Development of model for predicting elastic parameters in ‘bright’ field, Niger Delta using rock physics analysis

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A B S T R A C T

Accurate differentiation of reservoir fluid and determination of elastic parameters when some logs are not available is a major challenge in the petroleum industry and this study explored the potential of rock physics modeling to resolve these challenges. Suite of logs from four wells were provided, but only three wells were used for the analysis because well 3 does not have density log. Petrophysical properties were calculated from the logs using the respective equations and pseudo shear wave velocity was estimated from the P-wave velocity. The result of the rock physics analysis carried out using crossplots of acoustic impedance against P-wave velocity coloured with gamma ray log was able to separate the lithology into sand and shale both within the wells and the reservoirs of interest with the aid of the relevant rock physics models. Vp/Vs ratio against acoustic impedance crossplots coloured with density log indicated the pore fluid in the wells and mapped sand bodies to be water and oil. Two mathematical models for predicting elastic parameters in the absence of some necessary logs were developed and these models can be used in the Niger Delta and in other sedimentary basins of the world.

1. Introduction

The field of rock physics represents the link between qualitative geological parameters and quantitative geophysical measurements (Rob and Mike, 2014). Increasingly over the last decade, rock physics has become an integral part of quantitative seismic interpretation and stands out as a key technology in petroleum geophysics. Ultimately, the application of rock physics tools can reduce exploration risk and improve reservoir forecasting in the petroleum industry. The elastic properties such as velocity, density, impedance, and Vp/Vs ratio take an important role in reservoir characterization because they are related to the reservoir properties. To analyze these elastic properties, rock physics knowledge is a bridge that link these elastic properties to the reservoir properties such as water saturation, porosity, and shale volume.

Rock physics modeling can be utilized to build a template for efficient reservoir characterization (Odegaa and Avseth, 2004; Avseth et al., 2006; Andersen and Wijngaarden, 2007). In reservoir property analysis, the lithology and fluid content or saturation cannot be predicted efficiently by identifying different clusters in the cross-plot of elastic properties.

Accurate determination and understanding of lithology, pore fluid, pore shapes, and sizes are fundamental to other petrophysical analysis. Determining lithology and pore fluid are key for effective exploration and production of hydrocarbon. However, accurate prediction of lithology and pore fluid is, and will continue to be, a key challenge for hydrocarbon exploration and development (Kupecz et al., 1997). The accurate determination of lithology and pore fluid aids in the accurate determination of porosity, saturation, and permeability. The economic viability of a hydrocarbon field is also reliant on the quality and accuracy of lithology and pore fluid (Hami-Eddine et al., 2015). The growing difficulty in conventional (reservoir that uses the natural pressure gradient for hydrocarbon extraction) and unconventional (reservoir that requires special recovery operations outside the conventional operating practices) reservoir has made precise lithology and pore fluid prediction very essential (Hami-Eddine et al., 2015). The accurate determination of lithology and pore fluid also aid petroleum engineering decisions making.

Lithology and pore fluid can be unambiguously determined using core samples obtained from underground formation. However core sample analysis for lithology and pore fluid prediction is expensive and usually involves vast amount of time and effort to obtain reliable information (Chang et al., 2002). Hence, this method cannot be applied to all drilled wells in a field. Also, different geoscientists may obtain inconsistent results based on their own observation and analysis (Akinyokun et al., 2009; Serra and Abbott, 1982). Cuttings obtained from drilling operations can also be used to determine lithology and
pore fluid. The main disadvantage of using cuttings from drilling operation to determine lithology and pore fluid is that the retrieval depth of the cuttings are usually unknown and the samples are generally not large enough for precise and reliable determination of lithology and pore fluid (Serra and Abbott, 1982). Considering the limitations mentioned for other methodologies, there has been a growing interest in determining lithology and pore fluid using well log data which is cheaper, more reliable, and economical compared to the other methods stated above. Well logging also offers the benefit of covering the entire geological formation of interest coupled with providing general and excellent details of the underground formation (Serra and Abbott, 1982). Brigaud et al. (1990) observed that well logs offers a better representation of in-situ conditions in a lithological unit than laboratory measurements mainly because well logs sample finite volume of rock around the well and delivers uninterrupted record with depth instead of sampling of discrete point.

1.1. Rock physics

Rock physics is an indispensable tool for an efficient interpretation, providing the basic relationship between the lithology, fluid, and geological deposition environment of the reservoir (Chi and Han, 2009). Rock physics can also be applied to build a template to enhance reservoir characterization (Odegaard and Avseth, 2004; Avseth et al., 2005).

Rock Physics describes a reservoir rock by physical properties such as porosity, rigidity, compressibility; properties that will affect how seismic waves physically travel through the rocks. The Rock Physicist seeks to establish relations between these material properties and the observed seismic response, and to develop a predictive theory so that these properties may be detected seismically. It provides information that is valuable to provide the link between petrophysics, geomechanics, and seismic data and the internal rock properties such a porosity, mineralogy, pore space, pore fluid, etc.

1.2. Rock physics model

Rock physics model is a set of equations and statistics capturing the relationships between physical properties for a particular rock type or formation. Rock physics modelling makes use of the interdependencies between these properties and creates an opportunity to synthesize a more accurate and less uncertain picture, thus optimising the output of a shared model.

Once a model is established it can be used to predict missing or low quality well logs, model seismic reflectivity, calibrate rock physics
based seismic inversion and predict petrophysical properties from seismic impedances. Rock physics models can also be used to guide inversion of Vp, Vs, Rho properties from seismic to reservoir rock properties. This requires correctly processed and conditioned pre-stack seismic (AVO partial stacks) as well as optimised rock physics models.

There are a large number of rock physics models and relations that provide tools for data QC, characterization and generation of model scenarios (Rob and Mike, 2014).

The most commonly employed models can be categorized as follows:

(a) theoretical bounds,
(b) empirical models,
(c) contact models,
(d) inclusion models.

2. Rock physics templates

Rock Physics Templates (RPTs) are charts and graphs generated by using rock physics models, constrained by local geology, that serve as tools for lithology and fluid differentiation (Odegaard and Avseth, 2004). RPT can act as a powerful tool in validating hydrocarbon anomalies in undrilled areas and assist in seismic interpretation and prospect evaluation.

Rock physics diagnostic models and Gassmann fluid substitution relations are essential ingredients in generating the templates for a reservoir. The success of RPT analysis depends on the choice of proper model and correct geological information of the reservoir. The common form of RPT is between acoustic impedance (AI) and Vp/Vs ratio, as combination of these two elastic properties is a good lithology and fluid indicator (Avseth et al., 2005, Chi and Han, 2009). Other forms of RPT include combination of shear impedance (SI) and AI, elastic impedance (EI) and AI and Lame’s parameter (\(\lambda\)) and shear modulus (\(\mu\)).

3. Location and geology of the study area

The field is located within the onshore part of Niger delta (Fig. 1). The base map showed the location of the four wells and the seismic lines and the field belongs to an active oil producing company in Nigeria. It covers an area extent of about 51,187 km² and it lies within longitude 8.0°E to 8.3°E and latitude 4.0°N to 4.3°N. Water depth in the field ranges from 42 to 60 feet.
The Niger Delta basin is located on the continental margin of the Gulf of Guinea in equatorial West Africa and lies between latitudes 4° and 7°N and longitudes 3°E (Whiteman, 1982). It ranks among the world’s most prolific petroleum producing Tertiary deltas that together account for about 5% of the world’s oil and gas reserves. It is one of the economically prominent sedimentary basins in West Africa and the largest in Africa (Reijers et al., 1997). Three lithostratigraphic units have been recognized in the subsurface of the Niger Delta (Short and Stauble, 1967; Frankl and Cordy, 1967; Avbovbo, 1978). These are from the oldest to the youngest, the Akata, Agbada and Benin Formations (Fig. 2). The Akata Formation (Eocene – Recent) is a marine sedimentary succession that is laid in front of the advancing delta and ranges from 1968 ft to 19,680 ft (600–6000 m) in thickness.

It consists of mainly uniform undercompacted shales with lenses of sandstone of abnormally high pressure at the top (Avbovbo, 1978). The shales are rich in both planktonic and benthonic foraminifera and were deposited in shallow to deep marine environment (Short and Stauble, 1967). The Agbada Formation (Eocene-Recent) is characterized by paralic interbedded sandstone and shale with a thickness of over 3049 m (Reijers et al., 1997). The top of Agbada Formation is defined as the first occurrence of shale with marine fauna that coincides with the base of the continental-transitional lithofacies (Adesida and Ehirim, 1988). The base is a significant sandstone body that coincides with the top of the Akata Formation (Short and Stauble, 1967).

Some shales of the Agbada Formation were thought to be the source rocks, however; Ejedawe et al. (1984) deduced that the main source rocks of the Niger Delta are the shales of the Akata Formation.

The Benin Formation is the youngest lithostratigraphic unit in the Niger Delta. It is Miocene – Recent in age with a minimum thickness of more than 6000 ft (1829 m) and made up of continental sands and sandstones (> 90%) with few shale intercalations. The sands and sandstones are coarse grained, subangular to well rounded and are very poorly sorted.

4. Materials and methods of study

The interpretation was carried out on a workstation with the aid of PETREL™ and RokDoc software and suite of composite well logs were used for the interpretation.

Three out of the four wells were used because well 3 does not have bulk density log (RHOB).
4.1. Rock physics analysis

The approach used was to crossplot elastic properties against petrophysical parameters with the use of appropriate rock physics models for fluid and lithology identification.

Below are the parameters that were crossplotted:

(a) Acoustic Impedance against P-wave velocity colour-coded with GR log
(b) Vp/Vs against Acoustic impedance colour coded with density log

Fig. 5. Well Correlation Panel showing the Top and Base of Sand 2.

Fig. 6. Crossplot of AI against Vp for Well 1.
Fig. 7. Crossplot of AI against Vp for Well 1 to Generate Linear Equation.

Fig. 8. Crossplot of AI against Vp for Well 2.
To calculate the S-wave velocity, Greenberg and Castagna (1992) P-to-S-wave velocity transform (GC), which, in water-saturated siliciclastic rocks, is close to the mudrock equation of Castagna et al. (1985) was used:

\[ V_s = 0.862V_p - 1.172. \]

Shales generally have high Vp/Vs as compared to sand, and Vp/Vs ratio for hydrocarbons is generally lower than brine because P wave velocity is more sensitive to fluid changes than the S-wave velocity. The crossplot of Vp/Vs against acoustic impedance is a good pore fluid and lithology indicator as shown in Fig. 3. Changes in the fluid type result in changes in Vp/Vs ratio, thus the cross-plots of Vp/Vs and P-
impedance will assist in differentiating both fluid and lithology effect.

5. Results and discussion
5.1. Petrophysical analysis

Wells 1, 2, 3 and 4 were correlated from the northwestern to the southeastern direction and two sand bodies were mapped across the correlated wells as shown in Figs. 4 and 5. The well correlation panel showing the top and base of sand 1 (Fig. 4) shows that the sand body has varying proportion of sand and shale across the four wells. The thickness also varies across the wells, within a depth interval of 2510–2547 m in well 1, 2515–2535 m in well 2, 2490–2530 m in well 3 and 2502–2530 m in well 4. It is thickest in well 3 and thinnest in well 2.
Fig. 13. Crossplot of AI against Vp for Well 4 Sand 2.

Fig. 14. Crossplot of Vp/Vs against Acoustic Impedance for Well 1.
In well 1, the resistivity log reads a high value within sand 1 showing that it is hydrocarbon bearing, while the resistivity values are low for the same sand 1 in wells 2, 3 and 4. There is a thick column of shale above and below it which would enhance the sealing potential for the hydrocarbon within it. Sand 2 also depicts variation in thickness across the entire four wells as shown in Fig. 5. The sand body is cleanest in well 4, owing to the high proportion of sand-shale within it compared to others wells. The log readings are high across the wells, showing that they are all hydrocarbon bearing and there are also thick column of shale overlying and underlying them which serves as good seal.

![Fig. 15. Crossplot of Vp/Vs against Acoustic Impedance for Well 1 to Generate Equation.](image1)

![Fig. 16. Crossplot of Vp/Vs against Acoustic Impedance for Well 2.](image2)
Fig. 17. Crossplot of Vp/Vs against Acoustic Impedance for Well 4.

Fig. 18. Crossplot of Vp/Vs against Acoustic Impedance for Well 1 Sand 1.
Fig. 19. Crossplot of Vp/Vs against Acoustic Impedance for Well 1 Sand 2.

Fig. 20. Crossplot of Vp/Vs against Acoustic Impedance for Well 2 Sand 2.
5.2. Rock physics analysis

The mapped reservoirs were further analysed for fluid and lithology differentiation using rock physics analysis which involves crossplotting of elastic and reservoir parameters superimposed on some established rock physics models. Crossplots are visual representations of the relationship between two or more variables, and they are used to visually identify or detect anomalies which could be interpreted as the presence of hydrocarbon or other fluids and lithologies (Bello et al, 2015).

5.2.1. Acoustic impedance against P-wave velocity

Fig. 6 shows the crossplotting of acoustic impedance against P-wave velocity coloured with gamma ray log for well 1, the two lithologic types present within the well in a typical Niger Delta environment were delineated which are sand and shale. Shale is shown by reddish and yellowish clusters enclosed with a polygon depicting higher content of the radioactive elements within it. A rock physics model called unconsolidated sand line was overlaid to demarcate sand from shale which also shows that the sand is unconsolidated which is consistent with the work of (Doust and Omatsola, 1990). Since there is a linear relationship between velocity and acoustic impedance, because an increase in velocity will cause a corresponding increase in acoustic impedance which is the product of velocity and density, a linear relationship was obtained as shown in Fig. 7 which could be used as way estimating the estimating acoustic from velocity when density data is not available.

The linear equation is given as: 
\[ y = 762.84863 + 1.5028796 \times 1.6772088 \times x \]

where \( y \) is acoustic impedance and \( x \) is the velocity. The correlation coefficient is 0.853.

Fig. 8 shows the result of crossplotting acoustic impedance against velocity in well 2, an empirical rock physics model called Han’s dual input which is used for lithologic differentiation was used with gamma ray log as the third entity. Sand and shale were obviously separated, because shale especially when it is compacted by reason of the load has higher velocity and acoustic impedance than shale.

The crossplot of acoustic impedance against P-wave velocity coloured with gamma ray log for well 4 is shown in Fig. 9, clusters with low gamma ray reading is diagnostic of sand while high gamma ray reading connotes shale. Han’s dual input which is an empirical rock physics model was also used for the lithologic demarcation, shale is shown by reddish and yellowish clusters enclosed with a polygon. Rock physics analysis was carried out in all the reservoirs within the two sand bodies delineated, but in sand 1 only well 1 was analyzed since others wells that penetrated the sand are water charged. Acoustic impedance against P-wave velocity crossplot for well 1 sand 1 is shown in Fig. 10 with the overlay of Han’s dual input rock physics model, sand is shown with purple coloured clusters, red and yellow clusters represent shale. The proportion of sand within the reservoir is higher than shale and the rock physics model used was able to separate sand from shale.

The crossplot of acoustic impedance against P-wave velocity for...
well 1 sand 2 is shown in Fig. 11, the proportion of sand is much more than shale and the two lithologic types were also separated. Fig. 12 shows the crossplot for well 2 sand 2 with the two lithologies separated and there are points that clustered away from the rock physics model line with lower velocity and acoustic impedance respectively and this could probably be a gas sand.

Fig. 13 shows the crossplot of acoustic impedance against P-wave velocity coloured with gamma ray log for well 4 sand 2 and Han’s dual input superimposed on it, sand and shale clusters were separated and there appears to be more of sand than shale within the reservoir. Some points are also clustered away from the model line which could be probably gas sand, while some shale points are also clustered away from the model line and this could be compacted shale due to the higher acoustic impedance value they have.

5.2.2. Crossplot of Vp/Vs against acoustic impedance

The ratio of compressional and shear velocities was crossplotted with acoustic impedance and coloured with density log in order to identify the fluid within the wells. Fig. 14 shows the result Vp/Vs against acoustic impedance crossplot for well 1, the Vp/Vs has a data range of about 1.5–4.0 while the acoustic impedance range from about 3000 m/s/g/cc to 11,000 m/s/g/cc. Shale has higher Vp/Vs and acoustic impedance values than sand and since shear waves does not propagate through fluids, a sand body that contains hydrocarbon exhibit lower acoustic impedance and Vp/Vs value than sand or shale that does not contain hydrocarbon, therefore acoustic impedance and Vp/Vs are suitable for identifying the fluid within a reservoir.

The density of shale is higher than that of sand and water saturated sand has higher density than hydrocarbon bearing sand because water is denser than oil (Oyetunji, 2013). In Fig. 14, clusters with higher density values coloured red and yellow represent shale, while the low density clusters represent oil bearing sand. A logarithmic equation was generated from the crossplot as shown in Fig. 15 to serve as a means of estimating Vp/Vs from acoustic impedance and vice versa. The equation is:

\[ Y = 11.486141 + \log(x) \]

where \( y \) is Vp/Vs and \( x \) is acoustic impedance. The correlation coefficient is 0.771.

In Fig. 15 the clusters enclosed with a polygon represent oil sand while the other clusters represent shale, the higher density value clusters shows that the shale is wet. Fig. 16 shows the crossplotting of Vp/Vs against acoustic impedance coloured with density log for well 2, Vp/Vs range from about 1.5 to 2.8 and acoustic impedance has a range of 5000 m/s/g/cc to 11,000 m/s/g/cc. The low density oil bearing sand enclosed with a polygon was separated from the higher density wet shale.

Fig. 17 shows the crossplotting of Vp/Vs against acoustic impedance for well 4 with the clear demarcation of the oil bearing sand from shale. The acoustic impedance and Vp/Vs values in well 4 are lower than that of wells 1 and 2.

5.2.3. Crossplot of Vp/Vs against acoustic impedance for sand 1 and 2

In addition to the Vp/Vs against acoustic impedance crossplot analysis carried out for wells 1, 2 and 4, the analysis was done within sand 1 and 2 penetrated by the wells. Fig. 18 shows the crossplot for sand 1 well 1 where the oil bearing sand with lower Vp/Vs and acoustic impedance values have been separated. In Fig. 19, Vp/Vs was also crossplotted with acoustic impedance and coloured with density log for sand 2 well 1, the low density clusters having low density have been interpreted as oil bearing sand. Fig. 20 shows the crossplot for sand 2 well 2, the clusters with low Vp/Vs and acoustic impedance values represent sand that is hydrocarbon charged and in Fig. 21 which is the crossplot for sand 2 well 4, the oil bearing sand stands out as clusters of points having low Vp/Vs and acoustic impedance values.

Water-saturated sands at the deposition will have very high Vp/Vs because of the very low shear modulus (Taufik, 2016). However, the Vp/Vs ratio will decrease rapidly with increasing pressure, depth and burial. In the other hand, AI will increase as grains are packed together and cemented. The effect of mineralogy will be significant in RPT because clays and carbonates have higher Vp/Vs than quartz. However increasing shaliness will have different effect on AI depending on if the clay particles are laminating or pore filling. AI will increase if the clay particles are pore filling, and it will decrease if the clay particles are laminating. Finally, AI and Vp/Vs will decrease with increasing hydrocarbon saturation.

6. Conclusion

Rock physics analysis carried out by crossplotting elastic parameters with reservoir properties with the use of rock physics models were able to differentiate lithology and fluid within sands 1 and 2. Acoustic impedance versus P-wave velocity crossplot with gamma ray log as the third axis was able to differentiate lithology. The rock physics models used also assisted in the separation of sand from shale. The ratio of compressional wave velocity and shear wave velocity against acoustic impedance crossplots coloured with density log was able to differentiate water saturated shale from the oil sand. The linear equation that was generated that relate acoustic impedance with P-wave velocity and the logarithmic equation that connects Vp/Vs with acoustic impedance can be applied in the Niger Delta to predict one parameter from the other and vice versa.

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