Pakistan Journal of Hydrocarbon Research
Vol. 22 & 23, (June 2012 & 2013),p.63-71, 11 Figs.,02 Tables.

Facies analysis and dynamic depositional modeling: implications for hydrocarbon prospecting in the early 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 (DF1), representing deposition in a braided fluvial environment 2) Thin to medium bedded sandstone and interbedded clays (DF2), representing deposition in a meandering fluvial environment 3) Coal beds/organic clays (DF3), representing deposition in a deltaic (swampy) environment 4) Laterites (DF4), representing prolonged exposure of the platform under oxidizing conditions and 5) Lime mudstone-wackestones (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 the Laterite facies (DF3) and associated channel sandstone deposits of the braided river system that are interpreted to have been 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 also caused flood plain deposition in a meandering river system in the transgressive systems tract.

The diagenetic 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 of sandstones confirm good hydrocarbon prospects of the Datta Formation in the region.

INTRODUCTION

The Salt Range has been divided into three geographic divisions which are the Central, the Western and the Eastern part. The Central Salt Range is transitional between the Western and the Eastern parts in its stratigraphic setup. Rocks exposed in the Salt Range area range from infra Cambrian to Tertiary with marked absence of the rocks of Ordovician, Silurian, Devonian and Carboniferous age throughout the region (Shami and Baig 2002). The Mesozoic sequence is well developed in Western Salt Ranges and Trans Indus Ranges, but in most of the Central and Eastern Salt Range the Triassic, Jurassic and mostly the Cretaceous strata are conspicuously absent. The study area (Figure 1) lies in the Western Salt Range and the exposed Mesozoic rocks show major intra- and inter-system disconformities, a variety of environment both transgressive and regressive (marine and continental) cycles, which in turn are disconformably over and underlain by stratigraphic sequence of Tertiary and Paleozoic respectively (Fatmi, 1977). The lower Jurassic (Pre-Toarcian) Datta Formation is composed of sandstone, shale and siltstone with minor mudstone. At some places it contains ferruginous concretion and pebbles, and laterally changes into siltstone. It also contains fire clay, coal streaks/stringers, and carbonaceous beds. The shale is black to bluish-brown. The siltstone is dark grey to greyish yellow, fine to medium grained, and thin bedded. In the earlier investigations (Danilchik 1961,Danilchik and Shah,1967, Chaudry, et al., 1992 and Abassi, et al., 2010) a regional stratigraphic setup and different lithofacies with their paleoenvironments are described but no detail is available regarding the digenetic and sequence stratigraphic framework of the Datta Formation in the Western Salt Ranges. The aim of this paper is to record the facies variation and to investigate the effects of sea level fluctuations in depositional morphologies of the fluvio-deltaic settings. We also present the sequence stratigraphic model of the study area for a better understanding of the depositional dynamics of the basin. The petrophysical criteria (porosity/permeability) and the diagenetic fabric of different lithofacies suggest a good hydrocarbon reservoir potential of the Datta Formation.

MATERIALS AND METHODS

The Datta Formation has a maximum thickness of 138m in the Nammal Gorge Section. It comprises of a thick siliciclastic dominated sequence..A detailed stratigraphic log is prepared to show sedimentary facies variation and associated depositional and deformational features (Figure 2). In the study area the Datta Formation is composed of sandstone, shale and siltstone with limestone at some places. The sandstone is variegated in color, weathers to purple white to grayish-yellow colour, fine to coarse grained, thick bedded to massive, at places thin to medium bedded, hard, friable, ferruginous, mottled and cross bedded. The ferruginous concretions and pebbles are common in the sandstone. It also contains fire clay, coal streaks/stringers, carbonaceous beds, and laterite beds in the middle-upper part. In the present study

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Figure 1 - Location map of the study area (Nammal Gorge Section, shown with yellow arrow head) exposed in the Central part of the Western Salt Ranges, northwest Pakistan (Google Earth).

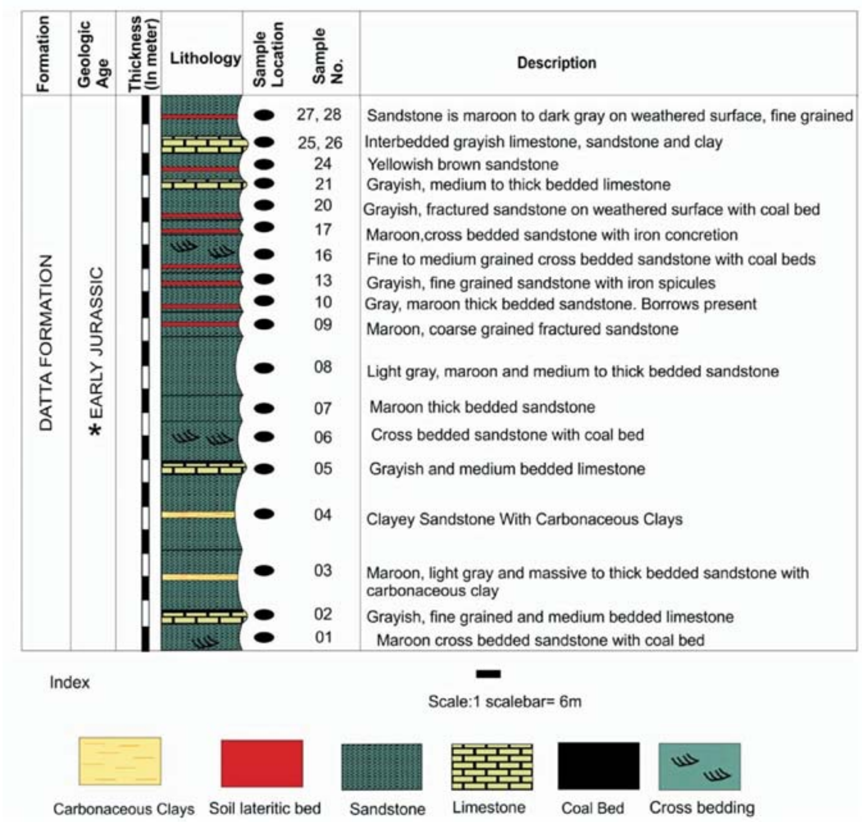

Figure 2 - Stratigraphic log of the Datta Formation, exposed in the study area.

The systematic rock sampling technique was utilized and collected twenty seven outcrop samples. These rock samples were thin sectioned and a digital camera fitted Nikon Microscope at the Department of Geology, University of Peshawar was used for the petrography. The quantitative data regarding the plug porosity and permeability of the selected rock samples is collected by using porosimeter and permeameter at the Hydrocarbon Development Institute of Pakistan (HDIP) for the hydrocarbon reservoir potential of the different facies. Integration of the outcrop data and petrographic information (facies, paleoenvironments and diagenesis) constrained the dynamics of the depositional settings in a sequence stratigraphic framework.

FACIES DISTRIBUTION

The Datta Formation is well developed in the Trans Indus Ranges, Salt Ranges and the Surghar Ranges. At the type locality the thickness is 212m but in Pannu Nala in the west the thickness increases to 230m, and over 400m in the Sheikh Budin Hill (Shah, 2009). In the south-western part and in the Khisor Ranges its thickness reduces to 150m. In the Nammal Gorge its thickness is 130m to 156m and decreases further east. In the Hazara area, its thickness ranges from 0-10m. In the Kala Chitta area its thickness is 6m. It rests unconformably on the Kingriali Formation in the Salt Range, Trans Indus Ranges, and the Kala Chitta area. In the Hazara area it unconformably overlies the Precambrian (Hazara Formation). Its upper contact with the Shinawari Formation is gradational (Shah, 2009). Except some carbonaceous remains, no diagnostic fossils have been reported from the formation. As the formation underlies the Shinawari Formation, which in its lower part has yielded Lower Toarcian ammonites, its age is inferred as Early Jurassic (Shah, 2009). In the present study the following lithofacies are recognized in the Datta formation exposed in the Nammal Gorge Section.

1) Cross bedded sandstone interbedded with siltstone (DF1)
2) Thin to medium bedded sandstone and interbedded clays (DF2)
3) Coal beds/organic clays (DF3)
4) Laterite (Df4)
5) Lime mudstone-wackestone (Df5)

1. Cross bedded sandstone interbedded with siltstone facies (DF 1)

The sandstone of DF1 facies displays yellowish colour on weathered surface and having a coarse grain texture (Figure 3). At some places this sandstone contains siltstone interbeds in the lower part of the formation. Petrography of the DF 1 facies confirmed presence of quartz, rock fragments, matrix and accessory minerals (Figures 4a-c and Table 1). Ferruginous clay, tourmaline and chert are present as accessory minerals. DF1 is classified as "sub-litharenite" (Pettijohn, et al., 1987). The rock texture indicates moderate to well sorting and sub angular to sub rounded grains fabric (Table 2).The mineralogical and textural characteristics of sandstone are defined by the maturity. The mineralogical maturity is determined by its quartz to feldspar ratio. The sandstones of the DF1 facies is texturally sub mature because grains are moderate to poorly sorted, sub angular to sub rounded and contain <15% clay (Table 2).

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 (Pettijohn, et al., 1987).

Figure 3 - Outcrop view of cross bedding in Sandstone of the DF1 facies in the Datta Formation exposed at the Nammal Gorge Section.

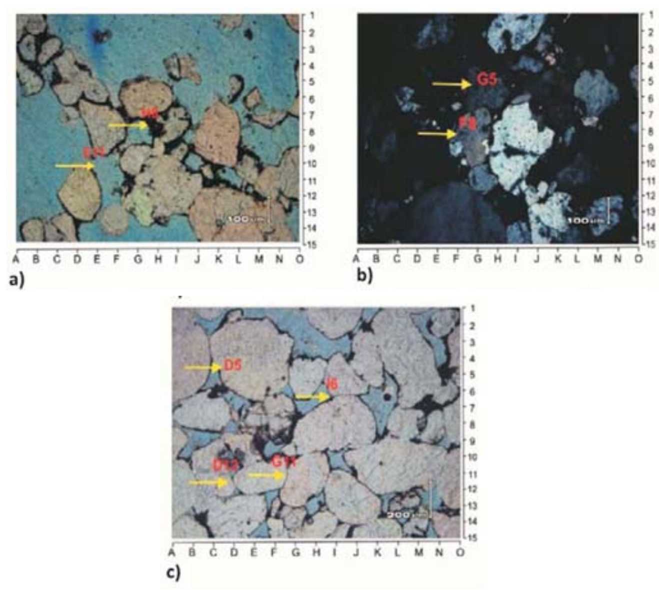

Figure 4 - a) Photomicrograph showing ferruginous matrix (H8), inter granular porosity (E11) in DF 1 Sub-litharenite facies (PPL, Mag. X4).

b) Photomicrograph showing polycrystalline quartz (F8) and monocrystalline Quartz (G5) in DF1 Sub-litharenite facies (XXL, Mag. X4).

c) Photomicrograph showing angular grain (D5) and concave convex contact (I6, D12 and G11) in DF1 Sub-litharenite facies (PPL, Mag. X4).

Table 1 - Petrographic data regarding component distribution of various lithofacies of the Datta Formation, exposed in the Nammal Gorge Section.

Thin section no.	Quartz% (Q-Quartz, m-Monocrystalline, p-Polycrystalline, t-total)			Rock Fragments% Carbonaceous clay%	Rock Fragments% Ferruginous clay%	Rock Fragments% Accesory Minerals%	Matrix% (Fe)	Faceis types	Pettijohn's (1987) Classification
	Q_m	Q_p	Q_t						
01	55	30	85	---------	04	01	10	DF 1	Sub-litharenite
02	< 10% allochems (Pelecypods, Sponge spicules) and 10% lime mud matrix							DF 5	Lime Mudstone (after Folk, 1964)
03	45	30	75	---------	02	03	20	DF 2	Lithic-greywacke
04	43	-----	43	09	02	---------	46	DF 2	
05	10 to 20% allochems (Pelecypods, Peloids and Sponge spicules) and > 10% grains							DF 5	Wackstone (after Folk, 1964)
06	70	10	80	---------	05	05	10	DF 1	Sub-litharenite
07	62	05	67	---------	---------	05	28	DF 2	Lithic-greywacke
08	65	05	70	---------	05	05	20	DF 2	
09	75	05	80	---------	05	05	10	DF 1	Sub-litharenite
10	75	-----	75	---------	10	05	10	DF 1	
11	60	05	65	---------	03	02	30	DF 2	Lithic-greywacke
12	75	-----	75	---------	04	01	20	DF 2	
13	25	-----	25	---------	---------	05	70	DF 2	
14	55	-----	55	---------	10	05	30	DF 2	
15	70	-----	70	---------	05	10	15	DF 2	
16	45	-----	45	---------	---------	05	50	DF 2	
17	35	03	38	---------	---------	02	60	DF 2	
18	70	-----	70	---------	---------	05	25	DF 2	
19	60	05	65	---------	05	05	25	DF 2	
20	55	05	60	---------	05	05	30	DF 2	
21	< 10% allochems (Pelecypods, Sponge spicules) and 10% lime mud matrix							DF 5	Lime Mudstone (after Folk, 1964)
22	65	05	70	---------	---------	05	25	DF 2	Lithic-greywacke
23	65	-----	65	---------	---------	05	30	DF 2	
24	60	-----	60	---------	---------	05	35	DF 2	
25	10 to 20% allochems (Pelecypods, Peloids and Sponge spicules) and > 10% grains							DF 5	Wackstone (after Folk, 1964)
26	< 10% allochems (Pelecypods, Sponge spicules and Peloids) and 10% lime mud matrix							DF 5	Lime Mudstone (after Folk, 1964)
27	75	-----	75	---------	05	05	15	DF 2	Lithic-graywacke
28	60	10	70	---------	---------	05	25	DF 2	

Table 2 - Petrographic data related to the textural and compositional maturity of various lithofacies of the Datta Formation, exposed in the Nammal Gorge Section.

Thin Section No.	Textural Maturity: Roundness	Sorting	Grain Size	Compositional Maturity: Minerology		Overall Maturity
01	SA-SR	mod-well	med-coarse	Quartz rich	DF 1	Submature-mature
02	Non clastic rocks					
03	SA	mod	Coarse	Quartz rich	DF 1	Immature-mature
04	SA-SR	Poor-mod	Fine-med	Lithic rich	DF 2	Mature-immature
05	Non clastic rocks					
06	SR-WR	Well	Coarse	Quartz rich	DF 1	Submature-mature
07	SA-SR	mod	med-coarse	Quartz rich	DF 1	Immature-mature
08	SA-SR	mod-well	Fine-med	Quartz rich	DF 1	Mature
09	SA-SR	mod-well	Fine	Quartz rich	DF 1	Submature-mature
10	SA-SR	Poor-mod	Fine-med	Quartz rich	DF 1	Immature
11	SA-SR	mod	Fine-med	Quartz rich	DF 1	Immature-mature
12	SA-SR	mod	Fine-med	Quartz rich	DF 1	Immature-mature
13	SA-SR	mod	Fine-med	Lithic rich	DF 2	Immature
14	SA-SR	mod	Fine-med	Quartz rich	DF 1	Immature-submature
15	SA-SR	mod	Fine-med	Quartz rich	DF 1	Immature-mature
16	SA-SR	mod	Fine-med	Lithic rich	DF 2	Immature-submature
17	SA-SR	mod	Fine-med	Lithic rich	DF 2	Immature
18	SA-SR	mod	med	Quartz rich	DF 1	Submature-mature
19	SA-SR	Poor-mod	Fine-med	Quartz rich	DF 1	Immature-mature
20	SA-SR	Poor-mod	Fine-med	Lithic rich	DF 2	Immature-submature
21	Non clastic rocks					
22	SA-SR	mod	med	Quartz rich	DF 1	Submature-mature
23	SA-SR	mod	Fine-med	Quartz rich	DF 1	Immature-submature
24	SA-SR	mod	Coarse	Quartz rich	DF 1	Submature-mature
25	Non clastic rocks					
26	Non clastic rocks					
27	SA-SR	mod	Fine-med	Quartz rich	DF 1	Immature-mature
28	SA-SR	Poor-mod	Fine-med	Quartz rich	DF 1	Immature-mature

2. Thin to medium bedded sandstone and interbedded clays facies (Df2)

At the outcrop scale the sandstones of the DF2 facies display maroon to grayish color on fresh surface and have a coarse grained texture. The sandstone consists of quartz, ferruginous matrix and accessory minerals (Figures 5a-c and Table 1). The abundance of quartz is varying from 25% to 75% (Table 1). Quartz grains are mostly medium grained but admixture of some coarse and fine grains are also present. The quartz grains are subangular to subrounded. Ferruginous matrix is present in relatively large amount i.e. 15 to 70% (Table 1). Accessory minerals are present with a varying abundance ranging from 1 to 10 %. Traces of zircon and tourmaline are also identified. The sandstones of the DF2 facies are mineralogically mature and texturally immature to sub mature (Table 2), and are classified as "lithic-graywacke" (Pettijohn, et al., 1987). Organic rich clays with stringers of coal (Figure 6) are also associated with the DF2 facies.

Interpretation: In DF2 facies medium to thick beds of the sandstone are overlain by medium grained siltstone which grades upward into shale. This shows a fining upward point bar sequence which is a very conspicuous geomorphic feature of a meandering river (Kadri, 1995). The presence of abundant carbonaceous material in shale is indicative of high vegetation present near the onshore portion of delta i.e. in meandering channel or in neighboring swampy environment (Hunt and Tucker, 1992).

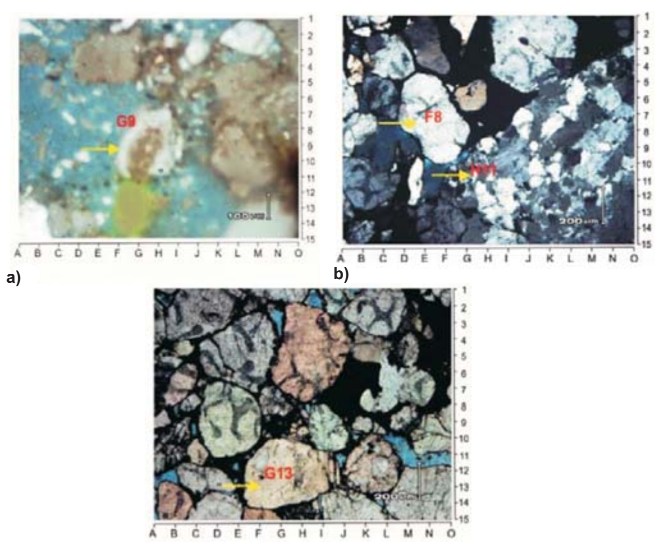

Figure 5 - a) Photomicrograph showing feldspar partially altered to clay (G9) in the DF2 Lithic-graywacke facies (PPL, Mag. X4).

b) Photomicrograph showing monocrystalline quartz (F8) and polycrystalline quartz (H11) in DF2 Lithic-graywacke facies (XPL, Mag. X4).

c) Photomicrograph showing coarse and subangular quartz grain (G13) in the DF2 Lithic-graywacke facies (PPL, Mag, X4).

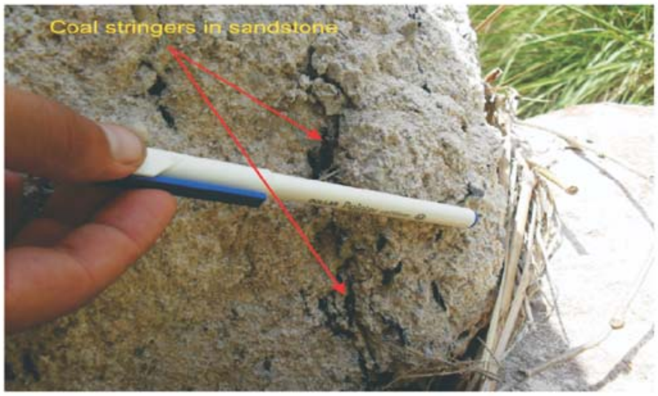

Figure 6 - Outcrop view of coal/organic matter stringers in the Datta Formation exposed at the Nammal Gorge Section.

3. 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 (Figure 7).

Interpretation: the coal and associated organic clays are indicative of over bank deposits in meandering river channel and swampy deltaic environment nearby (Myers, and Milton, 2007).The association of clays indicates transported nature of coal deposits.

4. Laterite facies (Df4)

The Laterite facies (DF4) is common in the middle- upper part of the Datta Formation in the Nammal Gorge Section. It has rusty brown to yellowish colour and having a variable thickness ranging from 1ft to 1m (Figures 8 a-b).

Interpretation: The laterite beds are the soil types, rich in iron and aluminum which are formed in hot and wet tropical areas. Nearly all laterites are rusty-red because of iron oxides. 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 (Myers and Milton, 2007).

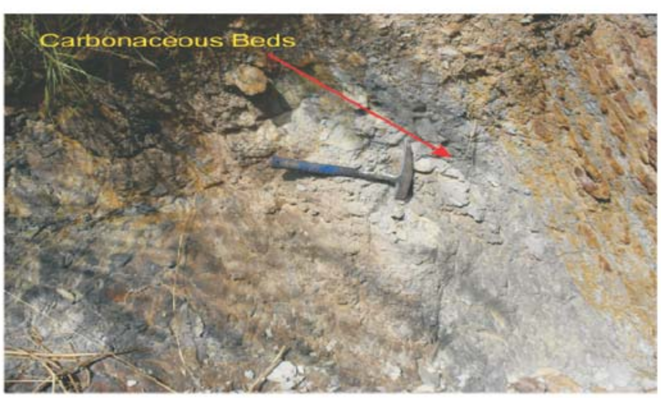

Figure 7 - Outcrop-view of carbonaceous beds in the Datta Formation exposed at Nammal Gorge Section.

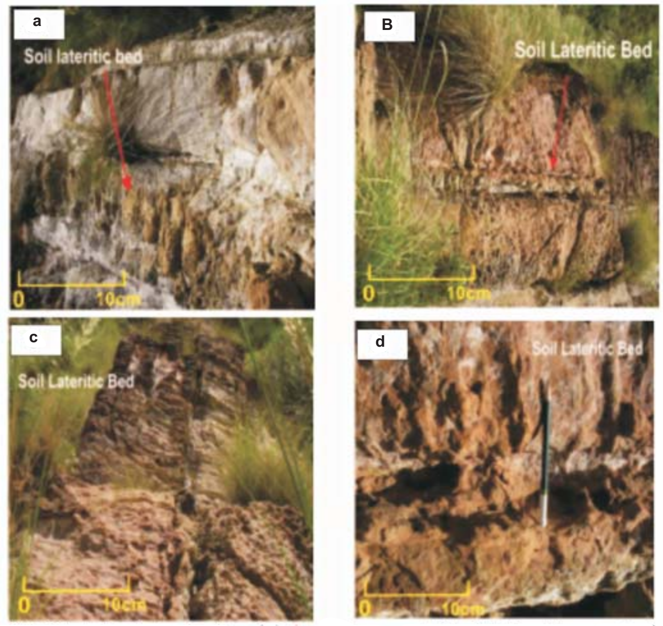

Figure 8a-d - Laterite beds at various intervals in the middle-upper part of the Datta Formation exposed in the Nammal Gorge Section.

5. Limestone interbedded with calcareous sandstone facies (Df5)

At outcrop scale the DF5 facies is represented by fine to medium grained, fossiliferous limestone of greyish to maroon colour. At some places this limestone contains iron concretions and is interbedded with clays and calcareous sandstone in the upper part of the formation. The DLF 5 facies is characterized by sponge spicules, pelecypods, brachiopods and peloids in a lime mud matrix (Figures 9 a-b).

Interpretation: The DF5 facies predominantly consists of lime mud matrix, low diversity fauna indicating deposition under a low energy condition while presence of the peloids indicates restricted lagoon environment of deposition (Flugel, 2004).

DIAGENESIS AND RESERVOIR CHARACTERIZATION

Major diagenetic 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.

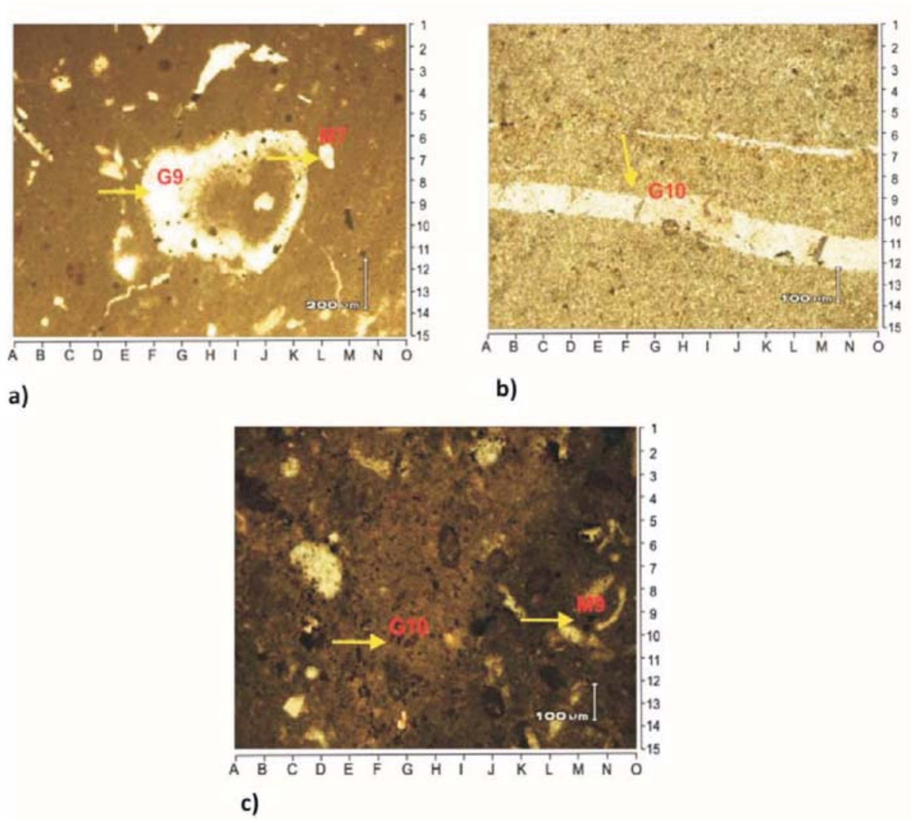

Figure 9 - a) Photomicrograph showing pelecypod (G9) and small brachiopod (M7) in DF 5 Lime mudstone-wackstone facies (PPL, Mag. X10).

b) Photomicrograph showing spar filled fracture (G10) in DF 5 Lime mudstone-wackstone facies (PPL, Mag. X10).

c) Photomicrograph showing sponge spicules (I12 and I9) in DF 5 Lime mudstone-wackstone facies (PPL, Mag. X4).

In the sandstones of the DF1 and DF2 facies compaction seems to have occurred immediately after the deposition and caused the expulsion of pore water from the sediments. Compaction related fractures and bended mica flakes are also common in DF1 and DF2. The clay cement (Figure 4c) represents syn-deposition early stage diagenetic phenomena while glauconitic cement represents an early phase of cementation. In the late diagenetic stage secondary silica is precipitated and presence of the iron oxide accounts for the oxidation or post diagenetic 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 in the study area.

In the carbonate of the 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 mineralogy of the bivalve fragments. Mechanical compaction (calcite filled multi fractures) represents a late diagenetic 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. Although porosity in carbonates can be enhanced by fractures, dissolution and burrows, in the case of DF5 facies, the fractures are filled by calcite (Figure 9c) and iron concentrations, and the burrows are filled by clasts reflecting a very poor or nil visual porosity and permeability. The selected five samples from the Nammal Gorge Section representing the DF5 facies, the maximum value of plug porosity is 0.229 % and the plug permeability is 0.00 ka md, reflecting a poor hydrocarbon reservoir potential.

SEQUENCE STRATIGRAPHY

Tectonic Sequences or the stratigraphic records of major falls and rises of sea level; their local development reflects the interplay of eustasy, tectonic subsidence, and sedimentation. Ideally, sequences are divisible into three phases, the low stand (or shelf margin), transgressive, and high stand systems tracts, each delimited below by a discontinuity, the sequence boundary, transgressive and maximum flooding surfaces (Haq, et al., 1987). The sequence stratigraphy is related with the petroleum potential of the basin fills. The sediments in lowstand systems tract deposited in the form of fan on the slope or as lowstand prograding wedge may contain potential reservoir rock. In case of transgressive systems tract continuous sheet sands can be deposited on the shelf and shoreline where it may act as a reservoir rock. The condensed sections deposited in the basin and other places may serve as source rock. While in highstand systems tract sediments are deposited on the shelf and slope, which serve as reservoir rock. Intra-formational seals in the form of clay and shale are also produced by these systems tracts (Haq, et al., 1987, Galloway, 1989 and Macdonald, 1986). The T-R sequence model (Embry and Johannessen, 1992) use the sub-aerial unconformity as the unconformable portion of the boundary on the basin margin and maximum regressive surface (MRS) as the correlative conformity farther seaward. This model represents alternative way of packaging strata into sequences. Maximum Flooding Surfaces (MFS) are used to subdivide the T-R sequences into transgressive and regressive systems tracts. The combination of different genetic types of deposits into one single unit, i.e. the regressive systems tracts, provides an easy way of subdividing the rock record into systems tracts.

Using T-R sequence model (Embry and Johannessen, 1992), two types of systems tracts i.e. RST and TST have been identified in the Datta Formation. Regressive systems tract (RST) is bounded by the maximum flooding surface (MFS) at the base and by the maximum regressive surface (MRS) at the top and is defined by the progradational stacking patterns in both marine and non-marine strata (Posamentier, and Vail, 1988). Five Regressive Systems Tracts (RST 1-RST 5) with a total thickness of 120.3m (Figure 10) are recorded in the Datta Formation. The RSTs depositional systems may be similar initially to those in TST, but the infill of shelf areas by progradation, and the decrease in the rate of relative sea-level rise, may lead to a decrease in tidal influence during early RST, and a decrease in the amount of coal, and of over bank, lagoonal and lacustrine shales. Channel sand bodies will become more common and more connected (Posamentier and James, 1993). In Datta Formation, the regressive systems tract (RST1 to RST5) consists of cross bedded sandstone interbedded with siltstone facies (DF1), and thin to medium bedded sandstone and interbedded clays facies (DF2) representing a progradational braided fluvio-deltaic depositional architecture (Figure 11).

The Transgressive Systems Tract (TST) is bounded by the maximum regressive surface (MRS) at the base and by the maximum flooding surface (MFS) at the top. This system tract forms during the portion of base level rise when the rates of rise surpass the sedimentation rates (Macdonald, 1986). In Datta Formation the Transgressive System Tract (TST1 to TST4) with a total thickness of 18m consists of Lime mudstone to wackestone (DF5) and Coal beds/organic clays (DF3) facies (Figure 11A). These lithofacies have been interpreted to be deposited in inner shelf (lagoon)-meandering fluvial dominated delta environment. The SB1-SB8 sequence boundaries are localized unconformities and are identified on the basis of subaerial exposure typified by the presence of soil lateritic beds along the various maximum regressive surfaces (Figure 10).

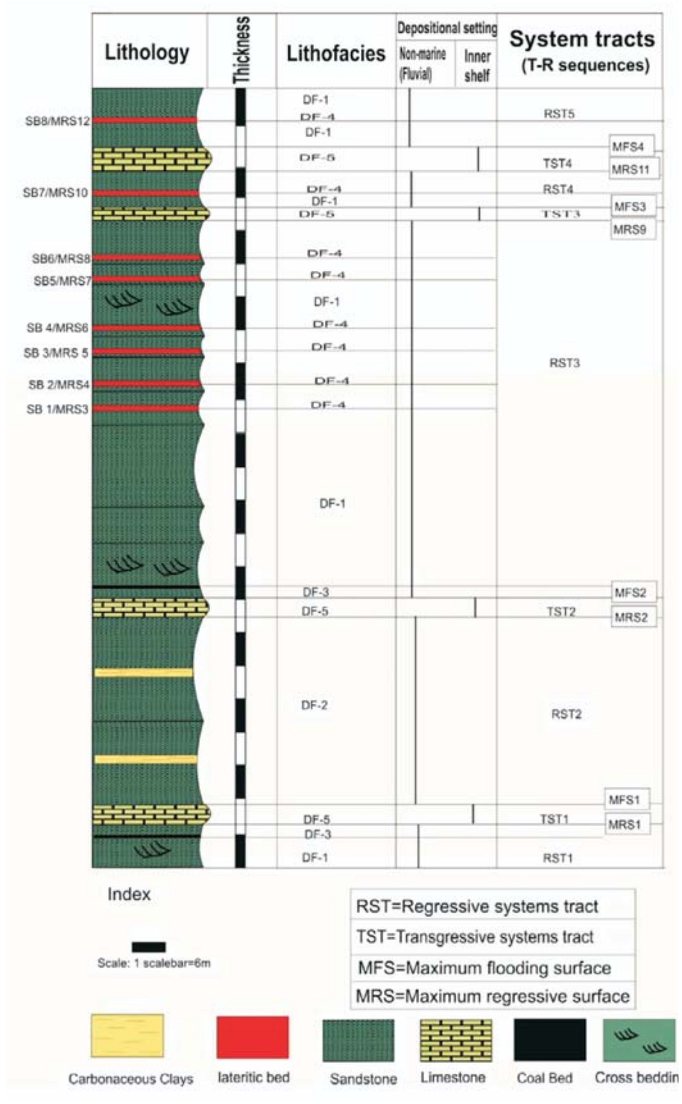

Figure 10 - Composite log showing vertical distribution of facies, depositional settings and Transgressive-Regressive sequences (systems tract) in the Datta Formation at Nammal Gorge Section (DF 1-DF 5 are various facies and SB 1-8 are sequence boundaries).

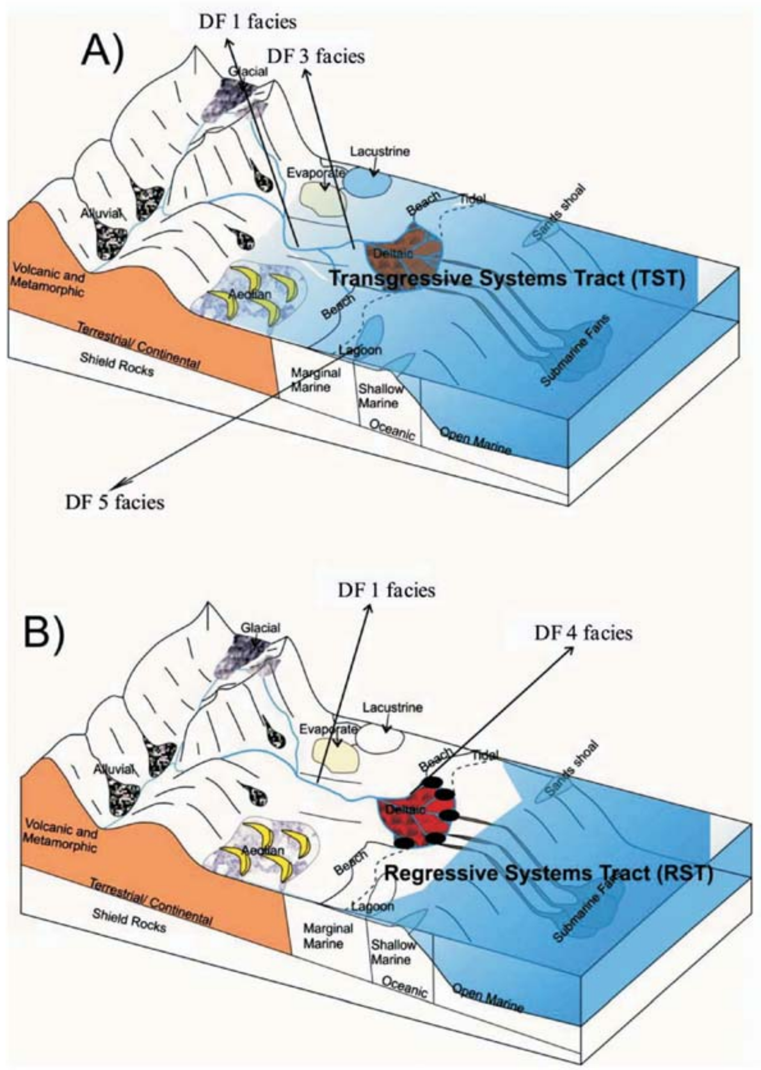

Figure 11a-b - Schematic representation of various depositional settings and Transgressive-Regressive Systems Tracts in the Datta Formation at Nammal Gorge Section (DF 1-DF 5 are various facies).

DISCUSSION

The difficulty of identifying sequence boundaries in fluvial system can be minimized by recognizing the juxtaposition of clastic facies on marine sediments (Macdonald, 1986) 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 (Posamentier and Allen, 1999). 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 (Figure 11b). The onset of the Transgression caused submergence of the abandoned delta lobes (Figure 11a) and favored the preservation of estuarine dominated shelf delta system in the TST1-TST4.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 sandstones in a high sinuosity meandering river system in the late transgressive phase.

SUMMARY AND CONCLUSIONS

Based on the outcrop and petrographic study of the Datta Formation, a sequence stratigraphic model and hydrocarbon reservoir characterization in the Nammal Gorge Section is presented. The following conclusions are drawn from this study.

1. The Datta Formation is predominantly composed of fine to coarse grained sandstone interbedded with limestone, coal and laterite beds at places.
2. Five lithofacies (DF1-DF5) facies are identified which represents different parts of a fluvial dominated delta-lagoon depositional setting.
3. The diagenetic fabric and cement stratigraphies of all DF1, DF2 and DF5 facies are presented, that shows good reservoir rock potential in DF1 and DF2 sandstone facies while DF5 carbonate facies possesses a poor potential.
4. The overall assessment of the hydrocarbon reservoir potential of the Datta Formation is moderate to good.
5. The Transgressive-Regressive (T-R) sequences are identified at third order scale having five RSTs and four TSTs.
6. The sequence boundaries SB1-SB8 are local in orgin and occurred due to delta lobe switching as a result of river avulsion in a period of regression.

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