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Utilizing Seismic Attribute Analysis in Reservoir Evaluation and Hydrocarbon Prospectivity Studies in the "Zech" Field, Onshore Niger Delta Basin, Nigeria

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Abstract

In order to better manage producing reservoirs and optimally place additional production wells, there is need to carry out a detailed hydrocarbon prospectivity studies in any given field. The aim of this paper was to integrate 3D seismic volume and wire-line logs from five wells with seismic attribute analysis in evaluating hydrocarbon prospects across the "Zech" field in the eastern part of the Coastal Swamp depo-belt of the Niger Delta Basin. Emphasis were on identification and correlation of reservoir intervals, formation evaluation, structural interpretation and mapping of reservoir tops, and amplitude extraction from seismic attribute analysis. Result from this prospect evaluation studies reveals that five reservoir zones (Z1, Z2, Z3, Z4 and Z5) were identified. Correlation of these reservoir zones across wells, shows that there were influence of structures on reservoir package, as variable thicknesses of zones were observed across faults. Petrophyiscal analysis of key reservoir properties shows that the reservoir of interest were characterized by average shale volume of 0.10 (10%), porosity of 0.23 v/v (23%) and permeability 1220 mD. In addition, the water saturations ranged between 0.08 and 0.39 v/v (8-39%), with corresponding hydrocarbon saturations that ranged from 0.60-0.91v/v (60-91%). These values indicate that the reservoirs properties were of good quality. Structural interpretation revealed the presence of growth faults and associated rollover anticline, collapsed crest structures, series of hanging walls and footwalls, which constitutes major hydrocarbon traps in the area. Generated structural top maps revealed that theses faults form structural closures. Extracted amplitude from seismic attribute analysis revealed the presence eight-hydrocarbon prospective zones that were amplitude supported. Generally, this integrated data and analytical approach is key in understanding reservoir evaluation and hydrocarbon prospectivity studies.

Keywords: *Seismic attribute; Reservoir properties, Formation evaluation; Hydrocarbon prospect, Niger Delta Basin.*

1. Introduction

Petroleum resources remain vital to the economy of several nations of the world. The enormous cost of exploration, with high level of precision, makes accurate interpretation of exploratory data indispensable in production. The integration of 3-Dimension seismic volumes and petrophysical data to enhance exploration has been a major technique commonly used. The major advantage is that seismic data can be used to interpolate and extrapolate between and beyond sparse wells within the proposed field. Although, hydrocarbon explorationists are faced with a lot of challenges associated with prospect identification, the integration of seismic attribute analysis in this study, will improve the accuracy of interpretation and prediction for better identification of prospective intervals in hydrocarbon exploration. The sensitivity of seismic attributes to lateral changes in continuity, energy and amplitudes enhances the visibility of seismic events [1]. Several seismic attributes reveal the presence of hydrocarbon as high amplitude anomaly and are known as bright spots [2]. These bright spot are calibrated against well data and structures to identify hydrocarbon accumulations and reservoir compartmentalization.

In addition, the applicability seismic attribute analysis to structural and stratigraphic analysis will allow for a better understanding and prediction of new prospects in the "Zech" field.

The objectives of this study were to; a) delineate reservoir zones and correlate same across well; b) understand the behaviour and continuity of these reservoirs zone; c) evaluate reservoirs using key petrophysical parameters; d) determine the structural framework and utilize seismic attributes such as amplitude attributes to unravel new identify new prospective zones across the "Zech" field (Fig. 1).

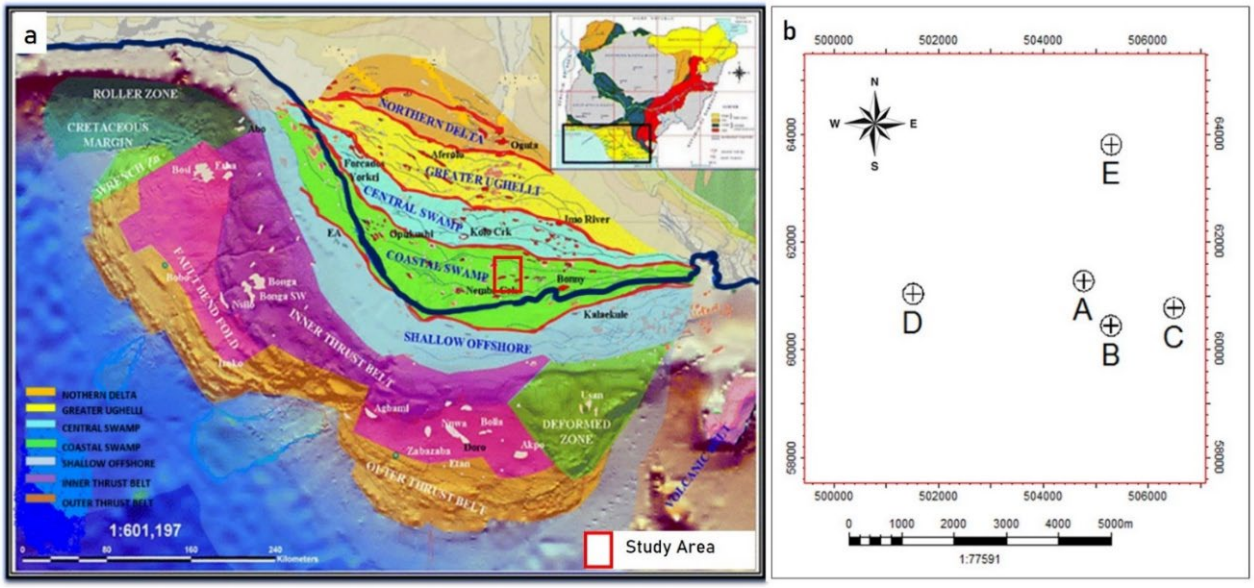

Fig. 1. a) Depo-belt map of Niger Delta Basin showing the study area with the inset map of Nigeria's sedimentary basins showing Niger Delta Basin. [4-5]. b) Map of the study area showing the distribution of wells

2. Geologic framework

The "Zech" field lies at the eastern part of the Costal Swamp Depobelt of the onshore Niger Delta Basin (Fig. 1a and 1b). The Costal Swamp is characterised by structures associated with rollover anticlines, growth faults, collapsed crest and back-to-back features [3].

The Niger Delta Basin is located along the west coast of equatorial Africa. It is one of the world's largest basins extending more than 300 km from apex to mouth with a sedimentary fill, which is entirely thought to reach a maximum thickness of about 12 km [3]. The Niger Delta Basin consists of Paleogene to Holocene marine clastic strata with three lithostratigraphic units, from the oldest to the youngest, all of which are strongly diachronous [6] (Fig. 2). The Eocene-Recent Akata Formation is a marine sedimentary succession that is laid in front of the advancing delta. It consists of mainly under compacted shales, clays, and silts at the base with lenses of sandstone. The Agbada Formation (Eocene-Recent) is characterized by paralic interbedded sandstone and shale which were deposited in a number of delta-front, delta-topset, and fluvio-deltaic environments [7-8]. The Miocene-Recent Benin Formation is the youngest unit and it is made up of continental sands and sandstones with few shale intercalations. The structural framework comprises of syn-depositional growth faults, which are predominant across the delta. They are formed during gravity changes and rapid deposition of sediments in the Agbada Formation. The faults are the major hydrocarbon trapping mechanism and are characterized by rollover anticlines and collapsed crest structures [9].

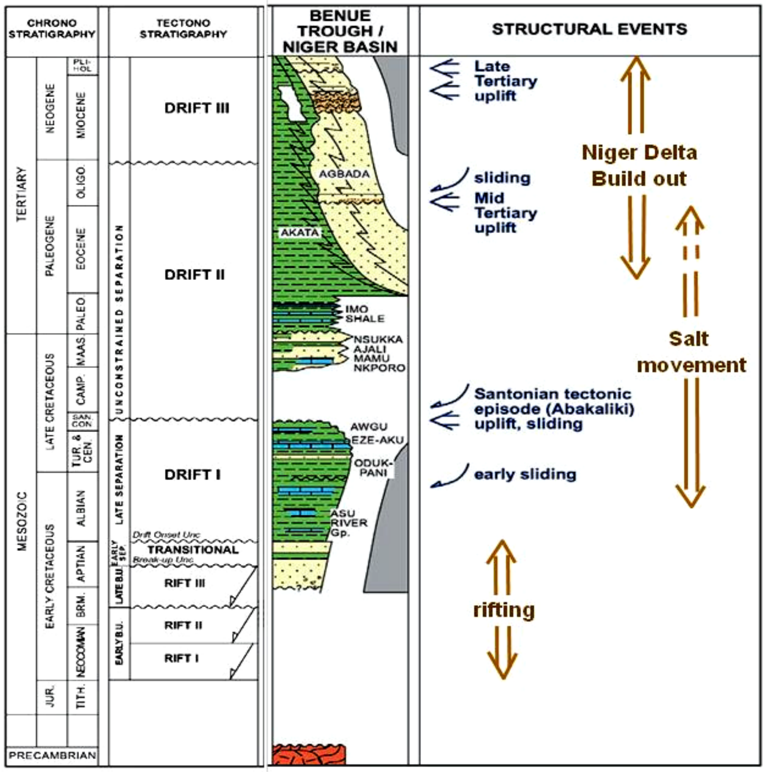

Fig. 2. Tectono-Stratigraphy of Niger Delta Basin showing major phases of evolution [6]

3. Methodology

Suites of wireline logs from five wells (A, B, C, D and E) and 3D seismic volume were used in this study. Gamma ray logs were used in delineating reservoir intervals (Z1, Z2, Z3, Z4 and Z5) across the field. Well log reservoir correlation was carried out across well using reservoir zones to help visualize the behaviour of reservoir packages along dip line (North-South) and strike (East- West) directions. These reservoirs were analysed for the presence of hydrocarbons using and also to predict the static condition of the reservoirs. Key petrophysical properties were evaluated using resistivity logs. These delineated reservoir zones were further subjected to petrophysical evaluation such as:

Shale volume, which calculates the volume of shale. These values help to discriminate between reservoir and non-reservoir rocks. Shale volume is calculated in the following way: First the gamma ray index, I_{GR} is calculated from the gamma ray log data using the relationship:

$$I_{GR}\frac{GR_{log}-GR_{min}}{GR_{max}-GR_{min}} \quad .... \qquad (1)$$

where: IGR = the gamma ray index; GR_{log} = the gamma ray reading at the depth of interest; GR_{min} = the minimum gamma ray reading. (Usually the mean minimum through a clean sandstone or carbonate formation.); GR_{max} = the maximum gamma ray reading (Usually the mean maximum through a shale or clay formation).

All these values were read off for each evaluating internal (0.5 feet) within a particular reservoir. Having obtained the gamma ray index, volume of shale was then calculated using the Larionov [10] equation for Tertiary deposits.

$V_{sh} = 0.083[2^{3.7 \times 1GR} -1.0]$ (Tertiary unconsolidated sand)… (2)

Porosity was also determined, as it is the percentage of voids to the total volume of rock. The formation density log was used to obtain formation porosity. The formation porosity was determined by substituting the bulk density readings obtained from the Density log within each reservoir into the equation (3):

$$\Phi_D = \frac{p_{ma}-p_b}{p_{ma}-p_f} \quad .... \qquad (3)$$

Effective porosity was estimated for each evaluating interval using the relation (4);

$$\Phi_e = \frac{p_{ma} - p_b}{p_{ma} - p_f} - V_{sh}\left\{\frac{p_{ma} - p_{sh}}{p_{ma} - p_f}\right\} \ldots \qquad (4)$$

where; p_{ma} = matrix density (usually 2.65g/cc sandstone), p_f = formation fluid's density (1.0g/cc for water and 0.8g/cc for hydrocarbon), p_b = formation bulk density (obtain from density log at 0.5ft. interval), p_{sh} = density of adjacent shale body.

Calculation of the water saturation for the uninvaded zone was achieved using the Simandoux [11] equation, which is a good general-purpose equation that accounts for the influence of shale with regard to water saturation. It is given below:

$$\frac{1}{R_t} = \frac{\Phi_e^m * S_W^n}{a * R_W} + \frac{Vsh * S_W}{R_{sh}} \ldots\ldots \qquad (6)$$

where; V_{sh} = volume of shale, Φ_e = effective porosity, S_w = water saturation of the uninvaded zone, R_t = true formation resistivity; R_w = resistivity of formation water; R_{sh} = resistivity of shale, n = saturation exponent; m = cementation factor; a = tortuosity factor.

Permeability is the property of a rock to transmit fluids. It is controlled by the size of the connecting passages (pore throats or capillaries) between pores. It is measured in Darcies or milliDarceis. The Timur [12] relations (shown in Eqn. 7) were used to obtain permeability value for the reservoirs delineated.

$$K = {8581 * \phi^{4.4}}\Big/{S^2_{wirr}} \ldots\ldots\ldots \qquad (7)$$

where; k = permeability in millidarcies; Φ = porosity; S_{wirr} = irreducible water saturation.

Fault picking and horizon mapping were carried out on seismic. These faults are represented on the seismic section as a discontinuous reflection along a preferred orientation. Sixteen (16) faults coded F1 to F16 were identified with the help of variance edge attribute which enhances the ability to visualize structural features on time slices [1] (Fig 3).

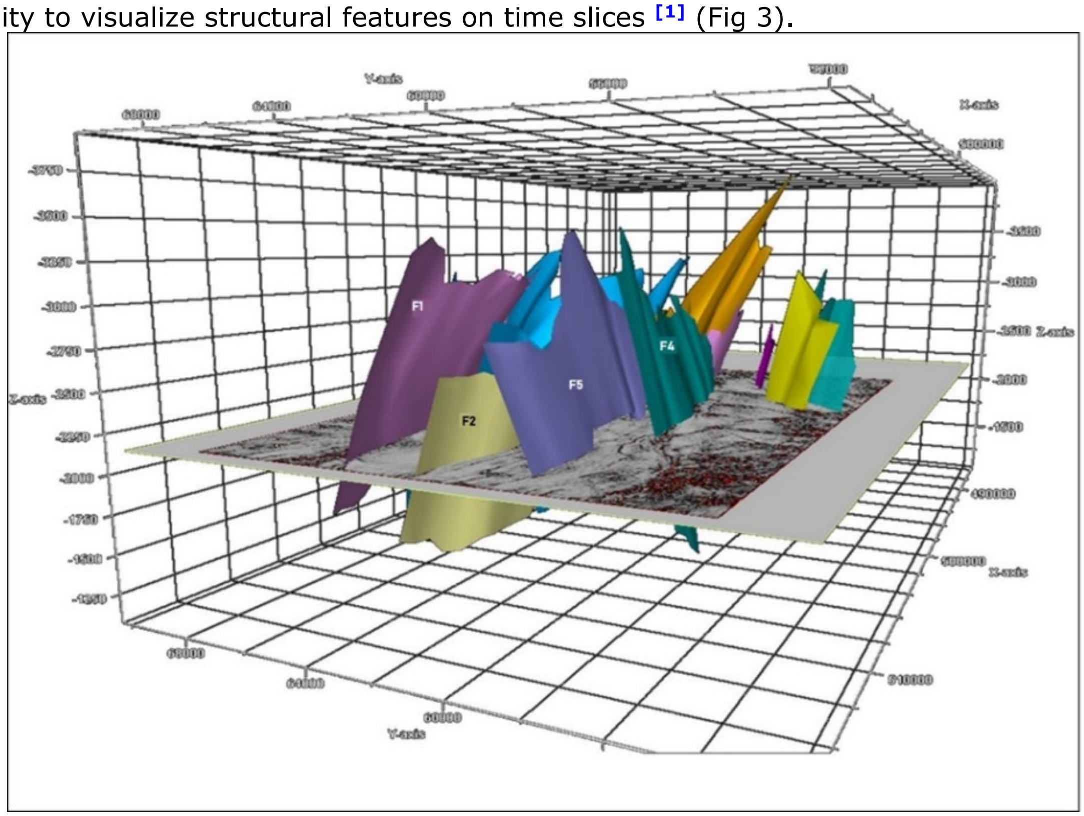

Fig. 3. 3D Seismic volume showing a time slice of variance edge with fault models across the field

Well to seismic match was carried out using the checkshot data from wells and pulse wavelet was extracted from the seismic volume and convolved with the acoustic impedance to obtain the synthetic trace along the well bore. Tops of identified reservoir intervals were mapped on seismic to generate time structural maps (T1 to T5). Structural top maps generated from these mapped reservoirs (Z1 and Z5) were depth converted using polynomial function developed from the checkshot (Fig. 4a, 4b and 4b). Attribute extractions were carried out on generated maps using seismic attributes such as root mean square amplitude (RMS), maximum amplitude and average energy [13]. Areas with good amplitude response (are direct hydrocarbon indicators) aided in prospect identification (Fig. 4c).

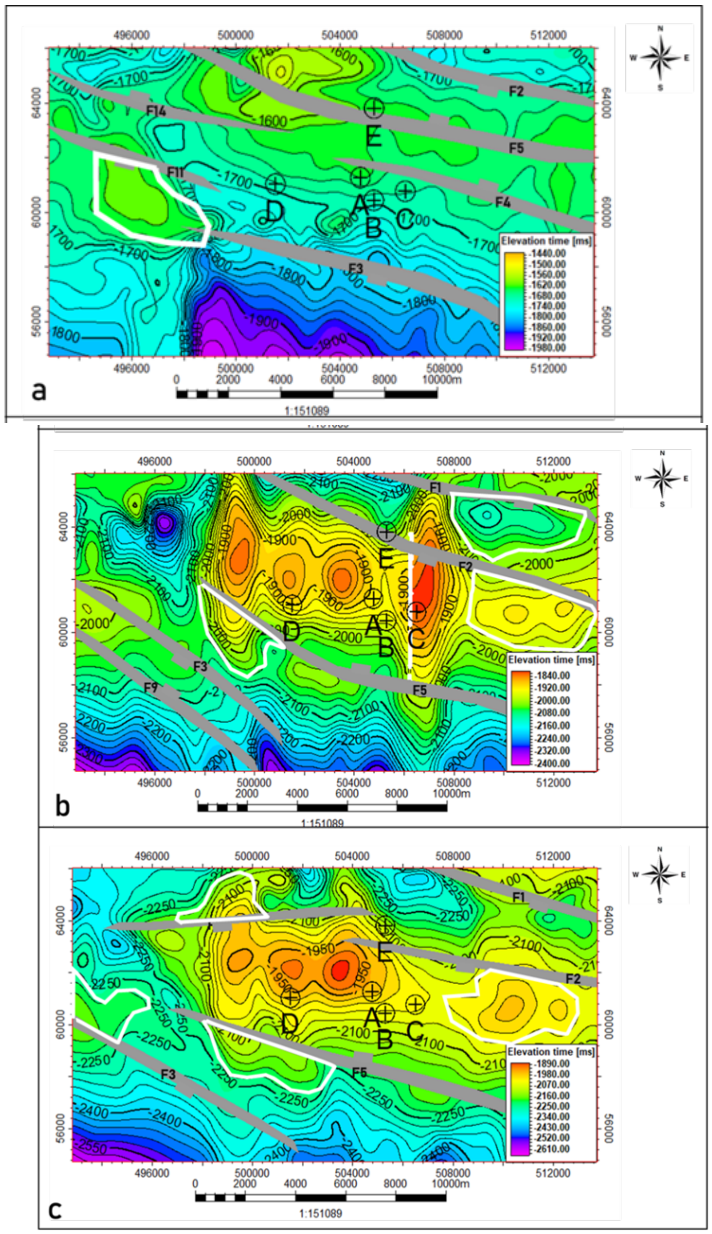

Fig. 4. a. Time structural map for R1 showing prospective zones with structural closures; b). Time structural map for R5 showing prospective zones with structural closures. c). Time structural map for R6 showing prospective zones with structural closures.

4. Analysis of results and discussion

4.1. Well Log reservoir correlation and formation evaluation

Well log reservoir correlation carried out along the dip direction (which cuts across wells E, A and B) revealed that reservoirs Z2, Z3, Z4 and Z5 are of laterally continuous with thick sand, whereas Z1 thins out down dip (Fig. 5). Similarly, the correlation across the strike direction, which cuts across wells D, A, B and C, shows that reservoirs Z2 and Z4 thin out towards the east, which implies there is poor sand development probably due to facies change. However, reservoirs Z1, Z3 and Z5 show thick continuous reservoirs across the field; with Z5 being the thickest sand. Variable thicknesses of reservoir packages were observed across the field possibly due to structural influence on stratigraphy caused by faults [14-15] (Fig. 5 and 6).

Analysis from the petrophysical evaluation studies reveals that five hydrocarbon-bearing zones were identified with high net-to-gross (NTG) values that ranged from 51-81%. The high NTG indicates the availability of good quality sand for hydrocarbon accumulation. The average volume of shale (Vs) value that range from 10-15% suggests that the reservoirs contain clay but not enough to impede fluid flow. The reservoirs show good to excellent porosity of 16 - 23%, which are of good quality. Permeability (denoting the capacity of the reservoir unit to transmit fluids) values range from 967 to 1220mD. These values indicate a good pore-grain connectivity that will optimize production [16]. In addition, water saturation values were relatively low especially in reservoir Z2 at an average of 0.08 which implies a hydrocarbon saturation of 0.92. Furthermore, hydrocarbon saturation for reservoirs Z1, Z3, Z4 and Z5 were obtained as 0.61, 0.70, 0.84 and 0.88 respectively (Table 1). From the above values, the "Zech" field shows the presence of producible hydrocarbon.

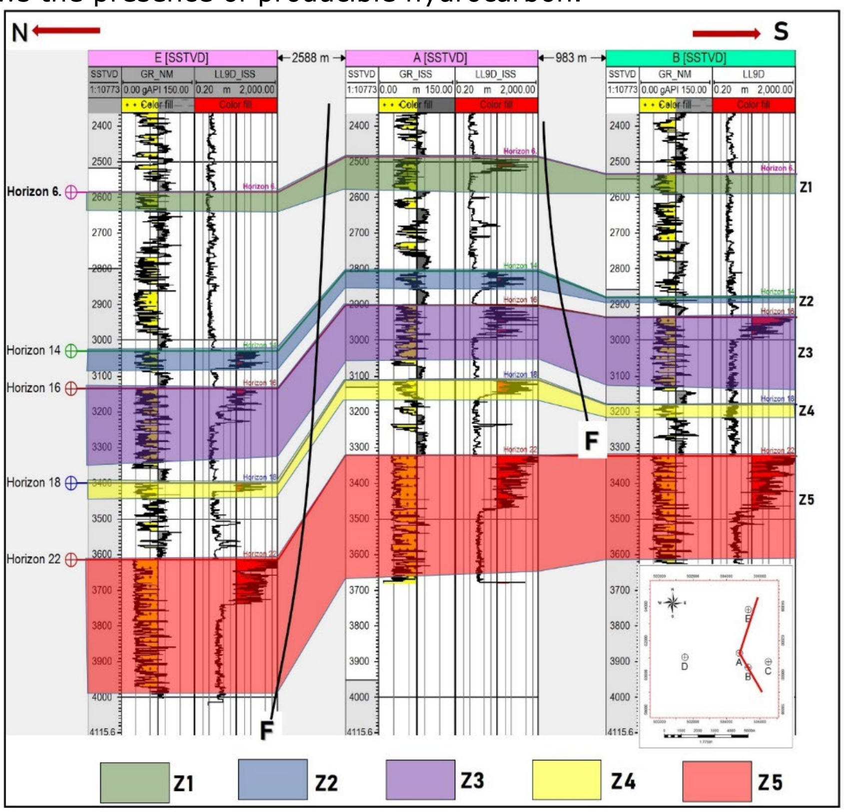

Fig. 5. Well log reservoir correlation along dip direction showing variable thickening (possibly due to fault)

Table 1. Average values of petrophysical parameters for the various reservoir zones across the field

Petrophysical parameters	Z1	Z2	Z3	Z4	Z5
Gross thickness (ft)	316	189.75	660	238.25	889.5
Net thickness (ft)	229.5	148.72	406.1	141.37	658.95
Net/Gross reservoir	0.726	0.783	0.622	0.612	0.724
Av Phi (v/v)	0.218	0.222	0.172	0.207	0.168
S_w (v/v)	0.394	0.089	0.305	0.157	0.118
S_h (v/v)	0.606	0.911	0.695	0.842	0.882
Permeability (mD)	1205	1220	985	1110	967

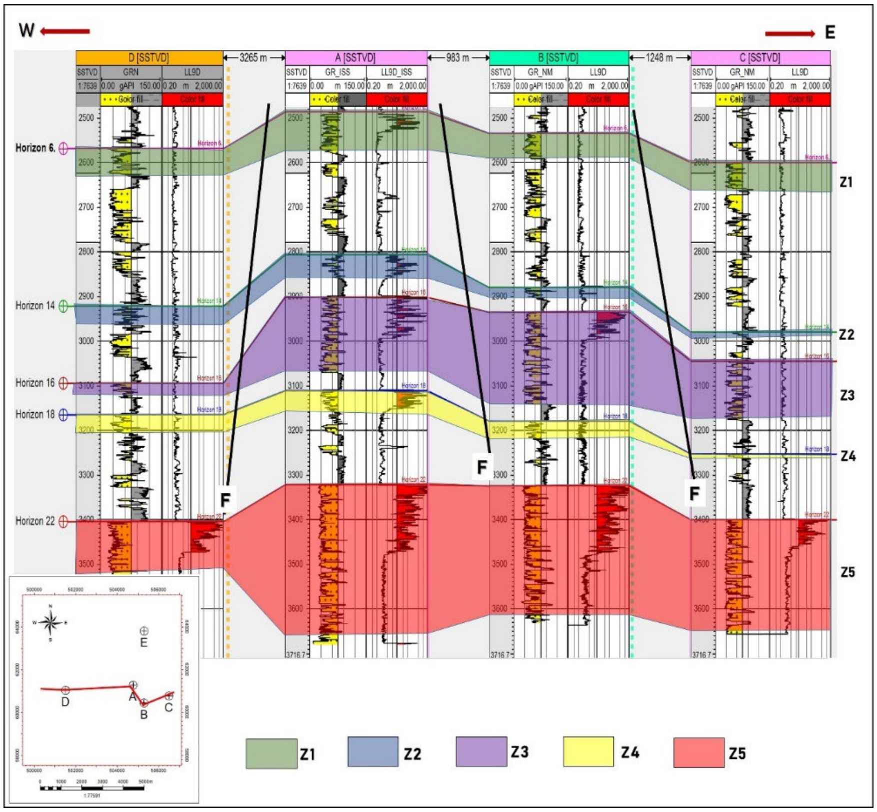

Fig. 6. Well log reservoir correlation along strike showing variable thickening (possibly due to fault and sediment thin out)

4.2. Fault and horizon interpretation

The structural analysis revealed 16 faults coded F1 to F16 with the aid of generated variance edge attribute. Two regional faults F1 and F3, which are listric in nature, dips basinwards. The field is dissected by several intermediate faults, which are antithetic and synthetic as well (Fig. 7). Fault interpretation reveals that the "Zech" field is characterized by several structural styles such as back-to-back, collapsed crest fault and rollover anticlinal structures. These structural styles constitute the structural traps for hydrocarbons in the field [17]. The two reservoirs, R1 and R5, which marks tops of reservoirs Z1 and Z5 were mapped. Deeper prospects were identified on these mapped tops. This reservoir top was coded as R6. The depth structural maps indicate areas with structural controls such as structural high and fault dependent closures, which are likely areas of hydrocarbon accumulation. This gave insights to possible prospects. The potential new prospects were identified as structural closure on R1 structural map (Fig. 8a). This closure is located on the footwall of fault F11 that dips basinward. In addition, the R5 top has faulted high, forming a collapsed crest structure (Fig. 8b). R6 has similar structure with R5, which is a typical example of a collapsed crest structure. The structural controls are also the three-way and four-way-dip closures (Fig. 8c).

4.3. Seismic attribute extraction analysis

Several seismic attribute analysis was integrated to enable identification new prospects in the field. Seismic attribute extraction methods such as root mean square, maximum amplitude and average energy were carried out on the three structural maps. This unravelled several areas with booming amplitude. The root mean square showed high amplitude anomaly in the North Central part of reservoir R1, as well as in the North East and North Central part of reservoir R5 (Fig. 9a and 9b). At a deeper depth in reservoir R6, a high amplitude anomaly was observed at the North East, North West and North Central part of the map (Fig. 9c). Furthermore, maximum amplitude showed high anomaly in the Western and in the Eastern part of reservoirs R1, R5 and R6 (Figs. 10a, 10b and 10c). The average energy amplitude extractions indicated high to medium amplitude anomaly in the North central and North West part of reservoir R1 (Fig. 11a), North East and North Central part of reservoir R5 (Fig. 11b), North West, North East and at the centre of reservoir R6 (Fig. 11c). These areas of high amplitude anomaly depicts presence of hydrocarbon accumulation [15].

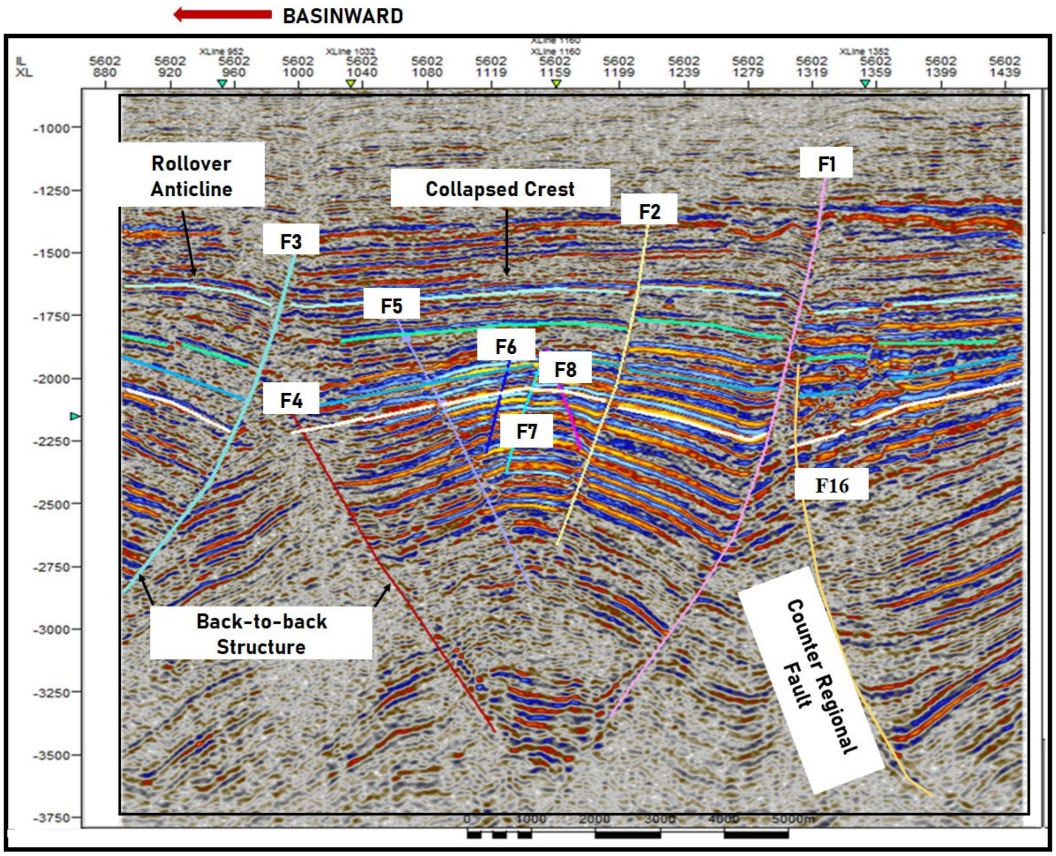

Fig. 7. Seismic section across the inline showing interpreted faults F1 and F3 and mapped reservoir intervals

4.4. Hydrocarbon Prospective zones and implications

The reservoir studies revealed that the field has several hydrocarbon prospective zones. The outcome of structural and stratigraphic analyses has shown that the area is characterized by some down-to-basin faults that are associated with rollover anticlines, which provides entrapment mechanisms for hydrocarbon accumulations. Generated structural top maps reveals the presence of proven hydrocarbon accumulation denoted by already drilled wells (A, B, C, D and E) within the central part of the three reservoir intervals. However, this study has unravelled several prospective intervals and zones away from these proven zones, zones utilizing amplitude-extracted maps.

Generated amplitude extracted map shows booming amplitude that are structurally controlled, hence pointing to the presence of some other prospects in the field [17]. The root mean square amplitude, maximum amplitude and average energy amplitude were used because of their sensitivity to direct hydrocarbon indicators and their pattern of bright spot anomaly superposition on the structural closures are discrete [18]. One hydrocarbon prospective zone (Alpha) was identified for R1 while three (Beta, Chi and Delta) were identified for R5, whereas four (Delta, Epsilon, Iota, and Kappa) were observed in R6 reservoir intervals. In R1 reservoir top, the prospective zone is a typical three-way fault dependent closure as they are bounded by one fault (Fig. 12a).

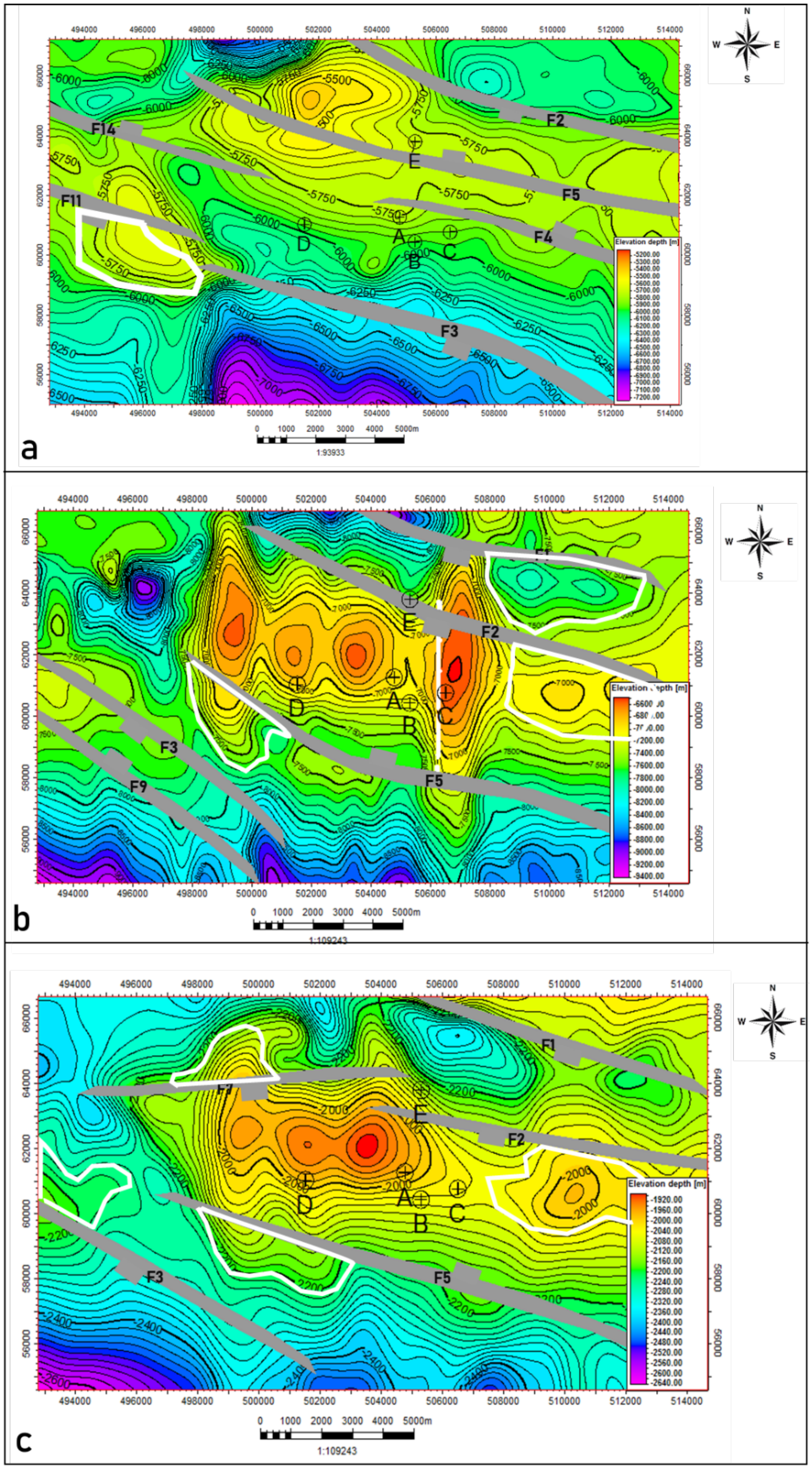

Fig. 8. a) Depth structural map for R1 showing prospective zones with structural closures. b). Depth structural map for R5 both showing two way dip closures. c). Depth structural map for R6 indicating a typical plan view of a collapsed crest structure

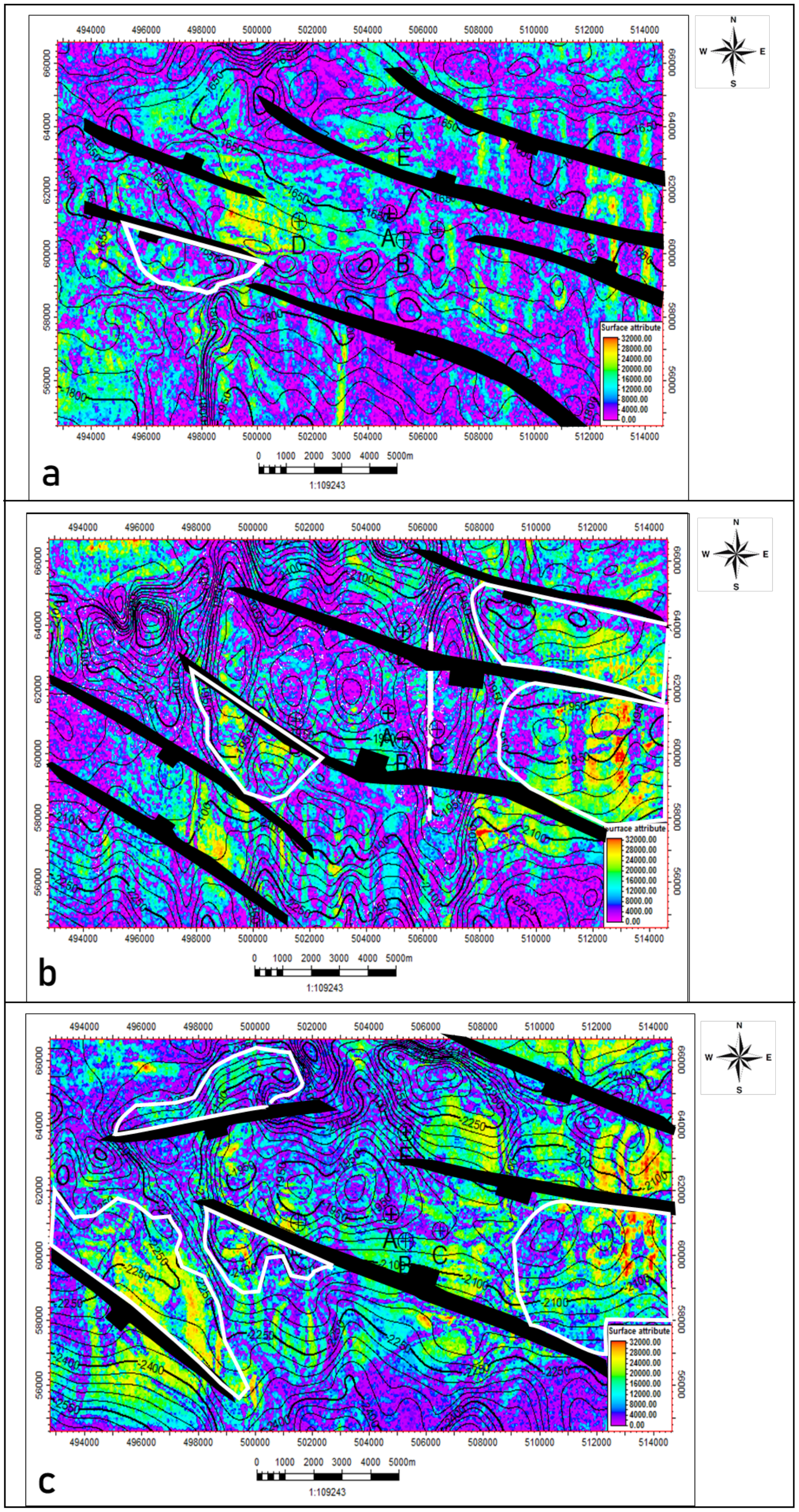

Fig. 9. a) R1 RMS map showing areas of medium to high amplitude as light green, yellow and red colours. b) R5 RMS map showing areas of medium to high amplitude as light green, yellow and red colours. c). R6 RMS map showing areas of medium to high amplitude as light green, yellow and red colours

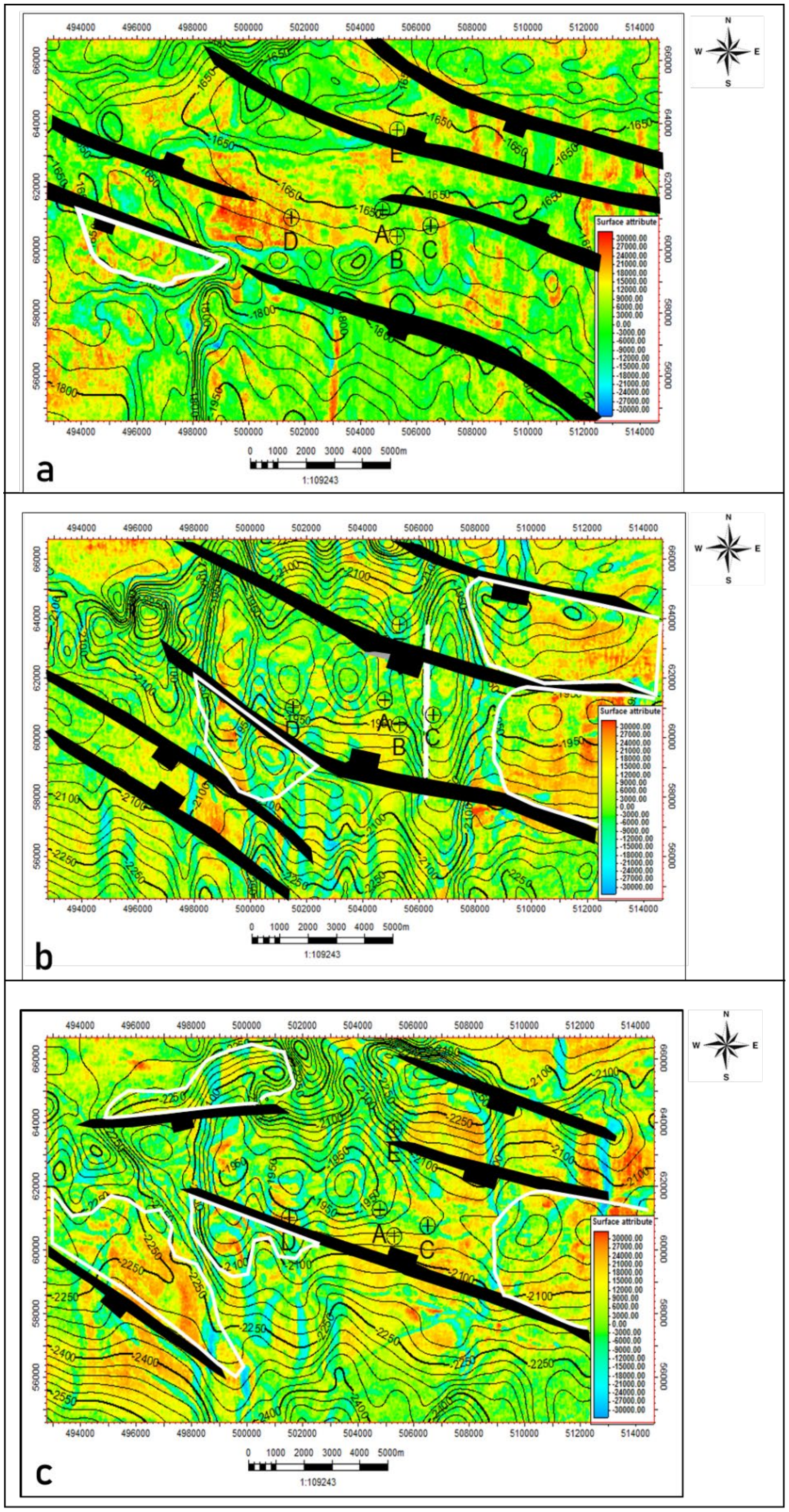

Fig. 10. a) R1 Maximum amplitude map showing areas of medium to high amplitude as yellow and red colours. b). R5 Maximum amplitude map showing areas of medium to high amplitude as yellow and red colours. c). R6 Maximum amplitude map showing areas of medium to high amplitude as yellow and red colours

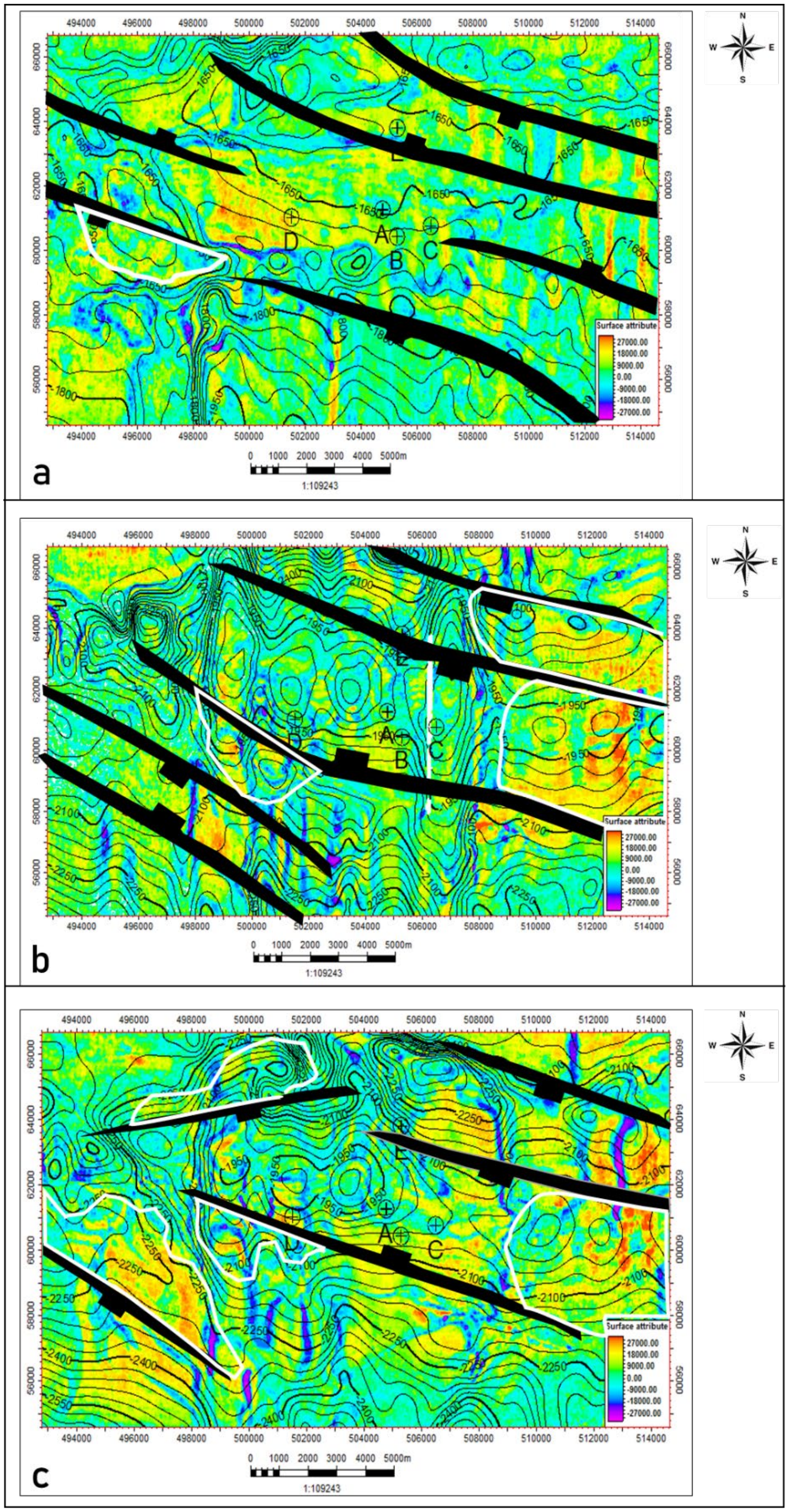

Fig. 11. a). R1 Average Energy map showing areas of medium to high amplitude as yellow and red colours. b). R5 Average Energy map showing areas of medium to high amplitude as yellow and red colours. c). R6 Average Energy map showing areas of medium to high amplitude as yellow and red colours.

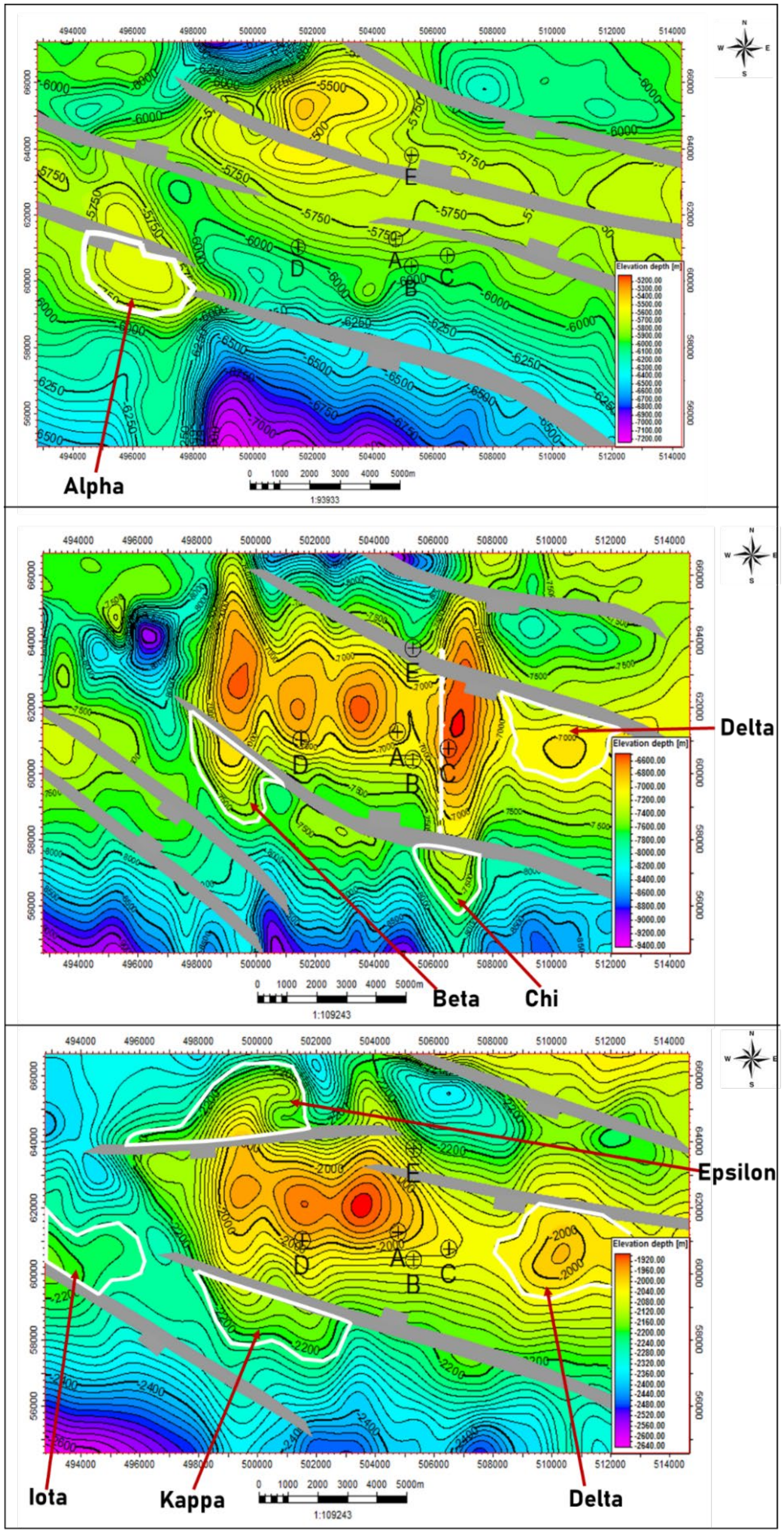

Fig. 12. a). R1 depth map showing identified prospect (Alpha). b). R5 depth map showing identified prospects (Beta, Chi and Delta). c). R6 depth map showing identified prospects (Delta, Epsilon, Iota, and Kappa)

In R5 reservoir top, the Beta and Chi zones, shows three-way fault dependent closures whereas, Delta zone reveals a four-way closure with high amplitude (Fig. 12b). Based on the trapping structures, Delta zone could be considered the best for hydrocarbon accumulation. Three out of four prospective zones (Epsilon, Iota, and Kappa) in reservoirs R6 top shows three-way fault dependent closures as they are bounded by one fault (Fig. 12c), while zone (Delta Prospect) shows a four-way closure as it is devoid of faults. Zone (Delta) offers the best hydrocarbon lead when compared with others, considering the developed entrapment mechanism for hydrocarbon accumulation. Overall, the integration of seismic attribute analysis in reservoir evaluation and hydrocarbon prospectivity studies is quite important in the prediction of new prospective zones away from already producing zone.

5. Conclusions

Reservoir evaluation and hydrocarbon prospectivity studies carried out using 3D seismic volume; wire line logs from five wells integrated with seismic attribute analysis have unravelled some key prospective interval across the "Zech" field of the costal Swamp Depobelt in the Onshore Niger Delta Basin. Five reservoir intervals were identified. Correlation across dip line and strike reveals that these reservoir packages were laterally continuous with variable thickness due to structural influence of stratigraphy. Results from formation evaluation show that parameter such as shale volume values were found to be relatively low in the range of 0.10-0.15 v/v (10-15%). Average porosity and permeability range from medium to high with values of 0.16-0.23 v/v (16-23 %) and 967-1220 mD respectively. These moderate to high values from porosity and permeability indicate a good to excellent porosity and permeability for the reservoirs. In addition, the low water saturation of 0.08-0.39 v/v (8-39%) obtained is an indication of good hydrocarbon saturation of 0.60-0.91 v/v (60-91%). Interpreted fault structures show that the major faults F1 and F3 were listric in nature and dips basinwards. These were associated with rollover anticlines characterizing by some collapsed crest structures. These structural styles provide good entrapments for hydrocarbon accumulation. Generated structural top maps from mapped horizons of three identified reservoirs (R1, R5 and R6) revealed structural closures that could allow for hydrocarbon accumulation. Maximum amplitude, root mean square and average energy attributes extracted on these reservoirs unravelled several eight prospective zones (Alpha, Beta, Chi and Delta, Epsilon, Iota, and Kappa) that could add to the existing reserve within the field.

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References

[1] Chopra S, Marfurt KJ. Seismic attributes for prospect identification and reservoir characterization: Society of Exploration Geophysicists geophysical development series, 2007;11
[2] Sheriff RE. Seismic Stratigraphy. International Human Resources Development Corporation (IHRDC), Boston 1980, 227.
[3] Doust H, Omatsola E. Niger Delta. In J. D. Edwards, & P. A. Santogrossi (Eds.), Divergent and Passive Margin Basins. American Association of Petroleum Geologists, Memoir, 1990; 48: 201-238.
[4] Obaje NG, Wehner H, Scheeder G. Hydrocarbon prospectivity of Nigeria's inland basins: From the viewpoint of organic geochemistry and organic petrology. America Associated of Petroleum Geologists Bulletin,2004; 88(3): 325-353.
[5] Ejedawe J. Nigeria potential waiting to be trapped. AAPG Explor., 2012; 33(5).
[6] Lawrence SR, Munday S and Bray R. Regional geology and geophysics of the eastern Gulf of Guinea (Niger Delta to Rio Muni): The Leading Edge, 2002; 21, 1112–1117.
[7] Short KC, Stauble AJ. Outline geology of the Niger Delta. American Association of Petroleum Geologists Bulletin, 1967; 51: 761–779.
[8] Stacher P. Present Understanding of the Niger Delta Hydrocarbon Habitat. In: Oti, M. N., and Postma, G., eds., Geology of Deltas, A. A. Balkema, Rotterdam 1995, 257-267.
[9] Larionov VV. Borehole Radiometry. U.S.S.R. Nedra 1969, Moscow.

[10] Simandoux P. Dielectric measurement on porous media, application to the measurements of water saturation: Study of behaviour of argillaceous formations. Revue de I'institut Francais du Petrol, 1963; 18(Supplementary issue): 93-215.
[11] Timur A. An investigation of permeability, porosity, and residual water saturation relationships for sandstone reservoirs. The Log Analyst, 1968; IX (4). SPWLA-1968 VIXN4A2.
[12] Dim CIP, Onuoha KM, Mode AW, Okwara IC, Okeugo CG. Characterizing the middle–upper Miocene reservoir intervals of a producing field in the Niger Delta Basin: an application of facies, sequence stratigraphic and petrophysical analyses. Arabian J. Sci. Eng., 2018; 44, 429–448. https://doi.org/10.1007/s13369-018-3502-x.
[13] Dim CIP, Onuoha KM, Ozumba BM. Hydrocarbon leads and prospects opportunities across a cluster of fields in parts of Onshore Niger Delta Basin Journal of African Earth Sciences, 2020; 164: 103804. https://doi.org/10.1016/j.jafrearsci.2020.103804.
[14] Dim CIP. Hydrocarbon Prospectivity in the Eastern Coastal Swamp Depo-Belt of the Niger Delta Basin – Stratigraphic Framework and Structural Styles. Springer Briefs in Earth Sciences. Springer International Publishing AG, Gewerbestrasse 2017, Switzerland, pp. 71.
[15] Omoja UC, Obiekezie TN. Application of 3D seismic Attribute Analyses for Hydrocarbon Prospectivity in Uzot –Field, Onshore Niger Delta Basin, Nigeria. International Journal of Geophysics, 2019; ID 1706416. https://doi.org/10.1155/2019/1706416.
[16] Knox GJ, Omatsola EM. Development of the Cenozoic Niger delta in terms of the "Escalator Regression" model and impact on hydrocarbon distribution: Proceedings KNGMG Symposium "Coastal Lowlands, Geology and Geotechnology," 1987: Dordrecht, Kluwer, 181-202.
[17] Anyiam OA, Andrew PJ, Okwara IC. Assessment of the heterogeneity and petrophysiscal evaluation of reservoirs in the "Akbar Field", Niger Delta, Nigeria. Journal of Petroleum Exploration and Production Technology, 2017; 7: 1035-1050.

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