Facies Analysis and Dynamic Depositional Modeling: Implications for Hydrocarbon Prospecting in the Lower Jurassic Datta Formation, Salt Ranges, Northwest Pakistan*

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Abstract

We describe the lithofacies, depositional sequences and diagenetic fabric of the Early Jurassic Datta Formation for the characterization of its hydrocarbon reservoir potential in the Salt Ranges, Northwest Pakistan. In the study area (Nammal Gorge Section), the Datta Formation is predominantly composed of fine to coarse-grained sandstone interbedded with clays and limestone at places. We collected the outcrop data and used microfacies analysis techniques to categorize five different facies which are 1) Cross bedded sandstone facies (DF1), representing deposition in a braided fluvial environment 2) Thin to medium bedded sandstone and interbedded clays facies (DF2), representing deposition in a meandering fluvial environment 3) Coal beds/organic clays facies (DF3), representing deposition in a deltaic (swampy) environment 4) Laterite facies (DF4), representing prolonged exposure of the platform under oxidizing conditions and 5) Lime mudstone-wackstone facies (DF5) representing deposition in a lagoonal environment. Based on the facies synthesis a dynamic depositional model is presented, which suggests seven repeated exposure cycles of the platform (SB1-SB7 sequence boundaries) represented by Laterite facies (DF3) and associated channel sandstone deposits of the braided river system that were deposited in a regressive systems tract. The unconformable sedimentation pattern is punctuated by subsequent marine transgressive cycles. These cycles preserve coal beds/ carbonaceous matter along with the carbonate facies in marginal marine settings and caused flood plain deposition in a meandering river system in the transgressive systems tract. The diagenitic fabric of the potential hydrocarbon reservoir intervals (DF1 and DF2 and DF5 facies) is also documented. The fractured quartz grains and bending in muscovite manifests compaction of rock while the presence of siliceous, calcitic, ferruginous, glauconitic and clayey cements indicate different phases of cementation. The observed visual porosity within the DF1 and DF2 facies is effective and includes inter-granular, intra-granular and fractured types. The experimental values of plug porosity and permeability along with sub-mature nature confirm good hydrocarbon prospects of the Datta Formation in the region.

Facies analysis and dynamic depositional modeling: implications for hydrocarbon prospecting in the Lower Jurassic Datta Formation, Salt Ranges, Northwest Pakistan

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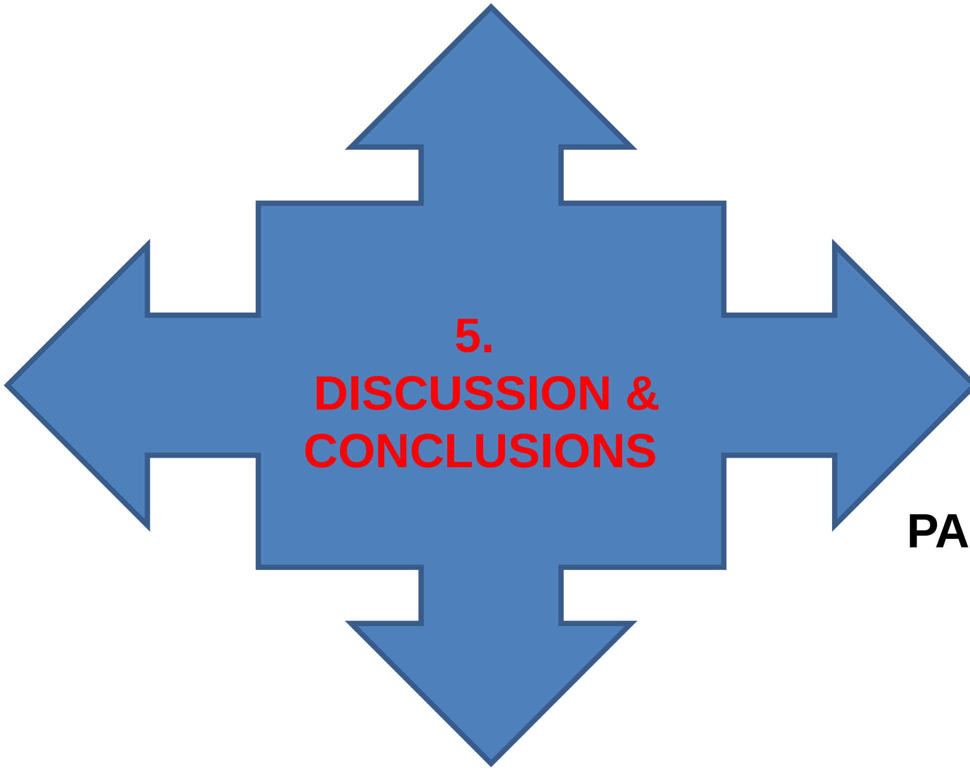
Pakistan Section

Presentation outline

1. INTRODUCTION
METHOEDS/LOCATION/SECTIONS

4. SEQUENCE STRATIGAPHY



2. FACIES AND PALEOENVIRONMENTS

3. DIGENESIS & RESERVOIR CHARECTERIZATION

INTRODUCTION

- **METHOEDS**
  - A siliciclastic rich unit, well exposed in the Upper Indus Basin
  - Well studied by previous workers

  WHAT IS NEW HERE ?
  - We established sequence stratigraphic architecture
  - Implications of digenesis for hydrocarbon reservoir rock characterization
  - **FIELDWORK (Composite stratigraphic log/Sampling)**
  - **LABORATORY WORK (Facies analysis/Paleoenvironments/digenesis)**
  - **INTEGRATION OF DATA (Sequence stratigraphic model)**

INTRODUCTION

- **LOCATION**
  - NAMMAL GORGE SECTION (CENTRAL PART OF THE WESTERN SALT RANGE)

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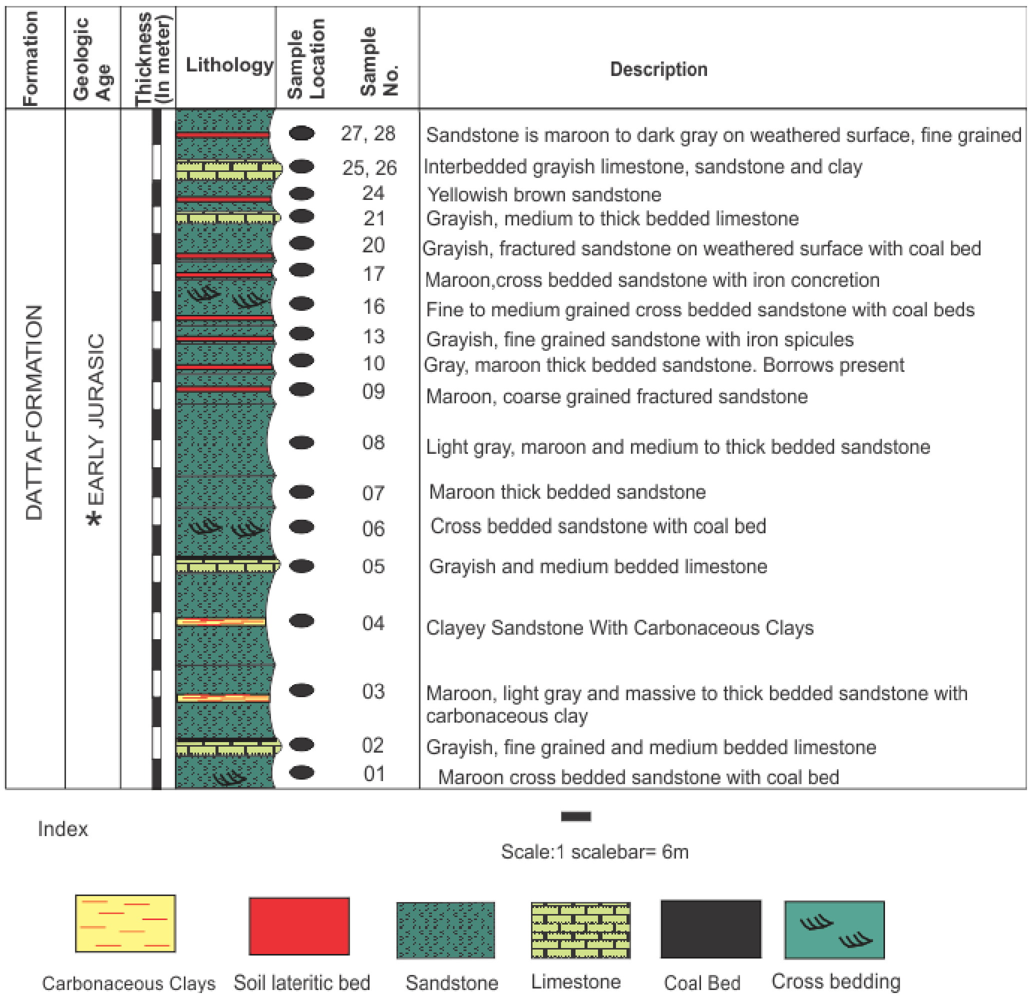
FIELDWORK

- **COMPOSITE STRATIGRAPHIC LOG**

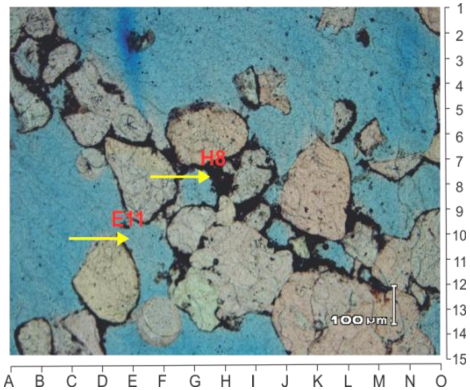


FACIES ANALYSIS

- **4-Facies recognized**
  - Cross bedded sandstone interbedded with siltstone facies (DF 1)
  - Thin to medium bedded sandstone with intebedded clays facies (DF 2)
  - Coal beds/organic clays facies (DF3)
  - Laterite Facies (DF 4)
  - Lime mudstone-wackestone facies (DF 5)

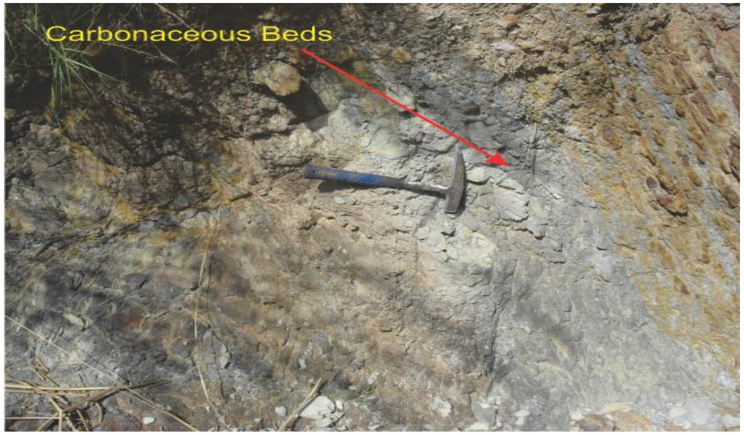
FACIES

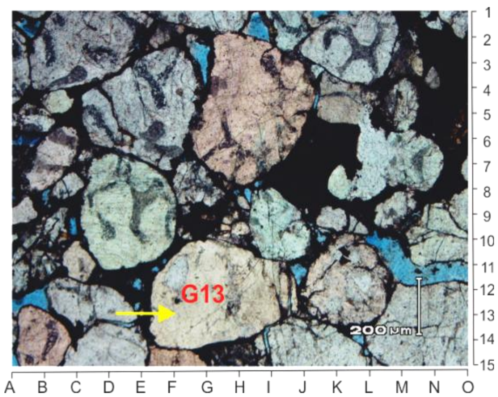
- **Cross bedded sandstone interbedded with siltstone facies (DF 1)**
  - Yellowish
  - Sub litharenite (texturally immature, Mineralogicaly mature)
  - **Interpretation:** The trough cross bedding of the sandstones and association of the siltstone interbeds in the DF1 facies indicates a very characteristic and common feature of fluvio-deltaic environment



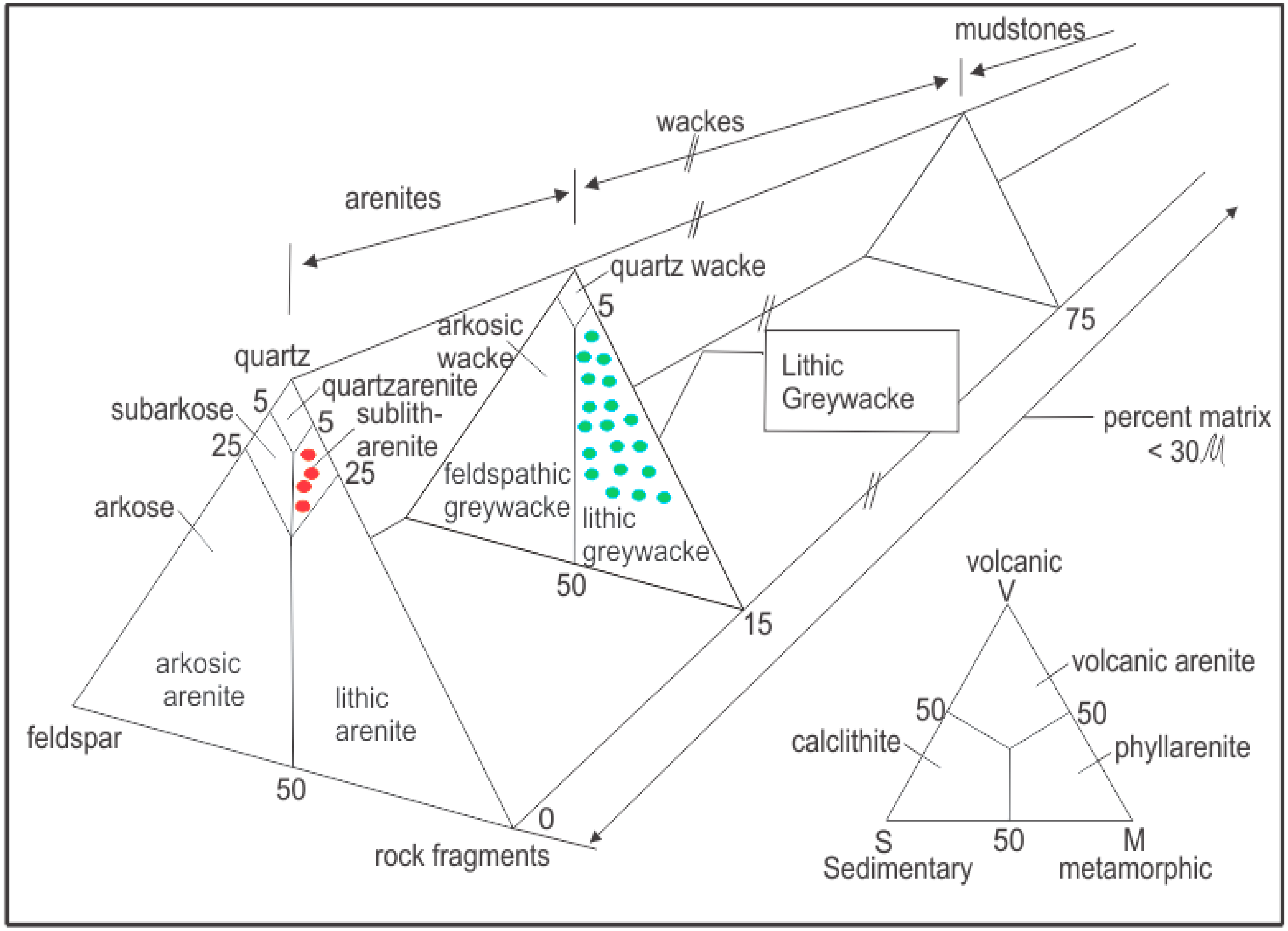
FACIES

- **Thin to medium bedded sandstone and interbedded clays facies (DF2)**
  - Maroon to grayish color on fresh surface
  - "Lithic-graywacke" Minerlogically mature and texturally immature
  - Organic rich clays with stringes of coal are also associated
  - **Interpretation:** A fining upward point bar sequence which is a very conspicuous geomorphic feature of a meandering river .The presence of abundant carbonaceous material is indicative neighboring swampy environment.





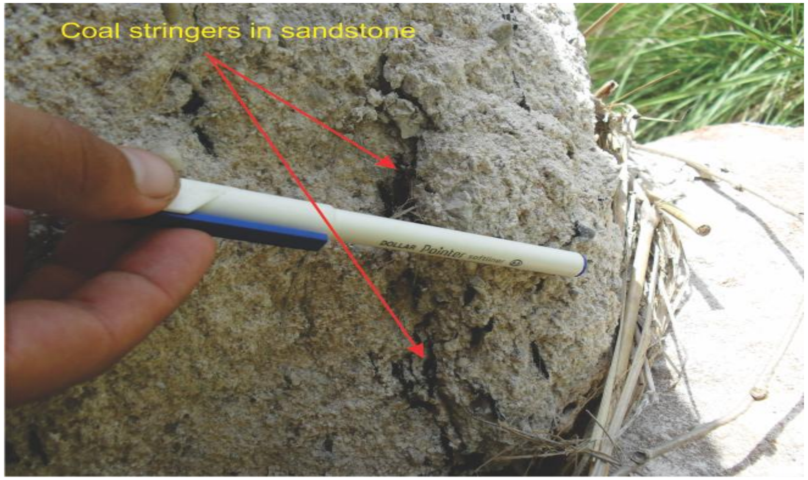
FACIES



mudstones
wackes
arenites
quartz wacke
5
arkosic
wacke
quartz
quartzarenite
subarkose
5
5
sublith-
arenite
25
25
arkose
feldspathic
greywacke
lithic
greywacke
50
15
75
Lithic
Greywacke
percent matrix
< 30
arkosic
arenite
lithic
arenite
feldspar
50
0
rock fragments
volcanic
V
volcanic arenite
50
50
calclithite
phyllarenite
S
Sedimentary
50
M
metamorphic

FACIES

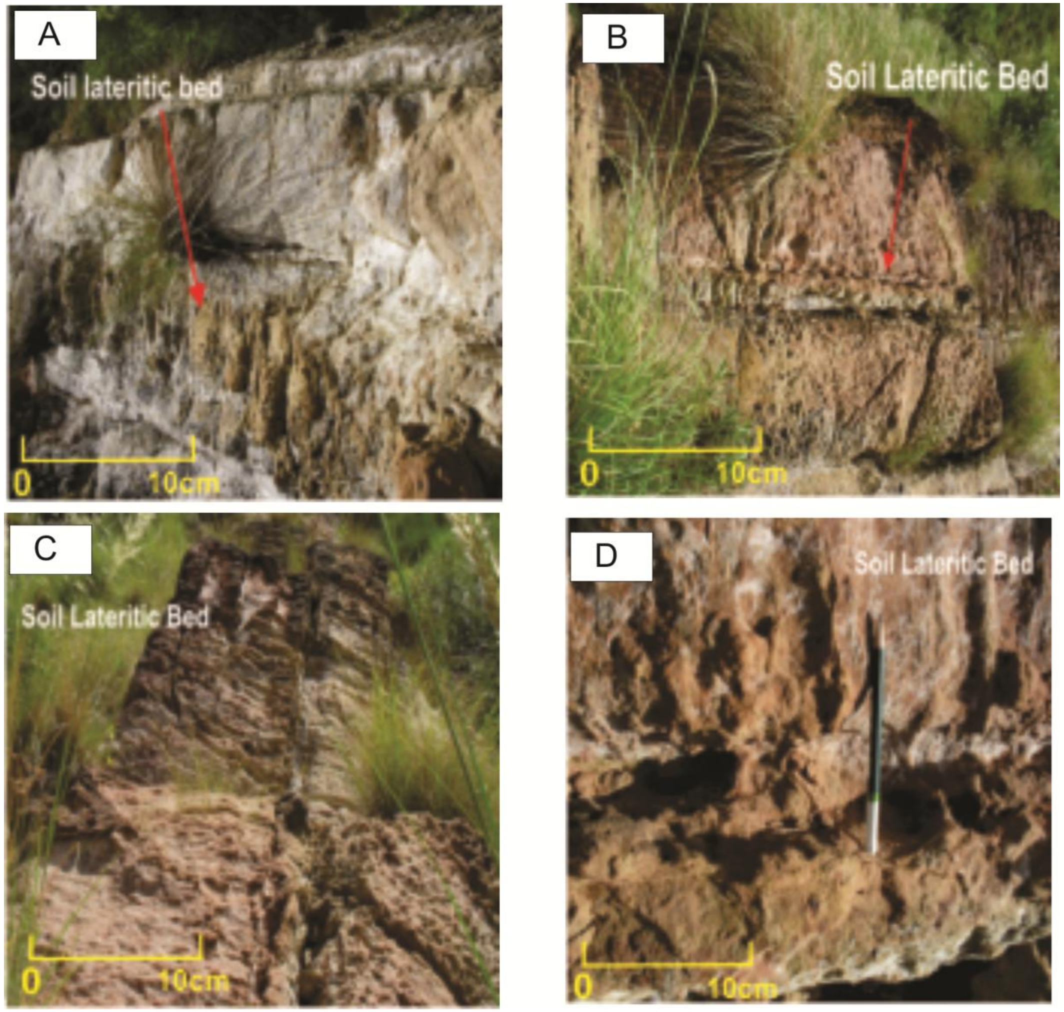
- **Coal beds/organic clays facies (DF3)**
  - The Coal beds and clays in the DF3 facies are rich in carbonaceous material and are dark grey to black in colour.
  - **Interpretation:** the coal and associated organic clays are indicative of over bank deposits in meandering river channel and swampy deltaic environment nearby.



FACIES

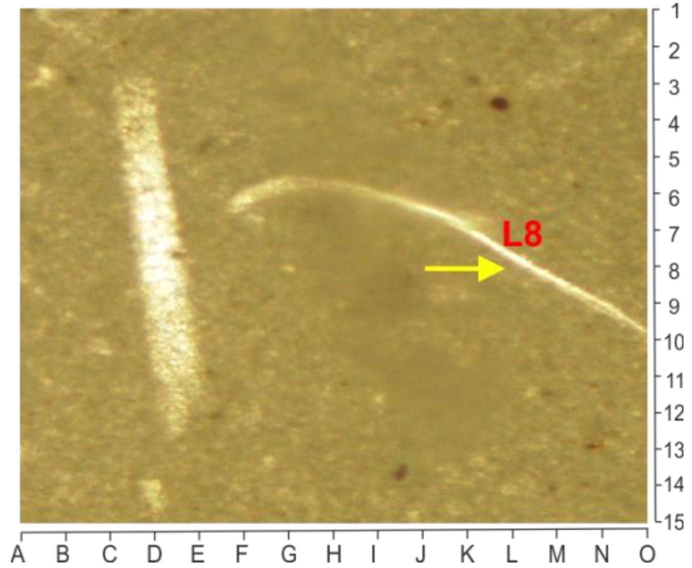
- **Laterite facies (DF4)**
  - The Laterite Facies (DF4) is common in the middle- upper part.
  - It has rusty brown to yellowish colour and having variable thickness ranging from 1ft to 1m.
  - **Interpretation:** They develop by intensive and long lasting weathering of the underlying parent rock. Tropical weathering (laterization) is a prolonged process of chemical weathering which produces a wide variety in colour and texture, grade, chemistry and or mineralogy and thickness of the resulting soils

FACIES


A
Soil lateritic bed
0
10cm
B
Soil Lateritic Bed
0
10cm
C
Soil Lateritic Bed
0
10cm
D
Soil Lateritic Bed
0
10cm

FACIES

- **Limestone interbedded with calcareous sandstone facies (DF5)**
  - Fossiliferous limestone of grayish to maroon colour (Lime mudstone)
  - The DLF 5 facies is characterized by sponge spicules, pelecypods, brachiopod and peloids in a lime mud matrix.
  - **Interpretation:** The DF5 facies is predominantly consisting of lime mud matrix, low diversity fauna indicating a low energy condition while presence of the peloids indicates restricted lagoon environment of deposition.



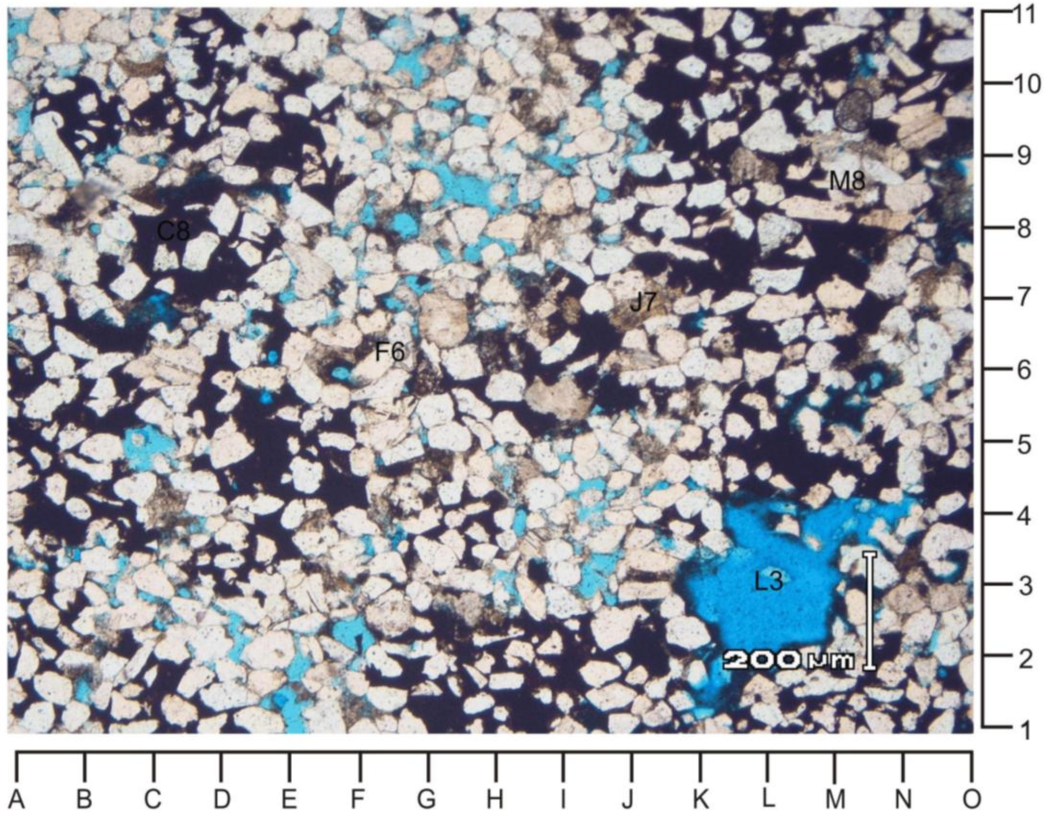
DIGENESIS AND RESERVOIR CHARECTERIZATION

- **COMPACTION, CEMENTATION AND MINERAL ALTERATION**
  - Major digenetic changes observed in the sandstones of the DF1 and DF2 facies are compaction, cementation and mineral alteration while the limestone in the DF5 facies indicates effects of cementation, mechanical compaction, neomorphism and recrystallization.
  - The compaction in sandstone is responsible for; (1) mechanical rearrangement of grains into tighter packing owing to slippage of grains past each other at points of contact (2) deformation of flexible grains such as micas (3) ductile and plastic deformation, particularly of malleable grains such as rock fragments, and (4) pressure dissolution of quartz and other minerals.

Reservoir characterization

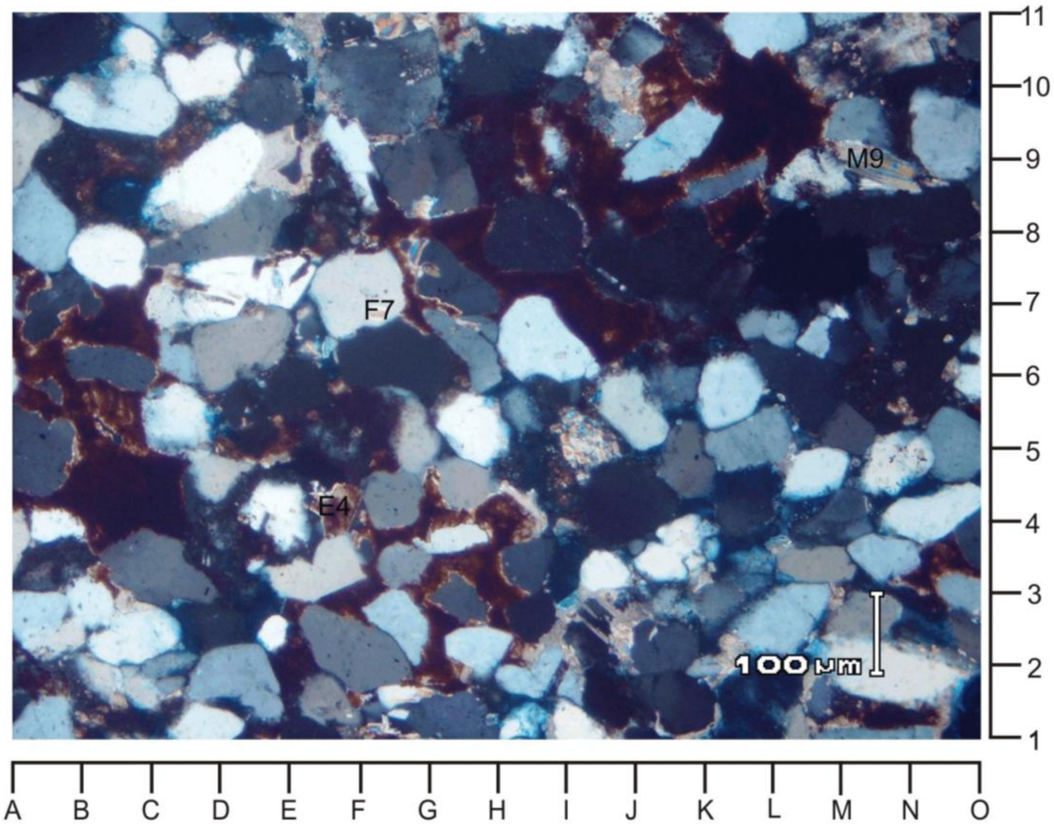
- In the sandstones of the DF1 and DF2 facies compaction occurred immediately after the deposition and caused the expulsion of pore water from the sediments. In the DF1 facies, compaction related fractures and bended mica flakes are common.
- The clay cement represents syn-deposition early stage digenetic phenomena while glauconitic cement represents an early phase of cementation. In the late digenetic stage secondary silica is precipitated and presence of the iron oxide accounts for the oxidation or post digenetic uplifting process. The mineral alteration is also common in the form of muscovite grains in the clayey cement.
- The observed visual porosity is inter-granular and fracture type and the pore spaces are wide and interconnected and show a moderate porosity.
- The primary porosity is reduced because of compaction and cementation while moderate permeability exists.
- The porosity/permeability values of the sandstone plug sample are 22.463 % and 5.59ka md indicating a good hydrocarbon reservoir potential.

DIGENESIS AND RESERVOIR CHARECTERIZATION



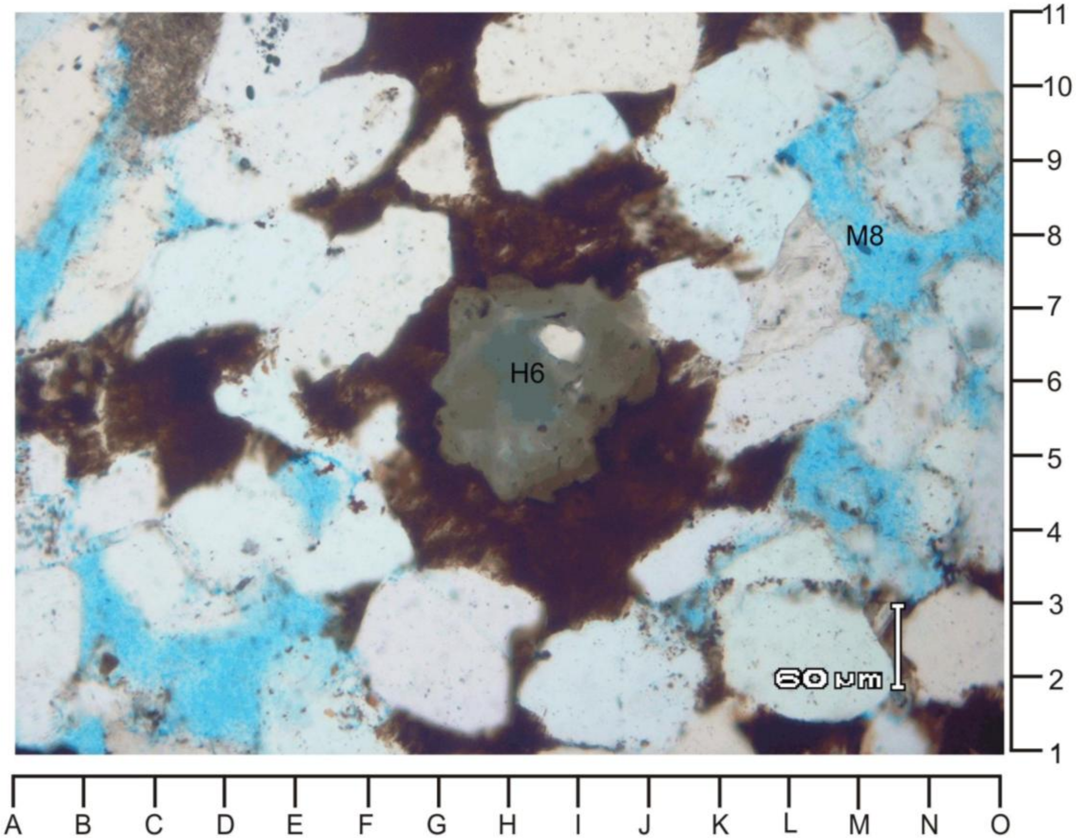
Photomicrograph showing Monocrystalline Quartz (F6), Mica (M8), infiltration of Ferrugineous clayey cement (C8), Intergranular Porosity (L3) and calcite matrix (J7) Datta Sandstone (PPL. Mag X04).

DIGENESIS AND RESERVOIR CHARECTERIZATION



Photomicrograph showing Monocrystalline Quartz having tourmaline inclusion (F7), Mica (M9) and goethite cement patches and calcite cement (E4) Datta Sandstone (PPL. Mag X04).

DIGENESIS AND RESERVOIR CHARECTERIZATION

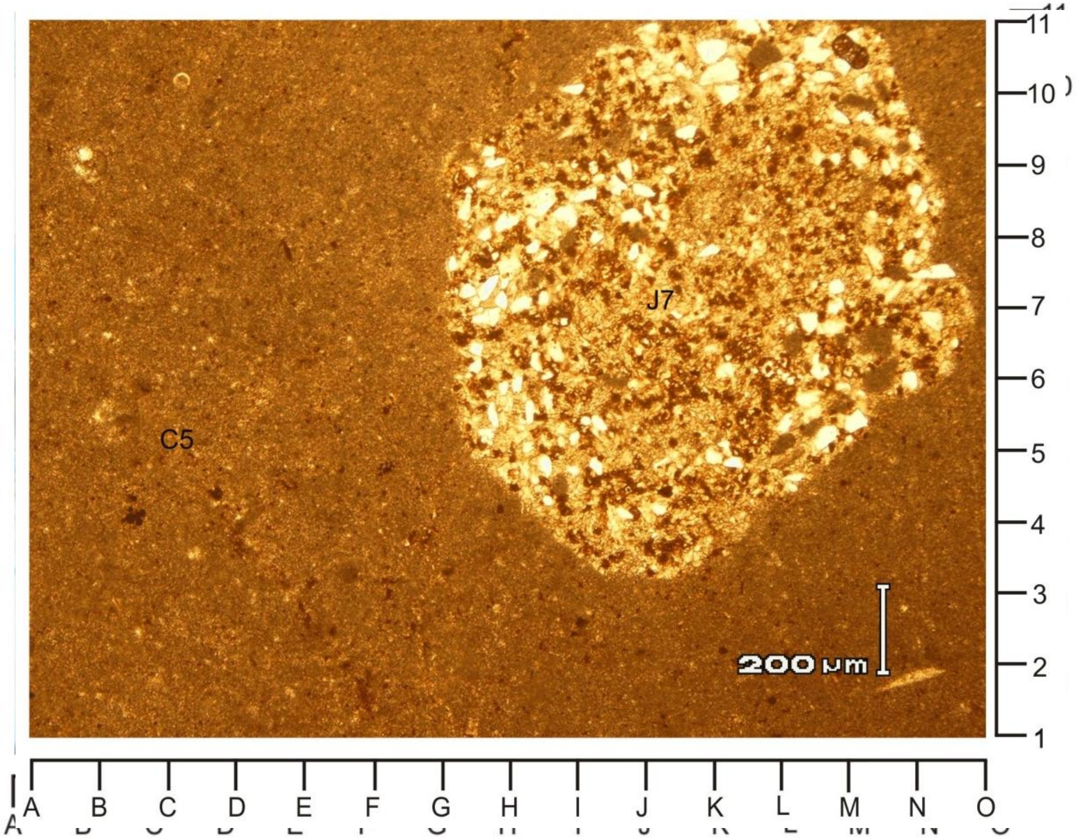


Photomicrograph showing Glauconite (H6) and Intergranular Porosity (M8) Datta Sandstone (PPL. Mag X04).

Reservoir characterization

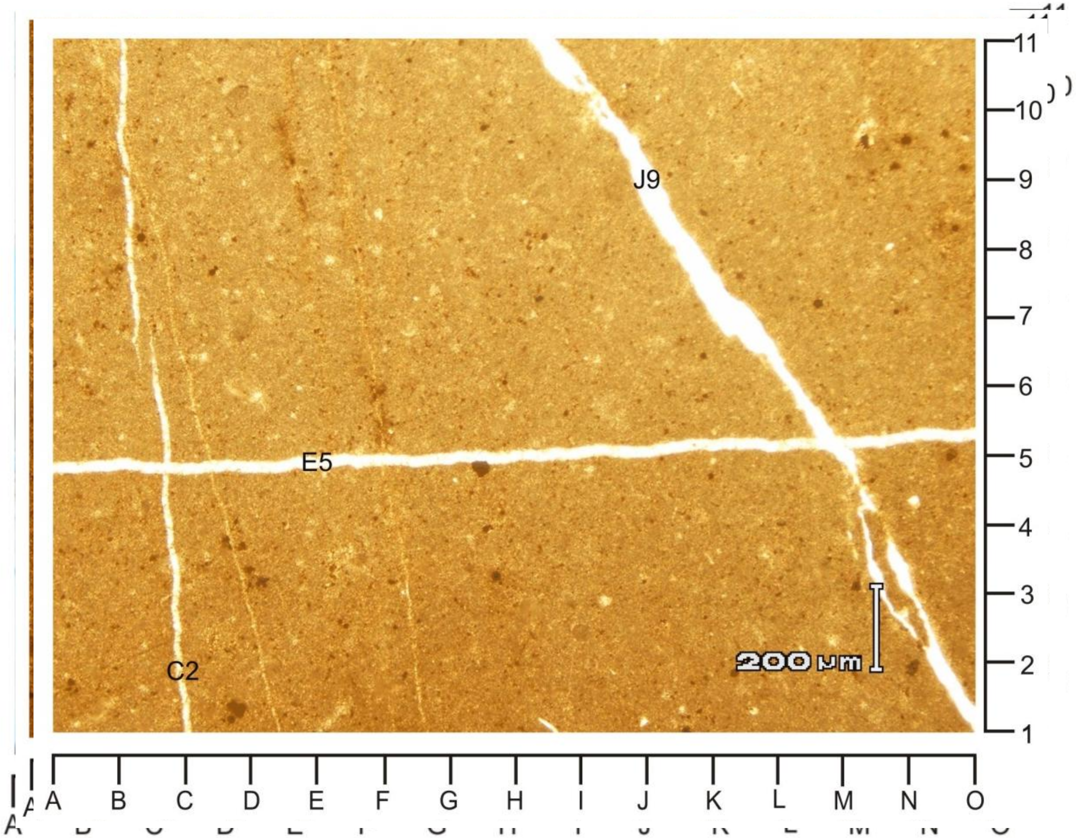
- In the carbonate of DF5 facies micrite cement is common and the neomorphic replacement of aragonite/high-magnesium calcite by low-magnesium calcite involves gradual dissolution of the original minerals and precipitation of calcite as shown by bivalves fragments.
- Mechanical compaction (calcite filled multi fractures) represents a late digenetic phase. Many carbonate rocks display millimeter- to centimeter-sized, mineral-filled (often calcite-filled) fractures. Most calcite veins are due to brittle failure and tectonic fracturing of lithified carbonates caused by stress and shear displacement, extensional movements or natural hydraulic fracturing.
- Fracture zones may penetrate vertically across lithologic and facies boundaries.

DIGENESIS AND RESERVOIR CHARECTERIZATION



Photomicrograph of mudstone microfacies displaying burrow filled by silt size quartz grains (J7) Datta Limestone (PPL. Mag X04).

DIGENESIS AND RESERVOIR CHARECTERIZATION



Photomicrograph of mudstone microfacies displaying episode of fractures in the limestone; first fracture (C2), second fracture (E5), third fracture (J9), all the fractures are filled by calcite and micrite is present as matrix (PPL, Mag. X04).

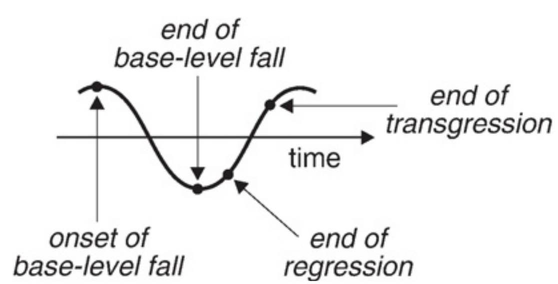
Reservoir characterization

- Although porosity in carbonates can be enhanced by fractures, dissolution and burrows but in case of DF5 facies, the fractures are filled by calcite and iron concentration and the burrows are filled by clasts reflecting a very poor or nil visual porosity and permeability.
- The plug porosity of the DF5 sample is 0.229 % and the plug permeability is 0.00 ka md reflecting a poor hydrocarbon reservoir potential.

SEQUENCE STRATIGRAPHY

Events \ Sequence model	Depositional Sequence II	Depositional Sequence III	Depositional Sequence IV	Genetic Sequence	T-R Sequence
	HST	early HST	HST	HST	RST
end of transgression				MFS	
	TST	TST	TST	TST	TST
end of regression					MRS
	late LST (wedge)	LST	LST	late LST (wedge)	
end of base-level fall			CC**		
	early LST (fan)	late HST	FSST	early LST (fan)	RST
onset of base-level fall	CC*				
	HST	early HST	HST	HST	

sequence boundary
systems tract boundary
within systems tract surface



SEQUENCE STRATIGRAPHY

CAN WE RECOGNISE SYSTEMS TRACT IN FLUVIAL ARCHETECTURE ?

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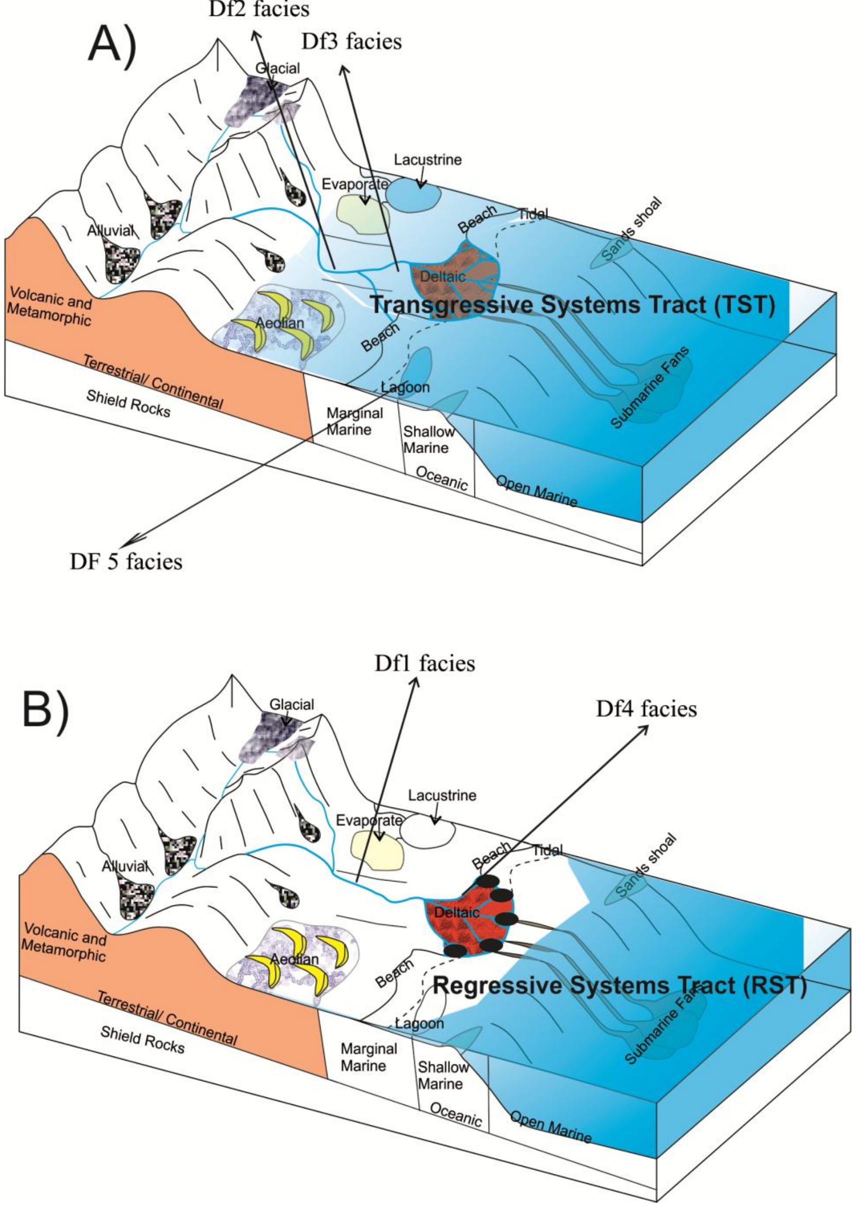
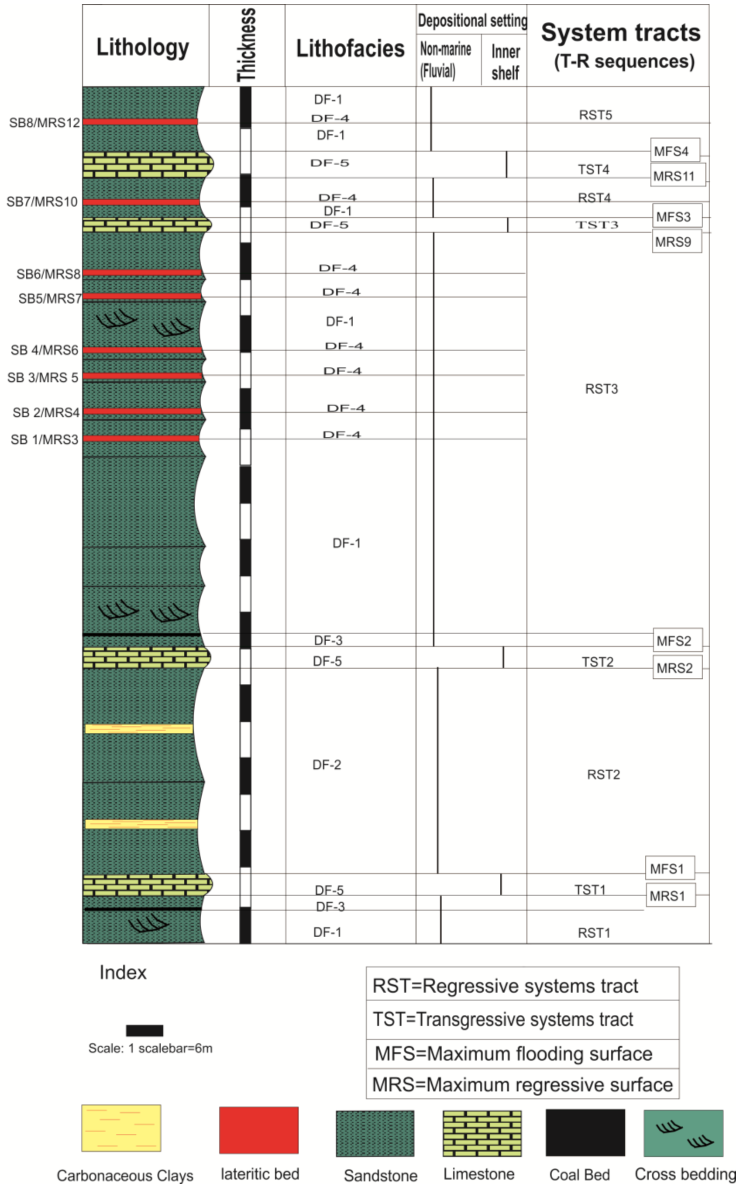
SEQUENCE STRATIGRAPHY



SEQUENCE STRATIGRAPHY



RST=Regressive systems tract
TST=Transgressive systems tract
MFS=Maximum flooding surface
MRS=Maximum regressive surface

DISCUSSION

- The difficulty of identifying sequence boundaries in fluvial system can be minimized by recognizing the juxtaposition of clastic facies on marine sediments and aerial exposure of the facies due to the delta lobe switching.
- The incision of rivers is governed by sea level fall but can also be attributed to the a) tectonic uplift b) increase discharge and power of the fluvial system c) decrease in the sediment load . All can account for the development of local unconformities (if the river avulsion is at small scale) or regional unconformities (if the river avulsion involves shift in major course of the channel).

- In the Datta Formation the abundance of exposure surfaces represented by the Laterite Facies (DF5) could be attributed to the process of delta lobe switching as abandoned channel signatures in the form of interbedded pebbly sandstone, siltstone and clays are seen associated with the soil horizons. The decrease in the sand body amalgamation, coal beds, organic clays and a decreasing tidal/wave influence in the Regressive Systems Tracts (RST 1-RST5) indicates deposition on a fluvial dominated prograding delta system.
- while the presence of pebbly sandstone supports a low sinuosity braided river system deposition in the early phase of the river incision .The onset of the Transgression caused submergence of the abandoned delta lobes and favored the preservation of estuarine dominated shelf delta system in the TST1-4.

- The culmination of the transgressive phase is recorded by the maximum landward penetration of the tidal influence favoring abundant preservation of the coal beds in the swampy environment. Flooding of the interfluves (incised valley fills) forming crevasse splays, levee deposits, and channelized sandstone in a high sinuosity meandering river system in the late transgressive phase.

CONCLUSIONS

- The Datta Formation is predominantly composed of fine to coarse grained sandstone interbedded with limestone, coal and laterite beds at places.
- Five lithofacies (DF1-DF5) facies are identified which represents fluvial dominated delta-lagoon depositional setting.
- The digenetic fabric and cement stratigraphy of all DF,DF2 and DF5 facies is presented that shows good reservoir rock potential of DF1 and DF2 sandstone facies while DF5 carbonate facies possesses a poor potential.
- The Transgressive-Regressive (T-R) sequences are identified at third order scale having five RSTs and four TSTs.
- The sequence boundaries SB1-SB8 are local in origin and occurred due to delta lobe switching due to river avulsion in a period of regression.

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ACKNOWLEDGEMENT

- We greatly acknowledge the constructive comments of the reviewer of this paper.

THANKS