Reservoir Compartmentalisation Study of the "X" Field of the Niger Delta, Nigeria

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Abstract

Natural gases vary in chemical and isotopic composition as a function of their formation and migration history. Compositional and isotopic variations are often caused by the mixing of two or more compositionally and isotopically different gases. The variations of isotopic properties of gases within a continuous reservoir are generally small but can be significant between fault blocks, baffles of one reservoir, or between unconnected but closely stacked reservoirs. These variations can be utilized to help solve many problems occurring during gas field development and operation. The study aimed at evaluating the availability of flow barriers or compartments within the "X" Field of the Niger Delta. Natural gas samples from 13 producing wells were used for this study. The variations in the molecular and isotopic composition of the gases were used to achieve the aim of the study. The gas samples were heated to their sampling point temperatures and analysed by the Gas chromatographic technique for their molecular composition, using GPA 2286, as a standard test method. The isotopic signatures for methane, ethane, and propane were computed using regression formulas. The results indicate similar molecular and isotopic composition for 11 wells at different locations of the reservoir except for wells S1 and S7. The similarity in the molecular and isotopic composition of the natural gas for the 11 wells suggests that those wells are communicating but there exists a barrier to communication between those wells and wells S1 and S7. The studied natural gases from the "X" Field of the Niger Delta are genetically related and may have been generated by the same source rock. The difference in molecular and isotopic composition between the natural gases from the 11 wells and wells S1 and S7 infers a baffle, impeding fluid communication between well S1, S7 and the remaining wells.

Keywords: Compartmentalisation, Natural gas, Niger Delta, Reservoir

1 Introduction

Larter *et al*. (1994) suggested reservoir geochemistry as a connection between reservoir geology and reservoir engineering. Afterward, various studies have been published where the use of geochemical methods yields information on production related issues. Examples include the detection of compartmentalisation (Smalley *et al.,* 1994; Levaché *et al.,* 2000; Wilhems *et al.,* 2001), productional location (Kaufman *et al.,* 1990; Bazan, 1998) and reservoir monitoring. Ubiquitous for lots of these applications is that they depend on compositional heterogeneities in reservoir hydrocarbons, frequently considered as a result of variations in source rock facies or source rock maturity. These heterogeneities may result from secondary post accumulation hydrocarbon alterations like biodegradation, water washing, or evaporative fractionation. If mapped spatially, these hydrocarbon heterogeneities can give information regarding reservoir architecture and connectivity (Larter and Aplin, 1994).

The study of reservoir connectivity and compartmentalisation is founded on the hypothesis that where fluid continuity in a reservoir is possible, wells within the reservoir or field may have dynamic fluid communication such that significant similarity in physical and chemical properties will show in fluids from such wells (Holba *et al.*, 1996). Accordingly, tools and methods have been developed to assist investigate this phenomenon. The fingerprint method used for the assessment of reservoir connectivity is well developed (Hwang *et al.*, 1994; Hunt, 1996; GeolabNor, 2004). The technique assesses fluid communication by the comparison of the molecular and isotopic composition of natural gases from the wells within a reservoir(s) (GeolabNor, 2004). In this study, we examined the geochemistry of the "X" Field of the Niger Delta to assess the reservoir's connectivity, since studies of this sort have not been carried out on the "X" Field .

1.1 Study Area

The Niger Delta is located in the Gulf of Guinea. It is margined in the east by the Cameroon volcanic line and in the North-western part by the Okitipupa ridge of the Dahomey embayment (Fig. 1). The Niger Delta sedimentary basin covers an area of about 75,000 km^2 (Haack *et al.*, 2000). The delta evolution is closely associated with the formation of a rift triple junction (an aulacogen known as the Benue Trough in Nigeria) during the separation of the continental crusts of South America and Africa in the Late Jurassic (Whiteman, 1982). Following the separation of the continental plates of South America and Africa, the opening of the Atlantic Ocean, in turn, gave rise to marine incursion as marked by marine sedimentation in the Benue Trough and the Anambra Basin during the Cretaceous period in Nigeria (Doust, 1989). As the Niger River increasingly fed elastics from the adjacent highlands during the early Tertiary, the Niger Delta began to form at the point where the Benue Trough adjoins the Atlantic Ocean (Doust and Omatsola, 1990). The Niger Delta consists of a subsurface sedimentary sequence up to 12 km thick in places that represent a progradational package, which has been extensively described and discussed (Short and Stauble, 1967; Avbovbo, 1978; Kulke, 1995). The sedimentary sequence represents prograding facies that are separable based on the sand-shale ratio and are divisible into three (Fig.2) lithostratigraphic units. The overpressured basal Palaeocene-Miocene Akata Formation (Knox and Omatsola, 1989) represents a deep marine shale sequence of prodeltaic facies approximately 6000 m thick. The Akata Formation is a low-stand system, at which time, terrestrial organic materials and clays were transported to the deepwater part of the receiving basin by low energy conditions and less oxygenated water (Stacher, 1995). The Akata Formation is overlain by over 4000 m of alternating sandstones and shales of parallic facies (Short and Stauble, 1967; Avbovbo, 1978). This interbedded sandstone and shale unit is called the Agbada Formation (Eocene- Recent). The Agbada Formation represents the deltaic system (delta front, fluvio-deltaic facies) of the sedimentary sequence (Tuttle *et al.*, 1999). The Benin Formation (Late Eocene-Holocene) overlies the Agbada Formation and is a sequence of about 2000 m of fluviatile sands and alluvium which represents the youngest bed in the sequence (Avbovbo, 1978).

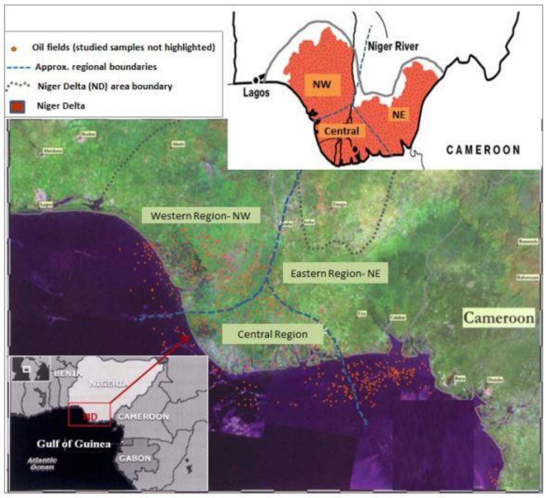

Fig. 1 Location of the Niger Delta in the southwestern Nigeria coast as indicated in the topmost enlarged area (Mitchell, 2006; Samuel, 2008)

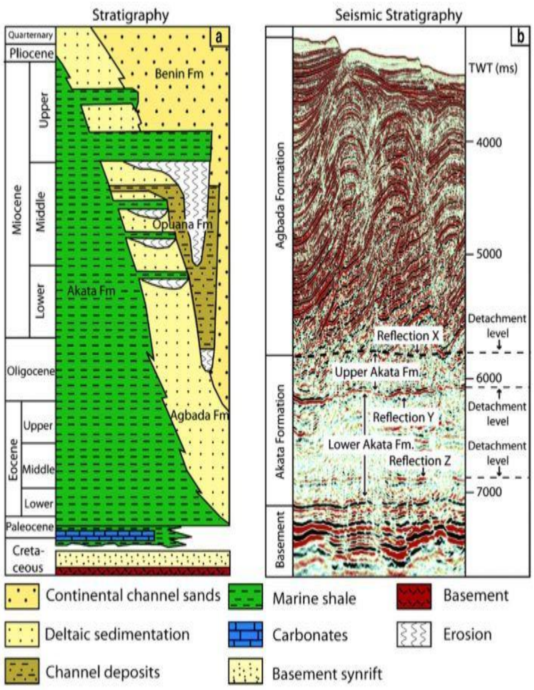

Fig. 2 Stratigraphy of the Niger Delta (Doust and Omotsola, 1990)

2 Materials and Methods Used

Thirteen (13) natural gas samples were collected from 13 producing gas wells in the "X" field of the Niger delta using isotubes. The integrity of the samples was confirmed through the opening pressure check. The gas samples were heated to their sampling point temperatures and analysed by the Gas chromatographic technique for their molecular composition, using GPA 2286, as a standard test method. The hydrogen sulphide contents of the samples were measured with Gastec tubes in accordance with ASTMD 4810. The carbon isotopic compositions and vitrinite reflectance were computed using the regression formulas by Berner (1989) (Equations (1), (2) and 3) and Faber (1986) (Equations (4), (5) and (6)) respectively as indicated below. The analytical results were subjected to data treatment and interpretation.

%methane=9.1ln(%Ro)+93.1…………….1
%ethane= -6.3ln(%Ro)+4.8…………… .. 2

%propane= -2.9ln(%Ro)+1.9……...…… ..3

$\delta^{13}C_{CH4}$(‰)=15.4log(10)%Ro-41.3………4
$\delta^{13}C_{C2H6}$(‰)=22.6log(10)%Ro-32.2……...5
$\delta^{13}C_{C3H8}$(‰)=20.9log(10)%Ro -29.7……..6

where, R_0 = Vitrinite reflectance of the gas generating source rock.

3 Results and Discussion

Alkane gases dominate the studied natural gases from the "X" field of the Niger Delta as indicated in Table 1, the $C_{1\text{-}5}$ gases range from 94.97% to 99.18%, with a mean value of 98.09%. The abundance of methane differs from 89.93% to 98.08%, with a mean value of 93.79%. The heavy hydrocarbon gases ($C_{2\text{-}5}$) have relatively low concentrations varying from 1.10% to 5.88% with a mean of 4.31%. The analysed natural gases are dry and of thermogenic origin ($C_1/C_{1\text{-}5}$ *100 <100) possessing gas dryness coefficients ($C_1/C_{1\text{-}5}$*100) varying from 94.23% to 98.89% with a mean of 95.61% (Bernard *et al.*, 1987; Golding *et al.*, 2013).

The stable methane carbon isotopes ($\delta^{13}C_1$) range from -43.63‰ to -37.64‰, with a mean value of -40.79‰ (Table 4.1). The mean carbon isotopic composition for the heavy hydrocarbon gases; ethane ($\delta^{13}C_2$) and propane ($\delta^{13}C_3$) are -27.47‰ and -28.15‰, respectively (Table 4.1). The plot of the relative composition of the hydrocarbon gases excluding methane, as shown in Fig. 3 provides more insights into the difference and similarities between natural gases. According to Dembicki-Jr, (2017), cross-plot of some of the hydrocarbon gas ratios is important to illustrate similarities and differences between the gases, as indicated in Fig. 3. The cross plot shows that 11 samples out of the 13 gas samples have similar patterns indicating close similarities in chemical composition, this implies that those gases are genetically related and can be said to have been generated by the same source rock at similar/same conditions of pressure and temperature. Sample S1 and S7 are widely spaced from the 11 other samples, and also conform to similar patterns different from the 11 samples. This may likely be attributed to the presence of a baffle preventing communication between the 11 wells and wells S1and S7 within the reservoir. The cross-plot of $i\text{-}C_4/n\text{-}C_4$ against C_2/C_3 indicated in Fig.4 also corroborates the findings in Fig.3.

According to Whiticar *et al.* (1986) and Hill *et al.* (2007), the heavier δ13C values obtained for the wells S1 and S7 might be due to an increase in the degree of maturity of the source rock. This is supported by their high dryness coefficients of 98.89% and 97.95% respectively (Bernard *et al.*, 1987; Golding *et al.*, 2013).

Differences in the average carbon isotopic signatures of methane, ethane, and propane contents between the gas samples taken from Wells S1, S7, and the remaining 11 wells (Table.1) suggests the presence of compartments within the "X" Field of the Niger Delta. The natural gas data were further analysed using star-diagrams (named as Gastar diagrams by Prinzhofer *et al.*, 2000) to evaluate the main processes (maturity, the efficiency of accumulation, or segregative migration) that affects the chemical and isotopic signatures of natural gases. Nine (9) geochemical parameters (C_1/C_2, C_2/C_3, $i\text{-}C_4/n\text{-}C_4$, $\delta^{13}C_1$, $\delta^{13}C_2$, $\delta^{13}C_3$, $\delta^{13}C_3\text{-}\delta^{13}C_2$, and $\delta^{13}C_2\text{-}\delta^{13}C_1$) proposed by Prinzhofer *et al.* (2000) were used as indicated in Figs. 5, 6 and 7. All of these parameters positively correlate with maturity, two parameters (the isotopic ratios differences) are linked to the efficiency of accumulation, and another two (those involving methane) are strongly affected by migration (Prinzhofer *et al.*, 2000). The gastar plots in Figs. 5 and 6 corroborate the initial findings of communication barrier between wells S1, S7, and the remaining 11 wells within the studied reservoir, which may be attributed to the presence of an impermeable geologic formation. Besides, the geochemical differences of gaseous samples from the studied reservoir support the notion of reservoir compartmentalisation. Although there exist slight differences between the isotopic and molecular composition of the remaining 11 samples, they are very close to analytical accuracy, reasonable connectivity between these wells could, therefore, be inferred

Table 1. Molecular and isotopic composition of the natural gases from the “X” field

Well	C_1	C_2	C_3	n-C_4	i-C_4	n-C_5	i-C_5	ʊ13C C_1	ʊ13C C_2	ʊ13C C_3
S1	98.08	1.02	0.05	0.02	0.01	0	0	-37.64	-26.31	-23.91
S2	93.83	1.74	1.68	0.43	0.65	0.21	0.17	-40.76	-27.43	-29.01
S3	94.61	1.57	1.17	0.29	0.44	0.14	0.12	-40.19	-27.17	-27.42
S4	92.82	2.26	1.89	0.48	0.69	0.22	0.15	-41.51	-28.21	-29.98
S5	94.86	1.28	1.59	0.38	0.53	0.16	0.13	-40.01	-26.72	-28.73
S6	91.82	2.30	1.98	0.49	0.72	0.23	0.16	-41.51	-28.21	-29.98
S7	96.76	1.43	0.31	0.08	0.12	0.05	0.04	-38.61	-26.95	-24.72
S8	93.7	2.34	1.55	0.37	0.58	0.21	0.16	-40.86	-28.37	-28.60
S9	93.33	1.69	1.66	0.41	0.61	0.18	0.15	-41.13	-27.35	-28.95
S10	89.93	1.89	1.6	0.4	0.58	0.17	0.14	-43.63	-27.67	-28.76
S11	93.82	2.24	1.99	0.47	0.70	0.19	0.16	-41.51	-28.21	-29.98
S12	94.86	1.28	1.59	0.38	0.53	0.16	0.13	-40.01	-26.72	-28.73
S13	90.9	1.98	1.1	0.27	0.43	0.16	0.13	-42.92	-27.81	-27.20

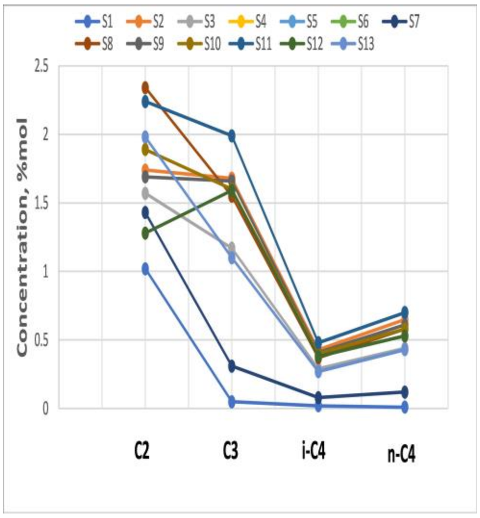

Fig. 3 Comparison of C_2–C_4 gas composition for use in gas-to-gas correlation (Dembicki Jr., 2017)

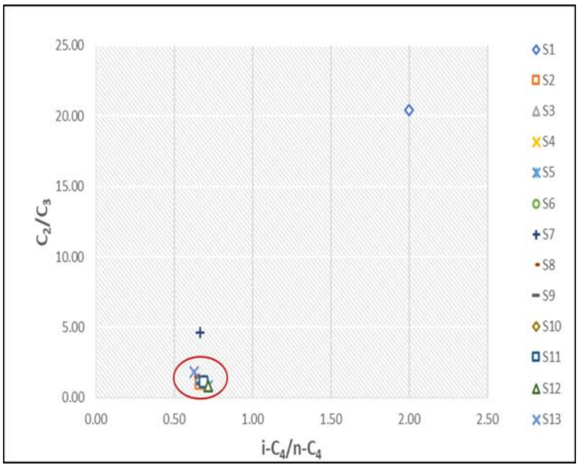

Fig. 4 Cross-plot of i-C_4/n-C_4 against C_2/C_3 in gas-to-gas correlation (Dembicki-Jr., 2017)

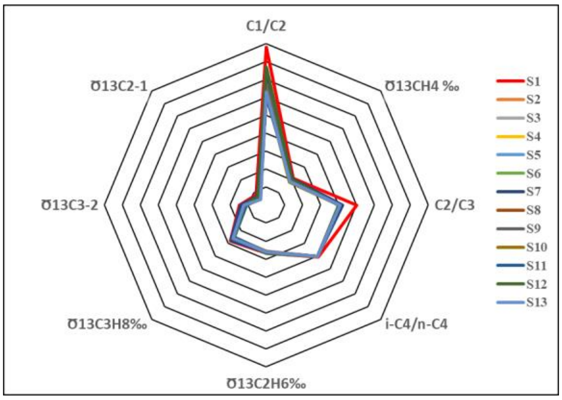

Fig. 5 Star diagram display of molecular and isotopic fingerprint of the “X” field natural gases (Prinzhofer et *al.*, 2000)

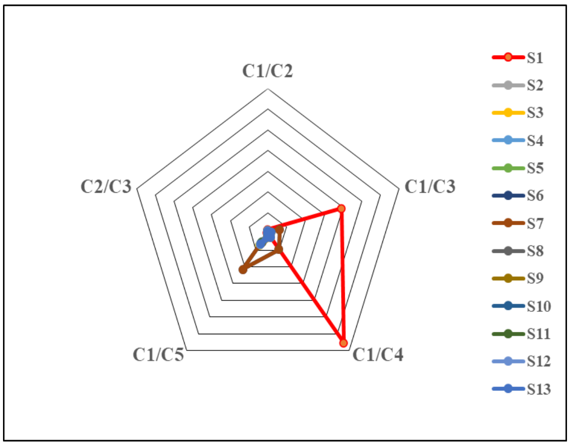

Fig. 6 Star diagram display of molecular fingerprints of the “X” Field natural gases (Prinzhofer et *al.*, 2000)

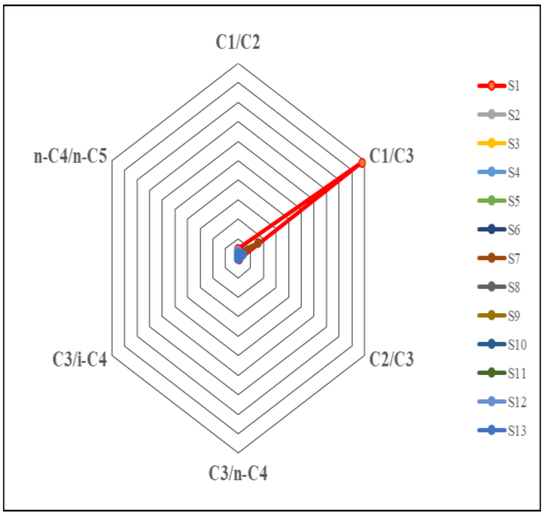

Fig. 7 Star diagram display of multi-parameter geochemical fingerprint of the "X" field natural gases (Prinzhofer et *al.*, 2000)

4 Conclusions

The results indicate similar molecular and isotopic composition for 11 wells at different locations of the reservoir except for wells S1 and S7. The similarity in the molecular and isotopic composition of the natural gases for the 11 wells suggests that those wells are communicating but there exists an impermeable geological formation which impedes communication between those wells and wells S1 and S7. The studied natural gases from the "X" Field of the Niger Delta are genetically related and may have been generated by the same source rock. The difference in molecular and isotopic composition between the natural gases from the 11 wells and wells S1 and S7 infers a baffle, impeding fluid communication between wells S1, S7 and the remaining wells.

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