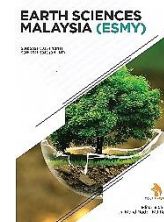


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## RESEARCH ARTICLE

**MESOZOIC DELTAIC SYSTEM AND SEQUENCE STRATIGRAPHIC MODEL OF THE LOWER JURASSIC DATTA FORMATION ALONG THE WESTERN SALT RANGE, PAKISTAN**Abdul Jabbar<sup>a</sup>, Ashar Khan<sup>b</sup>, Rizwan Sarwar Awan<sup>c</sup>, Sahib Khan<sup>d</sup>, Khawaja Hasnain Iltaf<sup>e</sup><sup>a</sup>Department of Earth Sciences, University of Sargodha, University Road, Sargodha, Punjab 40100, Pakistan<sup>b</sup>Water and Power Development Authority, Lahore 54000, Pakistan<sup>c</sup>School of Resources and Environmental Engineering, Hefei University of Technology, Hefei 230009, China<sup>d</sup>Oil and Gas Development Company Limited, Pakistan<sup>e</sup>Department of Earth & Environmental Sciences, The University of Texas at Arlington, TX 76019, USA<sup>\*</sup>Corresponding Author Email: [rsageoche@gmail.com](mailto:rsageoche@gmail.com)

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## ABSTRACT

In this research, the Early Jurassic Datta Formation from three outcrop sections of the western Salt Range has been extensively studied to elucidate facies architecture, sedimentary features, diagenetic features, sequence stratigraphy, and depositional model. Datta Formation is well exposed with massive thickness in the western Salt Range and the Trans Indus Ranges, while tapering in the central Salt Range further eastward, it dies out. Its mainly dominated by variegated sandstone, siltstone, shale, fire clays, laterites, and carbonates. Seven lithofacies has been identified and interpreted in the Datta Formation, i.e., (i). Fluvial Meandering Lithofacies (JDL-01), (ii). Braided Fluvial Lithofacies (JDL-02), (iii). Lateritic Lithofacies (JDL-03), (iv). Flood Plain Lithofacies (JDL-04), (v). Siliciclastic Lagoon Lithofacies (JDL-05), (vi). Carbonates dominant Lagoon Lithofacies (JDL-06), (vii). Swamps related Deltaic Lithofacies (JDL-07). Sequence stratigraphic analysis is primarily based on recognizing sequence surfaces, fining-coarsening upward trends, and types of facies. Two transgressive-regressive cycles are identified in the south-eastern section (Kassan Nala and Kaowali sections), while four sequences are identified in the Nammal Gorge section. These sequences are started with the underlying sequence boundary of LST and ended with the sequence bounding surface after HST. Datta Formation is possibly deposited in fluvial to deltaic environments in the study area, revealing a prograding delta with a shoreline oriented in the SW-NE direction and the siliciclastic detritus fed the fluvial system running over the Indian cratonic basement in the direction of N-NW. The lower part of the formation is deposited in fluvial settings, probably in the incised valley. The point bar sequences result from meandering channel facies and show association with overlying flood plain/overbank facies. Moreover, the lagoonal facies mainly covered the upper part of the formation and displayed mixed lithologies of delta plain to delta front setting. However, the repetition of these lithofacies in the study area at several points indicates the recurrence of depositional phases. The carbonaceous shales and coal streaks are evident by the presence of swamp or marshy lands. These conditions meet the criteria of deltaic settings. Furthermore, several laterites and fire clay horizons are also argue periodic sub-aerial exposure of the depositional area. Thus it is concluded that the depositional area lies in a fluvial to deltaic setting with major distributary channels and their flood plain in the adjoining delta plain to delta front part.

## KEYWORDS

Deltaic; Sequence; Laterite; Salt Range; Lithofacies; Paleoenvironment

## 1. INTRODUCTION

The Lower Jurassic siliciclastic sequence of the Datta Formation is well exposed in the Western Salt and Trans Indus Ranges, Hazara area, Kohat, and Kalachitta ranges in northern Pakistan. Its type section is located in the Datta Nala of the Surghar Range west of the Kalabagh fault (Figure 1). In the study area, it is composed of sandstone interbedded with siltstone, carbonaceous clays, and coal stringers. While, northwards, the siliciclastic facies change to mixed clastic and carbonate facies (Shah, 1977). The formation thickness at the type locality is 212 m. However, its thickness in the Nammal section decreases to 150 m, and further eastward constantly

decreases and ultimately pinches out in the eastern Salt Range. In other studied sections, i.e., Kaowali and Kasanwala sections, the thickness of the formation is 121.5 and 83.7 m. The location of the studied sections in the Western Salt Range is shown in Figure 2. This area has been in the thorough attention of famous geoscientists due to the completely exposed stratigraphic sequence from the Pre-Cambrian age to Recent. Datta Formation is a significant reservoir rock in the western Potwar and Kohat plateaus (Kadri, 1995). Most previous studies dealt with the stratigraphic and regional description of the Datta Formation. However, inadequate details are available on lithofacies and the depositional setting of the Datta Formation. This research is mainly based on geological field works and

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laboratory experiments. The main objectives of this research are as follow:

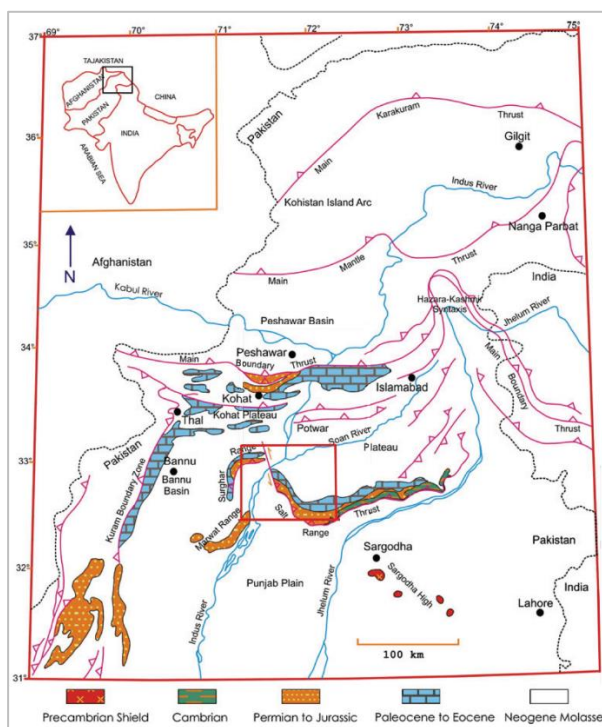
1. To understand the architectural sequence stratigraphy of the Datta Formation.
2. To interpret the palaeoenvironments settings of different lithofacies in the Datta Formation.
3. To present a unique palaeo-depositional model of the Datta Formation.

**2. PALEOGEOGRAPHY AND TECTONIC SETTING**

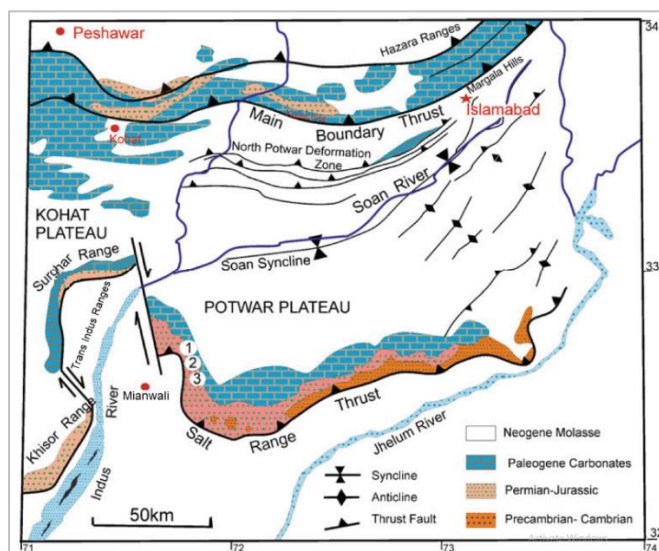
The research area is located in the western Salt Range, where Salt Range Thrust (SRT) marks the southernmost major thrust of the Himalayan system in Pakistan (Chaudhry et al., 1994). The Salt Range occupied a location at the northwestern extremity of the Indian Plate along the Tethyan margin during the Early Jurassic (Arias, 2007; Damborenea, 2002; Rees et al., 1999). With the breakup of Gondwana, the Indian Plate made the longest journey of all drifting continents, about 9,000 kilometers in 160 million years from Gondwana to Asia. Neotethyan ocean most likely disappeared entirely around the early Eocene (~50 Ma) when the Indian Plate was fully sutured to Eurasian Plate (Chatterjee, 2016). The Himalayan mountain range was created by the collision between the Eurasian and Indian plates (Gansser, 1964; Le Fort, 1975). The tectonic

process is still ongoing, and the continuous northward drift of the Indian Plate is uprising Himalayas.

Rifting of the Indian Plate resulted in many normal faults in Potwar Plateau, which were interpreted based on seismic data and geological sections (Kadri, 1995; Kazmi and Jan, 1997). Salt range thrust (SRT) has facilitated about ≥ 20 km shortening in the Salt Range sequence and at least ~ 10 km shortening in Trans Indus Ranges lying in the west of Salt Range (Lillie et al., 1987). Additionally, the low-density evaporites of the Infra-Cambrian Salt Range Formation uplifted the northwestern margin of the Indian Plate. This uplift resulted in the west-northwestward depression in the area and subsequent development of the fluvial system, which in Pakistan resulted in the deposition of the Datta Formation (Iqbal et al., 2015). Ongoing Himalayan orogeny uplifted the Precambrian Cenozoic strata, along the Salt Range Thrust, over the Molasse-type sediments of the Punjab Plain (Baker et al., 1988; Kazmi and Jan 1997). The Salt Range terminates by the Kalabagh Fault from the westward lying Trans Indus Ranges. This turning movement overlaps with a variation in the strike of rock units complemented by faulted lineaments (Gee and Gee, 1989). The Salt and Trans Indus Ranges form the leading thrust front of the Kohat Potwar fold-thrust-belt in the outer Himalayas, whereas Kalachitta and Hazara areas form the southern boundary of the Lesser Himalayas (Figures 1 and 2).



**Figure 1:** Tectonic map of the northwestern Himalayas, Pakistan exhibiting the study area (red box) in the western Salt Range (modified after Abbasi et al., 2012)



**Figure 2:** Locations of studied stratigraphic sections of Nammal (1), Kaowali (2), and Kassar Nala (3) in the western Salt Range.

### 3. STRATIGRAPHY AND SEDIMENTARY STRUCTURES

Precambrian to Miocene succession is exposed in the Salt Range. The oldest rock unit exposed in the area is the Salt Range Formation, while the youngest is the recent conglomerates. Lithostratigraphic units of the Kohat-Potwar area, highlighting the studied formation, are given in Table 1. The base of the Precambrian rocks is not exposed, but subsurface data supports the existence of a metamorphic sequence underneath the Salt Range Formation (Gee and Gee, 1989). The whole sequence of the rocks in the Salt Range is punctuated by several regional and local scale unconformities (Ghazi et al., 2015). In most parts of the Upper Indus Basin, Lower Jurassic is dominated by a thick siliciclastic sequence is known as the Datta Formation, a mixed clastic and carbonate sequence of the Shinawari Formation, an upper carbonate sequence of the Samana Suk Formation (Fatmi and AN, 1977). Datta Formation is well exposed in the western Salt Ranges, Surghar, Marwat, and Sheikh Budin Hills of Trans Indus Ranges and the subsurface of the Kohat and western Potwar foreland-fold-thrust belts (Shah, 1977).

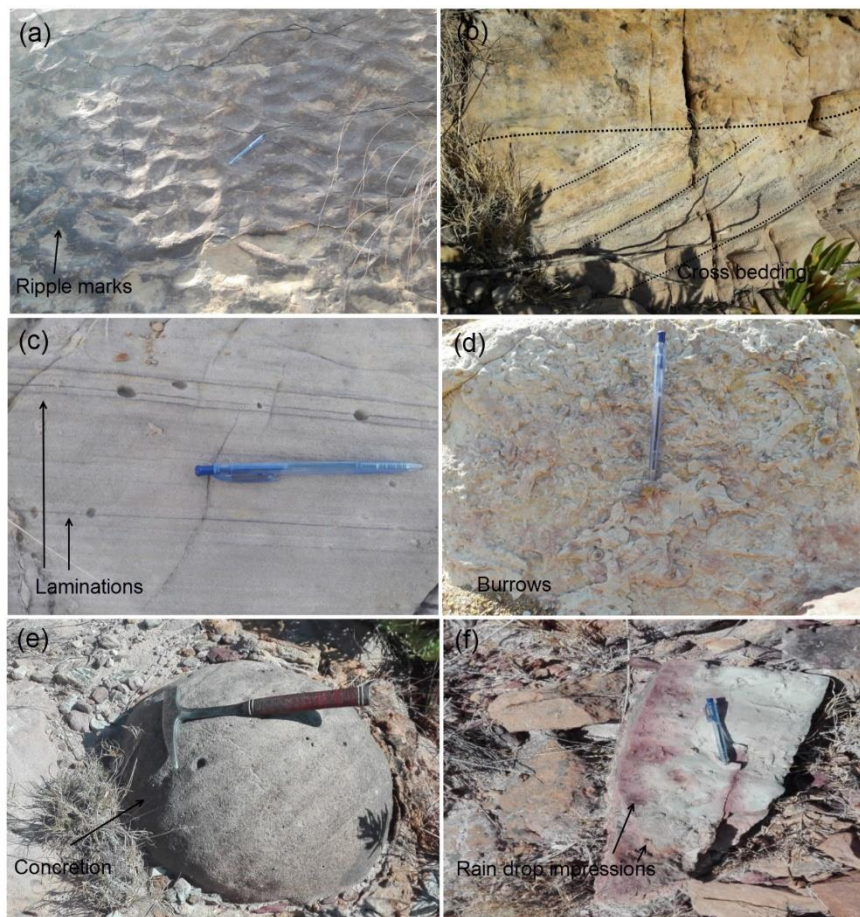
In the western Salt and Surghar Range (Trans Indus Ranges), Datta Formation is mainly comprised of the clastic facies, represented by varicolored sandstone (mostly white silica sand and oxidized hematitic sandstone), siltstone, fireclay, and carbonaceous shale. Marly carbonate facies are restricted only to particular localities. In the range front area, its thickness ranges from 150 to over 350 m; however, it decreases to 15–30 m in the Kalachitta area (Obaid et al., 2005) and about 20 m in the Hazara area (Chaudhry and Ahsan, 1999). In Kohat and Potwar fold thrust-belt, Datta Formation has been encountered in many wells and is composed predominantly of clastic facies with multistorey reservoirs (Kadri, 1995). Eastward in the central Salt Ranges and central and eastern Potwar fold-thrust-belt, the Jurassic rocks are eroded due to Pre-Tertiary uplift (Kazmi and Abbasi, 2008). In most parts of northern Pakistan, Datta Formation

has an unconformable contact with the underlying dolomite sequence of the Kingriali Formation, whereas, in the Hazara region, it rests unconformably over the Precambrian, Paleozoic, and Triassic rocks (Kazmi and Abbasi, 2008) and the upper contact with the Palaeocene Hangu Formation.

Datta Formation possesses various kinds of sedimentary structures. Some of these describe the energy of the depositional system, while others reveal subaerial exposure of sediment mass and vice versa. The relationship of primary sedimentary structures with the environment is essential because every structure is indicative of a specific environment. Ripple marks created by a series of a shallow marine, eolian, lake, or fluvial undulating wavelike forms with either symmetrical or asymmetrical slopes are observed in Datta Formation. In the Kaowali section, transverse catenary out of phase and asymmetrical ripples were found in dolomitic sand beds and symmetrical ripples in sand beds (Figure 3a). Likewise, cross-bedding has been observed at different levels in Datta Formation in all the studied sections. Figure 3(b) shows the trough cross-bedding in pebbly sandstone in Kassin Nala, which its geometry can easily distinguish. Also, the Laminations, small-scale planar bedding characterized by thickness less than 1 cm, have been observed in the Datta Formation, indicating flood plains deposits and low energy conditions in the Kassin Nala section (Figure 3c). Burrows are found in the study area in laminated silts, clays, and sandstone. Field observations revealed the presence of horizontal, inclined, and vertical types of preserved burrows (Figure 3d). Figure 3e shows concertina in the studied formation, which forms when minerals within a sediment precipitate before the lithification of rock. Raindrop impressions are also found in Datta Formation at different levels, especially at bedding planes of flood plains deposits. These impressions are indicative of the fact that bedding was exposed or subaerially exposed at rain landing. Figure 3(f) shows raindrop impressions in fine-grained sandstone samples collected from the Kassin Nala section.

**Table 1:** Generalized stratigraphic column of the study area (Iqbal et al., 2015).

Era	Period	Group (Formations of Baroch Group listed)	
CENOZOIC	Tertiary	Pliocene	Sivalik Group
		Miocene	Rawalpindi Group
		<b>Unconformity</b>	
	Eocene	Cherat Group	
		Paleocene	Makarwal Group
<b>Unconformity</b>			
MESOZOIC	Cretaceous	Surghar Group	
	Jurassic	Baroch Group	Samana Suk Formation Shinawari Formation Datta Formation
	Triassic	Musa Khel Group	
	<b>Permo-Triassic Boundary</b>		
PALEOZOIC	Permian	Zaluch Group	
		Nilawahan Group	
	<b>Unconformity</b>		
Cambrian	Jhelum Group		
PROTEROZOIC	Precambrian	Salt Range Formation	



**Figure 3:** Sedimentary structures/Characteristics of lithofacies observed in Datta Formation of the Salt Range (a) transverse catenary out of phase ripples in Kaowali section, (b) cross-bedding in pebbly sandstone of Kassan Nala section, (c) laminations in fine sandstone beds of Kassan Nala section, (d) burrows encountered in Kaowali section, (e) concretion observed in Kassan Nala section and (f) raindrop impressions in fine-grained sandstone sample collected from Kassan Nala section.

#### 4. ANALYSIS OF SEDIMENTARY FACIES

A number of lithofacies are recognized from the three measured sections of Kassan Nala, Kaowali, and Nammal Gorge. Datta Formation generally contains fluvial to marginal marine sedimentary origin. Thick sandstone units in the lower part are considered deltaic, and some parts are littoral (Abbasi et al., 2012). Upper sandstone units, interbedded with mudstones, are interpreted as deltaic to fluvial with some floodplain deposits and insignificant swamps-related environment. In contrast, conglomerates within this sequence are the product of river deposits, and carbonates are likely characterized by lagoonal or lacustrine deposits developed on the coastal plain (Obaid et al., 2005). The present study identified seven lithofacies in the observed three sections. Facies description is based upon observed characteristics of rocks, i.e., color, texture, and rock geometry at the microscopic and mesoscopic level. Thus, each facies specified a unique code, i.e., "JDL" where 'J' is for the age of formation (Jurassic), 'D' for Datta Formation and Lithofacies 'L.'

##### 4.1 Fluvial Meandering Lithofacies (JDL-01)

**Description:** The fluvial-meandering lithofacies comprised of medium-sized and thick-bedded quartz arenites with the usual abundance of iron concretions showing variable thickness with medium to coarse grain size and some pebbly intervals (Figure 4a). Other bedding patterns, like wavy, planar, lenticular, and laterally pinching, are also observed. Quartz grains that make about 90% of the fluvial-meandering lithofacies are well-rounded and well-sorted in monocrystalline form. Calcium carbonate is marked as a primary cementing material. Lithofacies occurred at several stratigraphic levels and represented a variety of colors and their associated shades. Along with its lateral extension, beds show lenticular and pinching out phenomenon, particularly at lower levels. Both trough and planar cross-bedding are very common in this type of facies. An overall fining upward sequence is marked.

Spherical sand concretions are common in fluvial-meandering lithofacies that laterally extend in a plane. They range from a few centimeters to half a meter in diameter (Figure 3e). Such spherical size decreases northward and diminishes in the Nammal Gorge section, and their size is lesser in the

Kaowali section than in the Kassan Nala section but more significant in number.

Different sizes of coal chunks/bands are also present but restricted to only the Nammal Gorge section. Some symmetrical ripple marks are also observed in the fluvial-meandering lithofacies. Iron oxides are common cementing material, so minor corrosion is also visible along grain margins. The multi-coloured sandstone bed from the Kaowali section is shown in Figure 4(b). Tourmaline, ferruginous clay, and chert exist as accessory minerals in the Nammal Gorge section (Ahmed Jr et al., 2013) and represent the sub-litharenite sandstone type (Pettijohn et al., 1987). Paleocurrent direction is from S-SE towards N-NW (Iqbal et al., 2015). Round gravels in a few parts like Kassan Nala were observed at the base of the beds, as shown in Figure 4 c.

**Interpretation:** The fluvial-meandering lithofacies are observed with ripples, planar and trough cross-bedding. Cross bedding at a larger scale is a product of the migration of dunes and mega ripples and is present in deeper parts of channels (Friedman and Sanders, 1978). Similarly, ripples created by oscillations are symmetric and indicators of less sedimentation and repeated reworking and rebuilding (Miall, 1985). These circumstances meet in flood margins of channels, crevasses, natural levees, and other low-energy environments (Willis, 1989). Such conditions are obtained in upper flow segments of flood systems. Trough crossbedding at lower parts and planar cross-bedding at the upper parts indicate point bar trends (Boggs Jr and Boggs, 2009). Thus based on fining upward sequence and cross-bedding pattern, fluvial-meandering lithofacies may belong to point-bar deposits.

Furthermore, the occurrence of bioturbations, mud cracks, and raindrop impressions indicate sub-aerial conditions (Remin et al., 2014). The coal streak's presence at the Nammal Gorge section suggests the deposition in the proximity of the delta plain setting. All these features strongly infer the mode of deposition in meandering channel margin with minor effects of flood plains at the distal extreme, and paleo flow direction is inferred as WNW. It also seems that the channel often changed its course (abandoned channel) or cyclic deposits because of rounded gravels at the base of beds and the repetition of coarse and pebbly sandstone.

#### 4.2 Braided Fluvial Lithofacies (JDL-02)

**Description:** The braided fluvial lithofacies comprises a sandy conglomerate to a clast-supported conglomerate (Boggs Jr and Boggs, 2009) that ranges in color from dark red, creamish, and yellowish-brown. The thickness of braided fluvial lithofacies ranges from half feet to a maximum of 4m in Kassan Nala and Kaowali, whereas 3m in Nammal Gorge sections with the last section contains smaller sized pebbles than the other two sections. These are characterized by the presence of abundant pebble to granule size clasts that varies in size from half cm to 5cm in diameter with an appreciable amount of finer sediments. Occasional angular to rounded, poorly sorted grains of dolomite, quartz, and sandstones are also present and cover the lower portion of braided fluvial lithofacies.

Major rock fragments are mostly pebble-sized quartz, cherts, and quartzite covers about 90% of the total clasts, and other granite-type rock fragments are also present (Figure 4d). The matrix consists of fine quartz with some coarse rich sand and iron-bearing material. Occasional sub-angular to rounded dolomite having grey to cream color are observed that are thought to be originated and transported from underlying Kingriali Formation. Trough cross-stratification is common in the braided fluvial lithofacies, and the cross-bedding sets generally display fining-upward trends. Post-depositional events include oxidation that left this kind of facies reddish and crumbling can be traced over 1000–1500m (Iqbal et al., 2015).

**Interpretation:** The braided fluvial lithofacies overlies the thick beds of laterites containing dolomitic, quartz clast, granitic, and other rock fragments. These facies are expected in two cases: rapid erosion of high lands (Boggs Jr and Boggs, 2009) or sedimentation under frigid climates where glacial activity strongly affects the basal beds because this carbonate scans only sustain in such very cold or very rapid elevation events. However, in the present scenario, the immensely cold climate of the glacier is neglected because very thick laterites lying at its base indicate its origin in a humid climate. Observed fining upward sequence in braided fluvial lithofacies is a characteristic of braided river system deposits. In addition, cross-bedding and conglomerate beds and finer materials like sands and silts are also present, which is the index property of bar deposits or the meandering river system. Thus, it is confusing to assign it the deposits of a braided river or meandering river. However, it can be inferred as bar deposits of a braided channel based on well-developed cross-bedding and fining upward sequence.

#### 4.3 Lateritic Lithofacies (JDL-03)

**Description:** Laterite horizons and some lateritic soil units are easily observed at various stages in the Datta Formation. Mainly it represents dark red, but rusty brown to yellowish colors are also present. Numerous lateritic residual soil beds are also present along various lithofacies in all three studied sections. These laterite units in the Nammal Gorge section bear thickness from 0.2 – 1m. In Kassan Nala and Kaowali sections, the thickness of one unit is 60m and 43m, respectively (Figure 4 e). The grain size of lateritic material varies from small nodules to clayey soil, occasionally sandy, dependent on the nature of the mother material, such as sandy, silty and clayey textures. Numerous reddish-white, yellow and grey dots are observable in these laterite horizons.

**Interpretation:** Most of the laterites are rusty-red due to the presence of oxides of iron. These soil types grow by the exposed severe and long-term weathering conditions of the material. Commonly tropical weathering, sometimes called laterization, is an elongated procedure of chemical type weathering that harvests long-range diversity in the color, grade, mineralogy or chemistry, thickness, and texture of the resulting soils (McKenzie and Selater, 1973). Lateritic material builds up on behalf of the weathering of parent rock that underwent tropical climatic conditions, strengthened during high rain-water and eminent temperature (Tucker, 1992). Thus, leaching occurs in tropical soils with acidic conditions, and good drainage is available. These tropical soils are usually enriched in aluminium content that develops in a hard, crunchy material known as laterite (Prothero and Berggren, 2014). Moreover, kaolinite, boehmite, and similar minerals in these horizons and traced back to humid, warm, tropical climate conditions that prevailed during the deposition of the Datta Formation (Abbasi et al., 2012). Apart from this, fire clay horizons, laterites, clean silica sand beds, and washed and abundant palaeosols also support the idea of warm cum humid environment near the tropical zone for the deposition of the Datta Formation.

#### 4.4 Floodplain/Overbank Lithofacies (JDL-04)

**Description:** The floodplain/overbank lithofacies encompasses laminated siltstone, shale, and thin interbeds of sandstone. Sandstone beds range in

color from white, grey, pink, yellow, and brown. Thin to thick-bedded silt and sandstone are mostly oxidized to represent reddish color (Figure 4 f & g). In sandstone, small-scale cross-bedding exist with ripple marks, mud cracks, and wavy beds. The sandstone beds are usually lenticular, forming thin to medium lens geometries separated by shale/clay interbeds. Shale/clay are light greyish to grey to greenish. Furthermore, bioturbations and climbing ripples are also present. Wood imprints and remains also exist in reddish sandstone. Siltstone and shale also contain beds of fireclays.

**Interpretation:** The floodplain/overbank lithofacies comprises finer sediments produced by low energy conditions (Nichols, 2009; Reineck and Singh, 1972). Moreover, fireclays are also associated with silt beds that specify their weathering and soil developing conditions (Tucker, 1992). It is a byproduct of periodic submerging and exposure. These conditions are available in the margins of river channels, flood plains, or delta-plain settings. In Datta Formation, floodplain/overbank lithofacies overlies the channel margin as well as channel belt deposits. Furthermore, the occurrences of climbing ripples and wooden remains suggest the deposition of flood plains. Likewise, lagoonal shale is overlying it, and some fining upward trends are also present, so it can be inferred that it may belong to over banks of deltaic distributaries.

#### 4.5 Siliciclastic Lagoon Lithofacies (JDL-05)

**Description:** The siliciclastic lagoonal lithofacies are mostly comprised of shales interbedded sandstones and siltstones. Some thinly bedded yellow to brownish colored dolomitic sandstone or sandy dolomite are also present that are associated with shale beds (Figure 4h). Shale is itself carbonaceous that has grey and black colors. Some shale layers have coal streaks. Sandstone and siltstone are greyish, representing a coarsening upward trend. Both vertical and horizontal burrows are present in carbonaceous shale, and sandstone beds comprise symmetric ripples on bedding planes. Planar cross-bedding can also be observed.

**Interpretation:** The siliciclastic lagoonal lithofacies are composed of shale, sandstone, and siltstone containing bioturbations, burrows, and ripples marks. Thus it represents a lagoonal environment along its mudflats based on faunal activities. Relative sea-level rise or flooding supports and provides a suitable environment for coal deposition (Emery and Myers, 1996). Carbonaceous content in sand and symmetrical ripples show a slight influx of clastic material. These beds gradually merge into carbonate beds further upwards. All these features indicate delta front or delta plain deposits. However, it is not distal from land as suggested by clastic input, though periodic and lesser in quantity. Another possibility of the siliciclastic lagoonal lithofacies is its deposition in lagoonal or inter distributary channel bay during relative sea-level rise.

#### 4.6 Carbonates Dominant Lagoon Lithofacies (JDL-06)

**Description:** The carbonate dominant lagoonal lithofacies are characterized by carbonate deposits with some shale and minor sandstone beds. These carbonates are mostly dolomites in Kassan Nala and Kaowali sections comprising yellow-brown color associated with shale beds. These dolomites are a few cm to half of a meter in thickness. Some dolomite beds are sandy and dolo-mudstone in nature (Figure 4i & j). Some sedimentary structures such as burrows and mud-cracks are also present. Sandstone and dolomitic sand beds show the fining-upward sequence and symmetrical ripples. However, in the Nammal Gorge section, medium to fine-grained, slight fossiliferous, greyish to maroon limestone is present (Figure 4k). These beds occasionally comprised of iron concretions with interbedded calcareous sandstone and clays generally in the upper portion of the formation. These carbonates also contain some fossils like pelecypods, sponge spicules, peloids, and brachiopods (Ahmed Jr et al., 2013).

**Interpretation:** The dominant carbonates lagoonal lithofacies represent carbonate deposits, but a small clastic influx is also present. Some quartz-rich sand with shale beds indicates some periodic siliciclastic invasion (Nichols, 2009). This formation was deposited on the Triassic-Jurassic boundary, representing a rapid uplift and further erosion of the late Triassic Kingriali Formation mainly composed of dolomites (Iqbal et al., 2015). Low input of siliciclastic material and carbonate deposition indicates low energy environments available in lagoonal or inter-distributary bay conditions.

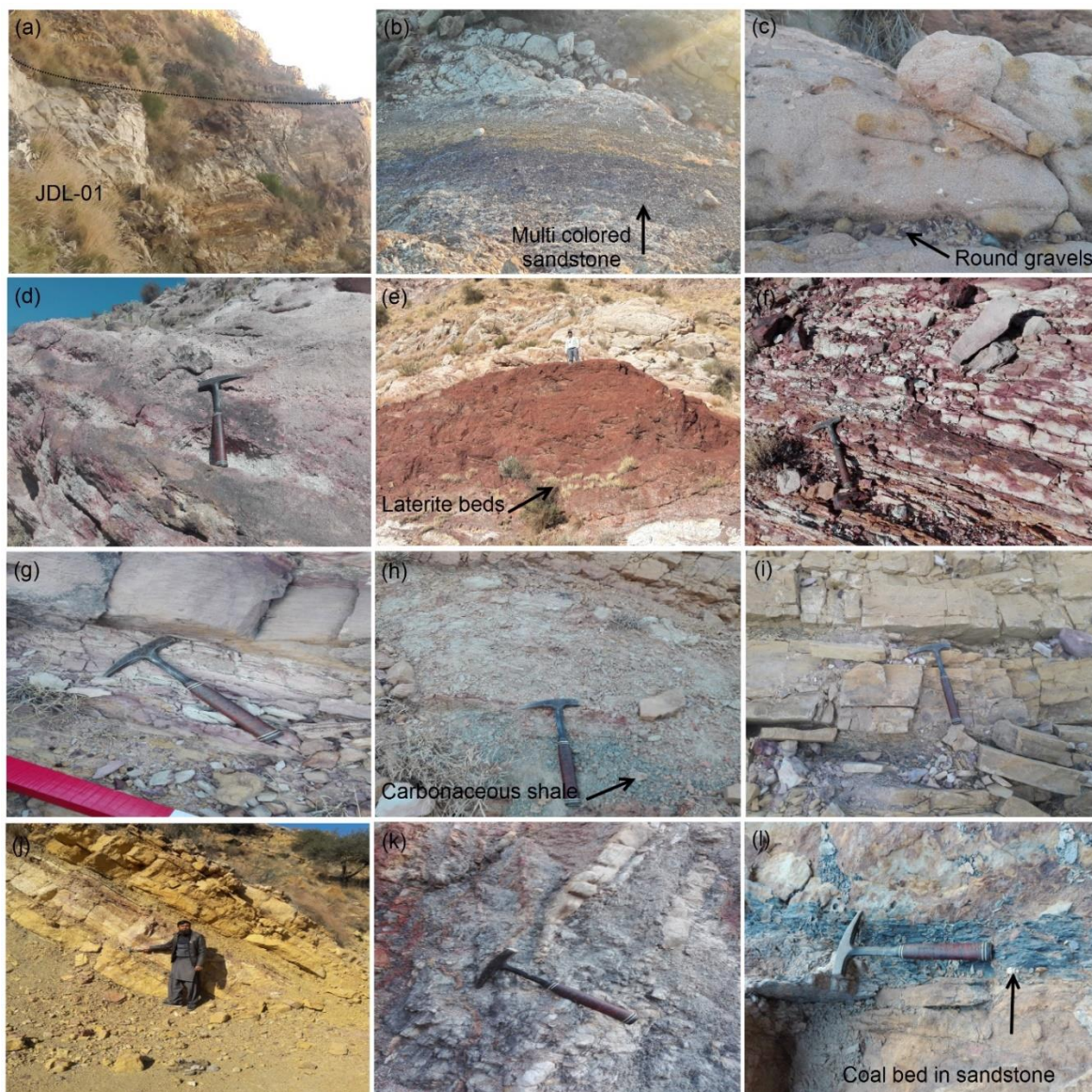
#### 4.7 Swamps-related Deltaic Lithofacies (JDL-07)

**Description:** The swamps-related deltaic lithofacies are mainly composed of black to greenish-grey carbonaceous shale interbedded with sandstone. It is intermittently splintery and calcareous rich in organic matter (Figure 4 (l)). Various wood fragments and leave imprints are present in the

carbonaceous shale unit, varying from 2-5 meters in thickness. Coal exists as stringers or tinny layers in the Nammal Gorge section marked by the tabular shape but laterally pinched out in parent lithology. Interbedded sandstone exhibits light to dark grey, laminated and thin-bedded, fine to medium-grained, wavy, and non-parallel cross-bedded. The thickness of the sandstone bodies fluctuates from thin to medium, with a total thickness of 0.5 – 1.0 meters individually.

Interpretation: Carbonaceous shale and coal are typical products of

swamps and marshland in a deltaic depositional setting; thus, indicate a swamp-related deltaic environment. It has associated interbeds dominant to deltaic parts. The flowing river transported sediments from exposure to the Indian cratonic basement rocks and finally deposited on a fluvial to the delta neighboring environment (Obaid et al., 2005). These cratonic interior sandstones are generally very mature and depict more monocrystalline quartz (Prothero and Berggren, 2014). Horizons of left-over laterite zone indicate severe chemical weathering under intense humid and tropical circumstances.



**Figure 4:** Characteristic lithofacies observed in Datta Formation of the Salt Range (a) massive sandstone bed belonging to JDL-01 facies from Nammal section, (b) multi-colored sandstone bed (JDL-01) from Kaowali section, (c) abandoned channel (JDL-01) from Kassan Nala section, (d) pebbly sandy conglomerate, JDL-02, from Kassan Nala section, (e) laterite beds, JDL-03, exposed in Kassan Nala section, (f & g) flood plain deposits, JDL-04, captured in Kassan Nala section, (h) carbonaceous shale, JDL-05, with interbedded siltstone and sandstone Kassan Nala, (i & j) dolomite, JDL-06, with interbedded carbonaceous shale in Kaowali and Kassan Nala sections (k) lateritic soil bed, JDL-06, grey limestone and carbonaceous shale in Nammal section and (l) coal beds in sandstone, JDL-07, from Nammal section.

## 5. PETROGRAPHIC AND DIAGENETIC ANALYSIS

The petrographic study deals with the source, occurrence, structure, and history of the rocks. During the geological field trip, 110 samples were collected, and among them, 20 samples were selected for thin sections and petrographic analysis. The ternary diagram is used for the classification of sandstone (Pettijohn, 1975) and provenance analysis (Dickinson et al., 1983) by analyzing framework grains of quartz, feldspar, and lithic fragments (QFL). This study also referred to textural maturity, mineralogical classification, sediment provenance, and diagenetic properties, which can be a diagnostic deposition source.

### 5.1 Mineralogy of Datta Formation

Quartz is the most common rock-forming mineral and is present throughout the Datta Formation, about 90% of the total composition (Figure 5 & 6). However, from bottom to top, quartz content decreases

while silty and dolomitic content increases. All of the quartz grains observed in thin sections are of monocrystalline (Qm), while the traces of cryptocrystalline quartz (Qc) are also observed (Figure 6 a-d). Most of the grains show linear, straight, or sutured boundaries (Table 2).

Fracturing and indents on grain surfaces are also typical in quartz grains. Most quartz grains have a thin coating of iron oxide and poor cementation (Figure 6b). The amount of feldspar varies between 0 to 1% among the selected and studied thin section. The absence of feldspar indicates humid and hot conditions at the time of deposition and late-stage diagenesis (Fielding et al., 2006). Its cleavage characteristic can easily be recognizable, and in most cases, carbonate grains are represented by calcite type in lime mud in the Nammal Gorge section. In contrast, dolomite and dolomitic sands are identified in the upper part of the other two sections (Figure 6c & d). However, it is interpreted to be a secondary type of dolomite resulting from magnesium-bearing fluids, either meteoric or connate water, that have altered calcite.

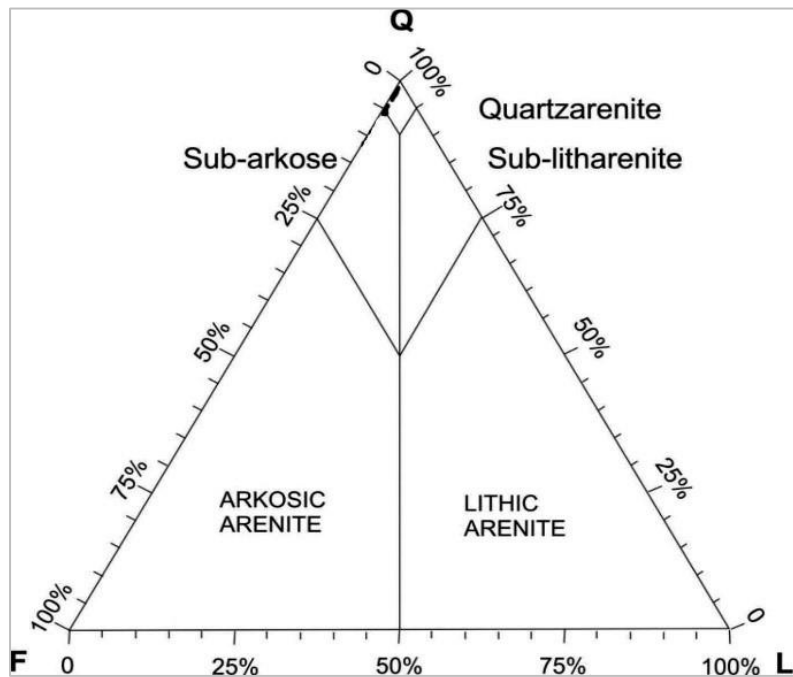


Figure 5: QFL diagram for classifying sandstone samples in thin sections from the studied sections (after Pettijohn, 1975).

Table 2: Petrographic Results of A Selected Thin Section of Datta Formation From the Studied Sections Showing Textural and Diagenetic Characteristics.

Sample No.	Sample No.	Sample No.	Sample No.	Sample No.	Sample No.	Sample No.
A1	A1	A1	A1	A1	A1	A1
A7	A7	A7	A7	A7	A7	A7
A8	A8	A8	A8	A8	A8	A8
A14	A14	A14	A14	A14	A14	A14
B10	B10	B10	B10	B10	B10	B10
B12	B12	B12	B12	B12	B12	B12
B14	B14	B14	B14	B14	B14	B14
B19	B19	B19	B19	B19	B19	B19
B20	B20	B20	B20	B20	B20	B20
C3	C3	C3	C3	C3	C3	C3
C4	C4	C4	C4	C4	C4	C4
C5	C5	C5	C5	C5	C5	C5
C7	C7	C7	C7	C7	C7	C7
C8	C8	C8	C8	C8	C8	C8
C11	C11	C11	C11	C11	C11	C11
C15	C15	C15	C15	C15	C15	C15
C16	C16	C16	C16	C16	C16	C16
C19	C19	C19	C19	C19	C19	C19
Spherical Concretion	Spherical Concretion	Spherical Concretion	Spherical Concretion	Spherical Concretion	Spherical Concretion	Spherical Concretion

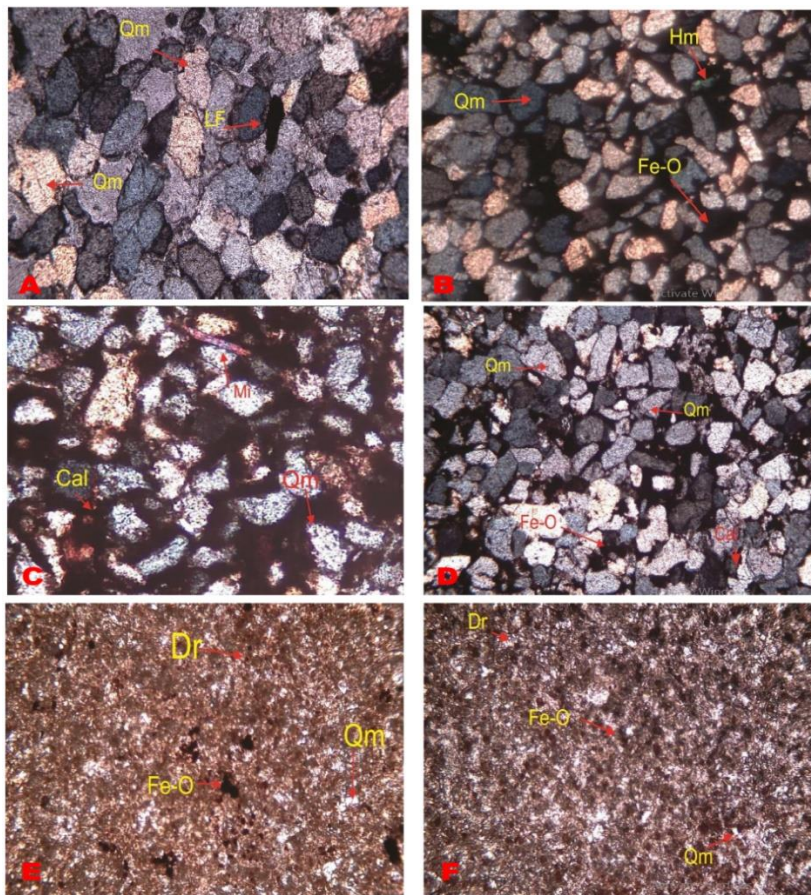
5.2 Diagenesis

Diagenesis is the sum of those processes by which initially sedimentary clastic assemblages attempt to reach equilibrium with their environments (Burley, 1986). In the present scenario, the most abundant type of cement is the ferruginous cement in sandstone, which covers about 5-10% of the total rock volume. Hematite cement is commonly found in the form of the pore spaces filling, disintegrating the grain margins and coating, and at places replacing grains and some other types of cement (Figure 6 & 7). Calcite covers about 1-3% of the total rock volume (Figure 7(c)), and the proportion of the calcite increases with a decrease in ferruginous cementing and vice versa. Its content is characterized by cleavage and high-order birefringence colors under cross light (Table 2).

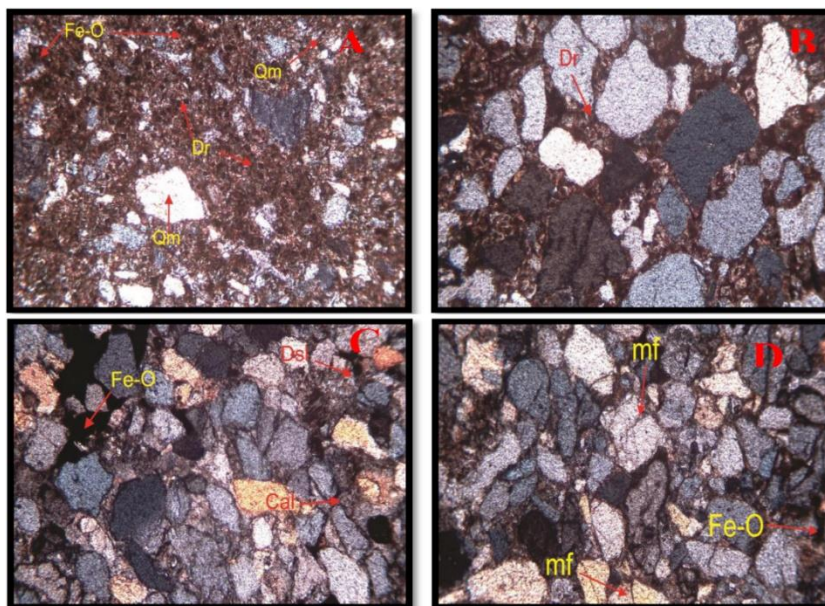
Almost all the studied sandstone samples represent quartz arenite without silt or clay fraction and depict moderate to well-sorted grains. Sandstone deposited by fluvial processes mainly displays well-sorted quartz grains, while the laminated sandstone beds and flood plain units demonstrate moderate sorting. On the other hand, sandy dolomite beds show a bimodal distribution of grains. The lower and middle parts of the formation displayed coarser sand grains gradually switching to medium in the upper part. Most grain-to-grain contacts are found as pointed, concavo-convex,

linear, and straight (Figure 7 c & d). The grains with sutural contact suggest mechanical compaction of grains (Flügel and Flügel, 2004). Due to the irregular spatial distribution of iron and calcite bearing solution, the grain contact is made unidentifiable (Figure 6 a & d). Dissolution has also been observed in some studied sections, mainly due to calcite or iron-bearing solutions.

The porosity of most sandstone samples is obscured by iron and calcite-bearing solutions. However, it appeared very dissimilar and fluctuated from less than 4% up to 15% by volume depending on the effects of solutions (Figure 6b & c). The type of porosity is mainly the intergranular type. The porosity of fine sandstone and laminated beds is less than 5%. Solution fluids affected and left their most significant influence on all diagenetic processes. However, calcite veins, iron-bearing solution paths, and magnesium-bearing solutions invade most solution fluids. Enrichment of magnesium played a role in dolomitization. However, due to partial-whole alteration of formerly developed dolomite units to a calcium-rich rock, the de-dolomitization occurred (Figure 7a & b) (Mehmood et al., 2018). This process can be seen in the upper parts of the Datta Formation in Kassan Nala and Kaowali sections, where all dolomite beds are found to be secondary type dolomite.



**Figure 6:** Microphotographs of Datta Formation showing the textural and mineralogical features of sandstone and carbonates. (a-d) show quartz arenite with cementing material (e & f) represent sandy dolomite. Where Qm (monocrystalline quartz), Dr (Dolomite rhomb), FeO (Iron Oxides), Cal (calcite), Hm (Heavy minerals), Mi (Mica) & LF (lithic fragments).



**Figure 7:** Photomicrograph displaying the framework and diagenetic features. (A) Dolomitization and a bimodal distribution, (B) de-dolomitization, (C) dissolution, and (D) fracturing. Qm=monocrystalline quartz, Dr=Dolomite rhomb, FeO=Iron Oxides, Cal=calcite, mf=micro fracture in grains, dsl=(Dissolution).

## 6. SEQUENCE STRATIGRAPHIC FRAMEWORK OF DATTA FORMATION

Sequence stratigraphic interpretation involves identifying and correlating stratigraphic surfaces that signify fluctuations in depositional trends by understanding and explaining subsequent, genetically related stratigraphic units bounded by these surfaces (Catuneanu, 2006). In the last two decades, sequence stratigraphy has been proved as a successful technique in the correlation of sedimentary rocks. The present study discusses facies concerning the depositional background and observed coarsening upward and fining upward trends and cycles. Using standard

sequence definitions, two sequences were identified in Datta Formation from Kassan Nala and Kaowali sections. System tracts and bounding surfaces are exclusively presented based on coarsening and fining sequences, geometrical behavior and type of specific depositional system upward.

### 6.1 Sequence Stratigraphy of Datta Formation in Kassan Nala And Kaowali Sections

Datta Formation in Kassan Nala and Kaowali sections exhibits approximately similar types of sequence stratigraphy except for variations in thickness which is more significant in the Kaowali section. Three

sequences have been identified and described from the facies analysis and some other attributes. The highstand system tract is identified from the base of the formation and it continued.

### 6.1.1 Sequence-1

Sequence-1 represents the lower part of the Datta Formation encompassing the fluvial sandstone and massive laterite deposits. It has a lower unconformable contact with Kingriali Formation. It contains only a highstand system tract (HST).

(i) Highstand System Tract (HST-I): After the Kingriali Formation (carbonates) deposition, Datta Formation started depositing with the deposition of fluvial sandstone belonging to HST. HST represents stillstand and normal regression processes (Catuneanu, 2006). This unit contains medium to thick cross-bedded sandstone, which is medium-grained and without sedimentary structures. This sandstone body represents a variety of colors and a high fracture system. The uppermost part of this sequence is marked by extensive deposits of laterites in both sections. This laterite unit is dark red colored and clay size to fine sand size splintery nature. So, it strongly argues for the exposure of earlier deposits in a tropical and humid environment for a long time. Thus, this unit is marked with sequence boundary (SB).

### 6.1.2 Sequence-2

The sequence-2 sequence is composed of lowstand system tract (LST), transgressive system tract (TST), and highstand system tract (HST) and confined at the base and top by Sequence boundaries.

(i) Lowstand System Tract (LST-II): The basal conglomerates demonstrates a facies deposition in the incised valley after the development of vast deposits of laterites. The fluvial sediments gradually filled these during the slow relative sea-level rise, representing LST (Catuneanu, 2006). The existence of dolomitic fragments in the basal conglomerate specifies reworking and assimilation of the underlying Kingriali Formation (Iqbal et al., 2015). Overlying fluvial sandstone lithofacies (JDL-01) are categorized by medium to coarse-grained planar and trough cross-bedded sandstone with basal gravel. Thus, the fining upward sequence directs alluvial aggradation and is related to initial slow relative sea-level rise after a long base-level fall (Hunt and Tucker, 1992). The sea-level rise rate seems slightly higher compared to the basal conglomerates of the chiselled and incised valley. These deposits represent multistory and multilateral sand bodies (Emery and Myers, 1996). Overlying fine to medium-grained laminated sands with siltstone indicate the increasing relative sea-level rise and thus increase in the accommodation space, resulting in decreased gradient and ultimately reduction in the fluvial ability to carry coarse sand and gravels (Miall, 2010). These conditions are ideal for the development of sinuosity of the channels (meander channel), and the top of these units marks a maximum regressive surface (MRS).

(ii) Transgressive System Tract (TST-II): Grey to pink colored shale with fine laminated sandstone units are present after the thick deposits of LST. The base of the units is marked as MRS. The deposition in transgression indicates a continuous supply of sediments via sea-level rise. The abundance of shale may point out a decline in the gradient of the channel with an increase in sea level. The cyclic deposition of sandstone and shale is due to possible seasonal flooding by the occurrence of shale at the top of each cycle. Therefore, MFS is marked at the top of a thicker shale unit.

(iii) Highstand System Tract (HST-II): Subsequent to the MFS, the carbonates and shale/clay deposition in the lagoonal system continues to be deposited above the MFS (Catuneanu, 2006). The uniform thickness of the interbedded shale with dolomites point out the deposition in a comparatively still stand of sea level and that the sequence demonstrates HST. However, in the Kassan Nala section, facies resemble the late TST units, and it is hard to specify the distinction between these system tracts. The upper part of the unit represented some shale horizons that are deposited during the relative sea-level rise, but due to base-level fall, it is exposed to humid and tropical weathering. These units indicate the presence of fire clay deposits of HST. The top surface of HST is marked by a sequence boundary and further onset of the next LST (Catuneanu, 2006).

### 6.1.3 Sequence-3

This sequence is comprised of LST, TST, and HST, respectively. Its lower surface is taken as sequence boundary (SB) after the HST of sequence-2.

(i) Lowstand System Tract (LST-III): Overlying the sequence boundary of HST, LST is present, which is considered by the deposition of thick-bedded, medium to coarse-grained fluvial sandstones. During this LST, a minor relative sea-level fall is considered. Thus a tentative sequence boundary is striking below this LST rather than a confirmed one. LST has its upper

surface marked in the Kasan Wala section by bioturbated fine-grained sandstone and rippled, while in Kaowali, shale/clay and siltstone are present. The upper limit of the units is marked by the onset of a new transgressive cycle as indicated by MRS, accompanied by relative sea-level rise. In Datta Formation, this relative rise in sea indicates the second transgressive surface and the second LST's upper boundary.

(ii) Transgressive System Tract (TST-III): TST is underlain by carbonates belonging to LST of sequence-3 and represents shale or clays much similar to earlier TST facies. However, it is a low period TST system. Thus MSF is placed on top of such beds in both sections.

(iii) Highstand System Tract (HST-III): HST of sequence-3 is underlain by the fluvial deposits. These are massive sandstone beds and represent some beds of high sea level but also cross-bedding and wood impressions and burrows, which indicate a sea-level rise but with normal regression and still stand condition. The top surface of the units represents the type-1 sequence boundary because a huge stratigraphic gap is present after the Early Jurassic Datta Formation. Late Jurassic and the whole Cretaceous succession is missing, and Hangu Formation belonging to Paleocene age is exposed.

## 6.2 Sequence Stratigraphy of Datta Formation in Nammal Gorge

In Nammal Gorge, Datta Formation is overlying the Kingriali Formation unconformably. However, four sequences are observed bounded by their sequence boundaries. The identified four sequences are described as below:

### 6.2.1 Sequence-1

This sequence represents the lowermost part of the formation, starts from LST, and is somewhat similar to other sections. This system is composed of sandstone, shale, and some carbonate beds.

(i) Lowstand System Tract (LST-I): It follows unconformity at its lower surface with the underlying formation and also sets as sequence boundary of the sequence-1. The lowermost unit of the system consists of pebbly sandstone. It shows the dark red color that is an indication of oxidation of iron-bearing units. These pebbles are mostly rounded to sub-rounded and are mostly dolomitic and quartzitic in nature. Above this, pale yellow to light grey sandstone showing both planar and trough cross-bedding is present. Above this, carbonaceous shale is present along with limestone beds. Coal seams are present with some beds in this carbonaceous shale. These strata represent slow relative sea-level rise with less accommodation space. Because in LST, due to high sediment supply and relative sea-level rise at later stages, chances of peat and coal accumulation increases many times at the top of the system. This system is overlain by MRS.

(ii) Transgressive System Tract (TST-I): After the MRS, finely laminated sandstone is interbedded with shale of red and grey color deposited in relative sea-level rise with more rate of accommodation and less sediment supply. It forms lenses of sandstone embedded in shale units. Sandstone beds often represent symmetrical wave ripples and worm-made vertical burrows. Grey-colored shale is splintery in nature. Reddish-brown to brown and color of shale specifies the oxidation while long periods of sub-aerial exposures of flood plains. Fine-grained siliciclastics along with organic matter lead to the formation of carbonaceous clays and coal typically along the abandoned channel. The system tract ends with the formation of MFS.

(iii) Highstand System Tract (HST-I): HST is present after MFS. This represents an increase in relative sea-level rise but at a slower rate and still stand situations, thus creating normal regression conditions. The lower unit of the system tract shows fluvial sandstone beds with a cross-bedding nature. Above these beds, limestone beds are present. In the upper part of the system, sandstone horizons contain coal beds. Because the system tract follows the MFS, at this time, maximum plant growth and sediment supply are observed, favouring the accumulation of coal and peat in HST.

### 6.2.2 Sequence-2

Following sequence boundary, a new cycle of base-level starts named sequence-2. It encompasses the following system tracts;

(i) Lowstand System Tract (LST-II): The system tracts started to deposit from fluvial sandstone beds, which exhibits cross-bedding of each two types due to fluvial normal regression, aggradation took place, and an overall fining upward sequence is observed because of a decrease in grain size and fluvial energy. Moreover, due to insufficient accommodation space available during low stand succession, paleosol (also laterites) may form at flood plain deposits. Coal seams produced within the LST are the

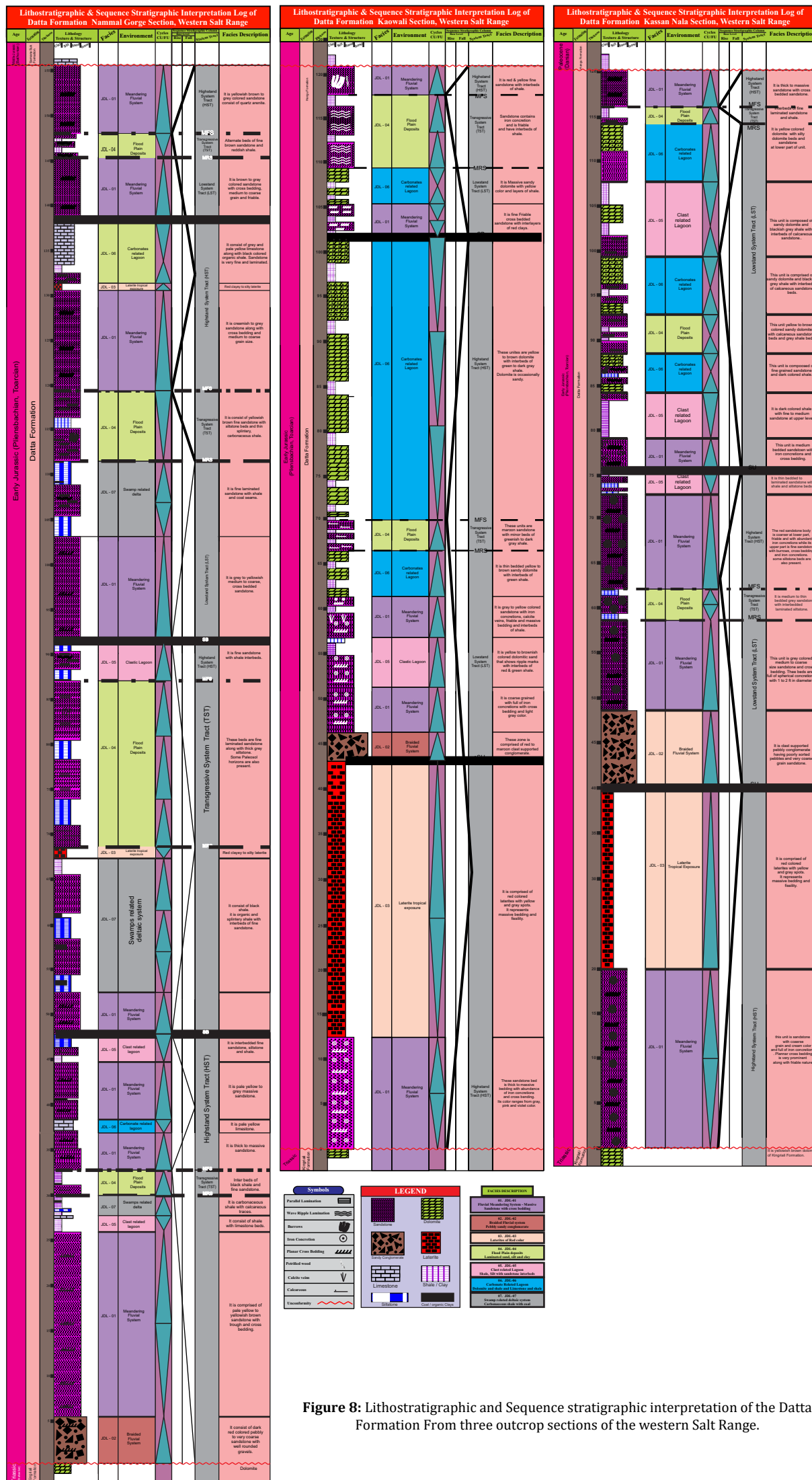


Figure 8: Lithostratigraphic and Sequence stratigraphic interpretation of the Datta Formation From three outcrop sections of the western Salt Range.

product of the low rates of creation of accommodation with a high influx of clastic sediment. With increasing rates of base-level rise with time, gradually, more accommodation becomes available to the overbank environment during the low stand stage. It increases the chances for peat accumulation, and consequent coal development tends to progress toward the top of LST (Catuneanu, 2006).

(ii) Transgressive System Tract (TST-II): TST successions have been deposited after MRS surface and are characterized by finely laminated sandstone with interbeds of siltstone of pinkish color. It indicates a rise in relative sea-level rise where the rate of sediment supply was outpaced (Catuneanu et al., 2009) by the rate of accommodation space creation. Some paleosol horizons are also present with these beds. That indicated the periodic exposure of beds during the TST stage. Sandstone beds contained wave ripples and burrows in lithic beds, while MFS restricted the system tract at the top.

(iii) Highstand System Tract (HST-II): After the MFS, relative sea-level rise but at a slower rate creating normal regression conditions, i.e., aggradation, while still stand conditions. However, at later stages, sea-level falls lead to deposition in nearby lagoonal areas where sediment influx was very low and fine grains were deposited in low-energy conditions. This system tract ended with the demarcation of sequence boundary.

### 6.2.3 Sequence-3

Sequence 3 presents three system tracts that are explained in the following sections;

(i) Lowstand System Tract (LST-III): It represents the fluvial sandstone deposited in its early stage, showing cross-bedding and medium to coarse grain size. However, in the upper stages, it shows low energy and sea level, while it supports the deposition in the deltaic system creating swampy conditions. Such an anoxic environment favored the formation of carbonaceous shale and coal seams. Fine laminated sand represents a rise in relative sea-level rise, but at later stages, ripple marks indicate low sediment influx along with organic contents and energy conditions. This succession is restricted at the top by MRS.

(ii) Transgressive System Tract (TST-III): It is composed of finely laminated sandstone with interbedded siltstone and shale. Also, the establishment of fine sediments containing burrows, wood fragments, and ripple marks with low sediment influx and high accommodation space. Because at later stages, the shoreline transgression end marks the peak for peat accumulation, thus leading to coal improvement on behalf of the high water table relative to the landscape profile representing a time characterized by a high accommodation for sediment supply ratio during the transgression. Thus finest and greater coal deposits are associated and overlapped with MFS (Catuneanu, 2006).

(iii) High stand System Tract (HST-III): Following the MFS, fluvial sandstone is deposited when the base level rises but at a slower rate.

However, at later stages, laterite deposits are found, which is indicative of relative base-level fall and sub-aerial exposure of previous deposits. This fall maintained the way to lagoonal settings with low sediment influx as indicated by fine calcareous sand beds and then shale deposits, but then clastic units diminished, and carbonates were found. Carbonates are mostly limestone of pale yellow to greyish color. Here a sequence boundary is found, and sequence-4 starts.

### 6.2.4 Sequence-4

This is the last sequence observed in Datta Formation after that Samana Suk Formation overlies unconformably on it.

(i) Lowstand System Tract (LST-IV):

The system tract results from fluvial succession and represents similar characteristics as the LST of Sequence-3, i.e., sandstone with cross-bedding and interbedded coal seams. These beds are bounded on top by MRS.

(ii) Transgressive System Tract (TST-IV):

This system is characterized by fine sandstone with lamination and shale. Sandstone and shale beds host coal streaks and seams. It also contains approximately similar properties, just like as TST of Sequence-3.

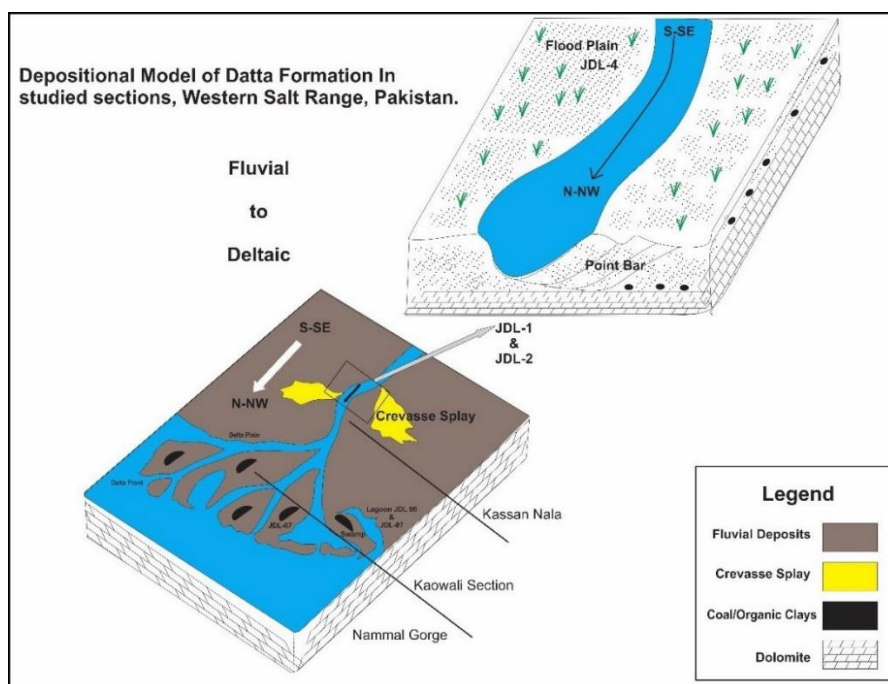
(iii) Highstand System Tract (HST-IV)

The succession after MFS specifies the HST and comprises fine sandstone with cross-bedding with maroon color on weathering. The fine-grain size of sandstone is symbolic of late flooding and relative sea-level rise where still overbank deposits are mounting up, demonstrating an early stage of HST. Overlying HST, there is an unconformity followed by Eocene Samana Suk Formation.

## 7. RESULTS AND DISCUSSION

### 7.1 Depositional Model of Datta Formation

The current study proposes a depositional model of the Datta Formation in the studied sections focusing on the lithofacies description and identification of paleo-depositional environments. Several lithofacies and environmental descriptions from the three studied sections concluded that the Kassan Nala section exemplifies more continental-type deposits that gradually shift to basinward (marine) parts. Additionally, overall thickness increases from S-SE to N-NW (Nammal Gorge). However, a fining upward sequence is observed that starts from coarse-grained conglomerates and pebbly sandstone containing sandstone of point bar. The size of such conglomerates, pebbles, and iron balls also reduced further northward. These facies are overlain by floodplain or over-bank deposits. These basal successions in three sections are taken as point bar deposits.



**Figure 9:** Depositional locations of different lithofacies identified in the Datta Formation from the three sections.

The clastic lagoonal and carbonated lagoonal lithofacies represents more basinward circumstances with slight marine influence in the N-NW part of the study area. Similarly, deltaic conditions with swampy environments identified in the Nammal Gorge section support this idea of N-NW flow of the fluvial system that gets closer to marine to marginal marine settings, as shown in Figure 8. The thicker deposition in the N-NW part of the study area suggests comparatively severe conditions faced in the S-SE. Thus Datta Formation denotes a prograding deltaic facies sequence (Figure 9).

The above discussion assumes that sandstone units associated with channel lags, siltstone, red clays and carbonaceous clays specify deposition in the far delta-plain setting of a fluvial-dominated delta with large fluvial distributaries (Miall, 2010). Presence of coarse sandstone and granule units that are considered to be deposited by laterally migrating sinuous distributary channels (Boggs Jr and Boggs, 2009) and braided channels along with cross-beds show that the main channel belts system was flowing over the exposed Kingriali Formation towards the north. Some lateritic soil units were also developed due to exposure to humid tropical climates on extensive flood plain areas.

Carbonaceous shales and coal seams also recommend the presence of marsh and swampy lands. Moreover, some fossils like gastropod and pelecypod worm activities such as burrows and bioturbations; organic matter like plants, leaves, and wood fragments also support a deltaic coast with well-developed distributary channels with broad flood plains; swamps and marshy areas and lagoons along both carbonate and clastic types were present. Therefore, the delta is supposed prograding delta with WNW with the depositional setting along the western margin of the Indian Plate across the Neo-Tethys coastline.

In the context of sequence stratigraphy, two major transgression-regression (T-R) cycles are inferred in the Kassan Nala sections, and four T-R cycles are identified in the Nammal Gorge section. The lower cycle specifies the more noticeable relative sea-level transgression and regression after the type-1 sequence boundary of pre-Jurassic. Three major system tracts, HST, LST, and TST, are interpreted in this cycle and fining and coarsening upward sequences. Sequence bounded surfaces bound these system tracts. Though the overlying sequences are almost similar to the former cycles and timid HST, LST and TST are interpreted. Petrographic analysis of the selected samples consisting of coarse sandstone, dolomitic sandstone, and fine sandstone expresses that fluvial sandstones are Quartz Arenite. Very well-sorted, and most grains are sub-angular with calcite and iron oxides. Sandstone facies that belong to flood deposits are fine and contain some clay content. A diagenetic study reveals that the porosity of sandstone is 5 to 20 %. Most of the grains have either concavo-convex contact or parallel to the long axis, and iron and calcite solution effects throughout the section

## 8. CONCLUSIONS

This research mainly focuses on the Mesozoic deltaic system and sequence stratigraphic model of the lower Jurassic Datta Formation along the western Salt Range, Pakistan. Following are the outcomes of this research:

- i. In the study area, Datta Formation abundantly comprises siliciclastic sediments with minor carbonates. Seven lithofacies are identified in the Datta Formation. These lithofacies are: (i). fluvial-meandering lithofacies, (ii). braided fluvial lithofacies, (iii). lateritic lithofacies, (iv). flood plain lithofacies, (v). siliciclastic lagoon lithofacies, (vi). carbonates dominant lagoon lithofacies, (vii). swamps-related deltaic lithofacies.
- ii. Datta Formation is possibly deposited in fluvial to deltaic environments and concludes as a prograding delta with a shoreline oriented in SW to NE direction. The lower part of the formation is a product of depositing fluvial setting, probably in the incised valley. The point bar sequences from meandering channel facies show association with overlying flood plain/overbank facies. Lagoonal facies mainly cover the upper part of the formation and display mixed lithologies of delta plain to delta front setting. Several laterites and fire clay horizons are also argued for periodic sub-aerial exposure of the depositional area.
- iii. Petrographic analysis shows the existence of coarse-grained sandstone, dolomitic sandstone, and fine sandstone. The fluvial sandstones indicate the presence of quartz arenite. Moreover, these sediments are well-sorted, and most grains are sub-angular, containing calcite and iron oxides. Sandstone facies that belong to flood deposits are fine and contain some clay content. Diagenetic study reveals that the porosity of sandstone is 5 to 20 %.
- iv. Based on sequence stratigraphic analysis, two major

transgression-regression (T-R) cycles are inferred in the Kassan Nala sections, and four T-R cycles are identified in the Nammal Gorge section. The lower cycle specifies the more noticeable relative sea-level transgression and regression after the type-1 sequence boundary of pre-Jurassic. Three major system tracts, HST, LST, and TST, are interpreted in this cycle and fining and coarsening upward sequences. Sequence bounded surfaces bound these system tracts. Other surfaces marked are maximum flooding and maximum surfaces. Though the overlying sequences are almost similar to the former cycles and timid HST, LST and TST are interpreted.

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