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TECTONIC INFLUENCE ON RESERVOIR QUALITY ASSESSMENT OF DEEPWATER SANDSTONES FROM THE OFFSHORE NIGER DELTA, NIGERIA

C.U. Ugwueze[1] and N.E. Ajaegwu[2]
[1]Department of Geology, University of Port Harcourt, PMB 5323 Choba, Port Harcourt, Nigeria
Email: charles.ugwueze@uniport.edu.ng;
[2]Department of Geological Sciences, Nnamdi Azikiwe University, Awka, Anambra State, Nigeria

Abstract
*The research inferred the influence of tectonic setting on reservoir quality assessment of deepwater sandstones (**Q** and **R**-reservoir sands) from the offshore Niger Delta with a view to delineating their tectonic setting, provenance and climatic belt using results of thin-section photomicrographs, core-based porosity and permeability data from three wells cored at various stratigraphic intervals. The study involved delineation of the spatial distribution of framework mineralogy, their petrophysical properties and types of diagenetic alterations. Point count modal analysis was employed, and involved counting up to 300 minerals per thin section slide. The mineral percentages totalling 100% from each of the stained thin-section photomicrographs was used to infer the sandstone composition and their provenance. The framework mineralogy was generally dominated by monocrystalline quartz, small amount of feldspars and insignificant amount of rock fragments. An infiltrated mudstone clasts were quite common. Traces of siderite overgrowth, quartz overgrowth, muscovite laths, zircon, leached quartz, and heavy minerals were also common. Potassium feldspar dominated over plagioclase feldspar. Some of the quartz grains were leached. The grains were poorly to moderately sorted with significant effective porosities. The thin-section photomicrographs showed good interconnected pores and loose to point-grain contacts. The reservoir sands have high porosity and permeability probably due to the unconsolidated nature of the sediments and dissolution framework grains. The average modal compositions of the quartz, feldspar and lithic fragment corresponded to 86.20%, 11.47% and 2.34% in Q-reservoir sand from Zebra-4 well; 88.14%, 9.68% and 2.18% in R-reservoir sand from Zebra-3well; and 97.47%, 2.03% and 0.50% in Q-reservoir sand from Zebra-2ST3 well respectively.The predominance of monocrystalline quartz over polycrystalline quartz in the thin-section were used to validate the derivation from a plutonic igneous rocks. Thus, the bulk of the Zebra reservoirs are inferred to be derived from a similar parent rock type (plutonic igneous rocks) with similar climatic conditions (hot and humid climate) and unique composition (quartz arenite with subordinate arkosic arenite) with the same tectonic setting (craton interior). The open pores and loose grain contacts were evidences that the studied reservoirs have undergone minor to insignificant mechanical compaction while leached quartz, quartz overgrowth and siderite patches indicate intergranular pressure dissolution.*
Keywords: *Tectonic Setting, Mineralogical Maturity, Reservoir Quality, Deepwater Sandstone, Niger Delta*

Introduction
One of the factors that create basins necessary to form clastic sedimentary rocks is tectonics. Once a basin is formed, the area surrounding the basin will shed its erosional debris. Such transported and deposited sediments could form sandstones. Clues to the tectonic setting in which the basin formed may be left in this accumulated sediments. Sediments formed from a magmatic arc that has not undergone extensive erosional dissection should consist of a high proportion of volcanic lithic fragments that contain a high ratio of plagioclase to alkali feldspar. With increasing erosional dissection, more plutonic rocks would become exposed and the sediment shed would contain a higher proportion of quartz and alkali feldspar. Sands derived from sources on continental blocks could come from two tectonic settings; if the continental block had recently split as a result of continental rifting, the sands would be quartzo-feldspathic with high ratios of alkali feldspar to plagioclase. However, if the sands were derived from high topographic areas located long distances from the depositional areas, the sands would be more quartz rich, showing a higher degree of mineralogical maturity.

The provenance of North American Phanerozoic sandstone has been studied by Dickinson *et al*. (1983) in relation to tectonic setting. The sandstone samples they analyzed plotted exclusively into the craton interior field, which they attributed to the maturity of the clastic sediments sourced from relatively low-lying granitoid area supplemented by recycled sands from associated passive margin basins.

Mansurbeg (2007) in his study of the distribution of diagenetic alterations and their impact on reservoir-quality evolution in four deep-water turbidite successions (Cretaceous to Eocene) from basins in active (foreland) and passive margin settings, revealed the impact of tectonic setting, depositional facies, and changes in the relative sea level in the distribution of diagenetic alterations in such basins. Huang (2012) studied the nature and porosity effects of illite in the Taiyuan Formation of the Northeast Ordos Basin. He attributed the intense illitization and relative scarcity of kaolinite in the area to the prolonged exposure to saline depositional pore-waters during Miaogou transgression in the early Taiyuan period. He observed that potassium feldspar dissolution was inhibited or slowed down by early penetration of potassium-rich fluids which may have provided other potential sources of potassium for illite formation at the expense of kaolinite during burial diagenesis. He also documented a positive correlation between the abundance of authigenic illite and variations in thin-section porosity for Taiyuan sandstone reservoirs, which he interpreted as an indication that the majority of the total sandstone volume was secondary porosity produced primarily by illitization at the expense of kaolinite and potassium-feldspar.

In trying to relate the influence of tectonic setting on reservoir quality assessment of deepwater sandstones, subsurface geological data interpretation became necessary. However, mapping depositional facies in the subsurface has been a challenge because information obtained from wellbores is basically one-dimensional and laterally discontinuous (Lewis *et al.,* 2008), whereas depositional facies can change dramatically in three-dimensions (3-D) across unexplored areas. The problem becomes particularly acute in frontier sedimentary basins such as offshore Niger Delta and in the deep stratigraphic levels where little well data are available (Billman, 1992). According to Lewis *et al.* (2008), some of the challenges involved in exploring deep-water reservoirs include delineating and modelling of reservoir quality, geometry, sand distribution and flow capability.

The field under study (Zebra Field) is located in the south-western part of the Niger Delta within the inner fold belt in the modern continental slope (Fig. 1). It ranges in water depth from 1,020 - 1,245m (Wood Mackenzie, 2011). The field was discovered in March 1996 by the Shell Nigeria Exploration and Production Company (SNEPCO) who has been operating it in partnership with Esso Exploration and Production Nigeria (Deepwater), Nigeria Agip Exploration, and Total Petroleum Nigeria on behalf of the Nigerian National Petroleum Corporation (NNPC) (Wood Mackenzie, 2011). Based on high proportion of mud in its depositional sequence and lack of well-developed vertical organization of facies, the Zebra reservoir sands (**Q**-sand and **R**-sands) are suggested to be deposited in a setting strongly influenced by slope setting where sediment-gravity flow processes dominated due to slope instability (Ugwueze *et al.*, 2014).

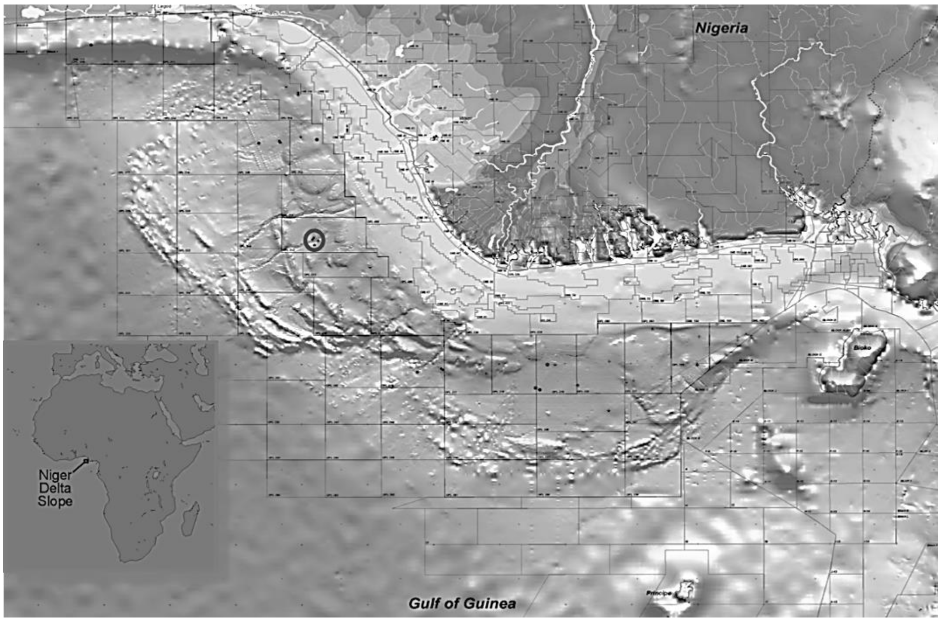

Fig. 1: Seafloor Image of the Niger Delta basin showing the Location of the Zebra Field (Wood Mackenzie, 2011)

Tectonic Evolution of the Delta Complex

The basin 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 the Abakaliki fold belt, in the south by the Gulf of Guinea and in the north by the Anambra basin (Burke *et al.,* 1971; Ajayi, 1995; Tuttle *et al.,* 1999 and Ejedawe *et al*, 2004 Fig. 2. The delta built out over the collapsed continental margin at the site of a triple junction formed during the middle Cretaceous. During the Cretaceous, the area presently occupied by the Niger Delta was the site of R-R-R (ridge-ridge-ridge) triple junction (Fig.2). 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 continents (Short and Stauble, 1967). The main sediment supply has been provided by an extensive drainage system, which in its lower reaches follow two failed rift arms; the Benue and Bida basins (Burke *et al*, 1971). Sediment input generally has been continuous since the late Cretaceous, but the regressive record has been interrupted by episodic transgressions. Weber and Daukoru (1975) described the evolution of the delta complex in three phases namely:

a Pre-Santonian basin evolution
b Santonian - Palaeocene basin evolution
c Eocene - Recent delta phase

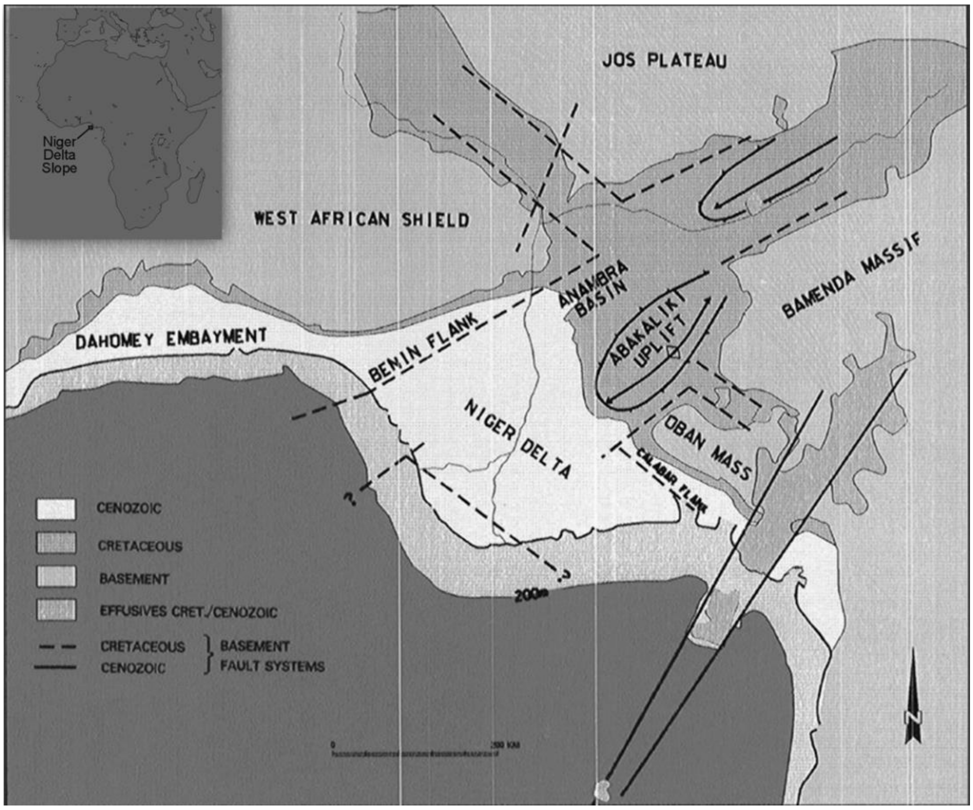

Fig. 2: Geologic Map of the Nigeria Sedimentary Basins showing the Niger Delta Mega Tectonic Frame (Ajayi, 1995)

A Pre-Santonian Basin Evolution

The oldest pre-Tertiary sedimentary basin; the Benue-Abakaliki Trough, originated as an arm of the triple junction rift-ridge system that initiated the separation of South American from Africa in the Aptian/Albian (Burke, 1972). The three arms of the system opened up at different times and different rates. In the South Atlantic, the opening started in the mid-Aptian by crustal stretching and down-warping accompanied by the development of coastal evaporite basins (Ejedawe, 2004). By lower Albian, it has reached the Gulf of Guinea and extended northeast to form the Benue-Abakaliki Trough. In the north Atlantic, the opening was much earlier, but slower reaching Senegal by upper Jurassic (Schull, 1988) (Fig.3).

B Santonian - Palaeocene Basin Evolution

Consequent to the Campano-Santonian folding, the Benue-Abakaliki trough was uplifted to form the Abakaliki high, while the Anambra platform was down-warped to form the Anambra basin. The sea then invaded the Benin flank basement adjoining the Anambra basin for the first time.

C Eocene - Recent Delta Phase

This stage was initiated in response to the epirogenic movement along the Benin and Calabar flanks and continued to build up the Niger Delta, up till present time. This stage was marked by regression that is frequently interrupted by minor transgression (Frankl and Cordry, 1967). Important tectonic elements found in the post Palaeocene delta were the Anambra basin, Abakaliki high, Afikpo syncline and Ikang trough. These gave the directions of clastic supply, the area of maximum deposition and the outline of the delta from early Miocene to mid Miocene.

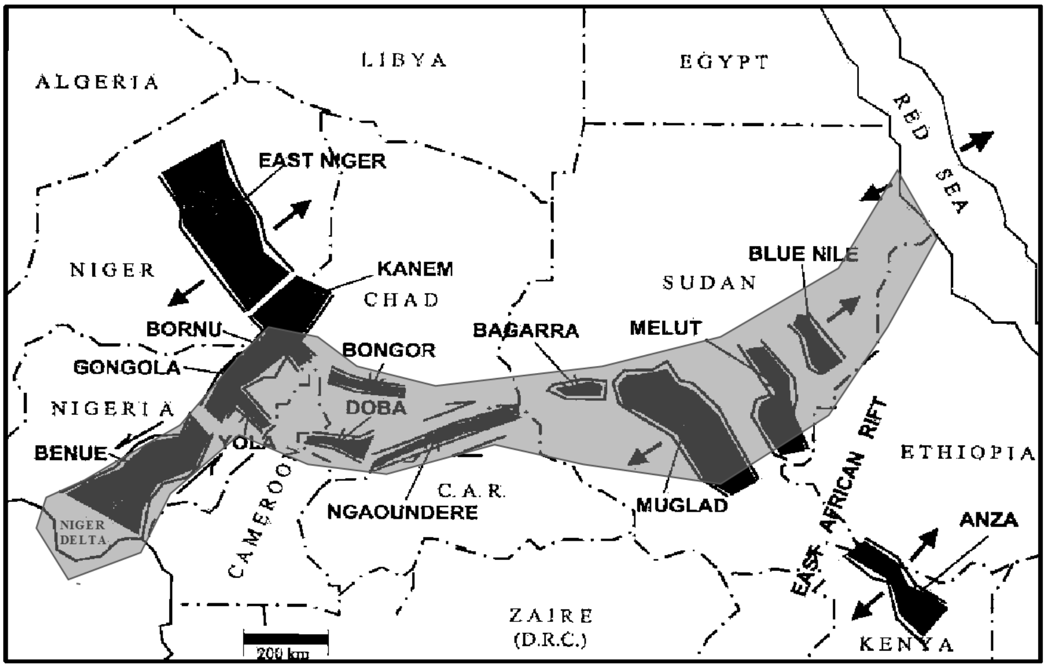

Fig.3: Regional distribution of the Central African rift basins (Schull, 1988)

Materials and Methods

The assumption that different tectonic settings contain characteristic rock types which, when eroded produce sandstones with specific compositional ranges has been used to characterize the sandstone composition and provenance of the Zebra reservoir sands. Core-based porosity and permeability data and stained thin-section photomicrographs each from Zebra-2ST3, Zebra-3 and Zebra-4 cored wells/intervals were used for the study. The data sets were provided by the Shell Nigeria Exploration Production Company Nigeria, and as such the detailed procedures and technicalities for the data generation were not discussed.

The study involved delineation of the types of diagenetic alterations, spatial distribution of framework mineralogy and their petrophysical properties. Point count modal analysis was employed, which involved counting up to 300 minerals per thin section slide. The mineral percentages totalling 100% from each of the stained thin-section photomicrographs was used to infer the sandstone composition and their provenances (Dickinson *et al.*, 1983; Osae *et al.,* 2006 and Ugwueze *et al.*, 2014). The results were re-calculated over 100 % following the procedures of Dickinson *et al.*, (1983) and Osae *et al.*, (2006). A summary of sediment textures and framework mineralogy (Mansurbeg, 2007) were interpreted from the thin-section together with a discussion of the reservoir quality (Aagaard *et al.*, 2009; Deschamps *et al.*, 2012 and Ugwueze *et al.*, 2014) of the sediments using the results of the core-based porosity.

Results and Discussion

Results of the Sandstone Composition and Provenance

The results of the thin-section analysis performed on the Zebra reservoirs are shown in the figures (**4-6**) and tables (**1-3**) below.

i. Results of the Thin-Section Photomicrographs of Q-Reservoir Sand in Zebra-4 Well against Depth

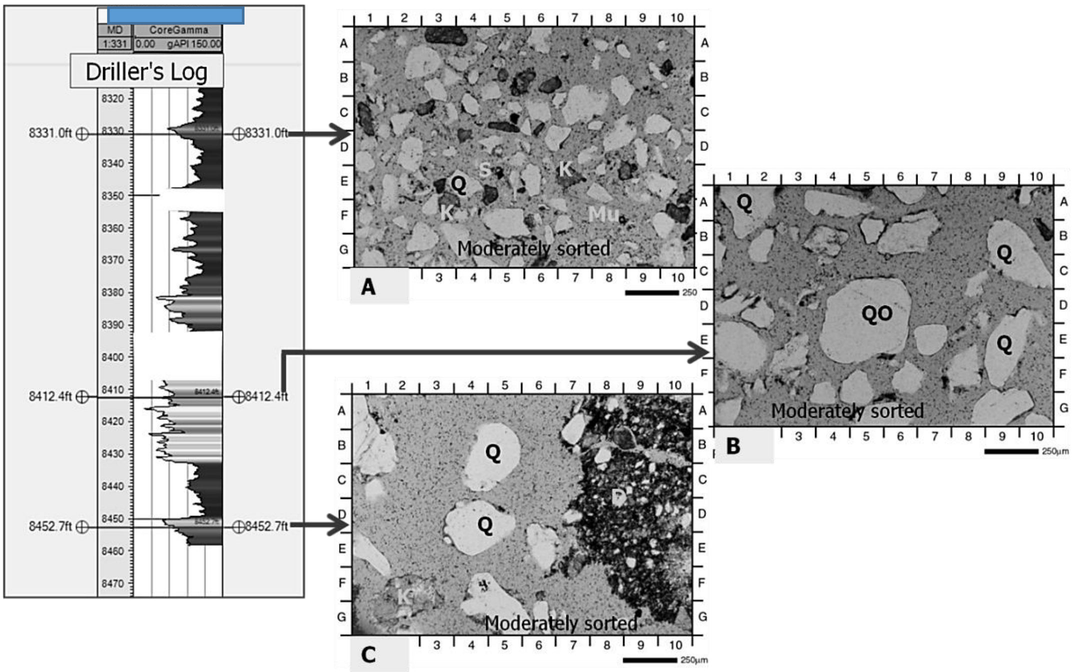

Fig.4: (A – C): Thin-section photomicrograph showing effects of compaction and cementation on framework minerals (D = Detrital Clay, K = K-feldspar, Q = Quartz, S = siderite Overgrowth, QO = Quartz Overgrowth, Mu = Muscovite)

Table 1: Summary of the Results of the Thin-Section Photomicrographs of Q-Reservoir Sand in Zebra-4 Well against Depth

S/N	Depth (ft)	Quartz (%)	Feldspar (%)	Rock Fragment (%)	Detrital Clay (%)	Sorting	Porosity (%)	Permeability (mD) to Air at 1000psig	Composition	Diagenetic Imprints
1	8331.0	72.5	13.7	1.3	Nil	moderate	5	2710	Arkosic arenite	Quartz overgrowth, siderite patches, intergranular pressure dissolution
2	8412.4	91.7	6.3	1.3	Nil	moderate	29	3970	Quartz arenite	Good inter connected pores, loose to point-grain contacts, minor mechanical compaction
3	8452.7	33.7	5.0	1.7	57.3	moderate	15	945	Arkosic arenite	Grain coating clays, limited overgrowth of quartz and k-feldspar, suppressed cementation

ii. Results of the Thin-Section Photomicrographs of R-Reservoir Sand in Zebra-3 Well against Depth

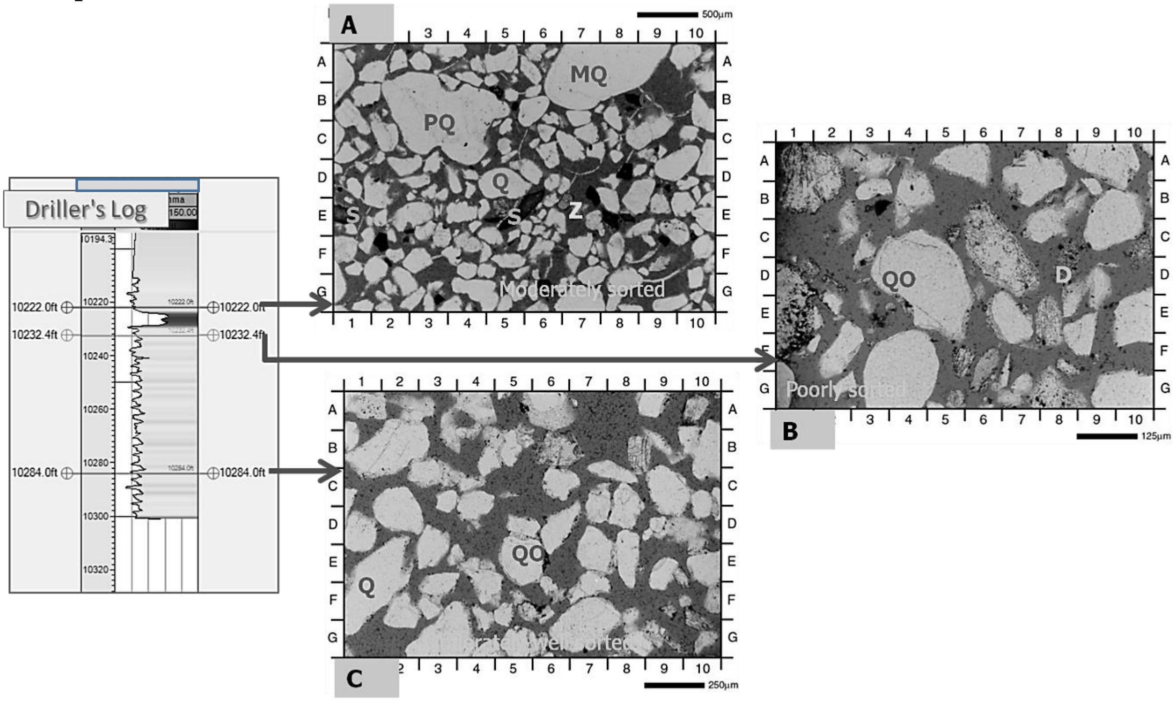

Fig.5: (A – C): Thin-section photomicrograph showing effects of compaction & cementation on framework minerals (R-Sand; Zebra-3 Well) (Q = Quartz, QO = Quartz Overgrowth, PQ = Poly Quartz, MQ = Mono Quartz, D = Detrital Clay, K = K-feldspar, Z = Zircon, S = siderite, O = Authigenic Opaque)

Table 2: Summary of the Results of the Thin-Section Photomicrographs of R-Reservoir Sand in Zebra-3 Well against Depth

S/N	Depth (ft)	Quartz (%)	Feldspar (%)	Rock Fragment (%)	Sorting	Porosity (%)	Permeability (mD) to Air at 1000psig	Composition	Diagenetic Imprints
1	10222.0	60	2.3	Trace	moderate	37.3	8150	Quartz arenite	Quartz present as rare authigenic syntaxial overgrowth cement on some quartz grains, carbonate present as a rare authigenic siderire cement, some rare secondary porosity due to partial dissolution of some detrital grains
2	10232.0	47.3	6.0	1.7	Moderate to poorly	42.7	5780	Quartz arenite	Minor authigenic opaques, minor authigenic syntaxial quartz overgrowth cement on some quartz, general sparsity of diagenetic cements
3	10284	44.3	7.0	Trace	moderate to well	47.3	6660	Quartz arenite	Some secondary porosity due to partial leaching of some detrital grains

iii. Results of the Thin-Section Photomicrographs of Q-Reservoir Sand in Zebra-2ST3 Well against Depth

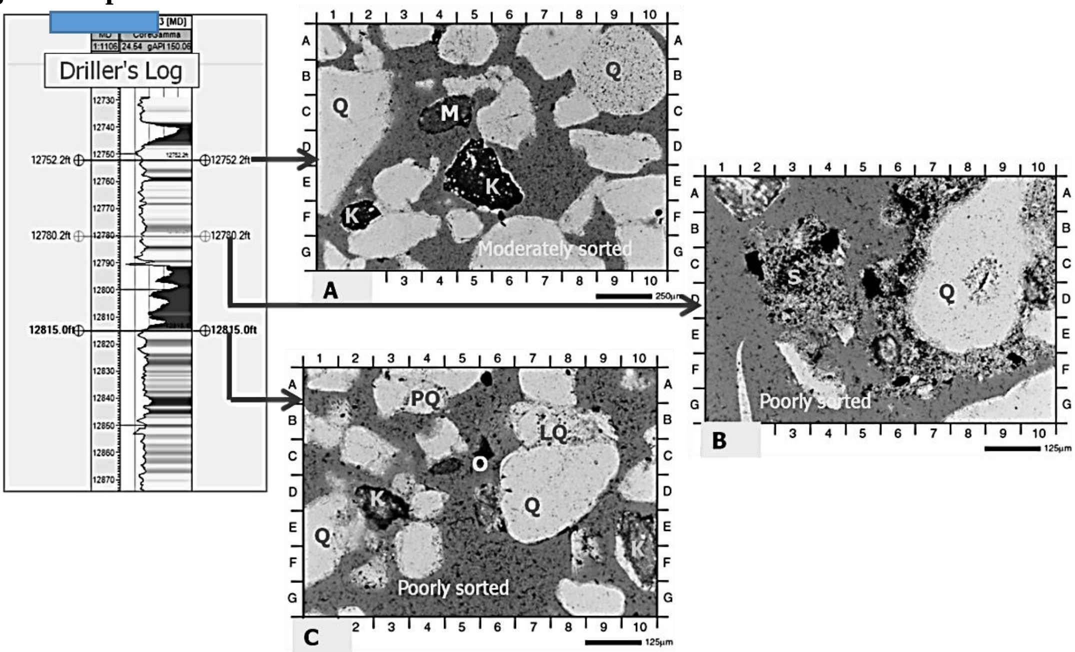

Fig.6: (A – C): Thin-section photomicrograph showing effects of compaction & cementation on framework minerals (Q-Sand; Zebra-2ST3 Well) (Q = Quartz, PQ = Polycrystalline Quartz, LQ = Leached Quartz, M = Mudstone clasts, K = K-feldspar, S = Siderite patches, O = Authigenic Opaque)

Table 3: Summary of the Results of the Thin-Section Photomicrographs of Q-Reservoir Sand in Zebra-2ST3 Well against Depth

SN	Depth (ft)	Quartz (%)	Feldspar (%)	Rock Fragment (%)	Detrital Clay (%)	Sorting	Porosity (%)	Permeability (mD) to Air at 1000psig	Composition	Diagenetic Imprints
1	12752.2	59	1.3	Trace	Nil	moderate	36.3	5210	Quartz arenite	Feldspar present as k-feldspar, rare heavy minerals including zircon, scattered infiltrated clays, absence of diagenetic cements
2	12780.2	70	0.8	Trace	4.3	poorly	24.5	4910	Quartz arenite	Unconsolidated thin section, minor scattered infiltrated clays
3	12815.0	68.3	2.0	0.7	Nil	poorly	28.3	3050	Quartz arenite	Minor authigenic opaques, presence of syntaxial quartz overgrowth, minor secondary porosity due to partial leaching of some quartz grains

The results of the point count modal analysis performed on the Zebra reservoirs are shown in Table 4.

Table 4: Results of the re-calculated Modal Analysis of the Thin-Section Photomicrographs

Wells/ Reservoir	Quartz (%)	Feldspar (%)	Lithic Fragment (%)	Total
	82.82	15.69	1.49	**100**
Zebra-4well (**Q-sand**)	92.35	6.34	1.31	**100**
	83.42	12.38	4.21	**100**
Average	**86.20**	**11.47**	**2.34**	
	94.79	3.63	1.58	**100**
Zebra-3well (**R-sand**)	84.92	12.03	3.05	**100**
	84.70	13.38	1.91	**100**
Average	**88.14**	**9.68**	**2.18**	

The average modal compositions of quartz, feldspar and lithic fragment corresponded to 86.20%, 11.47% and 2.34% in Q-reservoir sand from Zebra-4 well; 88.14%, 9.68% and 2.18% in R-reservoir sand from Zebra-3well; and 97.47%, 2.03% and 0.50% in Q-reservoir sand from Zebra-2ST3 well respectively (**Table 4**). The average values of the framework mineralogy were used to delineate the tectonic setting of the sandstone reservoirs as shown in figure 7. Comparatively, the analysed sandstone samples have more than 70% quartz, less than 30% feldspar and less than 20% lithic fragment distribution similar to that of Dickinson *et al*., (1983) that also plotted into the craton interior field. Hence, having satisfied the condition for craton interior field interpretation, the bulk sandstone reservoirs from the Zebra field are inferred to be quartz arenite with subordinate arkosic arenite (**Fig.7**).

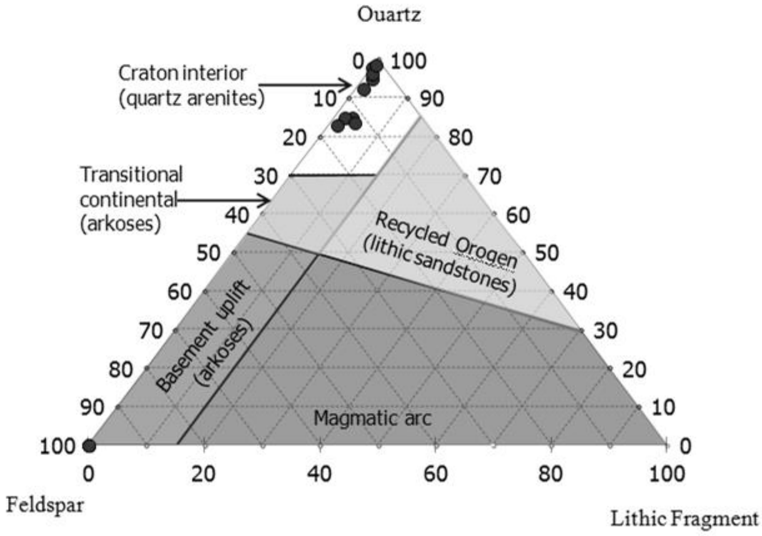

Fig.7: **Quartz-Feldspar-Lithic Fragment (QFL) Ternary plots showing Zebra reservoir sandstone composition and their tectonic setting (modified after Dickinson et al., 1983)**

Provenance study was also carried out for the reservoir sandstones under study using the average values of the framework mineralogy obtained (**Table 4**). According to Osae *et al.* (2006), sands generated from plutonic rocks in humid climate would have average quartz, feldspar and rock fragment contents of 60%, 27% and 13% respectively; whereas those generated from a plutonic source in a semi-arid climate would have an average modal composition corresponding to 27%, 39% and 34% respectively. Analogous average quartz, feldspar and rock fragment contents for a metamorphic-derived sands in a humid climate would be 74%, 6% and 20% respectively (**Fig. 8**). The average modal compositions of quartz, feldspar and lithic fragment in all the reservoir sandstones analysed were within the range recommended for both plutonic and metamorphic rocks deposited in a humid climate.

However, an argument in support of a plutonic origin were provided by the presence of zircon and tourmaline heavy minerals documented from the thin-sections (Zebra-3well, R-reservoir at 10222ft depth), which are known to be common accessory minerals of acid-intermediate igneous rocks (Feo-Codicido, 1956). Although, presence of zircon and tourmaline can also be the results of prolonged abrasion, chemical attack and/or indication of sediment reworking. Nevertheless, predominance of monocrystalline quartz over polycrystalline quartz in the thin-section can be used to validate the derivation from a plutonic igneous rocks (Blatt, 1979). Thus, the bulk of the Zebra reservoirs are inferred to be derived from a similar parent rock type (plutonic igneous rocks) with similar climatic conditions (hot and humid climate) and unique composition (quartz arenite with subordinate arkosic arenite) with the same tectonic setting (craton interior) (**Fig. 8**).

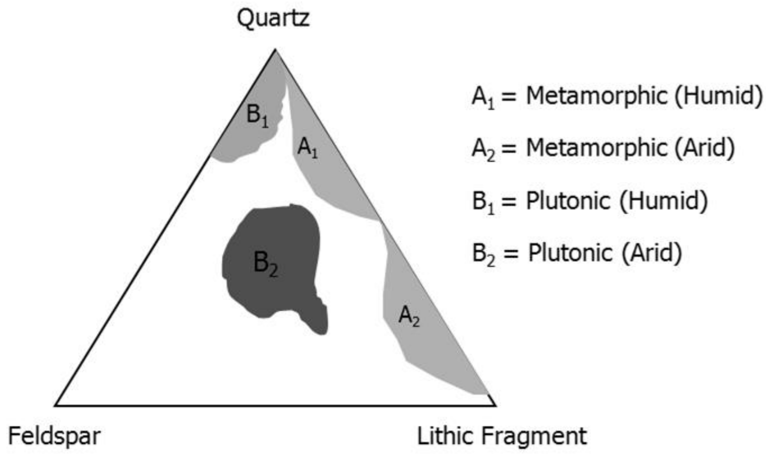

Fig.8: **Quartz-Feldspar-Lithic Fragment (QFL) Ternary plots of Zebra reservoir sandstones showing their provenance and climatic belts (modified after Osae et al., 2006)**

Influence of Tectonic Setting on Reservoir Quality Assessment

High quartz content of over 70% dominated between 8331 – 8412.4ft depth intervals in Q-reservoir sand from Zebra-4 well except at deeper depth (8452.7ft) where detrital clay (0ver 57%) dominated (**Table 1**). The reservoir sands displayed poor porosities at shallow burial depth (5%) and high porosities at deeper burial depths (10 to 29%), while good permeability was also interpreted at all burial depths ranging from 945 to 3970 mD. The reservoirs showed moderate sorting at all burial depths irrespective of the values of their framework mineralogy and compositions (**Figure 4** and **Table 1**). Quartz overgrowth, siderite patches, intergranular pressure dissolution were some of the diagenetic imprints observed from the thin-section. Good inter-connected pores, loose to point-grain contacts and minor mechanical compaction was also noted.
In R-reservoir sand from Zebra-3 well, high porosity was documented at all burial depths (10222 – 10284ft) averaging 42% even with variable sorting (from poorly to moderately well sorted). High permeability was also interpreted at all burial depths (3580 to 6660 mD). Average quartz content (approximately 50%) was documented. However, rock fragments were very low occurring mostly in traces (**Figure 5** and **Table 2**). Quartz is present as rare authigenic syntaxial overgrowth cement on some quartz grains while carbonate is present as a rare authigenic siderite cement. Some rare secondary porosity were observed probably due to partial dissolution of some detrital grains. Minor authigenic opaques were also observed. There was general sparsity of diagenetic cements in the reservoir.

Q-reservoir sand in Zebra-2ST3 recorded high porosity (24.5 to 36.3%) and permeability (4910 to 6070 mD). Feldspar is present as k-feldspar while rare heavy minerals including zircon were common occurrence. There was presence of scattered infiltrated clays and absence of diagenetic cements (**Figure 6** and **Table 3**). There was also presence of minor authigenic opaques, presence of syntaxial quartz overgrowth and minor secondary porosity due to partial leaching of some quartz grains.

From the study, framework mineralogy was generally dominated by monocrystalline quartz, small amount of feldspars and insignificant amount of rock. An infiltrated mudstone clasts were quite common. Traces of siderite overgrowth, quartz overgrowth, muscovite laths, zircon, leached quartz, and heavy minerals were also common. Potassium feldspar dominated over plagioclase feldspar. Some of the quartz grains were leached. The grains were poorly to moderately sorted with significant effective porosities. The thin-section photomicrographs studied showed good interconnected pores and loose to point-grain contacts. The open pores and loose grain contacts were evidences that the studied reservoirs have undergone minor to insignificant mechanical compaction while leached quartz, quartz overgrowth and siderite patches indicate intergranular pressure dissolution.

The presence of grain coating clays and limited overgrowth of quartz and k-feldspar was evidence of suppressed cementation by quartz overgrowths, replacive pyrite, siderite, kaolinite and replacive authigenic opaques (Mansurbeg, 2007). Insignificant compaction of sandstone could be attributed to suppressed quartz cementation caused by grain-coating clays (Al-Ramadan, 2006; Mansurbeg, 2007; Deschamps *et al*., 2012 and Ugwueze *et al.*, 2014). This significantly caused retention of effective primary porosity in the Zebra field. However, porosity retention could also be caused by low geothermal gradients, rapid rates of burial, grain textures or none availability of authigenic quartz cement (Mansurbeg, 2007 and Ugwueze *et al.*, 2014). The latter case may be a possibility due to the observed partial dissolution of framework minerals indicating that cement minerals necessary for binding grains were not yet mobilised.

Conclusion

The research set out to establish the influence of tectonic setting on reservoir quality assessment of deepwater sandstones from the offshore Niger Delta with a view to delineating their tectonic setting, provenance and climatic belt using results of thin-section photomicrographs, core-based porosity and permeability. The observed maturity in mineralogy can be attributed to a source that is quartz-rich where feldspar dominates over more chemically unstable lithic fragments. Nevertheless, passive margin sediments are known to be largely quartz-rich sediments that are derived from plate interiors or stable continental areas that may be deposited in intra-cratonic basins or on passive continental margins. This interpretation perhaps favours plutonic source with a humid and hot climatic conditions.

The reservoir sands generally showed good interconnected pores and loose to point-grain contacts, and have generally undergone minor to insignificant mechanical compaction, intergranular pressure dissolution and suppressed cementation by quartz overgrowths, replacive pyrite, siderite, kaolinite and replacive authigenic opaques with higher degree of mineralogical maturity, and thus good reservoir quality. Reservoir connectivity in the area was enhanced by the unconsolidated nature of the sediments, leaching, dissolution of framework grains and presence of inter/intragranular macropores of secondary origin.

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