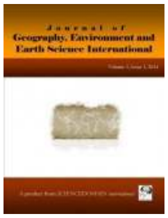

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Abnormal Pressure Detection Using Integrated Approach in "Oluku" Field, East Niger-Delta, Nigeria

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Authors' contributions

This work was carried out in collaboration between all authors. Author AOO conceived and designed the study, performed the pore pressure estimates and wrote the first draft. Author AAA managed the analyses of the study and proof read the first draft. Author OAO managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

This research reports overpressure occurrence in the eastern part of Niger Delta by using an integrated approach that combines the use of equivalent depth method, the Eaton equation with seismic reflection data. Sonic logs from four wells in the Oluku field were used. Pore pressure was calculated using Eaton equation and equivalent depth method and the result compared with pressure measurement data. The result showed that the eastern part of the delta is highly pressured with pressure regime that followed a typical ledged-tiered triple configuration with three episodes of overpressure. Prominent overpressure zones occur at depths of 4965 ft to 5099.5 ft, 7826 ft to 8337 ft, and 9424 ft to 10129 ft in Oluku-01 well, 4251.5 ft to 4408 ft, 7132.5 ft to 7495 ft and 9212.5 ft to 10000 ft in Oluku-02 well, 6322 ft to 6750 ft, and 9706ft to 10020 ft in Oluku-03 well and 4136.5 ft to 4275.5 ft, 7560 ft to 8000 ft, and 9038.5 ft to 9350 ft in Oluku-04 well. When

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compared with available pressure measurement data, computation using the Eaton equation was found to be closer to the pressure measurement data with the equivalent method underestimating the pore pressure. Seismic signature in the vicinity of the overpressure shows evidence of low velocity close to the shallow over-pressure zone probably due to under-compaction of sediments at shallow depth. Four regional faults in the study area contribute to abnormally high pressure at depth due to their sealing of permeable bed in the vicinity of kerogen-rich formation. This work reveals that the eastern flank of the Niger Delta exhibit higher degree of overpressure that the western flank. The knowledge of this is necessary for adequate planning before drilling into the formation in order to guard against dangerous drilling problems such as excessive cost overrun, well kicks and blowouts, lost circulation, stuck pipe and wellbore instability.

Keywords: Oluku field; hydrostatic pressure; lithostatic pressure; equivalent depth; abnormal pressure; Eaton equation.

1. INTRODUCTION

The concept of abnormal pressure within the subsurface of the earth has received worldwide attention and has been reported in various basins across the globe. This is premised upon the fact that it has caused a number of kicks during drilling activities for hydrocarbon exploration. Notable among the reports of abnormal pressure has been the works of [1] who reported overpressure occurrence in Baram basin in Brunei. [2] reported same occurrence in Central Sumatra basin and [3] who observed the same in Bengal basin of Bangladesh. Several authors have also reported abnormal pressure occurrence in the Gulf of Mexico. The Niger Delta of Nigeria is not an exception. Several workers have been able to report this from pressure measurement data as well as from seismic and well logs. Very recent works include the work of [4] who worked on porosity as a tool for detection of overpressure reported that there exists a close correlation between porosity and overpressure zones. [5] also investigated the shale pore pressure with the density log using the equivalent approach and observed that when properly calibrated with measured pore pressures, the density log can give reliable pressure prediction results in the Niger Delta, especially in the shallow section at temperatures < 70℃ but in deeper sections at temperatures >75℃, the equivalent depth method is unreliable. He also observed that shale intervals may provide vertical permeability barriers and create pressure compartments in some of the wells. The predominant over-pressuring mechanism in the shallow section, as evident from density and velocity reversals and, was found to be due to disequilibrium compaction. At greater depths (temperatures >75℃), a combination of equilibrium compaction and unloading mechanisms appears to be responsible for overpressure in the wells. [6] investigated the occurrence of overpressure in five of the wells in Afam oil field of the Niger Delta and observed that overpressure development occur at varying depths in the wells with the overpressured zones having characteristic high water saturation (52% to 80.36%) and low porosity (16.55% to 30.80%). Majority of these works were concentrated in the West and Central Niger Delta where extensive growth faults and roll over anticline play major roles in the abnormal pore pressure development. [7] reported that the magnitude of overpressure in the Niger Delta is highest and concentrated in the Agbada Formation of the central part of the delta. However, little is known about the eastern part of the Niger Delta. This research therefore aims to investigate this phenomenon in the eastern part of the Niger delta by using a method that integrates seismic data with pressure measurement data as well as information derived from wireline logs. We desire to detect abnormal pressure from seismic signature obtained from the area and estimate the magnitude of the abnormal pressure using two different methods and compare the results obtained with those of pressure measurement data obtained from selected depth intervals. This work is significant because it would go a long way to investigate not only the magnitude of overpressure in the eastern part of the delta but also the trend of variation in overpressure development across the delta.

1.1 Location of Study Area

The Niger Delta province lies roughly between latitudes 4°N and 6°N and longitudes 3°E and 9°E (Fig. 1). It is located in the southern part of Nigeria bounded to the northwest and west by the western African shield, which ends at the Benin hinge line and to the east, by the

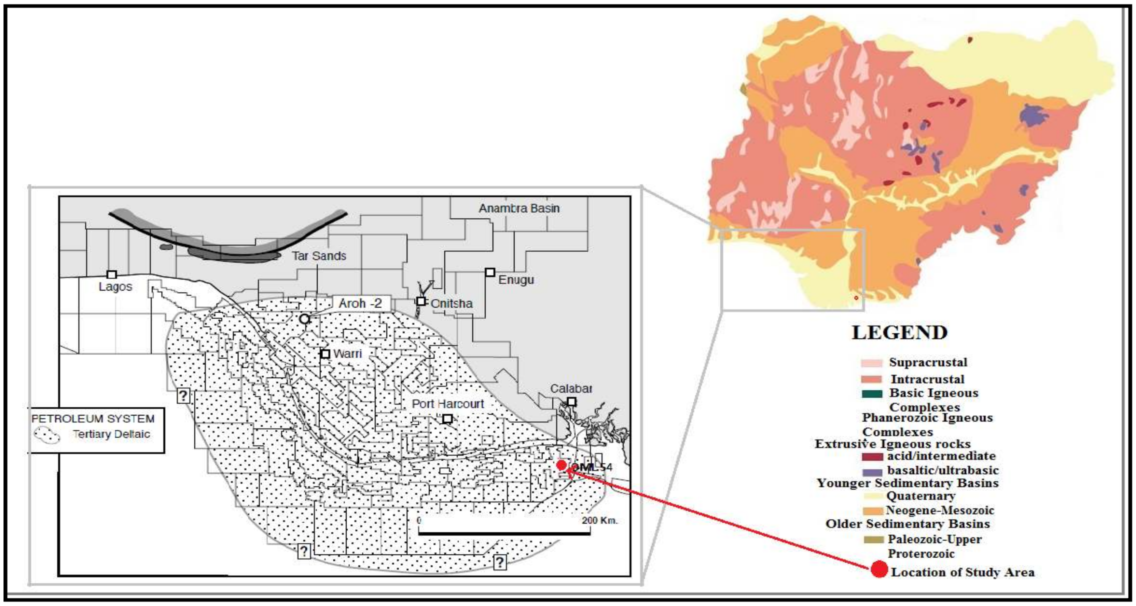

Fig. 1. The petroleum system of the Niger Delta

Calabar hinge line. To the northern part of the basin is the Anambra basin and Abakaliki anticlinorium. To the immediate south of the area is the Gulf of Guinea which extends into the Atlantic Ocean. Geologically, it is situated at the intersection of the Benue Trough and the South Atlantic Ocean where a triple junction developed during the separation of the continents of South America and Africa in the late Jurassic [8]. The total area of Niger Delta land mass covers about 75,000 sqkm. From the Eocene to the present, the delta is believed to have prograded southwestward, forming depobelts that constitute the most active part of the delta at each stage of its development [8]. These depobelts form one of the largest regressive deltas in the world with an area of some 300,000 km^2 [9,10] a sediment volume of 500,000 km, and a sediment thickness of about 12 km in the basin depocenter. An outline of the different geomorphology of the Niger Delta of Nigeria is shown in Fig. 1.

Lithostratigraphically, the delta is basically made up of the Benin formation which is the youngest and is a loose fresh water-bearing sand with occasional ignite and clay and going up to 7500 ft (2286 m) deep with no overpressure [11]. The Agbada formations, made up of alternations of sand and shales with the sand mostly encounter at the upper parts while shales are found mostly at the lower parts and finally the Akata formation which is the oldest and the thickest. It is thickest at the center of the delta and goes up to 1500 ft (457 m). Akata Formation consists mainly of marine shales and has been thought to be significantly overpressured. It is generally believed to be the main source rock of the hydrocarbons which are usually trapped in faulted rollover anticlines associated with growth faults.

2. MATERIALS AND METHODS

The materials used to study abnormal pressure in the study area include composite geophysical well logs, pressure measurement data, seismic sections and check shot data. The composite geophysics logs used are the gamma-ray, spontaneous potential, electrical resistivity, and sonic log and density logs. Preliminary work involves correction of logs for necessary effects prior to usage. The sonic logs were de-spiked to remove cycle noises that are associated with raw sonic logs. Correction was also carried out to correct logs relative to elevation. First, clean shale intervals were selected from the delineated overpressure zones using the volume of shale equation for Tertiary rock proposed by [12] given by

$$V_{sh} = 0.083(2^{3.7*I_{GR}} - 1) \quad (1)$$

The lithostatic pressure was estimated using the industry expression given by

$$S_v = 0.433 \int_0^z \rho_z \, dz \quad (2)$$

where S is the lithostatic pressure (psi), ρ_z is the bulk density of rock at any depth of investigation. In this work, the bulk density log will be used directly for the lithostatic pressure estimation in wells that had the logs. Hydrostatic pressure on the other hand shall be estimated by using the expression given by

$$P_h = \rho * g * H \quad (3)$$

where H is the depth of investigation (m), ρ is the density of water (g/cm^3) and g is the gravity (m/s^2) and P_h is the hydrostatic pressure (kPa). The gravity value of 0.0098 was used, the kilometer equivalent of the acceleration due to gravity 9.8 m/s^2. For this research, a water density value of 1.025 g/cm^3 (0.433 psi/ft), typical of West African environment was employed as the average formation water density. The secondly step involved the generation of the sonic-depth plot in each of the wells under investigation in order to determine the depth where there exists deviation due to abnormal pressure in each of the wells. The magnitude of the deviation from normal compaction trend in these zones was used to estimate the pore pressure using the equivalent depth expression proposed by [13] given by

$$P_p = P_{a,z} + (S_z - S_{a,z}) \quad (4)$$

and pore pressure expression proposed by [14] given by

$$P_p = S - \left(S - P_h \left[\frac{\Delta t_n}{\Delta t_{\log}} \right] \right)^{3.0} \quad (5)$$

where $P_{a,z}$ and $S_{a,z}$ are the pore pressure and the overburden stress at z respectively, the depth of interest and a, the depth along the normal compaction trend at which the measured parameter is the same as it is at the depth of interest, Pp is the pore pressure estimate, S, the lithostatic (overburden stress), P_h, the hydrostatic pressure, Δt_{log}, the sonic log value and Δt_n being the sonic log reading at the equivalent normally compacted interval. The value of Δt_n is easily estimated by using the normal compaction trend expression proposed by [15] given by the equation shown below;

$$\Delta t_n = \Delta t_m + (\Delta t_{ml} - \Delta t_m)\, e^{-cZ} \quad (6)$$

where Δt_m = transit time in matrix, Δt_{ml} = transit time in mud filtrate and Δt_n, the transit time at normal compaction trend, Z, the depth of investigation and c the compaction factor, given by Δt_{log} divided by 100 with values of c ranging from 1.0 to 1.5. The computed pore pressures using these methods were compared with real time pressure measurements data. The third stage involved the picking of the abnormal pressure markers which are points of abnormal pressure at which the sonic log data deviates from the normal trend in these wells with known overpressure zones. These markers were then tied to seismic in order to study the seismic signature in zones where there exists abnormal pressure development and it represents the horizon which tied the start of abnormal pressure in the wells. This represents the tops of abnormal pressure in the local area of the wells. There were seven wells in the Oluku field but only four collected the pressure measurement data. From the pressure data, there were four wells with elevated pore pressure; Oluku - 01 well, Oluku – 02 well, Oluku - 03 well and Oluku - 04 well. Oluku - well 5 does not show prominent overpressure development that could be useful for pore pressure estimation. However, Oluku – 06 well do not have pressure measurement data while Oluku – 07 was not used for pressure estimate due to the fact that it is a horizontal well. All the wells used for the research had Gamma ray, Neutron, Resistivity logs (such as the Dual laterolog) and sonic logs. Density log was lacking in Oluku – 03 well but was obtained by using the industry density – sonic [16] petrophysical expression given by

$$\rho b \log = 2.75 - \left(2.11 x \left[\frac{\Delta t_{\log} - \Delta t_{\max}}{\Delta t_{\log} - \Delta t_{fl}} \right] \right) \quad (7)$$

where **ρ**b log = estimated density log, Δt_{log} = sonic travel time as read from log, Δt_{max} = sonic travel time in rock matrix and Δt_{fl} = sonic travel time for fluid. In this case, the matrix is assumed to be shale because overpressure is best estimated using shale intervals. This is because under geopressure conditions shales do undergo undercompaction with anomalously low density and seismic velocity. The bulk density and sonic logs were used for the lithostatic and hydrostatic pressure as well as pore pressure estimation. Synthetic seismogram was generated using the check-shot data obtained from the field and was employed to tie the abnormal pressure tops to seismic in order to study the seismic signatures in the vicinity of overpressure zones.

3. RESULTS AND DISCUSSION

The log of sonic was plotted with depth for all the viable wells in the field. Table 1 is a summary of all the pore pressure values obtained for the selected depths using the Eaton and equivalent depth method. Fig. 2 shows the typical pattern of the pressure configuration observed in the study area. Generally, the pressure regime in the study area follows a legged tier pressure configuration having three episodes of overpressure. Overpressure was prominent at three zones except in Oluku-03 well where two zones of overpressure were noticed. The shallowest overpressure zone extends from about 4965 ft to about 5099.5 ft with hydrostatic, lithostatic and pore pressure estimate of about 48.7 MPa, 31.1 MPa, and 171.0 MPa respectively. The second zone is relatively thicker and it extends from a depth of about 7826 ft to a depth of about 8337 ft with hydrostatic, lithostatic and pore pressure estimate of 76.7 MPa, 50.9 MPa and 999.8 MPa respectively. The third zone was about 705 m thick and has the most intense overpressure episode with value of the pore pressure about fifty-three times far above the hydrostatic. The overpressure tops were observed at depths of 4965 ft, 7826 ft and 9424 ft in Oluku-well 1, 4251 ft, 7132.5 ft and 9212.5 ft in Oluku-well 2 and 4271.5 ft, 7866 ft and 9136.5 ft in Oluku -04 well respectively.

In Oluku – well 1, the three points selected for the overpressure estimation were picked at depths of 5152 ft, 7904 ft and 9987 ft respectively. Using the equivalent method, the magnitude of the pore pressure at the selected depths were 152.6 MPa, 852.3 MPa and 4657.5 MPa respectively while using the Eaton method at the selected depths, the pore pressures estimates were 170.9 MPa, 999.8 MPa and 5438.5 MPa respectively. In Oluku - 02 well, the shallowest overpressure zone extends from about 4251.5 ft and it is about 156.5 ft thick. Hydrostatic, lithostatic and pore pressure estimates were observed to be 42.6 MPa, 25.2 MPa and 68.8 MPa respectively. The second overpressure zone on the other hand is about 362.5ft thick. The hydrostatic, lithostatic and pore pressure estimates were found to be 72.6 MPa, 46.1 MPa and 275.2 MPa respectively. The third overpressure zone is observed at a depth interval of about 9212.5 ft to 10,000 ft. In this well, the estimated hydrostatic pressure observed far outweighs the lithostatic pressure with the hydrostatic pressure as low as 42.6 MPa in overpressure zone one to as high as 94.7 MPa in overpressure zone 3. This shows that fluid pressure is very much in control of the subsurface pressure condition. Three points selected for the overpressure estimation were picked at depths of 4291.5 ft, 7409.5 ft and 9663.5 ft respectively. The magnitudes of the pore pressure estimate using equivalent depth at the selected depths were found to be 75.2 MPa at a depth of 4291.5 ft, 30.0 MPa at a depth of 7409.5 ft and 1052.1 MPa at a depth of 9663.5 ft while Eaton method at these same depths gave pore pressure estimates of 68.8 MPa, 274.9 MPa and 913.9 MPa respectively. The results of pore pressure estimates using the equivalent depth methods and the Eaton method in this well is presented in Table 1.

In Oluku-03 well, logging measurements was carried out from 4490 ft below the subsurface. The log of sonic versus depth plot reveals only two prominent overpressured intervals. The shallowest overpressure zone was observed at interval from 4281 ft to 7623 ft while the deepest overpressure zone is relatively thicker and it extends from a depth of about 9706 ft to a depth of about 10,020 ft. The overpressure tops in these two zones were picked at depths of 4281 ft and 7623 ft respectively. There was no prominent normal compaction trend. Only two points within the overpressured interval were therefore selected for the overpressure estimation. These were picked at depths of 7139.5 ft and 9922.5 ft respectively. The equivalent depth method estimate gave a pore pressure value of 229.6 MPa and 100.5 MPa at both depths respectively while the Eaton method gave a slightly higher value above the equivalent methods. The values were 288.6 MPa and 120.6 MPa. In all Oluku wells, the pore pressure obtained using the Eaton method gave a closer approximate to the pressure measurement data. In Oluku-04 well, overpressure tops were picked at depths of 4136.5 ft, 7560 ft and 9038.5 ft. while the three points selected for the overpressure estimation were picked at depths of 4271.5 ft, 7866 ft and 9136.5 ft respectively. The shallowest overpressure zone of about 380 ft thick gave pore pressure estimate of about 560.5 MPa. The second zone which is relatively thicker, extending from a depth of about 7560 ft. to a depth of about 8000 ft, gave pore pressure estimate of 973.5 MPa. The third zone on the other hand which is about 311.5 ft. gave pore pressure estimate 2320.5 MPa.

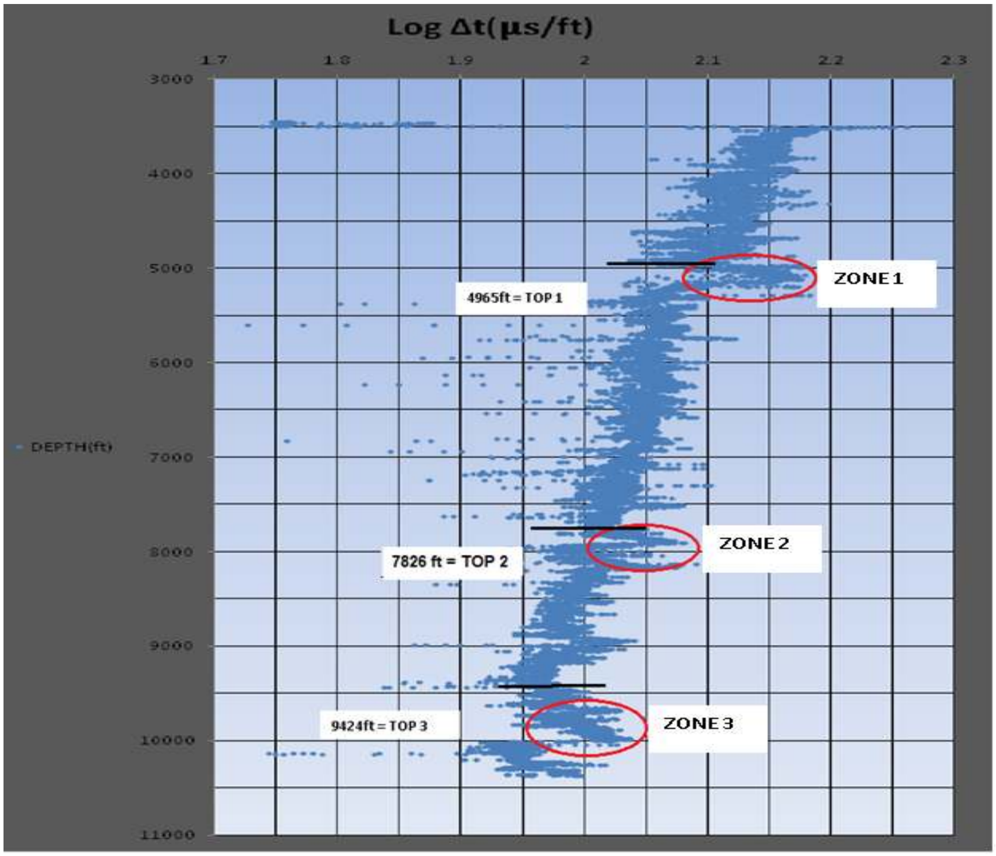

Fig. 2. Typical legged tiered overpressure configuration observed in the Eastern Niger Delta

Using the equivalent depth method at the selected depths, the pore pressure estimates of 514.3 MPa, 92.2 MPa and 1863.6 MPa were observed. Eaton method gave pore pressure estimates of 559.8 MPa, 972.4 MPa and 2319.6 MPa respectively. (Table 1). Generally, pore pressure was observed to increases with depth rapidly, implying that the deeper formations are hydraulically isolated from shallower ones. In most of the wells, overpressure estimation using the Eaton expression was also found to be closer in value to that observed in the pressure measurement data. The magnitude of pore pressure observed using the equivalent method was observed to be lower than the value obtained using the Eaton standard expression and the pressure measurement data, thereby resulting in underestimation of pore pressure. The observed under-estimation of the pore pressure using the equivalent method compared with the result of the pressure measurement data is not unconnected with the mechanism that produces the overpressure condition at that depth. [17] observed that such under-estimation of overpressure may be associated high shale porosities when estimated from sonic and density logs. [18] also observed that when equivalent depth method is used to estimate pore pressure, it usually bring about underestimation of pore pressure, especially when the overpressure is generated by disequilibrium compaction due to fluid expansion. This is partly because fluid expansion and uplift generate reduction in effective stress without being revealed in higher porosity with continuous compaction leading to under-estimation of pore pressure [19] and also because sonic log which is employed in the equivalent depth method is slower in fluid expansion overpressures due to textural changes in the rock [20]. The presence of under-compaction is consistent with the overpressure primarily caused by disequilibrium compaction [20,1]. Hence, the primary cause of overpressure in the study area could be inferred to be generated by disequilibrium compaction. This is in agreement with observation made by several other authors [21,22]. It is also observed that the hydrostatic pressure is always higher than the lithostatic pressure in the area. This behavior is common with regions where fluid pressure is in

Table 1. Results of pore pressure estimates using Equivalent method and the Eaton method Oluku 01, 02, 03 and 04 wells

	AOI (ft)	HP (MPa)	LP (MPa)	EDepth (MPa)	Eaton (MPa)	Press. Data (MPa)
OLUKU 01 WELL						
Overpressure	**Overpressure top at 4965 ft**					
Zone 1	5152	48.7	31.1	152.6	170.9	171.0
Overpressure	**Overpressure top at 7826 ft**					
Zone 2	7904	76.7	50.9	852.3	999.8	999.8
Overpressure	**Overpressure top at 9424 ft**					
Zone 3	9987	92.4	63.2	4657.5	5348.5	5351.0
OLUKU 02 WELL						
Overpressure	**Overpressure top at 4251 ft**					
Zone 1	4291.5	42.6	25.2	75.2	68.8	68.8
Overpressure	**Overpressure top at 7132.5 ft**					
Zone 2	7409.5	72.6	46.1	30.0	274.9	275.2
Overpressure	**Overpressure top at 9212.5 ft**					
Zone 3	9663.5	94.7	61.8	1052.1	913.9	915.3
OLUKU 03 WELL						
Overpressure	**Overpressure top at 6322.0 ft**					
Zone 2	7139.5	70.0	48.0	229.6	288.6	289.6
Overpressure	**Overpressure top at 9706.0 ft**					
Zone 3	9922.5	97.2	67.5	100.5	120.6	120.8
OLUKU 04 WELL						
Overpressure	**Overpressure top at 4136.5 ft**					
Zone 1	4271.5	41.9	24.5	514.3	559.8	560.5
Overpressure	**Overpressure top at 7560 ft**					
Zone 2	7866.0	77.1	51.1	92.2	972.4	973.5
Overpressure	**Overpressure top at 9038.5 ft**					
Zone 3	9136.5	89.6	60.2	1863.6	2319.6	2320.05

AOI = Adjacent Overpressure Interval, HP = Hydrostatic Pressure, LP = Lithostatic Pressure, EDepth = Equivalent Depth Method, Eaton = Eaton Method, Press. Data = Pressure Data

total control of the subsurface rock and it implied that the region consists mostly of gas and little oil. The only plausible explanation of this behavior is that there occurs a fast and quick breakdown of kerogen into gas at deeper depth and consequent accumulation of gas at shallow depth.

The higher value of pore pressure above the hydrostatic condition in Zone 1 indicates that the overpressure in this zone may be associated with disequilibrium compaction while in zone 2, it may be related to gas accumulation. Overpressure in Zone 3 may be due to hydrocarbon generation at greater depth and the temperature conditions of kerogen transformation at that interval. [23,24] observed that such intense overpressure in the subsurface rock at greater depth sometimes are related to kerogen transformation from the initial type of kerogen to oil and consequently to gas. The different zones of overpressure from depth plot and the points of departure from the normal compaction trend (which indicates the overpressure tops) were picked in each well. These well picks (or markers) were tied to seismics using synthetic seismograms. The synthetic seismogram obtained is as shown in Fig. 3. These markers were used to define the horizons for the overpressure tops in each well first and also with all the wells. Oluku -1 well is located in the western part of the study area while Oluku -04 well is located to the eastern part of the study area. Structurally, there is a change in the lithology of the first overpressured zone across the wells and this change in lithology is indicative of a change in travel time and consequently changes in the interval velocity [25]. At the shallowest overpressure zone (Zone 1), the top of the overpressure is not flat but follow the general undulating topography of the area. This might not be unconnected with the low velocity observed in that zone. Overpressure on seismic section is usually associated with velocity reversal and it is exemplified by seismic signatures which are not consistent with the general signature on the section. Within this zone, it is observed that the area is not affected by the regional faulting that occurs in the area. Also, the nature of the shallow overpressure zone observed can be associated with the age of the rock. Overpressure in shales especially at shallow depths is believed to be a common feature of "young" (<50 Ma) sedimentary sequences where there is rapid burial of sediments in which case there has been insufficient time for the pore pressures generated by this burial to dissipate. Sometimes, it may be associated with upper biochemical zone of gas generation, especially where these gases have accumulated in sand streaks bounded on all sides by plastic impermeable rocks. Since Niger Delta is of the Paleogene to Recent, wave-dominated delta, it is not exempted from this phenomenon. Gas usually modifies seismic signals, forming seismic anomalies that are then interpreted as pseudo-overpressure zones. This can easily be seen in Fig. 4 where the seismic signal in the vicinity of the shallow overpressure shows seismic anomalies different from those of the rock layers below. The second overpressure zone (Zone 2) can most likely be attributed to non-equilibrium compaction (under-compaction) because of high sedimentation rates. This zone is easier to predict than the third overpressured and usually causes little problems in drilling. The deepest overpressure zone poses the greatest risk, because its intensity can sometimes be difficult to be identified but may be associated with greater depths where intensive gas formation begins due to rapid breakdown of kerogen. From the estimation, the pore pressure value range from as low as 120.8 in Oluku-03 well to as high as 2320.0 MPa in Oluku-04 well. These values of pore pressure at greater depth is associated with fluid expansion due to rapid conversion of highly matured kerogen to oil and also from oil to gas [26]. When the kerogen to oil/gas conversion exceeds the rate of volume loss due to fluid flow, excess pore pressure is generated. The situation becomes complicated when there exists faulting at greater depth. From the seismic section, there exist four prominent regional faults marked F1, F2, F3 and F4. These faults might have contributed to the strong overpressure (hard overpressure, according to [27]) at depth. Overpressure caused by this mechanism is believed to have occurred as a result of permeable beds in a formation that has been displaced and sealed by impermeable beds such that the cracking of kerogen into oil with consequent conversion of oil into gas is not allowed to migrate easily causing abnormally high pressure build-up to develop [5]. [28] observed that sometimes, trapping of deep gas in sub-ledge, normally pressured intervals may be facilitated by anticlinal folding or faulting.

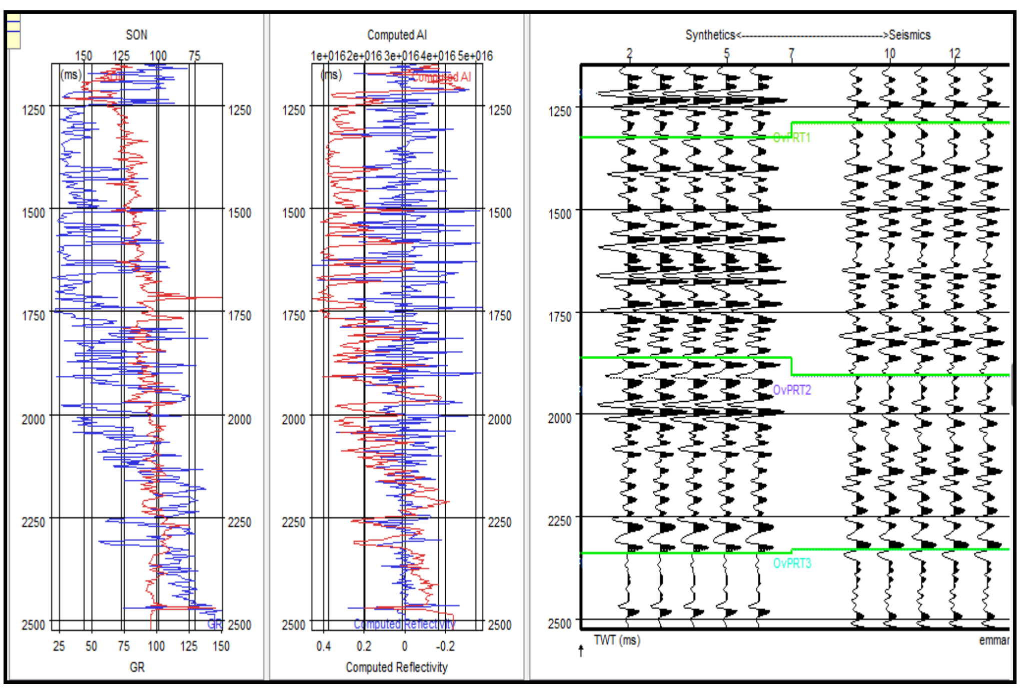

Fig. 3. Typical synthetic tie of the wells with seismic in Oluku wells

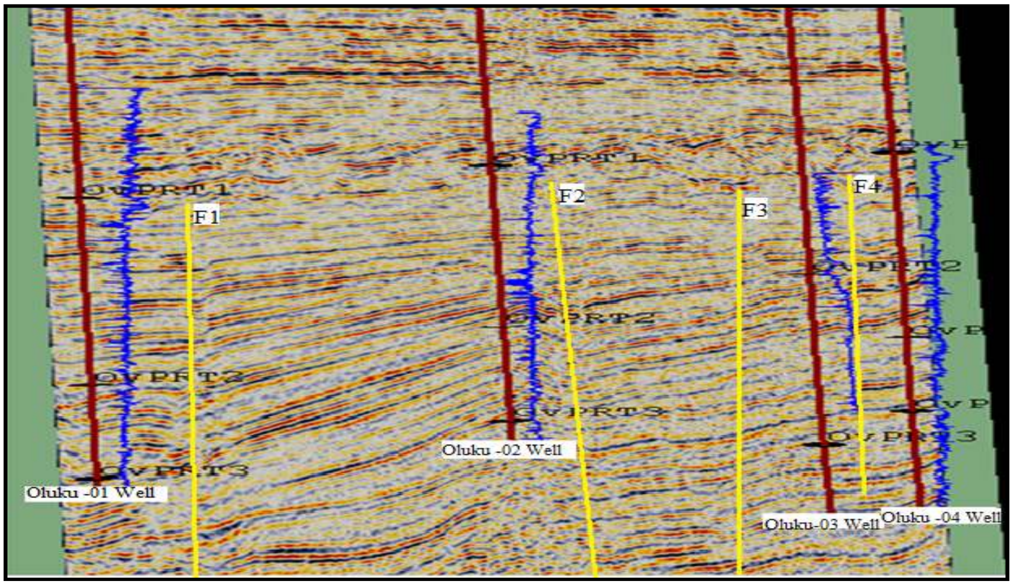

Fig. 4. Figure showing seismic section and well ties in Oluku - 01, Oluku - 02, Oluku - 03 and Oluku - 04 Wells (Faults in yellow, Wells in Red, Well ties in Blue, Overpressure tops marked by black color)

4. CONCLUSIONS

From the results obtained in this work, it is worthy to note the followings:

- Intense overpressure development is not limited to the central part of the delta as there are evidences from this work that the eastern Niger Delta has higher overpressure magnitude than the central part,
- The value of the pore pressure obtained using the Eaton equation is closer to that measured by the measured direct test (MDT) data than the value obtained using equivalent methods in the eastern Niger Delta,
- Granted that though overpressures in the Niger Delta are generally accepted to be generated by disequilibrium compaction, this study shows that this conclusion is only limited to certain parts and certain depths of the basin as there seem to be instances where overpressures in Niger Delta Basin are precipitated by regional fault coupled with kerogen breakdown at greater depths.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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