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Dynamic interplay of Sedimentation and Diagenesis on Miocene Clastic Reservoir Properties, Niger Delta Basin, Nigeria

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Abstract

The D7 sand is one of the hydrocarbon bearing reservoirs horizons penetrated by wells in Gbaran field, Central Swamp Depobelt onshore Niger delta Nigeria. Detailed examination of cores taken from the reservoir section in the Gbaran-6 and -7 wells, led to the recognition of thirteen lithofacies units which were then grouped into distinctive genetically related facies associations. The facies associations were grouped into upper and lower depositional sequences separated by a marine mudstone layer. The lower depositional sequence of the sands was interpreted as deposits of a prograding wave dominated shallow marine shoreface while the sediments of the upper depositional sequence were interpreted as transgressive estuarine deposits. Petrographic analysis of thin-section samples from the reservoir show that the sands are mainly quartz arenites and the main diagenetic effect on the reservoir is cementation due to quartz overgrowths. Calcite cements also occur locally in some sections, especially among the fine to silty grained transgressive sands of the upper reservoir sequence. Calcite cementation within the reservoir sequence was interpreted to be biogenic in nature and facies constrained. The calcitic cement was observed to have been dissolved and re-precipitated from carbonaceous shell fragments and peloids originally deposited within the sediment. Analysis of the petrophysical data from core plugs and observations from petrographic study showed that carbonate cementation had a more detrimental effect on reservoir quality within the reservoir than the silica cemented interval.

Keywords: **Miocene, Diagenesis, Sedimentation, Interplay, Reservoir.**

Introduction

The Niger Delta, located in the Gulf of Guinea, is one of the most prolific petroleum basins in the world, with commercial reserves discovered both onshore and offshore. Reservoirs in the Niger-Delta exhibit a wide range of complexities in their sedimentological and petrophysical characteristics, due to differences in hydrodynamic conditions prevalent in its depositional and post depositional settings. The Delta consists of Tertiary marine and fluvial deposits that overlie oceanic crust and fragments of the extended African continental crust. The reservoir under study is from two of the wells drilled by Shell Petroleum Development Company of Nigeria in the seasonal fresh-water swamp area, some 110 Km west of Port Harcourt (fig. 1). This work examines the interplay of depositional setting and diagenetic process on the reservoir properties of D7 sand and its implication for production in the field.

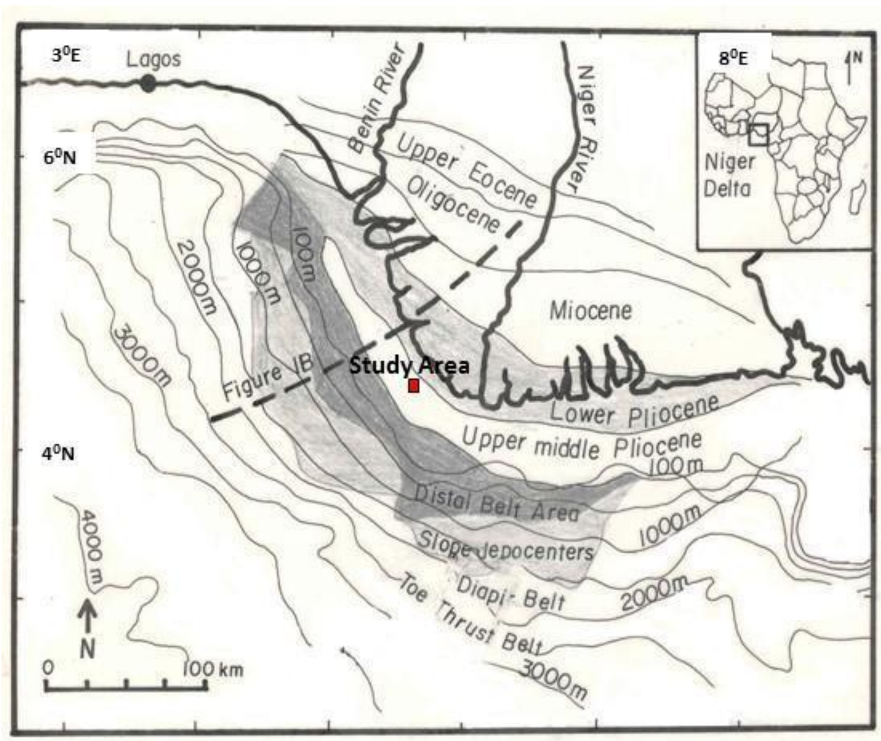

Figure 1: Map of Niger delta showing the location of the study area

Materials and Methods

The data available for this study include core data, thin section from selected interval, gamma ray log. Samples were taken from depths that reflect the major lithofacies unit within the reservoir intervals (fig.7), they were then cut into thin-sections and studied using petrographic microscope to determine the mineralogical composition, pore types, grain sizes and cementation extent. The depositional environments interpretations were inferred based on association of facies, textural trends and sedimentary structures. Rock composition and visible porosity were determined by a count of 200 points from each thin-section.

Lithofacies and depositional setting

The depositional environments were determined by dividing the rock into facies units through integration of sedimentological core description with gamma ray log signature from the two closely spaced wells. The depositional environment ranges from fluvio-marine to shallow marine setting.

Fossiliferous Sandy Mudstone facies (Sf)

This lithofacies consists of very fine to fine grained muddy sandstones with abundant shell debris forming a discontinuous wavy rippled structure with a milkish colour (fig. 2). The basal contact of this lithofacies is sharp while the upper contact passes gradationally into mudstone facies. This lithofacies unit is heavily bioturbated with burrows of *Thalassinoides* and occasional *Ophiomorpha* ichnofacies.

Interpretation: The shell accumulation represents erosional lag deposits. The milkish colour suggests high clay content. The high degree of bioturbation is common in deposits that were subjected to marine reworking in a quiet environmental setting. This lithofacies may represent the products of marine sedimentation associated with rise in sea level.

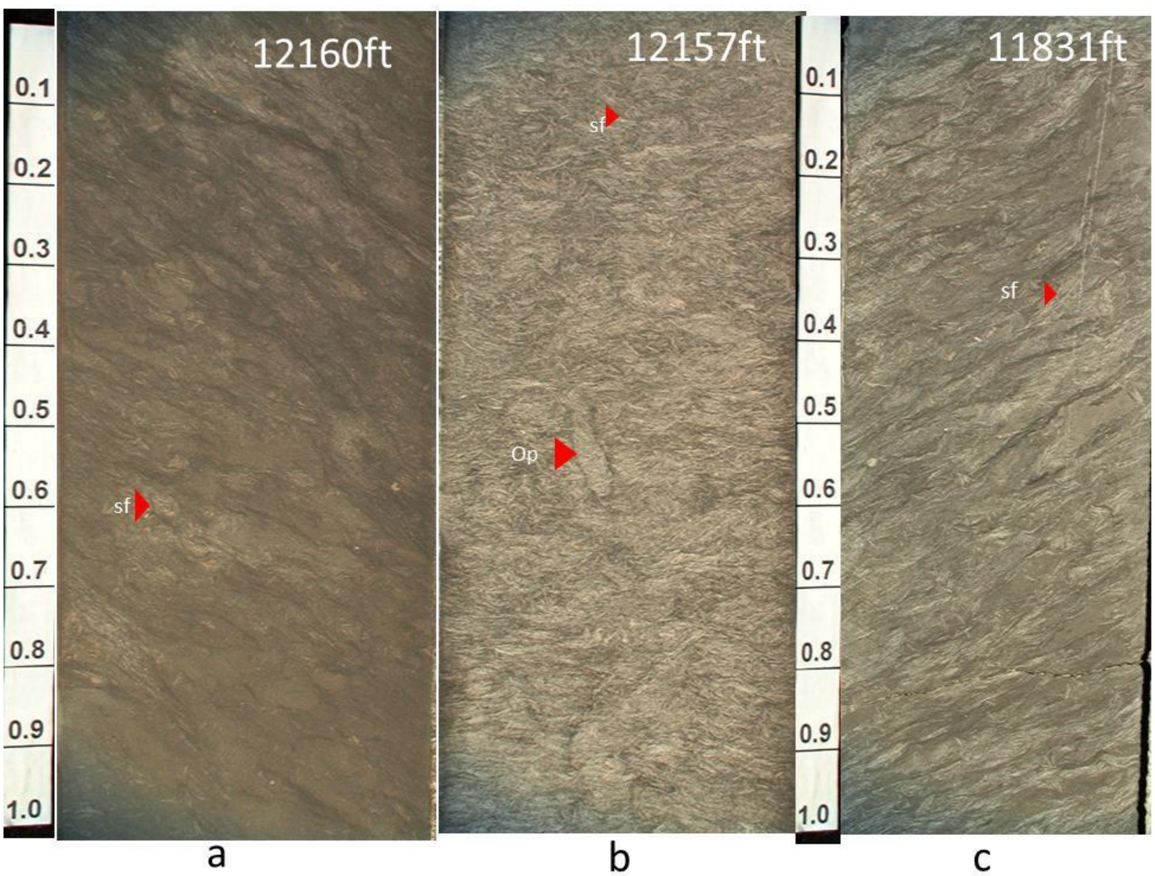

Figure 2: Bioturbated fine to medium grained sandstone; sf: shell fragment, Op: Ophiomorpha burrow

Wavy Bedded Sandy and Muddy Heterolith facies (HsW, HmW)

This lithofacies comprises wavy bedded very fine light brown sand and dark gray silty clay in which the clay percentage ranges from 50% to 60% of the lithology (fig.3). The sandy intervals are very well sorted. Bed thicknesses are typically on mm-to cm-scale. Sands are characterized by hummocky cross stratification and wavy ripple bedding. Interbedded silts and shales are laminated. Bioturbation ranges from barren to moderate, although cm-scale intensely bioturbated intervals occur. The trace assemblage comprises *Planolites* and *Paleophycus.*

Interpretation: This facies records the alternation of bedload and suspension depositional processes. Bedload sedimentation occurs during migration of 2D wave ripples under lower flow regime oscillatory wave currents. Sand deposition periodically interrupts suspension fallout of clay and silt. Hummocky cross stratification and alternating sandstone and mudstone beds suggest periodic storm energies of the shoreface setting. Facies suite suggests deposition in an open marine shoreface settings.

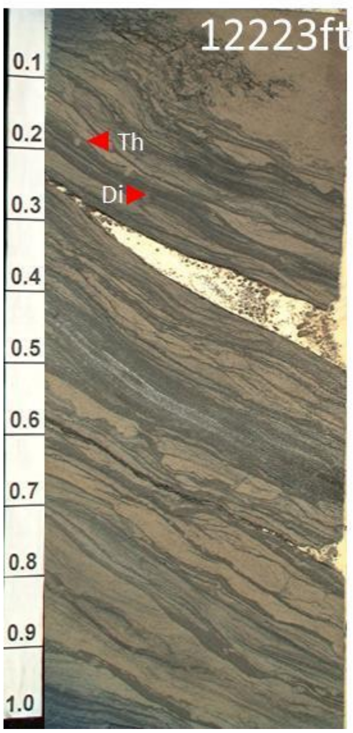

Figure 3:Wavy rippled sandy heterolith facies; Th:*Thalasinoides*, Di:*Diplocraterion*

Bioturbated fine to medium Grained Sandstone facies (SmB)

The sediments of this lithofacies consist of intensely bioturbated, fine to medium grained, moderately sorted sandstone (fig. 4). The beds are commonly structureless due to part or complete obliteration of primary sedimentary structures by bioturbation. Visibles clay in this lithofacies occurs in the form of burrow-wall linings. Occasionally mottled clay patches cross-cut by burrow traces may occur. Discontinous and irregular carbonaceous laminae and plant debris may be present. A few shell fragments occasionally occur within the sediments.The burrows are commonly lined by dark gray mudstones. Individual traces are difficult to distinguish due to overprinting. The common trace includes *Ophiomorpha nodosa* with thick walls. *Ophiomorpha* burrows may range up to 3cm in diameter. Sub-horizontal *Planolites* and sub-vertical *Skolithos* are also identifiable.

Interpretation: The sandstone is probably sorted by tidal currents and marine waves. Clay deposition was primarily in the form of wall lining of burrows. The presence of fossil shell particles is interpreted as an indication of lag deposits. Abundance of bioturbation and more open marine trace fossils indicate deposition below wave base (lower shoreface).

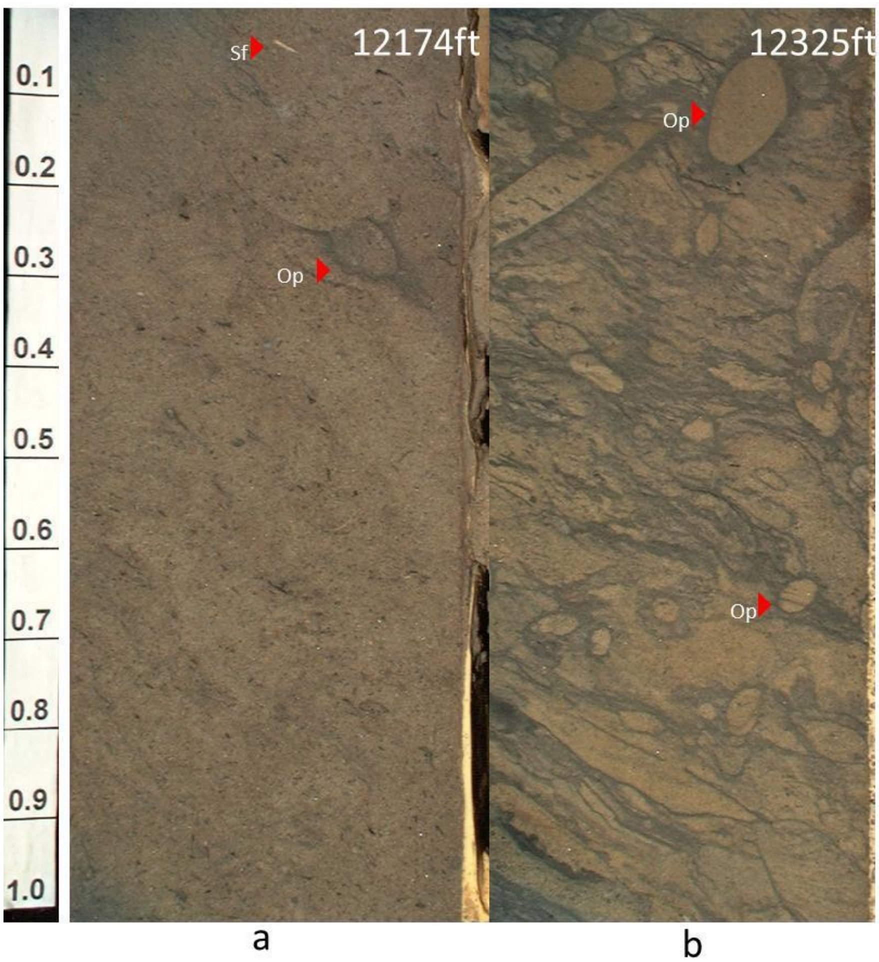

Figure 4: Bioturbated fine to medium grained sandstone; sf: shell fragment, Op: Ophiomorpha burrow

Cross Bedded Coarse to Pebbly Sandstone facies (ScX)

The lithofacies consists of medium to coarse grained, poorly sorted sandstones (fig. 5). The lithofacies is characterized by bimodal size sorting appearing as alternating coarser and finer grained strata. Visible clay is generally absent in this facies but occurs locally as mm thick foreset drapes, burrow linings and clay pebbles. Individual cross-strata are of the order of 2-6cm thick and are predominantly unidirectional, with reversed sets occasionally developed. The lithofacies commonly fines upward. Trough cross bedding is the dominant sedimentary structures in this lithofacies, though horizontal stratification and massive bedding may occur locally.

Interpretation: The cross beds are indicators of migration of subaqeous dunes formed under strong upper flow regime. The dunes were crescentic with trough shaped scour pits producing trough cross stratification. The coarse to pebbly grained character and poor sorting character of the sediments indicates fluvial sourcing. The monospecific (but robust) trace fossil assemblage records a stressed brackish marine environment (Dalrymple, 1992; Buatois et al., 2008). Intervals with bimodal sorting may indicate cyclic short term fluctuations in current strength and can be interpreted to reflect some tidal current modulation of the fluvial current that supplied the coarse sediments. The presence of mud flasers with alternate sand-shale units also confirms tidal influence.

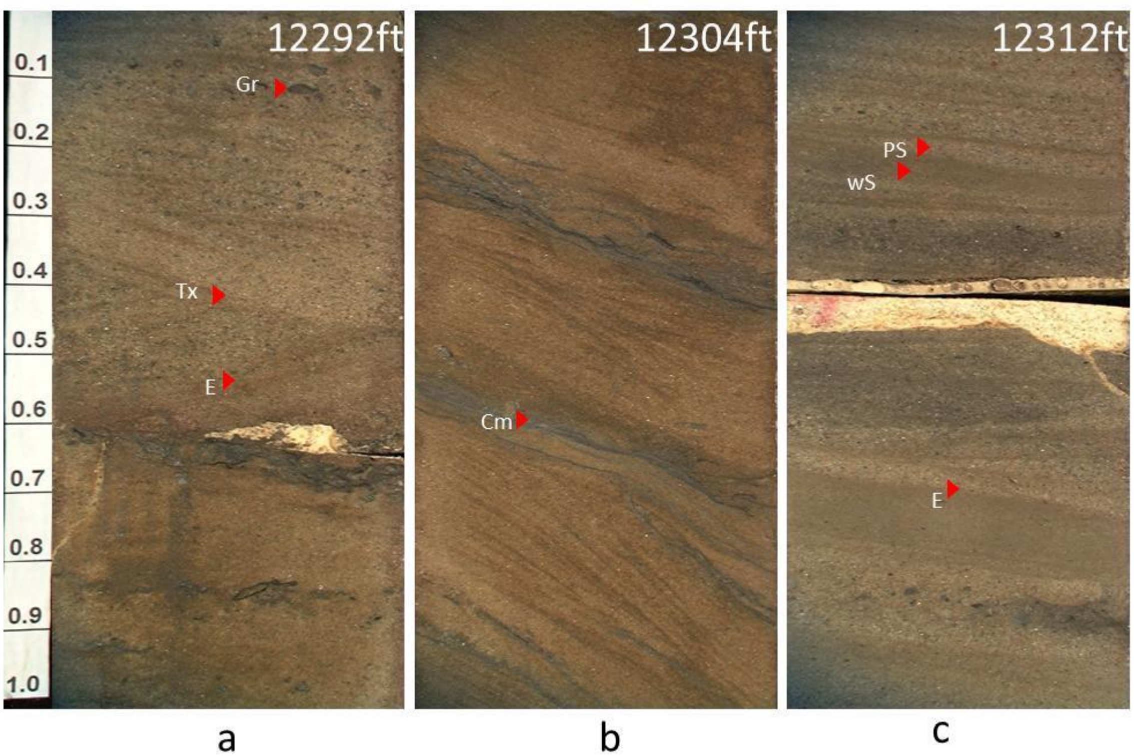

Figure 5: Cross bedded coarse to pebbly sandstone facies; Tx: Trough cross bedding, Gr:Granules, Cm: Carbonaceous material, E: Erosive base, Ps: Poorly sorted interval, Ws: Well sorted interval.

Cross bedded fine to medium grain sandstone facies (SmX)

The lithofacies consists of moderately to well sorted, fine to medium grained sandstones (fig. 6). They are commonly clean sand with little or no clay content. However in places where they are draped by mud it formed a bimodal sorting, appearing as alternating coarse and fine grain strata. Planar cross bedding is the dominant sedimentary structures though some reverse cross bedding and climbing ripples occur locally. It coarsens upward where it is underlain by wavy rippled sandy heterolith unit and may contain trough cross bedding. The level of bioturbation in this facies is low, though, local heavy bioturbation interval may occur with *Ophiomorpha* and *Diplocraterion* ichnofacies dominating the burrows. This lithofacies generally has a gradational contact with overlying unit.

Interpretation: Cross bedded sediments are formed under strong upper flow regime condition such as in channels and wave dominated environments (Walker, 1984). The well sorted character of the sediments is typical of marine sourced sands reworked by tidal and/or wave processes. Presence of clay drapes, mud flaser and the bimodal sorting is indicative of tidal current modulation of fluvial current which supplied the sediment. Intervals with sharp base are mostly related to channels. The sparse to barren trace fossil suite

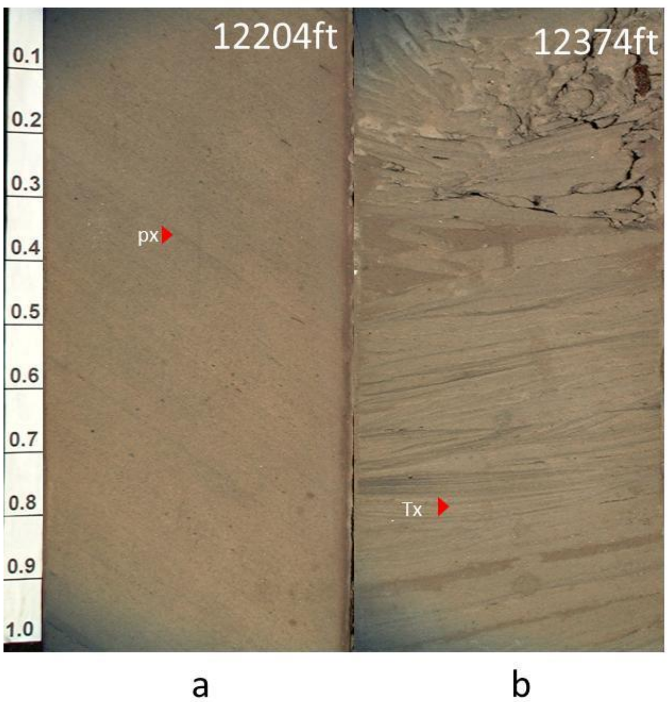

Figure 6: Cross bedded medium to fine grained sandstone; Px:Planar cross bedded sand, Tx: Trough cross bedding

The core analysis indicates that the sand body deposit within the upper shoreface setting, tidal and fluvial channels dominated by cross bedded medium to coarse grained sand facies with sparing bioturbation has a high porosity and permeability value compare to those deposit of lower shoreface and tidal flat system dominated by both sandy and muddy heteroliths.

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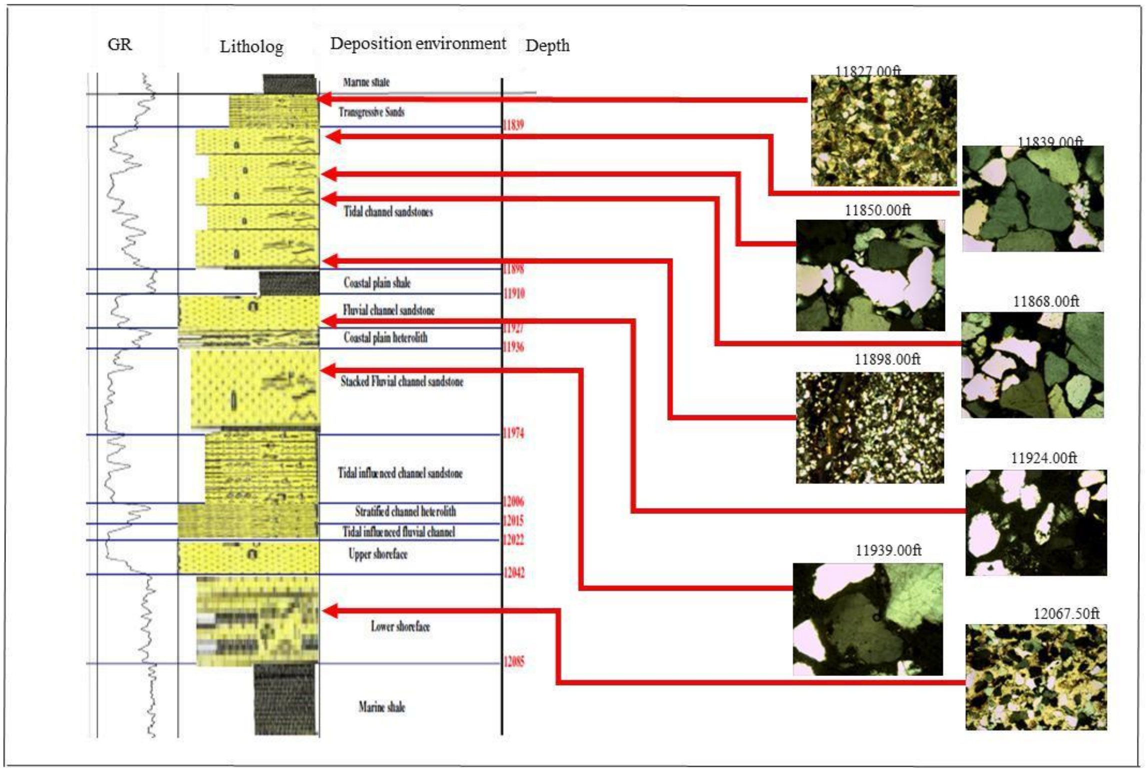

Figure 7: Thin-section depths from the Gbaran-7 core

Petrographic analysis

Table 1: Petrography results for the D7 reservoir section

Depth (ft)	Lithofacies	Sorting	Qzm (%)	Qzc (%)	Fld (%)	Rck frg (%)	Mic (%)	V.por (%)	Cemt (%)
11827	Sf	W	97	-	-	2.7	-	-	Calc
11839	SmB	P	59	33	0.3	0.3	0.3	10	Sil
11850.3	HsB	M	97	-	2	-	-	3	Sil
11863.5	ScX	M	53	38	-	0.3	-	10	Sil
11868	Sc	P	96	-	1	-	-	12	Sil
11898.6	HsC	W	98	-	-	0.3	0.3	-	Sil
11924	SmB	P	76	21	2	-	-	9	Sil
11939	HsW	P	88	9	3	1	-	10	Sil
11981	HmW	M	92	6	2	-	-	-	Sil
12068.8	HsC	W	96	-	3	-	-	-	Calc

Mineralogical composition

The reservoir interval is considerably dominated by monocrystalline quartz; however, polycrystalline quartz seemed to be more abundant in the coarser grained samples (fig. 8). This is a predictable relationship, with coarser grains more likely to be composite grains than the finer grains where the average grain size of the sand is more likely to be below the average grain size of individual crystals making up the composite grains (Humbert *et al*, 2008). Results of thin-section point count analysis are presented in table 1. The calculated Quartz: Feldspar: Rock fragment (QFR) ratios are plotted in the ternary sandstone compositional diagram in figure 9. With their detrital clay composition, the sandstone can be classified as quartz arenites, having QFR composition with more than 95% quartz.

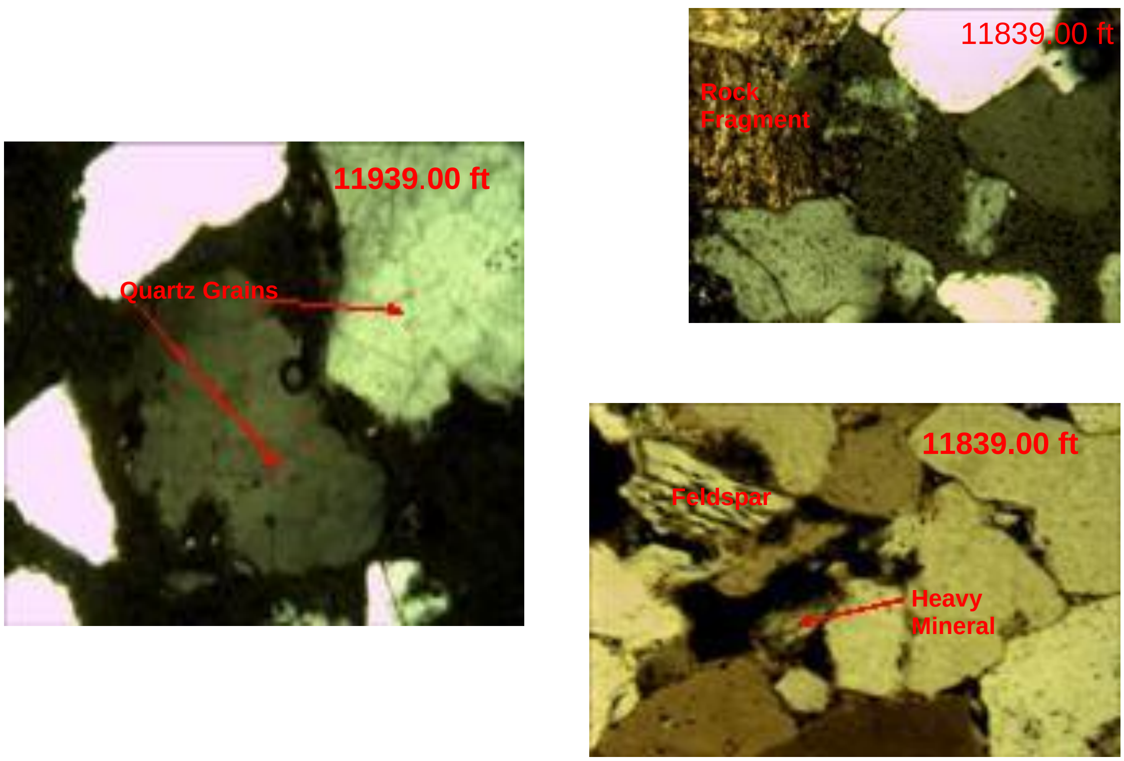

Figure 8: Photomicrographs showing some of the minerological components of the D7 reservoir sandstones

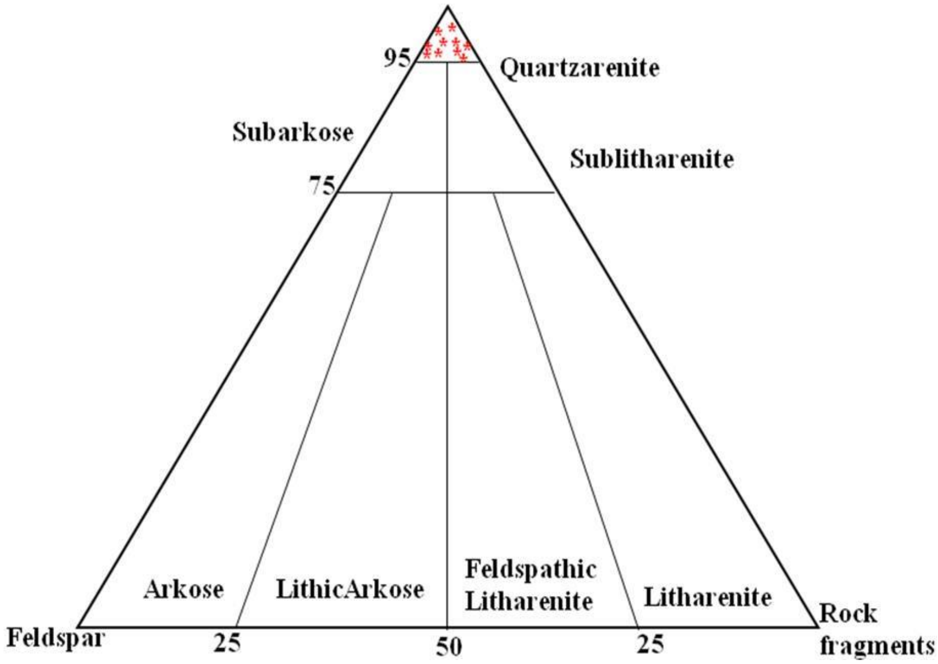

Figure 9: Ternary diagram showing plotted QFR Composition for the reservoir sandstones

Feldspar is almost totally absent from the reservoir interval and observed only in a few slides, with isolated grains of feldspar recorded in the analysis. The absence of feldspar is likely due to its decomposition to authigenic clay in the section. Similarly, lithic grains were only recorded in isolated slides and not in considerable quantities. Evidence of micaceous decomposition to authigenic clays abound in the finer grained samples indicating that the mica content would have originally been higher in the sediment at time of deposition.

Heavy minerals occur mainly within the coarser grained intervals. Carbonate occurred as cementation material in two of the ten slides (fossiliferous sand and cross bedded sandy hetrolithic unit), the calcite is dispersed throughout the matrix of the two slides with both samples consisting of very fine grained material. Clay content varied from section to section and increased with decreasing grain size, with sands above medium grain sized contained at least 20% clay (Selley, 2000). Almost all the clay appeared to be authigenic as the clay content composed mainly of kaolinite and chlorite from an earlier XRD analysis carried out on sidewall samples from the field.

Diagenetic process on D7 sand

Diagenetic processes exert a major influence on reservoir quality. The most important processes within the D7 sand are cementation by quartz overgrowths and the formation of authigenic clays. Locally important but less widespread processes are carbonate dissolution from shells and reprecipitation as carbonate cement as well as grain contact dissolution (Sommer, 1978). Compaction induced chemical deformation of ductile framework grains such as micaceous rock fragments and feldspars is significant as a source of porosity loss only in sediments where ductile grain content) is relatively elevated. However, it is often difficult to distinguish between purely compactional effects and those due to grain contact dissolution (pressure solution) or deformation/dispersion of labile grains associated with the onset of decomposition to authigenic clays. Evidence of compactional effects during burial diagenesis was observed in thin-section by considering the spatial arrangement of the grains and the nature of the contacts between them (fig. 10). Elongate or discoid grains tend to become reoriented, with their long axes parallel to the bedding and long grain contacts.

Quartz overgrowth cementation appears most advanced in some of the cleaner medium-grained sands where overgrowths are an important cause of porosity reduction and may in places totally occlude some intergranular pores. These were observed in thin-section by switching between plane-polarised light, which allows the edge of the original grain to be seen, and cross polars, which show that the original grains have been extended. In the finer grained samples, overgrowth development was observed to have often been inhibited to varying degrees by the presence of earlier formed authigenic clays, and in some cases, carbonates which occupy much of the pore system especially in the transgressive sand deposit.

Authigenic clay is present in most of the samples and is a product of decomposition of labile framework grains including mica, lithics and feldspar. The almost total lack of feldspar and mica throughout the interval, together with the common presence of kaolin pore fillings strongly suggests that the main precursor of kaolin clays is likely to have been feldspar. In addition there appears to be some evidence of decomposing among the lithic grains in the section. Identification of clay minerals in thin-section using the petrographic microscope is usually problematic, but sometimes they are observed as an even, brown rim around grains and were interpreted as pore and grain lining Chlorite clay cement layer. This interpretation is in line with XRD results from adjacent well.

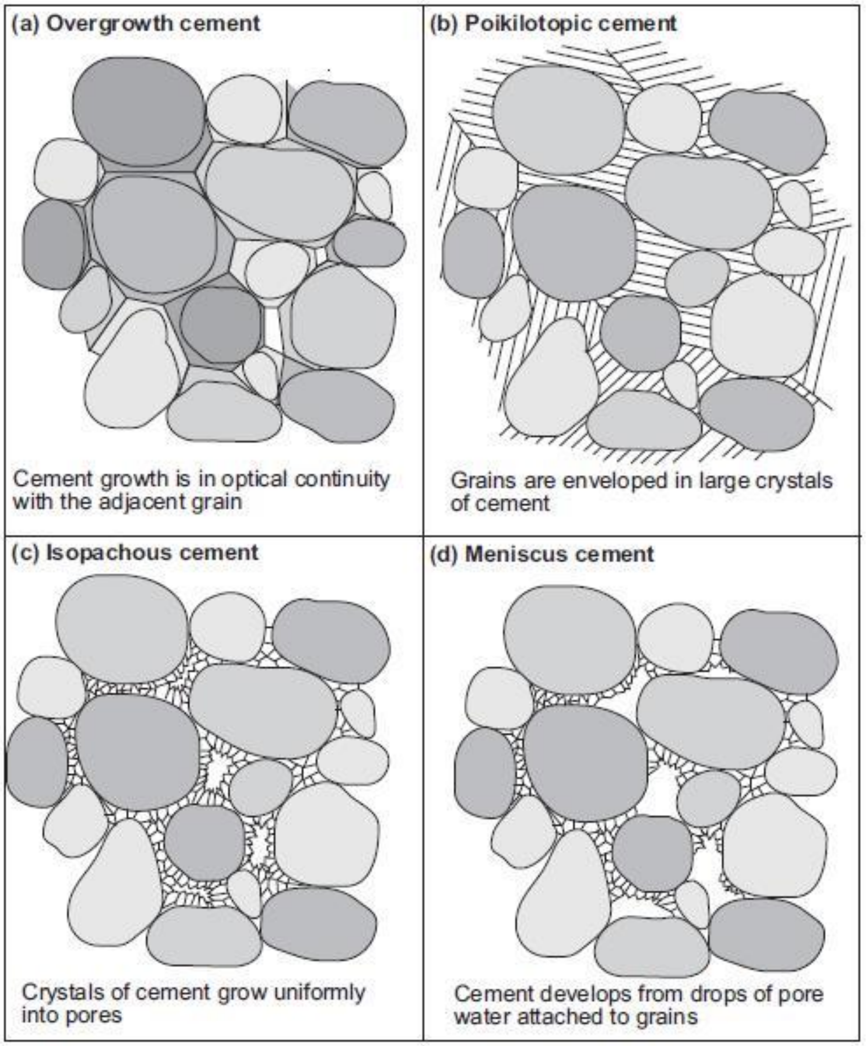

Figure 10: Cement fabrics: showing the different occurrences of cement in sediment (adopted from Nichols, 2009)

Diagenetic history of D7 reservoir sand

Diagenetic changes in the D7 reservoir sediments can be said to begin soon after burial. The sequence and rate of diagenesis was controlled by resident temperature and time (Schmidt and McDonald (1979). The following scenario for the diagenesis of the D7 sands is proposed: During the initial lithification, mechanical compaction reduced the primary pore space by approximately 25%. Also, soon after deposition, some of the heterolithic facies begin to experience sideritic cementation due to the precipitation of ferrous iron oxides and hydroxides near the sediment water interface. Calcite in the form of shells and shell fragments, were dissolved and reprecipitated as calcite cement. Additional carbonate cement was precipitated from fluids moving up dip through the sands. The first stage of diagenesis begun at deposition right up to when mechanical compaction was completed and chemical compaction proceeded to reduce the remaining primary porosity to irreducible limits (Nwachukwu and Odjeba, 2001). Clays present in pore spaces between sand grains altered to more stable forms and insulated some grains from further dissolution or later quartz overgrowths. Some silica cementation i.e. quartz overgrowth occurred. As burial diagenesis proceeded, hydrocarbons were generated from neighbouring source beds. As hydrocarbons migrated through the beds, they moved up-dip into stratigraphically and structurally trapped reservoirs.

Conclusion

Diagenetic processes exert a major influence on reservoir quality, but diagenetic processes are themselves ultimately controlled by original texture (grain size) and composition (Carozzi, 1993). This is because the relative importance of major porosity reducing diagenetic changes such as authigenic clay formation and quartz overgrowth cementation is dependent on the availability of labile grains that are precursors of authigenic clay. Thus in the cleaner medium and coarse-grained sands which contained few labile grains, quartz overgrowths are well developed but good macro-intergranular porosity still remains (Berg, 1986). In the finer sands, apparent abundance of mica and other labiles resulted in a high content of authigenic clay, limited overgrowth cementation but wide spread grain contact dissolution and in some cases calcite cementation.

Within the better quality, medium to very coarse-grained reservoir sands of the Tidal Channels, Stacked Channels and Point bars, macroporosity is mostly intergranular, although pore sizes have also been considerably reduced by quartz overgrowth. The result is that these better sands possess a well interconnected pore system, although pore lining chlorite clays occur in most of the samples from these sections. This clay may provide potential for fines migration damage to the reservoir, particularly in the medium-grained rather than the coarser grained sands, as pore throats may be small enough to be susceptible to blockage (Selley, 2000). Permeability is related mainly to grain size and the volume of macroporosity. With decreasing grain size, clay content increases, resulting in an increase in the proportion of microporosity and reduced permeability (fig.11).

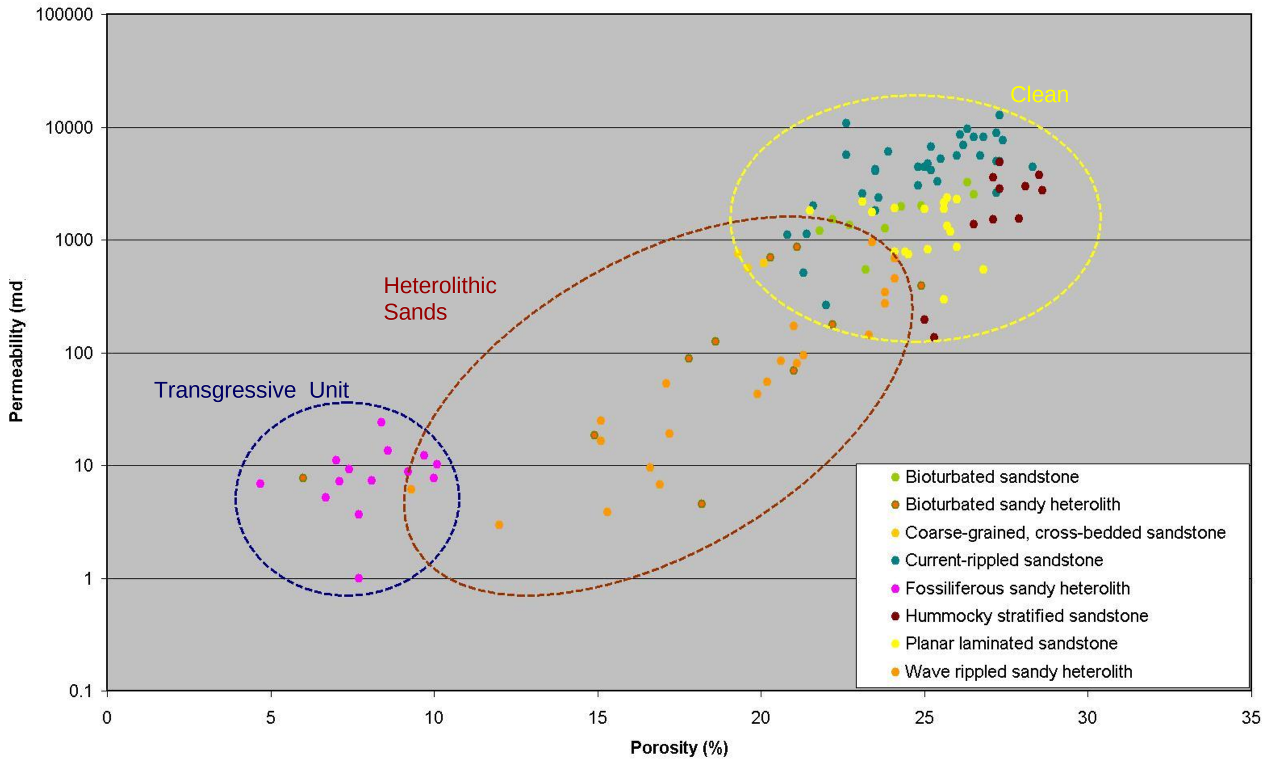

Figure 11: Plot showing the reservoir quality of the various lithofacies units in the D7 reservoir section (from core analysis data)

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