International Journal of Applied Science and Mathematical Theory E- ISSN 2489-009X P-ISSN 2695-1908,
Vol. 8 No. 1 2022 www.iiardjournals.org

Detection of Abnormal High Pore Pressure Zones in OML-58 in Niger Delta Oil and Gas Field

Orudukobipi Asime
Department of Science Laboratory Technology,
Captain Elechi Amadi Polytechnic, Rivers State, Nigeria

DOI: 10.56201/ijasmt.v8.no1.2022.pg53.70

Abstract

Having a prior and accurate knowledge of formation pore pressure is vital for any oil and gas producing sedimentary basin on socioeconomic and technical point of view. This will ensure safe and cost effective drilling operations; enable effective assessment of formation fluids migration pathway and trap configuration, unbundle basin modelling challenges and determine seal integrity. This study detected abnormal pore pressure zones using sonic-porosity logs from Two Wells (Well A and Well B) in OML-58 in the Niger Delta. The Niger Delta basin was assumed being extensional and compaction disequilibrium is the major cause of the abnormal high pore pressure in the study area. The slowness were digitized from the sonic logs at 25m depth interval; the sonic compressional velocities obtained by taking the inverse of the slowness; and the porosities computed using the Wyllie's equation. Deviation from the normal compaction trend method was employed for the detection of the abnormally pore pressured zones. Results showed that the porosity and slowness decreases with depth while the sonic compressional velocity increases with depth in Well A in line with the normal compaction trend. There were significant deviations from the normal compaction trends from the depth- porosity profile, depth-slowness and depth-sonic compressional velocity profile Well B. Well A has no abnormal high pore pressured zone and Well B has an abnormal high pore pressured zone at depth column of 2700m- 2775m. The determined abnormal high pressure zone falls within the range of depths of abnormal high pressure zones in the Niger Delta.

Key words: *Abnormal Pore Pressure, Normal compaction trend, Porosity, Slowness, Sonic compressional velocity*

Introduction

The primary goal of every oil and gas exploration and production (E&P) business is the safe drilling of a proven oil and gas reservoirs and optimization of the drilling and extraction process to save time and resources. This can be overcome by accurately determining the pore pressures while on course and appropriately preventing the disastrous effects of unknowingly drilling into a pore pressure zone with a high positive pressure anomaly. Because drilling into such zones in the subsurface without receiving prior notification can lead to extreme events such as well blow-out, pressure kicks, fluid influx and depletion of hydrocarbons in place due to uncontrolled burning (Tanko *et al*,2019,Abbey *et al*,2021). These hazards can pose large threats to life and the drilling prospect which has in the past led to loss of precious human life and fixed and floating capitals; destruction of the entire rig, oil spillage, destructions of aquatic lives and the ecosystem in Gulf of Mexico, USA etc. Severe negative pressure anomaly can also cause drillpipe to stick to the under pressured formation. (Atashbari and Tingay,2012;Das and Chattergee,2017). Imagine what the impacts of such disastrous effects will be on the fragile economy of a developing country such as Nigeria that solely depends on oil and gas.

Pore pressure is the fluid pressure in the pore spaces of a porous formation. It varies from hydrostatic pressure, to severe abnormally high pressure or overpressure, that is, from 48% to 95% of the overburden stress (Dasgupta *et al*,2016,Abbey *et al*,2019). If its value is lower or higher than the hydrostatic pressure (normal pore pressure), it is an abnormal pore pressure. Abnormally low pore pressure might occur in areas where fluids have been drained, such as a depleted hydrocarbon reservoir. Abnormally high pore pressure or overpressure might occur in areas where burial of water-filled sediments by impermeable sediment such as clay was so rapid that fluids could not escape and the pore pressure increased with deeper burial supporting the total overlying rock (Meng *et al*,2011; Stricker *et al*,2016;Van,2020).

Pore pressures in most deep sedimentary formations are not hydrostatic; instead they are over pressured and elevated even to more than double of the hydrostatic pressure. Abnormally high pore pressured formations exhibit higher porosities, lower bulk densities, lower effective stresses, higher temperatures, lower interval velocities and higher Poisson's ratios when compared with a normally pressured section at the same depth(Fan et al,2016;Luo,2016;Aird,2019). Abnormally high pore pressure can be caused by many mechanisms, such as compaction disequilibrium or under compaction, hydrocarbon generation and gas cracking, aqua-thermal expansion, tectonic compression or lateral stress, smectite/illite transformation, and osmosis, hydraulic head and hydrocarbon buoyancy(Zhang, 2011 ; Xie,2011;Yu et l,2014; Quays and Wans;2015).

In the field of exploration, pore pressure holds particular significance for drilling and discovery purposes. Knowledge of formation pore pressure is not only essential for safe and cost-effective drilling of wells as mentioned earlier, but is also critical for assessing exploration risk factors, including the migration of formation fluids; analysing trap configuration and basin geometry and seal integrity. It also provides calibration for basin modelling (Feng and Ye 2018; Kiatrabile *et al*,2016). Pore pressure can be predicted prior to drilling using seismic data for reservoir discovery to increase confidence in a certain prospect and ensure safety drilling. Pore pressures can also be predicted while drilling using 1-D sonic and resistivity logs from off-set oil and gas wells and drilling event reports. However, these approaches do not provide high resolution and real time understandings that are required for exploration and production in geologically complex oil and gas provinces (Understanding *et a*l,2013,.Tingay,2013;) Modern drilling teams often need a subsurface pore pressure map obtained by integration of pore pressure and geomechanics data in order to drill safely and efficiently in a complex province.

Oil and gas are still the major economic drives of Nigeria economy and the world irrespective of the impact of the current fall in Oil price in the global petroleum market. Global energy consumption has recorded more than a six-fold increase in the past five decades and about 75% of this supply has been met through fossil fuels (Tanko,2019;Goodwyne,2012). Although the fossil fuel or hydrocarbon is a depleting resource and its extensive use engenders environmental degradation, it still remains a key component in the energy plan for achieving Nigeria socio-economic development. Hence, the search for more hydrocarbons by the Exploration and Production (E&P) industry in the globe becomes a geometric progression, moving into more complex frontier oil and gas provinces such as deep water and ultra-deep plays, where well cost is very high (Chatterjee et al ,2011; Zhang,2011;Guo,2010;BaltenSperger *et al*,2012; Libin *et al* 2018).

Therefore, a clandestine move to increase productivity,miniminise cost of production, maximize profits through increased production and ensuring safety operation during exploitation on which this study anchored its viability, cannot be overemphasized. This study mainly focuses on using sonic log data to identify Abnormal pore pressured zones in two oil and gas wells (Well A and Well B) in OML-58, onshore Niger delta field.

The Study Area

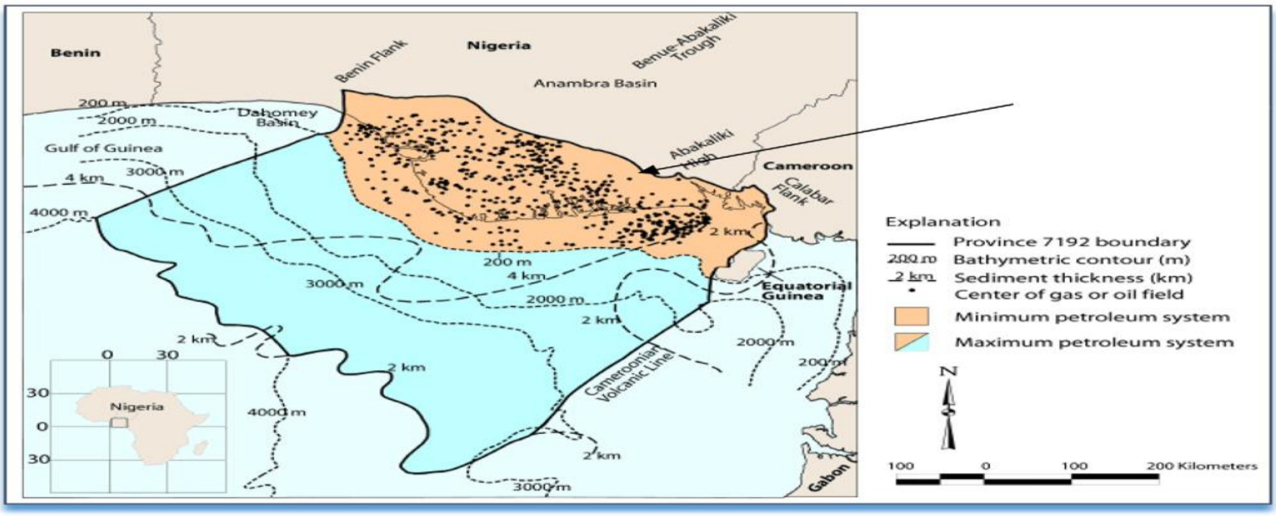


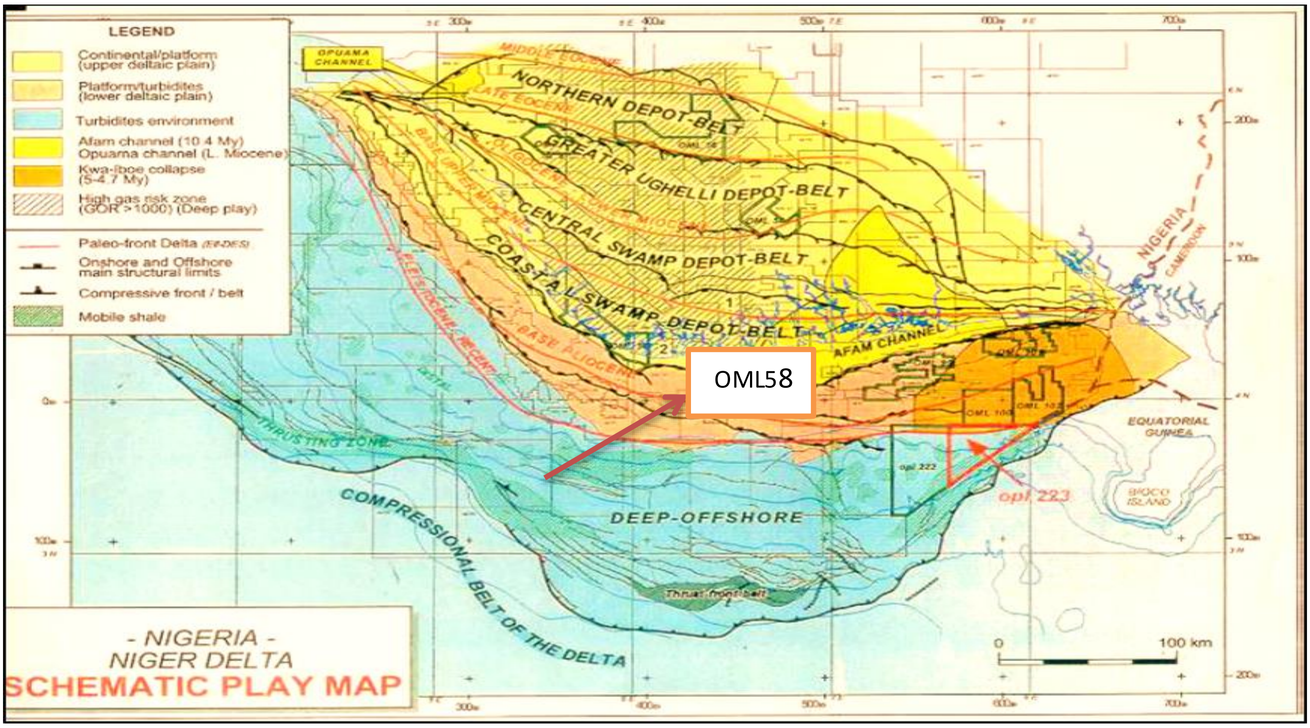
Figure 1: An Index Map of Nigeria and Cameroon showing Province Outline Maximum Petroleum System in Niger Delta (After Petroconsultant, 2001)

The Niger Delta occurs at the southern end of Nigeria, bordered by Atlantic Ocean and extends from about longitude 3^0-9^0E and latitude 4^030^1-5^020^1N . The Niger Delta Basin is one of the largest subaerial basins in Africa extends from the Calabar flank and the Abakaliki Trough in southeast Nigeria to the Benin flank in the west, protruding into the Gulf of Guinea as an extension from the Benue Trough and Anambra Basin provinces as shown in Figure 1. The Delta complex merges westwards across the Okitipupa High into the Benin Embayment. It covers a subaerial area of about 75,000 km^2, a total area of 300,000 km^2, and a sediment fill of 500,000 km^3 with depth ranging from 9–12 km. The Petroleum system of the Niger Delta Basin is known as the Tertiary Niger Delta Petroleum system.

Geology of the Niger Delta

The Niger Delta Basin is an extensional rift basin located in the Niger Delta and the Gulf of Guinea on the transform passive continental margin near the western coast of Nigeria proximal to Cameroon volcanic line, Equatorial Guinea and São Tomé and Príncipe. It was formed by a failed rift junction during the separation of the South American plate and the African plate, as the South Atlantic began to open from late Jurassic to the mid Cretaceous. The overall basin is divided into a few different zones due to its tectonic structure. There is an extensional zone, which lies on the continental shelf, caused by the thickened crust. Moving basin-ward is a transition zone, and a contraction zone, which lies in the deep sea part of the basin (Avbovbo,1978).

Five major depobelts are generally recognized, each with its own sedimentation, deformation, and petroleum history. Doust and Omatsola (1990) describe three depobelt provinces based on structure. The northern delta province, which overlies relatively shallow basement, has the oldest growth faults that are generally rotational, evenly spaced, and increases their steepness seaward. The central delta province has depobelts with well-defined structures such as successively deeper rollover crests that shift seaward for any given growth fault. The coastal Swamp depobelt housed the study location as shown in Figure 2: Last, the distal delta province is the most structurally complex due to internal gravity tectonics on the modern continental slope.



.Figure 2: Structural Map of Niger Delta Basin (After Petroconsultant, 2001)

The lithostratigraphy of the Niger Delta Basin as shown in Figure 3 consists of three main rocks stratigraphic units of Cretaceous to Holocene origin. These units represent the prograding depositional environments and are coined as Benin Formation, Agbada Formation and Akata Formation.

The Akata Formation is Palaeocene in age. It is mainly composed of thick marine shales locally intercalated with turbidite sands, and small amounts of silt and clay. The Akata Formation formed during lowstands in relative sea level and anoxic conditions. Its thickness approximately ranges 0-6000 metres. The upper boundary of the formation has been structurally deformed while diapirs and high pressure zones develop in large scale (Doust and Omotsola,1990; Baltensperger, 2012).

The Agbada Formation is represented by interbedded fluviomarine sands, sandstones and marine shales with a variable thickness range from 0-4500metres. The Formation dates back to Eocene in age in the North to Pliocene in the south. It is a marine facies defined by both freshwater and deep sea characteristics. This is the major oil and natural gas-bearing facies in the Niger Delta basin. The sandy parts of the Formation are known to constitute the main hydrocarbon reserviour and the shale constitutes the seals of the reserviour. The hydrocarbons in this layer formed when this layer of rock became subaerial and was covered in a marsh-type environment rich in organic content. It is estimated to be 3,700 meters thick.

In the Niger Delta, overpressures are found mainly in the centre of the delta at between depth of 6000ft (1828.8m) and 13000ft (3962.4m) to where the Agbada formation is at maximum thickness (Avbovbo,1978;Fan *et al*,2016).

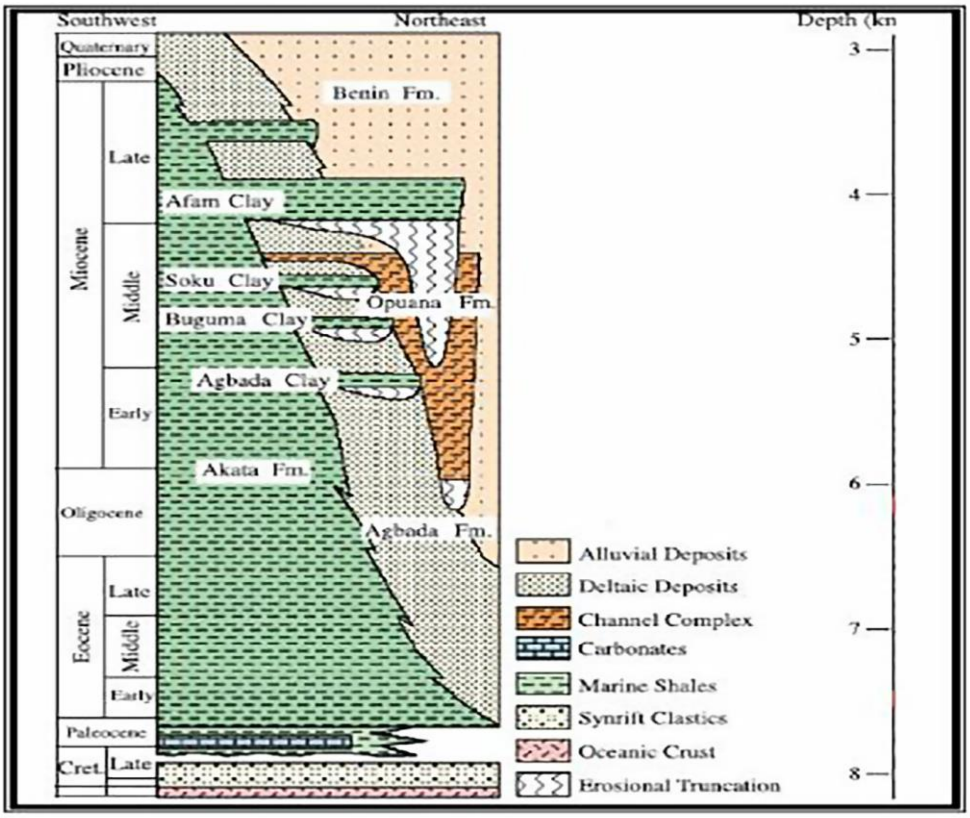


Figure 3: The Stratigraphy of Niger Delta(After Petroconsultant, 2001)

The Benin Formation is Oligocene and younger in age. It is composed of continental flood plain sands and alluvial deposits with thickness of 2,000 meters. From the Eocene to the present, the delta has prograded south-westward, forming depobelts that represent the most active portion of the delta at each stage of its development. These depobelts form one of the largest regressive deltas in the world with an area(Doust and Omatsola,1990).

Main Causes of Abnormal Pore Pressure in Niger Delta Basin

In a sedimentary basin abnormal high pore pressure can be caused by disequilibrium compaction, tectonic compression, hydrothermal pressurization, hydrocarbon generation, clay mineral transformation, fluid concentration and density difference, gypsum and anhydrite transforming, water surface irregularity, formation uplift and denudation(Zhu *et al*,2011;Li and Liu,2013;Abbey *et al*,2020). The ability of each of these mechanisms to generate abnormal high pressure depends on the rock and fluid properties of the sedimentary rocks and their rate of change under the normal range of basin conditions. However, in the Niger Delta basin, abnormal high pressure is mainly caused by compaction disequilibrium (Richard et al, 2011; Nweke and Dosunmu, 2013).

During crustal loading, the vertical or overburden stress increases and the pore fluids escape as the pore spaces became increasingly compacted. If a layer of low permeability, e.g. clay, prevents the escape of pore fluids at rates sufficient to keep up with the rate of increase in vertical stress, the pore fluid begins to carry a large part of the load and pore-fluid pressure increases (Luo,2016;Abbey *et al*,2021). This process is referred to as under compaction or compaction disequilibrium. This is the most well understood pore pressure mechanism used to explain and quantify abnormal high pore pressure in Tertiary basins where rapid deposition and subsidence occur, e.g. the Mississippi, Ornico and Niger Delta regions (Sargent et el, 2015; Li *et al*,2017).

Instrumentation and Method

The measurements were taken by seasoned geoscientist in Total Exploration and Production Nigeria Limited at OLo West (OML-58) while drilling into two oil and gas wells using sonde that contain sonic tool to transmit signal or wave that ranges 10Hz to 30 kHz, which were detected by receivers. Simultaneously several physical quantities were measured including the interval transit time or slowness in microseconds per foot of depth of investigation and recorded as composite logs. The transit time is the time taken for sonic wave to transverse one foot of formation (Tingay, 2013;Tanko et al., 2019, Guo et al,2010). The sonic logs were employed based on the assumptions that the transverse formations have uniformly distributed small pores and there is a simple relationship between slowness and porosity. The Niger Delta basin was assumed an extensional basin and that the main mechanism of abnormal high pressure generation is under compaction. The researcher exploited the deviation of formation properties from an expected or normal trend method to detect the abnormal high pore pressure zones.

The logs of Well A and well B are composite logs in three tracks collected from Total Exploration and Production Nigeria limited and are as shown in Figure 4. However, only the sonic logs in microseconds per foot were employed for the purpose of this study. Pore pressure abnormality might be due to increasing porosity with disequilibrium compaction or decreasing sonic compressional velocity due to higher fluid content.

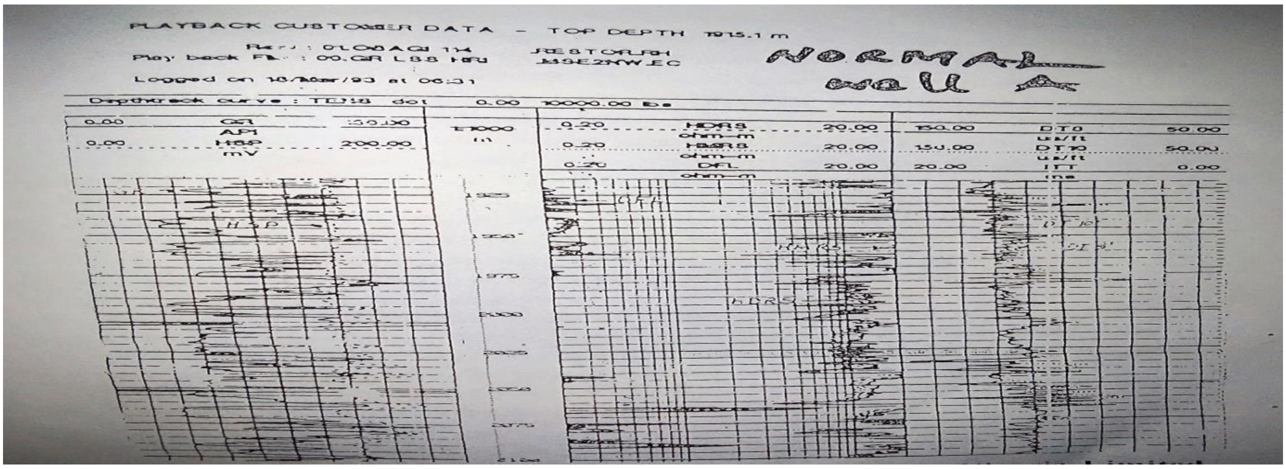


Figure 4: A section of the Composite Log(Well A) (Total E&P Nigeria Limited.2020)

The sonic interval transit times or slowness are represented by solid line on a scale ranging from 60µs/ft-100µs/ft for well A and 50µs/ft-150µs/ft for Well B both increases from right to left with a least vertical division of 10µs/ft. The sonic interval transit time values were picked by the researcher at regular interval of 5 metres per rate of penetration (m/RT) from the sonic logs of two study wells. The acoustic or sonic compressional velocities were computed in ft/ms by taking the inverse of the interval transit time (Δt) or slowness in microsecond per foot and multiplied by 10^3 The porosity was computed by employing Wyllie's equations given as:

$$\frac{1}{V} = \frac{\emptyset}{V_f} + \frac{1-\emptyset}{V_{ma}}$$ ……….equation1

which can be written in terms of interval transit time or slowness (Δt) as :

$$\Delta t_{log} = \emptyset \Delta t_f + (1-\emptyset)\Delta t_{ma}$$ ………..equation 2

This equation states that the slowness measured by the tool is the sum of the time spent in the solid matrix and the time in the fluid. This in turns give the sonic porosity $\emptyset_{sonic}$ as:

$$\emptyset_{sonic} = \frac{\Delta t_{log} - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \times 100\%$$ ……….equation3

Where V= Computed compressional sonic velocity computed from log

V_f = Interstitial fluid velocity

$\emptyset$ = Sonic log derived Porosity

Δt_{log} =Tool measured interval transit time or slowness

Δt_f= Transit time or slowness of the interstitial fluid

Δt_{ma}= Transit time or slowness in the matrix material

The oil and gas reserviour of the Niger Delta Petroleum system also known as the Tertiary Petroleum System are mainly composed of sandstones intercalated with small scale shale structures in the Agbada formation. The porosities were computed by assuming the matrix to be sandstone because it is more significant and the fluid to be fresh water base on the well locations. In view of these assumptions, the matrix interval transit time Δt_{ma}= 55.5µs/ft and Δt_f= 189µs/ft. The transit time (µs/ft), the sonic compressional velocity (ft/ms), Porosity (%) and Depth (m) are tabulated in Table 1 and Table 2 for Well A and Well B respectively.

For the detection of the abnormally pressured zones, the measured interval transit times in were plotted against depth to obtain the Depth-Slowness profile, the computed slowness also plotted against depth to have the Depth-Sonic compressional velocity profile, and furthermore the computed porosities were plotted against depth to obtain the Depth-porosity profile. The profiles are all on a semi-logarithm scale. For Well A, the profiles are presented as Figure5, Figure 6 and Figure 7 for slowness, sonic compressional velocity and porosity respectively. The deviation of these measured and computed quantities were observed from the normal or hydrostatic trend. For Well B, the same profiles are presented on a semi-logarithm scale as Figure 8, Figure 9 and Figure 10. The deviation of these measured and computed quantities were also observed from the normal or hydrostatic trend

Results

Table 1: Slowness (µs/ft), Sonic Compressional Velocity(ft/ms) and Porosity(%) for Well A

Depth(m)	**Slowness(µs/ft)**	**Sonic compressional velocity(ft/ms)**	**Porosity(%)**
1925	115.00	8.6957	44.6

1950	123.30	8.1103	50.8
1975	113.30	8.8261	43.3
2000	113.30	8.8261	43.3
2025	115.00	8.6957	44.6
2050	125.00	8.0000	52.1
2075	115.00	8.6957	44.6
2100	115.00	8.6957	44.6
2125	115.00	8.6957	44.6
2150	120.00	8.3333	48.3
2175	115.00	8.6957	44.6
2200	106.67	9.3747	38.3
2225	110.00	9.0909	40.8
2250	105.00	9.5238	37.1
2275	115.00	8.6957	44.6
2300	115.00	8.6957	44.6
2325	65.00	15.3846	7.1
2350	105.00	9.5238	37.1
2375	110.00	9.0909	40.8
2400	103.30	9.6805	35.8
2425	100.00	10.0000	33.3
2450	98.30	10.1729	32.1
2475	103.30	9.6805	35.8
2500	98.30	10.1729	32.1
2525	90.00	11.1111	25.8
2550	105.00	9.5238	37.1
2575	85.00	11.7647	22.1
2600	87.00	11.4943	23.6
2625	98.30	10.1729	32.1
2650	97.00	10.3093	31.1
2675	90.00	11.1111	25.8
2700	105.00	9.5238	37.1
2725	85.00	11.7647	22.1
2750	87.00	11.4943	23.6
2775	103.30	9.6805	35.8

Table 2: Slowness(µs/ft), Sonic Compressional Velocity(ft/ms) and Porosity(%) For Well B

Depth(m)	**Slowness(µs/ft)**	**Sonic Compressional Velocity(ft/ms)**	**Porosity(%)**
2700	127.00	7.8740	53.6
2725	77.00	12.9870	16.1
2750	130.00	7.6923	55.8
2800	150.00	6.6667	70.8
2825	83.00	12.0482	20.6
2850	90.00	11.1111	25.8

2875	85.00	11.7647	22.1
2900	100.00	10.0000	33.3
2925	110.00	9.0909	40.8
2950	95.00	10.5263	29.6
2975	93.30	10.7181	28.3
3000	93.30	10.7181	28.3
3025	88.30	11.3250	24.6
3050	95.00	10.5263	29.6
3075	93.30	10.7181	28.3
3100	93.30	10.7181	28.3
3125	113.33	8.8238	43.3
3150	95.00	10.5263	29.6
3175	108.30	9.2336	39.6
3200	90.00	11.1111	25.8
3225	85.00	11.7647	22.1
3250	98.30	10.1729	32.1
3275	85.00	11.7647	22.1
3300	97.00	10.3093	31.1

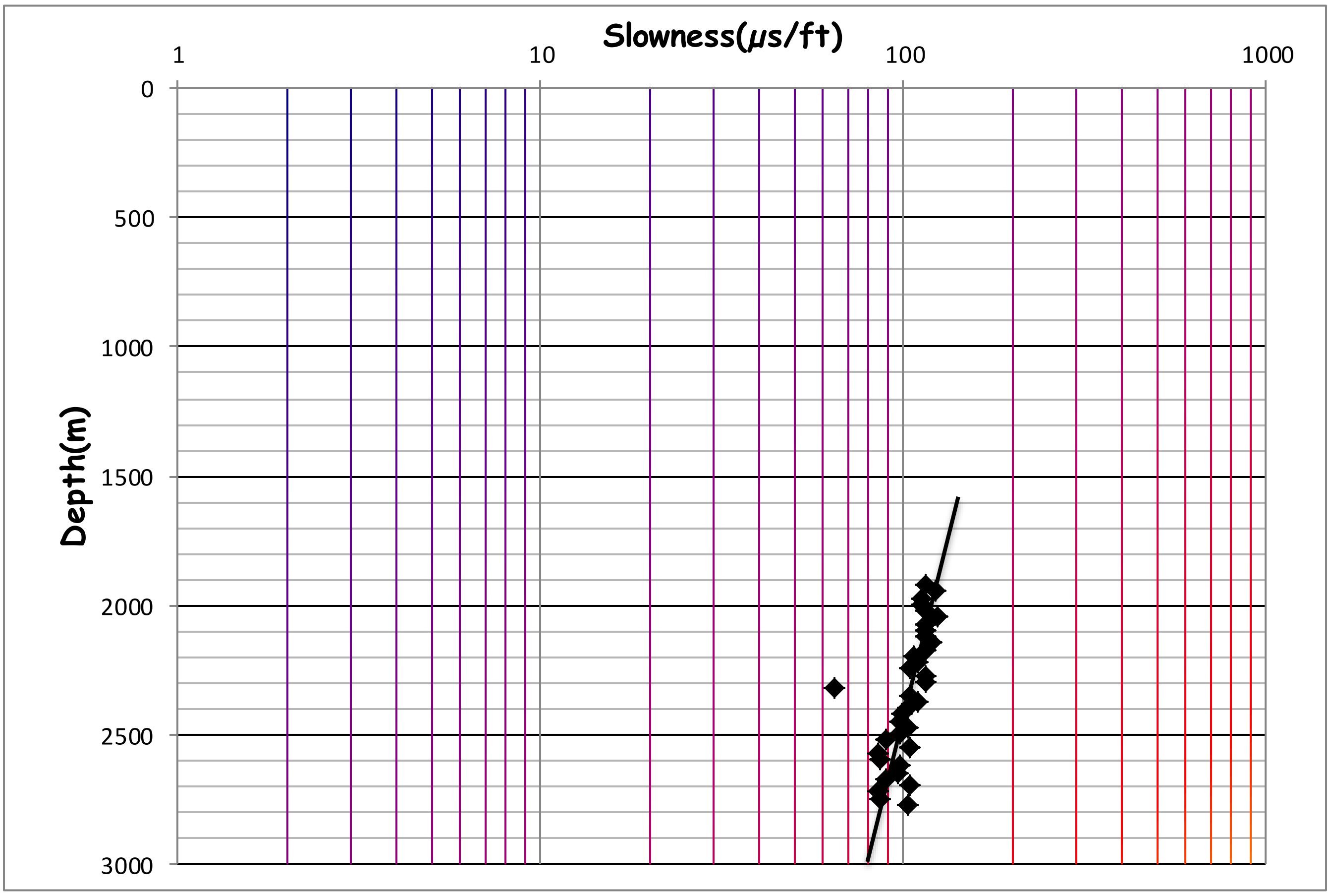


Figure 5 : Depth(m)-Slowness(µs/ft) Profile of Well A

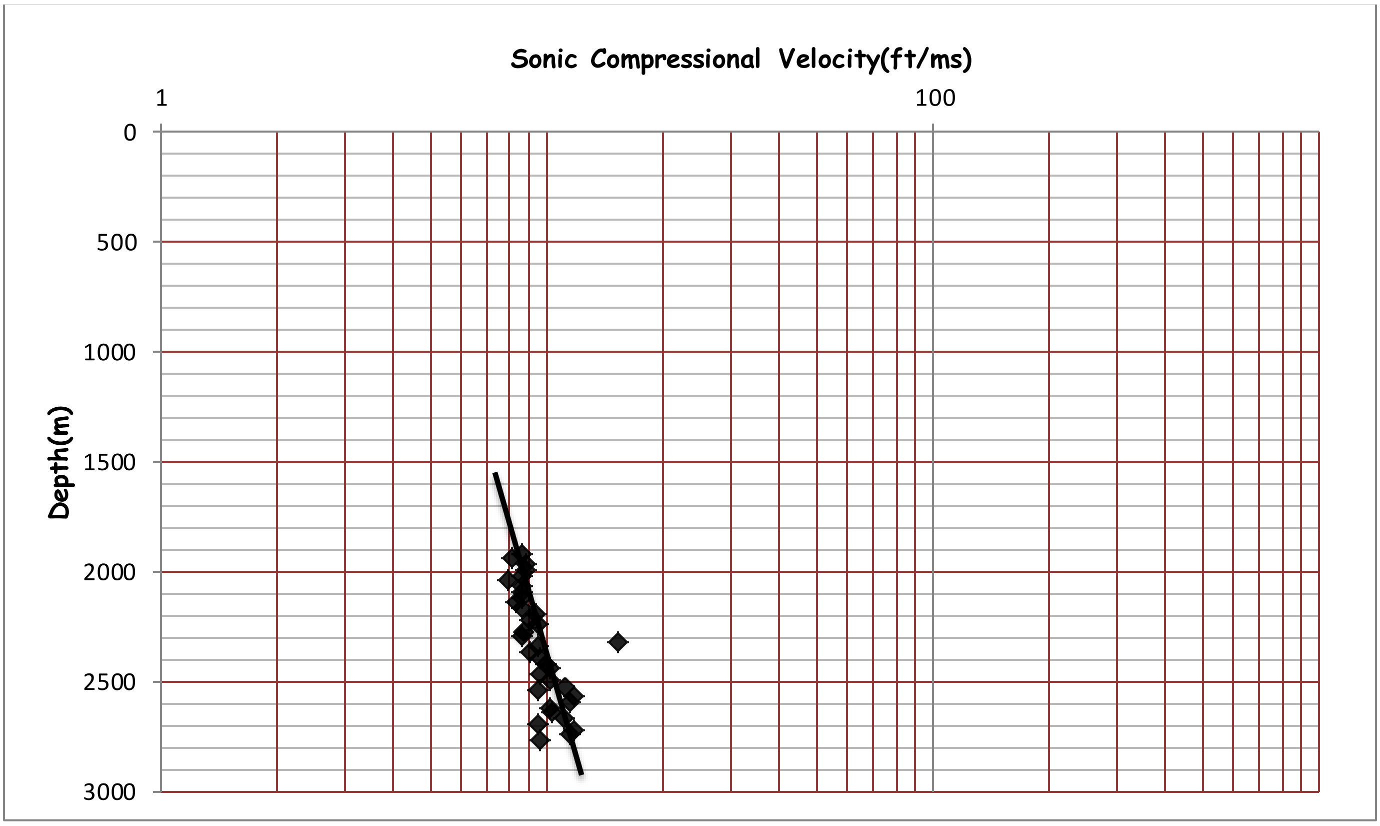


Figure 6 : Depth(m)-Sonic Compressional Velocity(ft/ms) Profile of Well A

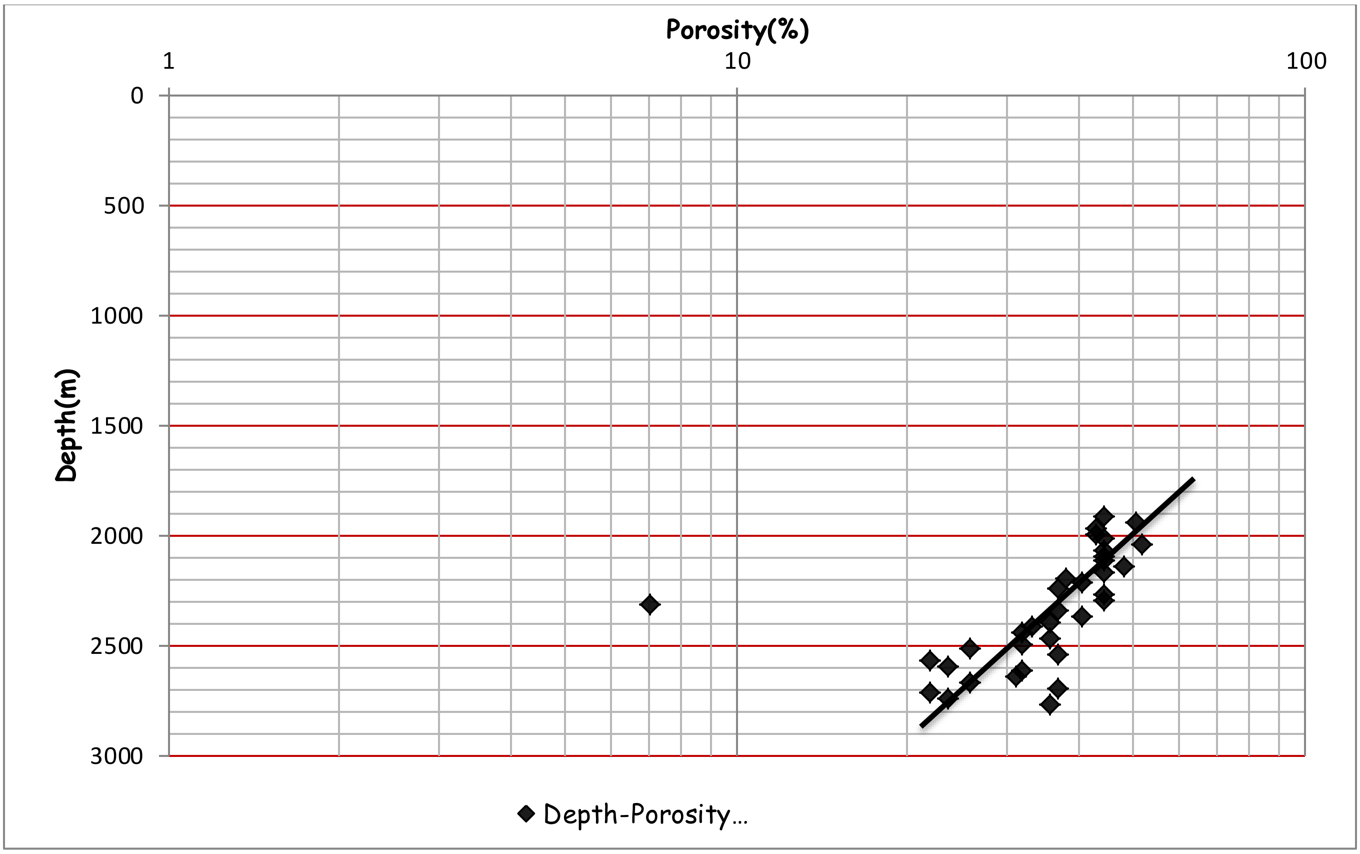


Figure 7: Depth(m)-Porosity(%) Profile of Well A

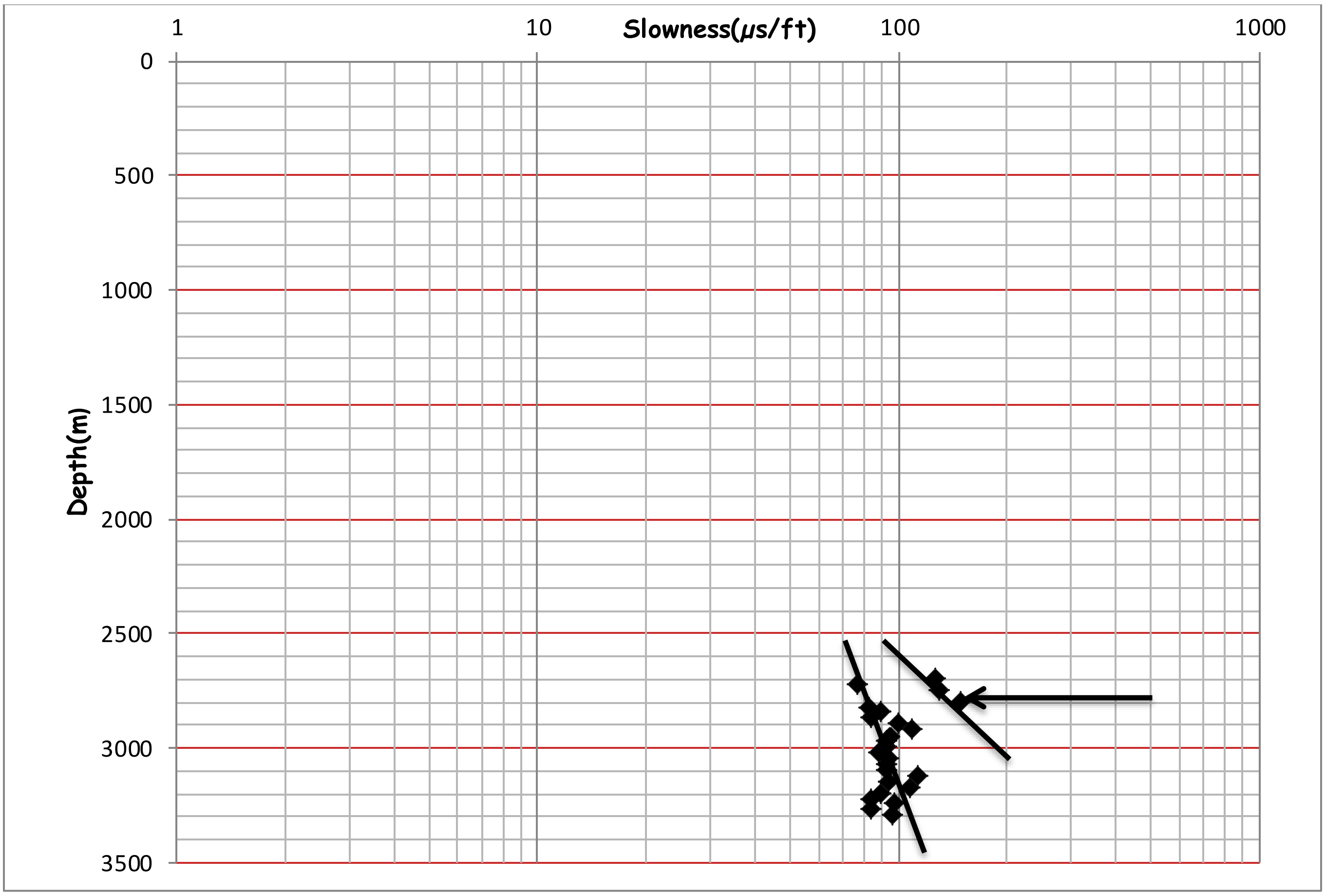


Figure 8: Depth(m)-Slowness(μs/ft) Profile of Well B

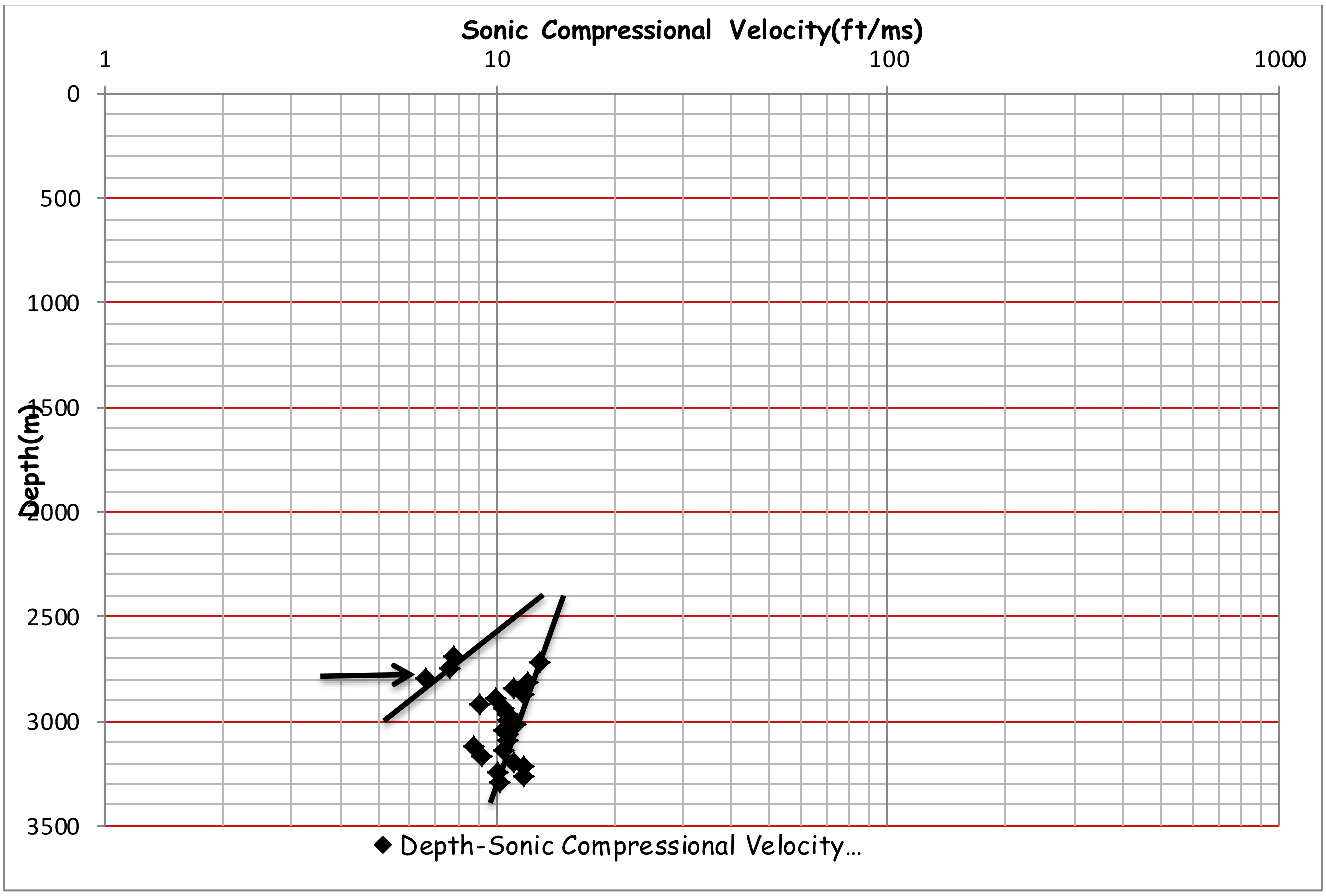


Figure 9 : Depth(m)-Sonic Compressional Velocity(μs/ft) Profile of Well B

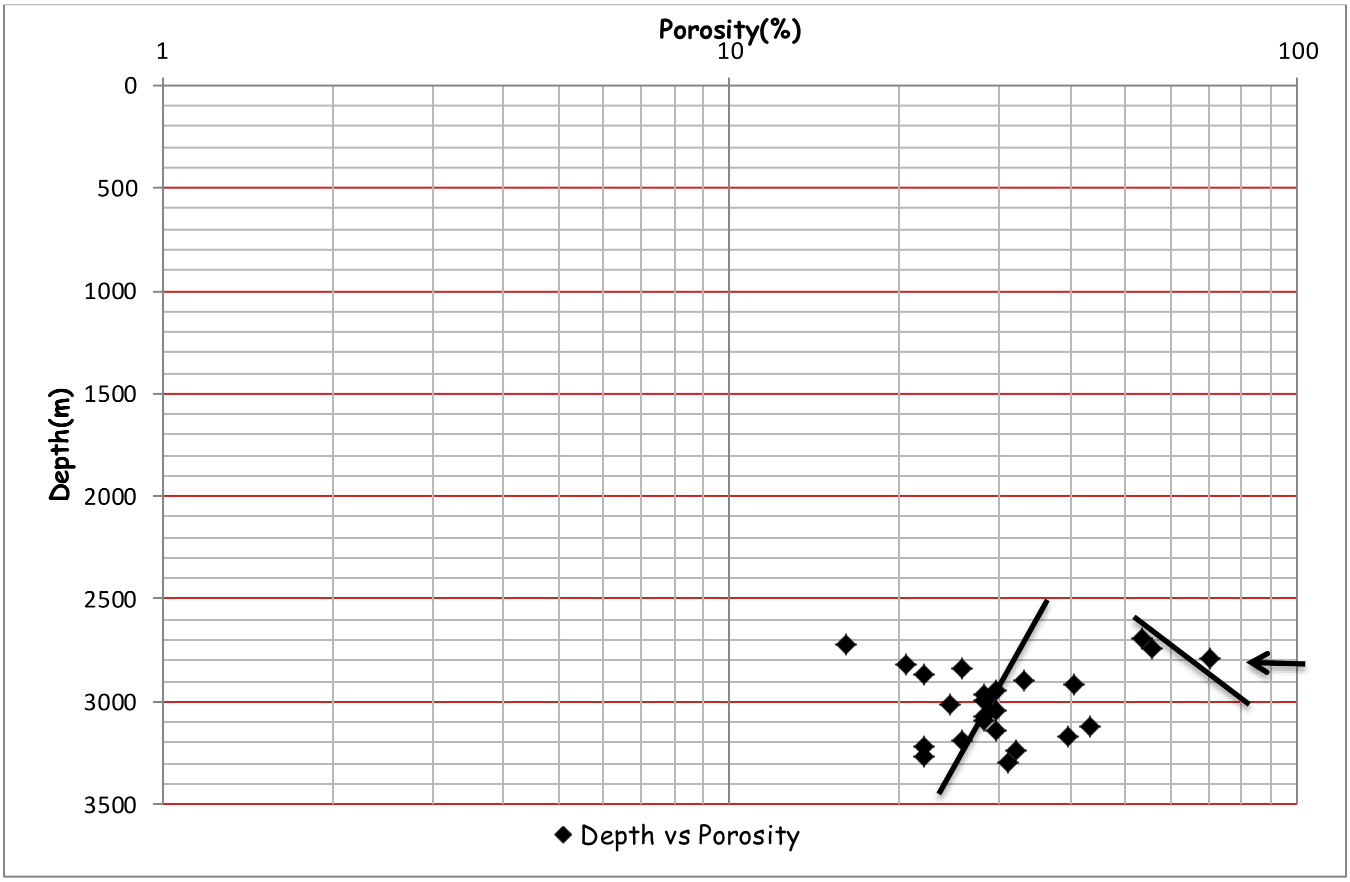


Figure 10 : Depth(m)-Porosity(%) Profile of Well B

Discussions

The researcher employed the geophysical well log method of pore pressure prediction in line with the assumption that disequilibrium compaction is the primary source of abnormally high pore pressure generation in the Niger Delta Basin. The slowness and porosity were expected to be decreasing with depth as the overburden stress increases. Conversely, the sonic compressional velocity in a normally pressured formation was expected to be increasing with depth following the normal compaction trend as the formation became increasingly consolidated. The compaction disequilibrium is often recognized by significant higher than expected porosities and slowness; and significant lower than expected sonic compressional velocity at a given depth.

The measured properties of sound waves are governed by the mechanical properties of several acoustic domains which include the formation matrix and architecture, the nature and quantity of trapped formation fluid column and the logging tool itself. Challenges from irregular hole or a tilted tool are avoided by using borehole compensation. In Figure 5, it was observed the slowness decreases with depth from 1925-2575m in line with the normal compaction trend in Well A. However, a point departure was observed at depth of 2325m with the lowest slowness (65µs/ft).The sonic wave might have travelled through a much consolidated rock at that depth. In addition, during the field measurements, such point departure might have been ignored and left uncompensated. Well A can still be classified as a normal Well because a point departure from the normal trend is quite insignificant to be coined otherwise. In Figure 8, that is in the Depth- Slowness profile for Well B, a significant deviation from the normal compaction trend occurred between the depths of 2700-2675m.This implied that Well B is over pressured at that subsurface zone.

In a normally compacted formation, sonic compressional velocity was expected to increases linearly with increasing burial depth following the normal compaction trend, as sound waves travel faster in a much consolidated formation. By considering Figure 6, it was observed that the acoustic or sonic compressional velocity increases with depth from 1925-2575m with a point departure at 2325m following the normal compaction trend. The point departure has a much higher velocity of 15.4ft/ms depicting a sonic wave travel in a more consolidation rock Statistically, this is just a point in a distribution and can be ignored; therefore the researcher inferred that Well A is a normally pressured well. In Figure 9, a significant deviation from the normal compaction trend was observed at depth ranging from 2700-2775m.This formation column can be regarded as an abnormally high pore pressured zone and the top of compaction disequilibrium occurred at 2700m in Well B.

As discussed earlier, porosity is an indicator (a function) of pore pressure, particularly for the abnormally high pore pressure generated from compaction disequilibrium. Figure 7 and Figure 10 illustrates how to identify compaction disequilibrium and abnormal high pore pressure from Depth- porosity profile in Well A and Well B respectively. Compaction disequilibrium occurs when the porosity is reversal generating abnormal high pore pressure. The starting point of the porosity reversal is the top of compaction disequilibrium or top of abnormal high pore pressure. In the formation with compaction disequilibrium, porosity is higher than those in the normally compacted one. In Figure 9, the porosity decreases with depth following the normal compaction trend from the initial depth of investigation that is 1925m through the final depth of investigation. This implies that Well A is a normally pressured well. However, in Figure 10, a significant deviation from the normal compaction trend was observed between the depths of 2700-2775m in the subsurface of well B. This implies that the top of abnormal high pore pressure occurred at 2700m Well B. is an over pressured well.

The observations from Figure 5, Figure 6 and Figure 7 are in line with each other following the normal compaction trends of slowness with depth, sonic compressional velocity with depth and porosity with depth. Therefore, there was no detected abnormally high pore pressure from Well A between the depths of investigation. Moreover, the observations from Figure 8, Figure 9 and Figure 10 of Well B are also in line with each other, all portraying significant departure from the normal compaction trend at depth between 2700-2775m.This implies the abnormal high pore pressured zone in Well B falls at the depth column of 2700-2775m.

Conclusion

In view of the findings of this research, it can be concluded that:

i. The geophysical well logging method is suitable for the determination of abnormal high pore pressure zones in the Niger Delta Basin where overpressure is mainly caused by disequilibrium compaction.
ii. With ease and simplicity, the sonic well log can be employed to accurately determine abnormal high pore pressure zones
iii. The porosity and slowness decreases with depth in Well A following the normal compaction trend.
iv. The sonic compressional velocity increases with depth in Well A following the normal compaction trend.
v. There is a significant deviation from the normal compaction trends of porosity, slowness

and sonic compressional velocity profile of Well B

vi. Well A has no abnormal high pore pressured zone.

vii. Well B has an abnormal high pore pressured zone at depth column of 2700m- 2775m.

viii. The determined abnormal high pressure zone falls within the range of predicted depth or zone in the Niger Delta.

Recommendations

Invariably, the complete loss of control while drilling into an abnormal high pore pressure formation is the greatest risk an Explorationist or Drilling Engineer would be exposed; therefore, such issues should always be handled with precautionary measures.

Other porosity logs such as density and resistivity should also be employed and the various results compared and integrated with the findings of this study for a quantitative determination of pore pressure.

The number of study wells in the study oil and gas field should increase for a Geostatically analysis and mapping of abnormal high pressure zones. Furthermore, other reserviour properties such as the fracture gradient should be determined using appropriate method and integrated with direct pressure measurement data such as the repeated formation pressure(RFT) for an accurate determination of pore pressure. The essentials of this study also improve well planning and enhance understanding of the influence of pressure on hydrocarbon potential in the area, proffering solution for drilling challenges and opening opportunities for future exploration in the Niger Delta.

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