PS Integrated Reservoir Quality Study of Deep-Water Clastic Deposits, Offshore Western Niger Delta, Nigeria*

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Abstract

The study aims at assessing the reservoir quality and heterogeneity in selected Deep-water wells by objectively evaluating the reservoir depositional facies, environment of deposition and sand body geometries, stratigraphic and structural positions, detrital composition, sediment source, pore architecture and pore-throat characteristics. Cores, thin-sections and SEM photomicrographs, XRD data, porosity and permeability data, and well log (gamma ray, sonic, resistivity and density) data were integrated at reservoir scale. Seven deep-water depositional facies (Coarse to pebbly, massive, poorly sorted, matrix supported conglomeratic facies {ScM}; medium, moderately to well sorted, normally graded facies {SmP}; fine to very fine, planar laminated, moderately to well sorted facies {SfP}; fine to very fine, cross, wavy to ripple laminated, well sorted facies {SfC}; sand-rich heterolithics with fine to silty mud intercalations and slump facies {HsP}; mud-rich heterolithics with diffuse parallel laminated silt, rip-up clasts, contorted and convolute bedding facies {HmP} and massive, laminated and brecciated mudstone facies {M}) were described from the cores using lithofacies scheme of "Davies et al 1997" integrated with "Bouma Sequences". These were grouped into four facies associations (coarse debris flow, sandy debris flow, mixed sand / mudslides and slumps and hemipelagic mud. The thin-section photomicrographs show that the studied reservoirs have undergone minor to insignificant mechanical compaction and intergranular pressure dissolution; have open pores that are well interconnected, loose to point-grain contacts; have suffered suppressed cementation by quartz overgrowths, replacive pyrite, siderite, kaolinite and replacive authigenic opaques. The framework mineralogy is dominated by monocrystalline quartz arenite as interpreted from modal

analysis. SEM photomicrographs show dissolution pits of framework feldspars, presence of inter- / intra-granular macropores and evidence of leaching by dissolution and kaolinization. Whole rock mineralogy (XRD) indicates that quartz, alkali feldspar, kaolinite, plagioclase feldspar, illite-smectite, pyrite, siderite and barite are the major minerals. The results of this study are expected to have important implication for ranking of hydrocarbon exploration prospects and optimisation of future development well locations in deep-water settings.

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1. Introduction

- Recent increases in global demand for hydrocarbons, declining production from mature provinces, and high oil prices are driving a new phase of international exploration for petroleum resources in deep offshore basins (Lewis et al., 2008).
- These are often data-poor areas where basin geology is poorly understood, making prospectivity and exploration risks difficult to evaluate.
- In the deep-water 'Doji-Field' Offshore Nigeria, there is an increasing industry concern about reservoir quality depreciation with an increasing depth with an attendant impact on potential exploration opportunities, which has posed a challenge to the future prospectivity of oil blocks in the offshore basin.

2. Aim & Objectives of Study

The aim of the study is to evaluate the geologic factors responsible for the observed reservoir quality variation with increasing depth in the field by objectively evaluating;

- their reservoir depositional facies,
- the detrital composition (framework, matrix and cement minerals) of the deepwater clastics,
- the pore volume, pore architecture, pore-throat characteristics of the diagenetic minerals associated with the deepwater deposits,
- flow unit characteristics of the reservoir layers,
- the composition and provenance of the reservoir sandstones.

3. Study Location

- The 'Doji-Field' is located in the Western part of the Niger Delta (Figure 1), about 75 kilometres offshore from Warri. It is a deep-water field that ranges in water depth from 1,020 - 1,245m. It has an aerial extent of about 1,408km² (Wood Mackenzie, 2011).

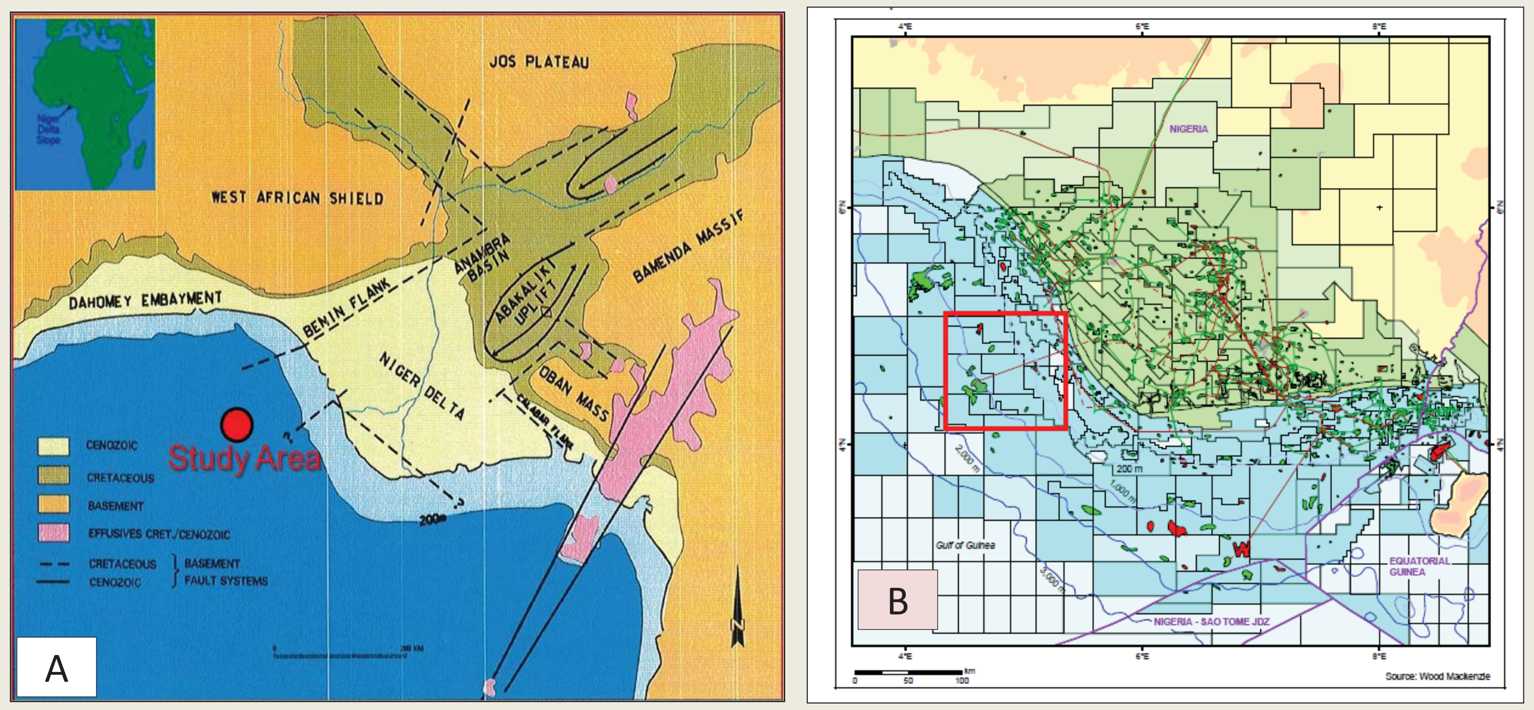

Fig.1: Map of Niger Delta showing Study Location (A: Burke *et al* .,1971; B: Wood Mackenzie, 2011)

4. Regional Geologic Setting

- The Cenozoic Niger Delta is situated on the continental margin of the Gulf of Guinea in the equatorial West Africa. It is bounded in the west by the Dahomey basin, in the east by Abakaliki fold belt, in the south by Gulf of Guinea and in the north by Anambra basin (Burke *et al*., 1971; Figure 1A).
- The evolution of the delta is related to the development of the R-R-R triple junction and the subsequent separation of South American and African continent. The delta built out over the collapsed continental margin at the site of the triple junction formed during the middle Cretaceous (Short and Stauble , 967).
- Three major lithostratigraphic units are defined in the subsurface of the delta, which are the Akata, Agbada and Benin Formations. There is a decrease in age basin-ward, reflecting the overall regression of depositional environments within the delta clastic wedge (Table 1; Short and Stauble, 1967).
- The Niger Delta consists of five depobelts namely: Northern Delta, Greater Ughelli, Central Swamp, and Coastal Swamp and Offshore Depobelts.

Table 1: Formations in Niger Delta Area, Nigeria (Short and Stauble, 1967).

Subsurface		Surface Outcrops		
Youngest known Age	Oldest known Age	Youngest Known Age		Oldest Known Age
Recent Benin Formation (Afam clay member)	Oligocene	Plio/Pleistocene	Benin Formation	Miocene
Recent Agbada Formation	Eocene	Miocene	Ogwashi-Asaba Formation	Oligocene
		Eocene	Ameki Formation	Eocene
Recent Akata Formation	Eocene	Lower Eocene	Imo shale Formation	Paleocene
		Paleocene	Nsukka Formation	Maestrichtian
		Maestrichtian	Ajali Formation	Maestrichtian
Unknown	Cretaceous	Campanian	Mamu Formation	Campanian
		Campanian/ Maestrichtian	Nkporo Shale	Santonian
		Coniacian/ Santonia	Awgu Shale	Turonian
		Turonian	Eze Aku Shale	Turonian
		Albian	Asu River Group	Albian

5. Data Set

- Slabbed cores from D-2, D-3 and D-4 cored wells,
- Core porosity and permeability performed on standard core plugs,
- Thin-section photomicrograph plates for the cored wells,
- Scanning Electron Microscope (SEM) images for the cored wells,
- X-ray diffraction (clay mineralogy) data for the cored wells,
- Suite of wireline logs for the cored wells,

6. Methodology

- **Core Description**
  Lithofacies scheme of Davies et al (1997) integrated with Bouma Sequence (1962) was adopted during the core description. The cores were described at the scale of 1:200ft to establish the lithofacies types, associations and depositional environments.
- **Petrographic Analyses**
  Sediment textures and framework mineralogy were interpreted from the thin-section photomicrographs with emphasis on diagenetic compaction and cementation of the studied reservoir sands. Pore architecture and pore-throat characteristics, types of authigenic clay minerals of the studied reservoirs were interpreted using SEM images provided. Semi-quantitative (clay mineralogy <2microns) analyses performed on the reservoir sandstones gave detailed mineralogy of each reservoir sands under study. Porosity and permeability cross plots of selected "Doji" reservoir sands were carried out in order to infer their hydraulic properties.
- **Sandstone Composition and Provenance Evaluation**
  Modal analysis performed on selected "Doji" reservoir sands were re-calculated over 100% for compositional evaluation and possible provenance interpretation following the works of Dickinson *et al*., (1983) and Osae *et al*., (2006).

7. Lithofacies Types

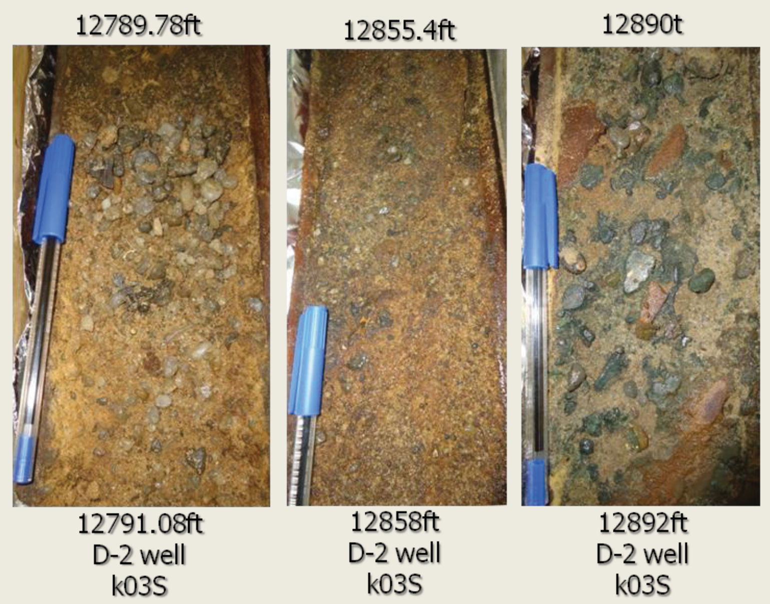

Fig.3: Massive, coarse, pebbly to granule, matrix-supported sandstone facies (ScM).

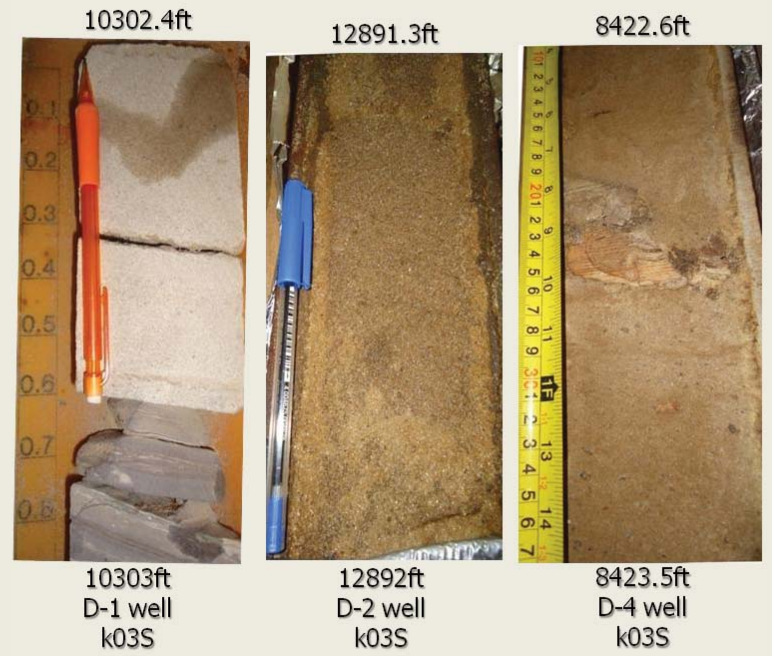

Fig.4: Massive, medium-grained, grain-supported sandstone facies (SmP)

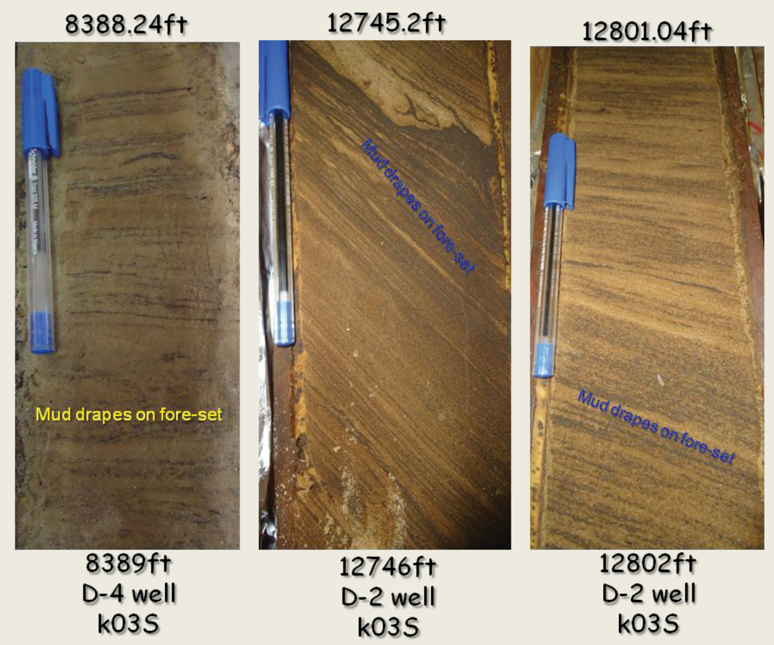

Fig.5: Fine to very fine-grained, parallel to cross laminated sandstone facies (SfP)

Fig.6: Fine to very fine-grained, cross to convolute laminated, sandstone facies (SfC)

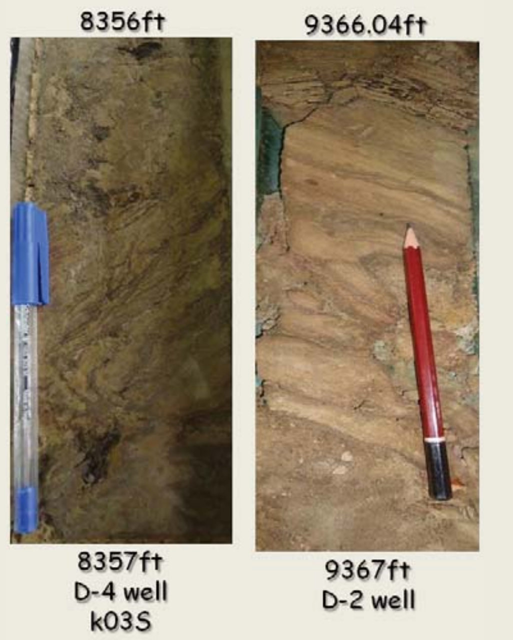

Fig.7:Sand-rich heterolithics (HsP)

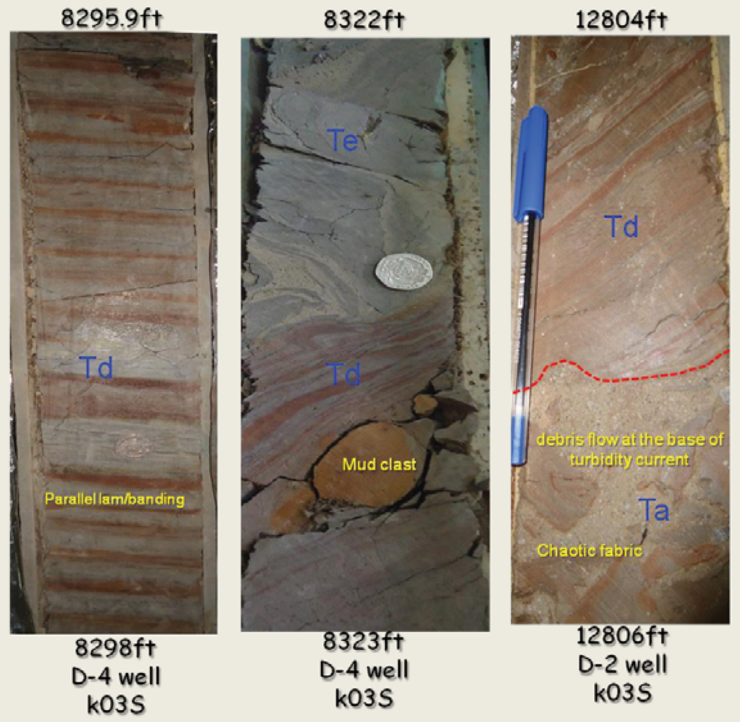

Fig.8: Mud-rich heterolithics (HmP)

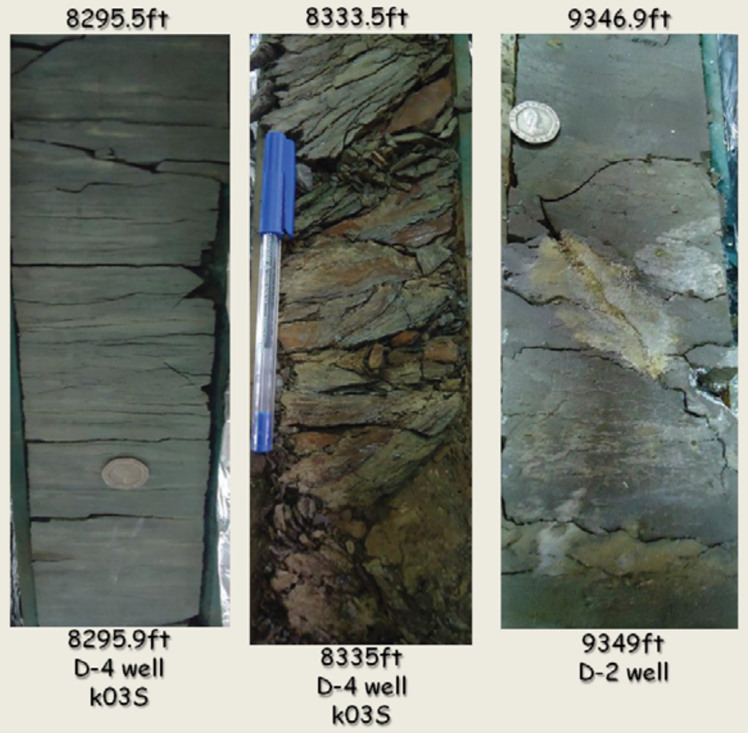

Fig.9: Massive mudstone (M)

8. Sedimentological Logs

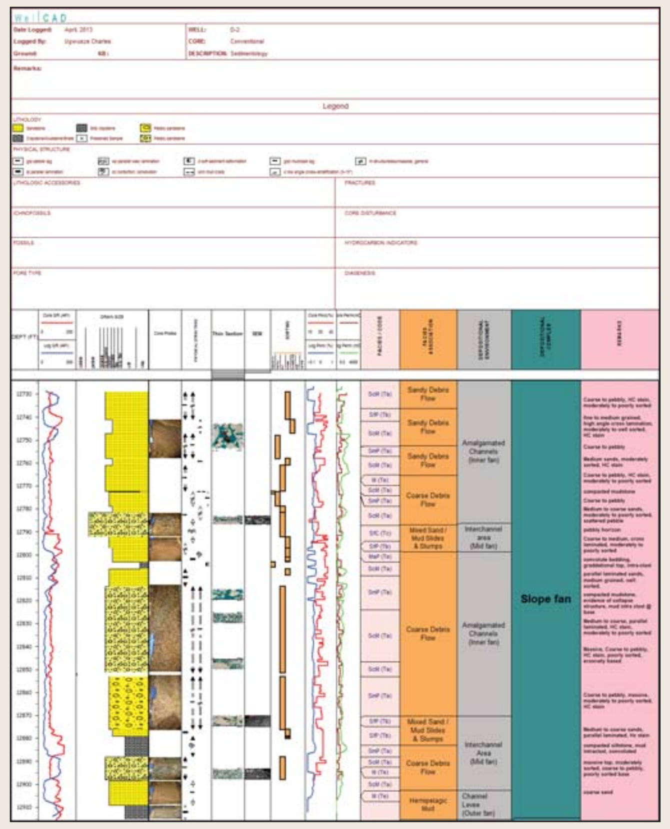

Fig.10:Sedimentological Log of k03Sand (D-2 well)

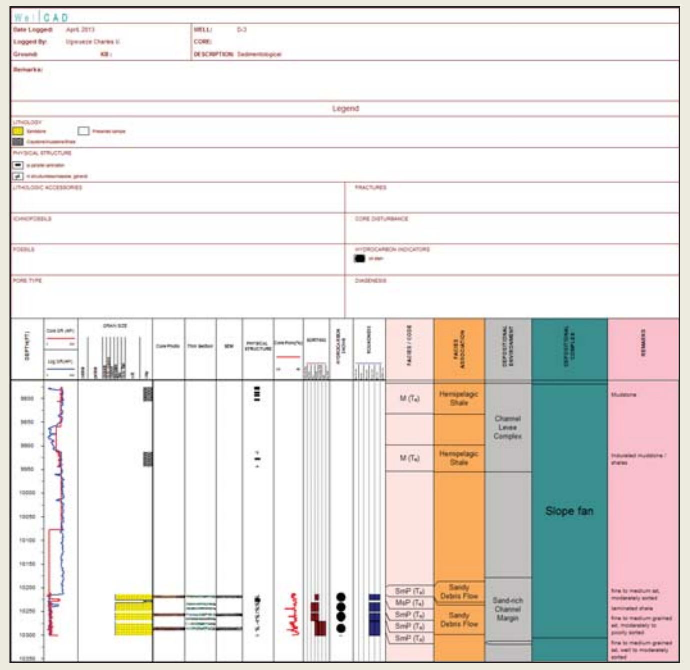

Fig.11:Sedimentological Log of k02Sand (D-3 well)

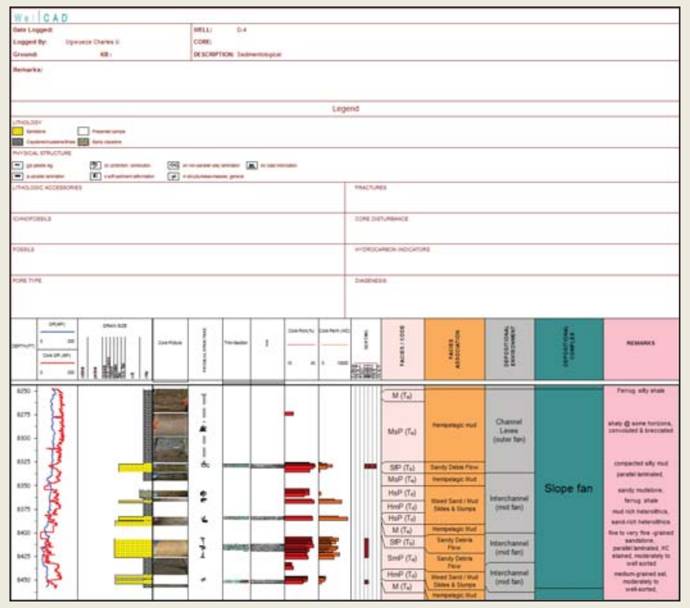

Fig. 12: Sedimentological Log of k03Sand (D-4 well)

7. Facies Association

Well / Reservoir	Facies Associations	Depositional Environment
D-2 well k03 Sand	-Sandy Debris Flow -Coarse Debris Flow -Mixed Sand / Mud slides & Slumps	**Amalgamated Channel Complexes**
D-3 well k02 Sand	-Sandy Debris Flow -Hemipelagic Mud	**Interchannel Areas**
D-4 well k03 Sand	-Hemipelagic Mud -Sandy Debris Flow -Mixed Sand / Mud Slides & Slumps	**Channel Levees**

8. Depositional Model

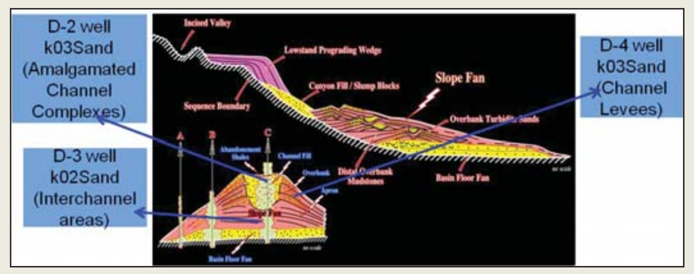

Fig.13: Hypothetical depositional model of the studied 'Doji' reservoir sands showing distribution of mixed mud-sand in a slope fan system (Reading and Richards, 1994)

9. Petrography

•Thin-Section

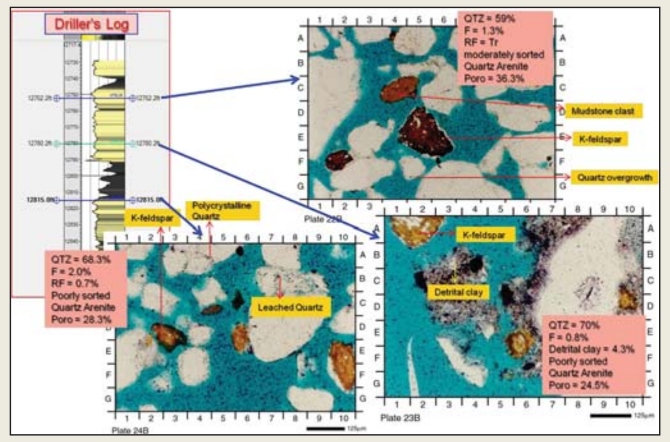

Fig.14: Effects of compaction & cementation on k03Sand (D-2 well)

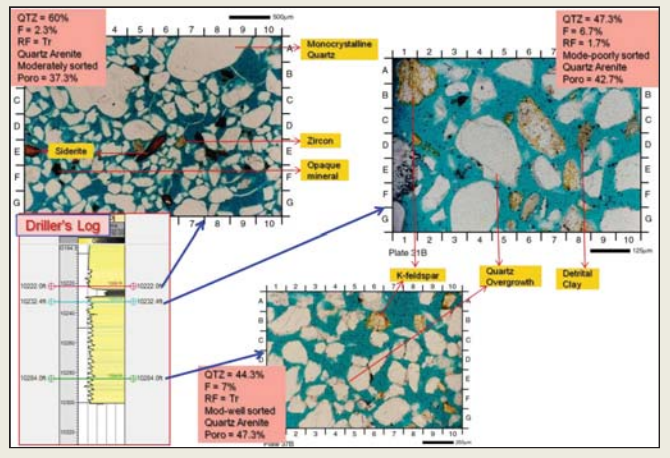

Fig.15: Effects of compaction & cementation on k02Sand (D-3 well)

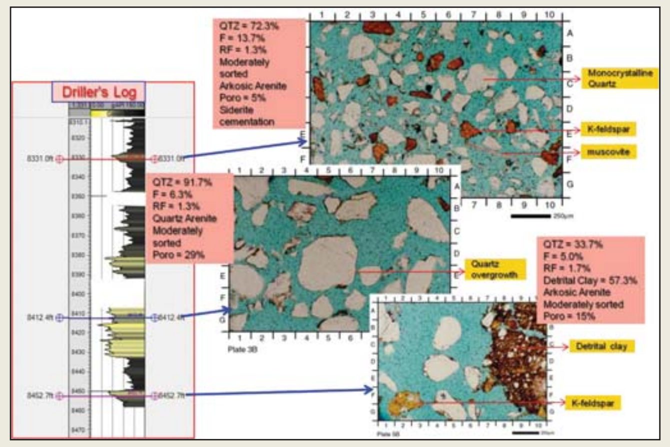

Fig.16: Effects of compaction & cementation on k03Sand (D-4 well)

• Scanning Electron Microscopy (SEM)

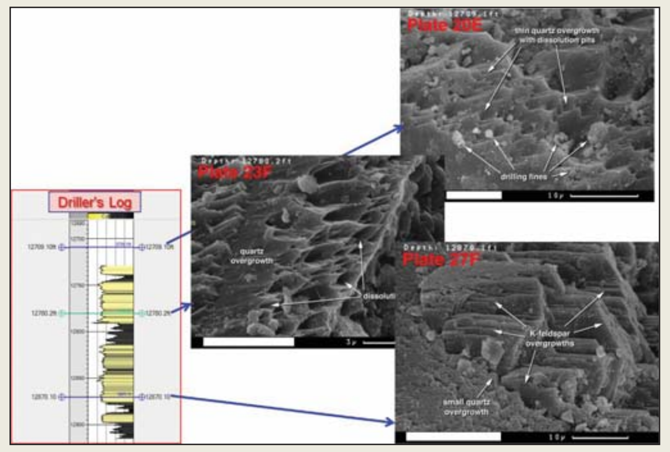

Fig.17: Pore architecture & pore-throat characteristics of k03Sand (D-2 well)

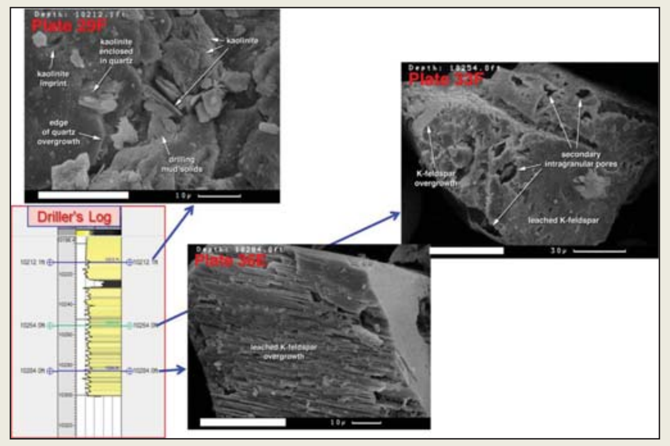

Fig.18: Pore architecture & pore-throat characteristics of k02Sand (D-3 well)

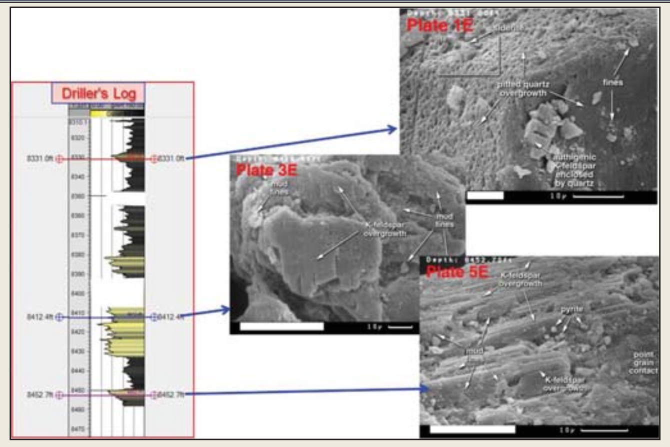

Fig.19: Pore architecture & pore-throat characteristics of k03Sand (D-4 well)

• X-ray Diffraction (Semi Quantitative Analyses)

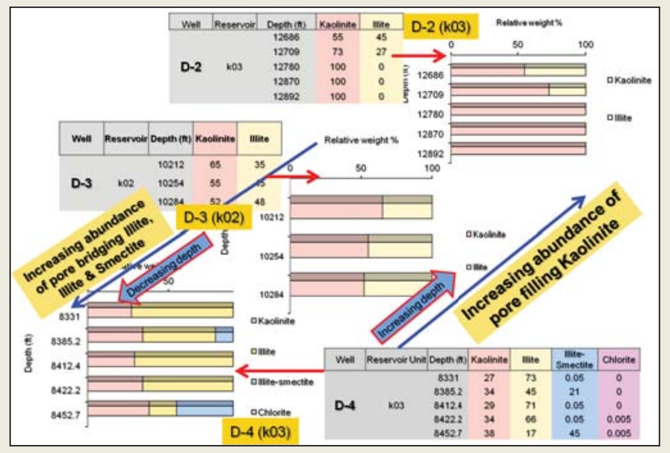

Fig.20: Clay Mineralogy (<2microns) across 'Doji' Reservoir Sands

10. Core Porosity & Permeability Cross Plots

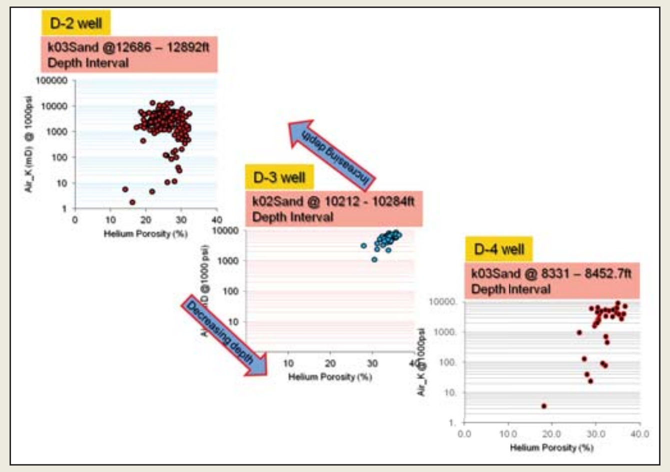

Fig.21: Core Porosity & Permeability Cross Plots of Selected 'Doji' Reservoir Sands

11. Sandstone Composition & Provenance Evaluation

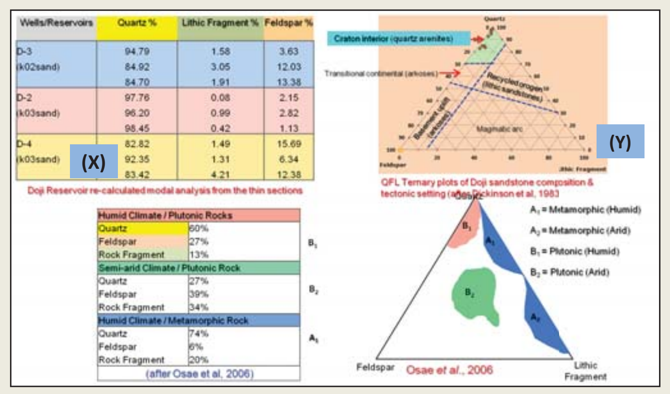

Fig.22: (X): Re-calculated modal analysis from the thin sections. (Y):QFL ternary plots of Doji sandstone composition & tectonic setting (Dickinson et. al., 1983).

12. Discussion of Results

Sedimentology:

- Seven deep-water lithofacies were described from the slabbed cores using lithofacies scheme of "Davies et al 1997" integrated with "Bouma Sequences":
  - ✓coarse to pebbly, massive, poorly sorted, matrix supported sandstone facies (*ScM*),
  - ✓medium, moderately to well sorted, normally graded facies (*SmP*),
  - ✓fine to very fine, planar laminated, moderately to well sorted sandstone facies (*SfP*);
  - ✓fine to very fine, cross, wavy to ripple laminated, well sorted facies (*SfC*);
  - ✓sand-rich heterolithics with fine to silty mud intercalations and slump facies (*HsP*);
  - ✓mud-rich heterolithics with diffuse parallel laminated silt, rip-up clasts, contorted and convolute bedding facies (*HmP*) and
  - ✓massive, laminated and brecciated mudstone facies (*M*).
- These were grouped into four depositional facies associations;
  - ✓coarse debris flow,
  - ✓sandy debris flow,
  - ✓mixed sand / mud slides & slumps and,
  - ✓hemipelagic muds.
- K03sand in D-2 well is interpreted as inner fan amalgamated channel complexes,
- K03sand in D-4 well is interpreted as outer fan channel levees,
- K02sand in D-3 well is interpreted as mid fan interchannel deposit.

Thin - Section

- The thin-section photomicrographs show that the reservoirs have undergone minor to insignificant mechanical compaction and intergranular pressure dissolution;
- have open pores that are well interconnected,
- display loose to point-grain contacts;
- have suffered suppressed cementation probably by quartz overgrowths, replacive pyrite, siderite, kaolinite and replacive authigenic opaques.
- The framework mineralogy is dominated by monocrystalline quartz arenite

Scanning Electron Microscopy (SEM)

- SEM photomicrographs show dissolution pits of framework feldspars,
- presence of inter- / intra-granular macropores and evidence of leaching by dissolution and kaolinization.

X-Ray Diffraction (XRD)

- Semi-quantitative (clay mineralogy <2microns) analyses performed on some sampled core plugs show variations in clay mineralogy across "Doji" reservoir sands with depth.
- At shallower depth intervals, pore-bridging illite and illite-smectite become increasingly more important in abundance (k03sand in D-4 well),
- while at a deeper depth intervals, pore-filling kaolinite becomes increasingly more important in abundance (k03sand in D-2 well; Fig.13).
- This is not unconnected with the depositional facies, types of diagenetic reactions at shallower and deeper depths as well as differences in stratigraphic settings of these reservoir sandbodies.

Core Porosity and Permeability Cross Plots

- Core porosity and permeability cross plots show a relationship between increase in porosity and permeability with depositional facies (Fig.14).

Sandstone Composition and Provenance Evaluation

- The modal analysis plots indicate that the reservoir sands are composed mainly of quartz arenites commonly sourced from stable cratons (plutonic in origin) in a humid climate (Figs.15X and Y).
- This evidence is supported by the presence of zircon and tourmaline heavy minerals observed in the thin-sections, which are known to be common accessory minerals of acid-intermediate igneous rocks (Feo-Codicido, 1956).
- Also predominance of monocrystalline quartz over polycrystalline quartz is another strong evidence of derivation from plutonic igneous rock (Blatt, 1967).

14. Conclusion

- Interplay between depositional facies and diagenesis appears to be the single most important factor controlling the abundance of clay minerals in the clastic deposits. Mixed sands, mud slides and slump facies generally possess higher diagenetically altered clay mineral abundance than coarse and sandy debris facies.
- Pore-bridging illite-smectite facies distribution also seems to be stratigraphically controlled likewise pore-filling kaolinite facies. The observed abnormal illite-smectite distribution in k03 reservoir sand in D-4 well cored interval were probably deposited in a shallower setting that had access to meteoric water. This can probably be within the flanks of an anticline. Diagenetic alteration at this interval will be highly favoured by meteoric water flux during a major fall in the relative sea level. This probably transformed the already formed kaolinite into mixed layer illite-smectite clay.

$$KAlSi_3O_8 + Al_2Si_2O_5(OH)_4 = KAl_3Si_3O_{10} + 4SiO_2 + H_2O$$

K-feldspar + authigenic Kaolinite = Authigenic Illite-Smectite + water

- At a deeper depth, pore-filling kaolinite would become more important. Kaolinitization of k-feldspar at this interval seems to be within a closed system as evidenced by near absence of mixed layer illite-smectite clay at this depth interval. Perhaps, this could explain the observed variation in reservoir quality with increasing depth in the "Doji-field" offshore Niger Delta basin.
- Through predicted reservoir quality in the selected "Doji" wells offshore Niger Delta, this study has demonstrated that hydrocarbon exploration prospects can be ranked and that future development well locations can as well be optimized in deep-water settings.

15. Acknowledgment

I graciously wish to appreciate the following wonderful individuals who contributed immensely to the success of this work; Ozumba Betram M - Head of Geological Services, SPDC Port Harcourt; Agbo Julius – Head of Deepwater Exploration West, SNEPCO, LAGOS; Gideon Giwa – Exploration Geoscientist, Shell UK; Pirmez Carlos P. - Senior Production Geologist, Shell Italia E&P; and the entire Geological Services Team, SNEPCO and SPDC management for the data and research internship opportunity.

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