Seismic impedance inversion and attribute analysis for reservoir characterization in an offshore depobelt, Niger Delta, Nigeria

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Abstract

The task of minimizing pitfall in quantitative reservoir assessment and evaluation is an integral aspect of any promising petroleum exploration and evaluation project. The Niger Delta oil province in Nigeria is chiefly composed of several pay zones with many stratigraphic intervals of sand and shale formations in varying proportion. Whereas conventional seismic interpretation technique poses certain degree of uncertainty in reservoir characterization, seismic inversion constraint by log data brings significant improvement in interpretation that reduces uncertainty in the delineation of reservoir characteristics, volume and distribution. In this present study, post-stack seismic inversion and seismic attributes analysis were used to evaluate the potentials and prospects of mapped reservoirs in a field, offshore depobelt, Niger Delta. The implementation of the tasks consists of mapping of structural framework, horizon picking, log editing and correlation, wavelet extraction, building of low-frequency model, acoustic impedance inversion and crossplot analysis of reservoir properties and attributes. A hybrid approach (formulated using Greenberg-Castagna equation) specific for the Niger Delta depobelts was used to estimate and generate shear wave velocity for the wells. Results obtained from inversion depict an acoustic impedance values in the range 150–280 ft/s g/cc and V_p/V_s of 1.25–2.50 at a depth range of 9250–9280 ft within the hydrocarbon-bearing sands in the two wells. Region of low acoustic impedance (representing high reservoir porosity) coupled with a corresponding low V_p/V_s ratio (indicating hydrocarbon accumulation) is presumed to have high prospects for exploration and well development. Altogether the degree of correlation between the inverted and actual impedance was found to be about 90% across the wells. It is evident that the acoustic impedance slice at 3000 ms depicts low acoustic impedance sand within 18,500–20,000 ft/s g/cc at the northeastern and southeastern regions of the field. High reflection amplitudes (bright spots) signifying hydrocarbon accumulation are also revealed on seismic attribute maps with surrounding shale diaper as the source rock. This study has revealed the prospect (i.e., existence of active petroleum system of probable economic value) of the delineated field in the Niger Delta depobelt.

Keywords Seismic inversion · Depobelt · Reservoir · Attributes · Exploration · Petrophysics

1 Introduction

Inherent risks and uncertainties associated with hydrocarbon exploration and exploitation have necessitated the need for improved seismic interpretation, lithology and fluid discrimination [1]. Newer and cost-effective technologies and innovations are needed to get over

these expected exploration challenges [2]. Seismic inversion technique has been used to improve reservoir characterization, since its inception in the early 1980s [3]. Consequently, it has now become a vital tool in the hands of geophysicists involved in reservoir planning and development [4–10]. Seismic inversion is based on seismic derived rock physical properties which are used

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in evaluating reservoir properties and conditions. This involves extracting elastic rock properties from seismic data based on amplitude, travel-time and phase information contained in a seismogram [11–13]. These procedures have made it possible to validate the relationship between elastic and petrophysical properties of reservoir rocks. Most seismic inversion techniques are sensitive to different properties of reservoirs. While these techniques have their respective unique advantages and disadvantages, the applicability of these techniques depends chiefly on the provided geological data, prestack and post-stack seismic data [14]. The incorporation of these techniques and their responses to various petrophysical and elastic properties from well logs, computed logs and inverted logs have translated into improved reservoir characterization [11, 15–20]. Petrophysical data are point data which give the real information within the well bore, while seismic data are a lateral sampling of the subsurface with poor resolution when compared with petrophysical data. Some pertinent information (e.g., porosity, permeability, heterogeneity, net pay thickness, etc.) necessary to evaluate a reservoir in terms of its ability to accumulate and deliver hydrocarbon is basically the products of reservoir characterization [16]. In addition, rock physics concepts and modeling have played vital roles in linking elastic rock properties (elastic wave velocity and impedance) to porosity, mineralogy (shale content), saturation, and pore fluid properties as well as predicting the effect of fluid substitution on porous and fractured reservoir and monitoring changes in reservoir elastic properties during production [21–25]. This has found numerous applications in establishing the link between seismic impedance and velocity inversion with physical reservoir properties. Generally, these empirical relations play important roles in data integration, especially in data sets that are difficult to acquire in situ. In well logging, a typical scenario is when shear wave velocity data are unavailable, and in which case different methods have to be developed with the objective of filling the data gaps [26]. Hence in situations where data quality is grossly inadequate, post-stack acoustic impedance inversion is able to effectively discriminate between hydrocarbon bearing zones and non-bearing zone. Also, analyses and interpretation based entirely on conventional seismic technique is very uncertain in predicting rock properties. Therefore, this study integrates structural interpretation, seismic acoustic impedance inversion (model based post-stack) as well as seismic attribute analysis to reduce the uncertainty in the prediction and delineation of the characteristics, disposition and distribution of hydrocarbon bearing reservoir in a field, offshore depobelt, Niger Delta.

2 The Niger Delta geological setting

The Niger Delta Basin covers a region of about 70,000 km² in the Gulf of Guinea, West Africa (Fig. 1). It was formed in the Early Tertiary, with the accumulation of sediments during the Mesozoic rifting of African and South American continents. It is divisible into continental, marginal marine and marine facies [27]. The Tertiary deltaic fill of the Niger Delta is represented by a strongly diachronous (Eocene—Recent) structure which is divided into three lithofacies units namely: Akata Formation, Agbada Formation and Benin Formation, respectively [28–30]. The Agbada Formation which is a paralic sequence of shale and sand interbeds is the primary reservoir of oil/gas in the Niger Delta clastic wedge. The matured Eocene and Miocene shale of the Akata and Agbada Formation constitute the major source rock [29, 31–33]. Synrift marine clastics and carbonates deposition which occurred during a succession of transgressive and regressive phases between the Cretaceous to Early Tertiary constitute the oldest dated sediments of the Albian age [34]. The differential loading of under-compacted shale at the bottom of the Tertiary Delta by the relatively heavy sandy deposits initiated the formation of growth fault in the basin, and this can result in growth fault plane or a roll-over anticline if sufficient movement takes place along the line of deposition [35]. Rapid sedimentation and gravitational instability during the accumulation of the Agbada deposits and continental Benin sands over the mobile under-compacted Akata prodelta shale, is the main cause of the growth fault. The generic and distinctive properties manifested by the oil bearing reservoir of the Niger delta are a function of the sand/shale ratio and sealing potential of the faults [36–38]. Two possible migration routes have been established in the Niger Delta. These are: (1) migration along the structure building faults which terminate in the Akata Formation and (2) migration from the seaward facies up-dip into the rollover structures [29]. Lateral flowage and extrusion of the Akata prodelta shale during growth faulting also account for the diapiric structure on the continental slope of the Niger delta in front of the advancing depocentre of paralic sediment [36, 38]. The series of punctuations in the progradation of the deltaic system defines a depobelt. Depobelts which strike Northwest—Southeast, sub-parallel to the shoreline, successively become younger basin ward, ranging in age from Eocene in the north to Pliocene offshore to the present day shoreline. The structural style deep water fold and thrust belts of the Niger Delta are system with a single basal detachment level, that is typically near the top of the Akata Formation and multiple basal detachment

Fig. 1 Regional geology of the Deepwater Niger Delta showing the “Apok” field. Adapted from [41]

levels, which causes massive structural thickening of the Akata Formation and refolding of shallow thrust sheets [39, 40].

3 Methodology

An integrated data set was used in this study for the structural mapping, seismic inversion and reservoir attributes analysis. These include: 3D post-stack seismic data, suites of well logs (gamma ray log, resistivity log, neutron log and density log) for wells Freeman-001, 003, 004 and 005 (Fig. 2). However, only two wells (Freeman-001 and 005) which are extensive and well-connected with the major reservoirs are considered for interpretation.

4 Well to seismic tie

Delineation of the geometry and structural framework of reservoirs was accomplished by tracking seismic reflection events on the seismic volume. Well data were converted from depth domain to time domain to correlate the well and seismic data for horizon picking. Figure 3 shows the seismic section with crossline and inline running east–west and north–south, respectively. Two horizons (1 and 2) were identified on the seismic volume (Fig. 3) and

incorporated into the workflow for seismic inversion. The zones of interest (sand bearing hydrocarbon) are located at reflection time 2852.5–28,625 ms (9240–9290 ft of TVD) and 3370–3390 ms (9700–9775 ft of TVD) for Freeman-001 and 005, respectively. Well to seismic tie was done using Hampson-Russell STRATA program [42] and Petrel software.

5 Wavelet extraction, model-based inversion and rock physics

In post-stack seismic inversion techniques, stacked (zero-offset) seismic data are used to produce images of acoustic impedance in depth or time. Acoustic impedance as one of rock physics elastic parameters is influenced by lithology, porosity, fluid content, etc. Wavelet extraction was conducted within the reflection time window to extract a zero phase wavelet from the seismic section and well logs. This process involves building an initial model with a starting low frequency model followed by modification through successive iteration to optimally fit the seismic data (Fig. 4), thereby minimizing error in the model-based inversion [43, 44]. This model-based inversion technique converts seismic data to a pseudo-acoustic impedance log at every trace. Figure 5 shows the wavelet in frequency and time domain, while Fig. 6 shows the corrected P-wave and time-depth shift for the inversion. As an input into

Fig. 2 Base map showing the available wells (Freeman-001, 003, 004 and 005 in the study area

Fig. 3 Horizon mapping on seismic section showing the location of freeman-001 and 005 penetrating the main reservoir and the two horizons identified for interpretation

Fig. 4 Inversion and interpretation workflow

the inversion, an initial acoustic impedance model (I_p) was generated from density (ρ) and P-wave velocity (V_p) log using the equation: $I_p = \rho * V_p$. The predicted and original acoustic impedance curves were compared via inversion analysis. The shear wave velocity was extracted using modified form of Greenberg–Castagna equation [45] to generate shear wave velocity for crossplot analysis. Velocity or impedance measurements in Lamé parameter, incompressibility (λ) and rigidity (μ) provide an alternative interpretation methodology [46]. Besides, two other attributes, LambdaRho ($\lambda\rho$) and MuRho ($\mu\rho$) or Lamé impedances, were formulated and introduced [47], and referred to the method as Lambda-Mu-Rho or LMR. Since there is a link between V_p and V_s using the modified Greenberg–Castagna equation, it is possible to calculate $\lambda\rho$ and $\mu\rho$ from $\lambda\rho = I_p^2 - 2I_s^2$ and $\mu\rho = I_s^2$ respectively, once compressional and shear impedance volumes are available where I_s is the shear impedance. Lastly, rock physics model (RPM)-based interpretation templates for LMR would permit interpretation and comparison of log or seismic derived elastic properties [47].

6 Seismic attributes analysis

Seismic amplitude was used for seismic attribute analysis in identifying hydrocarbon reservoirs and sediment depositional direction from its source. Seismic variance attribute extracted was used in delineating structures

that could serve as hydrocarbon accumulation. Rock physics properties analysis was carried out across Freeman-001 and 005 wells that penetrated the main reservoir. A crossplot of V_p/V_s against acoustic impedance (AI) which is a well-known fluid discriminator of hydrocarbon was obtained with the pseudo-shear wave velocities (V_s) calculated from a hybrid approach formulated using Greenberg–Castagna equation [48] specified for the offshore depobelts of Niger Delta region. This shows expected trend ($V_s = 0.919V_p - 1.14$) between compressional and shear wave velocities in a typical offshore Niger Delta Basin. Other authors have also established similar linear trend between shear wave and compressional wave velocities for some reservoirs in the northwestern part of the Niger Delta Basin as given in Table 1 [18, 45, 49].

7 Results and discussion

Reservoir characterization to evaluate reservoir properties from seismic data using impedance inversion model and interpretation has been carried out on two wells in this study. Figure 7 shows the time structural map with time ranging from 2550–3750 ms at contour interval of 150 ms for horizon 1 and 3100–4100 ms at contour interval of 200 ms for horizon 2. The corresponding depth map for the two horizons are presented in Fig. 8 with depth ranging from 2150–3350 ft at contour interval of 200 ft for horizon 1 and 2400–4500 ft at contour interval

Fig. 5 **a** Wavelet extracted on Freeman-005 using Petrel; **b** full wavelet in frequency domain; **c** full wavelength in time domain

of 300 ft for horizon 2. The circled crosses in Figs. 7, 8 and 9 indicate the locations of the wells. These delineated features show structural high or anticline (host to hydrocarbon deposit) at the northeastern part and structural low at the southwestern part of the map.

Analysis of relevant seismic attributes such as root-mean-square (RMS) amplitude helps as direct hydrocarbon indicators (DHI) in delineating potential hydrocarbon zones to enhance interpretation [50, 51]. Figure 9 depicts the RMS seismic attribute extracted for the two horizons. High amplitude is observable on eastern,

southeastern as well as southwestern parts for horizon 1, while for horizon 2, dim spots are observable at the eastern and southwestern parts on the RMS map. This might be attributed to poor resolution due to drop in frequency of the seismic energy. Figure 10 shows the seismic variance attribute map. On northeastern part, a shale diapiric structure is revealed as the main trapping mechanism over the anticlinal structure on the two horizons.

Synthetic seismogram and seismic data correlation for the two wells are shown in Fig. 11a, b. The total correlation

Fig. 6 Corrected P-wave and time-depth shift for inversion: **a** Freeman-001 and **b** Freeman-005, respectively

Table 1 Examples of the Greenberg-Castagna relationships predicted for some oil fields in the Niger Delta Basin

Linear relation between V_S and V_P	Formation	Authors
$V_S = 0.80416V_P - 0.85588$	Sand beds/reservoir	Horsfall et al. [49]
$V_S = 0.80430V_P - 0.85610$	Sand beds/reservoir	Oyedele et al. [18]
$V_S = 0.76969V_P - 0.86735$	Shale beds	Horsfall et al. [49]
$V_S = 0.77240V_P - 0.86680$	Shale beds	Oyedele et al. [18]
$V_S = 0.919V_P - 1.14$	Deepwater/Offshore reservoir	Ebere [45]

Fig. 7 Time structural map for Horizon 1 and Horizon 2, respectively

between the actual trace and synthetic trace used for inversion is about 90%. Figure 12a, b shows the result from the model-based inversion for Freeman-001 at 2950 ms and 9250 ft (TVD) and for Freeman-005 at 3350 ms and 9750 ft (TVD) respectively. Impedance map shows distribution of reservoir properties. Acoustic impedance map is the base for reservoir parameter distribution and dynamic

modeling. Figure 13a shows the cross section of acoustic impedance and V_P/V_S ratio, respectively. The crossplot of acoustic impedance (AI) and V_P/V_S using gamma log as legend to classify hydrocarbon zone is presented in Fig. 13b. The blue zone represents the probable sand bearing zone which depicts acoustic impedance values in the range 150–280 ft/s.g/cc and V_P/V_S ratio of 1.25–2.50 at a

Fig. 8 Depth map for Horizon 1 and Horizon 2, respectively

depth range of 9250–9280 ft within the hydrocarbon-bearing sands. A region of low acoustic impedance (representing high reservoir porosity) coupled with a corresponding low V_p/V_s ratio (indicating hydrocarbon accumulation) is presumed to have high prospects for exploration and well development. In hydrocarbon-saturated reservoir, acoustic impedance (AI) is usually lower for the reservoir sand medium than the surrounding shale formation. At a depth range of 9700–9750 ft and 9200–9250 ft, a lower AI is observed compared to the surrounding shale formation on the reservoir for Freeman-001 and Freeman-005, respectively. Lower values of AI (lower density, lower velocity) indicate better reservoir properties as porosity. Figure 14 shows the initial model built to enhance the inversion of whole seismic volume and the full inverted

volume of the model-based acoustic impedance inversion. The initial model is the prior low-frequency model generated from low-pass-filtered acoustic impedance logs from the wells and extrapolated along all the events in the seismic data. This is the absolute level of acoustic impedance for the seismic data. Figure 15 shows the correlated well inversion log of Freeman-001 and 005, which give a high correlation of about 0.90 between inverted acoustic impedance and initial well data. The low error in correlation increases the confidence of interpretation. Figure 16a shows the time slice of acoustic impedance at 3000 ms within the reservoir. The two wells fall within the regions of low impedance. This resistive, low impedance region is indicative of fluid-saturated medium. The Lambda-Mu-Rho (LMR) inverted volumes (Fig. 16b), in conjunction with LMR

Fig. 9 RMS seismic attribute extracted for Horizon 1 and Horizon 2, respectively

Fig. 10 Seismic variance attributes for: **a** Horizon 1 **b** Horizon 2, respectively

Fig. 11 Synthetic seismogram and seismic data correlation with the errors. The red and black traces are the synthetic and seismic trace, respectively. The red lines on the right-hand side of the seismic

trace indicate the error between the synthetic used for the inversion and real seismic data

Fig. 12 Generated logs showing P-impedance, computed S-impedance, V_p/V_s and porosity for the two wells: **a** Freeman-001; **b** Freeman-005 respectively

Fig. 13 **a** Cross section relationship of acoustic impedance (AI) and V_p/V_s ratio within the productive zone; **b** crossplot of acoustic impedance and V_p/V_s ratio using gamma log legend to classify HC zone (blue zone represents the probable bearing sand)

Fig. 14 **a** Initial model built for inversion; **b** Full inverted volume of model-based acoustic inversion

Fig. 15 Correlation of the two wells and relative error

histogram (Fig. 17b), indicate that AI clearly discriminates between hydrocarbon zones and the surrounding zone. The AI histogram shown in Fig. 17a also reveals a lower AI values for hydrocarbon zone compared with the surrounding shale.

8 Conclusion

Integrated 3D seismic interpretation, post-stack inversion and attribute analysis have been carried out for inclusive reservoir characterization in a field in offshore depobelt, Niger Delta, Nigeria. Results show robust integration approach as an important tool in reservoir characterization and its necessity in reducing the risks involved in drilling. Horizon mapping, crossplot analysis and inverted volumes facilitated the discrimination of hydrocarbon sands from shale sands. The inversion output also conforms with structure which makes for a very robust reservoir characterization. Amplitude anomalies observed on horizons showed

the presence of hydrocarbon in the delineated reservoirs. This was further established by the inversion results which improves the reservoir characterization. The inversion results (seismic variance attributes) also helped map lithologies (shale diapir from sand) and aided interpretation of the geological structure in the oil field depobelt Niger Delta. The attribute volume of acoustic impedance (AI) has assisted the delineation of hydrocarbon-saturated reservoirs and has also served as tools for mitigating risks connected with exploration works. The use of post-stack inversion results revealed better reservoir architecture and characterization in the field investigated. Consequently, that conventional 3D seismic interpretation should not be used as a stand-alone method for seismic interpretation due to the uncertainty in predicting rock physics analysis of oil reservoir is affirmed. The result obtained could be used to carry a dynamic modeling and monitoring. Finally, applying inversion algorithm on data from a specific geologic condition (i.e., Niger Delta oil province) is a major contribution from this study.

Fig. 16 **a** Time slice (3000 ms) of the distribution of acoustic impedance; **b** LMR($\lambda\rho$) inverted volume slice at -3000 ms

Fig. 17 **a** Acoustic impedance histogram model; **b** LMR histogram model

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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