystalline Quartz. (C) Gla= Glauconite, Dol= Dolomite and monocrystalline quartz with unit extension. (D) Thin section of sample ND-14 having Dolomite.

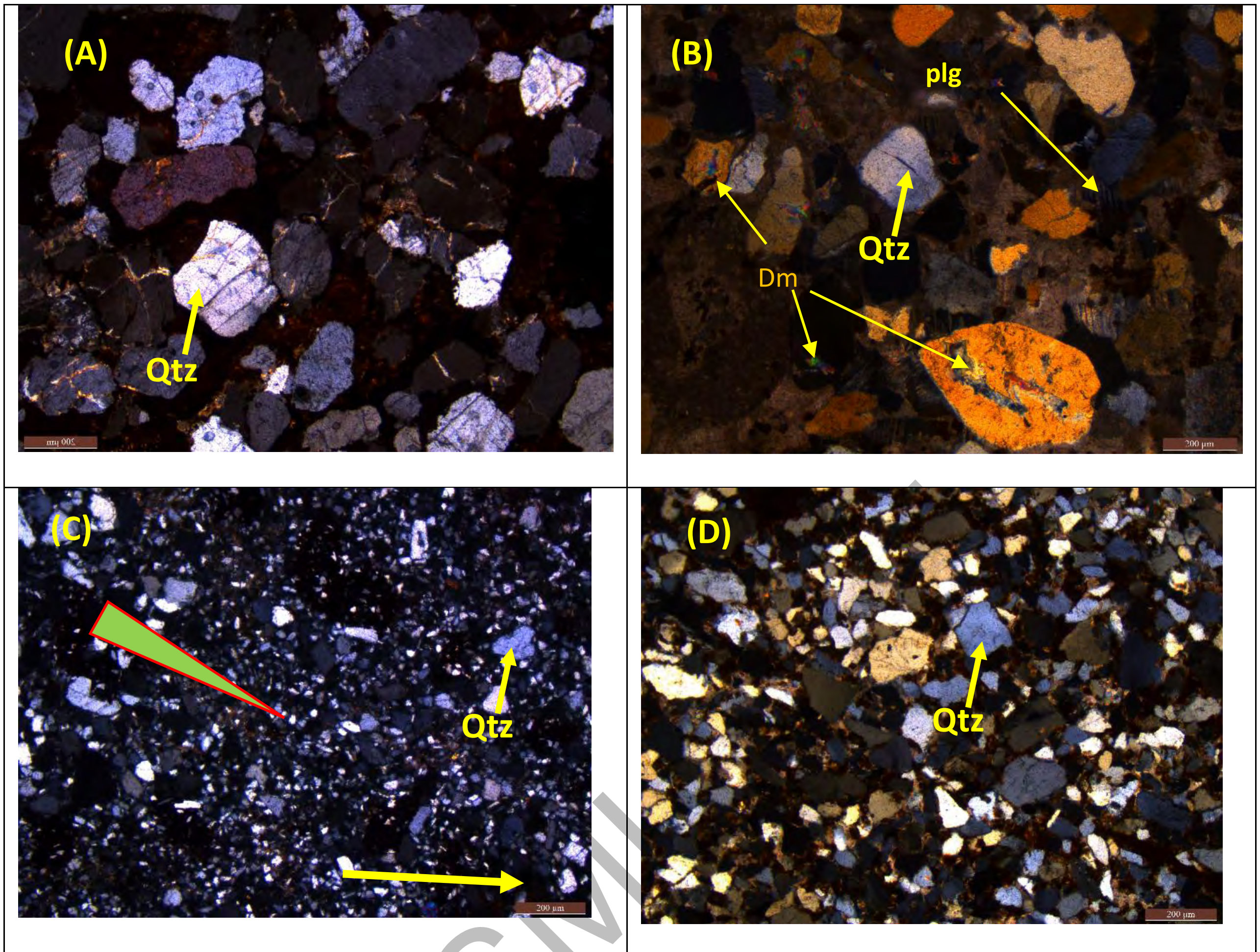

Figure 3.6. Petrographic study of the Datta Formation of Zaluch Nala section. (A) Polycrystalline quartz. (B) Plagioclase feldspar, Dm = Denser mineral and quartz. (C) Arrow shows fining upward sequence. (D) Monocrystalline quartz with unit extension.

Table.3.1. Point counting table of Datta Formation in Nammal Gorge Section

Sample	Q_{mue}	Q_{muu}	Q_{pq} (2-	$Q_{pq>3}$	Q_{Total}	A	P	F_{Total}	L_V	L_M	L_S	L_{Tot}	M	D	O	Total
ND-1	129	128	37	74	368	0	2	2	2	13	12	27	0	3	0	400
ND-2	314	61	19	2	396	0	0	0	0	0	0	0	0	4	0	400
ND-3	259	75	36	8	378	2	0	2	0	0	0	0	0	17	3	400
ND-4	175	124	37	28	364	8	0	8	4	8	12	24	0	2	2	400
ND-5	242	94	18	35	389	2	0	2	0	0	7	7	2	0	0	400
ND-6	156	107	29	98	390	0	0	0	2	2	6	8	0	2	0	400
ND-7	338	27	7	5	377	0	0	0	2	0	0	2	4	13	4	400
ND-9	310	55	26	2	393	0	0	0	3	0	2	5	0	2	0	400
ND-11	329	37	17	5	388	0	0	0	0	0	0	0	2	10	0	400
ND-13	298	78	12	3	391	0	0	0	0	5	0	5	0	4	0	400
ND-14	366	9	6	2	383	0	0	0	0	0	0	0	4	9	4	400
ND-15	320	24	20	8	372	0	0	0	6	0	0	6	10	12	0	400
ND-16	292	53	19	4	368	2	0	2	8	2	4	14	0	12	4	400
ND-18	340	35	13	2	390	0	0	0	2	0	0	2	0	6	0	400
ND-19	338	42	13	2	395	0	0	0	0	0	3	3	0	2	0	400
ND-20	265	80	35	2	382	4	0	4	2	0	2	4	0	2	8	400
ND-21	276	88	10	2	376	0	0	0	7	9	8	24	0	0	0	400
ND-23	370	12	8	2	392	0	0	0	0	0	0	0	0	8	0	400
ND-25	254	116	20	6	396	0	0	0	2	2	0	4	0	0	0	400
ND-26	252	72	18	2	344	0	0	0	2	0	2	4	4	48	0	400
ND-27	368	18	4	4	394	0	0	0	0	2	2	4	0	2	0	400
ND-28	298	62	30	4	394	0	0	0	2	0	2	4	0	2	0	400
ND-29	358	13	9	2	382	0	0	0	2	4	0	6	0	0	12	400
ND-31	288	100	6	2	396	0	0	0	0	2	0	2	0	2	0	400
ND-34	312	76	8	4	400	0	0	0	2	0	0	2	0	0	0	400
ND-36	338	48	8	2	396	0	0	0	2	0	0	2	0	2	0	400
%	72.9	15.8	4.4	2.9	96	0.13	0.0	0.19	0.4	0.4	0.5	1.5	0.2	1.5	0.3	100

Table.3.2. Point counting table of Datta Formation in Zaluch Nala Section

Sample	Q_{mue}	Q_{muu}	Q_{pq}	$Q_{pq>3}$	Q_{Total}	A	P	F_{Tota}	L_v	L_M	L_S	L_{Tota}	M	D	O	Total
SZ-1	360	22	12	4	398	0	0	0	0	0	0	0	0	2	0	400
SZ-2	367	14	8	4	393	0	0	0	2	0	2	4	0	3	0	400
SZ-3	370	18	6	2	396	0	0	0	0	0	0	0	0	4	0	400
SZ-4	365	20	6	2	393	0	0	0	0	0	0	0	0	3	4	400
SZ-5	362	28	2	0	392	0	0	0	0	0	0	0	0	2	6	400
SZ-6	384	8	4	2	398	0	0	0	0	0	0	0	0	2	0	400
SZ-8	381	6	2	0	389	0	0	0	0	0	0	0	0	7	4	400
SZ-9	384	6	2	0	392	0	0	0	0	0	0	0	0	2	6	400
SZ-11	384	10	4	0	398	0	0	0	0	0	0	0	0	2	0	400
SZ-12	383	13	0	0	396	0	0	0	0	0	0	0	0	4	0	400
SZ-13	360	25	5	2	392	0	0	0	0	0	0	0	0	4	4	400
ZD-2	374	16	6	0	396	2	0	2	0	0	0	0	0	0	4	400
ZD-12	358	16	12	2	388	0	0	0	0	0	0	0	0	0	12	400
ZD-13	358	14	8	4	384	0	0	0	0	0	0	0	0	0	18	400
ZD-15	368	17	6	0	388	0	0	0	0	0	0	0	5	0	7	400
ZD-18	378	12	8	0	398	0	0	0	0	0	0	0	0	0	2	400
ZD-19	352	28	8	2	398	8	0	8	0	0	0	0	0	0	2	400
ZD-21	338	22	12	5	377	2	0	2	0	0	13	13	0	6	14	400
ZD-23	364	17	10	2	393	0	0	0	0	0	0	0	0	2	5	400
ZD-26	362	29	2	0	393	0	0	0	0	0	0	0	0	2	5	400
%	91.9	4.2	1.5	0.38	97.9	0.15	0	0.15	0.02	0	0.1	0.2	0.0	0.5	1.1	100

3.2.1.3 Quartz, Feldspar and Lithic (QFL) Plots

QFL plot shoes that most of the sample are plotted near to the quartz Arenite very few are plotted in the Sublithic Arenite Portion(Fig.3.4A.B) (Pettijohn et al. 1973; Pettijohn 1974).All the samples are plotted indicate that the provenance of sediments was continental block(Fig.3.4C).

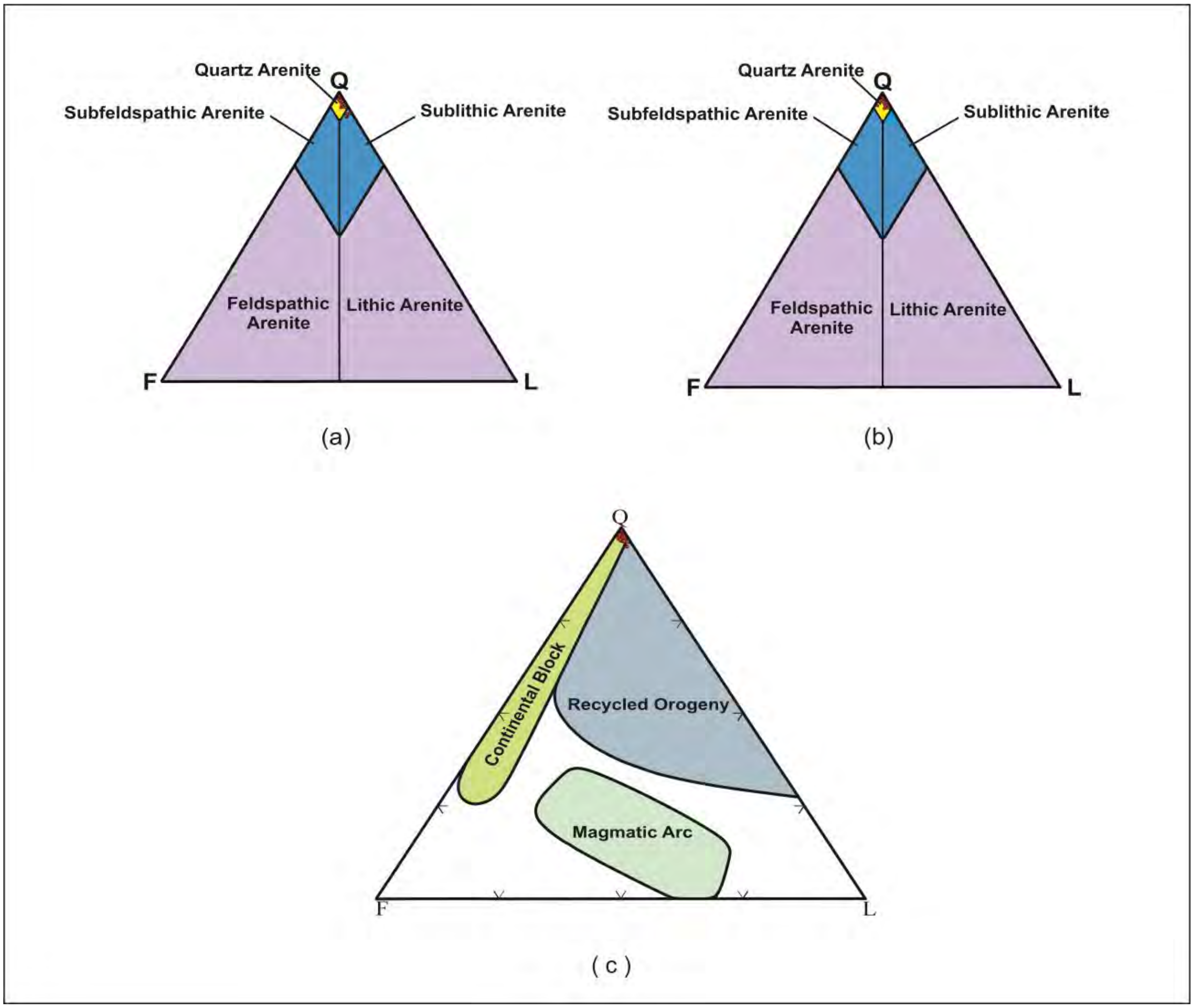

Figure 3.7. The QFL diagram of the Datta Formation and interpretation of the provenance. (a) Nammal Gorge and (b) Zaluch Nala (Pettijohn et al. 1973; Pettijohn 1974). (C) QFL tectonic setting discrimination plot for the sandstones (Dickinson et al., 1983).

3.3 Geochemistry

We selected 20 out of 71 samples of sandstones from both sections for geochemical analysis. These samples were crushed for 60 s using Herzog Gyromill (Simatic C7-621). In addition, 2-mm thick pellets were prepared from the pulverized sample by grinding 20 g of it with 0.4 g of stearic acid for 60 s and were loaded into each sample holder of the X-ray machine (Phillips PW1660) for analysis. As a result several major oxides ,elements were determined such as SiO_2, Al_2O_3, CaO, Fe_2O_3, K_2O, MgO, MnO, Na_2O, P_2O_5, TiO_2 and Cr_2O_3 (Table3.3and3.4) using X-Ray flurescences pectrometry (XRF) and trace elements via ICP-MS (Inductively Coupled Plasma Mass Spectrometry was used to investigate Ni, Sc, Sn, Nb, La, Ti, Ce ,Ba ,Co, Sr, Th, U,V,W And Zr in additional 0.5g of each sample digested in 95°C aqua regia (Perkin Elmer ELAN 9000,Sciex) . In the present work, we used all the necessary data described above to achieve the objectives of this study.

Table 3.3.Percentage of the major oxides of the Datta Formation in the Nammal Gorge.

Sample	SiO_2	Al_2O_3	FeO_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3
ND-1	63	0.58	4.53	0.18	9.56	0.04	0.03	0.05	0.58	0.01	0.003
ND-2	62	20.8	1.08	0.32	0.03	0.07	0.93	3.25	0.07	0.01	0.02
ND-3	58.7	1.87	28.15	0.75	1.53	0.01	0.1	0.38	0.06	0.57	0.01
ND-3	87.3	3.45	0.75	0.03	0.08	0.05	0.12	0.35	0.03	0.01	0.04
ND-4	92.1	1.6	0.81	0.17	0.03	0.01	0.08	1.16	0.04	0.01	0.04
ND-5	65.2	1.35	28.5	0.05	0.33	0.04	0.1	0.08	0.06	0.32	0.032
ND-6	55.8	22.5	0.84	0.2	0.04	0.07	0.62	2.25	0.07	0.02	0.017
ND-7	52.9	24.7	1.90	0.38	0.05	0.02	1.15	3.52	0.05	0.29	0.018
ND-8	7.86	4.15	10.35	12.0	25.5	0.11	0.43	0.24	0.06	0.01	0.018
ND-9	50.6	21.6	6.53	0.56	0.08	0.01	2.15	1.35	0.13	0.11	0.011
ND-10	75.9	2.21	5.75	7.23	15.7	0.12	0.2	0.21	0.05	0.01	0.023

Table 3.4. Percentage of the major oxides of the Datta Formation in Zaluch Nala.

Sample	SiO_2	Al_2O_3	FeO_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3
ZD-1	48.7	30.5	1.75	0.56	0.77	0.15	2	1.7	0.17	0.01	0.025
ZD-2	83.94	3.96	8.08	0.06	0.16	0.01	0.08	0.46	0.12	0.01	0.029
ZD-3	95.62	2.02	0.78	0.02	0.04	0.01	0.1	0.14	0.01	0.01	0.013
ZD-4	62.91	22.34	1.3	0.61	0.25	0.1	2.86	1.36	0.07	0.01	0.016
ZD-5	64.64	21.19	1.22	0.49	0.11	0.08	2.7	1.33	0.06	0.01	0.019
ZD-6	59.81	25.55	0.92	0.26	0.19	0.05	0.75	2.03	0.05	0.01	0.018
ZD-7	66,62	20.35	0.66	0.25	0.06	0.05	0.66	3.11	0.07	0.01	0.007
ZD-8	20.06	11.1	13.8	7.82	17.2	0.05	1	0.55	0.05	0.2	0.021
ZD-9	52.06	28.4	2.7	0.92	0.16	0.09	2.61	1.53	0.08	0.01	0.02
ZD-10	58.3	4.13	4.9	4.09	11.5	0.02	0.32	0.5	0.02	0.14	0.013

Table 3.5. The proportions of trace elements (ppm) of the studied samples of the Datta Formation in Nammal Gorge

Sample	Ni	Sc	Sn	Nb	La	Ti	Ce	Ba	Co	Sr	Th	U	V	W	Zr
ND-1	20	3	2	1.4	5.3	0.2	29.8	77	1.5	132.5	0.8	4.4	32	0.5	70.8
ND-2	24	24	9	60.9	60.9	0.3	124.3	163	9.1	134.8	30.9	15	189	5.2	954.6
ND-3	20	17	1	6	8.5	0.1	17	28	34.3	98	5.4	1.3	54	1.4	241.8
ND-4	20	3	2	8.3	14.6	0.1	33.1	57	2.4	84.5	11.4	1.5	62	2.5	207.7
ND-5	20	4	2	20.8	32.3	0.1	71.7	39	2.8	67.3	20.3	3.7	39	4.1	1051
ND-6	20	12	1	2.1	5.3	0.1	11.1	24	23.9	21.5	3.6	0.4	46	1.8	50.4
ND-7	33	21	7	41.4	108.8	0.1	286.7	113	9.7	68.3	26.9	10.8	127	3.6	638.4
ND-8	28	27	9	63.8	56.3	0.1	104.6	180	8.1	143.2	33.5	13.3	185	5.5	839.5
ND-9	20	6	1	4.9	14.3	0.1	27.5	37	7.4	121.8	4.3	0.4	36	0.6	45.9
ND-10	20	19	6	24.7	69.5	0.3	136.9	187	7.2	187.8	27.3	3.9	174	3.1	366.4

Table 3.6. The proportions of trace elements (ppm) of the studied samples of the Datta Formation in Zaluch Nala.

Sample	Ni	Sc	Sn	Nb	La	Ti	Ce	Ba	Co	Sr	Th	U	V	W	Zr
ZD-1	23	26	6	33.5	96.5	0.2	237.1	309	4.5	422.8	43.5	6.9	145	4.1	799.9
ZD-2	<20	4	<1	8.8	28.1	0.1	82.2	42	2.3	81.6	16.6	7	34	2.3	407.2
ZD-3	<20	1	<1	2.4	7.6	<0.1	15.4	30	1.2	28.2	2.5	0.5	11	1.1	58.9
ZD-4	24	19	<1	26	62	<0.1	130.1	305	2.9	160.3	24.9	3.9	155	2.5	414.7
ZD-5	<20	18	5	24.6	56.6	0.2	117.4	324	3.4	135.3	25.1	3.9	136	3	417
ZD-6	<20	19	2	39.1	50.2	0.1	82.7	128	3.8	115.4	30.9	6	129	5	733
ZD-7	<20	23	7	55.4	105.5	<0.1	311.6	140	2.5	81.5	41.1	9.8	116	5	721
ZD-8	<20	12	2	11.2	32.1	<0.1	68.5	145	15.5	186.3	12.7	1.8	79	2.5	101.6
ZD-9	34	19	6	30.7	74.3	<0.1	144.8	248	13	266.1	29.9	3.5	189	3.9	303.2
ZD-10	<20	6	<1	9.6	22.5	<0.1	48.8	51	8.2	125.4	8.9	1.5	60	1.6	331.8

3.3.1 Proxies Based on Geochemistry

Different geochemical proxies are used in sliciclastic sediments to determine different phenomenon.

3.3.1.1 Harker Diagram

In the Datta Formation sandstones have high SiO_2 contents averaging 96.95% in both sections. Variations in the major element geochemistry of the Datta Formation sandstones are shown on the Harker Diagrams. This diagram show the chemical constituents as a proportion to the SiO_2 i.e.Al_2O_3,Na_2O,K_2O and Fe_2O_3. (Fig. 3.7). Diagram shows a greater quartz content and a smaller proportion of other detrital grains (O. AitMalek et al., 2016).

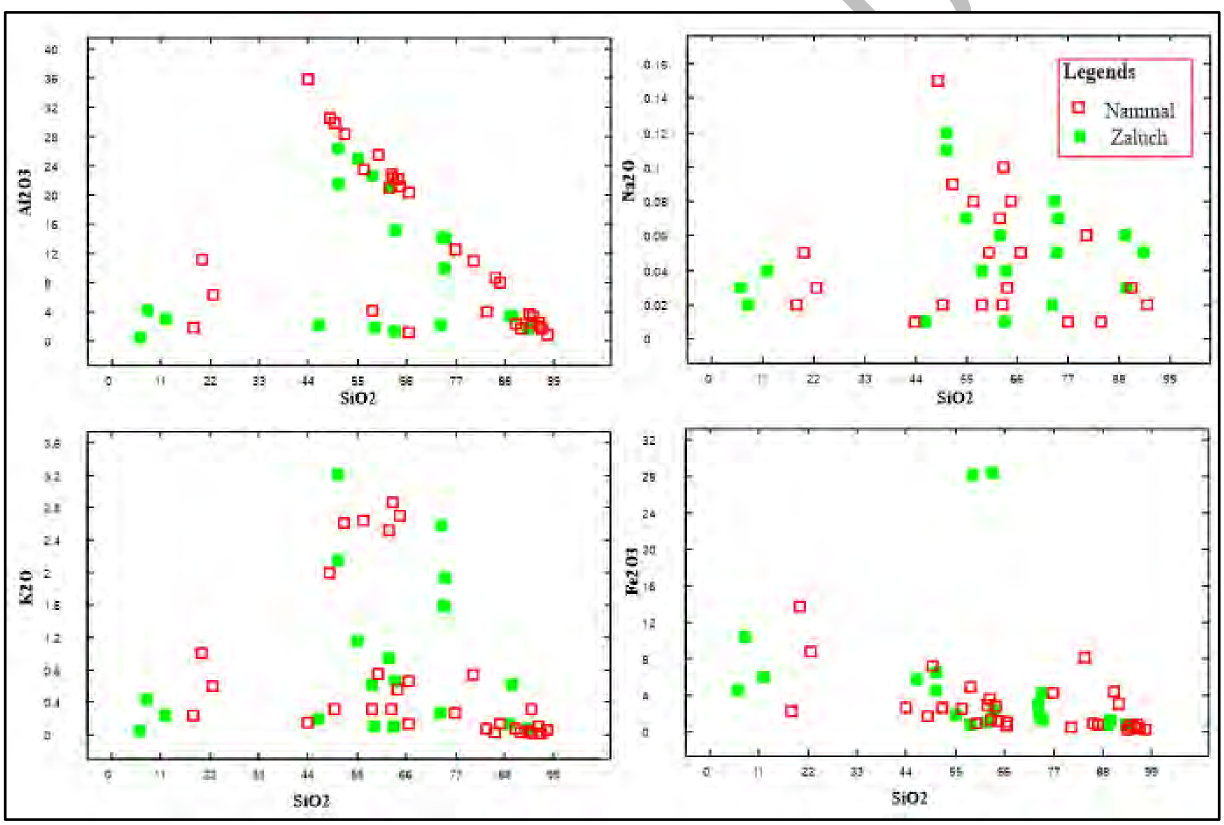

Figure. 3.8. Harker variation diagrams for the Datta Formation sandstones. A greater quartz content and a smaller proportion of other detrital grains (O. AitMalek et all, 2016)

3.3.1.2 Weathering and recycling

Th/U vs Th (ppm) bivariate plot (Fig.3.9) McLennan et al., 1993) indicates that the most of samples are plotted above the Upper Crust (UC) and close to the weathering Trend Line. Only three samples are plotted in the Depleted Mantle Source.

The Zr/Sc vs Th/Sc (Fig.3.10) McLennan et al., 1993) displays that most of the sample plotted around the junction between increasing recycle components and compositional variations.

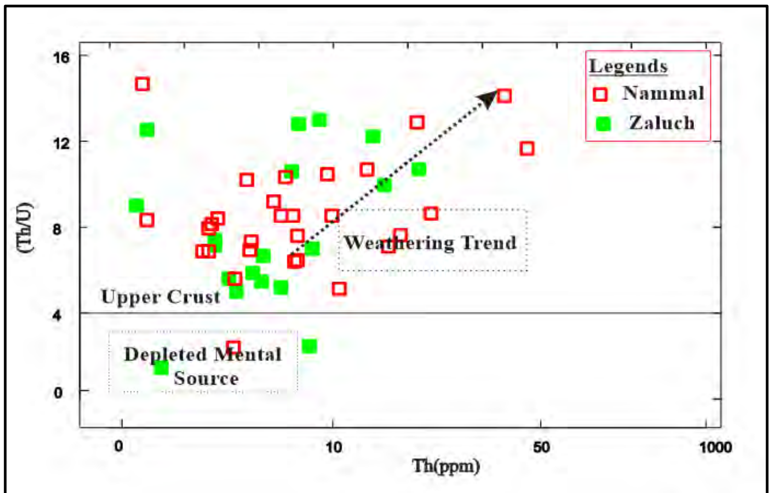

Figure 3.9. Th/U vs. Th (ppm) bivariate plot which interpret the weathering Trend (McLennan et al., 19)

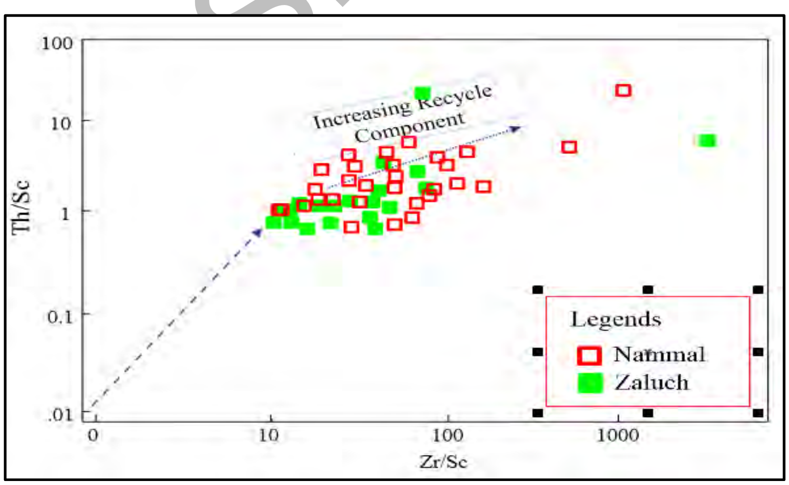

Figure 3.10. The Zr/Sc vs. Th/Sc bivariate plot show that the sediments are recycled (McLennan et al., 1993).

3.3.1.3 Tectonic Setting

(La/Sm) N vs Nb/La Plot (Fig3.11) (John et al.,2003; Boniface and Maruma, 2012) shows that most of the sample are plotted in the passive margin, very few are plotted in the active continental margin but it is very less in number. The minimum value of Nb/La value is 0.1 but the maximum value is 0.9.

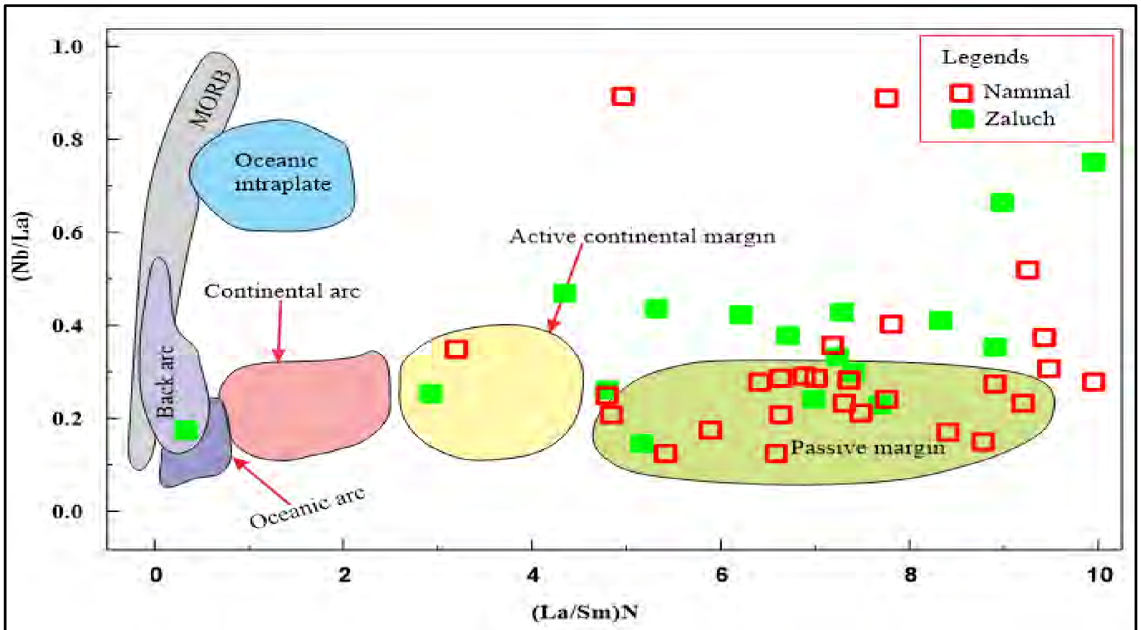

Figure 3.11 (La/Sm) N vs. Nb/La plot (John et al., 2003) indicating Sedimentation processes on a passive margin setting.

CHAPTER-04

Interpretation and Discussion

This chapter comprises the interpretation and discussion of the analysis of the data set in detail. The interpretation of the data set is carried out in three phases. In the first phase, the lithofacies have been discussed on the basis of field observation. In the second phase, petrographic studies have been discussed and in the third phase, the lithofacies have been interpreted on geochemistry basis.

4.1 Sedimentary Lithofacies

The Datta Formation in the western Salt Range i.e., Nammal Gorge and Zaluch Nala sections (Fig. 3.1) includes different lithofacies. Based on detailed field investigation and petrographic studies, five lithofacies were established in the western Salt Range.

4.1.1 Conglomerate Lithofacies

This lithofacies is white, light and dark grey in colour and lies in the lower part of the formation. It is consisting of angular to sub-angular and well-rounded pebbles of quartz, chert, and lithic fragment. It has finer sediments as a matrix, but it dominantly consists of granule and pebble-size particles. Therefore, this lithofacies is named as clast supported conglomerate (Boggs, 2006, 2009). Pebbly quartz and quartzite are the most common constituents in the whole lithofacies ranging from 90 to 95%. Poorly sorted dolomite and sandstone clasts are also present, but these constitute less than 10%. The sedimentary structures in this lithofacies are mainly graded bedding and cross-bedding. Erosional bedding plans are observed only in the Nammal Gorge section. The finning upward trend and well-developed trough cross-bedding are the common features of this lithofacies. According to the above description, angular dolomitic fragments show that these clasts were derived from the underlying Kingriali Dolomite. (Iqbal et al., 2015). The petromict conglomerates have a high rate of erosion because they have soluble dolomite clasts (Smith etal., 2006). The quartzose conglomerate lithofacies have ultrastable clasts which show the clast formation in the humid paleoclimate. In the present lithofacies the finning upward trend and well-developed trough cross-bedding show high energy conditions (Hoy and Ridgway 2003) and represent that the conglomerate lithofacies are point bar deposits.

4.1.2 Medium to Coarse Sandstone Lithofacies

According to the field observation this lithofacies consists of thick to very thick bedded sandstone and lies mostly in the lower part of the studied sections. It is light grey to dark grey and dark brown in colour and displays lenticular bedding and lateral pinching in both sections. Cross bedding, large-scale trough cross-beds, as well as cross laminations, are the common sedimentary structures. On the basis of the petrographic study, the sandstones are coarse to very coarse grained and have a finning upward sequence which shows the fluctuation in the depositional environment. This lithofacies is composed of quartz, with very minor amount of other grains i.e., feldspars and lithic fragments. Most of the grains are well-rounded to sub-round but in some places sub-angular fragments are also observed. Mostly, the grains are mono-crystalline but in some thin sections polycrystalline grains are observed but it is very less in amount (Fig. 3.6C). The sorting of grains increases upward so the upper part of the lithofacies is well sorted as compared to the lower part. According to the above discussion, the well-developed large-scale trough cross-bedding and cross-laminations indicate the migration of mega current ripples (Coleman 1981). This large-scale trough cross-bedding and cross laminations show the high energy conditions and the depositional environment of this lithofacies in a channel (Freedman and Sanders, 1978). The upper part of the lithofacies has cross-bedding which shows less sedimentation rate and marks the reworking of sediments (Reinbeck and Singh, 1975). According to the above discussion, the depositional environment of this lithofacies is the channel belt region.

4.1.3 Fine to Medium Sandstone Lithofacies

According to field investigation this lithofacies lies in the middle part and mainly consists of medium to thick-bedded sandstone with interbedded shale. In both sections lenticular bedding and pinching upward sequences are observed. The thickness of individual bed in outcrop are different (Fig 3.1). The lower part of this lithofacies in the formation is fine to medium grain sandstone. The fining upward of this lithofacies shows sandstone siltstone and shale sequence. Ripple marks, mud cracks, bioturbation, and cross-bedding (Fig 3.2A) are the common sedimentary structures of this lithofacies but do not have trough cross-bedding. According to the petrographic study the sandstones of this lithofacies are sub-angular to rounded and fine to medium grained and more than 90% quartz are monocrystalline (Fig 3.5B). The quartz grains are well sorted and possess iron oxide as pore filling cement. On the basis of above discussion, the finning upward sequence with associated shale beds indicates environmental conditions of the upper flow regime during flooding seasons, overbank flow, natural levees and crevasse splays (Boggs, 2009).

4.1.4 Interbedded Shale and Siltstone Lithofacies

According to field observation and petrographic study this lithofacies was identified at the middle and upper part of the Formation. It is comprised of shale and siltstone with interbedded fine to medium grain sandstone. Such type of lithofacies was identified in the floodplain setting (Ingram, 1954). Petrographic study shows that fine grain sandstone is composed of more than 90% of quartz. The quartz grains are mostly rounded and well sorted, and cross laminations are observed in the sandstone beds (Fig. 3.5B), while bioturbation and mud cracks are observed in the mud-dominated beds. In the lower part of the sandstone beds Plants remains (Fig 3.2B) are observed. Oxidation is a common phenomenon and fire clay is observed in the sandstone and siltstone beds. In the light of the above discussion, the deposition of fine-grained siliciclastic materials show low energy condition (Nichols, 2000). This type of conditions are usually observed in the fluvial channel margin and floodplain settings and also in the delta plain environments (Freedman and Sanders, 1978). The presence of plant remains, and other features show deposition in floodplain environments. The presence of fire clay shows weathering and soil forming processes and indicates that the deposition was not completely underwater but had undergone episodic exposure which are observed in flood plain environment (Tucker 1988).

4.1.5 Interbedded Shale and Dolomite Lithofacies

This lithofacies is comprised of yellowish-brown dolomite with interbedded black to dark brown carbonaceous shale (Fig. 3.3D) and associated with light to dark fine to very fine grain sandstone/siltstone. The petrographic study shows that most of the dolomite are pure (Fig. 3.5D) but in some places quartz grains are present. In the shale beds vertical and inclined burrows are observed and the associated sandstone/siltstone contain symmetrical ripples. The carbonates have shale and some quartz-rich sand beds, showing siliciclastic influx. The fining upward of the siliciclastic grains show the decline of siliciclastic supply and the deposition is less disturbed which show calm condition. These conditions are generally observed in lagoonal environments (Catuneanu, 2006).

4.2 Facies Association

Three lithofacies associations are recognized from different lithofacies. These associations belong to the fluvial-deltaic environments. The three types of facies associations are discussed below:

4.2.1 Channel Belt Facies Association

The channel belt facies associations consist of conglomerate lithofacies and medium to coarse sandstone lithofacies. This association is present in basal part of the formation in both sections i.e., Nammal Gorge and Zaluch Nala. Trough cross bedding are mostly common sedimentary structure, but at the base of conglomerates erosional bedding plains are also observed.This lithofacies association is interpreted as bar deposits with a multi braided channels (Tucker 1992).

4.2.2 Channel Margin and Floodplain Lithofacies Association

This association is comprising of fine to medium sandstone lithofacies and interbedded shale and siltstone lithofacies. The sandstone of this associations is different from channel belt facies association. Mudcraks, ripple marks, and bioturbation are the common feature of this association which are not observed in channel belt facies association. Trough cross bedding are not observed but in some places planer cross bedding are observed.

4.2.3 Lagoonal Lithofacies Associations

This association occurs in the middle and upper parts of the formation,which is comprised of interbedded shale and dolomite with some minor sandstone/siltstone lithofacies. The shale of this lithofacies is different from floodplain lithofacies which is black dark brown and ash color. The sandstones/siltstones are fine-grained have symmetrical ripples but minor cross-bedding are observed in some places.

Table 4.1. Description of Lithofacies and their associations.

Lithofacies	Field features	Interpretation	Lithofacies association
Conglomerate lithofacies	Angular to sub-angular and well-rounded pebbles of quartz. Clast supported conglomerate	finning upward trend , well developed trough cross bedding indicate point bar depositions.	
Medium to Coarse sandstone lithofacies	lenticular bedding and lateral pinching Cross bedding, large-scale trough cross-beds	the depositional environment is channel belt region	Channel belt lithofacies associations
Fine to Medium sandstone lithofacies	lenticular bedding and pinching upward sequences Ripple marks, Mud cracks	Flood plain settings	
Interbedded shale and siltstone lithofacies	shale and siltstone with interbedded fine to medium grain sandstone.	fluvial channel margin and floodplain settings	Channel margin or floodplain lithofacies associations
Interbeded shale and dolomite lithofacies	Yellowish-brown dolomite with interbedded black carbonaceous shale.	Shows calm condition lagoonal environments	Lagoonal lithofacies associations

4.3 Composition of Grains

The bulk framework grain composition plots (QFL) and certain geochemical proxies interpretation provided evidence about the composition of grains. The sandstones are mostly compositionally and texturally mature quartz arenites (Fig. 3.4A, B). The name suggested for sandstone after the (QFL) plots for sandstone classification are quartzitic/quartz arenites sandstone and represents a bunch of samples near the quartz apex and show that mostly sediments derived from the stable continental/cratonic (Fig. 3.4C) block under the hot and humid paleoclimate (Iqbal et al., 2021). During weathering and recycling unstable minerals such as feldspar were dissolved and differentially removed, and as a result the pure quartz was concentrated.

4.4 Geochemical Proxies

Variations in the major element geochemistry of the Datta Formation sandstones are shown on the Harker Diagrams (Fig. 3.7). The linear relationship of Al_2O_3, Na_2O, K_2O and Fe_2O_3 with SiO_2 in the Datta Formation sandstones is visible in these Harker variation diagrams. In general, SiO_2 increases and Al_2O_3, Fe_2O_3, Na_2O, and K_2O decrease in the Datta Formation sandstones due to the increase in mineralogical maturity (Fig. 3.7). This mineralogical maturity is characterized by an increase in the quartz content and a decrease in unstable detrital grains (e.g., feldspar and volcanic rock fragments) in the Datta Formation sandstones, which also reflects a stratigraphic trend. The negative correlation of SiO_2 with the other major oxides shows that the Datta sandstones have high SiO_2 contents and having more than 90% quartz (Osman 1996). The high content of SiO_2 and lack of other oxides indicate that studied samples contain quartz arenites which was deposited as a result of deltaic environment.

4.5 Weathering and Recycling

The oxidation and subsequent dissolution of U brought on by weathering lead the Th/U ratios to exceed the highest crustal levels. On the other side, additional sedimentary processes can lead to U enrichment, which would reduce the Th/U ratio. In such cases, a low Th/U ratio will be accompanied with a high U content. Most upper crustal crust typically has a Th/U ratio of between 3.5 and 4.0 (McLennan et al., 1993). In this instance, the number rises over 3.5-4.0 and reaches as high as 22.8 in one sample of Zaluch section. The average value of Th/U is 7.11, which indicates significant chemical weathering during the deposition of the Jurassic Datta Formation. Th/U vs. Th (ppm) bivariate plot (McLennan et al., 1993) is used to interpret the weathering trend of the siliciclastics.Presently, the plot indicates that more than 90% of values are above the upper Continental Crust (UCC) (Fig 3.9). The Th values are generally more than the depleted mantle source. Therefore, the higher position of the Jurassic samples on the Th/U axis above the UCC line (Fig. 3.9) indicates increasing intensity of chemical weathering.Zr/Sc vs. Th/Sc bivariant plot(Fig 3.10) is normally used to identify the limit to which the sediments are recycled. The Zr/Sc ratio is helpful indicator of weathering enrichments. According to the geochemistry data the concentration of Zr increases mostly in Nammal Gorge section as compared to Zaluch Nala section. The average Zr/Sc ratio of studied samples is 56.38, while the Th/Sc average ratios is 2.33(greater than 1), which indicates that the sediments are highly recycled, so the unstable mineral were dissolved and the stable mineral like Zr is remained(Fig 3.10)

4.6 Tectonic Settings

The sediments from the oceanic arc will have a high Nb/La ratio and a low (La/Sm) N ratio in the opposite range. While sediments from the source of the continental arc and an acidic source have a low Nb/La ratio, the opposing side has a high (La/Sm) N ratio (John et al., 2003).The (La/Sm) N vs. Nb/La plot indicates that the analyzed sections selected samples primarily plot in passive margin setting, while few of them plot in continental arc (Fig. 3.11). This bivariate plot demonstrates that all of the sediments came from felsic sources, with no mixture coming from basic sources.

4.7 Depositional Environment

On the basis of field investigation and petrographic study, five lithofacies were established in the Datta Formation western Salt Range i.e., Nammal Gorge and Zaluch Nala sections. These lithofacies are associated with three distinct assemblages on the basis of depositional setting, including the (Channel Belt lithofacies association), (Channel Margin and flood plain lithofacies association) and (Lagoonal lithofacies association).The channel belt lithofacies association predominates in the bottom portion of the lithological section, where it displays lenticular bedding with pinching behaviour on both sides of a thick-massive unit, illuminating sandstone deposition in a constrained environment. This association is overlain by channel margin and flood plain lithofacies association. The sandstone of this associations is different from channel belt facies association. Mudcraks ripple marks and bioturbation are the common feature which show low energy condition than channel belt facies associations. Channel margin lithofacies association is overlain by lagoonal lithofacies associations. Which is comprised of interbedded shale and dolomite with some miner sandstone/siltstone lithofacies. It have vertical and inclined burrows which show calm condition. Moreover, the sedimentological feature of sandstone and siltstone of the studied area composed of dominantly cross bedded sandstone reveals the early flow direction of sediments in the north-northwest. According to the geochemical proxies the sediments of the Datta Formation in the western Salt Range is highly weathered and recycled (Figs. 3.9, 3.10). The combined lithofacies association indicates that the

Jurassic Datta Formation in the western Salt Range exists more probably in fluvial-deltaic environment (Fig. 4.1).

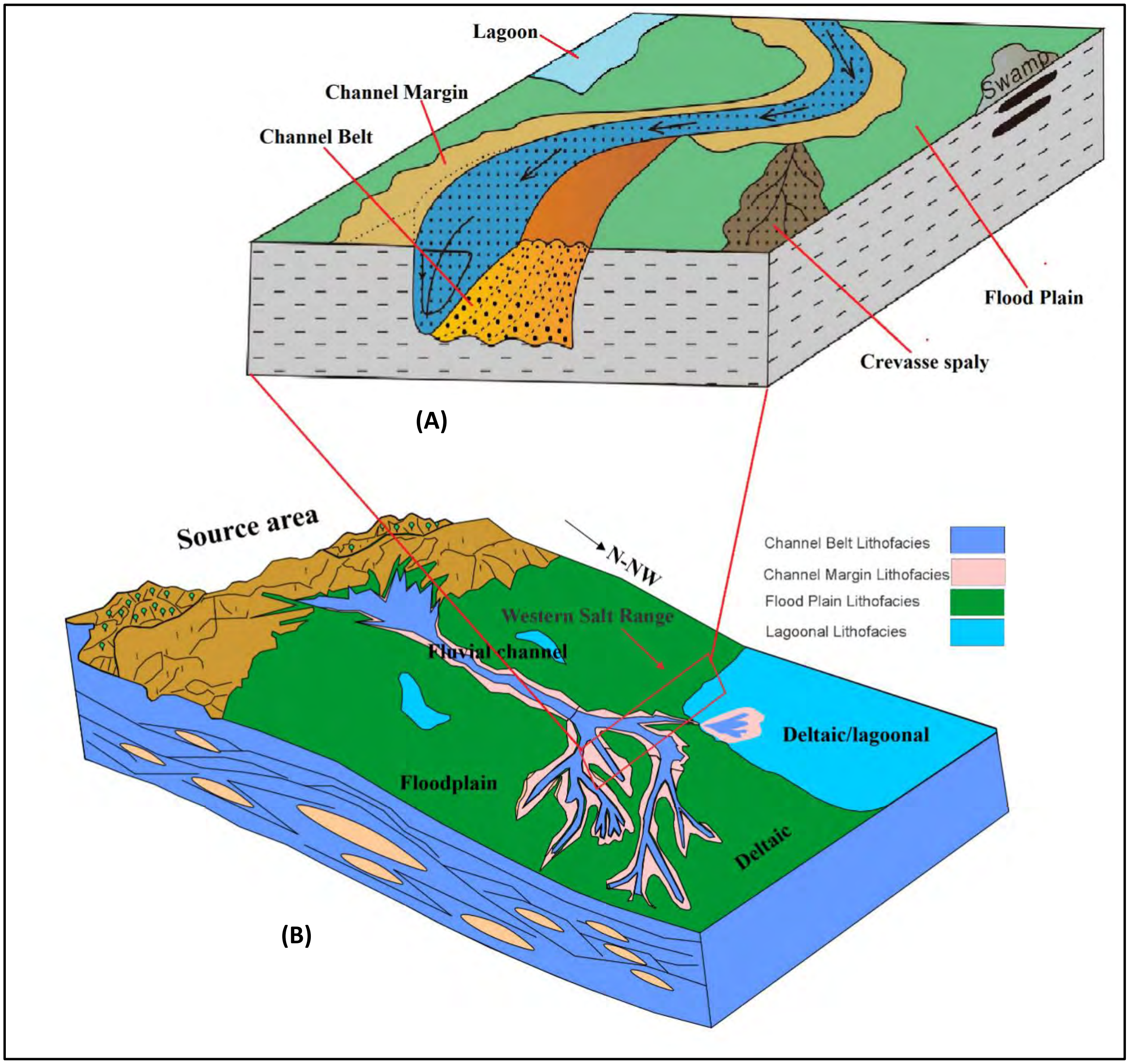

Figure 4.1. Depositional model for different lithofacies in Fluvial Deltaic Depositional System (modified from Galloway, 1981).

Summary

The Datta Formation in the western Salt Range, Pakistan comprises of thick sliciclastic rock unit with some carbonate deposits. In the studied sections i.e., Nammal Gorge and Zaluch Nala section, the formation is mainly consisting of conglomerate, sandstone, shale, fireclay, and some carbonaceous material.On the basis of field observation, five different types of lithofacies were established. Conglomerate lithofacies, which are white, light, and dark grey in colour and contain angular to well-rounded pebbles of quartz, chert, and lithic fragment. Mostly contain granule and pebble-size particles but fine grains are also present and lies in the lower part of the formation .The depositional setting of this lithofacies as point bar deposits under high energy conditions. The medium to coarse sandstone lithofacies is light grey to dark grey and dark brown in color and is present in the form of lenticular beds. Cross-bedding, large-scale trough cross-beds and cross laminations are the common sedimentary structures.This lithofacies was deposited in the channel belt area. The fine to medium sandstone lithofacies composed of fine-grained sandstone, siltstone and shale and it shows fining upward sequence. Ripple marks, mud cracks, bioturbation, symmetrical ripples, and cross bedding are the sedimentary structures present in this lithofacies. The depositional environment of this lithofacies is channel margin near to the floodplain environments. The middle and upper part of the formation consists of interbedded shale and siltstone lithofacies, which are comprised of shale and siltstone with interbedded fine to medium grain sandstone. Such type of lithofacies is deposited in the Flood plain environment. The fifth and last lithofacies which were identified in the field observation is interceded dolomite and shale lithofacies which is comprised of yellowish-brown dolomite with interbedded black to dark brown carbonaceous shale and associated with light to dark fine to very fine grain sandstone/siltstone. Most of the dolomite beds are pure but in some thin sections the sliciclastic influx are recorded. This type of lithofacies is deposited in calm conditions so the depositional setting of this lithofacies is lagoonal environment. In the light of above lathofacies three types of association were recognized namely channel belt lithofacies association, channel margin and flood plain lithofacies association, and lagoonal facies association.Petrographic results show that Sandstones are mostly mature quartz arenites in terms of composition and texture. Minor amounts of feldspar, lithic fragments, phyllosilicates minerals and denser minerals are also observed. The quartz grains are mostly rounded and will sorted but sub angular grains are also observed. Geochemistry data also demonstrate several phenomena such is the Harker diagram showing the linear relationship of Al_2O_3, Na_2O, K_2O and Fe_2O_3 with SiO_2. The SiO_2 increases and TiO_2, Al_2O_3, Fe_2O_3, Na_2O, and K_2O decrease in the Datta Formation sandstones due to the increase in mineralogical maturity. The Th/U ratio average is 7.11, which is above the standard value (3.5 to 4.0). The Th/U vs. Th (ppm)bivariate plot shows that more than 90% of values are above the Upper Continental Crust (UCC), It demonstrates the intense chemical weathering of sediments. The average Zr/Sc ratio of studied samples is 56.38, while the Th/Sc average ratio is 2.33 which is greater than 1, The Zr/Sc vs. Th/Sc bivariate plot shows that the sediments are highly recycled, resulting in the dissolution of unstable minerals and the preservation of stable minerals like Zr. The (La/Sm) N vs. Nb/LaPlot reveals that the majority of the samples are plotted in the passive margin, indicating that the sediments were derived from felsic sources.The aforesaid data led us to the conclusion that the Jurassic Datta Formation depositional setting in the western Salt Range most likely occurs in a fluvial-deltaic environment with some marine influx.

Conclusion

Field investigations and petrographic studies show that the Datta Formation's sandstone is compositionally and texturally mature quartz arenites. Field observation and petrographic study suggest that the Datta Formation shows three lithofacies associations on the basis of grain size and different sedimentary structures in the studied sections. The lithofacies associations show channel belt lithofacies associations, channel margin/flood plain lithofacies associations, and lagoonal lithofacies association. The geochemical plots reveal that sediments are highly weathered and recycled which is indicated by stable minerals preservation. The (La/Sm) N vs. Nb/La plot indicates that the selected samples are primarily plotted in passive margin setting. Detailed lithofacies associations, petrographic study and geochemical analysis reveal that the depositional setting of the Datta Formation in the western Salt Range i.e. Nammal Gorge and Zaluch Nala Sections are fluvial deltaic environment with some marine influence.

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