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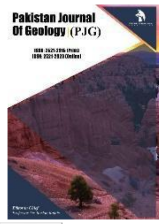


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*RESEARCH ARTICLE*

# AMPLITUDE AND FREQUENCY-BASED SEISMIC ATTRIBUTE ANALYSIS FOR HYDROCARBON PROSPECTIVITY STUDY OF 'OS' FIELD, NIGER DELTA, NIGERIA

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**ABSTRACT**

This study integrated amplitude and frequency-based post-stacked seismic attributes to delineate hydrocarbon prospects in the study area. The research aimed to achieve a comprehensive reservoir characterization by utilizing five well log suites, check shot, and seismic data. Two primary lithologies, sand and shale, were delineated from the well log data, and three reservoirs of significant thickness, intersecting the available well logs, were identified. Using synthetic seismograms and check shot data, a seismic-to-well tie was performed, aligning the well logs with the seismic section to facilitate the extraction of horizon time slices corresponding to the tops of the identified reservoirs for seismic attribute analysis. Seismic attributes that are a function of the amplitude (instantaneous amplitude), frequency (instantaneous frequency) and both (amplitude envelope) identified to be a direct hydrocarbon indicator were extracted and used for the analysis to obtain information about the hydrocarbon potential of the field. Horizon time slices for the three reservoirs were generated across all three attribute maps, allowing for the identification of zones indicative of hydrocarbon presence. Areas characterized by high instantaneous amplitude, low instantaneous frequency, and high amplitude envelope were highlighted and encircled as hydrocarbon prospects. The results reveal that the field demonstrates significant hydrocarbon potential based solely on amplitude and frequency-based seismic attributes.

**KEYWORDS**

Seismic attributes; Frequency; Oil and gas; Hydrocarbon prospects; Amplitude; Niger-Delta

## 1. INTRODUCTION

The global demand for oil and gas is continually increasing by factors such as population growth, and economic development. As proven reserves deplete, there is a need to maximize hydrocarbon production from all potential sources (Nehring, 2009). According to OPEC's projections, global energy demand is expected to increase by 52% by 2035 (El-Badri, 2013). Fossil fuels will remain the primary source of energy during this period, emphasizing the importance of efficient hydrocarbon exploration and production (El-Badri, 2013). To meet this growing demand, petroleum industries are increasingly focused on optimizing oil production through enhanced reservoir characterization and exploration techniques (El-Badri, 2013; Kantaatmadja et al., 2014). They were interested in improving the evaluation of reservoirs with complex and challenging geology which can lead to enhanced petrophysical characterization and hydrocarbon reserve forecasts. To achieve this, new technologies were explored for imaging the subsurface through reservoir modelling (Sinan et al., 2020; Sheykhinasab et al. 2023). 3D reservoir modeling, which can effectively delineate the geometry of sand bodies and address challenges posed by subsurface heterogeneity, has also been applied to assess and detect hydrocarbon prospects in the Niger Delta basin (Hammed et al. 2020). Integration of geostatistics aid in populating different reservoir properties across an oil field to identify prospective zones in the Niger Delta (Hammed et al. 2020; Falade at al., 2022).

Several studies have also been carried out to get new hydrocarbon prospects using seismic interpretation, and seismic inversion in diverse ways (Falade et al., 2024; 2023; Shankar et al., 2021; Akpan et al., 2020; Samakinde et al., 2020; Kafisanwo et al., 2018). 3D seismic data allows for detailed structural interpretation, revealing features such as four-way closures and fault systems, which are critical for identifying hydrocarbon reservoirs (Falade et al., 2023; Kafisanwo et al., 2018). However, modern seismic technology has significantly enhanced our ability to analyze subsurface structures and identify hydrocarbon prospects ((Falade et al., 2024; Posamentier et al., 2022; Khasraji-Nejad et al., 2021; Shankar et al., 2021; Akpan et al., 2020; Samakinde et al., 2020). Advances in seismic data acquisition, processing, and interpretation techniques have led to improved resolution and accuracy in analysis leading to hydrocarbon prospects. The seismic inversion method supports extracting elastic properties like P-wave impedance, S-wave impedance, and density to characterize the subsurface by giving insights into the lithology and fluid content. By analyzing these elastic properties, reservoir rocks can be distinguished from non-reservoir rocks as changes in density can provide clues about fluid saturation and porosity as changes in density can indicate fluid saturation and porosity (Falade et al., 2024; Shankar et al., 2021; Akpan et al., 2020; Samakinde et al., 2020). However, the interpretation of seismic inversion results can be complex and requires a thorough understanding of rock physics and geological principles.

The introduction of seismic attribute technology has transformed reservoir characterization, providing an alternative approach to understanding subsurface geology. Seismic attributes have become integral to modern petroleum exploration, playing a crucial role in unveiling valuable insights into the subsurface and aiding the assessment

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of potential hydrocarbon reservoirs. Each attribute, with its unique relationship to different reservoir geometries and features, has evolved into a powerful tool for prospect evaluation. However, the abundance and diverse applications of seismic attributes present a challenge in selecting the most relevant ones for effective data extraction, requiring a delicate balance between relevance and applicability (Posamentier et al., 2022; Khasraji-Nejad et al., 2021).

In practice, specific seismic attributes are tailored to suit various purposes. These techniques are extensively used in the oil industry to assess the characteristics of subsurface reservoirs, such as porosity and permeability, which are crucial for predicting hydrocarbon potential (Amigun et al., 2022; Ghoneimi et al., 2021; Etuk et al., 2020). Among the numerous seismic attributes, seismic amplitude emerges as a particularly crucial indicator. It exhibits robust correlations with porosity and liquid saturation, showcasing sensitivity to key reservoir properties such as velocity and density (Emudianughe, 2017; Anyiam and Uzuegbu, 2020). The importance of seismic amplitude resides in its capability to provide critical information about boundaries where acoustic impedance changes, enabling the differentiation between hydrocarbons and surrounding lithology (Emujakporue and Ofuyah, 2019; Simm and Bacon, 2014; Mavko et al., 2005). This attribute stands out as a key component in the reservoir characterization toolkit, contributing essential data for accurate delineation and understanding of subsurface structures.

Moreover, research has consistently shown that integrating multiple seismic attributes enhances the accuracy of subsurface analysis (Almasgari et al., 2020; Zhao et al., 2018). For instance, attributes like average energy amplitude, maximum amplitude, and root-mean-square (RMS) amplitude have been employed to identify potential hydrocarbon leads and prospects (Omoja and Obiekezie, 2019). The study also applied seismic attributes analysis techniques in the Malay Basin to identify bypassed hydrocarbon areas and reveal hidden geological features (Almasgari et al., 2020; Setiawan et al., 2018).

The effectiveness of integrating seismic attributes lies in the strategic use of attributes based on diverse theoretical foundations. Amplitude-based attributes capture reflections caused by material properties and content, making them suitable for hydrocarbon prospect assessment (Naseer, 2024; Khan et al., 2021; Liu et al., 2020; Emujakporue and Enyenihi, 2020). On the other hand, frequency-based attributes indirectly measure fluid content and lithology through their inverse relationship with seismic travel times. Regions with higher seismic velocity exhibit lower travel times, leading to higher frequency characteristics. Consequently, frequency-based attributes are highly sought after in subsurface characterization, particularly in hydrocarbon prospectivity studies, due to their unique ability to elucidate subsurface properties (Naseer, 2024; Ugbor and Onyeabor, 2023; Khan et al., 2021; Emujakporue and Enyenihi, 2020).

So the integration of seismic attributes will be valuable in enhancing hydrocarbon prospectivity studies in the Niger Delta Basin. Despite decades of exploration and production activities, this basin still holds untapped oil reserves, particularly in marginal areas. By combining amplitude and frequency-based attributes, the understanding of subsurface structures can be significantly enhanced for identifying potential hydrocarbon prospects that may have been overlooked in previous studies. This study evaluates the effectiveness of amplitude and frequency-based seismic attributes in identifying hydrocarbon prospects in the 'OS' Field, Niger Delta, which is crucial for meeting the growing energy demands driven by population growth. This research provides valuable insights into hydrocarbon exploration strategies and supports the ongoing efforts to optimize oil production in this region.

## 2. Study area and Geological Background

The 'OS' Field study area is situated in the near offshore region of the Niger Delta (Figure 1). Positioned on the Gulf of Guinea Basin, along the West Coast of Central Africa, it encompasses an area of approximately 614.4 $km^2$. The geographical coordinates of the Niger Delta span from longitude 5°E - 7°36'E and latitudes 4°12'N - 6°36'N (Nwachukwu and Chukwura, 1986) as shown in Figure 1.

The Niger Delta originated at a passive margin created by the separation of the African and South American plates from the Late Jurassic to the Cretaceous period (Doust and Omatsola, 1990). The entire basin consists of a regressive clastic sequence (Reijers, 1996; Ekweozor and Daukoru, 1984). Within the Niger Delta petroleum province, three major stratigraphic units have been identified: Benin, Agbada and Akata Formations (Short and Stauble, 1967) (Figure 2). The geological significance of these formations contributes to the region's proficiency in hydrocarbon production, solidifying its position as a key sedimentary basin in Nigeria. The Akata Formation which is the main source rock in the basin is composed majorly of shale. Overlying the Akata Formation is the Agbada Formation which acts as the primary reservoir in the basin and is characterized by alternating layers of sandstone and shale. The youngest formation is the Benin Formation which consists mainly of sand and is where most aquifers in the basin are found. Oil within these formations can become trapped in geological structures due to the impermeable nature of the shale layers in the Akata and Agbada Formations, which act as seals. These traps can be in the form of dip closures or against faults (synthetic or antithetic) as shown in Figure 2.

## 3. Materials and methods

The dataset employed in this research was obtained from the 'OS' Field, situated in the offshore region of the Niger Delta in Southern Nigeria. They include 3D seismic data in a SEGY-file Post Stack Migrated Volume format, well logs and check shot data. Five wells namely OS-1, OS-2, OS-3, OS-4, and OS-5 were utilized for the study. The spatial distribution of wells within the Niger Delta is presented in a base map (Figure 3). Techlog software was used for the analysis of well logs (well correlation), Hampson Russel software was employed for the seismic attribute analysis and visualization. The seismic attributes used to for this study are frequency-based attribute (instantaneous frequency), amplitude-based attribute (instantaneous amplitude), and a combination of amplitude and frequency-based attribute (amplitude envelope). The procedure adopted for the research which includes, reservoir delineation and well log correlation, well-to-seismic tie; extraction, gridding, analysis and RGB addition blending of seismic attributes and has shown in Figure 4.

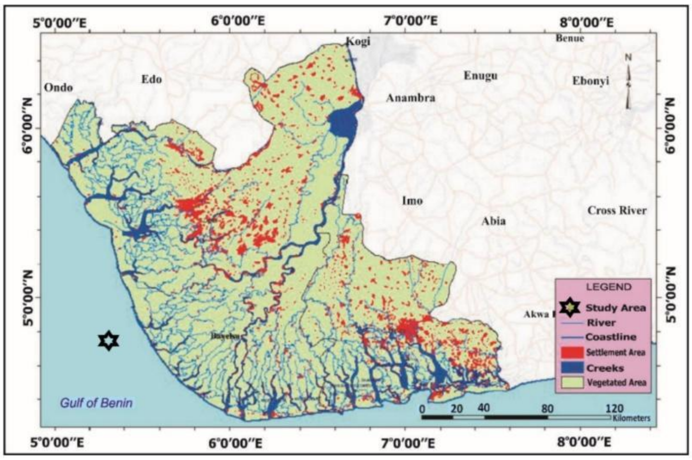


**Figure 1:** Map of Niger Delta showing the location of the study area (Adapted from Amangbara and Obenade, 2015)

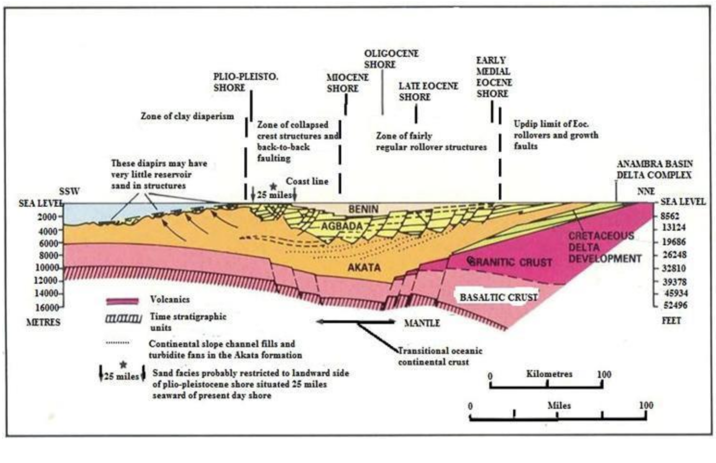


**Figure 2:** Generalized Dip Section of the Niger Delta with Major Formations and structural provinces of the Delta. (After Whiteman,1982)

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## 3.1 Well Logs

Lithologies were identified using a cut-off threshold of 75 API on the Gamma ray log to distinguish between sandstone reservoirs and shale lithologies. Three reservoirs were delineated and they were correlated across the wells to provide insights into distribution of geological formations in the field.

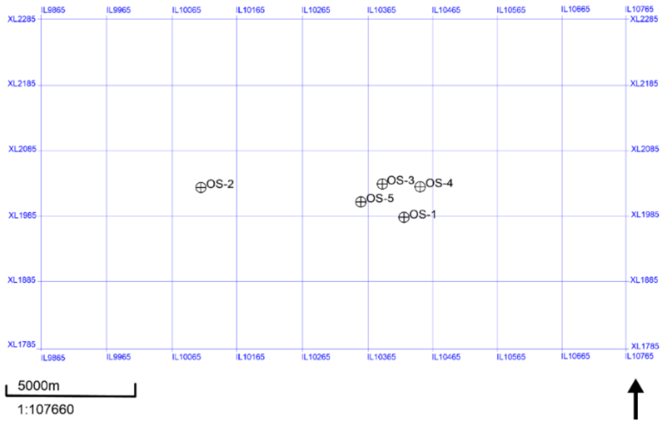



**Figure 3:** Schematic Base map showing the Study Area

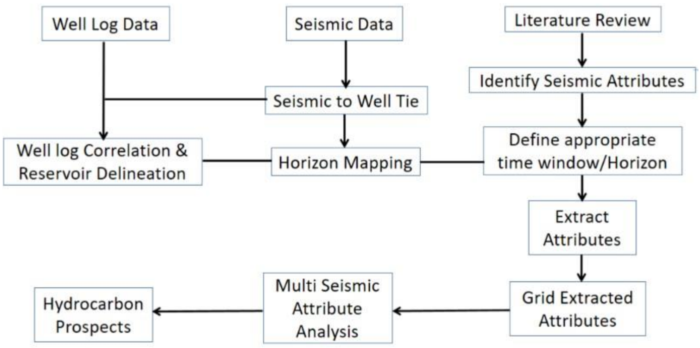



**Figure 4:** Workflow showing the Procedure of Seismic Attribute Analysis

## 3.2 Seismic Interpretation

To correlate wellbore information with the seismic data, a well-to-seismic tie was performed. This process uses checkshot data, which measures the travel time of seismic waves through known formations in the well, to convert seismic data from the time domain to the depth domain. This conversion allows for a more precise understanding of the reservoir's location within the seismic image. Synthetic seismogram for OS-5 was generated to further enhance the interpretation using sonic and density logs. The synthetic seismogram become valuable tools for matching with the seismic section once the well to seismic tie is established, enabling the generation of horizon time maps of the reservoir tops as the need arise.

## 3.3 Seismic Attributes

### *3.3.1 Instantaneous amplitude*

Amplitude refers to the magnitude of seismic trace values or the envelope of traces. The Instantaneous amplitude is a potent attribute employed to visualize sweeping changes in amplitude characteristics at a specific time. This attribute serves as a valuable indicator of hydrocarbons in seismic data analysis. High amplitude anomalies, known as bright spots, are often indicative of gas or oil presence in porous formations (Raef et al., 2017; Liu and Marfurt, 2007). However, the interpretation of seismic amplitudes for hydrocarbon detection is complex and influenced by various factors like reservoir lithology, seal features, and thickness (Sena and Swan, 1998). Integrating instantaneous attributes like frequency variations with amplitude anomalies can enhance the understanding of reservoir heterogeneities and aid in predicting hydrocarbon entrapment settings (Nanda, 2021). Therefore, considering instantaneous amplitude alongside other seismic attributes can improve the accuracy of hydrocarbon detection in subsurface exploration.

### *3.3.2 Instantaneous Frequency*

It is a measure of the rate of change of a seismic waveform over time. This attribute stands as a prime example of a physical seismic attribute due to its direct correlation with wave propagation, lithology, and other crucial physical parameters of subsurface rocks and reservoirs. Instantaneous frequency, a key seismic attribute, plays a vital role in characterizing subsurface geological formations (Ibekwe et al., 2023; Zhang et al., 2013). Its range of applications within seismic attribute analysis is extensive, encompassing various aspects of geological interpretation and significantly enhance the identification and mapping of hydrocarbon reservoirs.

### 3.3.3 Amplitude Envelope

This attribute is a measure of the average energy over a given time window. Amplitude envelope is also useful in mapping the continuity of a reflector. The amplitude envelope attribute is highly useful in mapping the continuity of a reflector, detecting channels, and characterizing hydrocarbon-charged sand units (Ming et al., 2022; Srisutthiayokorn et al., 2022). These attributes help in highlighting hydrocarbon anomalies by eliminating the influence of factors like reservoir thickness, thus enhancing the accuracy of detection (Syafiyanto et al., 2023). In subsurface data interpretation, such attributes aid in studying structural patterns and identifying hydrocarbon-bearing zones. By utilizing seismic attributes like amplitude envelope analysis, researchers can study structural patterns, and visualize areas with high amplitude reflections typical of hydrocarbon traps (Ibekwe et al., 2023; Ogbamikhumi and Igbinigie, 2020).

## 4. Results and Discussion

### 4.1 Well logs and Seismic Interpretation

Gamma ray logs were used to identify the lithology within the wells. The logs revealed the presence of two primary lithologies: sand and shale. This characteristic is indicative of the Agbada Formation, which is known for its interbedded sandstone and shale sequences. Figure 5 depicts a lithology log, where the yellow interval represents sand, and the grey interval represents shale. Three reservoirs were delineated across the five wells and the wells were tied to the seismic data using the check shot data (Figure 6) for its conversion to depth domain. This crucial conversion enabled the delineation of the observed reservoirs from the well logs onto the seismic sections. The horizons corresponding to these reservoirs were mapped on the seismic section using OS-5 well (Figure 7).

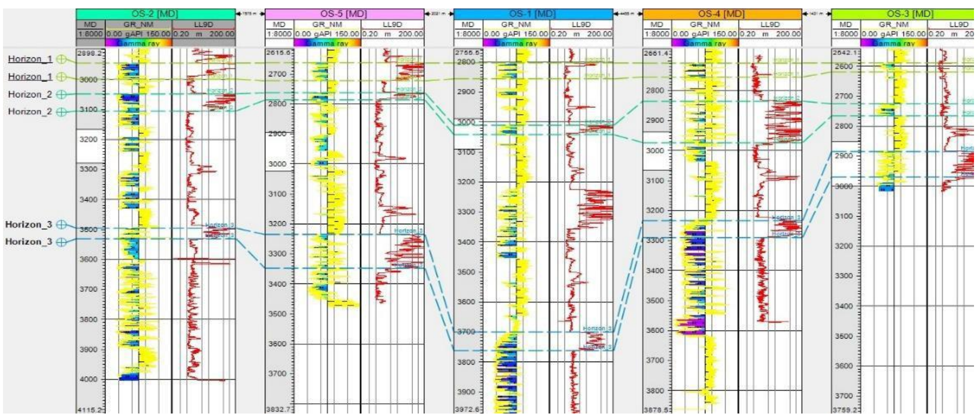



**Figure 5:** Well log Correlation panel of OS field

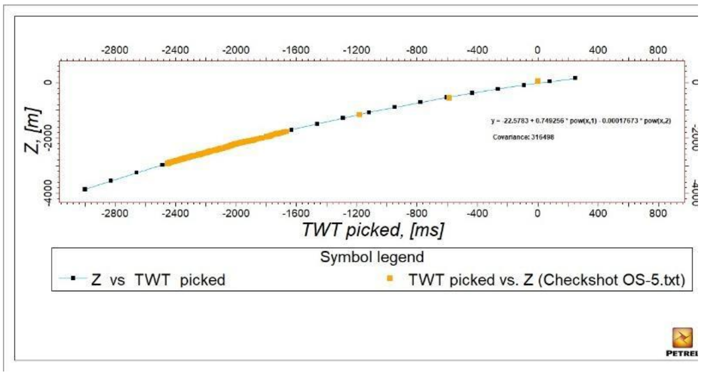



**Figure 6:** Conversion Graph from Time Domain to Depth Domain

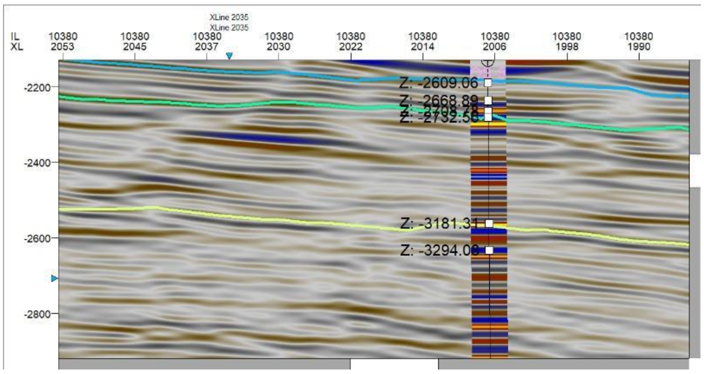
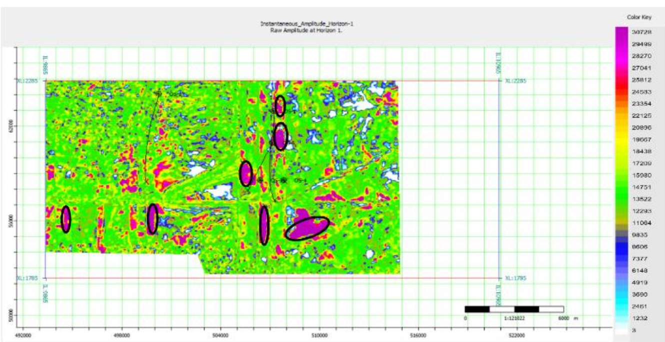



**Figure 7:** Seismic section showing interpreted horizons

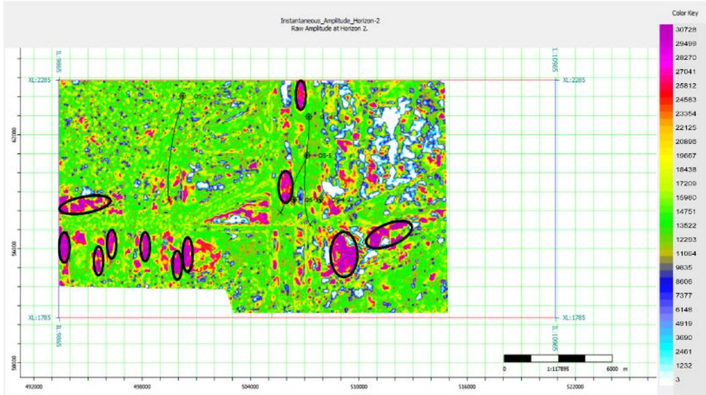
### 4.2 Seismic attributes

Figure 8a-c shows the distribution of instantaneous amplitude (IA) attributes of the horizons showing values ranging from 3 to 30728. The higher values are represented by purple, red to yellow colorations which is indicative of the presence of hydrocarbon since IA is a reliable indicator for the presence of hydrocarbon (Lawson-Jack et al., 2021; Emujakporue and Enyenihi, 2020; Chongwain et al., 2017. These zones of high instantaneous amplitude zones also suggest sediments with high reflectivity properties compared to surrounding sediments. This result compares favorably well with findings from other studies (Opara and Osaki, 2018; Adepoju et al., 2013; Chiadikobi et al., 2012). These areas hint at potential hydrocarbon prospect in the study area, with some zones being targeted for drilling. OS-1, OS-3 and OS-5 intersect with prospective zones in horizon 1, while OS-2 and OS-3 intersect with horizon 2, and Only OS-1 intersects with the prospective zones of horizon 3. There are more hydrocarbon prospects observed in horizons 1 and 2 when compared to horizon 3.

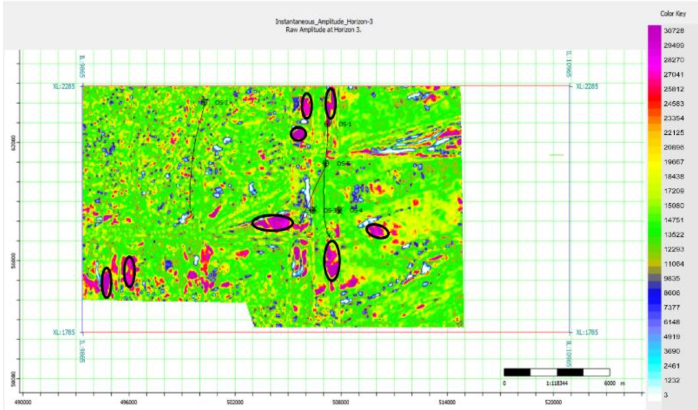
The result of the Instantaneous frequency analysis is shown in Figure 9a-c with values ranging from 2 (red) to 77 (purple). The lower instantaneous values (shown in red to yellowish colours) depicts highly porous sands, which may serve as potential hydrocarbon reservoirs. The applicability of this attribute in delineating bright spots and amplitude anomalies cannot be over emphasized (Opara and Osaki, 2018; Fozao et al., 2018; Islam et al., 2018). The segments displaying low Instantaneous frequency values on the map have the potential to be high quality hydrocarbon reservoirs. Coincidentally, some of the areas analysed to have high amplitude envelope on horizon 3 also have high instantaneous frequency which could be as a result of the fluid content.



(a)

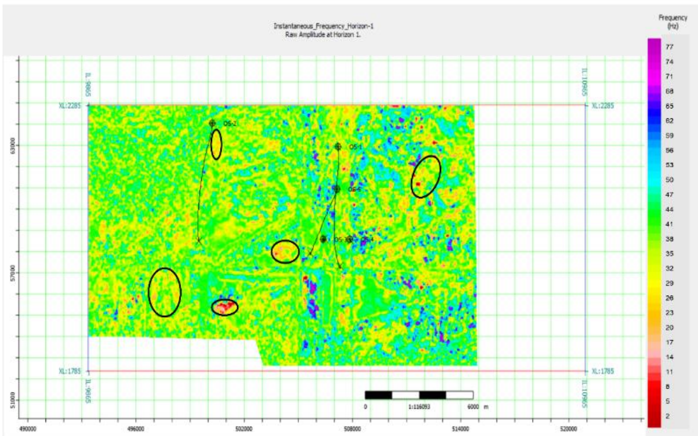


(b)

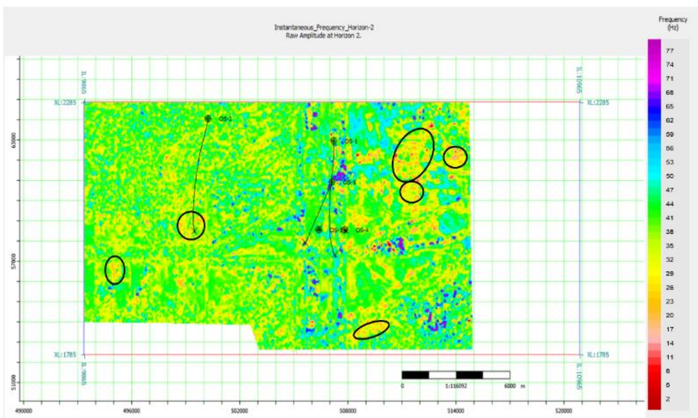


(c)

**Figure 8.** Horizon time slice of Instantaneous Amplitude inline 6875 for the tops of (a) Horizon 1 (b) Horizon 2 (c) Horizon 3



(a)



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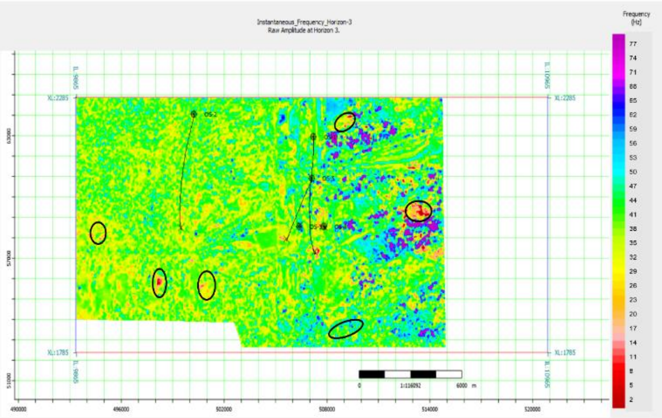
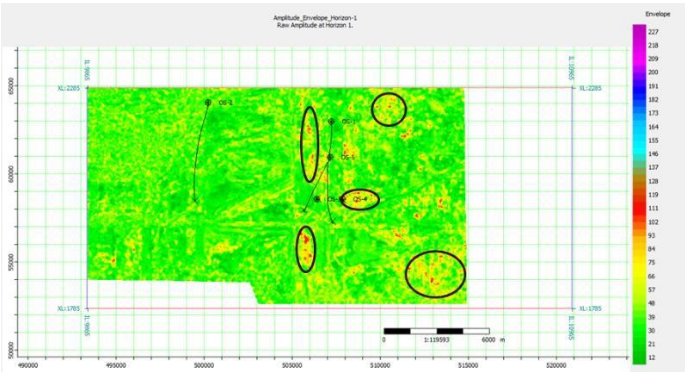


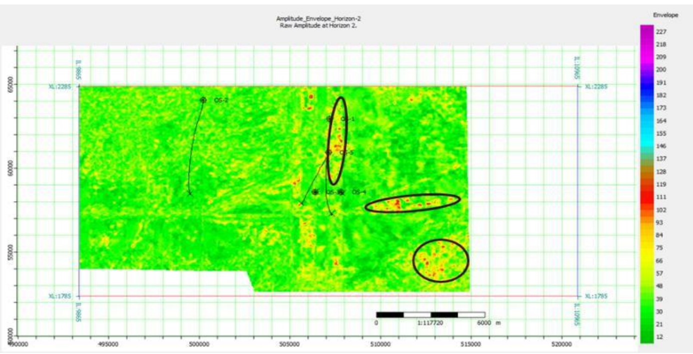
(c)

**Figure 9:** Horizon time slice of Instantaneous Frequency inline 6875 for the tops of (a) Horizon 1 (b) Horizon 2 (c) Horizon 3

Figure 10(a – c) represents the amplitude envelope (AE) values of the horizon time slices of the seismic data. The amplitude envelope value ranges from 0 (green) to 227 (purple). Shale intervals are typically characterized by a low seismic amplitude response. This weak reflection is often accompanied by a low amplitude envelope, reflecting the overall subdued nature of the seismic signal when encountering shale layers. Conversely, sand intervals generally exhibit high amplitude seismic reflections. This is because seismic waves travel more efficiently and with less energy loss through sandstones compared to shales. This stronger reflection translates to a high amplitude envelope on the seismic data. Areas with high amplitude envelope (yellow and red) indicate high amplitude within the horizons and are interpreted as hydrocarbon-bearing sand units. OS-5 and OS-4 wells are positioned in high AE zones on horizon 1, OS-1 and OS-5 wells on horizon 2, and OS-5 and OS-3 wells on horizon 3. The majority of high AE values are concentrated in horizon 3, particularly in the eastern part.



(a)



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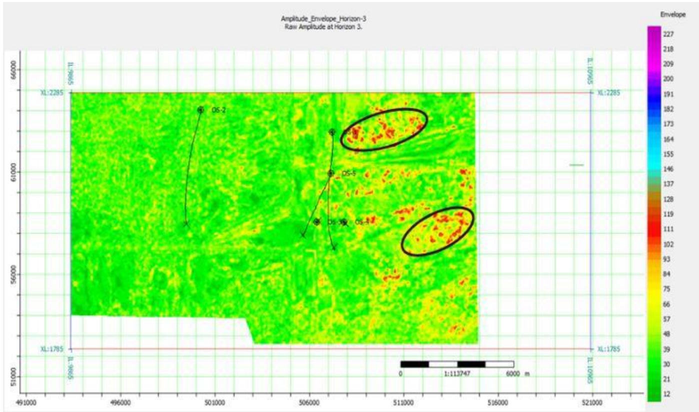

(c)

**Figure 10:** Horizon time slice of Amplitude envelope inline 6875 for the tops of (a) Horizon 1 (b) Horizon 2 (c) Horizon 3

## 5. Conclusions

In this study, Hampson Russel software was used in the extraction and population of different seismic attributes corresponding to hydrocarbon potential zones using seismic and well log data. The three delineated reservoirs were mapped on the seismic data across the five wells in the study area, with the OS-5 well serving as a key tie point for seismic-to-well correlation and the chosen seismic attributes were extracted. The seismic attributes used in this study include Instantaneous frequency, Instantaneous amplitude, and amplitude envelope. These attributes were interpreted with their relationship with the presence of reservoir sands and fluid contents which helps delineate potential hydrocarbon zones within the Agbada Formation. Results from these seismic attributes were analysed and used in highlighting hydrocarbon zones. High instantaneous amplitude, amplitude envelope and low instantaneous frequency correspond to these potential zones. The results suggest that horizons 1 and 2 hold more hydrocarbon prospects compared to horizon 3, with several wells intersecting with prospective zones. The eastern part of horizon 3, in particular, shows a high concentration of high amplitude envelope values, making it a promising area for further exploration. The analysis has led to a deeper understanding of how various seismic attributes were able to more effectively identify zones with a higher likelihood of containing hydrocarbons. The results from seismic attribute analysis can have great influence on hydrocarbon exploration and development by reducing associated risks. However, a more robust methodology of combining these seismic attributes should be worked on.


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## Author's contributions

Ayodele O. Falade: Conceptualization, Methodology, Software, Investigation, Writing-Reviewing and Editing. Olubola Abiola: Conceptualization, Methodology, Investigation, Validation, Editing, Supervision. John O. Amigun: Conceptualization, Methodology, Investigation, Validation, Editing, Supervision


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## Availability of data and materials

The data used in this study are proprietary to Shell Petroleum Development Company (SPDC) and can be obtained upon request through the Nigerian Upstream Petroleum Regulatory Commission (NUPRC). Due to privacy concerns, individual researchers cannot release the data without permission from the rights holder.

## Conflict of interests

The authors declare no conflict of interest.

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