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Elastic Property Variations of Hydrocarbon-Bearing Sandstones in *Uzondu* Field, Niger Delta Basin, Nigeria

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ABSTRACT: Comprehensive reservoir characterization requires integration of petrophysical evaluation and elastic property analysis to understand both storage capacity and seismic response. Therefore, the objective of this paper was to present the elastic property variations of hydrocarbon-bearing sandstones in Oil well A at Uzondu field, Niger Delta Basin, Nigeria using an integrated petrophysical and fluid replacement modeling (FRM). Five hydrocarbon-bearing sandstone reservoirs (Zones A–E) were identified within the depth interval of 8,100–11,470 ft, with a cumulative gross thickness of approximately 1,353 ft (412.39 m). Petrophysical evaluation indicates moderate to very high porosity (0.186–0.401), low water saturation (0.059–0.10), low clay volume (0.004–0.105), and moderate to excellent permeability (122.98–2,860 mD), confirming high-quality reservoir characteristics and strong hydrocarbon saturation across all zones. Fluid replacement modeling was applied to derive elastic parameters and evaluate depth-dependent stiffness variations. Compressional velocity (Vp) increases systematically from 5,693 ft/s in the shallowest reservoir to 13,475.8 ft/s in the deepest interval, while shear velocity (Vs) increases from 4,474 ft/s to 7,308 ft/s. Bulk density rises from 2.05 g/cc to 2.20 g/cc with depth. Correspondingly, acoustic impedance (Zp) increases from 11,671 to 29,647 ft/s·g/cc, and shear impedance (Zs) from 9,172 to 16,078 ft/s·g/cc. These progressive increases reflect burial compaction, porosity reduction, and enhanced rock stiffness rather than lithological variation, as all intervals are predominantly sandstone.

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The accurate characterization of hydrocarbon reservoirs in clastic-dominated basins, such as the Niger Delta Basin, is critical for optimizing exploration and production strategies. The Niger Delta is one of the most prolific hydrocarbon provinces in Africa, with thick sequences of interbedded sands and shales formed in a deltaic environment during the Tertiary (Short and Stauble, 1967). Reservoir sands are typically fine- to medium-grained, laterally variable, and often interbedded with thin shales that act as seals. This stratigraphic heterogeneity, combined with significant compaction and cementation effects, introduces substantial variability in elastic properties with depth, complicating seismic interpretation and reservoir evaluation. Elastic properties, including compressional velocity (Vp), shear velocity (Vs), bulk density (ρ), and derived impedances (Zp, Zs),

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are fundamental parameters controlling seismic response and reflecting the mechanical and lithological state of the reservoir. These properties are sensitive not only to lithology and porosity but also to burial depth, compaction, and fluid content, all of which affect rock stiffness and seismic reflection amplitudes (Castagna *et al.,* 1993; Avseth *et al.,* 2005; Avseth *et al.,* 2010). Accurate knowledge of elastic property variations is therefore essential for seismic calibration, reservoir characterization, and fluid discrimination. Traditional petrophysical analysis using well logs allows the identification of hydrocarbon-bearing intervals and estimation of key reservoir properties such as porosity, water saturation, and net-to-gross ratio (Nwankwo and Saadu, 2017; Omoja and Obiekezie, 2021; Lawson and Balogun, 2023). However, petrophysical logs alone do not provide a complete picture of elastic variations that govern seismic response. Fluid replacement modeling (FRM) is a well-established technique that estimates elastic parameters while accounting for the effect of reservoir fluids on rock velocities and density (Smith and Gidlow, 1987; Adeoye *et al.,* 2022; Hossain and Rahman, 2025; Salami and Nton, 2024). FRM allows the generation of depth-dependent elastic property trends that can be used to calibrate seismic models and improve interpretation accuracy (Mavko *et al.,* 2009; Adesanya *et al.,* 2021; Abe *et al.,* 2018).

Therefore, the objective of this paper was to present the elastic property variations of hydrocarbon-bearing sandstones in Oil well A at Uzondu field, Niger Delta Basin, Nigeria

MATERIALS AND METHODS

Location and geology of the study area: Uzondu Field is located in the south-south part of the Niger delta. It covers a perimeter of 16,547 meters and an area of 14,688,531 square meters. The area lies approximately between latitudes 4°32′N and 4°33′N and longitudes 6°59′E and 7°01′E, and is referenced in the Geographic Coordinate System (GCS), WGS 1984 datum (Fig. 1), This region is part of the coastal swamp and mangrove belt of the Niger Delta and is characterized by low relief, dense vegetation, and an extensive network of creeks and waterways. The presence of multiple waterways reflects the fluvial–deltaic environment that dominates the Niger Delta and influences sediment deposition and reservoir development.

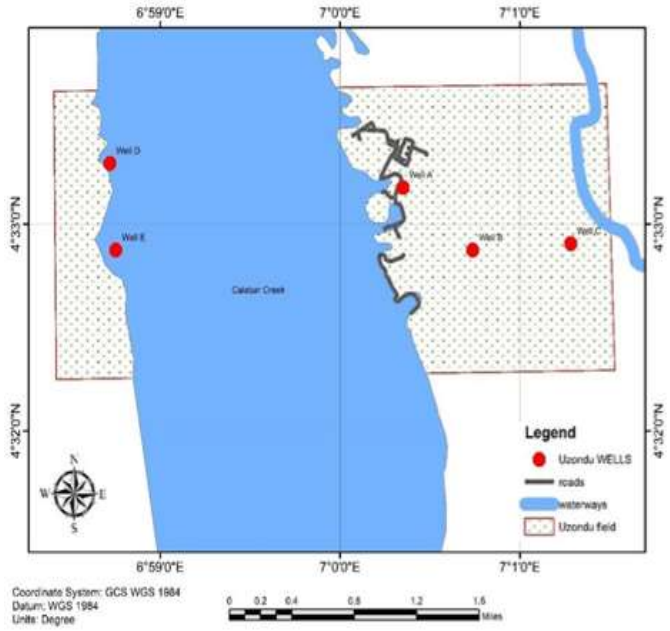


Fig. 1: map of the study area

A major surface feature within the study area is the Calabar Creek, which traverses the field from north to south and plays a serious role in shaping the geomorphology and sedimentary processes of the area. The presence of multiple waterways reflects the fluvial–deltaic environment that dominates the Niger Delta and influences sediment deposition and reservoir development.

The Niger Delta covers an area of about 75,000km^2 within the Gulf of Guinea, West Africa, Nigeria and is at least 11km deep in its deepest parts (Haack *et al.,*

2000). Although the modern Niger Delta was formed in the early Tertiary, sediments began to accumulate in this region during Mesozoic rifting associated with the separation of the African and South American continents (Evamy *et al.*, 1978; Doust and Omatsola, 1990). The structure and stratigraphy of Niger delta has been controlled by interplay between rates of sediment supply and subsidence (Doust and Omatsola, 1990). The Niger Delta province consists of three formation viz the Akata formation, Agada formation and Benin formation (Short and Stauble, 1967; Avbovbo, 1978; Doust and Omatsola, 1990). These three major lithostratigraphic units defined in the subsurface of Niger Delta reflect a gross upward coarsening clastic wedge (Lawrence *et al.*, 2002).These Formations were deposited in dominantly marine, deltaic and fluvial environments, respectively (Weber, 1987). Stratigraphically equivalent units to these three formations are exposed in southern Nigeria (Short and Stauble, 1967). The Niger Delta is characterized by syndepositional growth faults related to shale mobility and differential loading (Doust and Omatsola, 1990). These growth faults plays a critical role in sedimentation, reservoir development, hydrocarbon migration, hydrocarbon entrapment and reservoir compartmentalization (Corredor *et al.*, 2005). Growth faults form contemporaneously with sediment deposition, with displacement (throw) increasing with depth (Anomneze *et al.*, 2015). Many growth faults in the Niger Delta are listric (curved fault planes) that flatten with depth (toward a decollement or detachment horizon, often in the overpressured shale of the Akata Formation). This geometry leads to rollover anticlines on the hanging wall (Ajibade *et al.*, 2019; Etimita and Beka, 2019; Omoja and Obiekezie, 2019; Omoja *et al.*, 2025).

Description of data set and Method of analysis: The data set used for this study comprises of well log data from *Uzondu* field (*Uzondu*_A) made available by Shell Petroleum Development Company of Nigeria Ltd (SPDC). The well log include caliper (CAL) log, density (DEN) log, gamma ray (GR) log, p-wave log, resistivity (RES) log, and checkshot. Hampson-Russell software (HRS 10.6) program was used for this study. The well logs like gamma-ray, density, sonic, and resistivity were analyzed to identify hydrocarbon-bearing intervals. Key parameters computed include porosity, Shale volume (Vsh), Water saturation (Sw) and Net-to-gross ratio. Intervals with Low Vsh, moderate to high porosity, high resistivity, Low water saturation and low gamma-ray response were interpreted as hydrocarbon-bearing sands. Five (5) reservoir intervals (A–E) were delineated between 8,100 ft and 11470 ft.

The check shot data was used to calibrate the time - depth relationship of the well. This corrrection was applied to address discrepancies in velocities derived from the integration of the sonic interval transit time ((P-wave log). The check shot correction introduces a drift curve, which quantifies the difference between the integrated sonic time and the measured check shot time, thereby improving the accuracy of the velocity model. The S-wave log was then created using Castagna's mudrock equation (Castagna *et al.*, 1985) which relates S-wave and P-wave velocity by a linear equation 1

$$S - wave = C_1 * P - wave + C_2 \quad (1)$$

Where C_1 and C_2 are constant whose values are given as 0.86190 and -1172.00000 respectively.
Poission's ratio log was also created but since Castagna's equation is only valid for the wet background shale, a different calculation to model the gas sand within the target zone was used.
Fluid Replacement Modeling (FRM) was employed using Biot-Gassman's equation (Gassmann, 1951) which is given in equation 2

$$\mathrm{K_{sat}} = \mathrm{K_{dry}} + \frac{\left(1 - \frac{\mathrm{K_{dry}}}{\mathrm{K_m}}\right)}{\phi\frac{1}{\mathrm{K_{fl}}} + \frac{1-\phi}{\mathrm{K_m}} + \frac{\mathrm{k_{dry}}}{\mathrm{K_m^2}}} \quad (2)$$

Where K=bulk modulus, sat=saturated, dry=dry frame, m=rock matrix, fl=fluid and ϕ =porosity. Three new logs were created in the process. The new logs includes the P-wave log (i.e. P-wave_1_FRM), the Density log (Density_1_FRM) and the S-wave log (S-wave_Castagna_FRM). The shear modulus (μ) remains unaffected by fluid substitution. From the FRM results, these elastic properties were computed:

$$\text{Compressional Velocity } V_P = \sqrt{\frac{K_{sat}+\frac{4}{3}\mu}{\rho}} \quad (3)$$

$$\text{Shear Velocity } V_S = \sqrt{\frac{\mu}{\rho}} \quad (4)$$

$$\text{Bulk Density } \rho = (1-\phi)\rho_{ma} + \phi\rho_f \quad (5)$$

$$\text{Acoustic impedance } Z_P = V_P * \rho \quad (6)$$

$$\text{Shear impedance } Z_S = V_S * \rho \quad (7)$$

These parameters were computed for each reservoir interval (A–E) and analyzed as a function of depth

RESULTS AND DISCUSSION

The well log analysis of *Uzondu*_A reveals the presence of five(5) distinct hydrocarbon bearing reservoir zones (A-E) (Fig. 2) within the depth of 8100-11470 ft. All identified resrvoirs are characterized by sandstone lithology and are interpreted to be hydrocarbon-bearing, indicating favorable depositional conditions and consistent reservoir development across the well. The individual reservoir thickness ranges from 135ft to 537.5 ft, resulting in a cummulative gross reservoir thickness of approximately 1353 ft (412.39 m) (Table 1). The significant vertical stacking of these sandstone units suggests strong reservoir continuity and substantial hydrocarbon potential. Porosity values across the reservoir range from 0.186 to 0.401, with an average porosity of approximately 0.322, reflecting moderate to very high porosity, typical of unconsolidated to weakly consolidated deltaic sandstones of the Niger Delta. These values indicate good to very good reservoir quality, reflecting well-developed pore systems capable of storing hydrocarbon. The highest porosity was observed in Zone B while the lowest porosity occurred in Zone E, which remains within the range considered favorable for productive sandstone reservoirs.

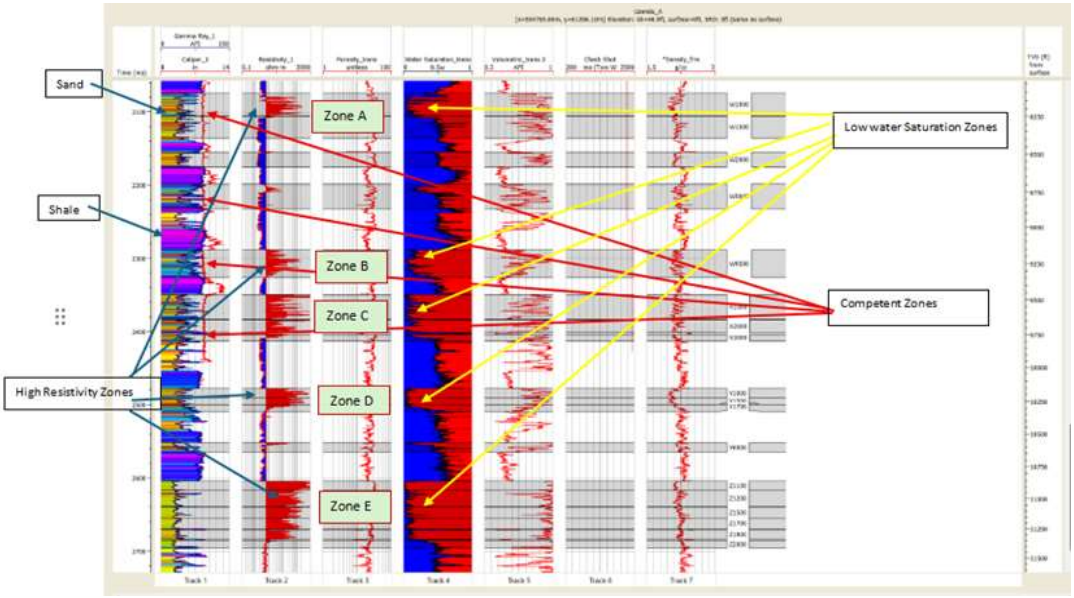


Fig. 2: results of well log analysis of *Uzondu*_A

Table 1: summary of well log analysis of well *Uzondu*_A

Rerservoir	Top Name	Top (ft)	Base (ft)	Gross (ft)	Net	N/G	Av Phi	Av Sw	Av Vsh	Perm(mD)
A	W1000	8155	8290	135	135.0	1.000	0.399	0.100	0.105	2660.00
B	W9500	9204	9393	189	188.5	0.997	0.401	0.074	0.078	2860.00
C	X1000 -X3000	9508	9845	319	319.0	1.000	0.338	0.079	0.043	1206.39
D	Y1000 -Y1700	10198	10374	173	173.0	1.000	0.284	0.059	0.023	532.49
E	Z1100 -Z2000	10904	11464	544	537.5	0.988	0.186	0.077	0.004	122.98

The overall porosity distribution supports the interpretation of high-quality resevoir rocks throughout the analyzed intervals. Water saturation values range from 0.059 to 0.1, with an average of about 0.079, indicating that hydrocarbons constitute the dominant pore fluid within the reservoir. Zone D exhibits the lowest water saturation (0.059), suggesting a high hydrocarbon saturation and enhanced production potential, whereas Zone A has the highest water saturationvalue of 0.1, which is still seggest goog reservoir quality. Despite these variations, all zones display water saturation levels consistent with hydrocarbon-bearing reservoir and remains economically attractive. Shale volume was generally low (Vsh ranges from 0.004 to 0.105) confirming a dominance of clean sands. Zone E has the lowest Clay volume of 0.004 while Zone A has the highest volume of clay of 0.105, the average clay volume of about 0.051 for the whole reservoir. Estimated permeability values range from 122.98 mD to 2,860 mD, with the highest permeability recorded in Zone B (2,860 mD) and Zone A (2,660 mD). These values indicate excellent pore connectivity and flow capacity, reinforcing the interpretation of these intervals as prolific reservoirs. Deeper reservoir zones (Zone D and Zone E) show a decline in porosity and permeability, attributed to burial compaction, but yet still retain fair reservoir quality.

The combined effects of substantial reservoir thickness, moderate to high porosity, very good permeability and relativel low water saturation and volume of clay indicate that the reservoirs in *Uzondu*_A are of good overall quality. Collectively, the quantitative results demonstrated that *Uzondu*_A contains multiple stacked, laterally persistent sandstone reservoirs with significant hydrocarbon potential, making the well a strong candidate for further development and production planning. The corrested sonic log was generated and displayed alongside the original logs in track 3 and 6 (Fig. 3), providing a more reliable representation of the subsurface velocities. The result of the fluid replacement modeling perfomed to calculate the correct S-wave behaviour for the gas sand is shown in (Fig. 4). Within the clean sandstone reservoir section identified as Zones A-E (which correspond to high resistivity), it was observed that the amplitude of the density log and that of Poisson's ratio log decreased, while P-wave log and S-wave log increase slightly.

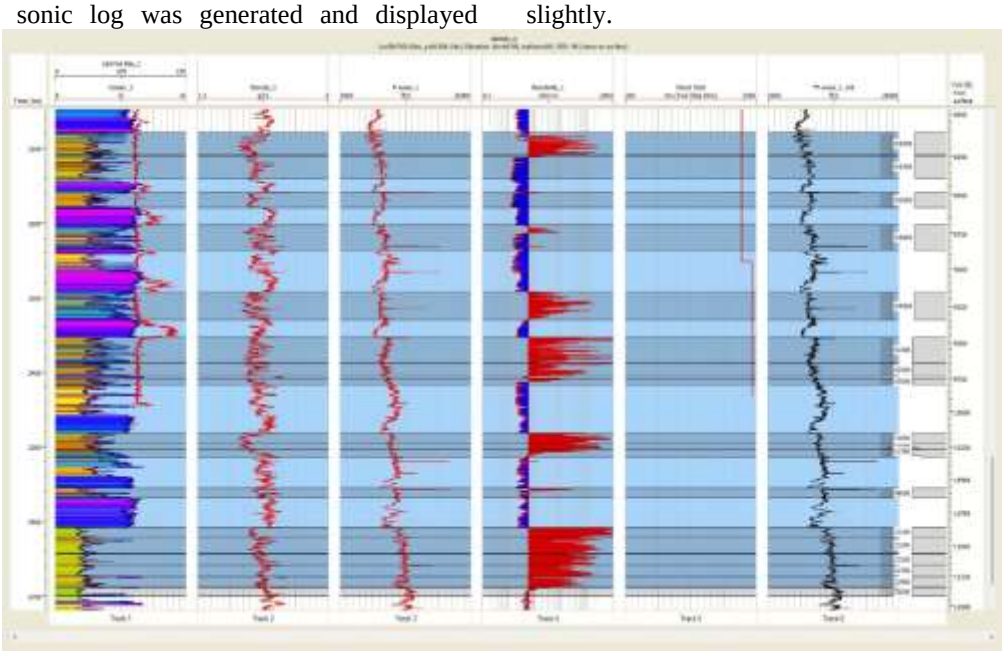


Fig. 3: Input logs showing the checkshot corrected P-wave log (track 6)

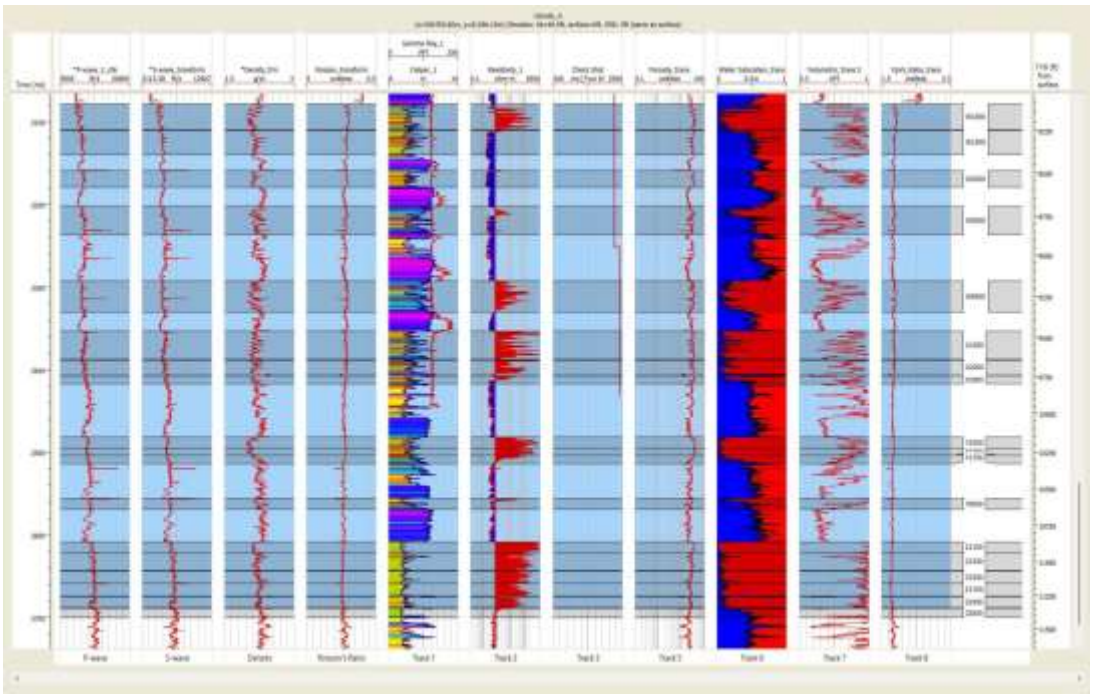


Fig. 4: S-wave and other logs (after FRM)

The result of the elastic parameters estimated after fluid replacement modeling (FRM) for Uzondu_A indicate systemic variation with depth that are consistent with compaction effects and changes in rock stiffness within the sandstone reservoirs. All reservoirs are classified according to litholgy as sandstone, allowing the observed wariations in elastic properties to be primarily attributed to depth-related changes in pressure, cementation and elastic moduli rather than lithological heterogeneity. Compressional wave velocity (Vp) (Table 2) shows a clear increasing trend with depth, rising from 5,693 ft/s in Reservoir A at 8,100 ft to 13,475.8 ft/s in Reservoir E at 10,850 ft. This progressive increase reflects enhanced rock stiffness due to compaction and improved grain-to-grain contact at greater burial depths.

A similar trend was observed in shear wave velocity (Vs), which increases from 4,474 ft/s to 7,308 ft/s across the same depth interval. The concurrent increase in both Vp and Vs suggests a general strengthening of the elastic framework of the sandstones with depth, consistent with mechanical compaction and possible cementation. Bulk density (ρ) also increases gradually from 2.05 g/cc in Reservoir A to 2.20 g/cc in Reservoir E. This density increase supports the velocity trends and indicates progressive reduction in porosity with depth, which is typical of sedimentary sequences subjected to increasing overburden stress. The relatively moderate density values across all reservoirs are still characteristic of sandstone and remain compatible with hydrocarbon-bearing intervals, particularly when considered alongside prior petrophysical results. Acoustic impedance (Zp) values exhibit a pronounced increase from 11,671 ft/s·g/cc in Reservoir A to 29,647 ft/s·g/cc in Reservoir E, driven by the combined effects of increasing Vp and density. This strong impedance contrast with depth implies that deeper reservoirs will produce stronger seismic reflections relative to shallower units, enhancing their detectability on seismic data. Similarly, shear impedance (Zs) increases from 9,172 ft/s·g/cc to 16,078 ft/s·g/cc, reflecting the stiffening of the rock matrix and increasing resistance to shear deformation. The elastic parameter trends indicate that the sandstone reservoirs in Well *Uzondu*_A become progressively stiffer, denser, and more impedance-dominated with depth. Reservoirs A to C exhibit lower velocities and impedances, consistent with relatively less compacted sandstones, while Reservoirs D and E display significantly higher elastic moduli, suggesting more consolidated reservoir intervals. These results provide a robust elastic framework for seismic interpretation, post-stack modeling and reservoir characterization in the *Uzondu* Field. The logs are shown in Figure 5

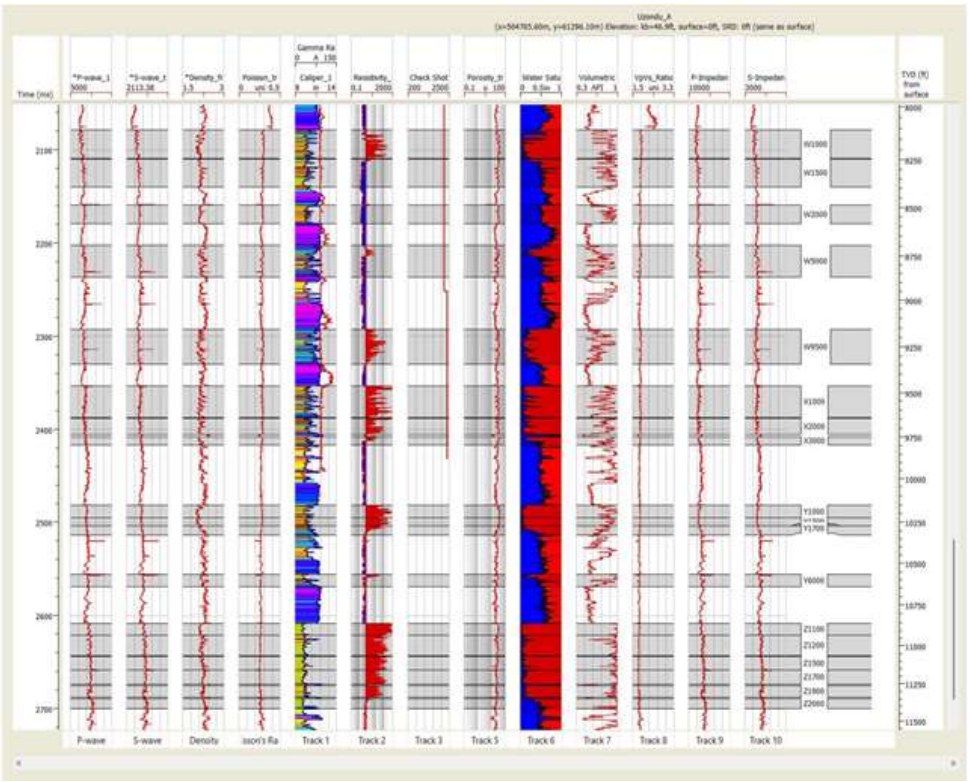


Fig. 5: showing elastic Impedances

Table 2: Estimated elastic parameters for well *Uzondu*_A after FRM

Reservoir	Lithology	Depth(ft)	Time(ms)	V_P (ft/s)	V_S (ft/s)	ρ (g/cc)	Z_P (ft/s.g/cc)	Z_S (ft/s.g/cc)
A	Sandstone	8100	2100	5693.0	4474	2.05	11671	9172
B	Sandstone	9150	2300	6865.0	4879	2.07	14207	10100
C	Sandstone	9460	2350	7302.3	5891	2.10	15335	12371
D	Sandstone	10150	2500	9169.5	6094	2.15	19714	13103
E	Sandstone	10850	2650	13475.8	7308	2.20	29647	16078

Conclusion: The results from the elastic property variations of hydrocarbon-bearing sandstones in Uzondu field, Niger Delta Basin, revealed a systematic depth-dependent increases in compressional velocity (Vp), shear velocity (Vs), bulk density (ρ), acoustic impedance (Zp), and shear impedance (Zs). The elastic property trends reflect progressive burial compaction, porosity reduction, and enhanced grain-to-grain contact rather than lithological variation, as all intervals are predominantly sandstone.

DECLARATIONS

Ethical Approval: This study did not involve human participants or animal experimentation and therefore did not require formal ethical approval. All procedures involving data handling and analysis were conducted responsibly and in accordance with standard academic and institutional guidelines.

Disclaimer (Artificial Intelligence): Author(s) hereby declare that generative AI technologies such as ChatGPT (Open AI), version 1.2026.43.0 have been used during language editing of this manuscript. The authors reviewed and edited the output and take full responsibility for the content of the publication.

Declaration of Conflict of Interest: The authors declare that no known conflict of interest or personal relationships that have influence the work reported in this paper.

Declaration of Data Availability: Data are available upon request from the corresponding author

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