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Application Of 4-D Seismic Data in Reservoir Monitoring and Management Using Seismic Inversion in Ida Field Onshore of Niger Delta Basin, Nigeria

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Abstract

This work highlights the potential for enhanced hydrocarbon recovery in the Ida Field by identifying viable bypassed zones and understanding production-induced reservoir changes through advanced seismic analysis. A 4-D seismic data in reservoir monitoring and management using the seismic inversion method was carried out in the Ida field onshore Niger Delta Nigeria to evaluate the production-related changes. The 3-D data sets were processed through non-amplitude preserving processing while 4-D data sets were processed through amplitude preserving for reservoir monitoring purposes. Three reservoir units were analyzed and they are designated as HD2000, HD3000 and HD5000. From petro-physical results, the initial average porosity and water saturation are 29.30% and 17.50% respectively. The average porosity and water saturation after the steam injection program are 36% and 28.33% respectively. The result shows an exponential increase in both water saturation and porosity concerning the time-steps due to production effects. The plots of fluid properties against temperature and pressure in the reservoir revealed that gas modulus, gas velocity oil density, and oil modulus decrease with increasing temperature while gas velocity and brine velocity increase with temperature. The result of histogram plot of the velocity ratio and P – impedance indicates high brine saturation in the reservoir which probably results from production-related changes. Finally, the inverted acoustic impedance of 3-D and 4-D seismic volume of the Ida field has enabled the discrimination of different lithologies, and fluids and the bypass hydrocarbon intervals away from the current well location to determine areas for further drilling in the field.

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Introduction

The Niger Delta region, one of the world's most prolific hydrocarbon provinces, is characterized by its complex geological formations and diverse reservoir types, which present both opportunities and challenges for oil and gas exploration and production (Tuttle *et al.*1999). As energy demand continues to rise, optimizing hydrocarbon recovery from existing fields has become increasingly critical. Traditional methods of reservoir evaluation often fall short in capturing the dynamic changes that occur during production, necessitating the integration of advanced technologies such as 4-D seismic monitoring (Burianyk *et al.*, 2000b; Calvert, 2005; Aniwetalu *et al.*, 2017).

4-D seismic data, which involves the repeated acquisition of seismic surveys over time, allows for the observation of temporal changes in reservoir properties, providing valuable insights into fluid movement and saturation changes (Mitra, 2024). 4-D seismic (time-lapse seismic) is used in reservoir monitoring to track changes in fluid saturation, pressure variations, and reservoir depletion patterns by comparing seismic surveys taken at different times. According to Mitra (2024), fluids like oil, gas, or water moving through the reservoir alter the rock's acoustic properties, and these changes are captured in the seismic data. Additionally, pressure variations affecting the seismic response can be inferred by analyzing the differences in seismic data over time. This information is crucial for optimizing production strategies, planning infill drilling, and managing enhanced oil recovery projects. This technique has proven effective in various fields, enabling operators to make informed decisions regarding reservoir management and enhanced oil recovery strategies (Sambo *et al.*, 2020). In particular, the application of seismic inversion techniques can further refine our understanding of subsurface conditions by transforming seismic data into quantitative estimates of reservoir properties, such as porosity and saturation (Aziz Abdolahi *et al.*, 2022). This technique is used to transform seismic reflection data into quantitative rock-property descriptions of a reservoir. By converting seismic data from an interface property (reflection) to a rock property (impedance), seismic inversion provides detailed information about the subsurface, such as lithology, fluid content, and porosity, (Pendrel, 2006). This process enhances the resolution and reliability of seismic data, making it a valuable tool for reservoir characterization and hydrocarbon exploration.

This study focuses on the Ida Field, located in the onshore Niger Delta, where the integration of 4-D seismic data and inversion techniques has been employed to evaluate production-related changes in reservoir characteristics. By analyzing the impact of steam injection on reservoir properties, this research aims to provide a comprehensive assessment of porosity and water saturation variations, as well as to identify bypassed hydrocarbon intervals that may present opportunities for future drilling. The findings of this study are expected to contribute significantly to the understanding of reservoir dynamics in the Niger Delta and to enhance the overall efficiency of hydrocarbon recovery in the region. Ultimately, the findings from this research will not only enhance the operational efficiency of the Ida Field but also provide a framework for similar applications in other fields within the Niger Delta and beyond, paving the way for more sustainable and effective resource management in the oil and gas industry.

Location and Geology of the Study Area

Ida Field is located in the Central Swamp, Onshore depobelt of western Niger Delta, Nigeria. The area is situated on the continental margin of the Gulf of Guinea in West Africa at the Southern end of Nigeria. Ida Field is located between Latitudes 4º and 7ºN and Longitudes 3º and 9º E. Three main subdivisions have been recognized in the subsurface of the Niger Delta complex, (Short and Stauble,1967). The basal unit is the Akata Formation, overlain by the Agbada Formation with the topmost unit as the Benin Formation. The Akata Formation is generally open marine and pro delta dark grey shale with lenses of silt stones, sand stones and plant remains at the top. Agbada Formation consists of cyclic coarsening upward regressive sequences and poor sorting from migration and deposition which indicates fluvial origin. Benin formation has an alternation of sands, silts and clay in various proportions and thicknesses, representing cyclic sequence off lap units.

Materials and Methods

Ida Field is located in the prominent Oil Mining Lease (OML) in the Onshore Depobelt in the western Niger Delta. The 3D seismic surveys (Base) were acquired in mid-nineties and covered about 120km^2. The maximum offset was less than 5000 meters, which was determined based on the geological information of the area while the target is about 3000m.

In August 2012, a 48-fold repeat acquisition (4-D seismic Survey or Monitor) was completed over the earlier 12 folds. The sample interval used is 4ms for the initial survey and 2ms for the reshoot survey. This implies Nyquist frequencies of 125Hz and 250Hz for the base and monitor respectively, since

$$FN = \frac{1}{2\ \Delta t} \qquad 1.0$$

Where F_N is the Nyquist frequency which is the maximum frequency recorded, and Δt is the sampling interval in milliseconds (ms). This is necessary to avoid anti-aliasing during sampling at the processing stage. The detailed processing flow of these data was specifically carried out in SPDC proprietary software in SIPMAP format. For the Base, the applied anti-lias filter was in the range of 110Hz- 72 dB/Oct while the range of frequency in the monitor was broader (5-125Hz). The monitor survey also has a higher common depth point (CDP) fold especially in the central parts of the survey area which peaks at about 800 CDP fold for each bin. It has a maximum far offset of 4484m compared to 2865m of the base. The data sets were processed through a non-amplitude preserving processing while 4-D datasets were processed through amplitude preserving processing for reservoir monitoring purposes. The research focuses on the analysis of reservoir changes between these two seismic vintages (1995-2012). In processing seismic datasets, the two major challenges were how to produce data with reliable amplitude preservation and repeatability, matching two different seismic surveys in such a way that any changes in velocities, amplitudes and frequencies should be the effects of CO_2 injection rather than artefacts derived from error in acquisition design. Available well log data of Density,Resistivity,Gamma,P.wave and Caliper (Figure 4.1a-b) were used to make a detailed record of the geologic formations penetrated by the 5 wells. Acoustic Impedance inversion and, crossplots of Gas modulus, Oil velocity, Gas velocity as a function of Temperature were applied to discriminate the fluid types. Data calibration and validation steps enhanced the reliability of the study, particularly in observing fluid displacement and pressure maintenance due to steam injection. By ensuring that the seismic data is accurately matched and validated against well log data, the study reveals significant increases in average porosity from 29.30% to 36% and water saturation from 17.50% to 28.33%. Additionally, the identification of bypassed hydrocarbon intervals through advanced 4-D seismic monitoring, supported by rigorous calibration and validation, underscores the effectiveness of reservoir management strategies, providing new opportunities for enhanced oil recovery in the Niger Delta.

Results and Discussion

Three reservoir units were analyzed and they are designated as HD2000, HD3000 and HD5000 (Figure1a-b). The results of average petro-physical parameters of the reservoir before the steam injection program in Ida Field were analyzed in Table 1 to 3. The highest porosity value was observed in HD5000 reservoir while the lowest porosity values occurred in HD2000 reservoirs. HD3000 reservoir has high water saturation probably due to production-related changes. However, from the available petro-physical results, the initial average porosity and water saturation of the field before the steam injection program are 29.30% and 17.50% respectively. The results of the injection program in the field show exponential increase in both water saturation and porosity to the time steps of production, hence 4D seismic provides real time insights into fluid movement and pressure changes within the reservoir, (Table 4 and Figure. 3.0). This means that as production and steam injection in the reservoir increase the porosity and water saturation also increase. The effect of these reservoir properties on in situ pressure and temperature was evaluated using Batzle and Wang (1992) relations. Reservoir fluid properties have different responses to the effect of temperature and pressure.

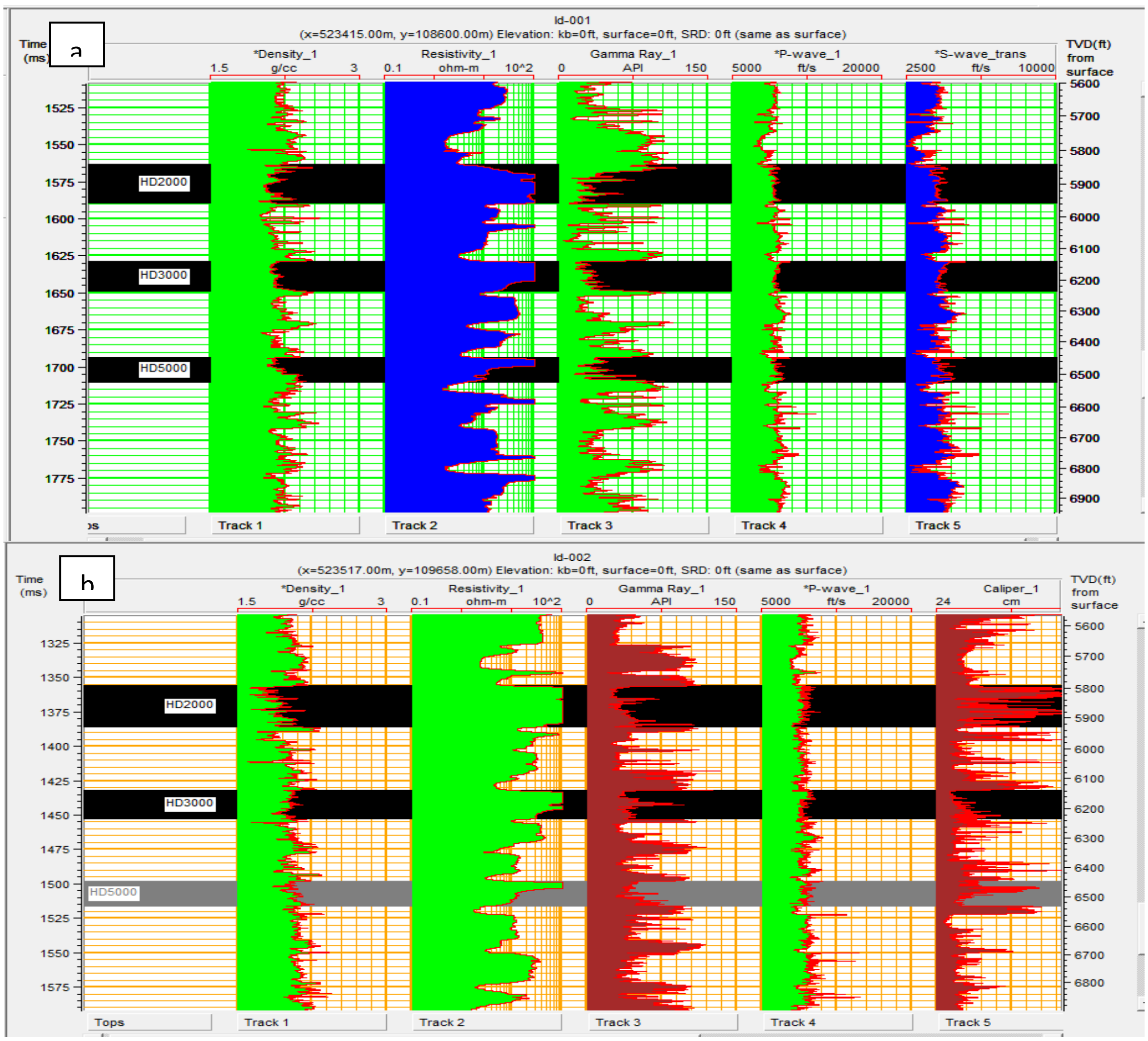

Figure 1a-b: The well logs section (Density,Resistivity,Gamma,P.wave and Caliper)

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Table 1: Petro-physical reservoir Properties of Ida-001

Horizons	Top depth	Base depth	Oil Down	HCWC	Porosity	Water Saturation
HD2000	5842	5964	5961	-	28	13
HD3000	6144	6243	-	6207	30	17
HD5000	6450	6533	-	6479	32	16

Table 2: Petro-physical reservoir Properties of Ida 002

Horizons	Top depth	Base depth	Oil Down	HCWC	Porosity	Water Saturation
HD2000	5842	5964	5961	-	28	13
HD3000	6144	6243	-	6207	30	17
HD5000	6450	6533	-b	6479	32	16

Table 3: Petro-physical reservoir Properties of Ida 003

Horizons	Top depth	Base depth	Oil Down	HCWC	Porosity	Water Saturation
HD2000	5932	5971	-	5932	28	12
HD3000	5983	6107	-	5983	32	15
HD5000	6629	6704	-	6629	30	9

Table 4: Average Water Saturation and Porosity of Ida Field after Steam injection Program

Time-steps (yrs)	Ave. Water saturations (%PV)	Ave. Porosity (%)
1999	18.35	30.20
2000	19.11	31.12
2001	20.03	32.00
2002	22.83	33.23
2003	25.32	34.20
2004	26.45	35.12
2005	27.67	36.80
2006	32.00	38.23
2007	35.65	39.00
2008	38.34	40.21
2009	41.45	40.71

It appears that gas modulus, oil modulus, and oil density, decrease with increasing temperature while Gas modulus and oil velocity increase with increasing pressure (Figure 2). In saturated hydrocarbon reservoirs, fluid modulus distributes in between gas, oil and water. The properties of modeled responses of pore fluids such as gas, oil and brines in the substitution zone were examined. We observed that gas can dissolve in brine due to the CO_2 injection during the enhanced oil recovery program. These reservoir fluids were differentiated using well log attributes crossplots. The plots distinguished hydrocarbon-charged zone, brine-charged zone and shale-dominated zones in the reservoir (Figure 4a and Figure 4b). The result indicates high brine saturation in the reservoir which probably results from production-related changes. The increase in water saturation in the reservoir is always acompanied by a decrease in the hydrocarbon. This is because as production increases in the reservoir more hydrocarbons are being produced resulting into increase in formation water. To extend the behaviour of the well properties to seismic data, acoustic impedance inversion of the base and monitor were carried out. The principal objective of seismic inversion is to transform reflectivity data into quantitative rock properties which is descriptive of reservoirs (Batzle and Wang, 1992). The inverted acoustic impedance of 3-D and 4-D seismic volume of Ida Field has enabled the discrimination of different lithologies, and fluids and bypassed hydrocarbon intervals away from the current well

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locations in the field (Figure 5a-b). The interpretation of these reservoir properties is based on their acoustic impedance ranges. Shale layers and brine-charged sand are associated with high acoustic impedance. The well locations in the inverted base are associated with low acoustic impedance which is indicative of hydrocarbon while the well locations in the inverted monitor are associated with an increase in acoustic impedance which is also an indication of production-related changes. The increases in acoustic impedance in the monitor were interpreted as production-related effect. The positive increase in acoustic impedance anomaly as observed in these areas is a result of water, replacing oil or CO_2 in the reservoir resulting to increase in reservoir pressure. The research on the Ida Field highlights significant observations regarding fluid displacement and pressure maintenance due to steam injection, which resulted in an increase in average porosity from 29.30% to 36% and water saturation from 17.50% to 28.33%. The study indicates that the effective reservoir pressure increases with fluid injection, leading to less compressible pore fluids and higher velocities, which are critical for maintaining pressure in the reservoir. Furthermore, the identification of bypassed hydrocarbon intervals through advanced 4-D seismic monitoring underscores the effectiveness of reservoir management strategies, providing new opportunities for enhanced oil recovery and optimizing hydrocarbon extraction in the Niger Delta. The zone in red, blue and purple are increasing order of acoustic impedance while zone in yellow and green correspond to reduction in acoustic impedance (Figure 1.5a-b) very low acoustic impedance are noticeable in the base and little in the monitor which is interpreted as hydrocarbon saturation or charged sand bodies since they exhibit consistently low acoustic impedance values. A considerable increase in acoustic impedance is observed in the monitor and when compared to the base indicates hydrocarbon saturation changes over time. The increases in acoustic impedance in the monitor were interpreted as production related effect. The positive or increase in acoustic impedance anomaly as observed in these areas are as a result of water replacing oil or CO_2 in the reservoir resulting to decrease in reservoir pressure

The bypassed hydrocarbon intervals were predicted by deriving stratigraphic attribute slices from the base and monitor. Low instantaneous phases are prevalent in the base, especially at well locations in the central parts of the field (Figure 6a). In the difference slice, the previously low instantaneous phase zones at well locations were replaced with a high instantaneous phase which is an indication of production induced changes (Figure 6b). Low instantaneous phase observed in the south-western parts of the slices away from the well locations were interpreted as bypassed hydrocarbon intervals. Pockets of bypassed hydrocarbon-bearing sands are also prevalent in the slice. The high instantaneous phase noticed around the well locations in the difference slice could probably be as a result of the water or CO_2 saturations in the producing reservoir. This result was also validated using instantaneous frequency attributes which reflect a similar pattern of the phase attribute. The bypassed hydrocarbon intervals were interpreted as viable zones for further drilling actions in the field (Figure 1.6a-b), as current producing zones have shown signs of depletions. The pressure regimes in the reservoir introduced by production-related changes were analyzed. This resultwas also validated using a crossplot of first and second Lame parameters. The Lamé parameter is sensitive to both fluids making it a reliable tool for prediction in the reservoir (Ji *et al.*, 2010; Ezeh, 2015).

As fluids are injected inside the reservoir, the effective reservoir pressure increases which also result in to increase in velocity (Figure 7a-c). Increasing pore pressure in the reservoir also tends to make the pore fluid or gas less compressible, tending to increase velocities. The velocity depth model revealed pressure variations at each depth interval in the field. The high-pressure variations at various reservoir depth intervals probably occur due to steam injection in the reservoir which creates stress paths in the reservoirs. These pressure imprints are indicated by high elastic impedance. The orientation of the pressure in the reservoir follows a similar injection pattern of northwest to southwest direction. This signifies that steam injection in the reservoir is the principal factor in the pressure builds up in the reservoir.

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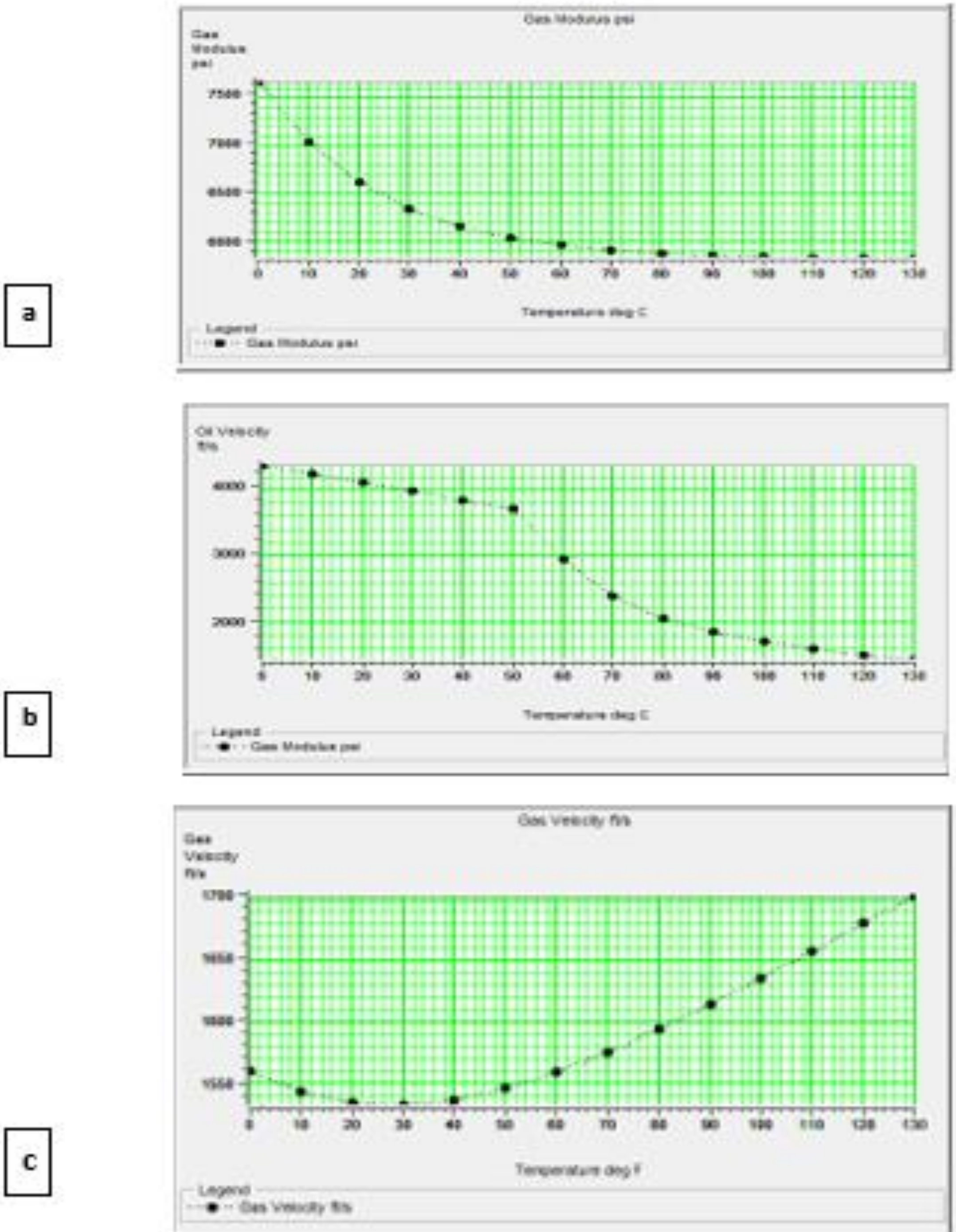

Figure 2: The plots (a) Gas modulus (b), Oil velocity (c), Gas velocity as a function of Temperature

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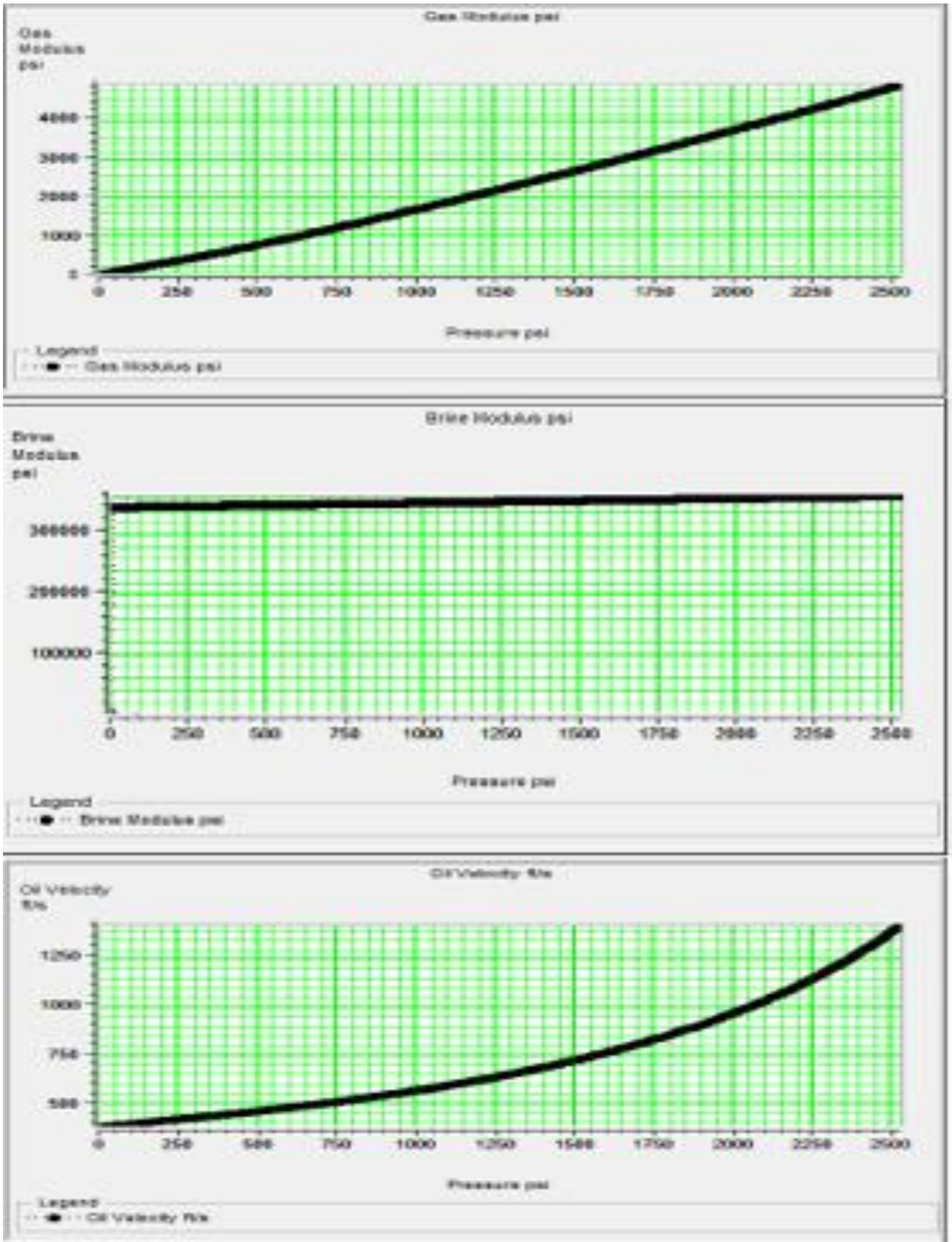

Figure 3 Plots (a), oil velocity (b) Gas modulus (c) , brine Modulus as a function of pressure

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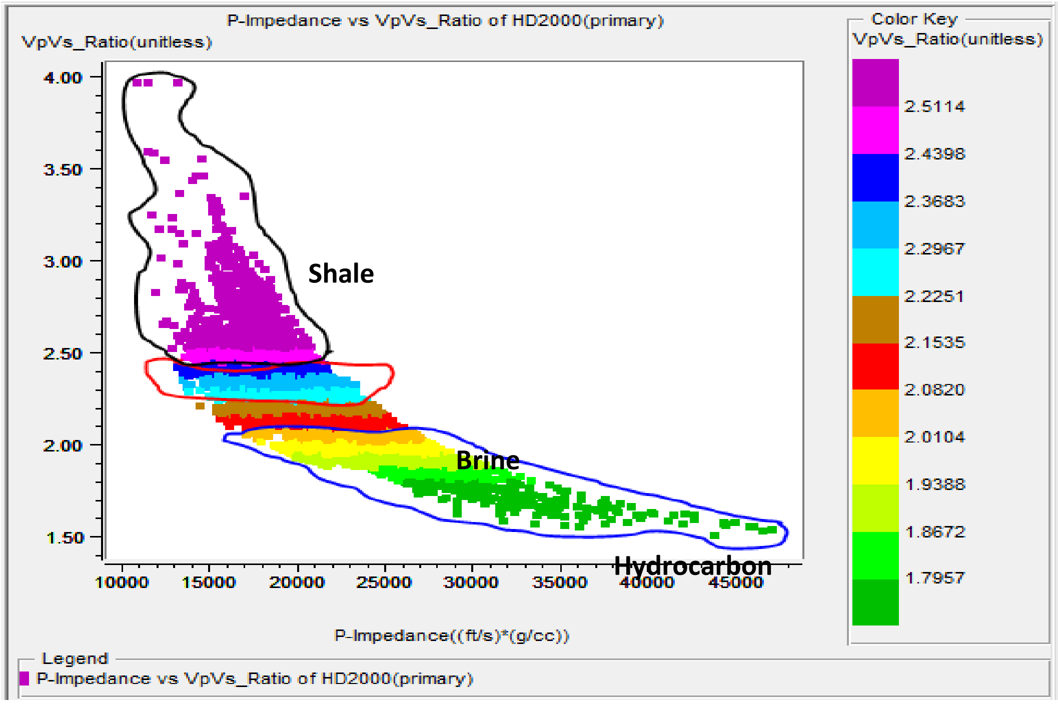

Figure 4a: The crossplots of velocity ratio versus P-impedance of HD2000

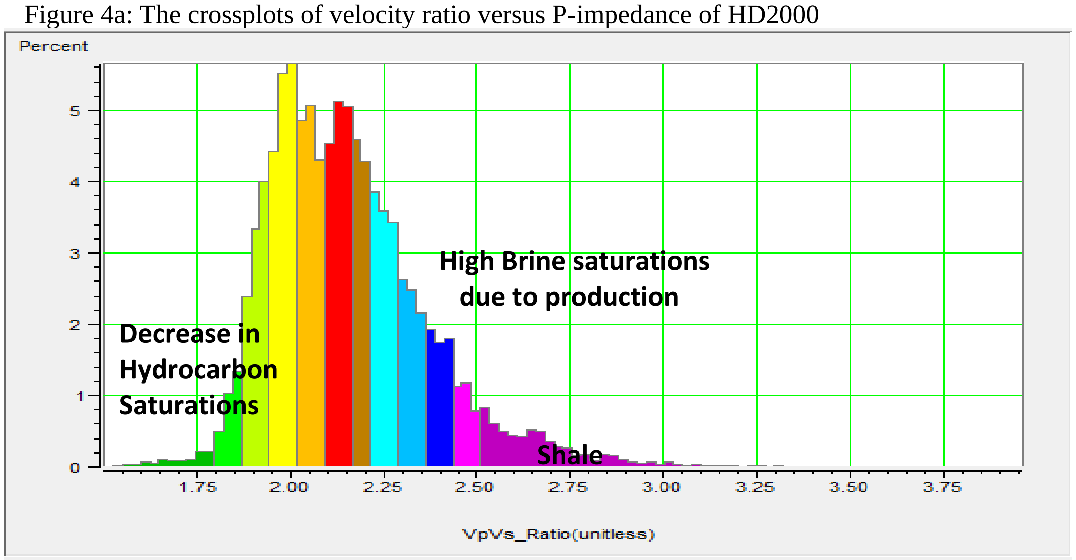

Figure 4b: Histogram plots of the velocity ratio indicating the rate of the HD2000 reservoir performance

Bypassed
hydrocarbon

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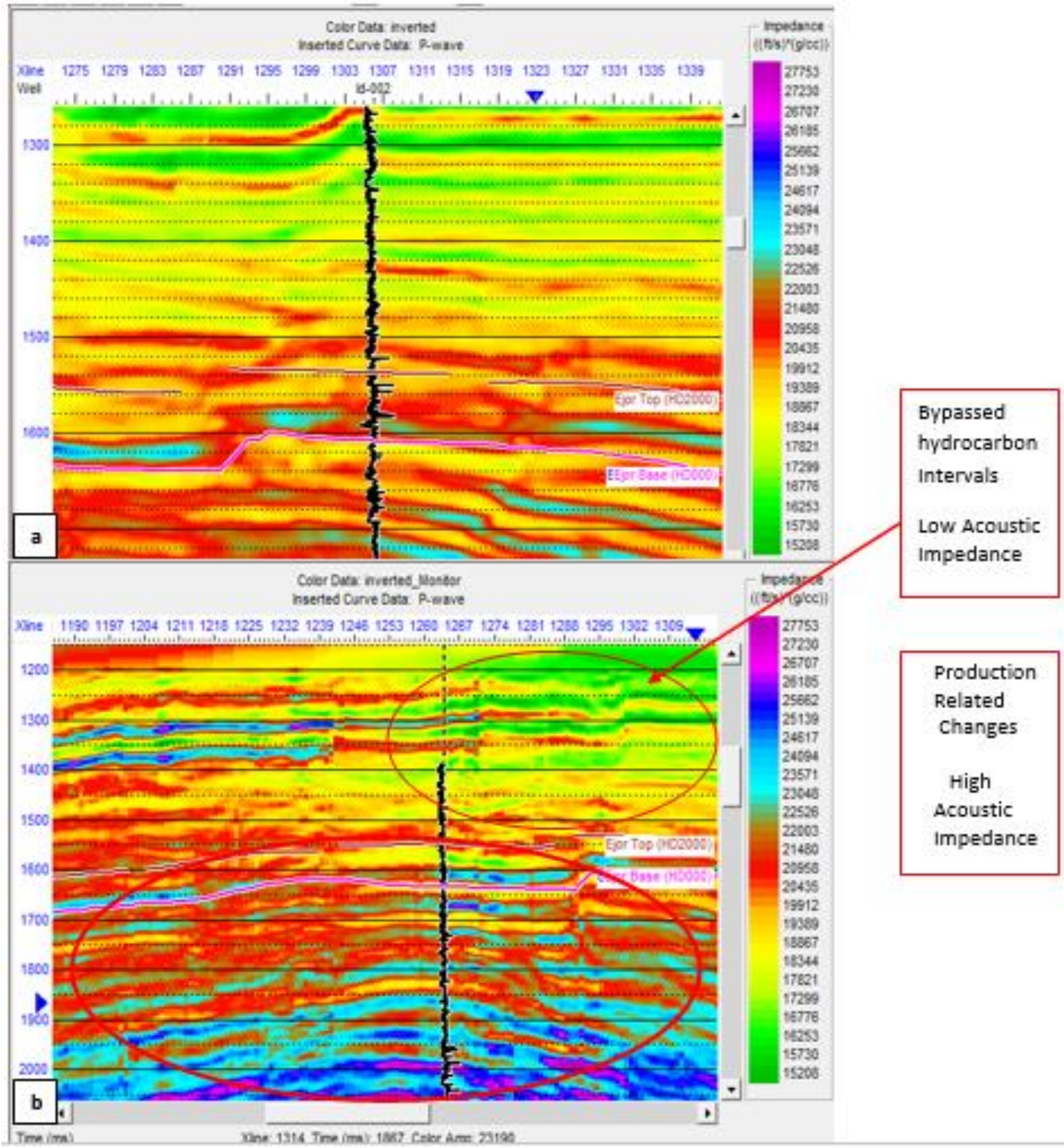

Figure 5a-b: The inverted acoustic impedance volume of the base and monitor with inserted Id-002

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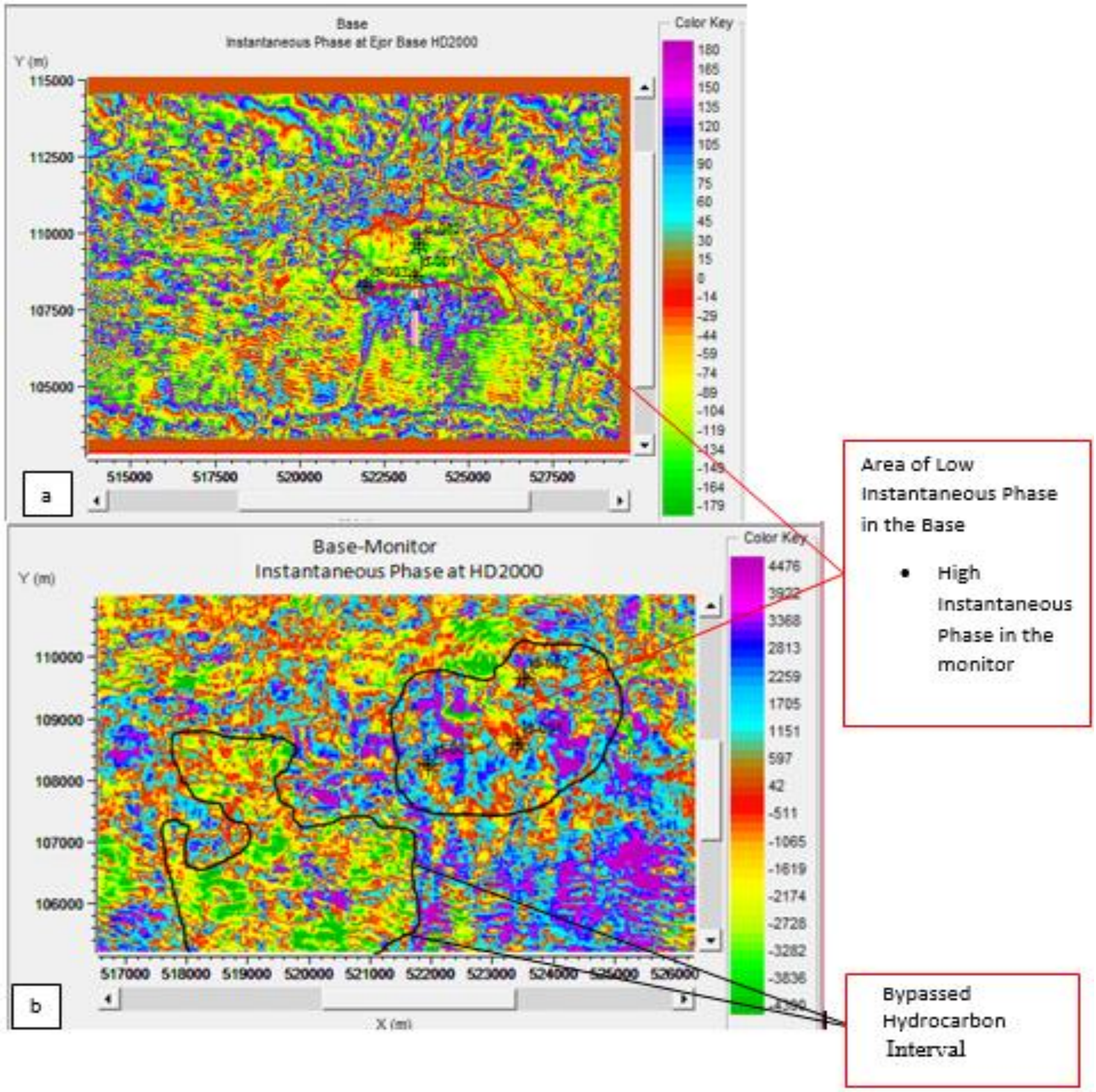

Figure 6a-b: The instantaneous phase slices taken at HD2000 seismic horizon from Base (a), and the Difference volume (b)

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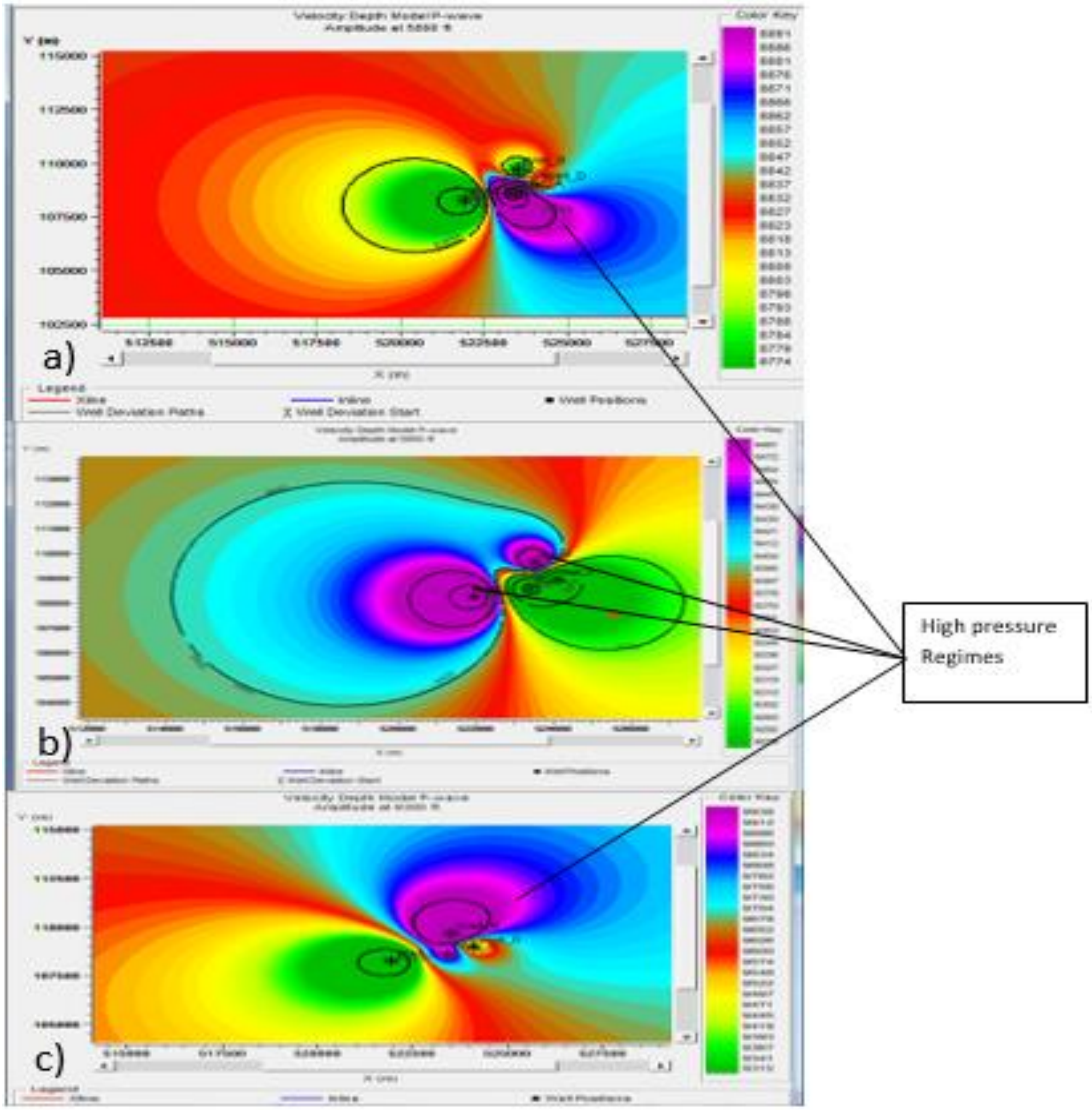

Figure 7a-c: Present the velocity depth model at depth level of 5890ft (1,795m) a, 5850ft (1783m) b, and 6300ft (1920m)

Conclusion

This study investigated the impact of steam injection on reservoir characteristics in the Ida Field, located in the Niger Delta, through the application of 4-D seismic data and inversion techniques. The analysis revealed significant changes in average porosity, which increased from 29.30% to 36%, and water saturation, which rose from 17.50% to 28.33%, indicating the effectiveness of the steam injection program. Additionally, the identification of bypassed hydrocarbon intervals through seismic inversion presents new opportunities for enhanced oil recovery, underscoring the importance of integrating advanced seismic methodologies in reservoir management.

In conclusion, the findings of this research demonstrate the critical role of 4-D seismic monitoring in understanding dynamic reservoir behaviour and optimizing hydrocarbon extraction strategies. By providing insights into production-related changes and identifying potential drilling targets, this study contributes to the ongoing efforts to maximize resource recovery in the Niger Delta.

Recommendation

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It is recommended that future research in the Niger Delta focus on the integration of advanced seismic methodologies, such as 4-D seismic monitoring, to further enhance reservoir management and hydrocarbon recovery strategies. Emphasizing the identification of bypassed hydrocarbon intervals and continuous monitoring of reservoir dynamics will provide valuable insights for optimizing extraction processes. This study presents an important application of 4-D seismic data in reservoir monitoring. Enhancing the discussion on seismic inversion, data integration, and interpretation of results will strengthen its scientific impact. More quantitative details on reservoir properties and time-lapse changes would improve the study's clarity and depth. Future work should focus on further refining these techniques and exploring their applicability in other complex reservoir settings to enhance overall production efficiency.
Additionally, collaboration with industry stakeholders could facilitate the application of these findings to similar fields, promoting sustainable resource management practices across the region.

Conflict of interest

All authors of this work hereby indicate that there are no actual or potential conflict of interest including any financial, personal or other relationships with other people or organizations within three years of beginning the submitted work that could inappropriately influence, or be perceived to influence the work.

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