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Growth Fault History Analysis of an Oil Field, Niger Delta, Nigeria

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Abstract
The growth fault history of an oil field in the onshore Niger Delta has been carried out. Both seismic and well logs data were used independently for the analysis. The seismic section contains two growth faults (x and y). The growth analysis involved plotting the change in depth (Δd) of corresponding markers in two wells or in a seismic section having growth faults against the depth (d) of the marker in the higher well or higher wall of the seismic section. The plot of the change in depth of markers against corresponding depths of higher structural wall for the seismic data showed three condensed section, one expanded growth, four sequence boundaries and five distinctive changes in the growth history for the seismic section. Two expanded growth, three condensed sections, four sequence boundaries and five distinctive changes were obtained for the well logs. The zone of significant information is the highest expanded zone. This is the zone of hydrocarbon accumulation. The depth of the reservoir varies between 1900 – 2000 and 2300- 2400 metres. The condensed sections are made of shale lithology and that act as seal for hydrocarbon in the expanded sections. This analysis has provided significant information about the stratigraphy and growth fault history of the study area.

1. Introduction

In an area where large volumes of loose sediments are rapidly deposited, such as deltas and coastal plains, growth fault and anticline are usually formed. Rollover systems are extremely common structures of thin - skinned extensional systems resulting from gravity force. A growth or down-to-the-basin fault moves as the sediments are being deposited. The weight of the sediments being deposited along the shore-line pulls the basin side of the fault down. The sediments are thicker (grow) on the down faulted side. The growth fault plane gradually deflects and flattens out with depth. The growth fault occurs in loose sediments and the deeper the sediments the larger the fault displacement [1].

Most times, rollover anticline occurs on the basin side of the growth fault. This anticline is caused by the curved fault plane, which is almost horizontal with depth. The growth fault may form near the delta front thereby leading to this part of the delta subsiding rapidly, resulting in very thick deposits with delta front facies stacked on top of one another. Rollover anticlines are prolific petroleum traps along the Gulf of Mexico coastal plain, and in the Mississippi and Niger River deltas.

Tectonic and sedimentary growth are important to petroleum exploration. This is because growth along faults creates both structural traps and seals [2] and this growth can occur the same time with the deposition of reservoir units in a sedimentary basin. The expanded sections that form downthrown to down-to-the basin normal faults are the highest growth sections found in petroleum regime. These expanded downthrown sections often contain large accumulations of hydrocarbon [3]. The hydrocarbon accumulation correlates not only to high growth intervals but often to the highest growth intervals within petroleum system [4, 5]. Large accumulations of hydrocarbons correlate to the timing of oil migration and fault movement. Therefore, it is necessary to understand the timing of fault growth and sediment deposition.

Sedimentary and tectonics growth analysis are also used in sequence stratigraphic interpretation, unconformities, correlation, problem related to salt and in extensional regime that typically contains growth sediment [6]. Expansion index is a ratio calculated by comparing a downthrown stratigraphic thickness to its correlative up-thrown thickness. Determination of the indices for a sequence of stratigraphy help in the timing and activity on growth faults. A plot of the indices provides a record of the movement of fault throughout its history.

The growth fault analysis in this work was carried out using both well logs and seismic data independently and the final results were then compared. The growth analysis involved plotting the change in depth (Δd) of corresponding markers in two wells or in a seismic section having growth faults against the depth (d) of the marker in the higher well or higher wall of the seismic section. This technique is known as the $\Delta d/d$ method [6, 7]. The results are display in graph which formed the growth history of the sedimentary sections. Application of the methods using well logs data involved locating two wells in a general dip direction so that one well is structurally higher than the other. Horizons (markers) were correlated from one well to the other. The differences in depths of the lower markers reflect growth. The difference in depth of each corresponding marker is plotted against its depth (d) in the structurally higher well.

The plot can be used to classified sedimentary environment into stable and unstable environment. In a stable environment, the vertical distance between correlative markers is small and the curves normally have gentle slope or almost flat. In an unstable growth environment the vertical distance between correlative markers is large and the slope of the curve is very steep. The slope of the plot reflects growth history of the interval plotted.

An understanding of growth history when integrated with geologic and geophysical data can help to distinguished faults from unconformities, locate sequence boundaries, subtle stratigraphic traps, and channel sand, and highest growth or highest potential interval. The objectives of this research are; to analyse growth in part of the Niger Delta sedimentary basin, to assess its impact on hydrocarbon exploration and to show that each sedimentary sequence experience different pattern of growth.

2. Geology of the Studied Area

The studied area is located within the Niger Delta sedimentary basin (Figure 1.0). The Niger Delta covers a 70,000 square kilometer area within the Gulf of Guinea, West Africa. Although the modern Niger Delta formed in the Early Tertiary, sediments began to accumulate in this region during the Mesozoic rifting associated with the separation of the Africa and South American continents [8, 9].

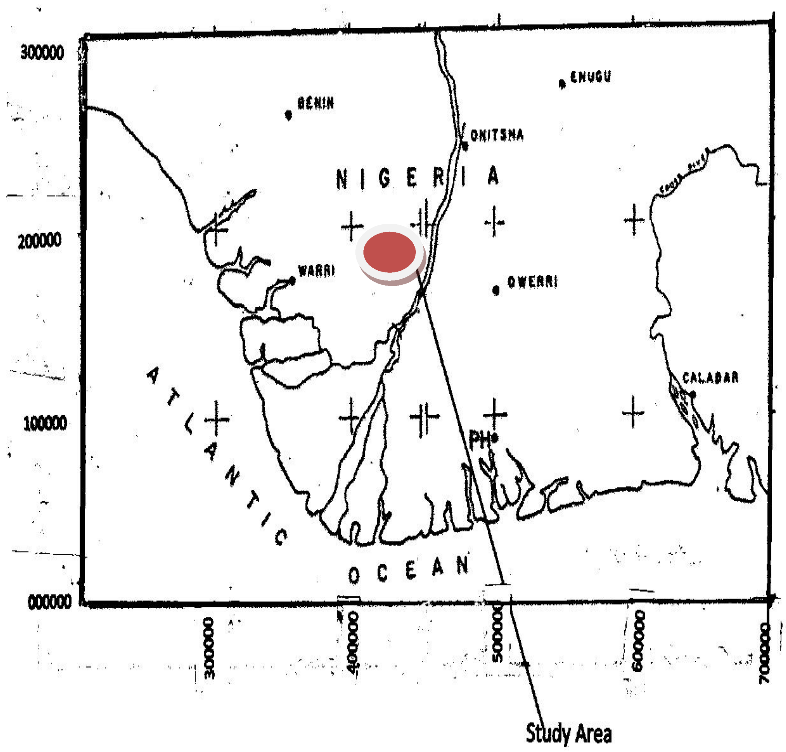

Figure 1.0. Map of Niger Delta Showing the possible location of the Study Area.

Tertiary Niger Delta deposits are characterized by a series of depobelts. Depobelts become successively younger basinward, ranging in age from Eocene in the north to Pliocene offshore of the present shoreline. Depobelts, tens of kilometers wide, are bounded by a growth fault to the north and a counter regional fault seaward. Depobelts define a series of punctuations in the progradation of this deltaic system. As deltaic sediment loads increase, underlying delta front and prodelta marine shale begin to move upward and basinward.

The formations of Niger Delta clastic wedge has been defined based on sand/shale ratios estimated from subsurface well logs [10]. The three major lithostratigraphic units defined in the subsurface of Niger Delta Benin, Agbada and Akata Formations. These Formations were deposited dominantly in marine, deltaic and fluvial environments [11].

The Benin Formation comprises the topmost part of the Niger Delta clastic wedge and it is described as the coastal plain sands which outcrop at the Benin-Onitsha area in the north to beyond the present coastline. Shallow parts of the Formation are composed of non-marine sands deposited in alluvial or upper coastal plain environment during progradation of the delta [9]. The Formation thins basinward and ends near the shelf edge. The deposit is predominantly continental in origin and consist of massive, highly porous, fresh water bearing sandstones with localized clay drapes and little shale intercalation which increases toward the base of the Formation. Texturally, it consists of fine grained sand. The grains are sub-rounded to well rounded, poorly sorted and partly unconsolidated. The thickness ranges from 0 - 2100m. It is thickest in the central area of the delta where there is maximum subsidence.

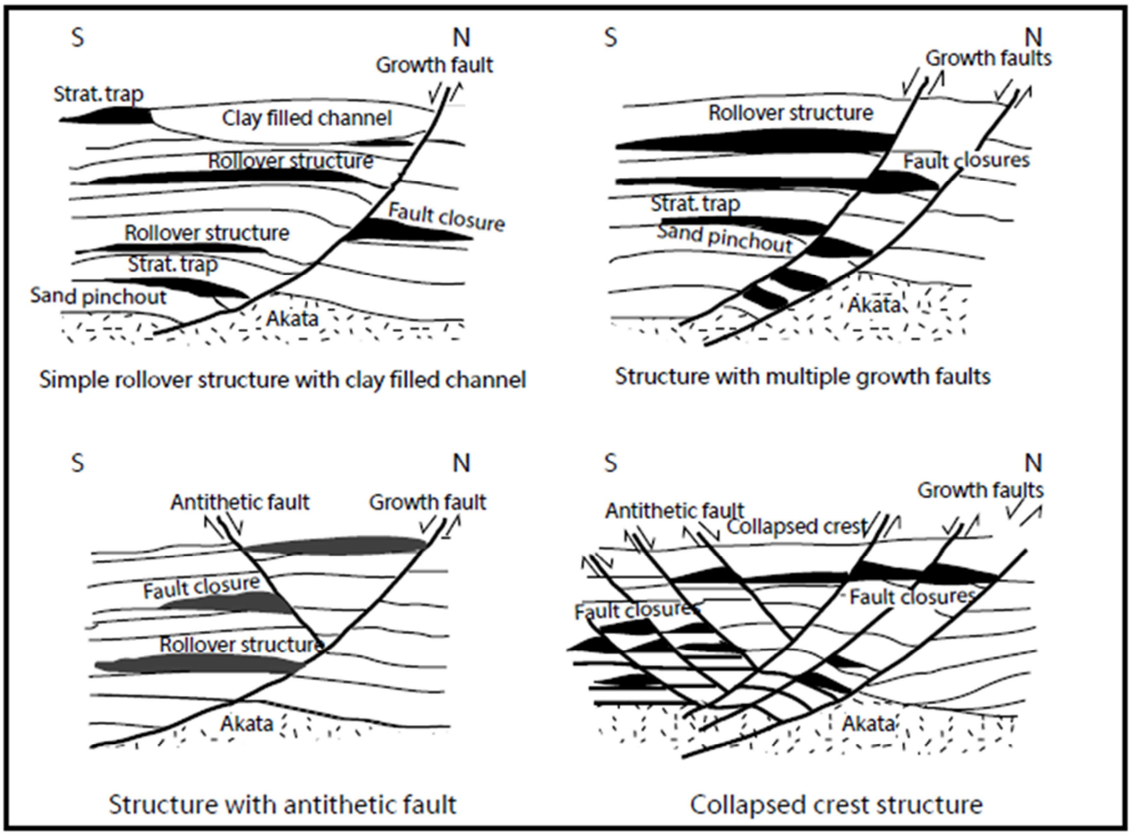

Figure 2.0. *Trapping system in Niger Delta. Examples of Niger Delta oil field structures and associated trap types. (Adapted from; 9 and 12).*

The Agbada Formation occurs as a paralic sequence of alternation of shale and sand throughout the Niger Delta clastic wedge. It increases in shale thickness with depth. The thickness ranges from 0-4500 m and its age is from Eocene to Pleistocene [9]. It crops out in southern Nigeria, where it is called the Ogwashi-Asaba and Ameki Formations respectively. The strata are generally interpreted to have formed in fluvial-deltaic environments [12]. The Formation underlies the Benin Formation and it is made up of interbedded fluvio-marine sands, sandstones and siltstone. Texturally the sandstone vary from coarse to fine grained, poorly to very well sorted, unconsolidated to slightly consolidated. The shales are medium to dark grey, fairly consolidated and silty with localized glauconites.

The Akata Formation occur as prodeltaic dark grey shales and silts with rare streaks of sand. The Akata Formation is estimated to be 6,400 m thick in the central part of this clastic wedge. These shales are exposed onshore in the northeastern part of the delta, where they are referred to as the Imo shale. The Akata Formation is the source rock of the Niger delta.

Deformation in the Niger Delta is thin skinned and has resulted from slope instability of gravitational origin [13 and

14]. The Akata shale has provided the necessary basal detachment. Thin-skinned structures are similar to those in other shale-based deltas, such as the Amazon Cone [15]. Deltas underlain by salt have similar features [16, 17 and 18]. However, in the Niger Delta, there is no evidence for salt. According to gravity modelling at the scale of the delta, the Akata Formation must have a low density, as in salt or poorly compacted shale [19]. However, the seismic velocity is very slow and that excludes salt [20]. One of the main structures due to slope instability in the Niger Delta are listric normal growth faults of extensional origin, on land and in shallow water; and folds and thrusts of compressional origin, in deep water at the toe of the slope [21 and 22].

Normal faults triggered by the movement of deep-seated, overpressured, ductile, marine shale have deformed much of the Niger Delta clastic wedge [13]. Many of these faults formed during delta progradation and were syndepositional, affecting sediment dispersal. Fault growth was also accompanied by slope instability along the continental margin. Faults flatten with depth onto a master detachment plane near the top of the overpressured marine shales at the base of the Niger Delta succession. Structural complexity in local areas reflects the density and style of faulting. Simple structures, such as flank and crestal folds, occur along individual faults. Hanging-wall rollover anticlines developed because of listric-fault geometry and differential loading of deltaic sediments above ductile shales. More complex structures, cut by swarms of faults with varying amounts of thrown, include collapsed-crest features with domal shape and strongly opposing fault dips at depth as shown in Figure 2.0 has been described.

Petroleum in the Niger Delta is produced from sandstones and unconsolidated sands predominantly in the Agbada Formation. Characteristics of the reservoirs in the Agbada Formation are controlled by depositional environment and by depth of burial. Known reservoir rocks are Eocene to Pliocene in age, and are often stacked, ranging from 15 to 45 m thick [8]. The thicker reservoirs likely represent composite bodies of stacked channels [9]. Based on reservoir geometry and quality, the most important reservoir types has been described as point bars of distributary channels and coastal barriers bars intermittently cut by sand-filled channels [23]. The lateral variation in reservoir thickness is strongly controlled by growth faults. The reservoir thickens towards the fault within the downthrown block. The grain size of the reservoir sandstone is highly variable. The fluvial sandstones tend to be coarser than the delta front sandstones.

3. Materials and Methods

3.1. Theory

Growth history can be obtained by accurate estimation of the thickness of sedimentary strata at two different points in the downthrown side of a growth fault. According to [1], assuming the thickness of an interval of sediment is d and the time taken for its deposition is t, then the sedimentation rate is given as

$$S = \frac{d}{t} \tag{1}$$

Where
S = sedimentation rate
d = thickness of sediment interval
t = time taken for deposition

The sedimentation rate for that interval may change between two locations within an oil field. The change in sedimentation rate for the two locations is given as

$$\Delta S = \frac{\Delta d}{t} \tag{2}$$

Where
ΔS = change in sedimentation rate
Δd = difference in sediment thickness

Taking the ratio of the change in sedimentation rate to the sedimentation rate, we obtained

$$\hat{S} = \frac{\Delta \mathrm{d}}{d} \tag{3}$$

Where
$\hat{S}$ = change in sedimentation rate to the sedimentation rate
d = thickness of sediment interval
Δd = difference in sediment thickness

The materials used for this research include geological well logs, seismic sections and check shot data. The well logs data consist of gamma ray and resistivity logs. The logs were obtained from two oil wells. The growth analysis was carried out using both the well logs and seismic data independently and the final results were then compared. The gamma ray log was also used for lithology identification and well correlation while the resistivity log was used for hydrocarbon reservoir identification.

3.2. Applying the Techniques to Well Log Data

In order to apply the above techniques to well logs, the logs from two wells located at the downthrown side of the growth faults were correlated. The vertical depth of each marker in the wells was taken and the depth differences for each correlation marker in the two wells was calculate. The computed depth difference for the various horizons is then plotted against the depth of the correlations in the structurally high well.

3.3. Applying the Techniques to Seismic Data

Applying the above theory to seismic data, both growth faults and horizons were identified and traced in the seismic section. In between two the growth faults, two imaginary lines were drawn with dashed lines to define the area used to obtain the data for the analysis. These dashed lines are parallel to each other and to the bounding growth faults.

Various horizons or markers were identified in the seismic section. These markers were traced from the downthrown to the upthrown side of the faults across the two dashed lines. The markers time in the two dashed were obtained by tracing the points where they cut the seismic lines to the vertical axis of the seismic section. The times obtained were converted to depth with aid of the available check shot data. The depth difference of the various markers obtained for the two dashed lines were then plotted against depth obtained from the structurally high dashed line.

4. Results and Discussion

The interpreted seismic section is shown in Figure 3.0. The seismic section is characterized by series of parallel reflections offset and deformed by listric normal faults. The seismic character changes with depth. Detailed analysis of the reflection characteristics of the seismic section shows that reflections within the upper part are parallel, have moderate to good continuity and high amplitude variation. In the basal part of the seismic section, it was observed that seismic amplitudes are very low and reflections are discontinuous and chaotic. The chaotic constitute low reflectivity package, lacking laterally continuous internal reflections. It extends higher under the foot walls of the faults.

Structure in the study area is dominated by two growth faults (x and y) that trend east – west and dip basin ward. These faults become less apparent as seismic record becomes obscured by transparent zones at depth. The down dropped blocks of the faults are deformed into broad anticlines.

The growth faults were identified and marked. The inclined dashed lines (a and b) are locations for correlation data in the plot. Twenty one markers were correlated in the seismic section and were used to construct the Δd/d plot shown in Figure 4.0. The plot shows the growth history relative to the seismic section. A polynomial approximation was fit for the data. The interval between correlation 6 to10 is an expanded growth interval because it has a positive slope on the plot. The slope is almost flat between correlation 17 and 20 indicating no growth. The intervals between correlations 1`-6, 14-17 and 20-21 are condensed sections because the slopes are negative. The maximum growth occurs between 6 -10 within the depth of 1900 -2000 metres. The plot shows five distinctive changes in the slope of the plotted data and four major breaks in the growth trends. The break at correlation point 6, 14, 17 and 20 marked major sequence boundaries.

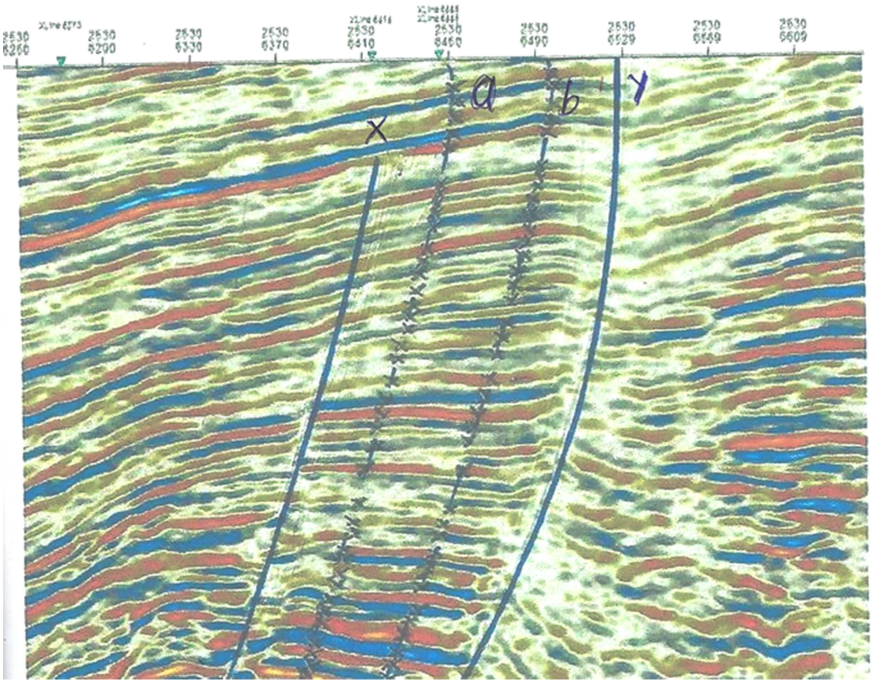

Figure 3.0. *Seismic section of the study area. Inclined dashed lines are locations for correlation data in the plot.*

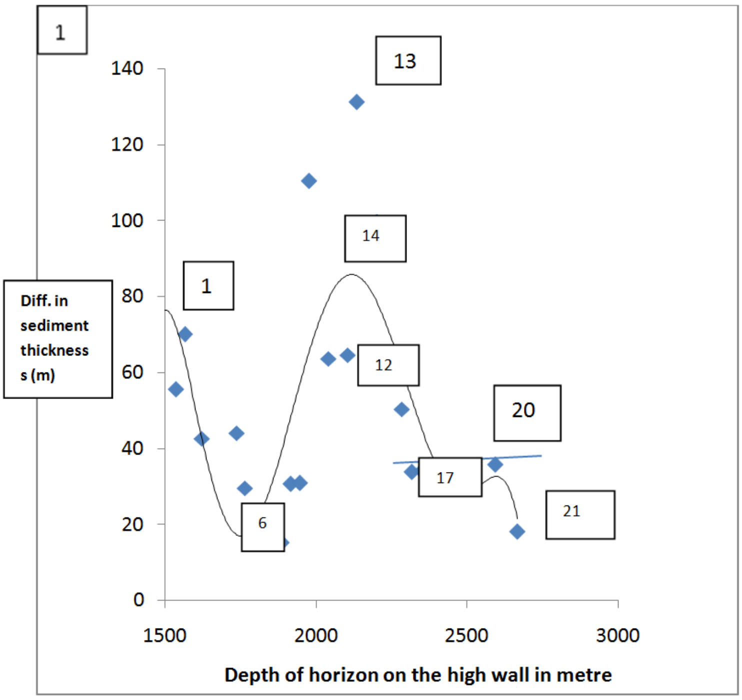

Figure 4.0. *A Δd/d plot of data obtained from the seismic data.*

The correlated panel for the two wells is shown in Figure 5.0. The major lithologies encountered in the wells are sand and shale. This is typical of the Agbada Formation in the Niger Delta. Twenty five markers were correlated across the two wells. Figure 6.0 is the Δd/d plot generated from the correlation data obtained from interpretation of the well logs. The interval between 3-6, and 14-19 are expanded growth interval because they have positive slopes on the plot. The intervals between correlation 1-3, 6-14 and 17-22 and 23-25 are condensed sections because the slopes are negative. The maximum growth occurs between from 14 to 19. The plot shows five distinctive changes in the slope of the plotted data and four major breaks in the growth trends. The breaks at correlation point 3,6,14 and 19 mark major sequence boundaries. The depth of the reservoir varies between 2200 - 2400 metres. The interval between 20 and 23 is assumed to be no growth region although the polynomial was unable to capture it.

Comparison of the two results shows that the well logs and seismic data analysis are almost the same. Four sequence boundaries were obtained from both analyses. The expanded section is the reservoir and the depth varies from 1900 to 2000 and 2200 to 2400 metres in the seismic and well log data respectively. The condensed section is usually associated with shale and hence they usually formed the seal. The sequence boundaries are the zone of unconformity due to erosion or non-deposition of sediments.

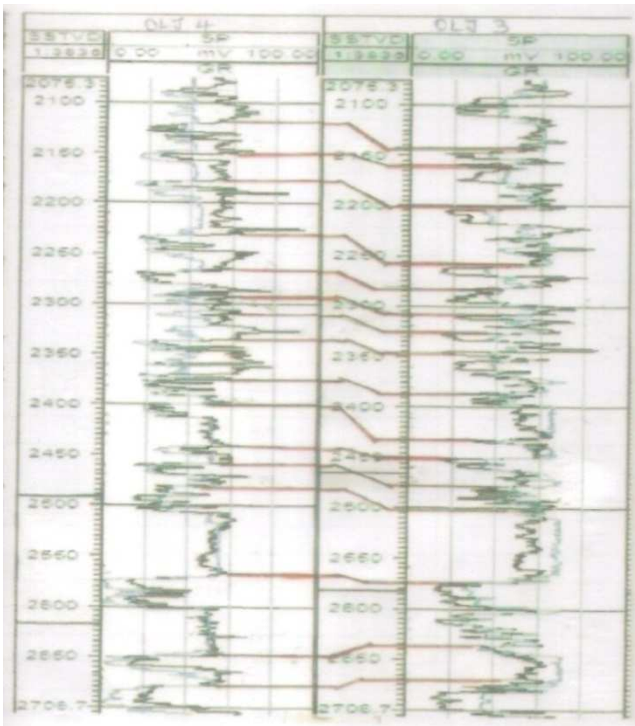

Figure 5.0. *Well logs use for the correlation of the two wells.*

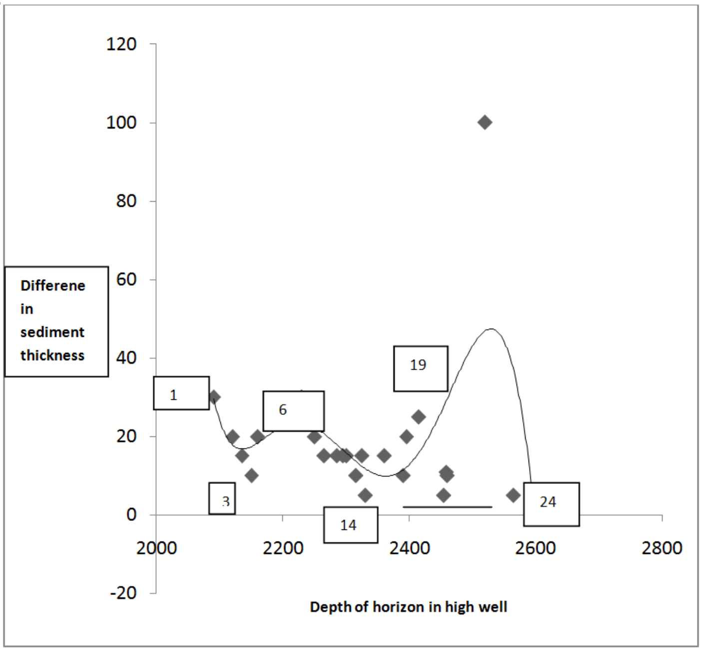

Figure 6.0. *A Δd/d plot of data obtained from the Well logs.*

5. Conclusion

The change in depth versus the depth in the higher wall plot for the seismic and well log data has proven to provide significant information about the stratigraphy and growth history of the studied area. The plot was successful in identifying sequence boundaries, condensed sections, expanded growth intervals, non-growth sections and major breaks in the growth trends. The techniques also helps in defining the hydrocarbon potential of the study area by indicating that the area of maximum growth is the zone of significant reservoir and the condensed sections are the areas of slow depositions where clay and shale are found.

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