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SUBSURFACE STRUCTURAL AND STRATIGRAPHICAL EVALUATION OF SAPELE SHALLOW FIELD, NIGER DELTA, SOUTHERN NIGERIA.

[1]Mujakperuo, B. J. O. and [1*]Airen, O. J.
[1] Department of Physics, Faculty of Physical Sciences, University of Benin, Nigeria
*Corresponding author Email: osariere.airen@uniben.edu, +2348039591347

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ABSTRACT

This research presents the results of the subsurface structural and stratigraphical evaluation of the Sapele Shallow field of the Niger Delta. 3D seismic cube and well log data were used in carrying out this research work. Analysis of the three horizons' structural maps showed the subsurface's structural geometry and the presence of a possible trapping mechanism, which controls the accumulation of hydrocarbons in the studied area. Interpretations of faults that described the structural setting of the field showed three major faults trends from East to West whiles dipping southward with other minor faults. The stratigraphy of the study area thickens from north to south (basinward). Also, the root-mean-square (RMS) amplitude maps analysis of the various horizons reveals that all horizons mapped in the studied area have bright spots (Sweet Spot) except horizon 7.

Keywords: Structural, Stratigraphical, Horizons, Hydrocarbon, Bright Spot.

INTRODUCTION

Subsurface structural and stratigraphical evaluation is the concatenation of all relevant information that is required to describe a reservoir in terms of its ability to store and produce hydrocarbons. This entails knowing the complete reservoir architecture, including the internal and external geometry, its model with the distribution of reservoir properties and understanding the fluid flow within the reservoir. Such information helps improve production rates, rejuvenate oil fields, predict future reservoir performance, minimize cost expenditure, and help oil companies manage accurate financial models. According to Haldorson and Damsleth (1993), the principal goal of reservoir characterization is to outsmart nature to obtain higher recoveries with fewer wells in better positions at minimum cost through optimization. The oil and gas industry is a technology-driven industry, our ability to locate and extract hydrocarbons from beneath the ground surface is tied directly to the evolution of technologies, concepts, and interpretative sciences. These technologies are seismic-based methods for imaging features beneath the ground's surface, advances in well logging techniques, improvements in the ability to drill in deep water beyond the continental shelf, the advent of horizontal drilling, micropaleontology, biostratigraphy, to name a few.

Virtually all the petroleum in the Niger Delta is found in paralic sands. The hydrocarbons are trapped in rollover anticlines or against growth faults, especially along the footwall. Minor stratigraphic traps also occur in some fields due to lateral facies changes or in association with clay-filled channels (Orife and Avbovbo, 1981). The Niger Delta is comprised of five off-lapping siliciclastic sedimentation cycles. These cycles or depobelts as they are more typically called, grade 250 kilometers southwestward over oceanic crust that underlies the Gulf of Guinea (Stacher, 1995). The depobelts are defined by synsedimentary fault trends that formed in response to different rates of subsidence and sediment supply (Doust and Omatsola, 1990). As the delta prograded, when local subsidence diminished greatly, the focus of sediment deposition was forced to shift seaward, forming a new depobelt (Doust and Omatsola, 1990). Each depobelt is a separate unit that corresponds to a break in regional dip of the delta and is bounded landward by growth faults and seaward by large counter-regional faults or the growth fault of the next depobelt seaward (Evamy *et al.,* 1978; Doust and Omatsola, 1990). Five major depobelts are generally recognized, each with its own sedimentation, deformation, and petroleum history (Tuttle *et al.,* 1999).

Although there is petroleum accumulation throughout the Agbada Formation, there are several directional trends that form an "oil-rich belt" where the largest oil accumulations are found (Ejedawe, 1981; Evamy *et al.*, 1978; Doust and Omatsola, 1990). This belt extends offshore from northwest to southeast and roughly corresponds to the transition between continental and oceanic crust. The oil- rich Agbada belt is also located within the axis of maximum sedimentary thickness. This hydrocarbon distribution was originally attributed to timing of trap formation relative to petroleum accumulation. Evamy *et al.,* (1978), however, showed that there was no relationship between the growth of faults and the distribution of petroleum. Weber (1987) suggested that the oil-rich belt "golden lane" coincides with a concentration of rollover structures across depobelts having short southern flanks and minor paralic sequences to the south. Doust and Omatsola (1990), suggested that the distribution of petroleum is likely related to heterogeneity of source rock type and/or segregation due to remigration. Haack *et al.,* (1997) and Tuttle *et al.,* (1999) suggested that the accumulation of these source rocks was controlled by pre-Tertiary structural sub-basins related to basement structures. Stacher (1995), used sequence stratigraphic concepts to develop a hydrocarbon habitat model for the Niger Delta. This model, constructed for the central part of the Niger Delta, relates deposition of the Akata and Agbada Formations to relative sea level changes. Pre-Miocene Akata shale was deposited in deep water during low stands and is overlain by progradational Miocene Agbada strata. The Agbada Formation in the central portion of the delta was deposited on a shallow ramp as mainly high stand (hydrocarbon-bearing sands) and transgressive (sealing shale) systems tracts; third order low stand system tracts are not easily recognizable within the Agbada Formation. Faulting in the Agbada Formation provided migration pathways and formed structural traps, whereas shales in the transgressive system tracts provide excellent seals.

The source rocks for the petroleum accumulations in the Niger Delta has been a controversial subject. Some workers favor the shales of the Agbada Formation as the main source rock (Short and Stauble, 1967; Lambert-Aikionbare, 1982). Whereas others

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believe the main source to be the marine Akata Formation (Weber and Daukoru 1975; Ekweozor and Daukoru, 1984). Short and Stauble, (1967) and Frankl and Cordy, (1967) were the first to propose an origin from the Agbada Formation, but were challenged by Weber and Daukoru, (1975) and Ekweozor and Daukoru, (1984) who claimed that in most parts of the delta, the Agbada Formation is immature. They sought a source within the Akata shales, which they expected would be a better-quality source because there were deeper and more mature than the Agbada shales (Doust and Omatsola, 1990).

The main source rock in the Niger Delta is related to the position of the oil generative window (OGW) over time (Evamy *et al.*, 1978; Ejedawe, 1981). In the central part of the delta where the OGW is very deep, Akata shale is believed to be mainly gas generating, while Agbada shale is the main oil source. In the western delta, the OGW lies within the Agbada Formation, and it is the main oil source, whereas the underlying Akata shale is the main gas source. In the eastern delta, however, the Agbada Formation is relatively thin and the top of the OGW lies well within the Akata shales, which are the main source of hydrocarbons in this area. Bustin (1988), established that it is a mixture of type 2 kerogen (characterized by the relatively hydrogen-rich maceral exinite, e.g. spores and pollen of land plants, primarily marine phytoplankton cysts) and type 3 kerogen (contains sufficient hydrogen to be gas generative but not enough hydrogen to be oil-prone), which generates light oil and gas respectively, Ejedawe *et al.*, (1984), suggested that thermal conditions rather than kerogen type is the main factor influencing oil and gas occurrence in the Niger Delta. Tissot *et al.*, (1987) also supported this conclusion.

In general, migration of generated hydrocarbon postdates the cessation of sedimentation and structural deformation. In some places, migration is very local and occurred from the paralic shales into the sands. Weber (1971), proposed that when the overpressure shales on the up-thrown side of a fault are juxtaposed against hydrostatic pressured sands on the down-thrown side, cross-fault migration takes place due to pressure differential.

(a) Location of the Study Area

The Sapele Shallow field is situated in the proximal portion of OML 41, located in the Northwestern (Greater Ughelli Depobelt) part of the Niger Delta (Figure 1).

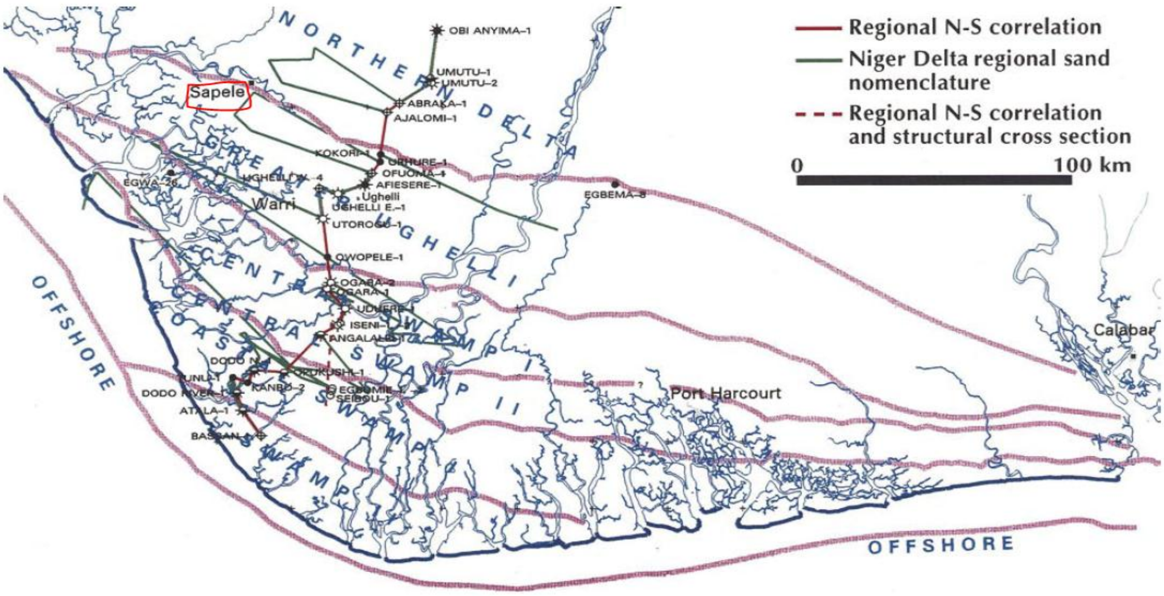

Figure 1: Location map of Niger Delta Depobelts, Showing the Study Area (Reijers et al., 2011).

(b) Structure and Stratigraphy of the Niger Delta

The Niger Delta complex is cut by numerous approximately East-West trending synsedimentary faults and folds. These structures are related to growth faults and were initiated by differential loading of the underlying under compacted Akata shales. The growth faults flatten with depth into a master detachment plane near the top of the over pressured Akata shale sequence. Most of the faults are listric normal faults, although other types include crustal faults, flank faults, counter regional faults, and antithetic faults (Reijers et al., 1997). The stratigraphy of the Niger Delta is closely related to its structure. The development of each being dependent on interplay between sediment supply and subsidence rate (Figure 2). According to Frankl and Cordy (1967), Knox and Omatsola (1989), the modern Niger Delta is made up of three subsurface stratigraphic units. The delta sequence is mainly a succession of marine clays (Akata Formation) overlain by paralic sediments (Agbada Formation) which were finally capped by continental sands (Benin Formation).

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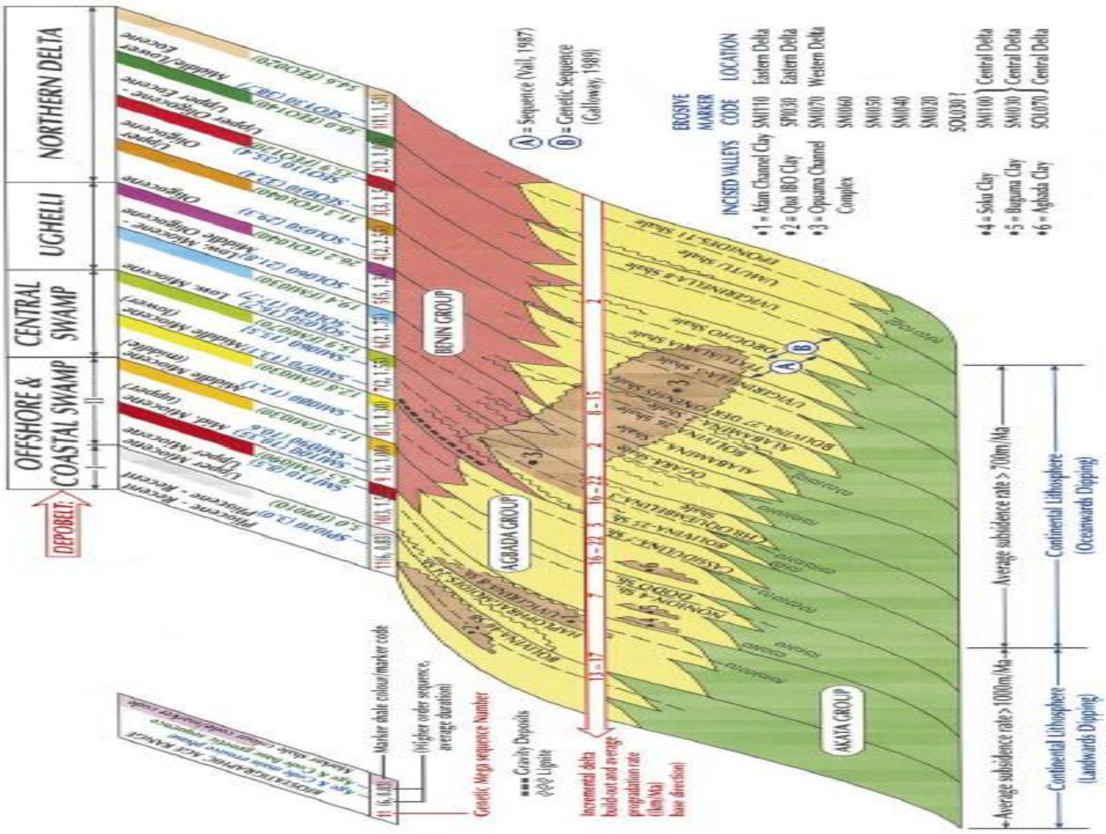

Figure 2: Diagrammatic Representation of the Stratigraphic Evolution of the Niger Delta (Reijers, 2011).

MATERIALS AND METHODS

The materials used in carrying out this research are a suit of seismic and well logs data provided across the field. These subsurface data belong to Seplat Petroleum Development Company PLC (Seplat Energy PLC) and was released under the approval of the Department of Petroleum Resources (DPR), Nigeria. Petrel®2016 (Schlumberger software) was used in the data interpretation.

RESULTS AND DISCUSSION

(a) Well to Seismic Integration

Regional stratigraphic markers (MFSs and SBs) identified from well log sequence stratigraphy were calibrated as well-tops along well track and displayed against seismic. This made it possible to tie these markers/surfaces to seismic events (Figure 4). Evidence in seismic such as reflection terminations and geometry were interpreted and used to constrain their picks. However, not all picks in the well-log sequence stratigraphic panel were adequately tied to seismic all through the area of interest. Some very old MFS and SB were not picked in the study area where they did not penetrate older units, and hence it was difficult to tie and map these older markers across faults. Similarly, very young MFS and SB which lie within the chaotic and discontinuous reflections were also difficult to map across the whole study area. Pattern recognition and basic stratigraphic and structural geology principles were used to extrapolate and map these markers across the study area.

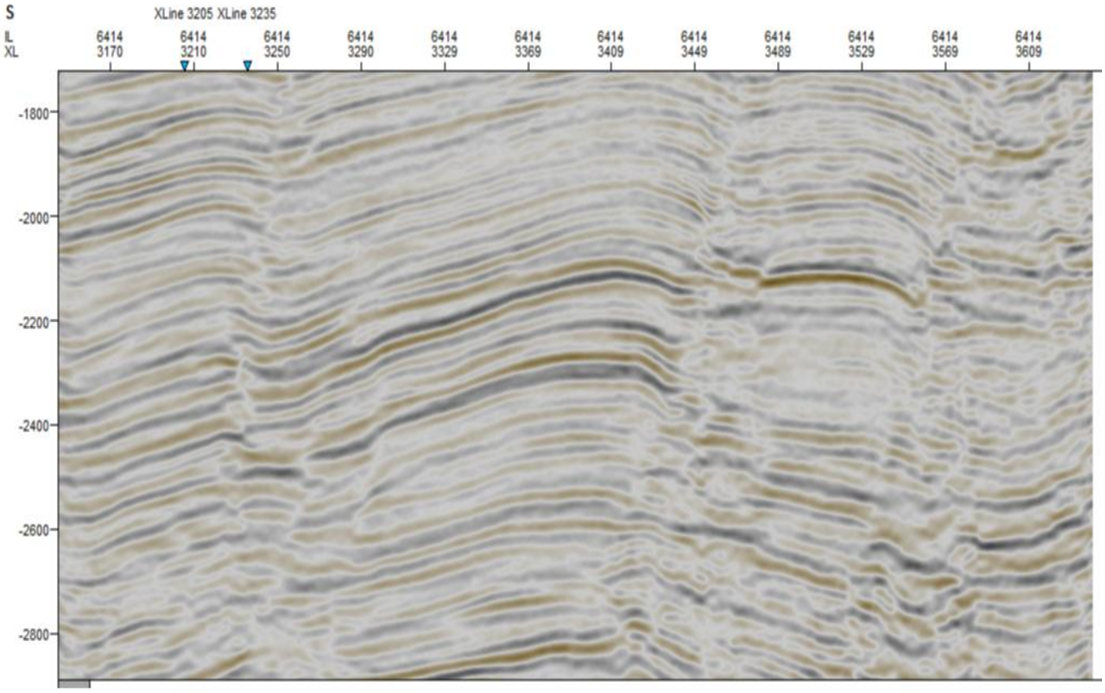

Figure 3: Seismic Section of the Study Area (Using Petrel®20

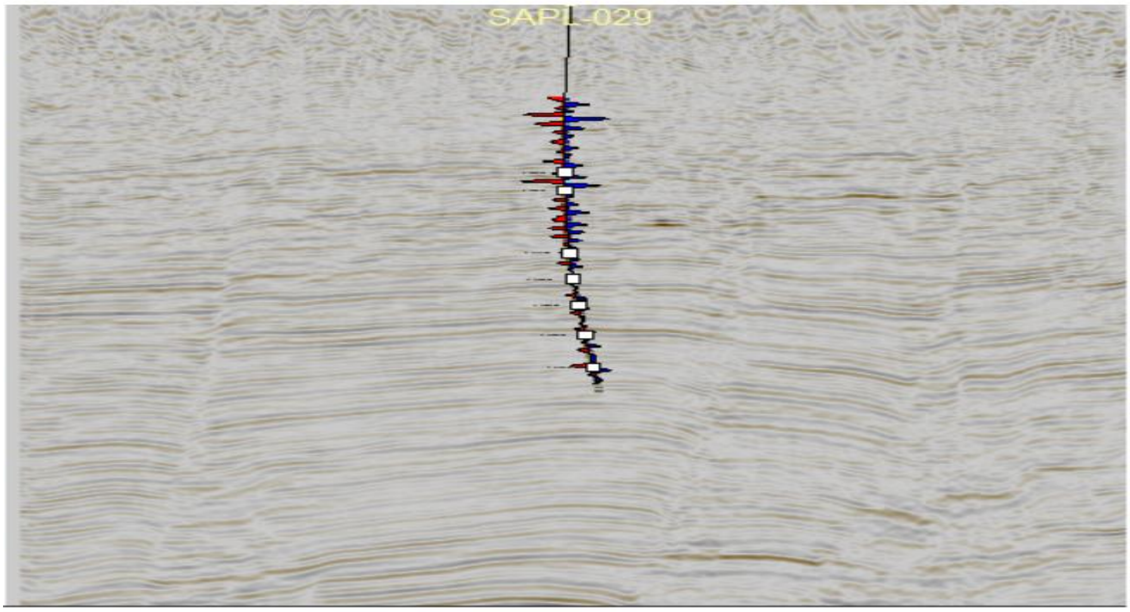

Figure 4: Well to Seismic integration of Sapele shallow well 29 (Using Petrel®2016).

(b) Fault Interpretation

Seismic volume and semblance map revealed reflection discontinuities and patterns which are identified and interpreted as faults (Figure 5). These fault sticks were interpreted manually using interactive 3-D windows. The fault stick picking was done systematically at a very close spacing to get as much detail as possible. This was particularly important and quite helpful at the very deep sections of the seismic section where tracing of fault continuity becomes more challenging due to data quality deterioration with increasing depth, although some of the faults were linear especially the shorter ones, most of the interpreted sticks were large listric faults. The

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bounding regional (down-to-basin) faults are mainly listric in nature and concave basin ward. They are mainly synthetic, having the same dip direction as the regional stratigraphic package.

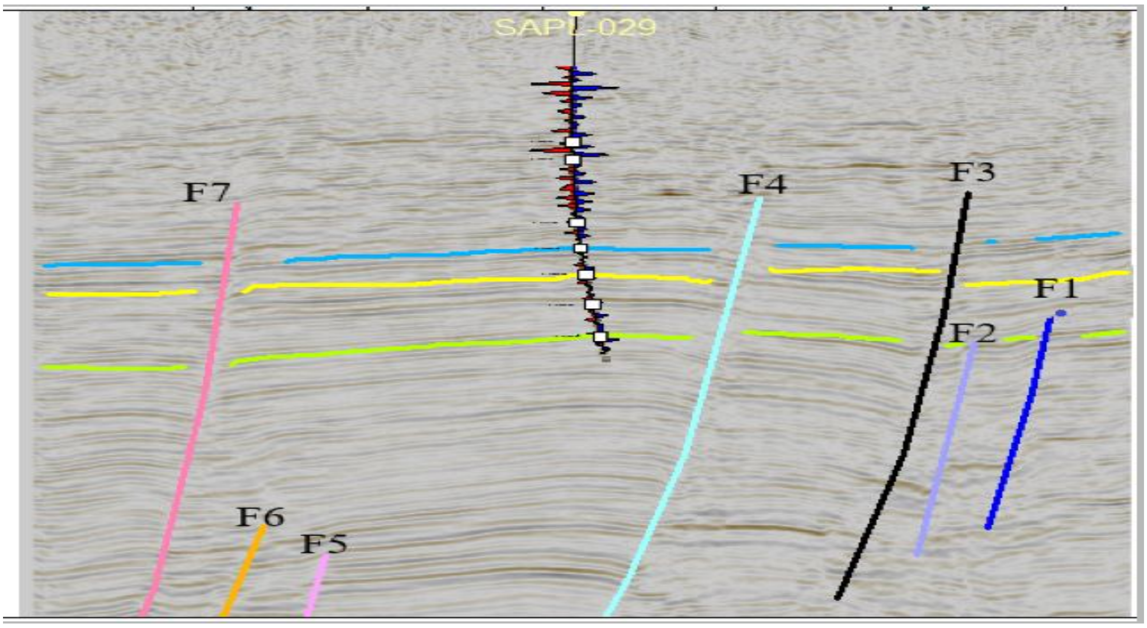

Figure 5: Fault mapping of Sapele Shallow Field (Using Petrel®2016).

(c) Horizon Interpretation

Three key horizons with their tops and bases were interpreted and mapped with respect to their seismic continuity and good seismic to well correlation from respective fields. Structure contour maps were produced for each of the horizons. High amplitude reflection events corresponded to sand units while low amplitude reflection events corresponded to shale units (figure 6).

Horizon picks were done iteratively in in-line and crossline directions and corrected for mis-ties. In areas where reflection quality and characteristics are of good quality, lines are picked at larger intervals while in areas where reflection quality is relatively poor and characterized by discontinuities and chaotic lines were picked at closer intervals in order to reduce mis-ties to an acceptable minimum. The three horizons that were mapped across dip and strike sections are namely horizons 4, 5 and 7 respectively.

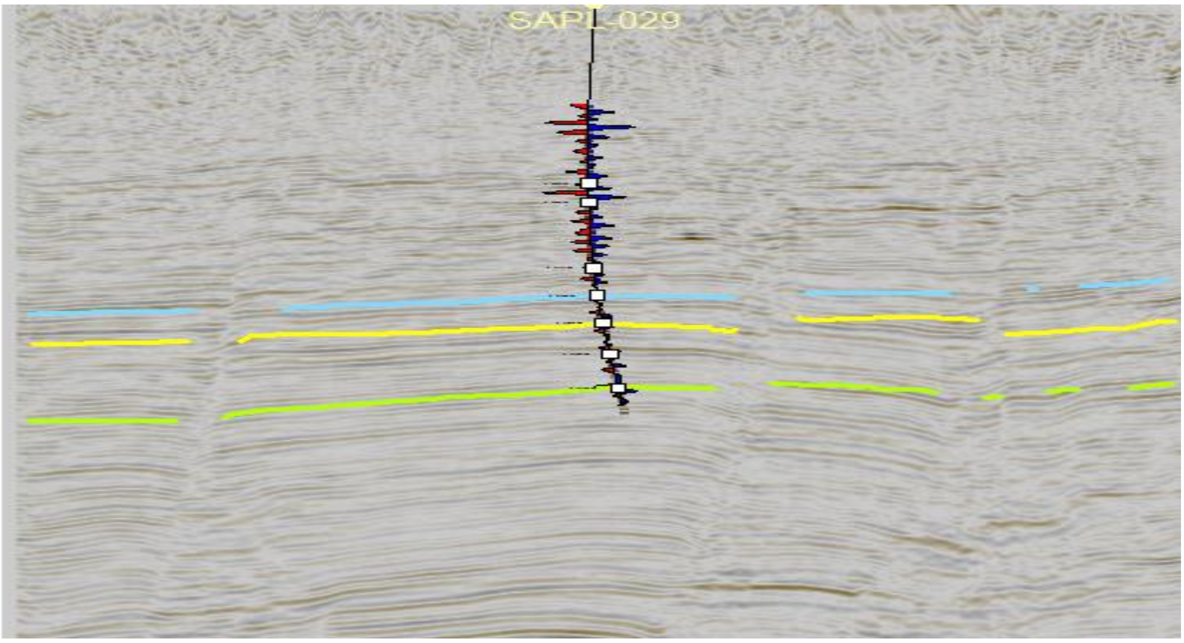

Figure 6: Horizon Mapping of the Study Area (Using Petrel®2016).

(d) Geologic Modelling

This step entails modeling of the interpreted fault horizons to generate a three-dimensional framework of the faults and horizons. Seed grids were generated across mapped/picked faults and horizon lines. This was gridded using the appropriate module in software interface to produce structural and stratigraphic framework and generate horizon maps of selected regional markers. Furthermore, boundary polygon was created on these fault sticks and horizon lines to generate structural top maps. Figures 7, 8 and 9 show the fault and horizon framework in a 3-D window.

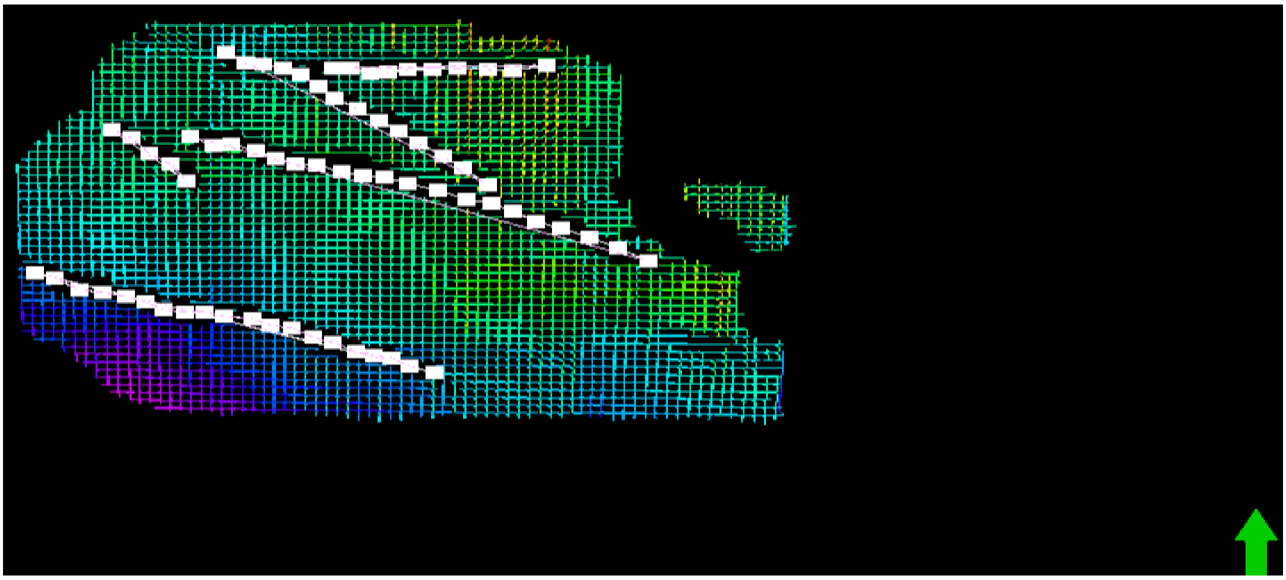

Figure 7: Structural model of Sapele shallow horizon 4 (Using Petrel®2016).

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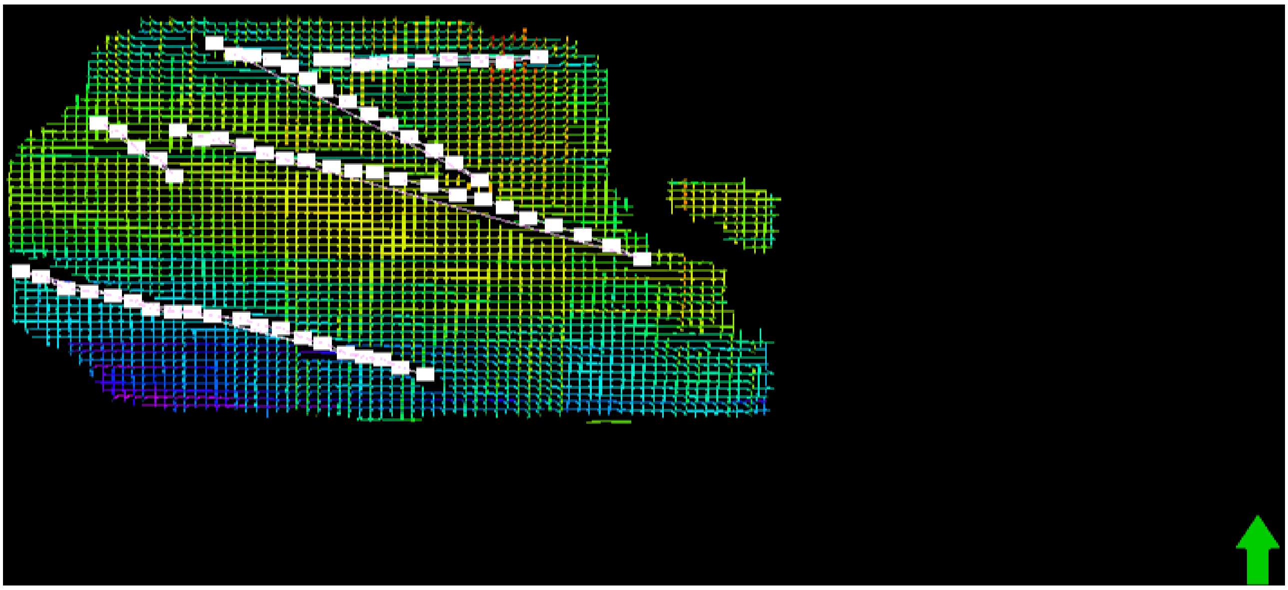

Figure 8: Structural model of Sapele shallow horizon 5 (Using Petrel®2016).

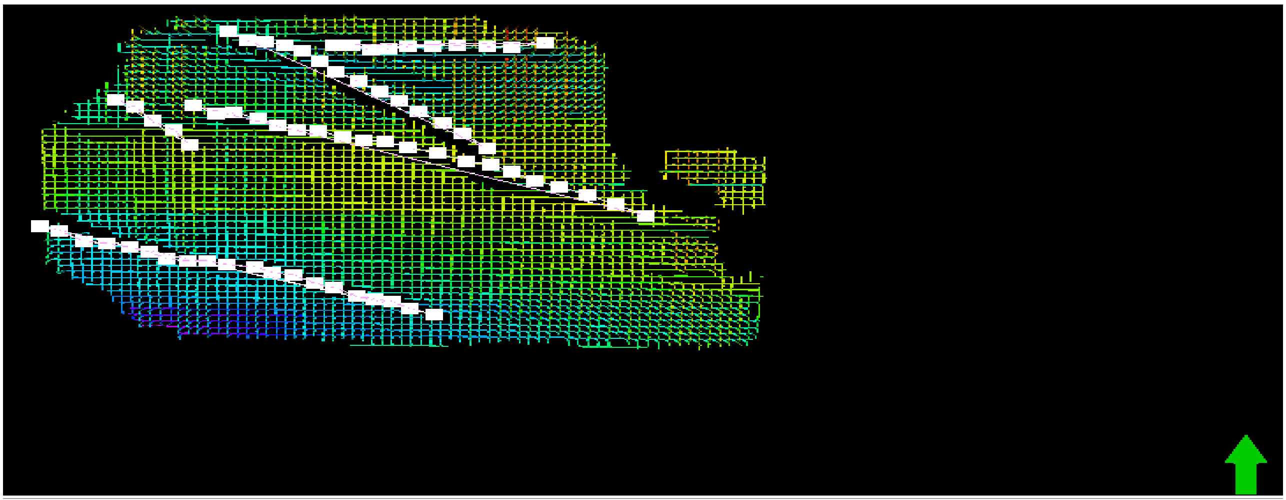

Figure 9: Structural model of Sapele shallow horizon 7 (Using Petrel®2016).

(e) Time–Depth (T–Z) Conversion

Time–depth conversion was done using the check shot data of the field. The 1D polynomial function plot (from T-Z relationships) generated was based on Petrel's depth conversion and Microsoft Excel workflows. The polynomial equation indicates that R2 coefficient is high (approximately = 1.0) thus giving a high confidence that the time–depth relationship is correlatable (Figure 10).

Two-Way Travel Time (TWT) vs Z (Checkshot)

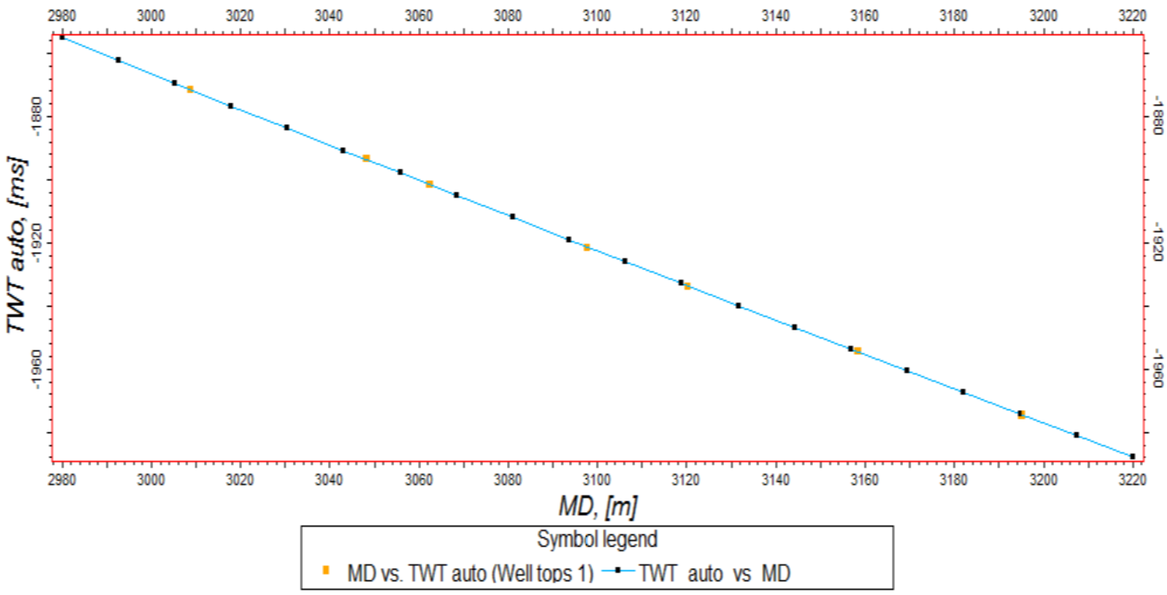

Figure 10: Time-Depth (T-Z) curve generated from checkshot data (Using Petrel®2016).

(f) Time Structure and Depth Maps

Structure maps tend to reveal geological structures that can be a target for exploration. Analysis of the contoured time structure map for the study area indicates that the time structure at the top of this horizon exhibits moderate to high structure trends from northwest to southeast that is caused by the effect of a major fault. On the northwestern side of the fields, the time structure at the top of this formation has a low structure. Several minor faults exist in both the Eastern and Western portions of the study area. The time and depth-generated maps were placed side-by-side and they both display the same structures. These maps showed that the major structures accommodating the hydrocarbon are growth faults and rollover anticlines. (Figures 11, 12, 13, 14, 15, and 16).

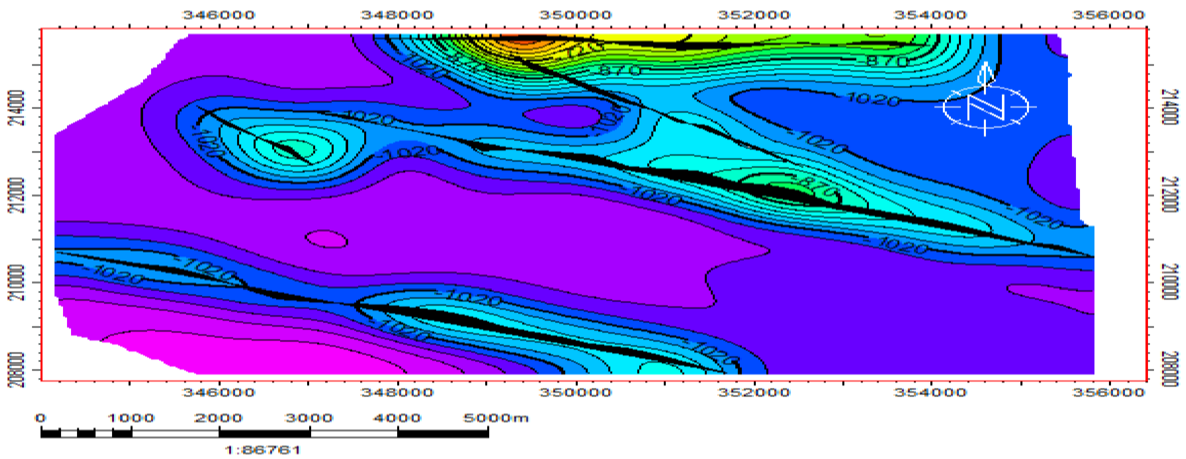

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Figure 11: Time Structural Map of Sapele Shallow Horizon 4 (Using Petrel®2016).

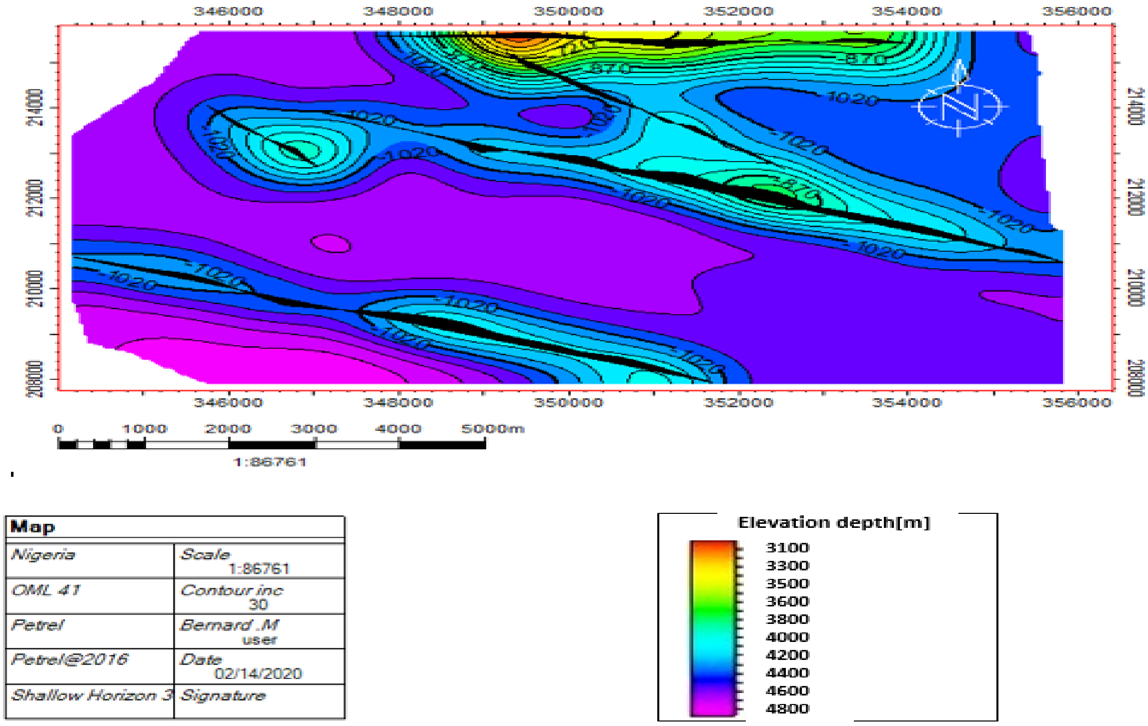

Figure 12: Depth Structural Map of Sapele Shallow Horizon 4 (Using Petrel®2016).

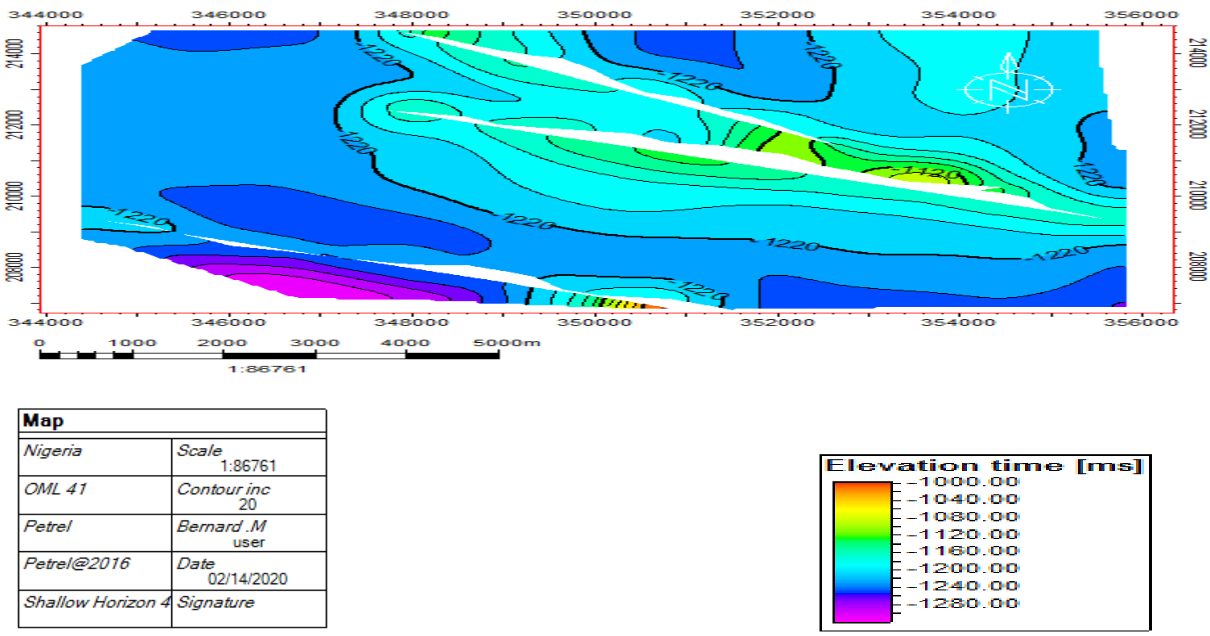

Figure 13: Time Structural Map of Sapele Shallow Horizon 5 (Using Petrel®2016).

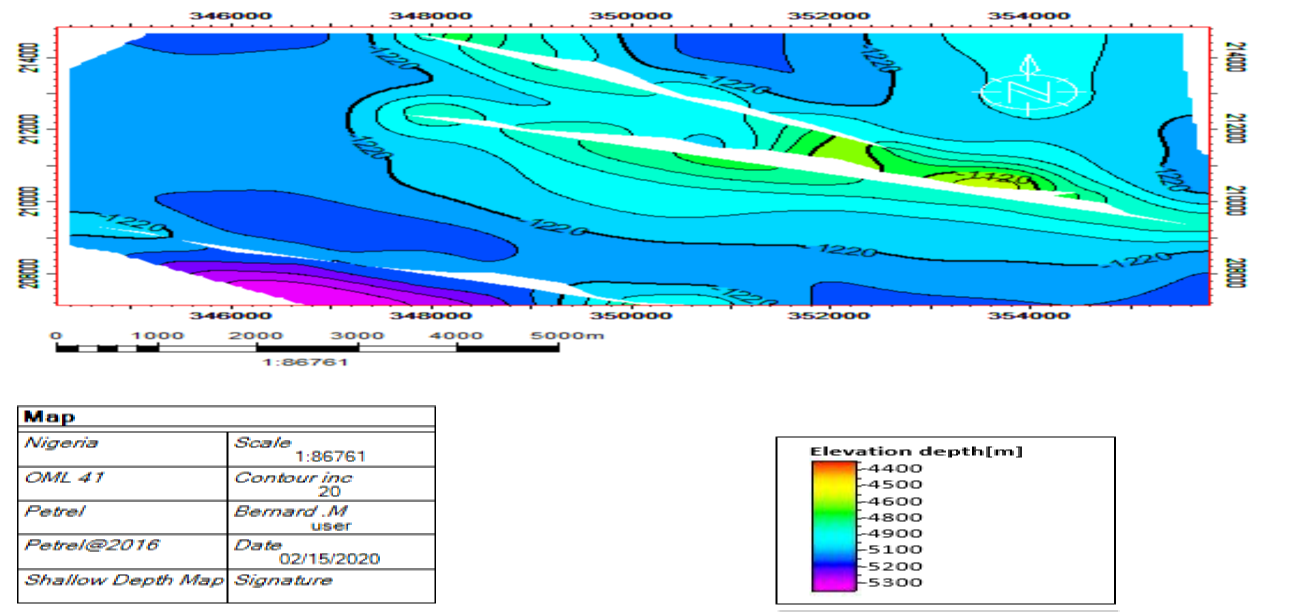

Figure 14: Depth Map of Sapele Shallow Horizon 5 (Using Petrel®2016).

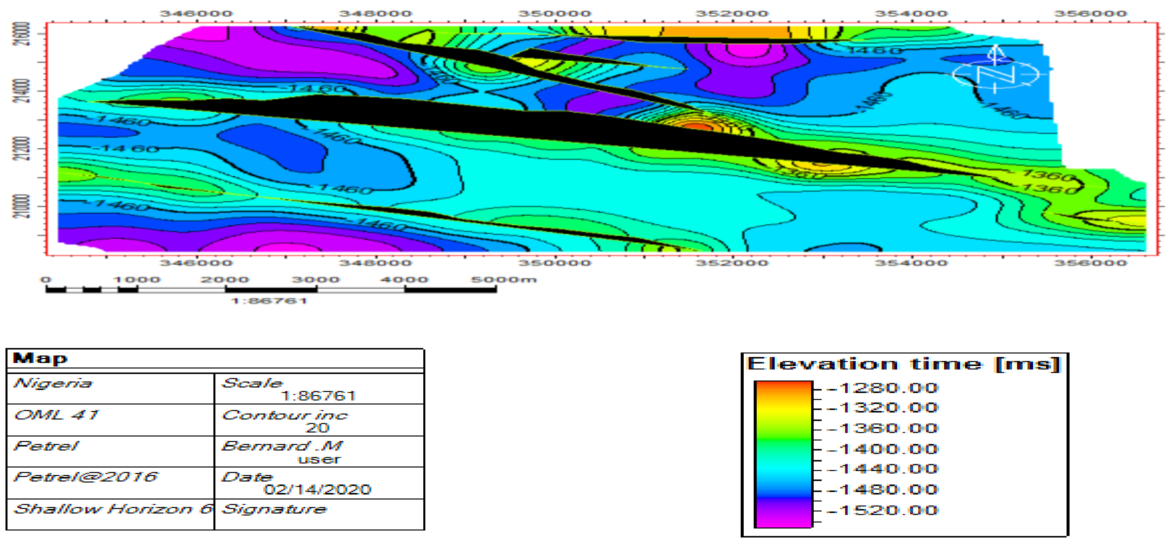

Figure 15: Time Structural Map of Sapele Shallow Horizon 7 (Using Petrel®2016).

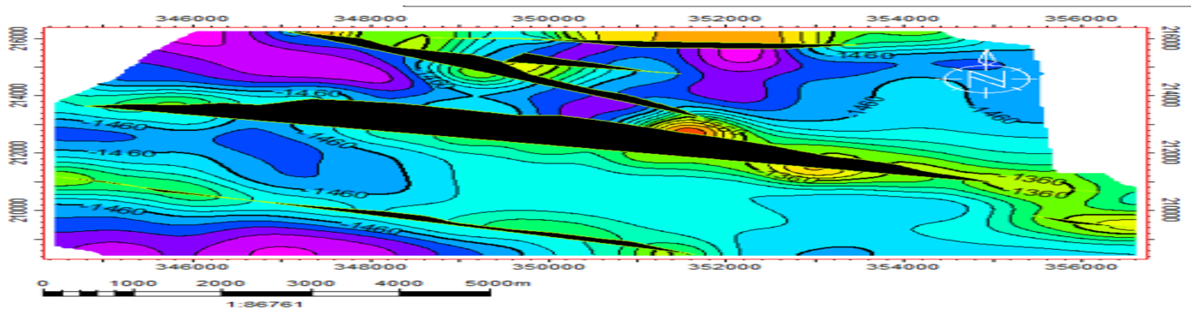

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Figure 16: Depth Structural Map of Sapele Shallow Horizon 7 (Using Petrel®2016).

(g) Field Entrapment Structure Identification

Fault and horizon interpretations in the study area, aided identification of entrapment structures and their classification. From assessments carried out on the fault network and key horizons, the field has more of E-W trending regional faults, rollover anticlines and collapsed crest structures. The closures are fault dependent. Also present are regional hanging wall closure (RHW), simple faulted rollover (SFR) and back—to—back (B-B) structures. The seismic interpretations show that at deeper levels, the fault structures die out. However, the shallow and intermediate intervals are more intensely faulted by E-W trending with dominance of collapsed crest structures which proves that the study area has a complex subsurface structure.

(h) Root-Mean Square Amplitude Analysis

Amplitude maps of the study area show the area extent of the bright spots (Sweet spots) of various seismic attributes computed from the horizons. Having identified several qualitatively bright spots, seismic amplitude was correlated with the well-log data of interest. The observed outstandingly strong reflection (bright spots) is indicative of reservoir rocks, which may be due to the presence of hydrocarbons in the identified sands (Figures 17, 18, and 19). Amplitude levels are portrayed by the intensity of the colour, high amplitudes being represented by the range of reddish yellow colour and the lower amplitude by the range of dark blue areas. The high amplitude pattern observed around the well locations indicates bright spot which may be caused by a locally greater-than-normal velocity contrast between two layers. Similar bright spots were located on northern part of the map which may probably be good prospects that is yet to be proven. Amplitude maps were generated for the 3 mapped horizons from the study area to complement the structural interpretation. The distinct zones of anomalous amplitude coincide with structural high already delineated and which also coincided with the regions where wells have been drilled. Since the amplitude map correlates with the structurally high locations and bright spots from seismic attributes analysis, the distribution of low amplitudes and high amplitudes would be a useful guide in the developmental well drilling of the study area.

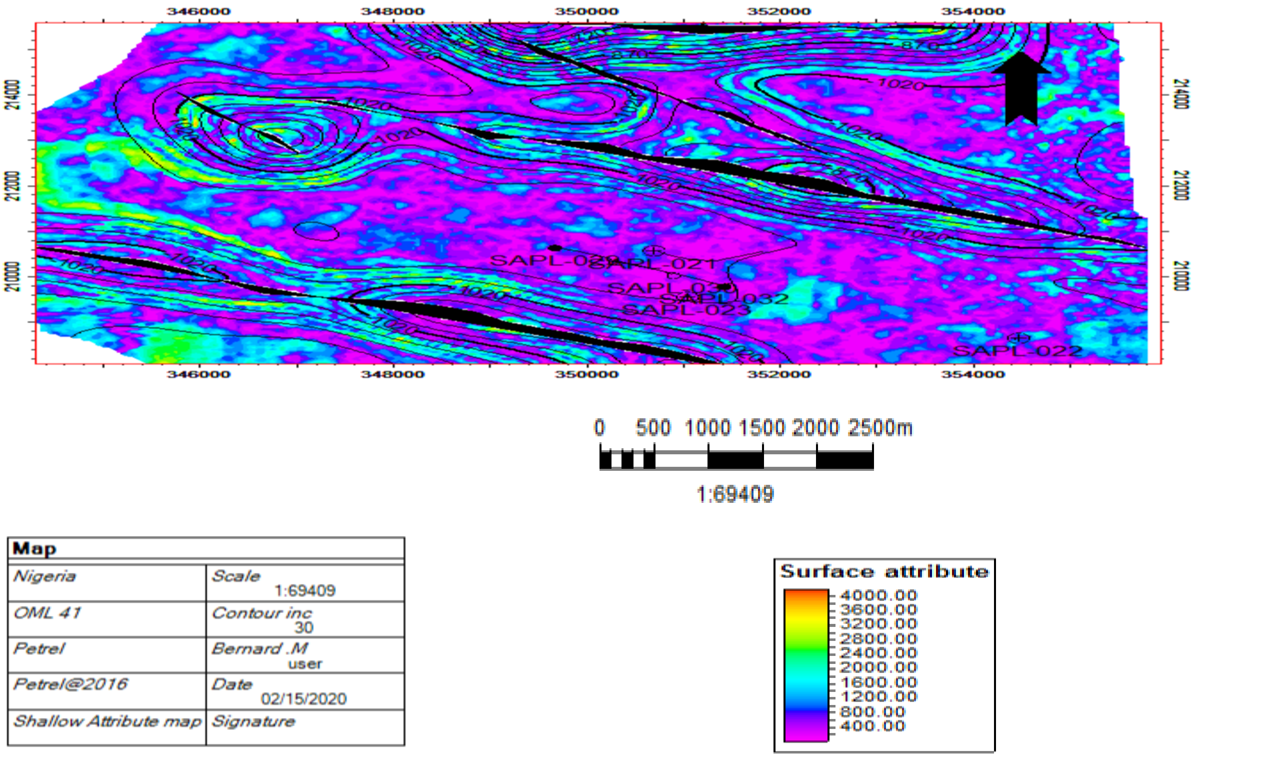

Figure 17: Root-Mean Square Amplitude of Sapele Shallow Horizon 4 (Using Petrel®2016).

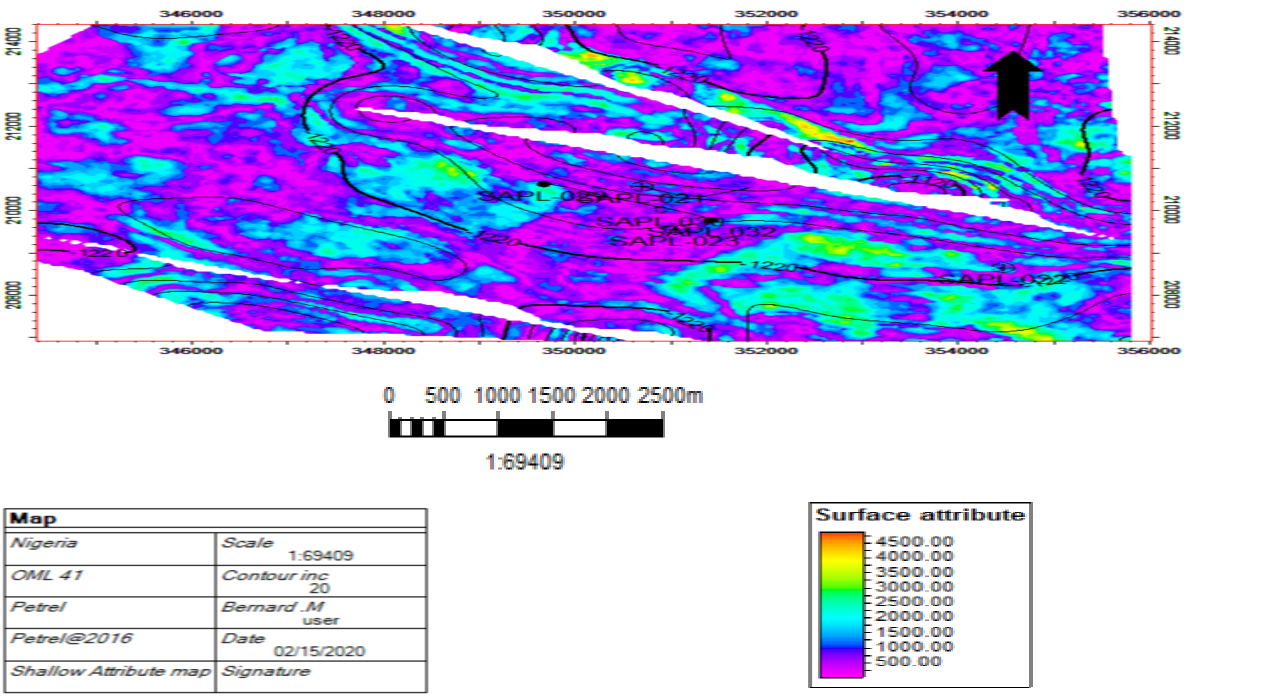

Figure 18: Root-Mean Square Amplitude of Sapele Shallow Horizon 5 (Using Petrel®2016).

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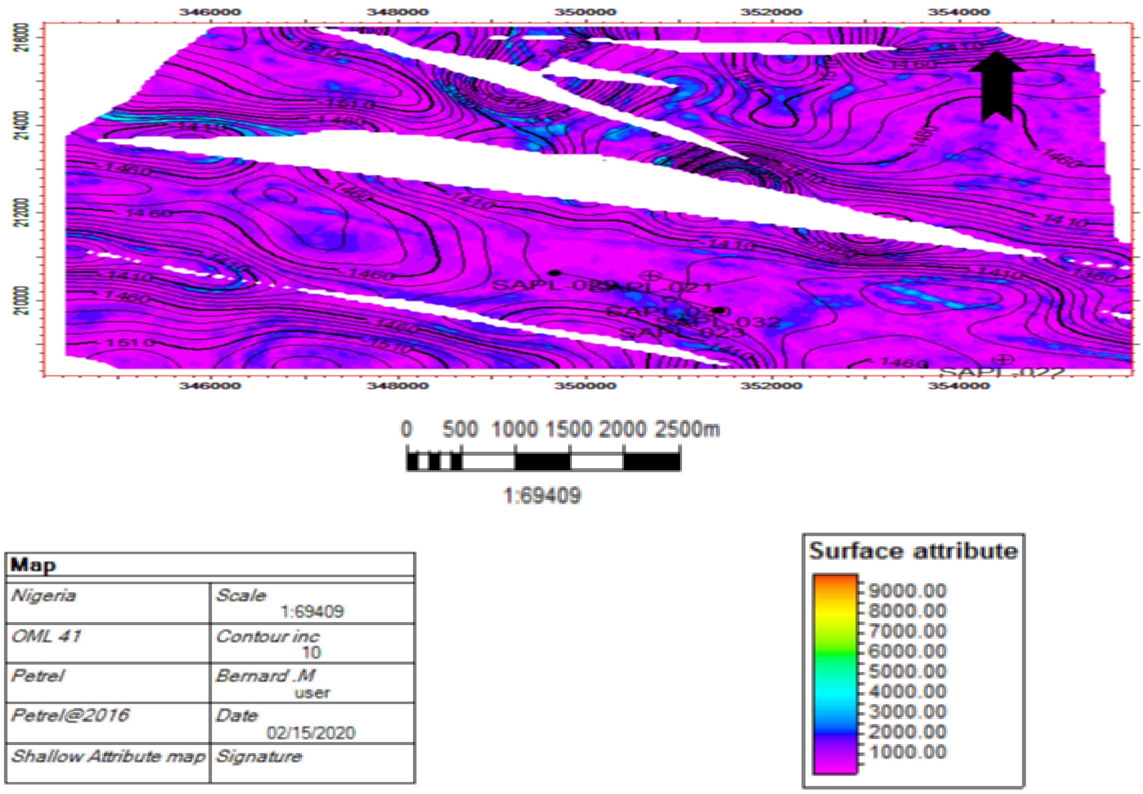

Figure 19: Root-Mean Square Amplitude of Sapele Shallow Horizon 7 (Using Petrel®2016).

CONCLUSION

The delineated stratigraphy of the studied area thickens from north to south (basin ward). While the structural interpretation reveals that the study area has high fault density. These faults trend with appreciable throw, which can serve as potential pathways for hydrocarbon migration and accumulation. Typical structural styles are those of the anticlines, which also have the possibility of possessing multiple pay horizons, and they are major parts of most giant oil fields in the Niger Delta

Also, the root-mean-square amplitude maps of the various horizons reveal that all horizons mapped in the study area have bright spots except horizon 7 (Figure 19). The bright spots on the RMS amplitude map (Figures 17 and 18), are an indication that the core north and northeast area of the field may contain possible new reservoirs that are yet to be identified.

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Conflict of Interests

All authors declare that they have no conflicts of interest

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