Petrophysical Analysis and Sequence Stratigraphy Appraisal from Well logs of ‘Bobo’ field, South-Eastern, Niger Delta

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Abstract
This work highlights the importance of Petrophysics to hydrocarbon exploration and the relationship between petrophysical variables and the associated depositional environment as they are sought to be established from correlation of petrophysical properties with sequence stratigraphy. Petrophysical analysis began with lithology identification where it was established from well logs assessments that the study area is characterized by sand-shale interbedding having brief serrated wiggles and multiple parasequences stacked within the main sequences. The reservoirs formations were interpreted for their fluid content using appropriate logs. In all, three hydrocarbon bearing sands were discovered, and porosity estimates in the reservoirs were very high varying between 0.19 and 0.39 suggesting good economic opportunities. Sequence stratigraphic interpretation was carried out to interpret the depositional environments around the area using well log motifs. The interpretation shows three main categories of depositional environments that are dominant in the area and these include: coastal deposits and pro-delta sands, shoreface sands and reworked sandstones, slope fan and the basin floor fan environment. It is predicted that the shoreface sands and reworked sands are the best region of hydrocarbon accumulation. The interpretation model is that the fluvial system flushes abundant clay to fine sand onto the delta front. These fine sediments in all probability are reworked by marine processes of moderate wave energy. This in the region has been predicted to be one of the contributing factors for the hydrocarbon accumulation observed in the area.

Keywords: Petrophysics, depositional environment, sequence stratigraphy, reservoir, porosity

INTRODUCTION
In an oil prone area like the Niger Delta, even though Hydrocarbons are within the subsurface, they cannot impulsively gush to the surface when penetrated by a production well (Aigbedion and Iyaiy, 2007). On the contrary, most reservoir hydrocarbons reside in the microscopic pore spaces or open fractures of sedimentary rocks like sandstones. To produce them, detailed geological, petrophysical knowledge and data are needed to guide the placement of production platforms and well paths (Stat Oil Research Group, 2003). This can consequently help to optimize hydrocarbon recovery, and to improve predictions of reservoir performance.

Well-log sequence stratigraphy on the other hand, being an integral part of well-log seismic sequence stratigraphy allows the geoscientists to divide a rock section into series of genetic units bounded by condensed section and their associated maximum flooding surface using wire line log signatures (Nton and Esan, 2010, Rotimi, 2010, Vail, 1977). Each sequence can be sub-divided into smaller sediment packages called systems tracts on the basis of characteristic well-log patterns (Ola-Buraimo et al., 2010). Sequence analysis and system tract study allows the prediction of the environment of deposition and this can be related to the petrophysical property values obtained. The study is aimed at solving the assumptions that stems from connecting reservoir stratigraphy with rock properties. The main objective of this work is for assessment of hydrocarbon potential in the field by petrophysical inference and analysis, and subsequently in the Niger Delta, shaliness (which is a measure of the cleanliness of the reservoir) is a parameter to be considered as it can give a wrong impression of estimated petrophysical values like porosity and hydrocarbon saturation when they are not corrected for (Aigbedion and Iyaiy, 2007).

In addition, studying the spatial uniformity of the saturating reservoir fluids can be crucial to oil and gas production (Schlumberger, 1989). Petrophysics can, thus be used to study the lateral change in content of fluids as it helps presume the lateral continuity or extent of the reservoir when seismic data is not available (Adeoye and Enikanoselu, 2009). This thus mitigates failure in hydrocarbon exploration. Therefore estimates of lithology, fluid content and porosity are indispensable. Also in the evaluation of clastic reservoirs such as obtained in the Niger Delta, shaliness (which is a measure of the cleanliness of the reservoir) is a parameter to be considered as it can give a wrong impression of estimated petrophysical values like porosity and hydrocarbon saturation when they are not corrected for (Aigbedion and Iyaiy, 2007).

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Identification of depositional environments to infer relationships between petrophysical values and the depositional environment of the area. It is thought that through this, the lateral variations in petrophysical values may be explained, and there would be a better understanding of the significance of petrophysics to exploring hydrocarbon in terrain similar to the study area.

**MATERIALS AND METHODS**

The area of study is located in the southeastern part of Niger Delta (Fig 1). These includes LAS format of composite well logs comprising mainly gamma ray, resistivity, volume of shale, density and neutron logs from three wells. Schlumberger’s Petrel software was used to interpret the data. A typical gamma ray well log through the Agbada Formation in BOBO field has values that are very high near the base of the Formation. In the upper part of the successions, within the Benin Formation gamma ray values are generally low.

Gamma-ray logs measure natural radioactivity in formations (Schlumberger 1989), therefore enabling qualitative identification of zones of shale (interpreted from high gamma readings) and sand (low gamma readings). A gamma ray log cutoff value of 70API was chosen after proper visual examination of log signatures. High gamma ray values between 80-150 API units were classified as shale intervals. On the other hand intervals with low gamma ray values that fall below 70 API units were considered sand units. In Niger-Delta, the sand units are regarded as the reservoir units because shale is not porous and permeable enough to host, retain and release fluid.

![Study area](image)

**Fig 1:** Study location and base map of the study area.

Therefore in the sand units delineated, differentiation between reservoir fluids (hydrocarbon and water) was done using the resistivity log. Since the resistivity of hydrocarbon is higher than that of the formation water (Schlumberger 1989), hydrocarbon sand units were inferred from high resistivity values observed from the deep resistivity reading tool log available (Rouns) which measures the uninvaded zone resistivity (true formation resistivity).

Porosity values for the identified hydrocarbon reservoirs were estimated. The porosity log utilized was the bulk density log which records only the bulk density of the formation; therefore, density porosity was estimated using equation from Asquith (2004) for the intervals of interest (hydrocarbon bearing intervals).

\[
\phi = \frac{(\ell_{ma} - \ell_{b})}{(\ell_{ma} - \ell_{f})}
\]  

(1)

Where:

- \(\ell_{b}\) = Measured bulk density from log,
- \(\ell_{f}\) = fluid density (flushed zone),
- \(\ell_{ma}\) = rock matrix density.

Because of the considerable presence of shale in the reservoirs, the measured porosity was corrected for the volume of shale using Dewan (1983):

\[
\phi_{cor} = \phi_a - V_{sh} \phi_{sh}
\]

(2)

where

- \(\phi_{cor}\) = shale corrected density porosity
- \(\phi_a\) = Density porosity
- \(V_{sh}\) = Shale volume
- \(\phi_{sh}\) = density porosity of nearby shale.

To understand the probable reason for the likely change in petrophysical values laterally, sequence stratigraphic interpretation was done to classify the depositional environments. The most important stratigraphic surfaces were the **maximum flooding surfaces** (MFS) and **Sequence boundaries** (Rotimi, 2010). Each surface was recognized by their distinct log motifs. Maximum flooding surfaces were defined by high-gamma-ray value intervals that separate overall fining upward from coarsening upward intervals within sequences. This is also associated with low resistivity values. In most cases this is used to define the top of the transgressive system tract. Sequence boundaries, were defined by looking for abrupt bases of low-gamma ray- value intervals on the well logs because abrupt changes in gamma-ray logs response are commonly related to sharp lithological breaks (Catuneanu, 2006).

Three general log signatures were used to classify the depositional environments and thus system tracts were inferred over the stratigraphic intervals. Intervals that start with low gamma ray values and then gradually increase upward are interpreted to signify a gradual fining-upward trend and these are characteristics of reworked sand units and shoreface sands environments (Vail, 1977). Intervals with high gamma ray values that gradually decrease are interpreted as upward-coarsening trend and the depositional environment inferred was coastal deposits and pro-delta sands in the highstand system tract. Blocky intervals were defined by cylindrical pattern of the gamma ray log motif value and essentially were interpreted to be the basin floor fan environment.
RESULTS AND DISCUSSIONS

Lithology and Reservoir Sands Characteristic

The interpretation of gamma ray logs from the wells studied for lithology identification presents clearly that the intervals is dominated by alternating sand and shale sequences, the sand occurring more frequently at the top of the log whereas the shale occur more frequently as the logging deepens (Fig. 2). The unavailability of core data from the field of study made necessary some assumption that is centered on integrated use of well log signatures and result of computed porosity crossplots from log analogs available.

In differentiating the fluids saturating the reservoir, Wells 01, 02 and 03 were studied and different reservoirs were encountered. In this study, well 01 (Fig. 3) is used as the case study while the results from the other wells (02 and 03) are presented in Tables. The reservoir sands marked TT, UU and VV in wells 01 respectively, are all probably water bearing evidenced from the resistivity log signatures that records low resistivity values within these intervals (Fig. 4). The reservoir sand AA in well 01 is hydrocarbon bearing as is inferred from the alternating high resistivity log reading. Moreover, neutron-density overlay show the predicted gas – oil contact to be around 5800 ft while the oil-water contact is 5880 ft (Fig. 3). This reservoir occurs from 5805 ft – 5907 ft with net sand (i.e shale fraction/ intercalation) thickness of 88 ft. More hydrocarbon reservoir sands were interpreted in this well, for instance, reservoir sand BB occurs from 6088 ft-6180 ft with net sand thickness of 92 ft. Sand CC occurs from 7060 ft - 7140 ft with net sand thickness of 80 ft. (See Table 1.1, 1.2 and 1.3 for summary of reservoir analysis in other wells).

Figure 2: Lithology Identification was done using the gamma ray signature.

Figure 3: Hydrocarbon Identification, and reservoir markers (fluid contact and reservoir thickness,) of reservoir sands in well 01.

Figure 4: Hydrocarbon Identification, and reservoir markers (hydrocarbon and water reservoir sands are differentiated in well 01.)
From the above, the hydrocarbon prolific reservoir sands include AA, BB, and CC (inference from high resistivity log reading in the range of 0.44 ohm/m – 3326 ohm/m) and they are within the specified interval discussed above, from two of the three wells (wells 01 and 02). In well 02, the extension (continuity) of reservoir sands AA, and BB were found (Fig. 5). Also in well 02 (fig. 5B), hydrocarbon sand that is not related to previously identified hydrocarbon reservoirs was identified and showed in Fig. 5. However in well 03, the reservoir sands were expressed as unascertained, because of the absence of resistivity log which can indicate hydrocarbon show (Fig. 6). It is expected that these reservoirs will however have high hydrocarbon saturation values if they contained hydrocarbon in the sand units, due to general observation of high porosity in the reservoirs (shale units) when compared with others with not as porous as the shale units.

**Hydrocarbon Indication**

**Volume of Shale and Porosity (Φ)**

The average volume of shale within the hydrocarbon sands AA, BB, and CC ranges from 0.10 to 0.66 respectively. In the reservoir sands, in well 01 and 02, the shale content was generally low (average value of 0.1 in Fig 5B). Low shale content occurrence recorded at these intervals indicates the hydrocarbon
reservoir is fairly clean. However in well 03, (Fig 6), much shaliness of the reservoirs was encountered. Unfortunately, there was no resistivity log to identify hydrocarbon reservoir sands.

The porosity (DPHI) values were calculated from formation density log for the hydrocarbon intervals using equations from Asquith (2004). In instances where shale content may affect porosity values, shale effect was corrected for. Porosity within the reservoir sands is fairly uniform and the average effective porosity from the wells ranges from 0.17 and 0.39 in the hydrocarbon reservoir sands. Table 1.4 and 1.5 is a summary of individual porosity values obtained from individual reservoirs in each well. These values considered to be quite appreciable for commercial hydrocarbon production.

Sequence Stratigraphic Interpretation

Three sequence boundaries were defined with the gamma ray and resistivity log. Two corresponding sequences were therefore delineated. Instance of sequence stratigraphic interpretation is shown from well 01 (Figure 7). Highstand system tract of sequence tops the sequence and consist of upward coarsening log patterns. Hydrocarbon reservoir sand BB is located in this region. The depositional environments interpreted from these signatures are the coastal deposits and pro delta sands. Hydrocarbon reservoir sands AA is located in the transgressive system tract of sequence with its characteristic fining upwards log patterns. Based on the separated interval (variably preserved) of fining upward log sequence, this environment is interpreted to be within the reworked sandstone units and shoreface sands. This signature was observed and consistent in wells 02 and 03 (Fig. 8).

The transgressive system tract is truncated on its top by the shale blanket that represents the maximum flooding surface which denotes the maximum level of landward incursion. The maximum flooding surface was defined by pronounced high gamma ray log signature throughout all the wells where it was observed.

Log patterns observed in the lowstand system tract at the basal part of the stratigraphic column suggest the basin floor fan depositional environment because log response for a basin floor fan environment are usually blocky, with a sharp top and bottom bracketing clean sand (Catuneanu 2006, Rotimi, 2010). It was observed in all the three wells. Reservoir BB is located in the highstand system tract while CC is located in the lowstand system tract.

Petrophysical Values and Depositional Environments Correlations

Petrophysical properties were determined for only the hydrocarbon bearing sandstones units of the basin. These reservoirs include: reservoir sand AA, BB and CC. On the other hand, the depositional environments interpreted include: coastal deposits and pro delta sands, reworked sand units and shoreface sands, slope fan and basin floor fan environments. Fluvial sandstones can exhibit a wide range of porosity (0-18%) (Vail, 1977) and this was discovered to be true for the intervals where they have been observed (Table 1.4). Channel deposits also comprise the best reservoir quality bodies within a delta system (Scheiing and Atkinson, 1992). But for this interpretation, channel sand interpretations were disregarded because of the limitation of amassing evidence on the logs.

From the study, the basin floor fan, have customary porosity values (average of 0.22). On the other hand, according to Vail, 1977, slope fans can exhibit several depositional styles depending on the vertical gradient of the slope. This can be the reason for the range of porosity values observed in them (0.22, 0.30 and 0.50 in Table 1.5). Other characteristics of the slope fans reservoirs were the thin thicknesses associated with them. This coupled with the rapidly alternating lithologies in the depositional environment probably reflects a multitude of discrete depositional events and (or) significant variation in sediment supply.

The best region of hydrocarbon accumulation predicted is the shoreface sands and reworked sands. The interpretation model is that the fluvial system washes abundant clay to fine sand onto the delta front. These fine deposits in all probability are reworked by marine processes of moderate wave energy. This depositional environment can be traced laterally on a spatially sufficient data to know the reservoir extent laterally.
CONCLUSION
Bobo Field appraisal has been carried out from petrophysical analysis and well-log sequence stratigraphy from three wells. Analysis on well logs suggested that hydrocarbon bearing reservoir sands reservoirs AA, BB, and CC exist in the field. Porosity estimates in these reservoirs vary from 0.22 to 0.36 and the net thicknesses of the reservoir sand ranges from 20 ft to 175 ft. These have been deemed to be quite appreciable for commercial hydrocarbon production. Three categories of depositional environments have been interpreted namely: coastal deposits and pro delta sands, reworked sand units and shoreface sands, slope fan and basin floor fan environments.

Porosity estimates is highest observed in the channel and shoreface environment. Therefore it is assumed that this environment supports hydrocarbon accumulation. This may be because they have been formed in areas where there is slope stability and unhurried deposition of sediments. Exploration of hydrocarbon in this field is suggested to be targeted at the region of portion observed in the interpretation as channel and shoreface deposits. In frontier basins and other similar locations with identical geological expressions it is advised to explore the petrophysical uniqueness with sequence stratigraphic signatures. This work had been able to relate the importance of depositional strata in terms of volume of shale and porosity such that in hydrocarbon exploration, integrating petrophysics with sequence stratigraphy to characterize the portion of our basin that is most prolific for adequately choosing points of siting production wells and also a good means of eliminating barren lithological units.

REFERENCES


Fig. 7: Sequence stratigraphic interpretation (Sequence 1) in Well 01 showing sequence boundaries, system tracts and hydrocarbon reservoirs.

Fig. 8: Well correlation showing overall reservoir and stratigraphic interpretation from the 3 wells. The well correlation is used to trace and validate the depositional environments features.