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Application of Time-Lapse (4D) Seismic for Reservoir Monitoring using Rock Attributes: Case Study of 'X'-Field, Offshore Niger Delta

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Abstract

Time-lapse 3D Seismic, often abridged as '4D-seismic', is an advanced surveillance tool for monitoring fluid saturation and other property changes in reservoirs due to hydrocarbon production or water/gas injection. 4D seismic and well log data were utilized in monitoring reservoirs in 'X' Field using rock attributes extracted from time-lapse 3D seismic data. Two reservoir markers, identified as HD1000 and HD2000, picked from well logs were marked as HD2 and HD2_Version2 horizons on the base and monitor seismic volumes. Horizon slices of acoustic impedance (AI), Poisson ratio (σ), water saturation, density (ρ), Lambda rho (λρ) and porosity were extracted from impedance volumes for the base and monitor seismic using neural network technique. The acoustic impedance slices of the base and monitor horizons show no distinct change, suggesting that this attribute is not very sensitive to changes in the type of fluid in the reservoir. Poisson ratio slices indicate an observable change for the base and monitor horizons. Its value increased in horizon HD2 of the monitor slice. Hydrocarbons have a lower Poisson ratio than water. Therefore, as hydrocarbon is withdrawn from the reservoir during production and replaced with brine, higher values of Poisson ratio predominates. Water saturation slices show low water saturation in the base slices, which implies high hydrocarbon saturation. In the monitor slices, an increase in water saturation was observed due to the replacement of hydrocarbon with brine. The monitor horizon slices for ρ and λρ exhibited a significant increase in the attributes compared to the base slices. No appreciable difference was observed in porosity slices for both horizons. These findings are indicative of pressure depletion and hydrocarbon extraction, and justifies that '4D-seismic' can be used to monitor changes in the reservoir due to hydrocarbon production. This is invaluable in alleviating the risk involved in reservoir management decisions.

Keywords: *Time-lapse 4D Seismic; Rock attributes; Hydrocarbon production; Seismic inversion; Horizon slice.*

1. Introduction

The Niger Delta basin is graded among the most productive basins in the world and, due to its productivity, has become the focal point of oil exploration in Nigeria. The basin is often marked by complex faults and structural features that provide an excellent hydrocarbon trap, but may not contain oil and gas in economical quantities [1]. This leads to great uncertainties in the reservoir properties [2], which strongly influences the exploration, production and development of fields within the region. The study area 'X'-field in the Niger Delta offshore is one of these fields. The seismic reflection method has unarguably proven to be one of the most efficacious tools in hydrocarbon exploration till date. The main objective of a 3D seismic survey is to detail structures, precise definition of subsurface features and physical properties of rocks suitable for accumulation of hydrocarbons. Several researchers have published a compendium of literature to justify this truth [3-5].

During the production life cycle of a reservoir, changes in fluid saturation, pressure, and temperature result in changes in reservoir properties that can be detected and monitored by repeated 3D seismic surveys, generally referred to as "4D seismic monitoring". The 4D seismic reservoir monitoring technique can significantly increase the recovery factor of new and existing fields by mapping the position and movement of reservoir fluids, locating by-passed hydrocarbons, and optimizing infill drilling locations, to reduce ambiguities associated with misinterpretations leading to drilling of dry wells. "4D seismic monitoring", is an advanced surveillance technique based on the analysis of repeated 3D seismic surveys obtained at a sizeable time interval prior to production and at diverse stages after production [6]. Assuming seismic repeatability, changes in fluid movement and pressure can translate into changes in the attributes of the reservoir rock, causing them to either rise, decline, or remain relatively stable in assessment. These relative changes in reservoir rock attributes as a function of time are the result of hydrocarbon production and related movement [7].

Analysis of seismic to reservoir monitor is generally performed using the seismic inversion technique. Seismic inversion is the process of converting interface-based seismic data into a quantitative rock property descriptive of the reservoir [8-10], thus providing useful information for quantitative estimates of reservoir properties [10-11].

Although time-lapse (4D) studies is a relatively new technology for monitoring reservoirs, it has attracted considerable attention from researchers in recent times. Staples *et al.* [12] used two 4D seismic data sets to gain new insights into the structure and dynamic behavior of the Gannet-C oil and gas reservoir in the central North Sea of the United Kingdom. The 4D data showed large tracts of reservoir units that were previously believed to be absent or thin in much of the reservoir. Time-lapse seismic was also used by Tura *et al.* [13] for field development in Nembe Creek, Southern Nigeria. According to the authors, time-lapse seismic data in the creek serve two purposes; in order to better design the new lateral track wells as part of an ongoing drilling program and to locate deviated oil zones. They found that some lateral wells could be realigned based on 4D seismic to minimize exposure to early water production. Olaide *et al.* [14] reviewed the application of 4D seismic in the Niger Delta basin of Nigeria and asserted that the technique is used to understand reservoir drainage performance, enable better well placement, identify bypassed oil, detecting fluid communication, understanding of internal architecture of the reservoirs, and locating infill wells for future re-development. Alamini-okuma and Ofuyah [15] started that 4D seismic survey, when integrated with other subsurface information, can unify reservoir performance data and optimize geological models, and recommended that multinational oil and gas prospecting companies should carry out a reshoot of all their previously shot fields to be able to utilize the robust capabilities of this technique.

The study area 'X'-Field located deep offshore Niger Delta, with high production allocation uncertainty, requires 4D seismic monitoring to increase the reliability of the reservoir model. Therefore, the aim of this study is to monitor fluid changes in the reservoir using rock properties and attributes with high fluid sensitivity extracted from 4D seismic data (base and monitor volumes), to monitor hydrocarbon withdrawal effects and map potential oil zones bypassed during hydrocarbon production. This will abate the risk involved in reservoir management decision, which is critical for any new drilling program in the field.

2. Geology of the study area

The study area 'X'- Field lies between latitudes $4^0$37'36''N – $4^0$40'00''N and longitudes $6^0$35'E - $6^0$40'E, sited on the offshore Niger Delta (Figure 1a). The study field consists of four wells as shown in the base map (Figure 1b). The name given is fictitious for proprietary purposes and only valid for this study. The Niger Delta is the largest delta in Africa which dilates through 75,000 km^2 with clastic fill of 9000–12,000m (30,000–40,000ft) and cease at divergent hiatus of transgressive sequence [16]. The Delta is a prograding depositional complex within the Cenozoic Formation of Southern Nigeria. It stretches from the Calabar flank and Abakaliki trough in Eastern Nigeria to the Benin flank in the West and launches to the Atlantic ocean in the South. It infringes into the Gulf of Guinea as an extension from the Benue Trough and Anambra Basin provinces [17]. From the Eocene to Recent, the Delta has prograded the

Southwest, forming depobelts that represents the greatest active portion of the delta at each stage of its evolution [2, 18-19]. The growth and augmentation of the Niger Delta commenced in Mid-Eocene by a major regression which began with the build-up of the Ameki Formation West and East of the Niger river [17]. The sediment supply in the Delta is procured from two drainage systems, the Niger-Benue system through the Anambra Basin North of Onitsha. The stratigraphy of the Niger Delta basin is knotted by the syn-depositional sag of the clastic wedge as shale of the Akata Formation deployed under the load of prograding deltaic Agbada and fluvial Benin Formation deposits [16, 20-23].

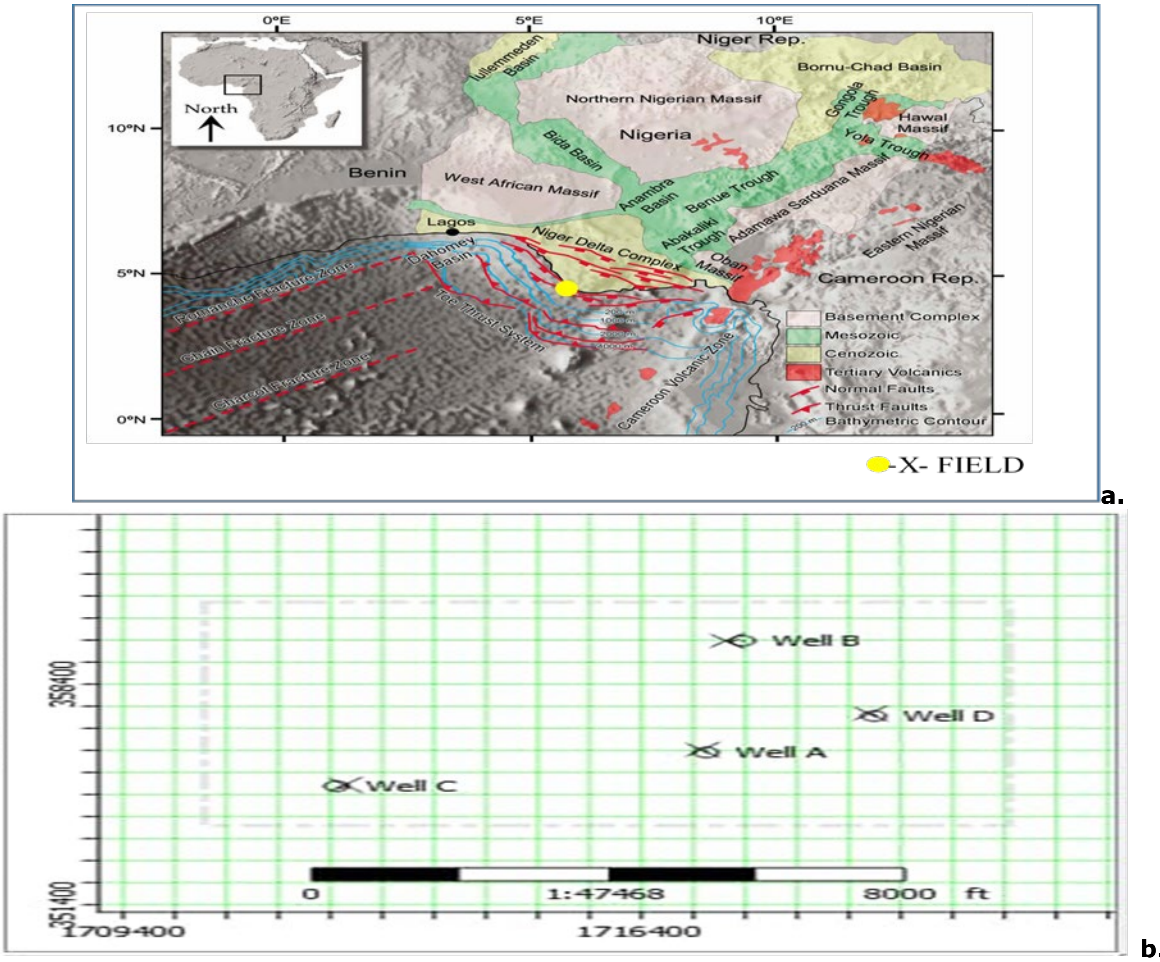
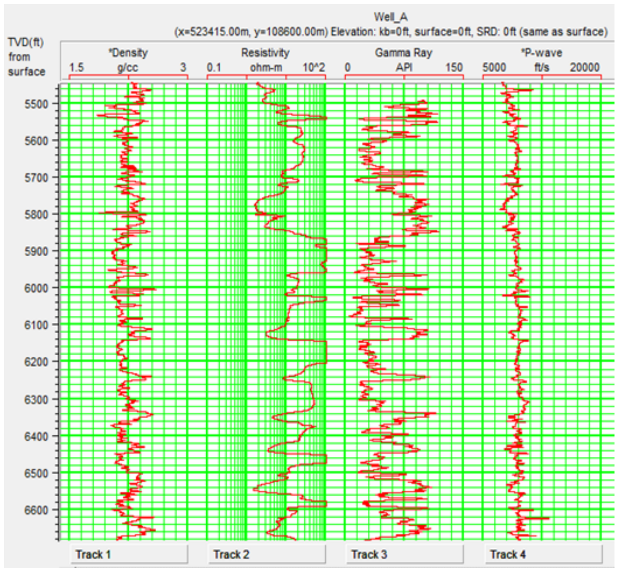


Figure 1. (a) Map of Niger Delta showing the possible location of the study area indicated by a yellow circle (modified from [21]) (b) Base map of study location 'X'-Field showing seismic lines (inlines and crosslines) for the 3D seismic acquisition and the various well locations

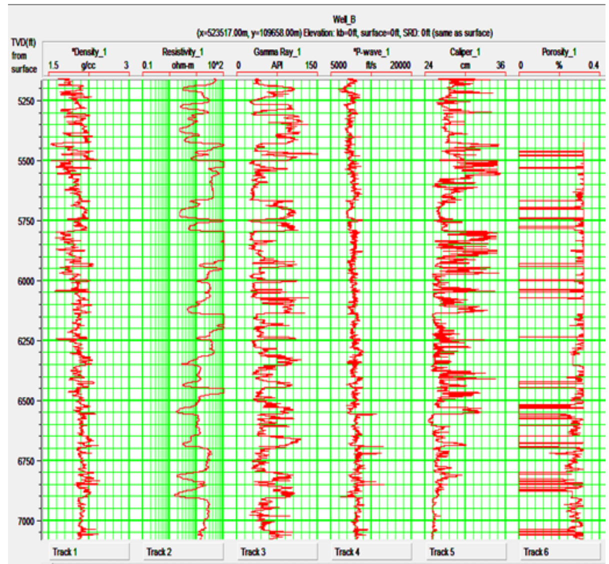
3. Materials and methods

3.1. Database

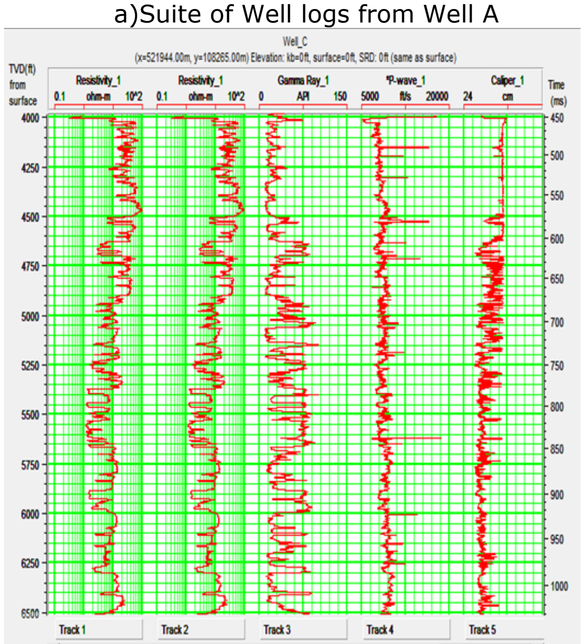
In this study, the data set used consists of a 3D time-lapse seismic data volume (4D) made up of a base and monitor volume. The time-lapse data (base and monitor volumes) were obtained from the same field in the Niger Delta. Baseline data was acquired during the early stage of field development to aid developmental plans, while monitoring data was acquired much later (after a period of fifteen years) with the goal of imaging the reservoir to monitor production effects and mapping of the oil zones that were probably by-passed. The two data sets were processed in parallel to take advantage of 4D seismic effects. A suite of composite logs from three (3) wells identified as Well A, Well B, and Well C were also provided (Figure 1b). Well A contains records of gamma-ray (GR), resistivity, compressional sonic velocity, and density logs to depth of 6680ft (Figure 2a). Well B contains gamma-ray (GR), resistivity, compressional sonic velocity, density, caliper and porosity logs to depth beyond 7050ft (Figure 2b), while Well C contains gamma-ray (GR), resistivity, compressional sonic velocity, and Caliper logs to depth of 6500ft (Figure 2c).



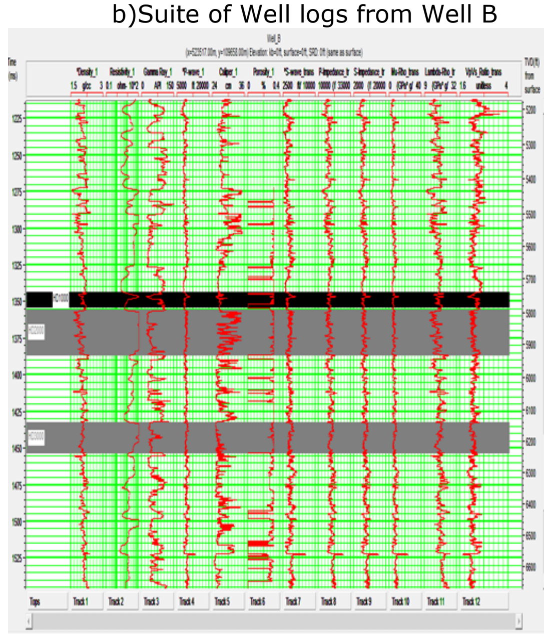
a)Suite of Well logs from Well A



b)Suite of Well logs from Well B



c)Suite of Well logs from Well C



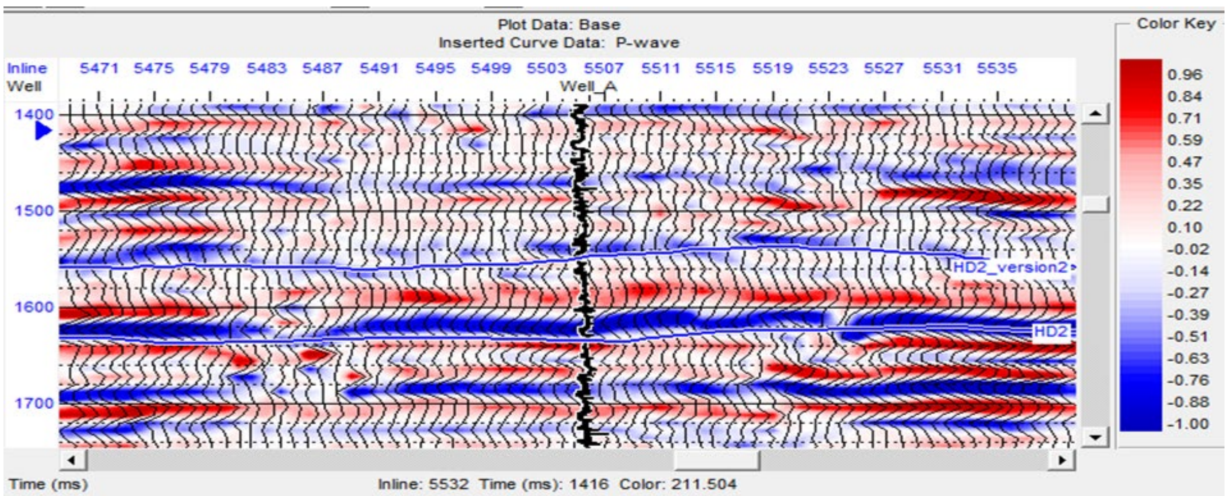
d) Edited and corrected logs with reservoir markers

Figure 2. (a, b, c) Suite of Well Logs from Wells_A, B, C. (d) Well log suites showing reservoir markers HD1000, and HD2000. The logs in tracks 7 – 12 were derived from the original logs using available rock physics relations. A median filter was applied to the P-wave, S-wave and density logs to remove the high-frequency components effect

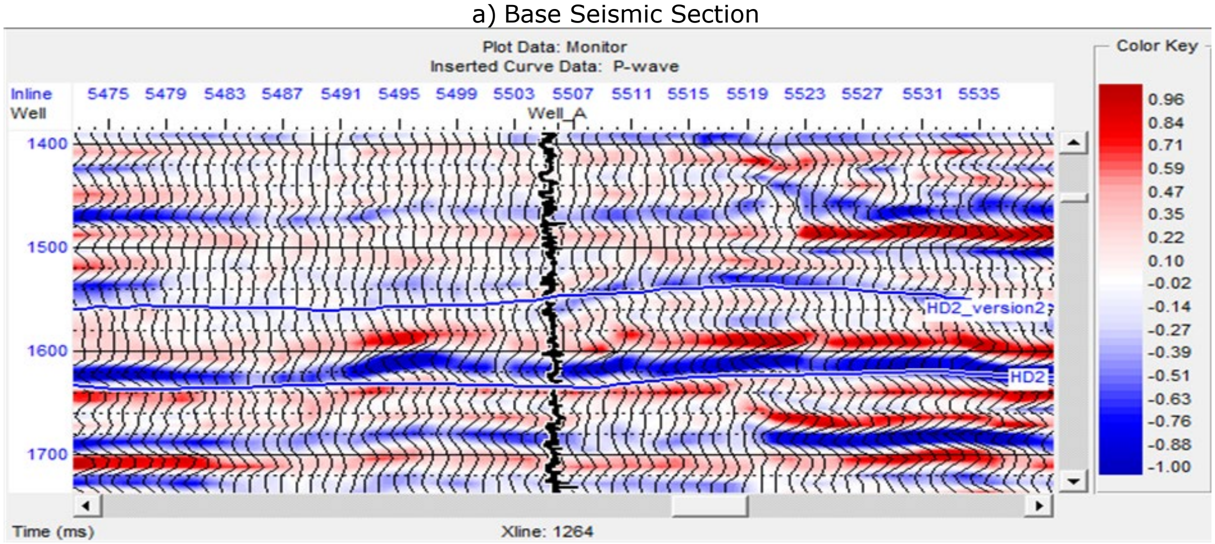
3.2. Methods

3.2.1. Log editing, conditioning and picking of reservoir intervals

Well logs form the basis for relating seismic properties with the reservoir. The first step in this study was to edit, normalize and interpret the well logs before they could be used for the reservoir study [24]. This is due to events such as mud filtrate invasions, well-bore washouts, casing points, missing data points, and insufficient log suites during acquisition. Mud filtrate invasion occurs during drilling with overbalanced mud weight conditions. The severity of these conditions varies widely depending on permeability, mud weight, mud type and fluid saturation. If synthetic seismograms are generated from the uncorrected sonic and density logs, the result will not match when correlated with the seismic data [25]. The well logs were loaded into Hampson Russell (HR) software program, and reservoir intervals were selected using a combination of low gamma-ray, high resistivity, low density, relatively low compressional sonic velocity, and high porosity signature in Well A and B (Figure 2 a and b). A hydrocarbon-charged sand reservoir is characterized by low gamma-ray counts, high resistivity value, low density value, low sonic velocity (reduction in sonic velocity is a direct hydrocarbon indicator), and high density-derived porosity. The reservoir windows were marked and labeled at various depths in the wells as reservoir markers HD1000 at depths of 5835ft-5885ft in well A and 5740ft-5780ft in well B and HD2000 at depths of 5942ft-5964ft in well A and 5795ft-5935ft in well B (as indicated in Figure 2 a and b). The reservoir markers HD1000 and HD2000 were marked as HD2 and HD2_Version2 each on the base and monitor seismic volumes as indicated (Figures 3 a and b).



a) Base Seismic Section



b) Monitor Seismic Section

Figure 3. (a, b) Base and Monitor Seismic sections with inserted P-wave logs (from Well A), showing the Seismic horizons (HD2 and HD2_Version2) as indicated

3.2.2. Seismic difference volume, wavelet extraction, and well-to-seismic correlation

The Seismic difference volume (Figure 4) was generated by subtracting the baseline from the monitor 3D seismic data. The idea is to map areas associated with 4D effects caused by production around the wells and to guide the extrapolation of other zones that have similar responses in both baseline and monitor seismic volumes. Well to seismic correlation, the process of aligning the synthetic trace with one or more seismic traces near the well location was also performed. The Wavelet used in the correlation process was extracted both from the well and from the seismic within a frequency bandwidth of 0 - 100 Hz. Figures 5 a and b, show the extracted wavelet in the time and frequency domains. This process is important to ensure that the wavelet used in the inversion process matches the phase and frequency of the seismic data. The synthetic traces were calculated by convolving the density and sonic logs with the seismic wavelet.

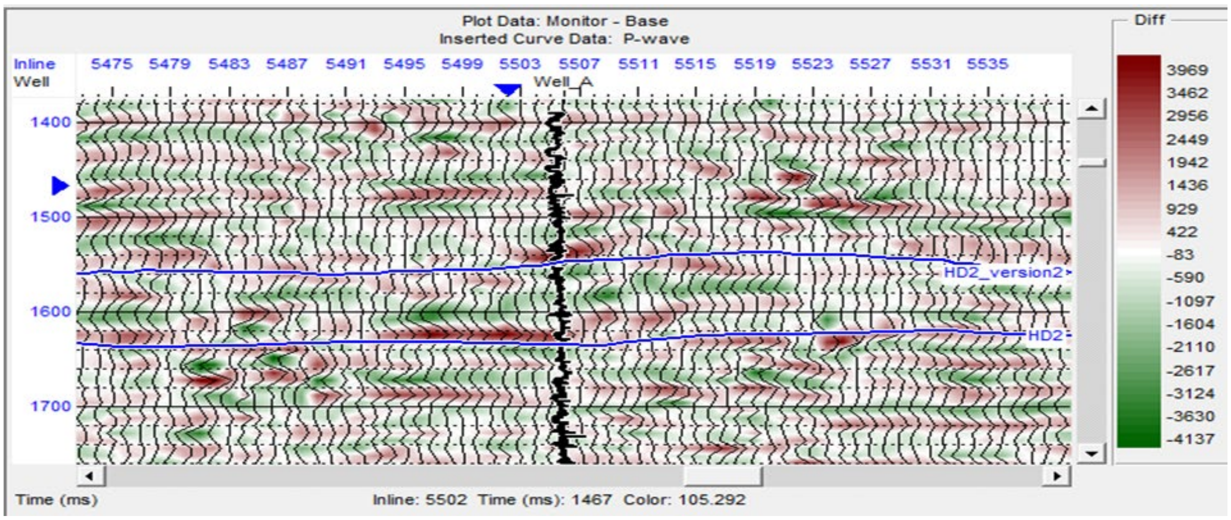
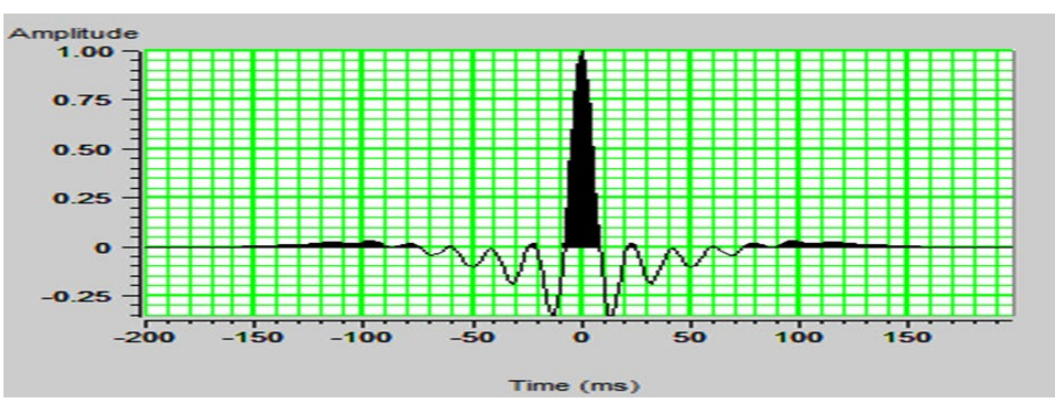


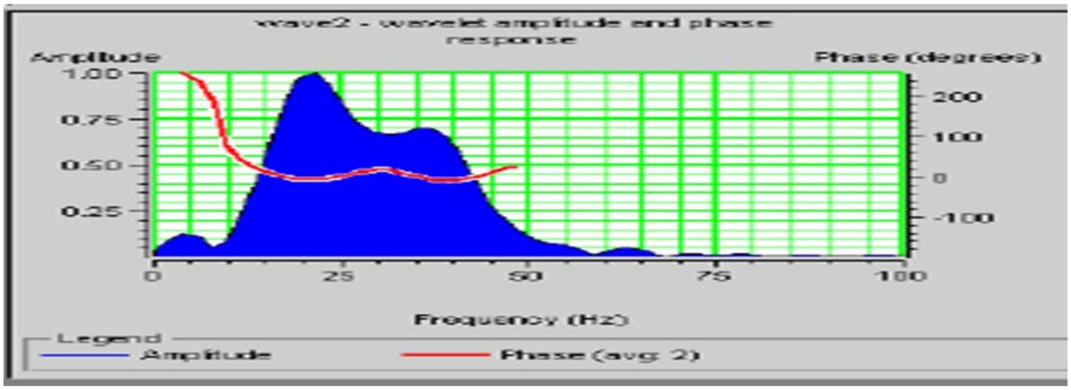
Figure 4. Seismic difference volume obtained by subtracting the Base seismic from the Monitor

The composite trace is a single average trace that is an average of adjacent traces around the well location. Seismic averaging was done by averaging traces within a time shift of ±1 on the inline and crossline of the well. The logarithmic correlation process improves the correlation between events in the synthetic trace and events in the seismic data.

In our analysis, a time window of 1550 to 1635 ms was chosen to limit the analysis to a trace area around the well. A good correlation was achieved between the synthetic seismogram (blue) and the real seismic traces (black) which is indicated by a high correlation coefficient of 0.713 (Figure 5c).



a)



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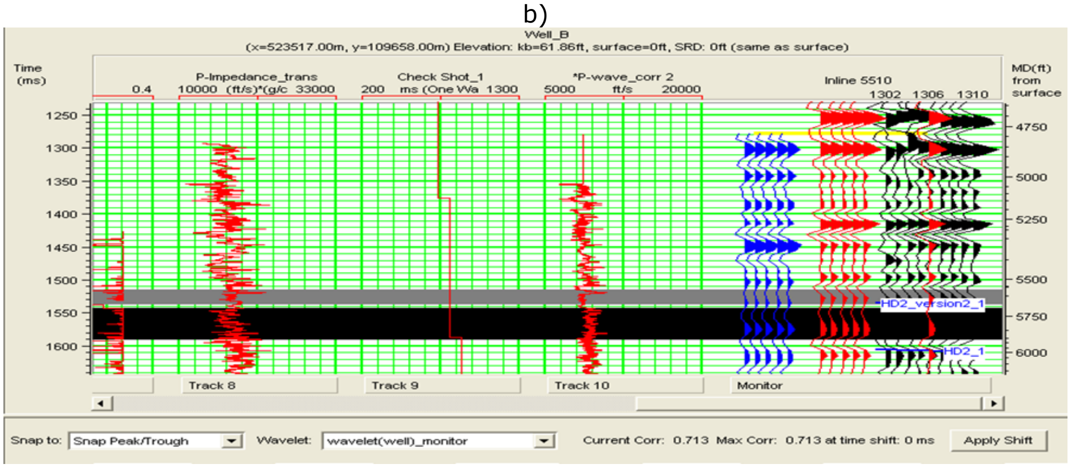


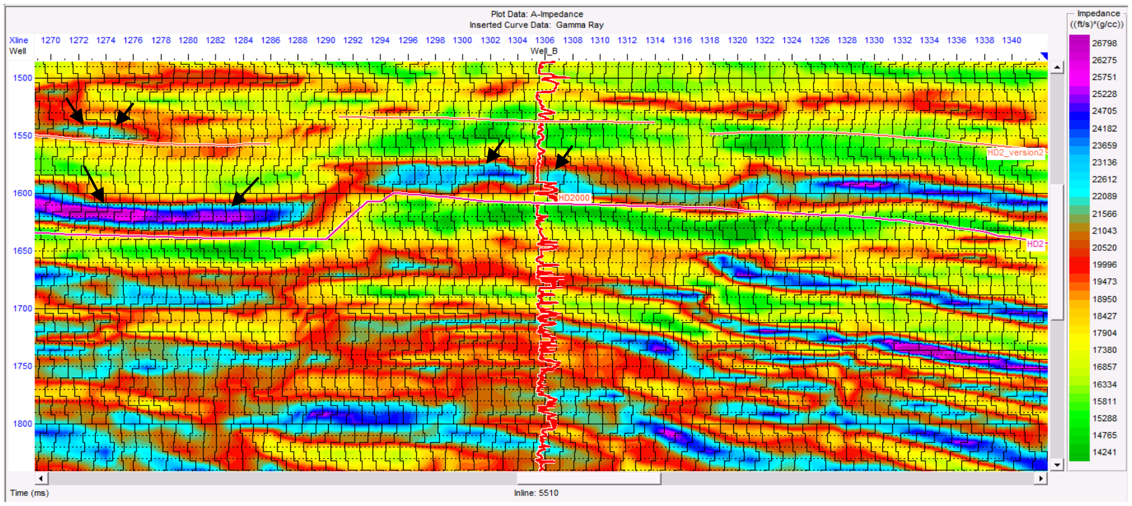
c)

Figure 5. Extracted Seismic Wavelet in (a) time domain (b) Frequency domain (c) Seismic-to-well correlation. High correlation co-efficient of 0.713 at zero time shift for seismic-to-well tie indicates a good match between the synthetic seismogram (blue) and the real seismic trace (black).

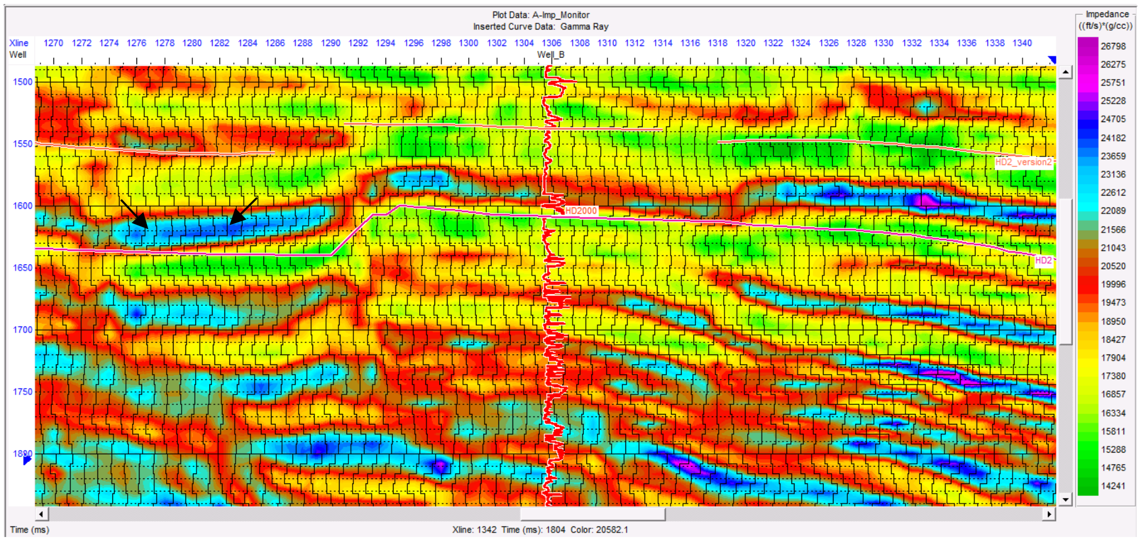
3.2.3. Acoustic impedance inversion and rock attributes extraction

Acoustic impedance (AI) which is the product of rock density and P-wave velocity, was inverted from 4D seismic data using the model-based acoustic impedance inversion technique reported by [26] in [10, 27]. In this technique, an initial low-frequency acoustic impedance model was obtained from well B (control well). Acoustic impedance inversion is the transformation of seismic data into pseudo acoustic impedance records on each trace, with all the information from the seismic data retained [28]. The seismic base and monitor data were inverted into acoustic impedance sections (Figure 6 a, b). In Figures 6 a and b, notice areas of observable changes in the acoustic impedance section for the monitor (as indicated) not observed in the acoustic impedance section for the base. These changes validate the time-lapse (4D) effect of hydrocarbon production in the field over time, since acoustic impedance is closely related to lithology, porosity, pore fill, and has a strong relationship with one or more rock properties.

Horizon slices of Acoustic impedance (AI), Poisson's ratio (σ), Water saturation (Sw), Bulk density (ρ), Lambda rho (λρ) and Porosity (ø) were extracted from acoustic impedance volumes for the base and monitor using a neural network technique [29]. These rock attributes are known to be sensitive to fluid saturation and changes in the reservoir. The two horizons HD2 and HD2_Version2 marked in the base and monitor impedance sections (Figure 6 a, b) were chosen as reference points for taking the slices. Two zones marked as Zone 1 (around the producing well) and Zone 2 (away from the producing well) were marked as reference points on the base and monitor horizon slices for interpreting time-lapse changes in rock attributes within the reservoir.



a



b

Figure 6. Acoustic impedance section inverted from (a) Base seismic volume (b) Monitor seismic volume

4. Results and discussion

On analyzing the results, we found segments with signatures of diagnostic attributes of those expected from hydrocarbon charged sands. The acoustic impedance slices for the base and monitor volumes in the HD2 and HD2_Version2 horizons are shown in Figure 7a-d. A Slight increase was observed between the acoustic impedance values for the base and monitor, particularly within the marked areas (Zone 1 and Zone 2). Zone 1, which is located around the well area, is expected to continue to change over time due to hydrocarbon production.

The relative change in acoustic impedance between the base and monitor as indicated by the color code in Figure 7a-d is not distinct, and shows that the attribute is not very sensitive to changes in fluid types within the reservoir during hydrocarbon production.

Poisson's ratio slices for the base and monitor are shown in Figure 8a-d. A distinct change was observed in Zone2 of the HD2 horizon for the base and monitor slices (Figure 8 a and b). Poisson's ratio was observed to increase in Zone2 of the monitor slice for the HD2 horizon. In general, hydrocarbons have a low Poisson's ratio value compared to water. Since hydrocarbons are removed from the reservoir during production and replaced by water (brine), a higher Poisson ratio is expected over time, which is reflected in Zone2 of the monitor slice (Figure 8b). In Zone1 of the HD2_Version 2 horizon, Poisson's ratio was high in the base slice (Figure 8c), while in the monitor slice (Figure 8d) the value decreased.

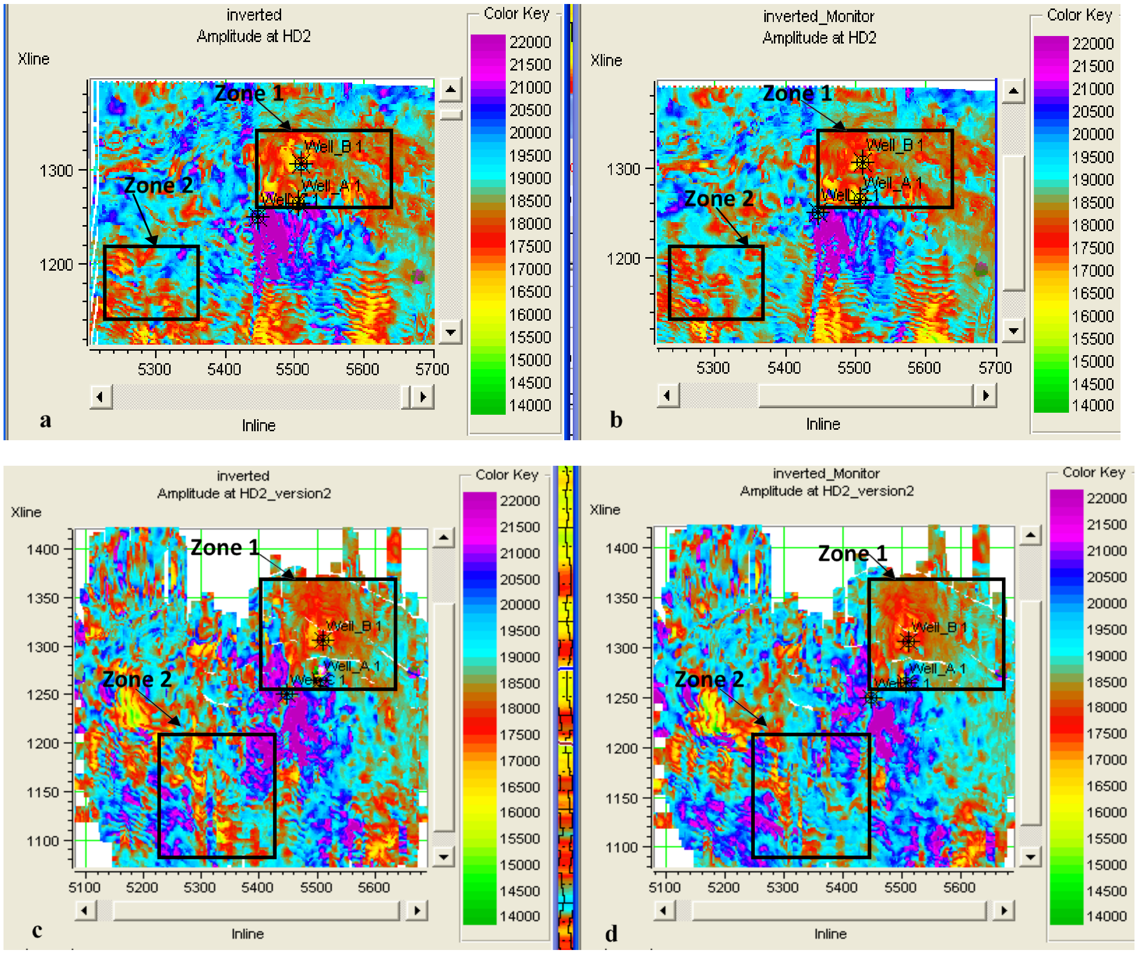


Figure 7. Acoustic impedance slices for (a) Base at HD2 Horizon (b) Monitor at HD2 Horizon.(c) Base at HD2_Version2 Horizon (d) Monitor at HD2_Version2 Horizon

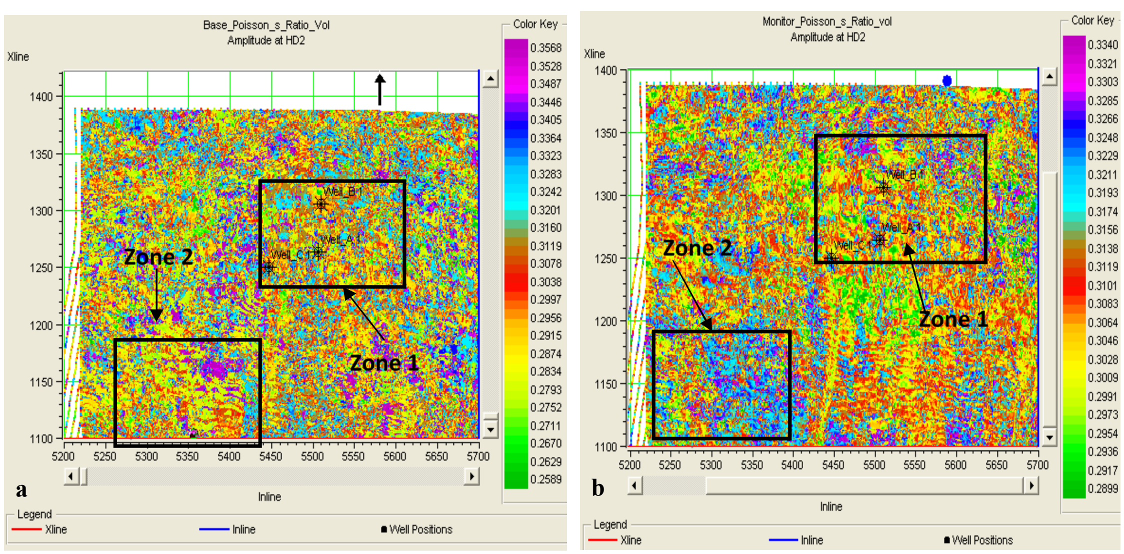
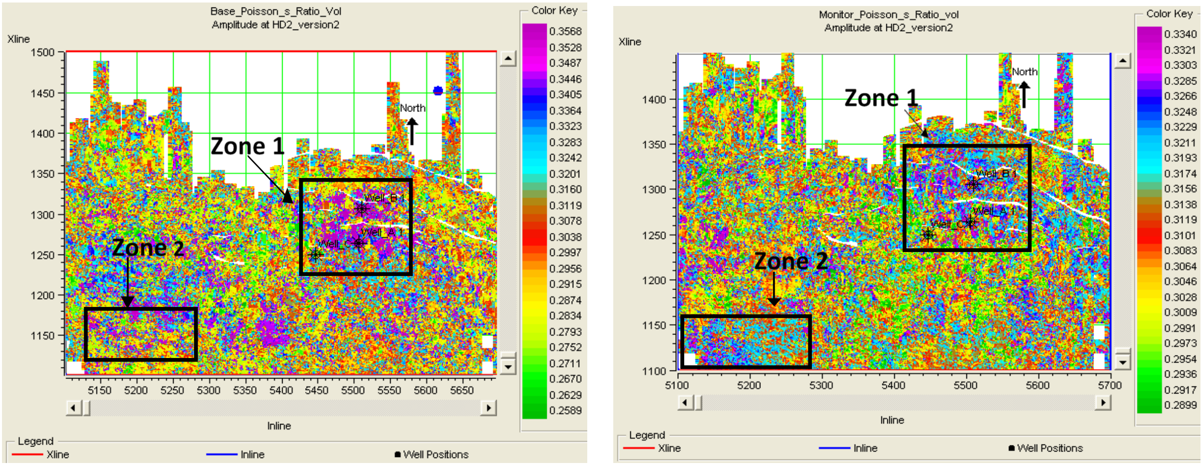


Figure 8. Poisson's ratio slices for (a) Base at HD2 Horizon; (b) Monitor at HD2 Horizon



c d

Figure 8. Poisson's ratio slices for (c) Base at HD2_version2 Horizon (d) Monitor at HD2_version2 Horizon. Notice 4D (time-lapse) changes in the attribute especially within the marked zones

This scenario suggests pressure depletion and hydrocarbon extraction from the reservoir. The Water Saturation slices for HD2 and HD2_Version2 horizons for the base and monitor are shown in Figures 9a-d. The monitor horizon slices show a distinct increase in water saturation for both the HD2 and HD2_Version2 horizons (Figure 9 b and d) especially in Zone2. Low water saturation implies high hydrocarbon saturation and vice versa. The increase in water saturation observed in the monitor slices is due to the removal of hydrocarbons and subsequent replacement by brine. Figure 10a-d show bulk density slices for the HD2 and HD2_Version2 horizons for the base and monitor. In the HD2 horizon, low bulk density was observed in the base slice (Figure 10a) particularly in Zone1 (around the producing well area).

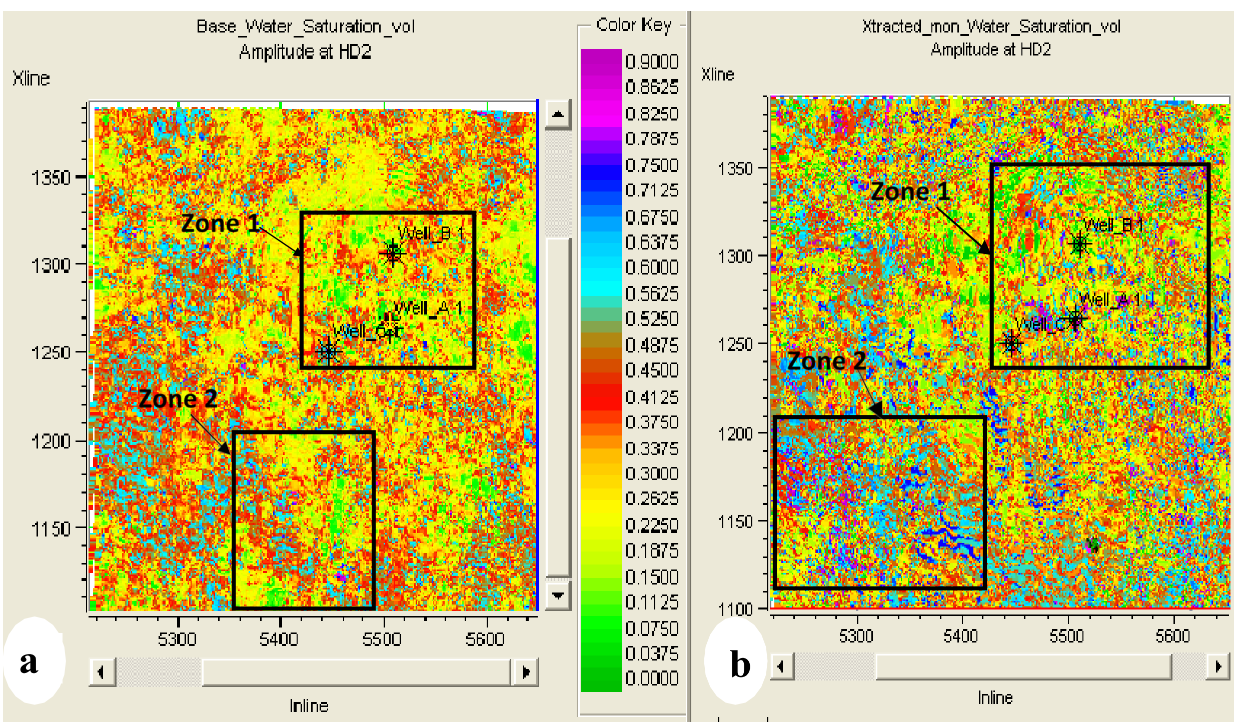


Figure 9. Water Saturation slices for (a) Base at HD2 Horizon (b) Monitor at HD2 Horizon

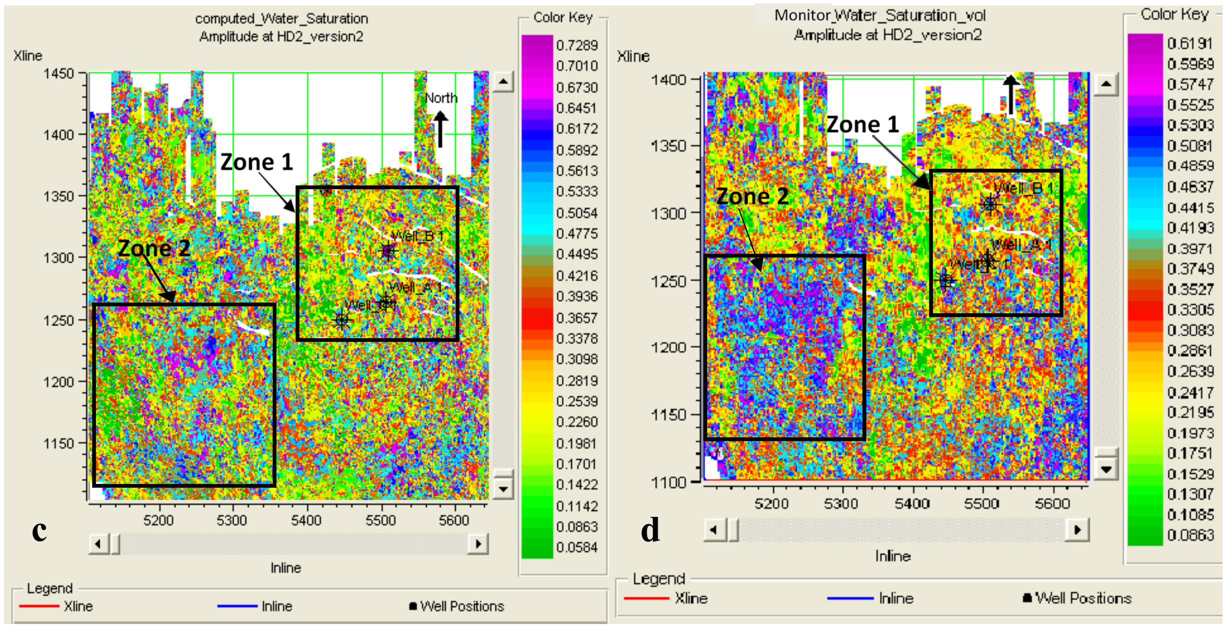


Figure 9. Water Saturation slices for (c) Base at HD2_version2 Horizon (d) Monitor at HD2_version2 Horizon

Hydrocarbons have a lower density than water (brine), these lower values are expected for the base that was acquired before the start of hydrocarbon production. The Monitor slices (obtained after significant hydrocarbon extraction) show a marked increase in bulk density compared to the base case (Figure 10b and d). The lambda rho slices on the HD2 and HD2_Version2 horizons for the base and monitor slices are shown in Figure 11a-d. The base slices on the HD2 and HD2_Version2 horizons show relatively low values of the lambda rho attribute compared with the monitor slices. This observation is plausible, since hydrocarbon – charged sands are generally characterized by low lambda rho values [7, 30]. The Monitor slices show predorminately higher lambda rho values in both horizons, as shown in Zone1 and Zone2 (Figure 11b and d). This must have resulted from the removal of hydrocarbons and subsequent replacement by brine. The porosity slices for the base and monitor in the HD2 and HD2_Version2 horizons are shown in Figure 12a-d. For the HD2 and HD2_Version2 horizons, no observable changes are found between the base and monitor slices. This is a distinct suggestion that changes in fluid types do not affect porosity. Therefore, the extraction of hydrocarbons does not have a momemtous effect on the porosity of the reservoir.

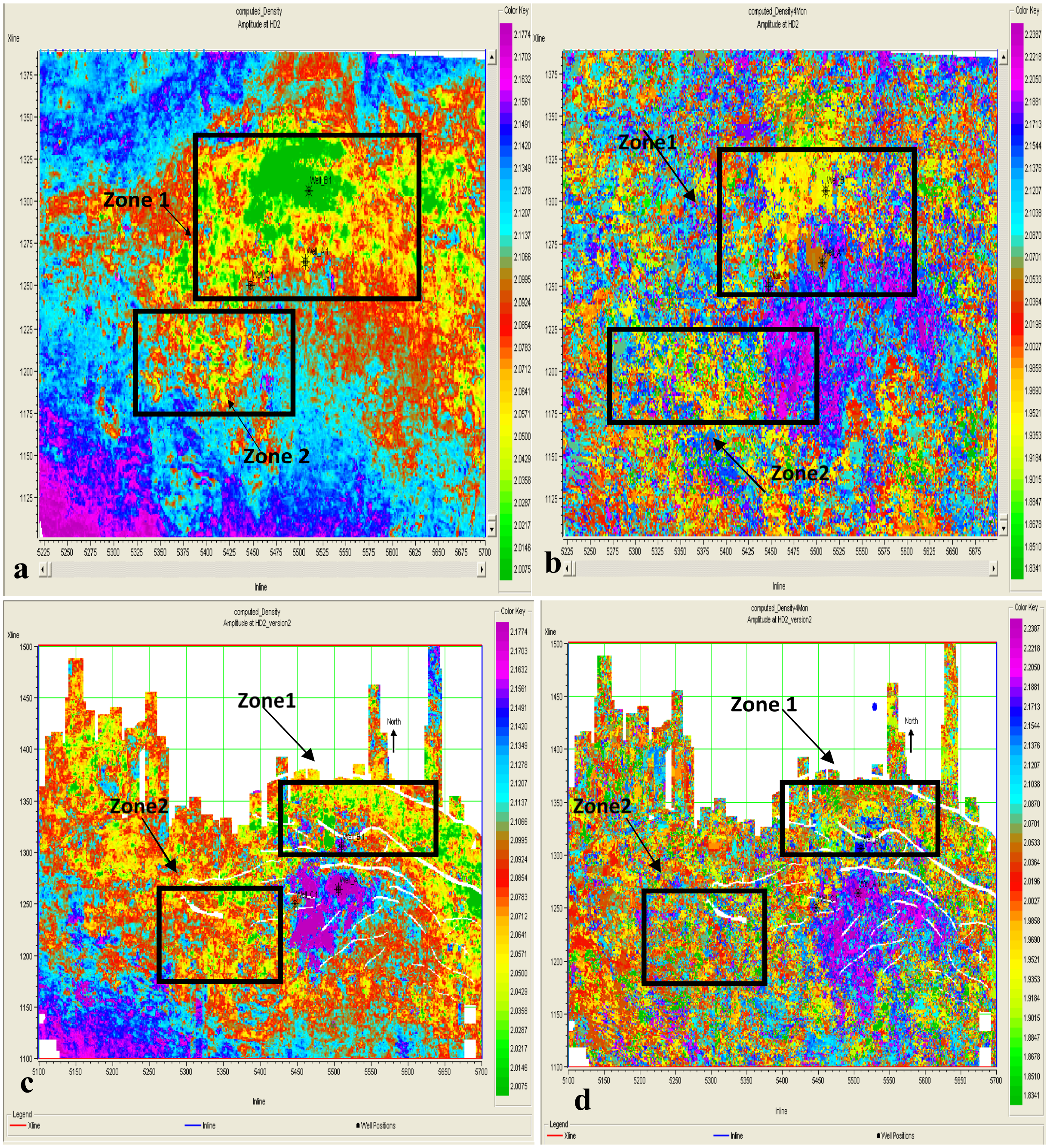


Figure 10. Bulk Density slices for (a) Base at HD2 (b) Monitor at HD2 (c) Base at HD2_Version2 (d) Monitor at HD2_Version2

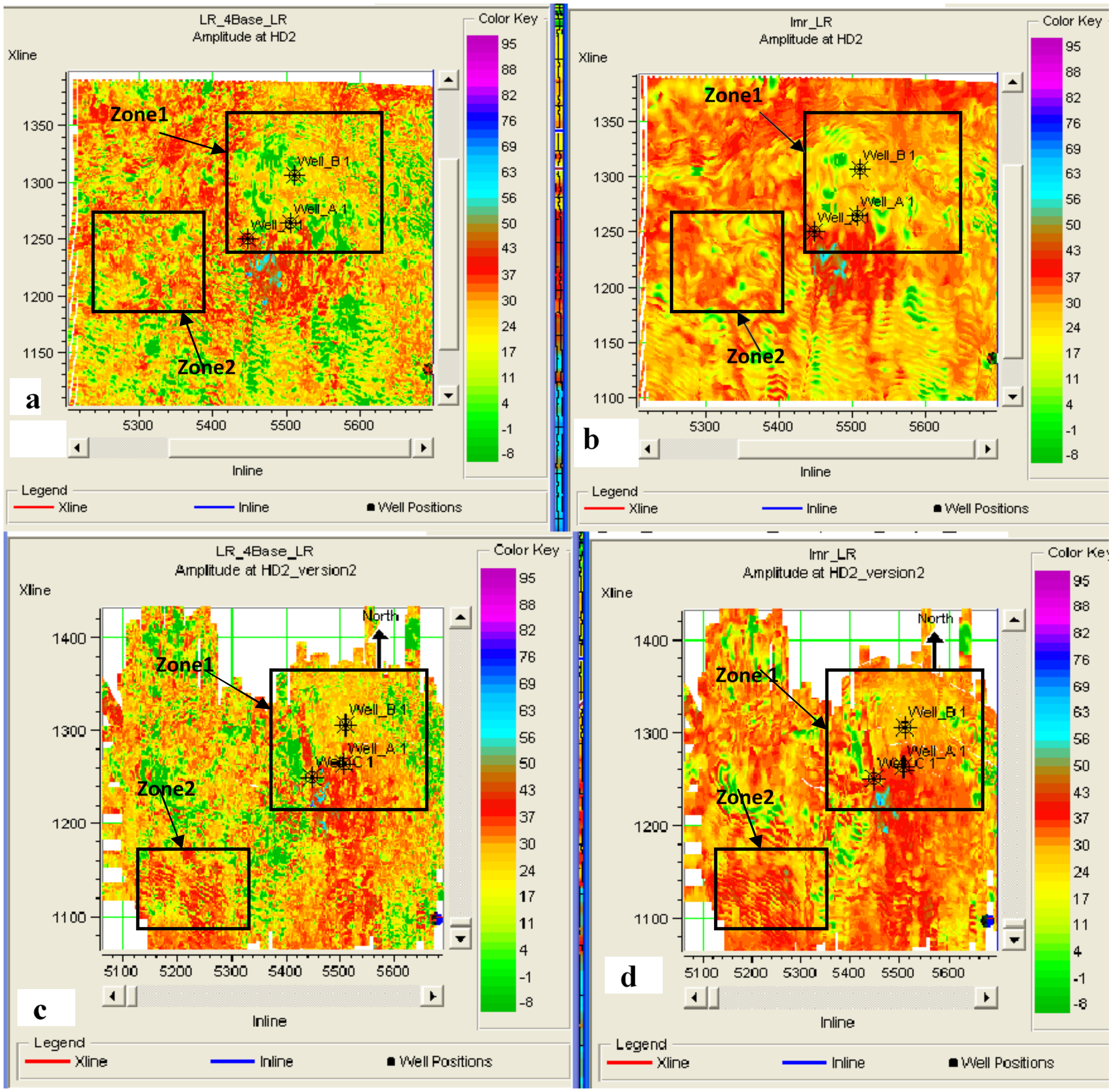


Figure 11. Lambda rho slices for (a) Base at HD2 (b) Monitor at HD2 (c) Base at HD2_Version2 (d) Monitor at HD2_Version2

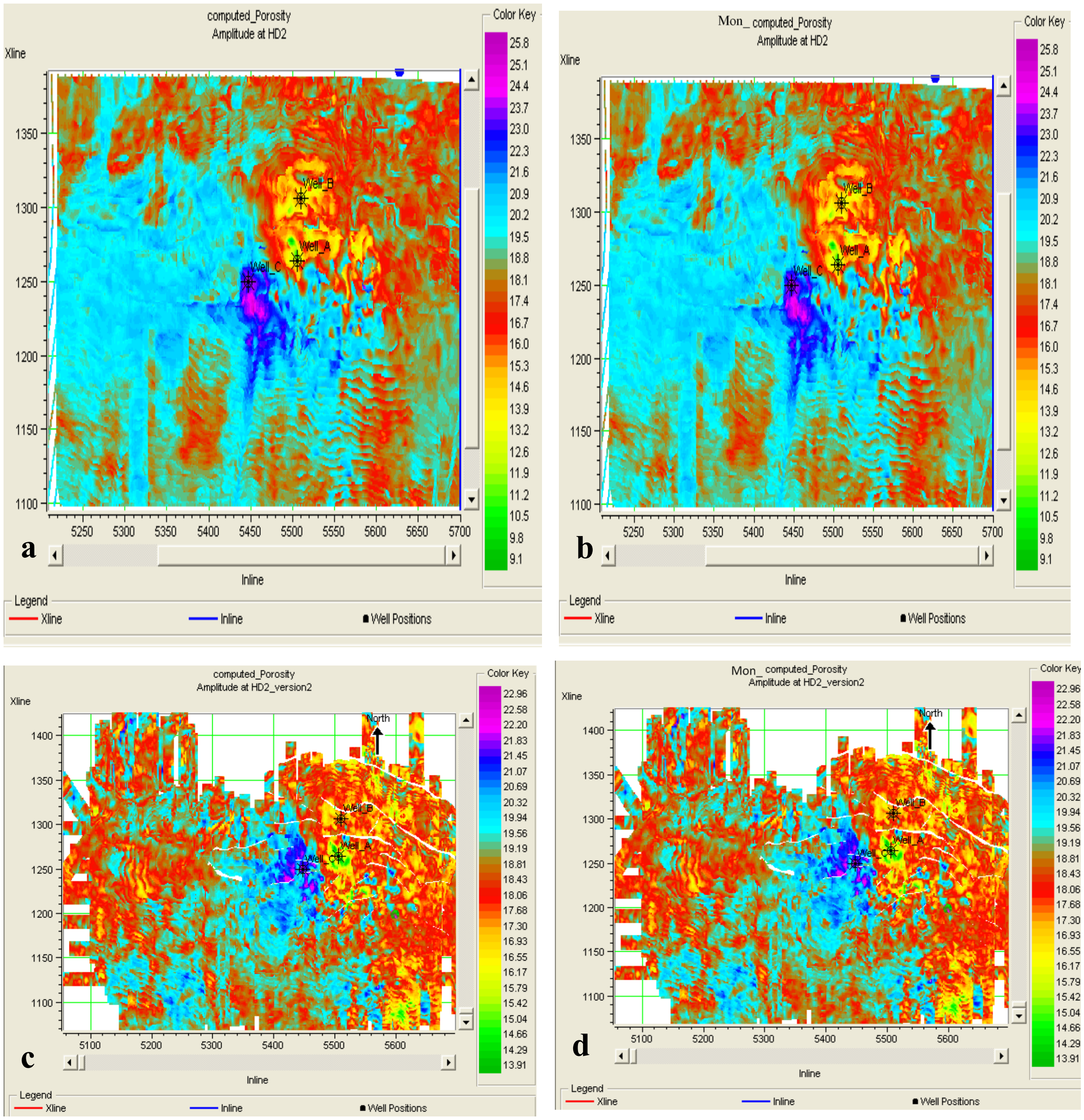


Figure 12. Porosity slices for (a) Base at HD2 (b) Monitor at HD2 (c) Base at HD2_Version2 (d) Monitor at HD2_Version2

5. Conclusion

The amount of change between the base and the monitor gives an estimate on how sensitive the attribute is to fluid changes within the reservoir. Poisson's ratio, water saturation, Lambda rho and bulk density showed significant changes between the base and monitor slices in the HD2 and HD2_Version2 horizons. An indication that these attributes are highly sensitive to lithofluid changes within the reservoir during hydrocarbon production. The change in the value of the attribute is as a result of the extraction of hydrocarbons from the reservoir between the moment of acquisition of the base and its subsequent replacement by water (brine). In the porosity slices for both horizons a significant deviation was observed in which no appreciable difference was observed between the porosity slices for the base and monitor horizons. Therefore, the replacement of hydrocarbons by water (brine) in the reservoir does not significantly affect the porosity. This study validates that 4D seismic is an advanced surveillance and indispensable tool for resolving areas of complex geometry and non-homogeneous reservoirs that conventional 3D seismic cannot properly interpret.

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Conflicts of interest/Competing interests

All the ethical principles of research in the data collection, preparation, analysis and interpretation were implemented.

Availability of data and material

Not applicable.

Code availability (Software used)

Hampson-Russell suite version 10.3.2.

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