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# Geological and Seismic Delineation of D2000 and D4000 Petroleum Reservoirs Within Afenmai Field, Niger Delta Basin, Nigeria

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**Abstract:** Afenmai Field is an old petroleum discovery within Central Swamp Depobelt on the eastern part of the Nigerian Niger Delta basin. Eight wells were drilled within the field, and Wells 006 and 008 respectively encountered petroleum in the D2000 Sand and D4000 Sands. This study was conducted to firm up the reservoirs' spatial extent as well as their pore fluid distribution, which has hitherto been unattended to. To achieve this, the reservoirs were correlated within a framework of parasequence sets that was created from sequence stratigraphic interpretation of combined lithologic, geophysical and foraminiferal data. The reservoir tops were then tied at Well 008 to seismic reflections within a 3D seismic volume, and mapped through the volume. Root mean square (RMS) amplitude was extracted from the seismic volume along mapped reservoir surface. The depth maps produced reveal a southward concave, major synthetic structure building fault across the entire field. A series of en echelon synthetic faults are revealed on the NW and SE of the upthrown block of the major synthetic structure building fault. The D2000 Sand constitutes a rollover anticline with entrapped saturated petroleum in a four-way anticlinal closure that lacks fault support. The western, eastern and northern parts of the reservoir are yet to be penetrated by a well. Petroleum is entrapped in a three-way closure within the D4000 Sand in the western part of the upthrown block of the major synthetic structure building fault. Average RMS amplitude characterise the petroleum reservoir at Well 008 location and immediate vicinity. The values become low westward within the delineated reservoir. Opportunity for productive drilling exists within the undrilled part of the delineated reservoir, westward of Well 008. Opportunities for productive drilling also exist within the undrilled western, eastern and northern parts of the delineated D2000 reservoir sand.

**Keywords:** Reservoir Extent, Fluid Distribution, Seismic Reflections, Anticlinal Closure, Three-Way Closure, Productive Drilling

## 1. Introduction

Petroleum is a compound name for crude oil and natural gas. It is a complex hydrocarbon occurring in pores of subsurface rocks. Sometimes, petroleum oozes to the surface as a seep or spring. More commonly, it is trapped into commercial accumulations by rock configurations at thousands of feet (or metres) within the subsurface. Such commercial accumulations are searched for by using combined geological and seismic techniques to create subsurface models and identify areas favourable for petroleum entrapment. The identified areas constitute prospects. Exploration wells are drilled to ascertain petroleum accumulations within the prospects. The prospects become petroleum fields if commercial petroleum accumulations are found within them. Petroleum fields invariably exist in sedimentary basins, which are earth crustal depressions within which sediments accumulated and eventually became lithified to form sedimentary rocks within thousands to millions of years (geological period). The Niger Delta basin is a typical sedimentary basin with ubiquitous hydrocarbon accumulations. The basin contains 5 per cent of the world's oil and gas reserves [1].

### *1.1. Location of the Study Area*

The Niger Delta basin is the composite of sedimentary bodies built up at the mouth of the Benue-Niger river system, onto the Atlantic Ocean during the Tertiary [2]. It lies within Latitudes 4°N to 9°N and Longitudes 4°E to 9°E. One of the petroleum fields in the onshore Niger Delta basin is Afenmai Field. It is within the eastern part of the basin's Central Swamp Depobelt (Figure 1). Afenmai Field is a pseudo name adopted to preserve data confidentiality and economic interest of the asset owners.

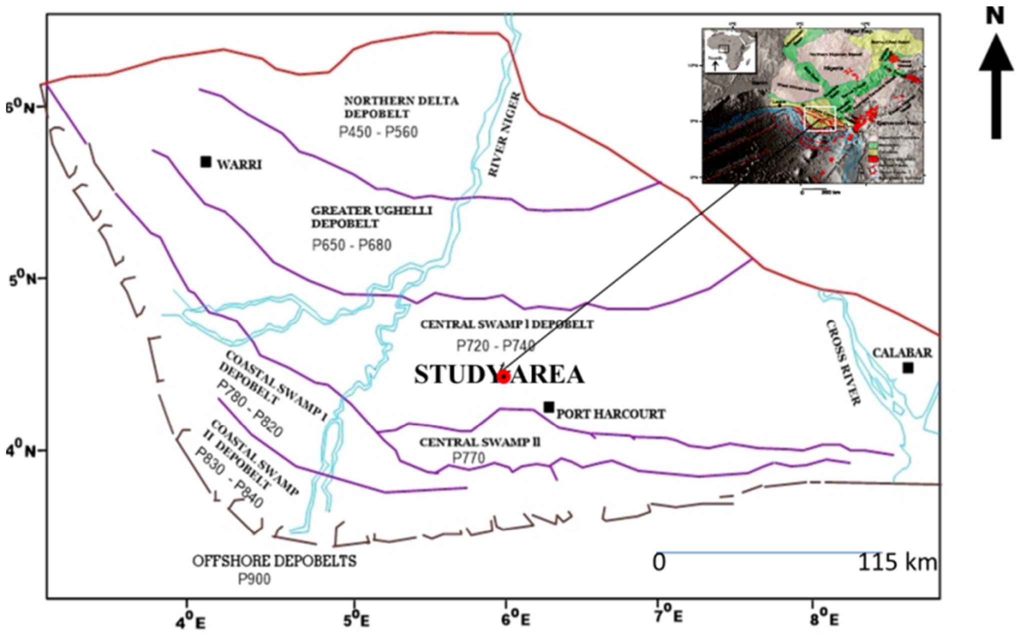



*Figure 1. Study Area (Afenmai Field).*

### *1.2. Definition of the Research Problem*

Petroleum was found in D2000 Sand within Well 006, after drilling five previous wells. Step out wells, namely W007 and W008 did not encounter petroleum in the D2000 Sand. However, well W008 found petroleum in D4000 Sand. The lateral extent of the D2000 and D4000 reservoirs was yet to be established at the time of this study. The fluid distribution in the reservoirs was also unascertained. This work was conducted to upgrade the appraisal status of the field by re-mapping hydrocarbon bearing D2000 and D4000 reservoirs to delineate the lateral extent of the reservoirs' pore fluid. Delineating the lateral of the reservoir pore fluid will enable cost effective optimal production from the reservoirs.

## 2. Conceptual Framework, Regional Geological Overview, Relevant Literature Review

### *2.1. Conceptual Framework*

Continued successful exploration and exploitation of petroleum accumulations requires an understanding of the reservoirs' stratigraphy and compositional attributes [3]. The required understanding is optimally achieved by mapping sequence stratigraphically delineated petroleum reservoir tops on three dimensional (3D) seismic data. The technique is a synergistic approach to re-mapping known petroleum bearing, because high horizontal resolution (150-1000 m) of seismic data is combined with high vertical resolution (2 cm-2 m) of well data.

Sedimentary rocks and their petroleum content result from sedimentary environments. On the corollary, both areal and temporal relationships of sedimentary rocks predetermine the stratigraphic positions of oil and gas accumulations. Consequently, correct delineation of lateral extent of pore fluids of known petroleum reservoirs, as well as ascertaining new petroleum accumulation prospects, hinge on accurate sedimentary rock correlation and reservoir structure determination. The use of sequence stratigraphy technique to interpret the combined well log and benthic foraminiferal data provides a reliable framework for accurate sedimentary rock correlation. 3D seismic data provides a high resolution 3D image of the subsurface for capturing reservoir structure. Seismic structural and seismic attribute mapping of petroleum reservoirs identified from sequence stratigraphic approach will accurately ascertain reservoir pore fluid lateral extent and thereby reduce development drilling failures.

### *2.2. Regional Geological Overview*

Cenozoic sedimentary sequence dominates the Niger Delta basin. The sequence comprises Akaka Formation, Agbada Formation and Benin Formation. The Akata Formation lies at the base. It consists of monotonous marine shelf to bathyal shale facies. The shale is occasionally interrupted by sand

and silt beds deposited bathyal environment as deep water channel fills, levee-overbank deposits and sheet sands. Onshore, the formation has been penetrated between 12000 ft and 18000 ft. Onshore, the formation has been penetrated between 12000 ft and 18000 ft [4]. Agbada Formation overlies the Akata Formation. It comprises alternations of sandstones, sands, siltstones, mudstones and shales. They are predominantly inner neritic sediments. Littoral, middle neritic, outer neritic and bathyal sediments are also present. The uppermost formal lithostratigraphic unit is the Benin Formation. It is constituted by fresh water bearing, massive continental sands and gravels deposited in littoral environment. It also contains occasional siltstones, mudstones, shales and lignite streaks deposited in fluvial channel levees, abandoned fluvial channel, back swamps and oxbows. Both Agbada and Benin Formations contain clay-filled gullies which are considered their members (Figure 2).

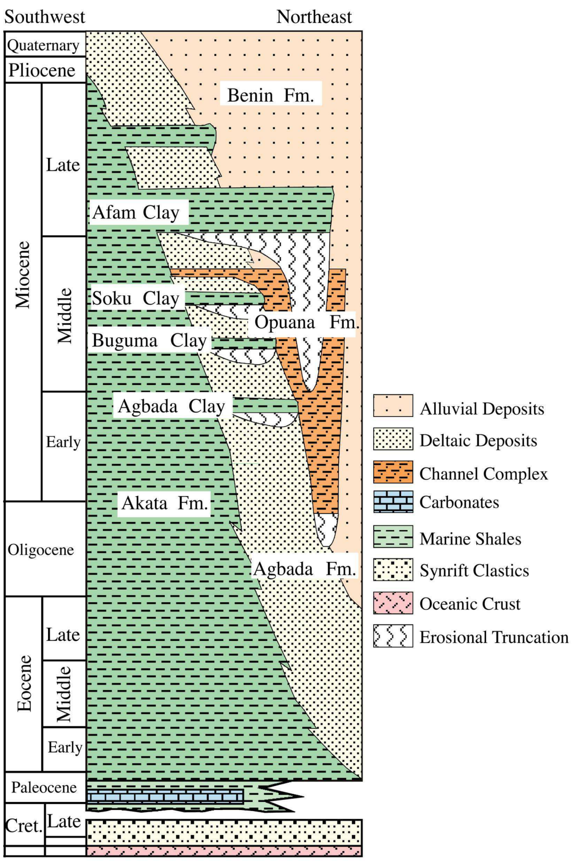



***Figure 2.*** *Clay-filled gullies in Agbada and Benin Formations [5].*

### *2.3. Review of Relevant Literature*

The origin and evolution of Nigerian continental margin and sedimentary basins were shaped by continental plate extensional activities during the Cretaceous [6-10]. In such geological settings, sedimentary progression is dominantly seaward, and stratigraphy is the dominant element controlling spatial positions of petroleum accumulations [11]. Seismic structural mapping of Jurassic and Paleozoic reservoirs of QABR gas fields in Egypt was carried out by Abuzaid, M. et al [12]. Their work flow comprised seismic – to – well tie to identify reflectors, fault identification, picking and correlating reflectors and generating depth maps. Structural analysis of 3D seismic data was conducted by Obasuyi, F. O. et al [1] for middle reservoir sands in onshore Niger Delta basin. They identified petroleum bearing sand units on gamma ray (GR) and resistivity logs, and posted the reservoir tops onto the 3D seismic data using checkshot data. The reservoir tops were mapped, structure map produced and reservoir spatial extent delineated. Stratigraphic correlation framework was created for Afenmai Field by Unuevho, C. and Onuoha, K. M. [13]. They employed sequence stratigraphic technique to correlate genetically related sandstone and shale bodies within chronostratigraphically significant surfaces. They found hydrocarbon bearing sands within the Lowstand systems tract and highstand systems tract. Hydrocarbon bearing sands in Akos Oil Field were delineated by Emujakpome, G. O. and Enyenihi, E. E. [14]. They delineated the reservoirs on well logs, tied the delineated reservoir tops to 3D seismic volume using checkshot data, and then conducted seismic horizon structural and attribute mapping. They found that high amplitude values characterise hydrocarbon bearing sands. Reservoir characterisation was carried out for Ohaji Field by Kadiri, A. I. et al [15]. They first identified the reservoirs on well logs, and posted the reservoir tops onto 3D seismic volume, using checkshot data. The reservoir tops were then mapped and reservoir structure maps were produced. They found that petroleum was contained in anticlinal closures, independent of faulting. Amplitude supported structural plays were used as basis for identifying new prospective zones across nine fields in onshore Niger Delta basin by Dim, C. I. A. et al [16]. They captured the amplitude supported structural plays using sequence stratigraphic, structural and reservoir production tools. Seismic structural and seismic attribute mapping have also been employed to delineate reservoir fluid lateral extent within Niger Delta fields by Oluwatosin, O. and Olowokere, M. T. [17]. Some reservoir sandstones in Bisol Field within onshore Niger Delta were re-mapped by Bayowa, O. G. and Boluwade, B. S. [18], using 3D seismic and checkshot data, as well as open- hole geophysical logs. They tied reservoir tops to seismic horizons by creating acoustic impedance log from sonic and density logs, and convolving the acoustic impedance with Ricker wavelet.

## 3. Materials and Methods

### *3.1. Materials*

The software used for stratigraphic correlation and seismic interpretation in this work is *Petrel 2008.1.1*. The data used are subsea vertical depth (SSVD) to top and base of sand and shale units, foraminiferal information, open-hole geophysical logs, checkshot data, and 3D seismic volume. The geophysical logs comprised gamma ray, resistivity, and neutron and density log data. The foraminifera information comprise *Nonion, Cassigerinella, chiloguembelina, Uvigerina,* and *Bolivina* generic occurrence.

### *3.2. Methods*

The project was set up in a workstation with *Petrel 2008.1.1* geology and geophysics interpretation software, and named Afenmai Field. The Imperial (British) unit system was selected for depth value storage because depth data for the study were given in feet. Global position coordinates were stored in metres, which is the unit with which they were provided. The Selected Co-ordinate Reference System for the data base is Minna in Nigeria Mid Belt. The well base information, geophysical logs and 3D seismic volume were imported into the project. The lithologic data was plotted on the geophysical logs. The top and base of the lithologic units were appropriately adjusted in consonance the with respective gamma ray response. Lithologic modeling of the gamma ray log was performed. The foraminiferal data was interpreted in terms of depositional environments and paleo bathymetric depths. The top of Agbada Formation was identified as the base of the shallowest thick regional marginal marine shale in the wells, and correlated throughout the log framework. Parasequence sets were modelled from integration of lithologic model with gamma ray log motif and paleo bathymetric interpretation of the foraminiferal data. The D2000 Sand and shale unit, D4000 Sand and shale unit as well as E1000 Sand and shale unit were identified and correlated across the log framework, using parasequence set boundaries as chronostratigraphic surfaces. This correlation technique is after Van Wagoner, J. C. et al [19], Larue, D. and Legarre, H. [20], Hassan, S. S. et al [21] and Parvin, A. and Woobaidullah, A. S. [22]. Checkshot data is available for only Well 001. Sonic and density logs were available for only Well 008. The checkshot data was shared into Well 008, used to calibrate the sonic log data. The calibrated sonic log data, density log and Ricker wavelet were used to associate the correlated sand tops with seismic horizons in the 3D seismic volume. Seismic structural mapping of horizons corresponding to D2000 and D4000 sand tops was conducted on every tenth inline and crossline. The mapped horizons were gridded in the seismic volume, and time map was created. The time map was converted to depth map using velocity function obtained from the checkshot data. Root mean square (RMS) amplitude and instantaneous frequency values were extracted along the mapped horizon tops and RMS amplitude and instantaneous frequency maps were created. Reservoir fluid contacts were plotted into the depth map and reservoir delineation and fluid distribution was achieved.

## 4. Results and Discussion

### *4.1. Sedimentary Correlation Aspect*

The SSVD to top base of D2000 Sand body, its foraminifera content as well as foraminifera content of shale above and below it are given in Table 1. The D2000 Sand body is barren in fossils. This indicates it is a littoral sand body. The foraminiferal content in the shale below it reflects outer neritic to upper bathyal shale body. The base of D2000 Sand appears to represent vertical juxtaposition of littoral to inner neritic facies directly over outer neritic to upper bathyal. Thus the base is an unconformity surface. The surface is field wide and thus is a candidate sequence boundary. It is a chronostratigraphic correlation surface.

***Table 1.*** *Depth (SSVD) and foraminifera information on D2000 Sand neighbouring shale.*

| WELL | SSVD (FEET) D2000 SAND | SSVD (FEET) D2000 SAND BASE | FORAMS WITHIN D2000 SAND | FORAMS WITHIN SHALE ABOVE D2000 SAND | FORAMS WITHIN SHALE BELOW D2000 SAND |
|---|---|---|---|---|---|
| W001 | 6542 | 6656 | BARREN | NOT GIVEN | *NONION* |
| W002 | 6562 | 6697 | BARREN | NOT GIVEN | *UVIGERINA* |
| W003 | 6771 | 6868 | BARREN | *UVIGERINA* | *BOLIVINA* |
| W004 | 6795 | 6862 | NOT GIVEN | NOT GIVEN | NOT GIVEN |
| W005 | 6247 | ------- | BARREN | *NONION* | *BOLIVINA* |
| W006 | 6528 | 6641 | BARREN | NOT GIVEN | *CHILOGUEMBELINA (CHILO)* |
| W007 | 6570 | 6668 | BARREN | NOT GIVEN | CASSIGERINELA/ CHILO |

The SSVD to top and base of D4000 Sand body, its foraminifera content as well as foraminifera content of shale above and below it are given in Table 2.

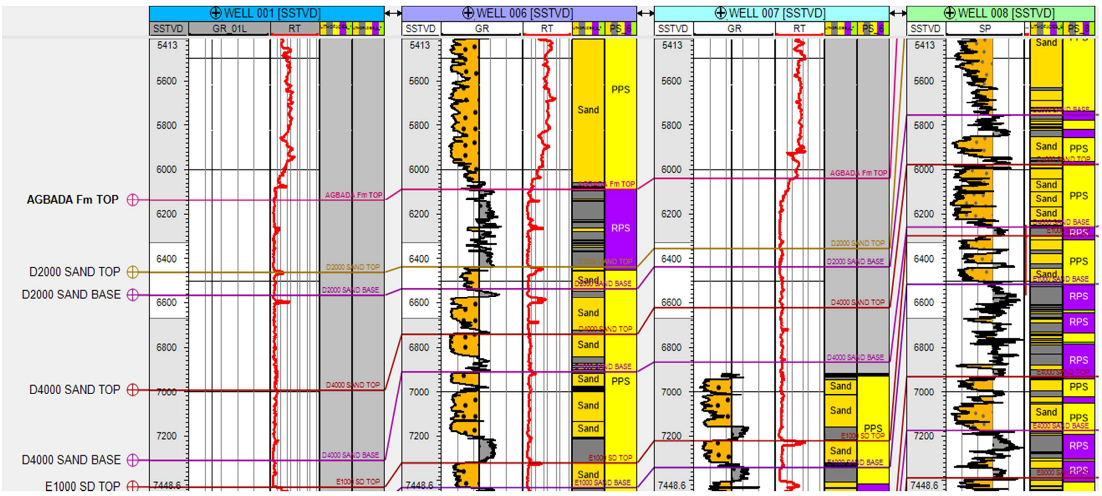
***Table 2.*** *Depth (SSVD) and foraminifera information on D4000 Sand neighbouring shale.*

| WELL | SSVD (FEET) D4000 SAND | SSVD (FEET) D4000 SAND BASE | FORAMS WITHIN D4000 SAND | FORAMS WITHIN SHALE ABOVE D4000 SAND | FORAMS WITHIN SHALE BELOW D4000 SAND |
|---|---|---|---|---|---|
| W001 | 6972 | 6998 | *NONION* | NOT GIVEN | *NONION* |
| W002 | ------- | -------- | NOT GIVEN | NOT GIVEN | *NOT GIVEN* |
| W003 | 7152 | 7168 | BARREN | BARREN | *UVIGERINA* |
| W004 | 7085 | 7097 | NOT GIVEN | NOT GIVEN | NOT GIVEN |
| W005 | 6553 | ------- | BARREN | *NONION* | *NONION* |
| W006 | 6960 | 6990 | NOT GIVEN | NOT GIVEN | *CHILO/CASSIGERINELA* |
| W007 | 6998 | 7017 | BARREN | NOT GIVEN | *CASSIGERINELA/ CHILO* |
| W008 | 6086 | 6338 | *CASSIGERINELA* | NOT GIVEN | *CASSIGERINELA* |

The D4000 Sand body is foraminifera barren at some well sites (sites of W003, W005 W007) and contains *nonion* at W001 site. It also contains *cassigerinela* at W008 site. This implies that the top of D4000 Sand represents a depositional surface that passes from littoral (foraminifera barren interval) through inner neritic (*nonion* bearing interval) to middle neritic and upper bathyal areas (indicated by *cassigerinela*). According to Hubbard, R. J. et al [23] and Coe, A. L. and Church, D. [24], such a surface is a chronostratigraphic surface that is analogous to present day sea bed. The foraminiferal content of the shale body below it indicates inner neritic to upper bathyal depositional environments, thereby implying that the base of D4000 Sand is a chronostratigraphic surface suitable for correlation. Unlike lithostratigraphic correlations (such as presented by Nazeer, A et al [25] and Ukpong, P. N. et al [26]), chronostratigraphic correlations connect synchronous surfaces and avoid exaggerated reservoir continuity [19, 23-25].

Chronostratigraphic correlation of the Agbada Formation top, D2000 and D4000 Sands in Wells 001, 006, 007 and 008 is shown in Figure 3.

The Agbada Formation top is placed at the top of the first thick marine shale penetrated. The sharp decrease in the resistivity trend reflects a shale body with pores filled with saline water, which indicates marine facies. This agrees with criteria for identifying the top of Agbada Formation given by Short, K. C. and Stauble, A. J. [27]. The D2000 Sand top separates retrogradational parasequence set above from progradational parasequence set below. This indicates a transgressive surface, which is a chronostratigraphic surface [19]. The base of the D2000 is correlated within the progradational parasequence set immediately below its top. The top and base of D4000 Sand are correlated within the same progradational parasequence set. All the correlations avoided transgressing time boundaries.




Note: PPS means progradational parasequence set, while RPS means retrogradational parasequence set

***Figure 3.*** *Chronostratigraphic correlation of Agbada Fm top, D2000 and D4000 Sands.*

### *4.2. Seismic Interpretation Aspect*

Figure 4 shows the specific reflections that correspond to the top of D2000 and D4000 Sands at the position of Well 008 on Inline 24850. The top of the reservoirs coincide with trough reflections.

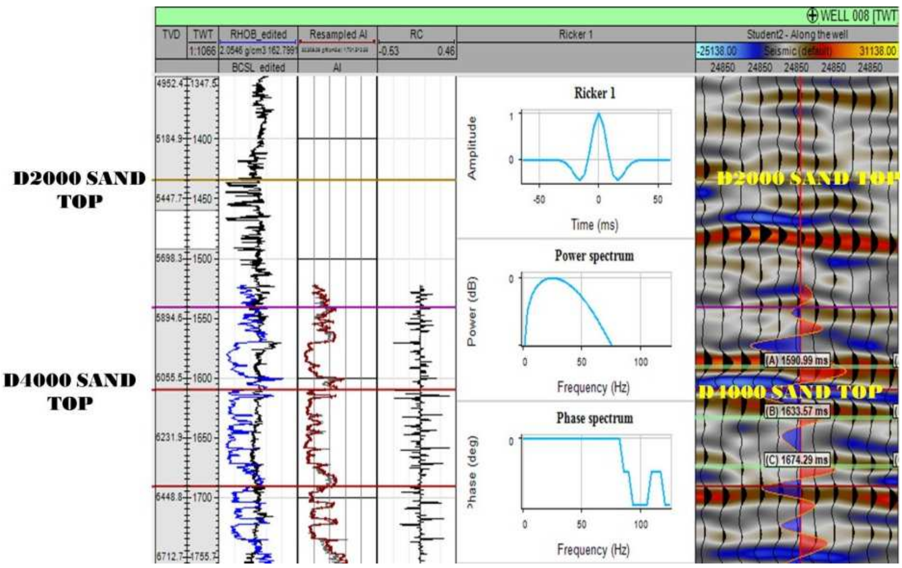



***Figure 4.*** *Positions of D2000 and D4000 sands at Well 008 position on Inline 24850.*

The depth maps produced from mapping the top of the D2000 Sand and D4000 Sand are respectively Figures 5 and 6.

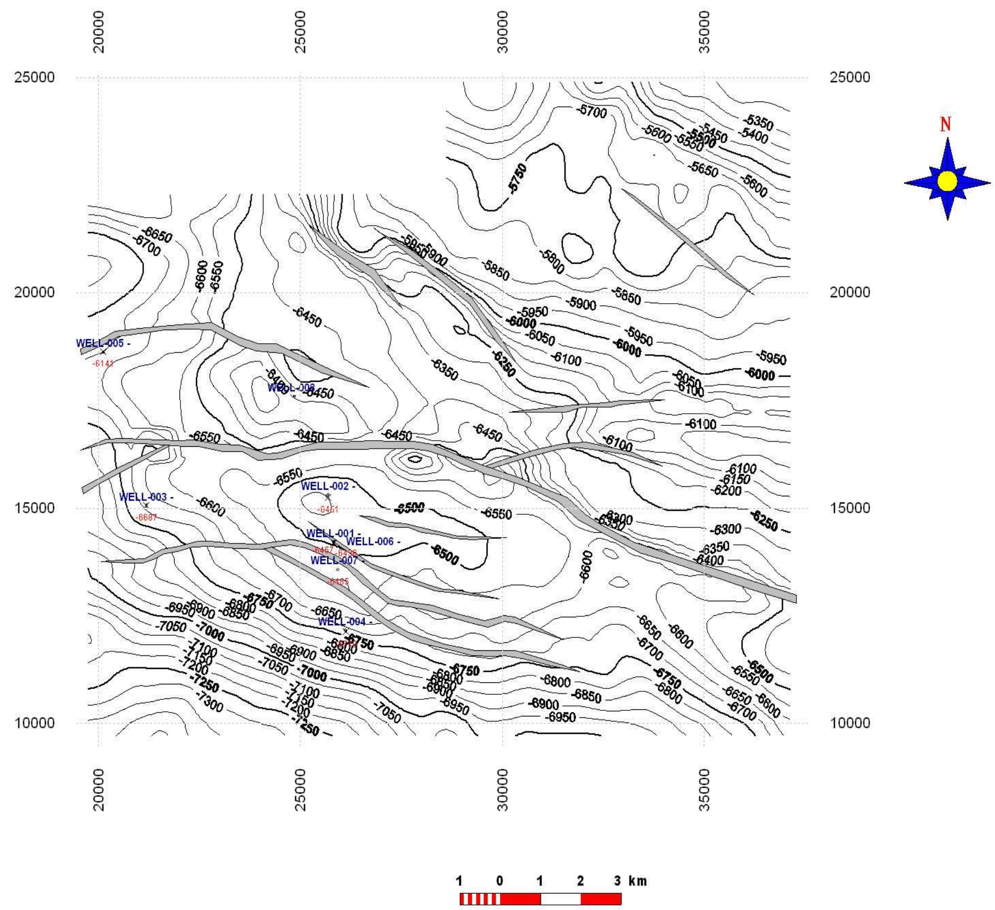



*Figure 5. Depth map for top of D2000 Sand.*

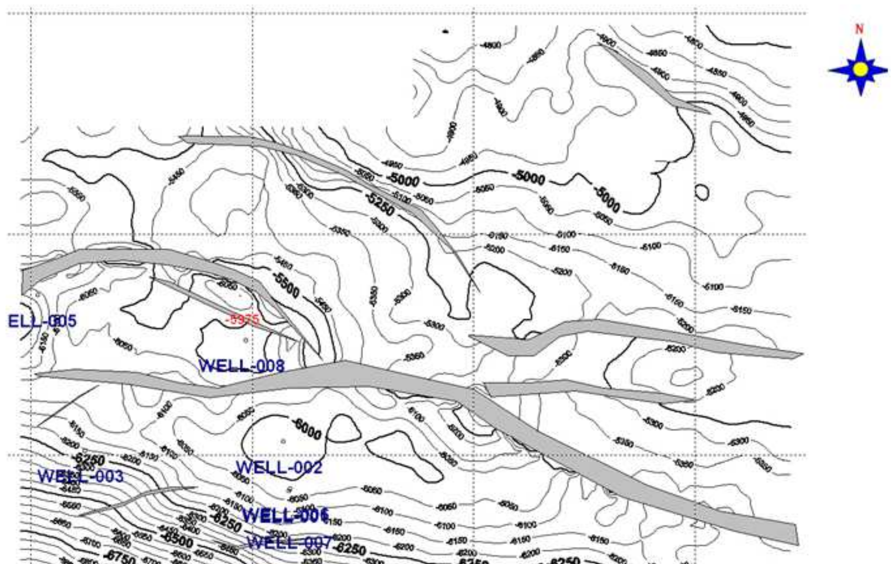



*Figure 6. Depth map for top of D4000 Sand.*

The maps reveal a major structure building fault trending NW-SE for about two-thirds of its length on its eastern portion and trending E-W in its remaining portion in the west. This fault is shaped concave southwards. NW and SE of its upthrown block are a series of structure building faults arranged en echelon. They vary in shape from concave southwards to linear. The sands constitute rollover anticlines on the downthrown block of the major structure building fault. A small crestal fault exists along the NW-SE crestal axis of the D2000 rollover anticline. On the southern flanks of both rollover anticlines are parallel and en echelon crestal faults that trend NW-SE. Similar E-W trending major growth faults were reported by Oresajo, B. S. et al [28] in Emi Field within Offshore Depobelt in the eastern Niger Delta. Omoja, U. C. and Obiekezie, T. N. [29] also found rollover anticlinal structures within the central part of Uzit Field in onshore Niger Delta basin.

The seismic RMS amplitude extracted along the reflections corresponding to the top of the D4000 Sand is Figure 7. The amplitude varies from -1 to +1. The petroleum bearing part of the reservoir is characterised by average RMS amplitude (-0.5 to 0.5). Seismic instantaneous frequency extracted along top of D4000 Sand reveal the accumulation within the reservoir is characterised by medium instantaneous frequency characterise hydrocarbon accumulation within the reservoir (Figure 8).

The observed RMS pattern within the petroleum accumulation differ from high RMS values observed in petroleum accumulations within parts of the Niger Delta by Omoja, U. C. and Obiekezie, T. N. [29], Nwazeapu, C. V. et al [30], and Oyeyemi, K. D. and Aizebeokhai, A. I. [31]. Simm, R. [32] emphasized that seismic attributes characterise petroleum accumulations differently in different fields. Weber, K. [33] also observed that petroleum accumulations in different fields within the Niger Delta exhibit different geoscience attributes.

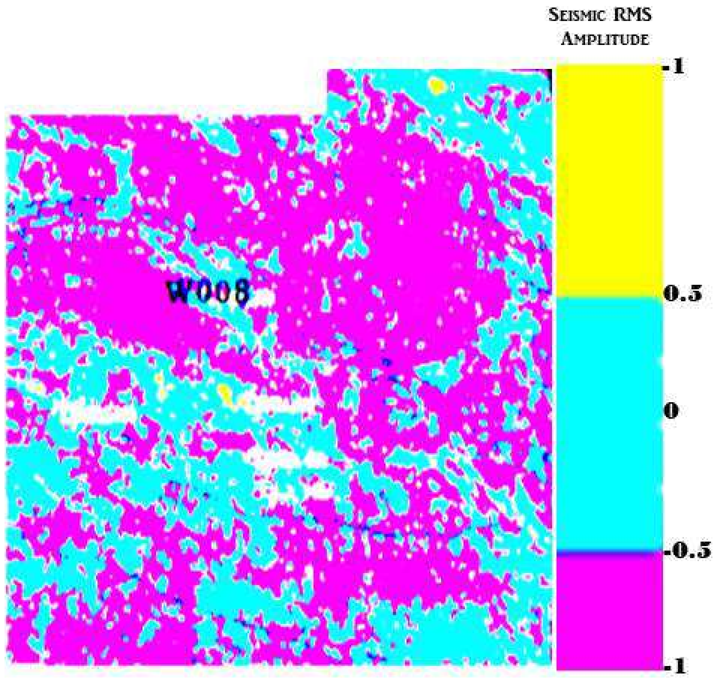



***Figure 7.*** *Seismic RMS amplitude extracted along top of D4000 Sand.*

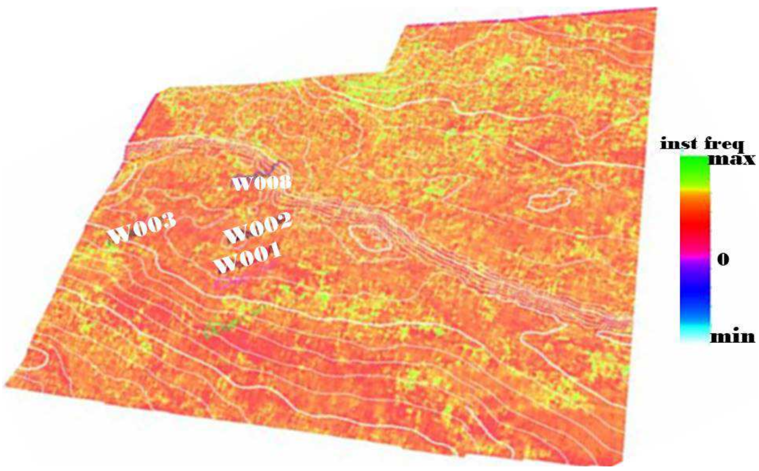



***Figure 8.*** *Seismic RMS amplitude extracted along top of D4000 Sand.*

Data provided states that D2000 sand contains hydrocarbon only in Well 006 out of the eight wells drilled in the study area. Gas-oil contact information provided in the Well 006 is 16553ft while hydrocarbon-water contact (HWC) in the well is 6562ft. This implies that HWC is also the oil-water contact. Figure 9 shows the delineation of the D2000 petroleum sand as well as the spatial distribution of its pore fluid, which resulted from incorporation of the fluid contact depths into the depth map. The D2000 petroleum sand constitutes a roll-over anticline in which saturated hydrocarbon is entrapped within a four-way anticlinal closure without fault support. No well has tested the western, eastern and northern parts limbs of the delineated reservoir. These parts constitute opportunities for productive drilling.

Oil was found within D4000 sand only in Well 008 in the study area. The inclusion of the oil-water contact depth (6100ft) in the depth map gives the spatial delineation of the reservoir (Figure 10). The trap for the oil accumulation is a 3-way closure closing on a small structure building fault at the western portion of the upthrown block of the major structure building fault. At the site of Well 008 where oil was found in the sand and its immediate vicinity, RMS amplitude is of average value. The value becomes low westward, thereby introducing failure risk westward into the delineated reservoir. However the western part of the delineated D4000 reservoir is yet to be tested, and thus constitute opportunity for productive drilling.

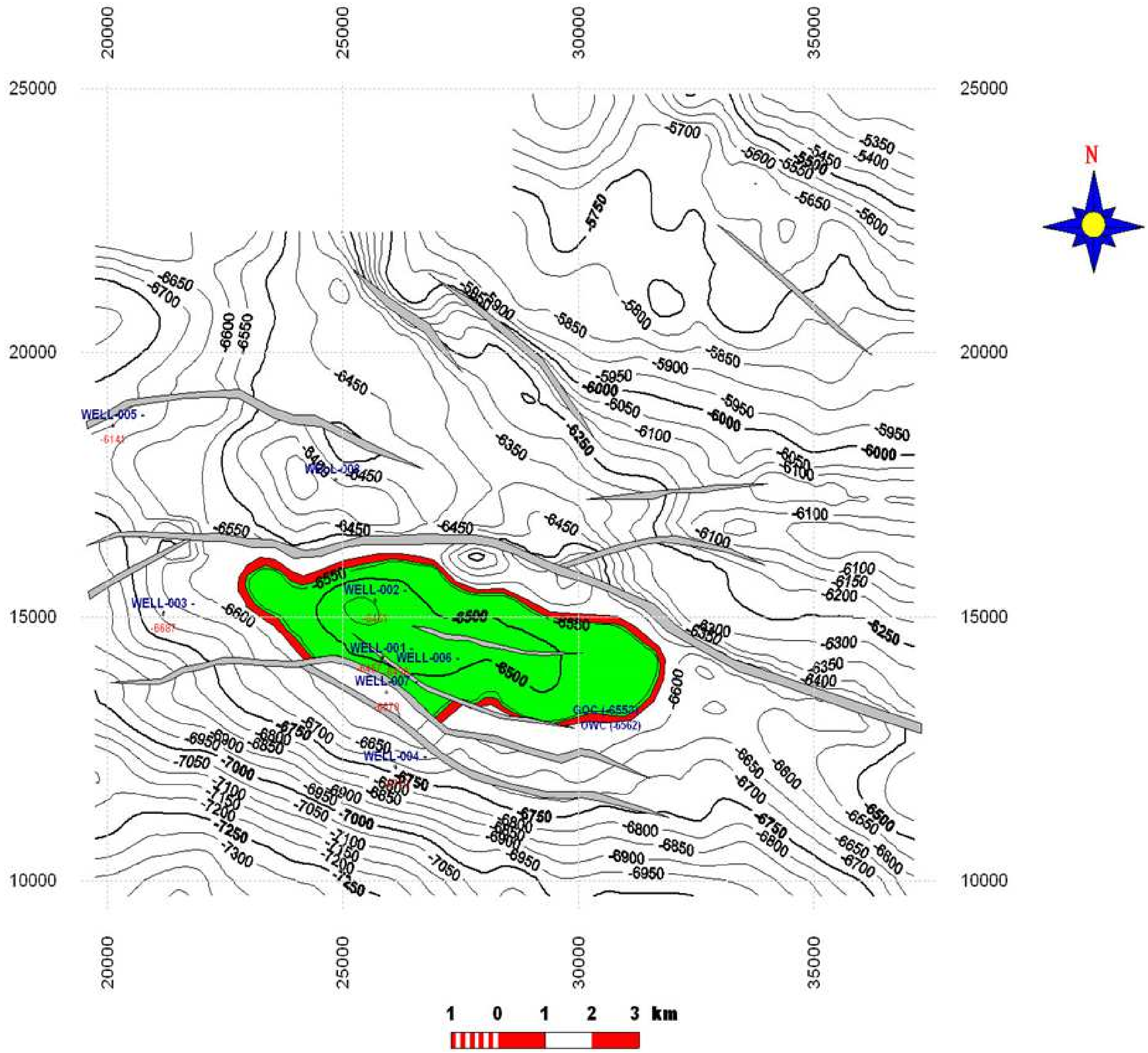



*Figure 9. Areal extent of gas (green) and oil (red) accumulation in D2000 sand.*

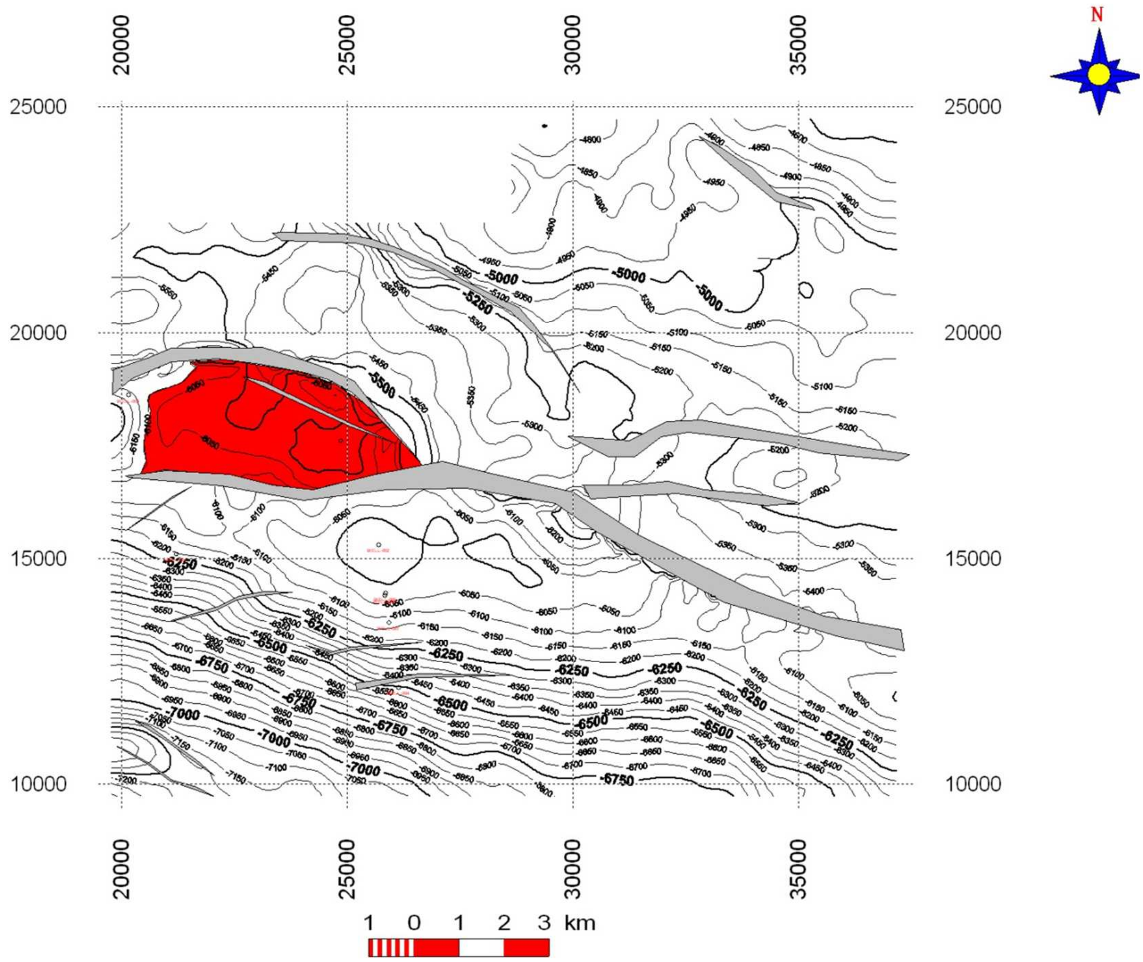



***Figure 10.*** *Areal extent of oil (red) accumulation in D4000 Sand.*

## 5. Conclusion

The D2000 petroleum reservoir sand is a rollover anticline on the downthrown block of a major synthetic structure building fault the runs across the field. Oil with gas cap is trapped in a four-way closure within the sand. Opportunities for productive drilling are revealed within the undrilled western, eastern and southern parts of the delineated reservoir.

The D4000 Sand contains unsaturated petroleum within the western part of the upthrown block of the major synthetic structure building fault. The petroleum content is trapped in a three-way closure. Average RMS amplitude value characterise the reservoir. A large part of the delineated reservoir is yet to be drilled westward of Well 008, where the sand contains unsaturated petroleum. This part presents constitute opportunity for productive drilling.

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