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ORIGINAL RESEARCH ARTICLE

Assessment of Three Non-Linear Approaches of Estimating the Shale Volume Over Yewa Field, Niger Delta, Nigeria

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ABSTRACT
Accurate shale volume estimation is an important approach in reservoirs characterization as it forms the basis upon which evaluators can ascertain the hydrocarbon content of the reservoirs. The porosity, gamma ray, neutron-density and deep induction logs data were used to arrive at suitable shale volume estimates of the field studied. Analysis of well logs data was done using the TECHLOG Exploration software. Delineation of reservoirs was carried out with OpendTect software. The Microsoft excel spreadsheet was utilized to accurately estimate other suitable petrophysical parameters such as the permeability, water saturation, hydrocarbon saturation and the porosity. Three different non-linear shale volume models, the Larionov, the Steiber and the Clavier models were used to determine the reservoirs' shale content across three wells of Yewa reservoirs characterized by varying thicknesses. Variation in the depths down hole for each of the methods revealed that shale volume estimates with the Larionov model was determined across thickness 142.646 m with top and bottom depths of 1946.605 m and 2089.252 m respectively in well Y1, thicknes 90.678 m with top and bottom depths of 2164.690 m and 2255.368 m respectively in well Y2 and thickness 107.290 m with top and bottom depths of 2303.374 m and 2410.663 m respectively in well Y3. The estimates with Steiber model were respectively determined across thicknesses 85.649 m, 95.098 m and 121.371 m for Y1, Y2 and Y3 reservoirs, and top and bottom depths of 1947.571 m and 2033.219 m in well Y1, 2041.754 m and 2136.851 m in well Y2 and 2144.979 m and 2266.442 m in well Y3 and the one with Clavier model were respectively determined across thicknesses 146.456 m, 147.752 m and 94.869 m for Y1, Y2 and Y3 reservoirs and top and bottom depths of 1760.601 m and 1907.057 m in well Y1, 1920.312 m and 2068.068 m in well Y2 and 2078.812 m and 2173.681 m in well Y3. The lowest shale volume average estimate was recorded from the Larionov model. Nevertheless, one cannot conclude that the Larionov model is the most reliable as values obtained may be because of instability in the sensitivities of utilized well logs and the complexities in the properties of wells down hole. A further investigation of the sensitivities of the well logs and the down hole properties of the wells showed that the Larionov method gives reasonable, consistent, and repetitive intervals when compared with the Steiber and the Clavier models. The Larionov model is hereby recommended for use in the study area.

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INTRODUCTION
Well logs are two-dimensional plots revealing various values of petrophysical parameters against corresponding depth and presented in signatures which can be interpreted (Shaaban and Ahmed, 2014). Well logs interpretation is very critical in accurately estimating petrophysical parameters such as shale volume (V_{sh}), water saturation (S_w), hydrocarbon saturation (S_h), porosity (φ) (Zhao *et al.*, 2016). Shale is made up of grainy, fine, broken sediment revealing high potential of fissility and composed of sticky soft, thin, flat smooth matters. Shale is composed of six percent feldspars, two percent iron oxide, five percent trioxocarbonate minerals, twenty-eight percent quartz and fifty-eight percent clay (Adepehin *et al.*, 2022). The shale volume is one of the most fundamental and basic

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reservoirs properties that are needed to clearly determine the actual shale content in the hydrocarbon (HC) reservoirs (Adepehin *et al.*, 2022). This is very essential in estimating accurately, other geophysical (petrophysical) parameters such as water saturation, effective porosity, permeability and Net to Gross thickness which are instrumental and germane in determining the (hydrocarbon) HC potential, quality of reservoirs and realistic estimation of HC reserves (Omoja and Obiekezie, 2021). Estimation of the reservoir shale volume can be done with different models which have been well explained in literatures. The (Larionov, 1969), the (Steiber, 1970) and (the Clavier *et al.*, 1971) models were used to estimate the reservoir shale volume across different thicknesses down hole. Generally, Shale volume is estimated utilizing the γ **−ray logs,** as they are direct measurements of reservoir shale radioactive content (Al-Azazi and Albaroot 2022). This doesn't imply that other well logs signatures do not show records of the existence of shale, it only means that they cannot be easily interpreted as the ones done with only γ **−ray** logs (Boldyrev *et al.,* 2022). The Niger Delta basin is highly rich in petroliferous products. It is made up of spacious sources rocks which are capable of harboring hydrocarbon and other reservoir fluids (Adepehin *et al.*, 2022). The Niger Delta reservoirs are majorly characterized by high volume of petroliferous crudes which are recoverable with engineering techniques that best suit the field of study (Avbovbo, 1978). There exist reasonable deposits of hydrocarbon that can be commercialized in the Niger Delta basin and an accurate estimation of the shale volume will no doubt assist in making reasonable decisions before exploration (Ejedawe, 1981). Estimation of the V_{sh} is an important step in evaluating a formation. It is the ratio of the total quantity of clay alongside other particles (silts) to the entire volume of rock (Al-Azazi and Albaroot 2022). Shale exists in three different forms in a formation (Igbal and Rezaee,2020). They occur as particles dispersed in the pores or laminated particles in the layers or minerals contained in the structural matrix of the rocks. Stratified formations are made up of different quantity of shale. Theoretically, shale volume estimate falls within 0 to 1 or 0 to 100% (Igbal and Rezaee,2020). Kamel and Mabrouk, (2003) developed an equation for estimating the shale volume from the porosity logs examples of which include acoustic, density and neutron logs. The developed equation is based on different parameters made accessible from the logs (Kamel and Mabrouk, 2003). Some of these parameters are the matrix effects, the fluid nature and the inherent shaly parameters. Shale presence in reservoirs with permeable rocks, if not accurately computed will result to wrong estimation of the acoustic or neutron porosity and this can as well result to wrong behaviors of other logs (Baiyegunhi *et al.,* 2022). Many log-originated shaliness are now being employed to determine shaliness estimated from information provided from one or more than one well (Baiyegunhi *et al.,* 2022). The use of more than one shaliness indicator often time yields reliable shale volume estimate when compared to when a single indicator is used (Baiyegunhi *et al.,* 2022). Every used indicator is capable of giving the actual or the upper limit of the value of the shale content. The least value of this limit is most time taken as the actual value of the shale volume, although other factors may be responsible for the decrease in the estimated value but this may be corrected with another non-linear approach of shale volume estimation (Ejieh and Ideozu, 2018). Reservoir rocks can be said to be clean if the shale volume is less than 10%. If the shale volume is greater than 10% but less than 34%, the rocks can be termed shaly (containing some quantities of shale), Shale volume up to or greater than 34% reveals a pure shale formation (Szabo *et al.,* 2021). Knowing the volume of shale will help the reservoirs analysts to correctly predict other petrophysical parameters which are also important in ranking a reservoir (Pandey *et al.*, 2020). Adequate knowledge of the shale content of a reservoir also assists in accurate assessment of the quality of the rocks and this will in turn determine the hydrocarbon content of the reservoir (Pandey *et al.*, 2020). Data obtained from the neuton-density, resistivity and spontaneous logs can be employed in estimating the volume of shale but the γ-ray log has overtime been used and it has stood out among other methods of estimating the reservoir V_{sh} (Kamayou *et al.*, 2021). When two or more non-linear shale volume estimation models are compared, it is normal to experience one out of the models which stands out in terms of producing low, consistent and reliable estimates which best suit the study area (Kamayou *et al.*, 2021). This can be determined by first interpreting the well logs and then employs the interpretation to estimate the shale volume. The linear approach works on the assumption that only clay and shale minerals are contained in the formation (Zagana *et al.,* 2022). The assumption on which the linear shale volume approach works often time overestimate the reservoir shale volume in areas which are also composed of other inherent radioactive materials (Szabo and Dobroka, 2013). The (Larionov, 1969), the (Steiber, 1970) and the (Clavier *et al.*, 1971) methods are non-linear approaches well defined for particular ages of formation and geographical locations. Based on the peculiarity of the study area, these models are well designed to mitigate the deficiencies inherent in the linear approach. It is right to mention that the Larionov, 1969 model stood out among the non-linear methods of estimating the reservoir shale volume because it gives the lowest, comparable and consistent estimates when compared to the Steiber, 1970 and the Clavier *et al.*, 1971 models. Although,the Larionov, 1969, the Steiber, 1970 and the Clavier *et al.*, 1971 models are all still accompanied by traces of radioactive contents inherent in the chemical build-up of the reservoirs which can unconsciously make evaluators overrate the reservoirs, nevertheless, errors inherent in them cannot be compared to that of the linear method. The lowest value recorded with the Larionov, 1969 model doesn't translate to the approach being the most reliable as values may be as a result logs sensitivities fluctuation. The three non-linear models depend on the estimated I_{GR} originating from the linear approach. The usual practice of utilizing the most reliable γ-ray log of the area under study for I_{GR} estimation is usually accompanied by very high level of errors and uncertainties. Overtime in the Niger Delta region of Nigeria, exploration processes have been done first by having an in-depth knowledge of the reservoir V_{sh} but these estimations have been accompanied by various uncertainties and irregularities due to radioactive elements (minerals) in the formation and so there's an urgent need for a method that will minimize or totally eradicate the uncertainties. This research work seeks to compare three non-linear models "the Larionov, 1969, the Steiber, 1970 and the Clavier *et al.*, 1971" models of estimating the shale volume using well log data from "Yewa" field, Niger Delta, Nigeria and predict the most reliable and consistent model based on stable sensitivities of the well logs in the study area. Findings of this work will assist reservoirs engineers and evaluators to better assess reservoirs before taking decisions on exploration.

Study Area

The study area is a basin located in the Niger Delta. The identified field "Yewa" occurs within respective latitudes and longitudes ($5^{\circ}49' N$ and $6^{\circ}78' N$) and ($6^{\circ}59' E$ and $6^{\circ}66' E$). Figures 1 and 2 show the geology and map of the studied location respectively. The geology of the subsurface of the location clearly shows that of hydrocarbon zone located in the Niger Delta region of Nigeria (Asubiojo and Okunuwadje, 2016). Well bored in the location enhances the procurement of geophysical wireline well logs used for this research (Aigbadon *et al.,* 2022). The Niger Delta is a basin which is majorly characterized by clastic stratified deposits which can be traced to formation from the recent Eocene through the evolution of the Paleocene to the evolution of the early Pre-santonian depression (Aigbadon *et al.,* 2022). The Niger Delta stratigraphy comprises of the Akata, Agbada and the Benin formations which are respectively made up of potential source rocks, reservoirs at certain depth in water and minor quantity of silt and shale, sequences alternated by partly sandstones and partly shale, dividing-channels and deltaic originating plains and gravels and sand (Iheaturu *et al.,* 2022).

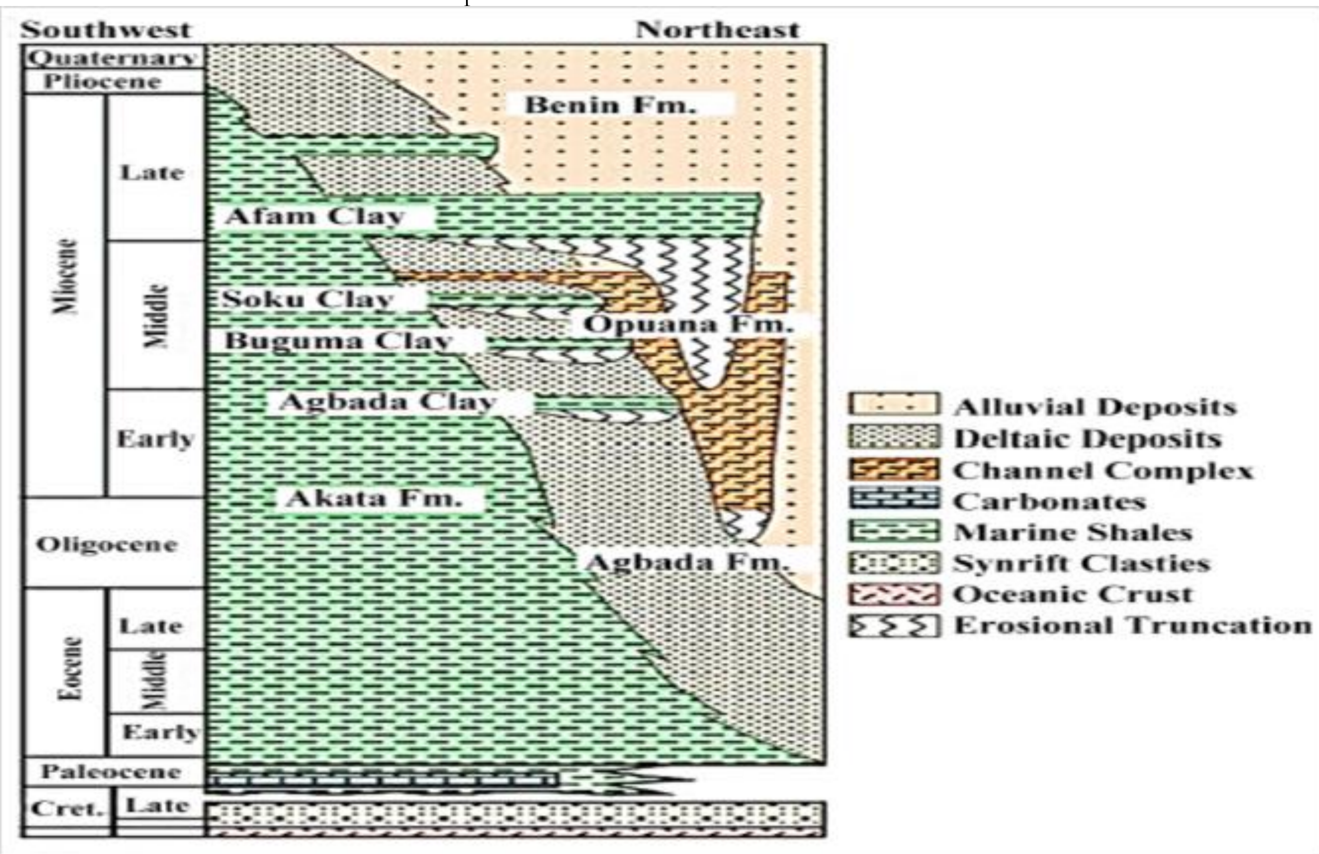

Figure 1: Niger Delta Litho-stratigraphy

MATERIALS AND METHODS

Three wells Y1, Y2 and Y3 in Yewa field were identified and seven different types of geophysical logs which include the caliper, sonic, spontaneous potential, resistivity, neutron, density and gamma ray logs were utilized for this research (Table 1). TECHLOG Exploration software and Microsoft excel spreadsheet were utilized for the analysis of data. Reservoirs' delineation was done with the OpendTect software to eliminate wrong or null values.

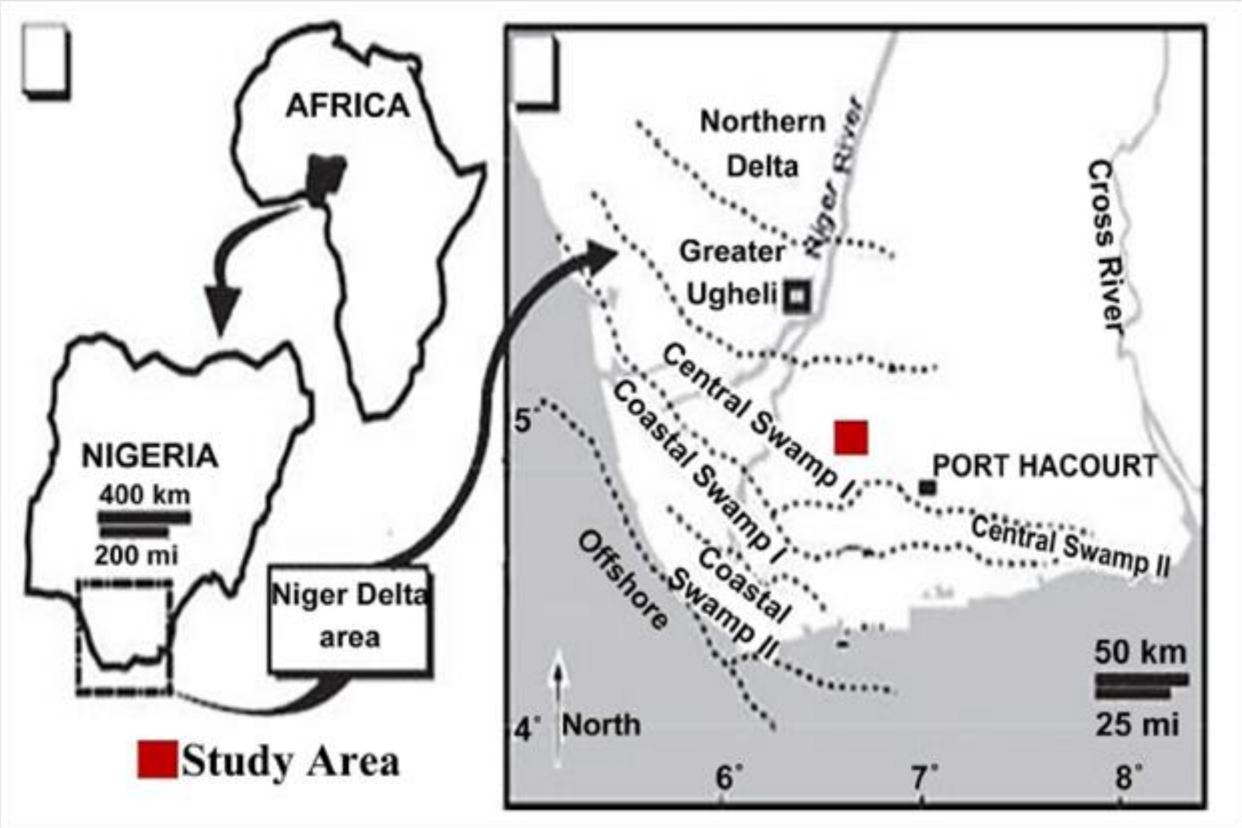

Figure 2: Map of the Studied Location

Table1: Suites of available well logs

Name	Caliper	Sonic	Spontaneous Potential	Resistivity	Neutron	Density	Gamma Ray
Y1	P	P	P	P	P	P	P
Y2	P	P	A	P	P	P	P
Y3	P	P	P	P	P	P	P

P= Present, A= Absent

The lithology was identified to distinguish between the shale and sand bodies. The γ-ray log was employed to determine the shale volume. The shale volume computation was done across the intervals mapped out in Yewa reservoirs with three non-linear models. These are the Larionov, the Steiber and the Clavier models. The three non-linear models were chosen based on the peculiarity of the study area and the fact that they do not assume that the formation contained only clay and shale minerals but rather mitigate the deficiencies inherent in the linear models. Despite the long year these models have been invented, they proved to be more effective in the study area and this explains why they were adopted for this study. The γ-ray index (I_{GR}) for clean and tertiary reservoir rocks were estimated as their values will be required to estimate the shale volume. The relation shown in equation 1 is used to estimate the gamma γ-ray index (Al-Azazi and Albaroot 2022).

$$I_{GR} = \frac{\gamma_{ray} - \gamma_{ray\ matrix}}{\gamma_{ray\ shale} - \gamma_{ray\ matrix}} \quad (1)$$

Where,

I_{GR} = γ_{ray} index

$\gamma_{ray} = \gamma\ ray\ reading$ (log reading)

$\gamma_{ray\ shale}$ = γ_{ray} reading in a formation of (100%) shaliness

$\gamma_{ray\ matrix}$ = γ_{ray} reading in a formation of (100%) clean rock

Estimation of Volume of Reservoir Shale

Records from research show that Niger Delta hydrocarbon reservoirs are majorly sand from the Agbada formation. Nevertheless, some elements of shale deposits still exist alongside the dominant sandstones (Mode *et al.*, 2013). This little element of shaliness has the ability to determine the hydrocarbon content of the reservoirs significantly (Mkinga *et al.,* 2020). The shale volume is estimated from the three aforementioned models as follows:

Larionov model of 1969

$$V_{shLarionov} = 0.083(13 I_{GR} - 1) \quad (2)$$

Steiber model of 1970

$$V_{shSteiber} = \frac{\gamma_{ray} Index}{3 - (2\gamma_{ray} Index)} \quad (3)$$

Clavier *et al* model of 1971

$$Vsh_{Clavieretal} = \sqrt{[1.7(3.38 - (I_{GR} - 0.7)^2} \quad (4)$$

Where,

$V_{shLarionov}$ = Larionov shale volume for tertiary rock

$V_{shSteiber}$ = Steiber shale volume for tertiary rocks

$Vsh_{Clavieretal}$ = Clavier *et al* shale volume for tertiary

$I_{GR} = \gamma - ray$ *Index*

The Non-Linear and the Linear Shale Volume Estimation

The non-linear shale volume estimation models such as the Larionov, the Steiber, and the Clavier *et* models are meant for particular geographical characteristics which are also common in the study area. These models respond only to a particular age of rocks in the formation. The linear approach is designed not for particular geographical prevalent characteristics but rather for all existing characteristics of the formation. The prevalent radioactive characteristics in the formation is one of the reasons, the non-linear approach gives lower V_{sh} than the linear approach (Adepehin *et al.*, 2022). Nevertheless, the two methods require γ-ray response across a planned depth down hole and determination of $\gamma -$ ray index (I_{GR}) for reservoirs with clean rocks with no traces of shale and that of 100% shale zones (Pico and Salina, 2017).

RESULTS AND DISCUSSION

Five potential reservoirs were identified from each of the Yewa wells, Y1, Y2 and Y3 all of which were respectively labeled as RSV1, RSV2, RSV3, RSV4 and RSV5. Analysis of the five mapped out reservoirs was done using geophysical well logs. All the five identified reservoirs RSV1, RSV2, RSV3, RSV4 and RSV5 were correlated across all the three Yewa wells, Y1, Y2 and Y3. Each of the shale volume estimation models were tested across varying thickness in each of Y1, Y2 and Y3. The Larionov, the Steiber and the Clavier models were respectively examined across the thicknesses of (142.646 m, 90.678 m and 107.290 m), (85.649 m, 95.098 m and 121.371 m) and (146.456 m, 147.752 m and 94.869 m) for Y1, Y2 and Y3 wells. The variation in the thicknesses at which these models were examined was to determine the consistency of each of them, so as to take decision on which of them best suit the area studied. The reservoirs thicknesses for all the wells were determined by subtracting the top from the bottom. Table 2 shows the reservoirs thicknesses across Y1, Y2 and Y3 wells. Figure 3 shows geophysical log correlation across all the wells.

Table 2: Variation in Reservoirs Thickness Across the Wells for All the Models

Well	Depth (m)	Larionov model	Steiber model	Clavier model
Y1	Top	1946.605	1947.571	1760.601
	Bottom	2089.252	2033.219	1907.057
	Thickness	142.646	85.649	146.456
Y2	Top	2164.690	2041.754	1920.312
	Bottom	2255.368	2136.851	2068.068
	Thickness	90.678	95.098	147.752
Y3	Top	2303.374	2144.979	2078.812
	Bottom	2410.663	2266.442	2173.681
	Thickness	107.290	121.371	94.869

Figure 3: Geophysical log correlation across all the wells.

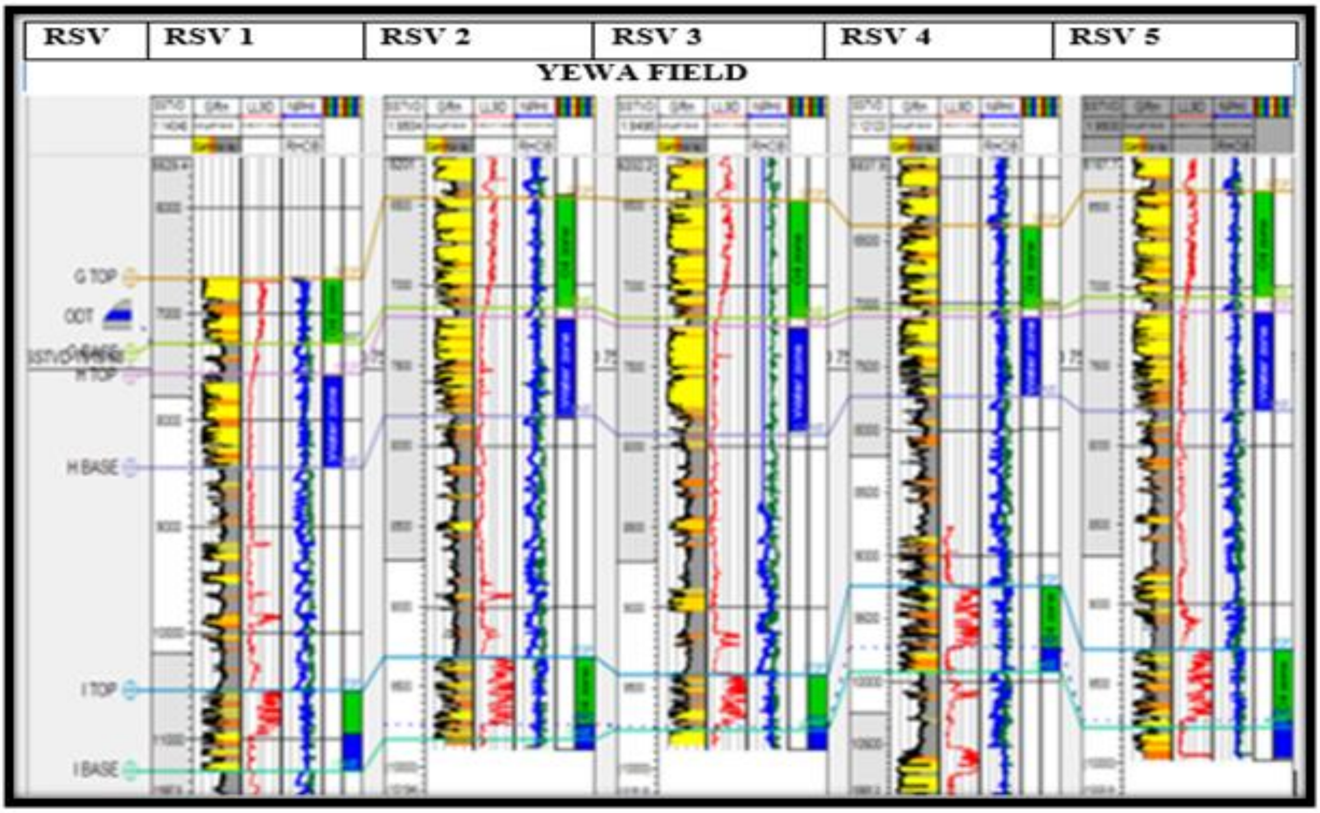

Figure 4: Log showing Reservoirs Thicknesses in Yewa Field

Discussion on the Reservoir Shale Volume

Table 3, 4 and 5 show the reservoirs shale volume obtained respectively with the Larionov, Steiber, and Clavier models. There is an increase of shale as depth increases in Yewa field. This is in line with the research done by (Kamayou *et al.*, 2021). The formation of Agbada in the Niger Delta was described as shale-sand intercalation. The Larionov model of shale volume estimation gives the lowest in tables 3, 4 and 5. The Gamma-ray index is denoted by (IGR) and the unit of measurement of shale volume - voids per volume is denoted by (v/v)

Table 3: Shale Volume from the Larionov, the Steiber and the Clavier Estimation Models Yewa 1

Reservoir	IGR (v/v)	Larionov V_{sh} (v/v)	Steiber V_s (v/v)	Clavier V_{sh} (v/v)
RSV 1	0.269	0.084	0.110	0.139
RSV 2	0.279	0.088	0.115	0.145
RSV 3	0.348	0.131	0.159	0.198
RSV 4	0.301	0.104	0.131	0.163
RSV 5	0.336	0.122	0.151	0.188

Figures 5 and 6 show that the Larionov model of shale volume estimation gives lower and consistent estimate when compared to the Steiber and the Clavier models. The Steiber estimation model produced estimates higher than that of the Larionov but less than that of the Clavier. It is worthy to mention that the use of other estimation models apart from the Larionov model in the study area is likely to overrate the shale content of the reservoirs and this can as well affect the judgments of reservoirs engineers in ranking the reservoirs for the production of hydrocarbon. This is in line with the work of Kamayou *et al.*, (2021). The work was based on estimating the volume of shale using different estimation models across different reservoir thicknesses in a field of Niger Delta known as VIA. They however concluded that the Larionov estimation model is the best for use in the area studied.

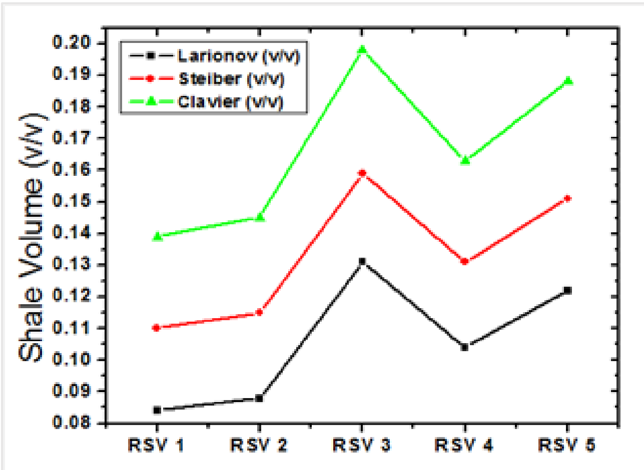

Figure 5: Comparison of Shale Volume Estimation Models in Yewa 1

Nosrati *et al*., (2014) estimated the shale volume using the combination of sonic, density and neutron logs in a trioxocarbonate succession. Results obtained from (Nosrati *et al*., 2014), further showed that the γ-ray log method gives a more reasonable value when compared to that of the porosity log.

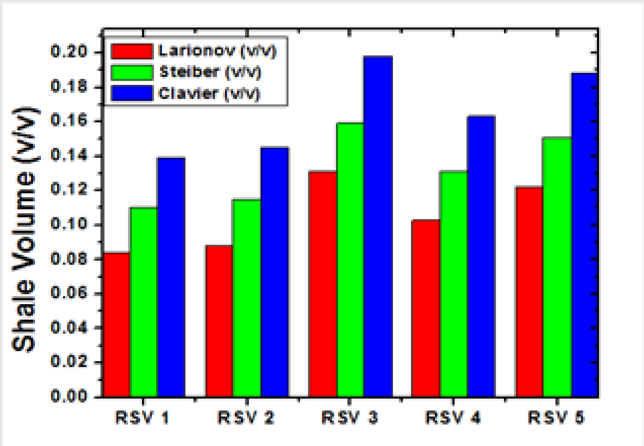

Figure 6: Relationship Between the Larionov, the Steiber and the Clavier V_{sh} Models in Yewa1

Table 4: Shale Volume from the Larionov, the Steiber and the Clavier Estimation Models Yewa 2.

Reservoir	IGR (v/v)	Larionov V_{sh} (v/v)	Steiber V_{sh} (v/v)	Clavier (v/v)
RSV 1	0.149	0.040	0.056	0.071
RSV 2	0.195	0.058	0.078	0.098
RSV 3	0.177	0.051	0.070	0.088
RSV 4	0.212	0.072	0.091	0.113
RSV 5	0.211	0.070	0.090	0.112

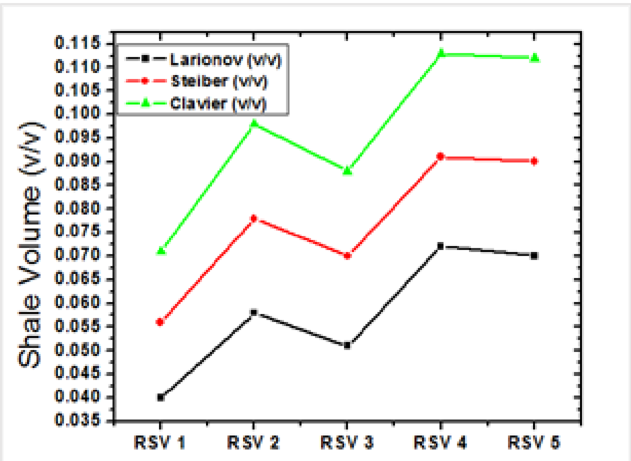

Figure 7: Comparison of Shale Volume Estimation Models in Yewa 2

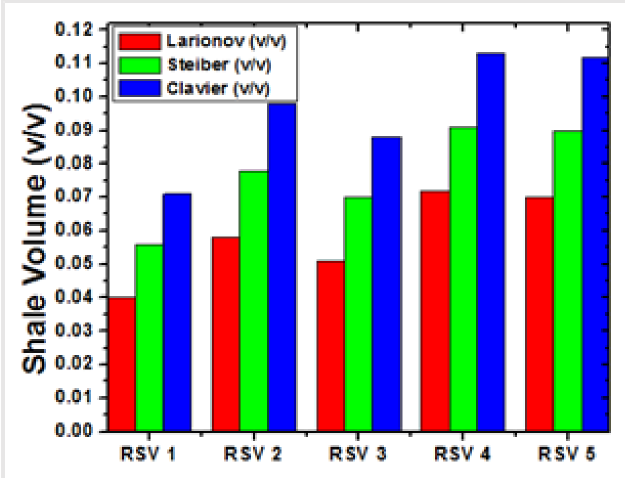

Figure 8: Relationship Between the Larionov, the Steiber and the Clavier V_{sh} Models in Yewa2

Figures 7 and 8 showed that the Larionov estimation model gives the least value when compared to that of the Steiber and the Clavier models. The Larionov estimation model ranges from 0.04 v/v to 0.07 v/v for RSV 1, RSV 2, RSV 3, RSV 4 and RSV 5 (Figures 7 and 8). The Steiber estimation model gives shale volume values which range from 0.055 v/v to 0.09 v/v for all Yewa reservoirs. The Clavier estimation model produces values of shale volume in the range of 0.07 v/v to 0.11 v/v for all identified reservoirs in the study area. Similar to the result obtained in Yewa 1, the Larionov estimation model gives the lowest, consistent and realistic estimates for all the reservoirs. (Moradi *et al*., 2016) determined the shale volume distribution pattern in CO_3^{2-} gaseous reservoirs using gamma-ray log and core analysis. Results obtained from the (Moradi *et al*., 2016) work was used to estimate the reservoir permeability and porosity in order for decisions to be taken as regards the HC potential of the reservoir. (Adepehin *et al*., 2022) worked on the effect of shale volume on the hydrocarbon potential of Green field in Niger Delta using geophysical well logs. The Green field is however concluded to be high in hydrocarbon as the shale volumes for all the five identified reservoirs were discovered to be very low.

Table 5: Shale Volume from the Larionov, the Steiber and the Clavier Estimation Models Yewa 3.

Reservoir	IGR) in (v/v)	Larionov V_{sh} (v/v)	Steiber V_{sh} (v/v)	Clavier V_{sh} (v/v)
RSV 1	0.021	0.004	0.007	0.009
RSV 2	0.042	0.006	0.010	0.013
RSV 3	0.025	0.005	0.009	0.012
RSV 4	0.039	0.009	0.014	0.017
RSV 5	0.041	0.009	0.015	0.018

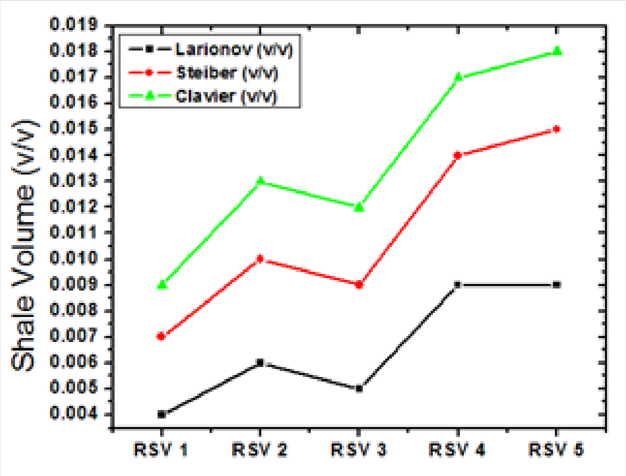

Figure 9: Comparison of Shale Volume Estimation Models in Yewa 3

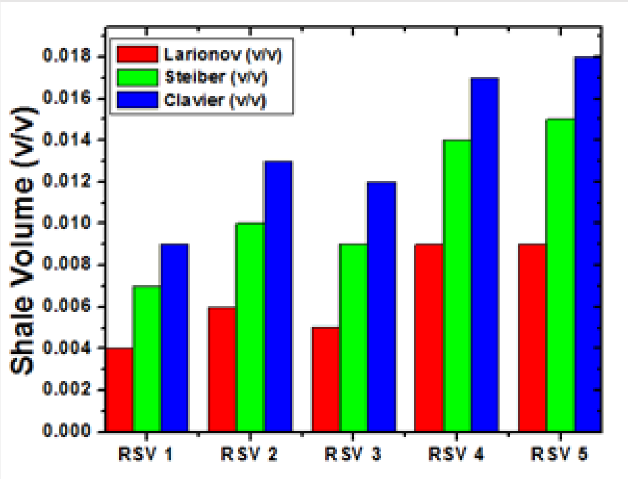

Figure 10: Relationship Between the Larionov, the Steiber and the Clavier V_{sh} Models in Yewa3

Similar to Yewa 1 and 2 in figure 9 and 10, Yewa 3 produces shale volume estimate that is highest with the Clavier model, higher with the Steiber model and lowest with the Larionov model. The Larionov (Non-linear) model gives estimates that range from 0.004 v/v to 0.0085 v/v for all the Yewa 3 reservoirs. The Steiber shale volume estimation model produces values ranging from 0.0065 v/v to 0.0145 v/v for all the Yewa 3 reservoirs. The Clavier estimation model gives the highest shale volume estimates which range from 0.0085 v/v to 0.018v/v for all the Yewa 3 reservoirs. The Larionov estimation model gives the lowest, consistent, repetitive and realistic estimates when compared to the two other estimation models. The work of (Adjei *et al.*, 2019) is similar to the findings of this research. They focused on probabilistic estimation of the shale volume using three different softwares in a hydrocarbon basin in Bornu, Nigeria. Result from the (Adjei *et al.*, 2019) showed that probable values can be obtained for the shale volume as the V_{sh} estimate in a particular reservoir when gamma ray method is considered between two upper intervals of shale.

Results obtained from all the Yewa reservoirs which established the Larionov model as the most appropriate in the study area as it gives the lowest shale volume correlate with that of previous works from (Nosrati *et al.*, 2014), (Moradi *et al.*, 2016), (Adepehin *et al.*, 2022) and (Adjei *et al.*, 2019). Petrophysical evaluation of reservoirs shows that a low shale volume is a clear indication of high hydrocarbon potential and this is line with the result of this research. Adopting the Larionov shale volume estimation model in the study area means that there exist other minerals such as sand apart from clay and shale in the field. The three chosen non-linear models work with particular ages of rocks which are prevalent in the study area.

CONCLUSION

Five reservoirs were identified and correlated across the Yewa field. There exist variations in thicknesses of the reservoirs across the field. These thicknesses are substantial enough to be reconsidered for future developmental decision. The interbedded zones of the reservoirs are made up of minor shale intercalations which are capable of impeding fluid flow. The entire delineated reservoirs were observed to contain oil alongside some water. Some correlated intervals show minor presence of oil and this can be attributed to high shale and water deposits.

Careful assessment of three non-linear shale volume estimation models – The Larionov, the Steiber and the Clavier models shows that the Larionov model gives the lowest, consistent and repetitive shale volume when compared to the other two. This is because of the peculiarity of the study area and the reasonable values obtained from the model. Petrophysically, the Yewa reservoirs have substantial hydrocarbon deposits in the subsurface porespaces and the producibility determinants are reasonable enough to facilitate secondary migration of these deposits into the borehole, if improved upon.

Results obtained from this work show that the Larionov (Non-linear) estimation model eradicates the uncertainties common with the linear model and gives the lowest estimates for RSV 1, RSV 2, RSV 3, RSV 4 and RSV 5 in Yewa 1, Yewa 2 and Yewa 3 reservoirs. As low shale volume estimate is a clear indication of high porosity, permeability and hydrocarbon content, the Larionov (Non-linear) model is however recommended for use in the area studied.

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