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Flow Unit Characterization: Key to Delineating Reservoir Performance in "Aqua-field", Niger Delta, Nigeria

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Abstract: This study presents a cost effective and quantitative method for the characterization of flow units and prediction of hydrocarbon recovery of the reservoirs in wells D and E, "Aqua field", Niger Delta. It involves petrophysical evaluation of well log data in order to obtain porosity and permeability values which were useful in identifying and characterizing flow units with the help of the Stratigraphic Modified Lorenz Plot (SMLP). This plot was then used to identify the number of flow units, key flow unit characteristics and anticipated production performance of the hydrocarbon bearing reservoir and the data subjected into a numerical simulator that allows better resolution characteristics of the well. The D-1 reservoir interval has five flow units, which comprise both speed zones and baffle intervals. Reservoirs E-1 to E-4 also have a total of 21 flow units. High values of flow unit speed and high angle flow capacity inflexion indicate speed zones which are prone to sharp decline, while baffles of low value flow unit speed and low angle flow capacity show shallow to steady production decline with time. A better understanding of the fluid flow variations within the reservoir intervals helps in the accurate design of reservoir simulation model for effective hydrocarbon recovery and management.

Keywords: Reservoir heterogeneity, Flow unit, Flow capacity, Nigeria.

INTRODUCTION

Characterization of reservoirs to delineate flow units is the key to successful oil field development programs. Various methods have been proposed for sub-dividing reservoirs into layers such as lithofacies, petrofacies, electrofacies, and hydraulic flow units or flow units. Flow units, which do not always coincide with geologic lithofacies, subdivide reservoirs into zones (layers) based on hydraulic flow properties and are best suited to determine reservoir layering for flow-simulation studies. This method is valuable because the recovery efficiency of such reservoir is influenced by its heterogeneities, especially the distribution of porosity and permeability. Hence, to develop a reservoir model that represents the reservoir's properties, one must be able to define the vertical distribution of the rock and fluid properties in each reservoir interval. The delineation of reservoirs into flow units with distinct hydraulic flow properties is useful in identifying possible preferential flow zones. To achieve this, the knowledge of porosity and permeability is essential for developing an effective reservoir description that controls the strategies involved in well completions, stimulation, and reservoir management.

The Niger delta basin has numerous marginal productive or abandoned oil fields whose production records are non-existent and thus hampers further development. The purpose of this study is to identify reservoir flow units from well logs D and E, using the Stratigraphic Modified Lorenz (SML) plot. These wells were drilled in the "Aqua-field", Central Swamp I Depo-Belt of the Niger delta. The earlier the flow unit determination is done in the life of a reservoir, the greater the understanding of the future reservoir performance.

GEOLOGIC SETTING AND STRATIGRAPHY

The Niger delta clastic wedge spans a 75,000 km^2 in southern Nigeria and is located at the apex of Gulf of Guinea, offshore Nigeria. It lies between latitudes 3° and 6°N and longitudes 5° E and 8°E (Fig.1).

The stratigraphy of the Niger delta consists of three diachronous lithostratigraphic units that form a major regressive cycle from Eocene to Recent in age (Fig.2). These are the continental top facies (Benin Formation), the paralic delta front facies (Agbada Formation) and the Akata Formation which form the pro-delta facies represented by a prograding depositional facies that are distinguished mostly on the basis of sand-shale ratios which apparently decrease in age, basinward (Short and Stauble, 1967). The

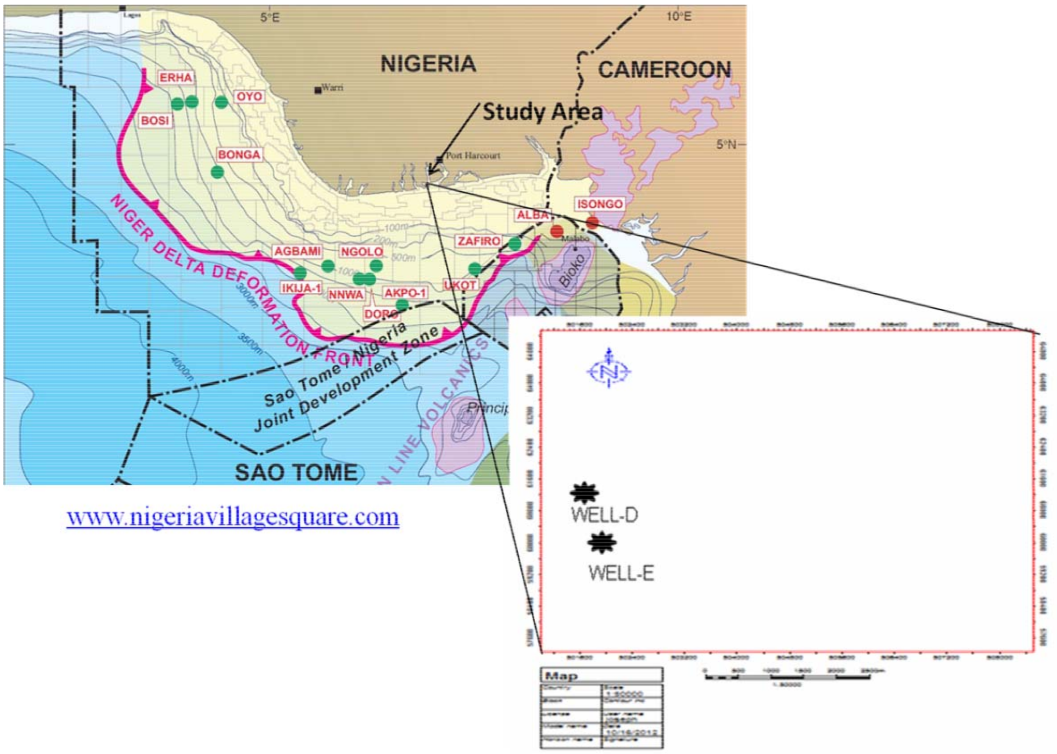

Fig.1. Index map of Niger Delta, Nigeria showing the study area and the studied wells D and E

Benin Formation is the shallowest unit of the Niger delta clastic wedge and occurs throughout the entire onshore and part of the offshore Niger delta. The overall thickness of the formation varies from 1,000 ft in the offshore to 10,000 ft, onshore. Various structural units are identifiable within the formation: point bars, channel fills, and natural levees. The oldest known age of the Benin Formation at the surface is Miocene while at the sub-surface, Oligocene.

The Agbada Formation underlies the Benin Formation and occurs throughout Niger delta clastic wedge with thicknesses ranging from 3,000 m to 4,500 m, where it outcrops around Ogwashi and Asaba, southern Nigeria (Doust and Omatsola, 1989). The lithologies consist of alternating sands, silts and shales, arranged within ten to hundred feet successions, and defined by progressive upward changes in grain size and bed thickness. The strata are generally interpreted to have formed in fluvial-deltaic environments. The formation ranges in age from Eocene to Pleistocene. Most structural traps observed in the Niger delta developed during syn-sedimentary deformation of the Agbada paralic sequence (Evamy et al., 1978). The interbedded shales within the formation form the primary seal.

The Akata Formation is the basal sedimentary unit, estimated to be 21,000 ft thick in the central part of the clastic wedge (Doust and Omatsola, 1989). It is characterized by dark grey shales and silts, with rare streaks of sand of probable turbidite flow origin (Doust and Omatsola, 1989). The Akata shales are typically under-

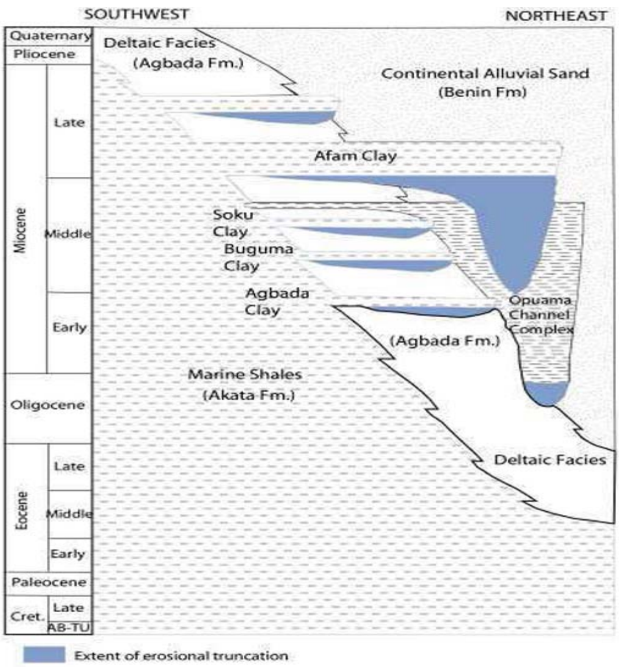

Fig.2. Stratigraphic column showing the three formations of the Niger Delta (Shannon and Naylor, 1989; Doust and Omatsola, 1990).

compacted and over-pressured. The shales also form diapiric structures including shale swells and ridges which often intrude into overlying Agbada Formation. The Akata Formation (Paleocene to Recent) is thought to be the main source rock of hydrocarbons in the Niger delta (Doust and Omatsola, 1989).

MATERIALS AND METHODS

In this study, a suite of well logs from wells D and E (Fig.3), obtained from the 'Aqua field' of the Niger Delta were analyzed using the Stratigraphic Modified Lorenz (SML) plot. This is a plot of the cumulative flow capacity and cumulative storage capacity of the reservoir derived from its petrophysical evaluation values. The cumulative flow and storage capacities were estimated using the Maglio and Johnson (2000) formula.

$$\%kh_{cum} = k_1(h_1-h_o) + k_2(h_2-h_i) + \ldots\ldots k_i(h_1-h_i)/\Sigma k_i(h_1-h_{i-n}) \quad (1)$$

$$\%\phi h_{cum} = \phi_1(h_1-h_0) + \phi_2(h_2-h_1) + \ldots\ldots \phi_i(h_1-h_i)/\Sigma\phi_1(h_1-h_{i-n}) \quad (2)$$

Subunits with similar porosity and permeability characteristics were identified and key flow unit characters and production performance were interpreted based on the inflexions on the slope of the flow capacity in the SML plots. Also, the cumulative porosity, ϕ-ft (%) and cumulative permeability, k-ft (%) were calculated for every 0.5ft of the hydrocarbons bearing intervals. Then, the tabulation of the porosity, ϕ-ft (ϕH) and permeability, k-ft (KH) for each of the 0.5ft interval, and expressed as a percentage of the total porosity, ϕ-ft and permeability, k-ft, summed over the entire hydrocarbons bearing zone. A log of Flow Unit Speed (FUS) was generated by plotting the ratio of cumulative permeability, k-ft and cumulative porosity, ϕ-ft against depth to confirm the key flow characteristics already delineated.

RESULTS AND DISCUSSION

Reservoir D-1

The results show that five flow unit intervals were delineated using the Stratigraphic Modified Lorenz plot (Fig. 4). The reservoir's storage capacity has a 45^0 trending with separation from the flow capacity, which indicates that some pores are not contributing to the flow. Flow units 1, 2 and 4 are speed zones which have a high angle trend flow capacity with low average volume of shale value of 0.03v/v decimal. These speed zones equally have higher porosity and permeability values compared to other flow unit intervals (Tables 1 and 2). At a reservoir interval of 183 ft, flow units

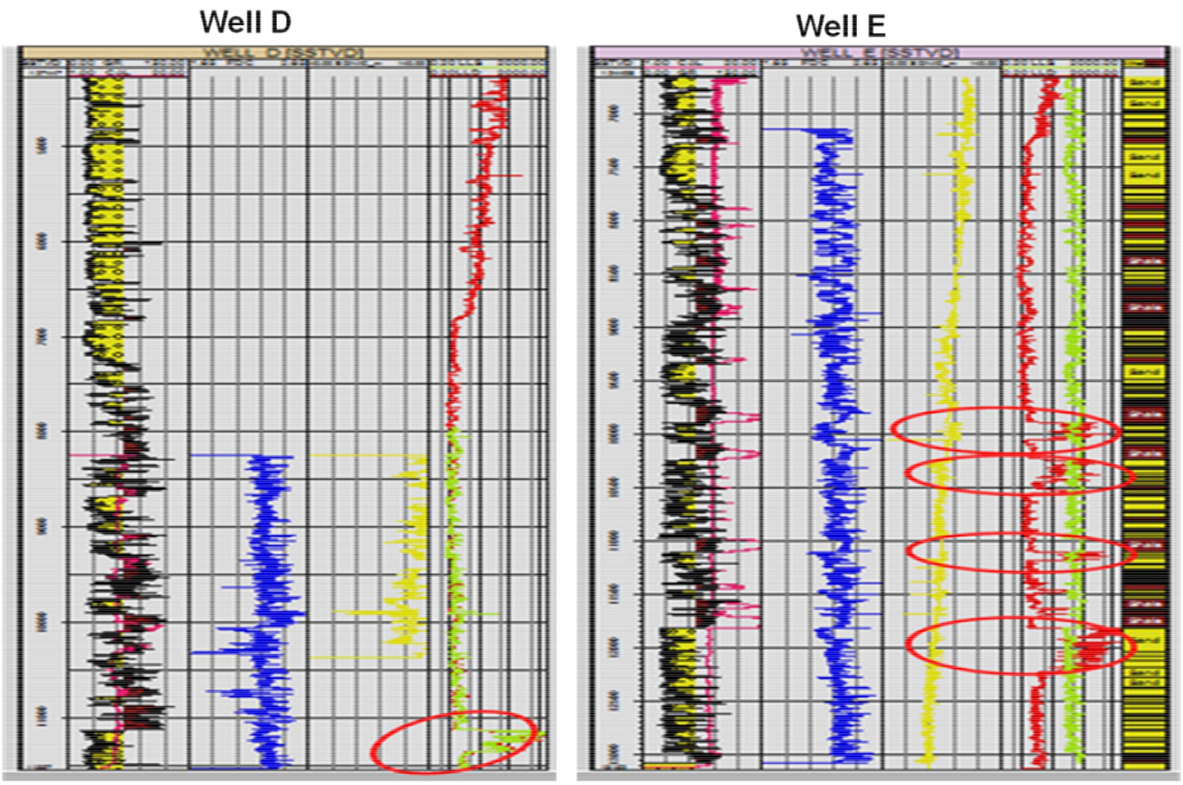

Fig.3. Log response plot for Aqua Well D and E

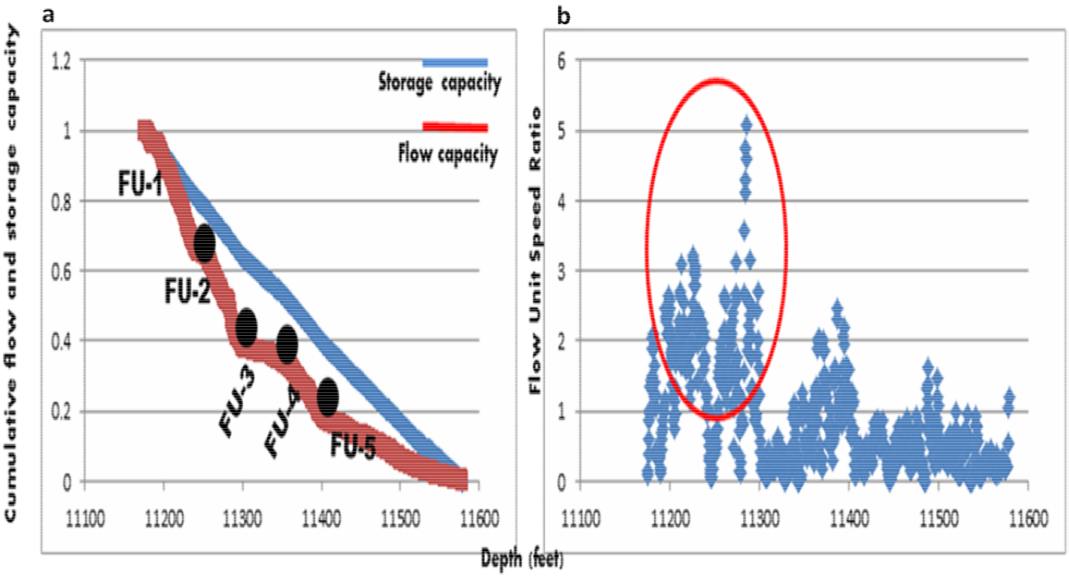

Fig.4. (a) Stratigraphic Modified Lorenz (SML) and **(b)** Flow unit speed (FUS) plots for Reservoir D-1 intervals (11175-11579ft).

1, 2 and 4 contribute 51.9% and 77.7% of storage capacity and flow capacity respectively. These zones have a steep and sharp decline, which is shown by the high values of flow unit speed greater than 1.11 (Table 2). This is indicated by the red circled region in the flow unit speed (FUS) plot (Fig. 4). Also, flow units 3 and 5, which represent the baffles, have a thickness of 217 ft with an average shale volume of 0.06v/v. The average porosity and permeability for these baffles are 0.18v/v and 364.81mD respectively, and they have low values of flow unit speed less than 1 (Fig. 4 and Table 2). Long time production dominance will be from these intervals which contribute 48.09% storage capacity and 22.1% flow capacity.

Reservoir E-1

In this reservoir, seven flow units were delineated based on the inflection points along the flow capacity trend line (Fig.5). The storage capacity is evenly distributed throughout the reservoir as evidenced by the plot of a 45° trend. The overlap between the flow capacity and storage capacity shows that all the pores are contributing equally to the flow. Flow units 2, 4 and 6 are conduits (speed zone) which are indicated by a higher degree trend angle of flow capacity (Fig.5), contributing about 65.27% flow capacity and 93.57% storage capacity. These units also have the highest value of flow unit speed greater than 1.4 (Fig.5, Tables 1 and 3). An anticipated sharp and steep decline period that is relatively short is observed for these conduit intervals considering the difference in the percentage of the flow and storage capacities. Flow units 1, 3, 5 and 7, which have a relatively lower angle or horizontal flow capacity trends, are baffles and/or seals. They contribute about 60.07% of

Table 1. Average Petrophysical Properties evaluated for Aqua Wells D and E Reservoirs

Wells/ Reservoirs	Depth Interval (ft) Top	Base	Thickness (ft)	NGR	V_{sh} (v/v)	ϕ_e (v/v)	S_w (v/v)	S_h (v/v)	BVW(v/v)	S_{wir} (v/v)	K (mD)
D-1	11175	11579	404	0.96	0.042	0.20	0.31	0.69	0.058	0.13	891.32
E-1	9943	10133	190	0.56	0.11	0.24	0.14	0.86	0.031	0.11	3471.82
E-2	10294	10361	67	0.98	0.064	0.23	0.10	0.90	0.021	0.11	2163.47
E-3	11157	11254	97	0.87	0.071	0.25	0.14	0.86	0.03	0.09	3885.13
E-4	11863	12228	365	0.93	0.04	0.23	0.07	0.93	0.016	0.10	2480.44

Table 2. Summary of Flow and Storage capacity and Flow unit speed for Reservoir D-1

FU#	Depth interval (ft)	Thickness (ft)	V_{sh} (v/v)	Av.ö (v/v)	Av.K (mD)	öH (%)	kH (%)	FUS
1	11175-11248	73	0.03	0.23	1695.84	21.10	34.81	1.65
2	11249-11307	58	0.04	0.22	1674.84	16.61	27.4	1.65
3	11308-11361	53	0.07	0.17	365.08	11.78	5.47	0.46
4	11362-11414	52	0.03	0.21	1067.12	14.19	15.49	1.11
5	11415-11579	164	0.04	0.18	364.54	36.31	16.63	0.46

FU# = Flow unit number; V_{sh} = Volume of shale; Av.ö = Average porosity; Av.K = Average permeability; öH = Storage capacity; KH = flow capacity; FUS = Flow unit speed.

storage capacity and 38.2% flow capacity at an interval of 120 ft. The values of flow unit speed, porosity and permeability for these units are relatively low compared to the conduit zones (Fig. 5, Table 3). These zones are expected to have a steady to shallow decline in production, and will sustain long time hydrocarbon production.

Reservoir E-2

A total of six flow units were delineated in this reservoir (Fig.6). Flow units 1, 2 and 3 are speed zones (conduits), having a total thickness of 21 ft with an average volume of shale, porosity and permeability values of 5%, 0.26v/v and 3471.46mD respectively. These flow units contribute a total storage capacity of 39.94% and flow capacity of 58.14% within the interval. A high value of flow and storage capacities suggests a steep decline with production which is also reflected by high values of the flow unit speed plots (Fig.6, Table 3). The baffle or seal zones are represented by flow units 4, 5 and 6, which are 41 ft thick. They contribute a total storage capacity of 60.06% and 41.94% flow capacity

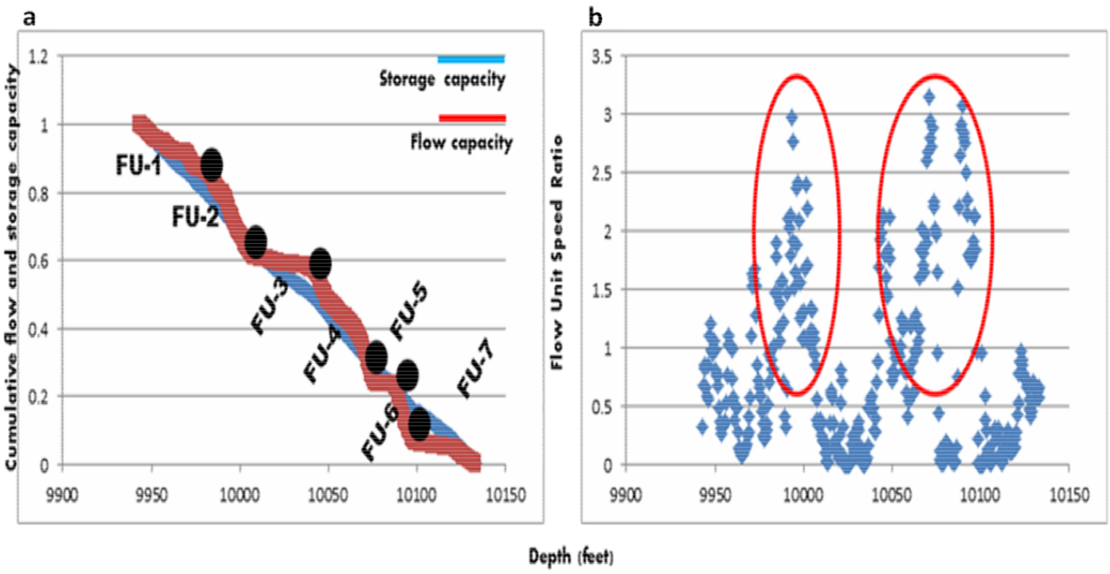

Fig.5. (a) Stratigraphic Modified Lorenz (SML) and **(b)** Flow unit speed (FUS) plots for Reservoir E-1 intervals (9943-10133ft).

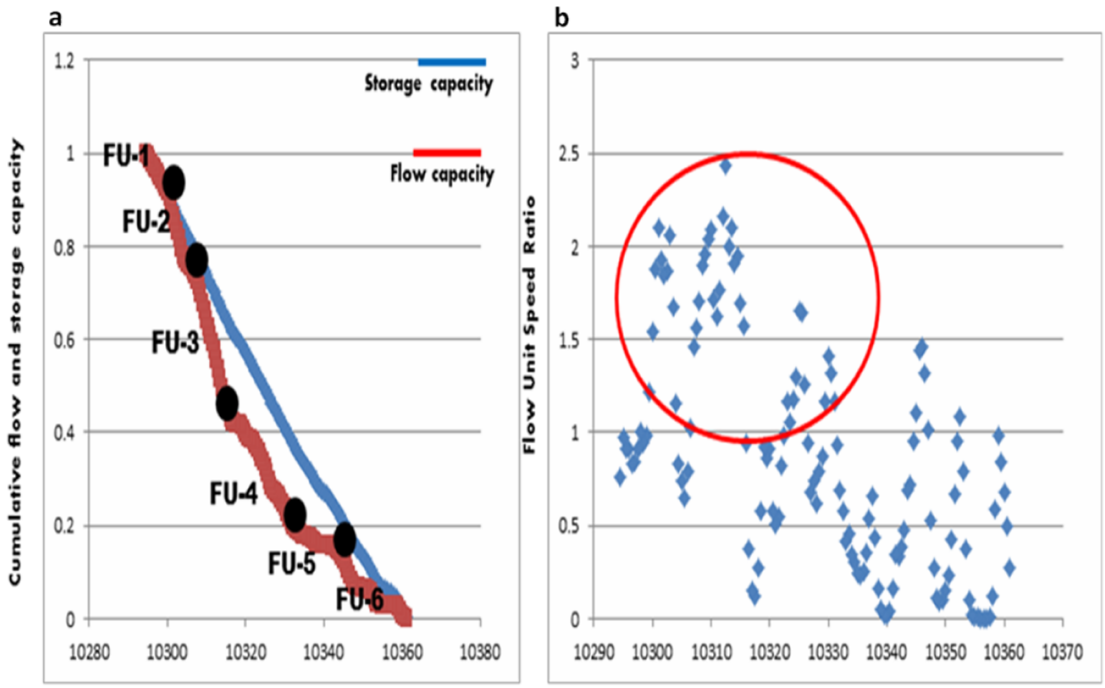

Fig.6. (a) Stratigraphic Modified Lorenz (SML) and **(b)** Flow unit speed (FUS) plots for Reservoir E-2 intervals (10294-10361ft).

Table 3. Summary of Flow and Storage capacity and Flow unit speed for Reservoirs E-1, E-2, E-3 and E-4

FU#	Depth interval (ft)	Thickness (ft)	V_{sh} (v/v)	Av.ϕ (v/v)	Av.K (mD)	öH (%)	kH (%)	FUS
Reservoir E-2								
1	9943-9991	48	0.09	0.25	2945.63	26.75	21.77	0.81
2	9992-10010	18	0.06	0.28	6096.74	11.75	17.47	1.49
3	10011-10043	32	0.18	0.19	1086.54	13.77	5.41	0.39
4	10044-10079	35	0.06	0.27	5808.19	21.63	35	1.62
5	10080-10089	9	0.20	0.21	3162.54	4.64	4.78	1.03
6	10090-10101	11	0.05	0.25	7080.85	6.55	12.8	1.95
7	10102-10133	31	0.15	0.21	1293.69	14.91	6.24	0.42
Reservoir E-2								
1	10294-10300	6	0.06	0.25	2543.25	10.65	11.40	1.07
2	10301-10305	4	0.04	0.26	3833.70	8.65	13.22	1.53
3	10306-10317	11	0.05	0.26	4037.44	20.64	33.42	1.62
4	10318-10333	15	0.04	0.24	2141.89	25.34	23.64	0.93
5	10334-10345	11	0.06	0.20	927.02	15.77	7.67	0.49
6	10346-10361	15	0.12	0.19	994.12	18.95	10.63	0.56
Reservoir E-3								
1	11157-11172	15	0.05	0.31	11269.07	20.63	47.59	2.31
2	11173-11183	10	0.11	0.21	1207.24	9.49	3.51	0.36
3	11184-11194	10	0.03	0.29	6459.81	13.15	18.76	1.43
4	11195-11217	22	0.13	0.21	1286.05	20.34	7.81	0.38
5	11218-11254	36	0.05	0.24	2317.22	36.39	22.33	0.61
Reservoir E-4								
1	11867-11975	108	0.03	0.27	5210.22	35.80	64.76	1.81
2	11976-12006	30	0.08	0.19	1050.15	7.13	3.58	0.50
3	12007-12228	221	0.04	0.22	1296.27	57.07	31.66	0.56

FU# = Flow unit number; V_{sh} = Volume of shale; Av.ϕ = Average porosity; Av.K = Average permeability; ϕH = Storage capacity; KH = flow capacity; FUS =Flow unit speed

(Table 3). These flow units are characterized by low values of flow unit speed as well as porosity and permeability. Long time production can be sustained from these flow unit intervals, which usually have a shallow decline with production.

Reservoir E-3

The five flow units identified in reservoir E-3 show that the speed zones are found in units 1 and 3, while the baffles are in units 2, 4 and 5 (Fig.7). The storage capacity plot at a 45^0 trend on the SML plot and the separation between the storage and flow capacities shows that not all pores are contributing to the flow. The speed zones have a high trend angle of flow capacity with an average volume of shale, porosity and permeability of 0.26v/v, 4% and 3290.35mD respectively. These intervals contribute about 31.29% to storage capacity and 44.82% to flow capacity for a thickness of 17ft. An anticipated steep decline as production progresses is indicated by the high value (> 1.4) plot of flow unit speed (Fig.7, Table 3). On the other hand, flow units 2, 4 and 5 are typically baffles with lower slope inflexion for flow capacity and low values of flow unit speed (< 1.0). It contributes 66.22% storage capacity and 33.65% flow capacity (Table 3). Higher volume of shale and lower values of porosity, permeability and flow unit speed were observed for these intervals compared to the conduit zones. A shallow decline with production is anticipated within these zones with long time production contribution.

Reservoir E-4

This interval is dominantly of sands with net to gross ratio of 0.93. The average values for its shale volume, porosity and permeability are 0.04v/v, 23% and 2480.44mD respectively. The flow unit distribution within the reservoir E-4 delineated using SML and FUS plot were implored to upscale a reservoir interval of 365 feet (Fig.8). A total of three flow units were delineated based on the flow capacity inflexion. Flow unit 1 (11867-11975 ft) is a speed zone, which is shown by the low values of shale volume and high values of porosity, permeability, flow capacity and flow unit speed (Fig.8, Table 3). These intervals contribute a total of 64.76% flow capacity and 35.8% of storage in the reservoir, indicating a steep decline as production progresses. Flow units 2 and 3 (11976-12228 ft) are baffles with higher values of shale volume and lower values of porosity, permeability and flow unit speed compared to the flow unit 1. The storage and flow capacities contribution from these units are about 64.4% and 35.24% respectively, which is an indication of

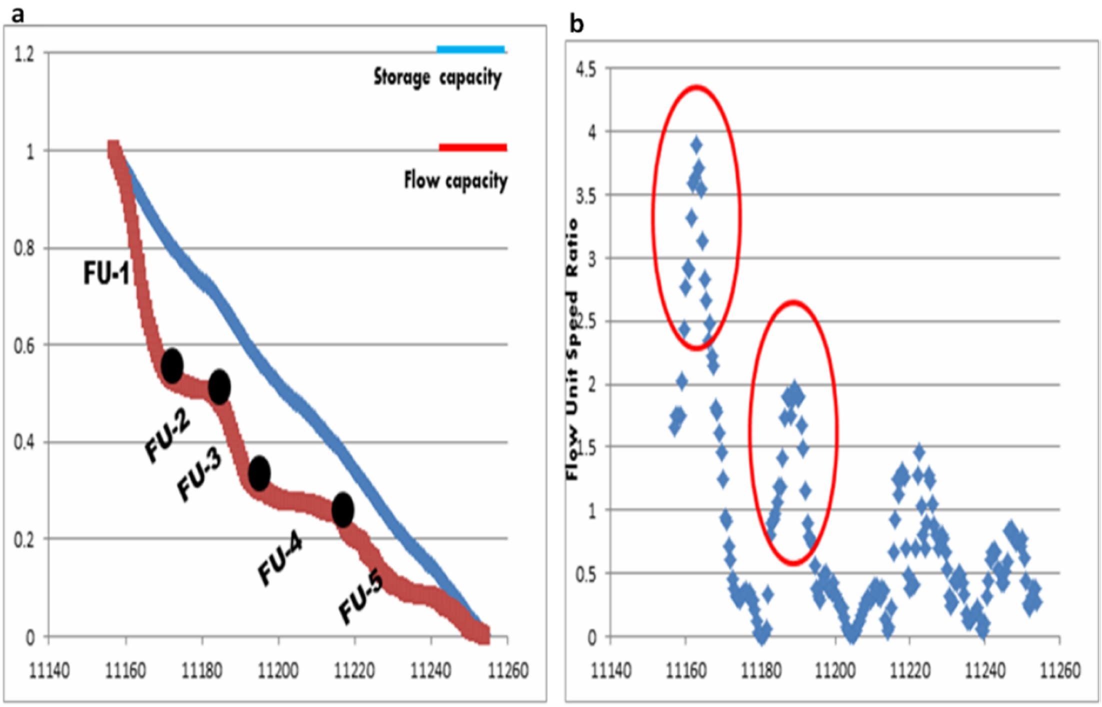

Fig.7. (a) Stratigraphic Modified Lorenz (SML) and **(b)** Flow unit speed (FUS) plots for Reservoir E-3 intervals (11157-11254ft).

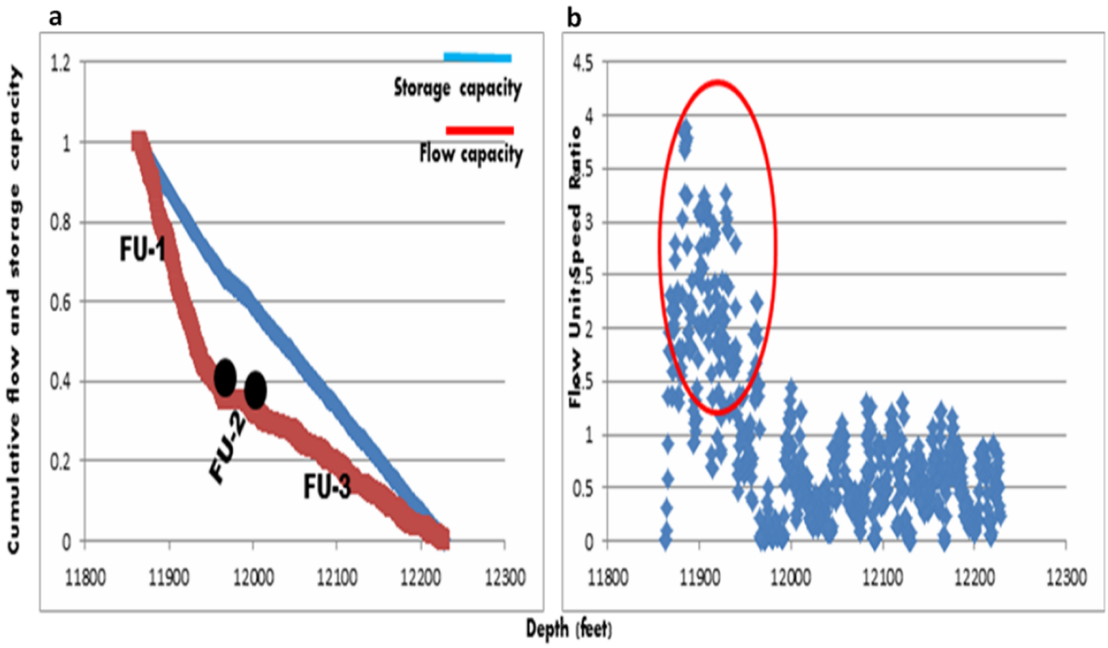

Fig.8. (a) Stratigraphic Modified Lorenz (SML) and **(b)** Flow unit speed (FUS) plots for Reservoir E-4 intervals (11863-12228 ft).

long time dominance with production. The units are also expected to be associated with shallow decline.

CONCLUSIONS

Flow unit characterization has been effectively used in this study to delineate units of similar fluid flow features within the reservoirs of wells D and E in the "Aqua field", Niger delta. These units represent the speed zones and the baffles. Well D reservoir has five (5) flow units with a thickness of 404ft. The speed zones are 131ft thick while the baffles are of 269ft thick. Additionally, Well-E reservoirs have twenty-two (22) flow units with a total thickness of 719ft. The baffle zones which are characterized by steady shallow flow performance make up 518ft thickness while 201ft thickness constitutes the speed zones (conduit). The "Aqua field" reservoirs are dominated greatly by baffle flow unit intervals characterized by low values of flow unit speed as well as porosity and permeability, whereas the speed zones usually have high flow unit speeds, porosity and permeability. Hydrocarbons production over a long time can be steadily sustained from these baffle flow unit intervals, which usually have a shallow decline as compared to the speed zones with sharp decline in production . The identification of the flow units guides in the accurate design of reservoir simulation, apart from capturing the reservoir heterogeneity, which is a major factor that affects oil recovery especially during the enhanced oil recovery stage.

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