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ESTIMATION OF MULTIPLE SOURCES OF OVERPRESSURES USING VERTICAL EFFECTIVE STRESS APPROACH: CASE STUDY OF THE NIGER DELTA, NIGERIA

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Abstract

The relationship between formation overpressures and porosity, and overpressures and stress regime can differ significantly depending on the geological setting and mechanisms responsible for generating overpressures. Therefore, the most important aspect in modeling over-pressures becomes a thorough study of the mechanisms and geological settings of a particular basin. A new velocity–effective stress model capable of estimating other sources of overpressures besides under compaction from velocity data was proposed and used in this paper with the objective of determining and accounting for overpressures from multiple sources. Data obtained from wells with a variety of geological settings within the basin were used to achieve a better understanding of the major causes of overpressures in the Niger Delta basin. This study has revealed the presence of velocity hysteresis (i.e., unloading effects) in several wells in the basin. Most overpressures in the basin occurred within the depth range of 6000 ftss to 13000 ftss with top of hard overpressures (>0.60psi/ft) having a regional mean of 12000 ftss. Similarly, results revealed a correlation of depth to high overpressures with zones of hydrocarbon maturation and smectite- to –illite transformation. The hard overpressures observed at depth in the Niger delta coincided with the time- temperature related fluid expansion mechanisms resulting principally from unloading. These findings therefore have shown that under compaction is not the sole overpressure generation mechanism in the basin as has been widely believed.

Keywords: Overpressures; Effective Stress; undercompaction; fluid expansion; Niger delta.

1. Introduction

The quantity of hydrocarbon accumulation is a function of generation, migration, entrapment, sealing and preservation. All of these factors are affected by the history of fluid movement in a thermo-chemical setting. Fluid movement within a basin therefore depends primarily on pressure variation [1]. Thus, one can improve both hydrocarbon exploration and later oil production with a better understanding of the fluid pressure environment. Overpressure influences many fluid related aspects of petroleum geology including diagenesis and reservoir quality. Similarly, the processes of migration and accumulation of oil and gas are strongly influenced by overpressured systems [2,3]. It often constitutes a hazard in drilling wells and directly impacts on drilling costs and the safety of petroleum exploration.

The relationship between formation overpressures and porosity, and overpressures and stress regime, can differ significantly depending on the geological setting and mechanisms responsible for generating overpressures. These factors should be included in any simulation approach. The most important aspect in modeling becomes a thorough study of the mechanisms and geological settings of a particular basin. Attention must therefore be paid to pore fluid and rock stresses in sedimentary sequences, because the knowledge of vertical and lateral stress patterns in a depositional basin is helpful in evaluating its history and development. A thorough quantitative understanding of compaction mechanics, the relationship between the total overburden stress, effective stress, and pore stress (pressure) in fine-grained clastics is required to recognize the potential development of abnormally high pressured formations. Most traditional pore pressure and basin models have assumed disequilibrium compaction to be the sole pressure generating mechanism. By not accounting for other pressure generating mechanisms they become physically incorrect and require trend-line shifts to match formation pressures [4,5] .These models should therefore be reviewed and upgraded to incorporate other dominant sources of overpressures in other to properly model subsurface pressures and their influences on source rock maturation and migration of hydrocarbons. A thorough quantitative understanding of compaction mechanics, the relationship between the total overburden stress, effective stress, and pore stress (pressure) in fine-grained clastics is required to recognize the potential development of abnormally high pressured formations.

The processes often responsible for the generation of abnormally high formation pressures can be grouped into three categories: (1) changes in the rock pore volume, (2) changes in the fluid volume within the pores, and (3) changes in the fluid head. All three of these broad categories require changes that occur faster than the formation is able to drain-off the excess pressure. The mechanisms proposed for increasing fluid pressure in sedimentary basins include:

(a) Rapid loading causing compaction disequilibrium that is common in fine grained rocks [6-9];
(b) Fluid expansion mechanisms resulting in unloading of the compaction curve [4,10-14];
(c) Effect of gas buoyancy in sealed units [8,15];
(d) Hydrocarbon generation [16-18] and oil-to-gas cracking [19-21];
(e) Smectite to illite transformation and clay dehydration [22-24];
(f) Aquathermal expansion and thermal expansion of fluids [3,25-29];
(g) Compression / lateral tectonic stress [15, 30]and
(h) Osmosis in shales [15, 31].

Generating overpressures from the latter three mechanisms are considered to be small in most cases [8]. The contribution of horizontal compression to overpressure generation is considered to be minor in passive continental margin basins [32].

Swarbrick and Osborne [32] proposed that the major mechanisms for large magnitude overpressure in most extensional sedimentary basins are compaction disequilibrium due to rapid loading in fine grained sequences, and fluid volume expansion during gas generation. Mann and Mackenzie [33] proposed that compaction disequilibrium was the dominant mechanism for observed fluid overpressure in the Gulf of Mexico and the North Sea based on an empirical relationship between overpressure gradient, permeability and deposition rate. Luo and Vasseur [34] presented an argument that the excess pressure is so great that it cannot be explained by compaction alone in some areas, such as the United States' Gulf Coast. It is believed that excess pressure would dissipate once burial slows to a rate at which fluid loss matches the addition of overburden stress [8,26]. Hunt et al.[35], stated that fine grained quartz and carbonates stop compacting at porosities around 3%, whereas shales containing minerals with large surface areas, such as smectite and illite, stop compacting at porosities around 10%. Luo and Vasseur [21] maintained that hydrocarbon generation is the most important mechanism within source rocks based on a comparison of the depth of the oil window and the top of the overpressured zone. Similarly, Surdam et al, [36] explained that gas generation and accumulation are the likely origin for the overpressure in reservoirs sealed by clay. It is generally believed that fluid expansion allows an increase in fluid volume without the creation of a perfect seal [4-5,10-11,29,37]. Moderate overpressures could develop by disequilibrium compaction due to loading and restricted fluid escape. It is however believed that extreme overpressures observed at depth in many basins worldwide coincide with the time - temperature related fluid expansion mechanisms [4,10].

Disequilibrium compaction mechanism has been commonly proposed by most authors to be the sole mechanism of the observed overpressures in the Niger Delta basin [38-39]. This study therefore has the objective of determining the dominant sources of overpressures in the onshore Niger Delta, and measuring their contributions to the regional overpressure regime in the Niger Delta. A velocity- effective stress model capable of estimating multiple sources of overpressures was therefore proposed and used in this study

2. Background Geology of the Niger Delta basin

The onshore portion of the Niger Delta Province is delineated by the geology of southern Nigeria and southwestern Cameroon. The northern boundary is the Benin flank- an east-northeast trending hinge line south of the West African basement massif. The northeastern boundary is defined by outcrops of the Cretaceous on the Abakaliki High and further east-south-east by the Calabar flank-a hinge line bordering the adjacent Precambrian (Fig. 1&2). The province covers 300 000 km^2 and includes the geologic extent of the Tertiary Niger Delta (Akata- Agbada) Petroleum System.

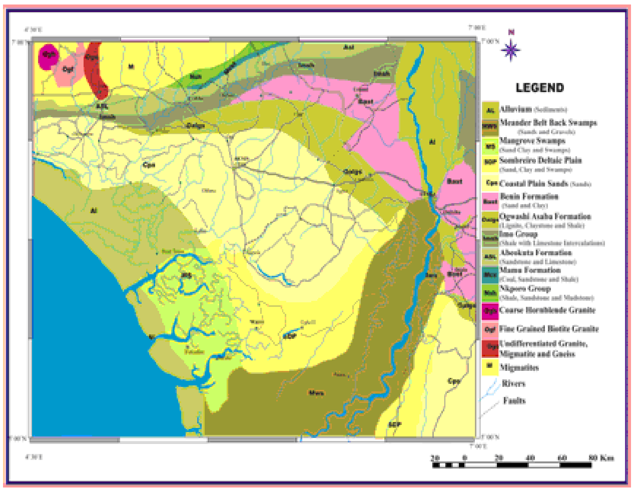

Fig. 1. Geology map of the Niger delta basin

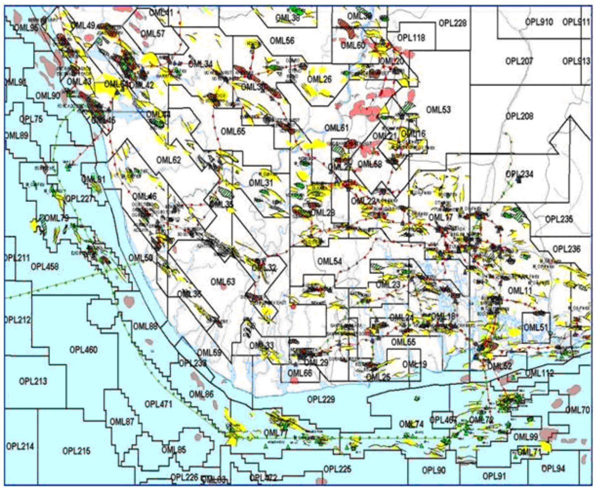

Fig. 2.Prospectivity map of the Niger delta basin showing the different Oil Mining Leases (OML)

Sedimentary deposits in the basin have been divided into three large-scale lithostratigraphic units: (1) the basal Paleocene to Recent pro-delta facies of the Akata Formation, (2) Eocene to Recent, paralic facies of the Agbada Formation, and (3) Oligocene-Recent, fluvial facies of the Benin Formation [39-41]. These formations become progressively younger farther into the basin, recording the long-term progradation of depositional environments of the Niger Delta onto the Atlantic Ocean passive margin. The stratigraphy of Niger Delta is complicated by the syn-depositional collapse of the clastic wedge as shale of the Akata Formation mobilized under the load of prograding deltaic Agbada and fluvial Benin Formation deposits. A series of large-scale, basinward-dipping listric normal faults formed as underlying shales diapired upward [42]. Blocks down dropped across these faults filled with growth strata, changed local depositional slopes, and complicated sediment transport paths into the basin.

The primary source rock is the upper Akata Formation, the marine-shale facies of the delta, with contribution from interbedded marine shale of the lowermost Agbada Formation. Oil is produced from sandstone facies within the Agbada Formation, however, turbidite sand in the upper Akata Formation is a potential target in deep water offshore and possibly beneath currently producing intervals onshore [43]. The Tertiary section of the Niger Delta is divided into three formations, representing prograding depositional facies that are distinguished mostly on the basis of sand-shale ratios.

Three major depositional cycles have been identified within Tertiary Niger Delta deposits [40,42]. The first two, involving mainly marine deposition, began with a middle Cretaceous marine incursion and ended in a major Paleocene marine transgression. The second of these two cycles, starting in late Paleocene to Eocene time, reflects the progradation of a "true" delta, with an arcuate, wave- and tide-dominated coastline. These sediments range in age from Eocene in the north to Quaternary in the south [42]. Deposits of the last depositional cycle have been divided into a series of six depobelts [42] also called depocentres or megasequences, separated by major syn-sedimentary fault zones. These depobelts formed when paths of sediment supply were restricted by patterns of structural deformation, focusing sediment accumulation into restricted areas on the delta. Such depobelts changed position over time as local accommodation was filled and the locus of deposition shifted basin-ward [42].

3. Fundamental Theory

Before relating the velocity to the effective stress and hence the pore pressure, we must understand the compaction process. This means relating the porosity to the effective stress for a given rock type under hydrostatic conditions. Mechanical compaction starts immediately after deposition and is driven by the effective vertical stress from the increasing overburden. The freshly deposited loosely packed sediments tend to evolve, like an open system, towards a closely packed grain framework during the initial stages of burial compaction and this is accomplished by the processes of grain slippage, rotation, bending and fracturing. Such re-orientation processes are collectively referred to as mechanical compaction, which generally takes place in the first 1-2km of burial. After this initial porosity loss, further porosity reduction is accomplished by the process of chemical compaction such as pressure solution at grain contact. Chemical compaction involves dissolution and precipitation of minerals and is mainly controlled by temperature over time. In sandstone, the onset of quartz cementation and transition from mechanical to chemical compaction starts at 70-80^{o}C [44]. In shales, the transition from mechanical to chemical compaction is often related to the gradual alteration from a smectite to a more illitic and/ or chloritic clay, which as a rule of thumb starts at 60-70^{o}C [44]. This does not mean that all chemical reactions occur at these temperatures.

Overpressure most commonly occurs when low permeability sediments inhibit pore fluid from escaping as rapidly as the pore space would like to compact. Excess pressure develops as the weight of newly deposited sediments squeezes the trapped fluid. Because the fluid has a low compressibility, it supports a majority of the additional overburden load and retards further compaction. As a result, the effective stress and sonic velocity changes more slowly during subsequent burial than they would under normal pressure conditions. This effect is shown on a plot of velocity versus vertical effective stress as a loading curve. This overpressuring process is referred to as undercompaction or compaction disequilibrium. However, overpressure can also be caused within the pore space by (charging) fluid expansion mechanisms such as heating, hydrocarbon maturation, and expulsion/ expansion of intergranular water during clay diagenesis. Here, overpressure results from the rock matrix constraining the pore fluid as the fluid tries to increase in volume. Unlike undercompaction, fluid expansion can cause the pore fluid pressure to increase at a faster rate than the overburden stress. When this occurs, the effective stress decreases as burial continues. The formation is therefore said to be unloading. Since sonic velocity is a function of the effective stress, the velocity also decreases and the velocity reversal zone develops. It is believed that a reversal in consolidation occurs when sediments are unloaded , either in response to a decrease in total stress or by fluid expansion overpressure generating mechanisms [4].Sediments are not elastic and do not recover back along the loading path but regain only part of their original volume along an unloading path. There is strong evidence that sediments recover some part of their volume when total stress is reduced. During unloading by stress relief, rocks rebound and recover only part of their original volume by elasto- plastic and crack propagation mechanisms

While velocity reversal zones are indicative of formations that have undergone unloading, not all velocity reversals are the result of unloading. However, the cause of a velocity reversal (and therefore the cause of overpressure) can be determined by several well established methods which include: (a) Crossplot of the velocity versus effective stress data within and outside the velocity reversal zone [5, 37] ;(b) Similarly, unloading can be detected by a cross plot of velocity versus density data [14] ;(c) Sonic velocities and resistivity generally undergo more elastic rebound than bulk density and porosity. Therefore, an indicator of in-situ rebound (unloading) is a depth interval in which sonic velocity and resistivity data appear anomalously low in comparison to bulk density and porosity measurements [12,37];(d) Determine the dominant cause of overpressure by using certain established geological conditions and parameters like geothermal gradient,etc. [24-25,29,45] ;(e) Similarly, the temperature at which overpressure begins is a key piece of information in identifying the cause of overpressure [24,29].

3.1 Porosity, Velocity and Effective Stress Relationships

The general mathematical model of compaction and diagenesis considers the fluid sediment system as a porous medium consisting of multiple mineral species. It is a well known fact that a compaction process causes reduction of porosity. Porosity therefore is the most direct measure of compaction. In general, the compaction of the rock framework occurs in response to the maximum vertical stress. In the Niger Delta and indeed worldwide, the generation of overpressure is often related to the sedimentation rate. Although numerous mechanisms have been proposed for the origin of overpressures, it is possible to derive a general expression for their generation rate based on the concepts of rock and fluid mass conservations which describes the most reasonable generation mechanisms. For a porous medium the conservation of mass of the fluid and solid phases with respect to fixed space coordinates may be expressed by a basic hydrodynamic equation given as follows [34,46] :

$$\left(\varphi\beta + \frac{\alpha\varphi}{1-\varphi}\right)\frac{dP}{dt} = \frac{1}{\rho}\nabla.\left\{\frac{\rho k}{\mu}\left(grad\ \vec{\rho}\right) - \rho\vec{g}\right\} + \frac{\alpha\varphi}{1-\varphi}.\frac{ds}{dt} + \alpha\varphi\frac{dT}{dt} + q \qquad (1)$$

where $\frac{dP}{dt}$ = rate of change of excess fluid pressure i.e. pressure above hydrostatics.

$\left(\frac{\alpha\varphi}{1-\varphi}\frac{dP}{dt}\right)$ and $\left(\frac{\alpha\varphi}{1-\varphi}.\frac{ds}{dt}\right)$ represent the effect of compaction.

$\left(\alpha\varphi\frac{dT}{dt}\right)$ = pressure generation / dissipation term as a result of temperature (T) changes i.e. aquathermal effect.

q = represents the discharge of fluid volume within the pores by reactions and processes like clay mineral dewatering, this in turn will generate excess pressure.

$\frac{1}{\rho}\nabla.\left\{\frac{\rho k}{\mu}\left(grad\ \vec{\rho}\right) - \rho\vec{g}\right\}$ = an excess pressure dissipation term, i.e. how fast lateral or vertical flow can drain the excess pressure (this term is essentially a form of Darcy's law).

Equation (1) above demonstrates that fluid movement is intimately linked to excess pressures which are generated primarily by increasing vertical load. This governing equation for excess pressure generation relates the vertical effective stress history to the rate of dissipation of excess fluid pressure and the spatial gradient in the excess pressure of fluid velocity field. The dissipation of overpressure depends on the hydrological properties of the sediments (that is porosity, permeability, etc).

In this paper, we have reviewed the causes of overpressures in the Niger Delta and subsequently suggested a systematic workflow to condition velocity data and build a robust pressure model. A new velocity- effective stress model is proposed for estimating multiple sources of overpressures. It is a pair of velocity - effective stress relationship for both the loading and unloading case respectively. This calibrated pressure model is unique because it takes into account burial depth, temperature gradient and shale diagenesis as well as compaction and its associated loading and unloading trends. The summary of the proposed model is given as follows [47]:

Loading case

$$V = \left(1-\varphi_0 e^{-\sigma/k}\right)^{-x} \qquad (2)$$

$$\sigma = k\ln\left[\left(\varphi_0 v^z\right)/\left(v^z - 1\right)\right] \qquad (3)$$

For the unloading case we have

$$V = \left(1-\varphi_0 e^{-\frac{\sigma v\max.eff}{k}} e^{-\frac{\sigma v\max.eff - \sigma v}{k^1}}\right)^{-x} \qquad (4)$$

$$\sigma = k^1\ln\left(\frac{v^z}{\varphi_0 v^z + 1}\right) - \sigma_{\max}\left(\frac{1}{k} + \frac{1}{k^1}\right) \qquad (5)$$

Where: k = compressibility coefficient for the rate of porosity loss with increasing vertical effective stress, k^1= incompressibility coefficient (decompressibility modulus) describing the caused by a reduction in vertical effective stress i.e. measure of the plasticity of the sediments.

v = velocity, x = acoustic formation factor exponent dependent on lithology. z = reciprocal of x ,σ = vertical effective stress (VES), σ_{max}= maximum vertical effective stress, which is vertical effective stress at the onset of unloading, Φ_o = initial porosity which is facies dependent.

4. Data presentation and analysis

Determining pore pressures from interval velocities (sonic and seismic) is based on the assumption that there is a consistent regional relationship between acoustic velocity and effective stress. Well log data in fifty (50) wells within the onshore Niger delta were used to assess the reliability of the link between shale acoustic velocities and pressure, and to establish appropriate density and overburden trends. Specifically, sonic logs, gamma ray and density logs were used for calibration while porosity, resistivity, spontaneous potential and caliper logs were used for quality control and lithologic correlation respectively. Pressure data in the form of repeat formation test (RFT), Leak of Test (LOT), and mud weight (Mwt) data were used in this study. Other datasets used include checkshot and temperature data.

Sonic log velocities corrected for cycle skipping were used to predict pressures in the offset wells and then compared with direct pressure measurements, using the Tau Compaction model. Standard model compaction trend settings were adjusted where necessary to get the most consistent match between predicted pressures for shale acoustic velocity and actual measured pressure from the well. This method is purely empirical but has proven a valid approach in the Baram delta, Gulf of Mexico and the Niger delta basin [48-49]. Similarly, pressure prediction using sonic velocities were repeated in the various wells using the Bowers model and the proposed model to determine the contribution of other sources of overpressures besides undercompaction.

5. Presentation of Result

Fig.3 is a typical loading (virgin) curve showing absence of unloading in Oo-2 well while fig.4 shows the checkshot data inverted to sonic velocity data in Ah-01 well showing velocity reversal at the depth of 11000ftss. Similarly, these wells showing velocity reversals were revealed as off-trend wells in the predicted versus measured pressure crossplot in fig.5. Predicted overpressure data (from the Tau Compaction model) were compared with measured well pressure data revealing pressure underprediction at deeper intervals (fig.6). This overpressure underprediction was noticed in some wells (revealed as off-trend wells in predicted versus measured pressure cross plots) especially in Ah-01, Kc-01 and Kc-039 wells. The cause of this velocity reversal and the subsequent pore pressure underprediction in these wells were further investigated in fig.7 using the sonic velocity versus vertical effective stress crossplot revealing unloading. Unloading was also observed in these off-trend wells in different fields in the Niger delta, which is an indication that fluid (thermal) expansion mechanism is the dominant cause of overpressures in these wells. It was also observed that most of these reversal zones with high pressures especially at Ah-01, Kc-01 and Kc-39 wells all occurred at deeper intervals of the wells. To accurately measure the pore pressure in these wells other effective stress models besides the compaction model were used to predict the pressures. The Bowers' and the proposed models were used and the accurately predicted the pressures at this interval (see fig.8).

Fig.9 is the overpressure map of the onshore Niger delta showing pore pressure gradient in psi/ft with overpressure gradient increasing towards offshore reaching values nearing lithostatic. Similarly, depth to top of overpressures varies between 4500ftss to over 17000ftss with the depth increasing towards the sea (fig.10).Pore pressure versus depth crossplot in the Niger delta revealed that the depth to overpressures greater than 0.61psi/ft ranges from 10000ftss to over 17000ftss. The depth and temperature at which high pressures occurred was investigated in many of the overpressured wells studied to establish the possible overpressure generation mechanism. In most of the wells especially Kc-01, Oi-02 and Kc-39(see table 1), it was discovered that the onset of hard overpressure in the wells occurred at a depth range of 11000 to 17000ftss and at a temperature range of 200 -220^{o}F (102.91^{0}C). These results are indications of the fact that the possible cause of the hard overpressures of >0.60psi/ft is thermal expansion mechanism and not undercompaction as previously believed. Similarly, there seem to be a consistent relationship in the Niger delta basin, of hydrocarbon generation and overpressure [47,50]. Hydrocarbon generation is one of the most important mechanisms within the shales of the basin based on the comparison of the depth of the oil kitchen and the top of the overpressured zone in the Niger delta. The depth to the oil kitchen varies between 10,000ft – 14000ft in the Niger delta [39] (Evamy et al, 1978), coinciding with the depth at which most of the overpressure (>0.60psi/ft) cases are recorded. Similarly, the temperature range (90 –150°C) at which most of the high overpressure cases are recorded in wells co incide with the temperature range of clay diagenesis, hydrocarbon generation and thermal expansion [39,51].The temperatures of 240°F (115°C) and 300°F (150°C) are considered to represent respectively the top of the oil and gas kitchens for Tertiary provinces in general and Niger delta in particular. Similarly, the depth to the oil kitchen in the Niger delta varies between 10000ft – 14000ft with the depth to the gas kitchen been slightly deeper [39].

Table1 Some deep exploration wells ("HPHT wells") drilled by SPDC in the Niger Delta.

S/ NO	Well	OML	Depoblet	Depth TVD (ft)	Pore pressure gradient (psi/ft)	Temperature of overpressured horizont (°F)	Remarks
1	El - 05	33	Coastal Swamp II	16277.5	0.8700	220	Overpressured
2	Gn - 05	28	Central Swamp I	15977.5	0.7180	200	Overpressured
3	Nd - 01	32	Coastal Swamp I	15287.7	0.8397	215	Overpressured
4	Ab -60	17	Central Swamp I	14616	0.8250	205	Overpressured
5	Oi - 02	16	Central Swamp I	11550	0.8220	201	Overpressured
6	Ko - 10	11	Central Swamp II	12500	0.8470	220	Overpressured
7	An - 01	21	Central Swamp I	12228	0.8010	210	Overpressured
8	Ka - 03	72	Offshore Depobelt	14090	0.8110	215	Overpressured
9	Kc-39	28	Central Swamp I	14587.926	0.7060	212.60	Overpressured
10	Sb-01	35	Coastal Swamp I	17082.639	0.8200	218	Overpressured

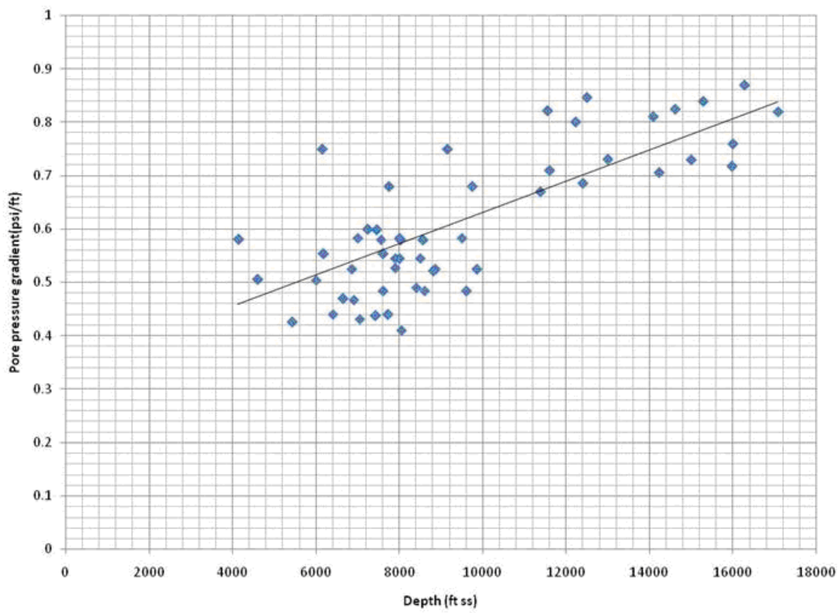

Fig. 11. Pore pressure – depth cross plot showing depth of overpressure occurrence in the study area

6. Discussion

Wallem,[51] stated that in the Niger delta, smectite clay minerals convert to illite at temperatures of about 90-100°C. Similarly, methane gas is generated biogenically within sediments during shallow burial at temperatures greater than 80°C [52].The temperature at which overpressures begins is a key piece of information in differentiating generation mechanisms. At about 95°C (203°F), smectite accelerates its transition to illite. If overpressure begins near 95°C, it is one signal that thermal processes dominate. If overpressure begins at a temperature significantly less than 95°C, other processes are more likely to be the cause of overpressure [24, 29]. The diagenesis of mixed layer illite/smectite clays during progressive burial is widely recognized as an important empirical diagenetic geothermometer [23, 53-56]. The diagenetic trend in the illite/smectite clay is known to be temperature dependent and believed to be related to regional hydrocarbon generation [57-58].Several authors [55-56] indicate that the main compositional and structural changes in the illite/smectite burial diagenetic sequence are an increase in illite layers, an increase in interlayer potassium and an increase in the amount of aluminum substituted for silicon in the tetrahedral layer; an release of Mg^{2+}, Fe^{2+}, Ca^{2+},Si^{4+},Na^{+} and water. The released water can make less or equal to thirty five percent (≤35%) of the volume of the smectite crystallite [59]. These mechanisms are thought to generate the extreme overpressures, which approach or even exceed the fracture gradient in most sedimentary basins like the Niger Delta basin.

Bolas et al,[60] revealed that hard overpressures generated by low porosity shales can never be accounted for by effective stress driven compaction alone. Ward [4] demonstrated that pore pressure gradients in excess of 0.87psi/ft is a function of sediment temperature instead of burial depth and that all investigated basins had attained such high fluid pressure gradients before the temperatures reached 150^{0}C.Caillet and Batiot [61] modeled the temperature (based on compaction alone) of the base of the Akata Formation in the Niger Delta to be in excess of 180^{0}C. This modeled pore pressure history of the Akata Formation suggests that the pore pressure started to deviate from hydrostatic at about 1km -3km burial depth showing that the onset of hard overpressures in the area is within this range. However, several deep wells (with depth ranges of 13000ft-18000ft) drilled in the Niger delta by AGIP oil revealed wells with pore pressure gradients up to 0.87psi/ft [62].The modeling results of Caillet and Batiot [61] thus demonstrate the inherent problems with modeling based solely on effective stress –driven compaction. Extreme overpressures cannot be modeled by this method unless a very shallow onset of overpressuring is invoked. It can therefore be concluded that high fluid pressures in general cannot result from effective stress driven compaction alone, especially not in low porosity shales [60-61,63-64].Extreme overpressures are a temperature related phenomenon through mechanisms such as hydrocarbon generation, clay – mineral diagenesis and aquathermal pressuring, all working together. Only moderate overpressures can develop by disequilibrium compaction due to loading and restricted fluid escape. The extreme overpressures observed at depth in the Niger delta coincide with the time temperature related fluid expansion mechanisms: hydrocarbon generation, clay – mineral diagenesis and aquathermal pressuring.

Ichara and Avbovbo [65] established that in the Niger delta, overpressuring cannot be accounted for by a single factor but the interplay of several factors operating in the basin. This is believed to be the interplay of hydrocarbon generation/ accumulation, charging, aquathermal effects, dehydration of anhydrates, shale diagenesis and tectonics.

7. Conclusion

A new velocity–effective stress model capable of estimating other sources of overpressures besides compaction disequilibrium from velocity sonic data was proposed and used in this work. It is therefore believed that fluid expansion mechanisms such as organic matter maturation and cracking, thermal expansion and mineral diagenesis all working together can all charge the fluid pressure within the pore space. These mechanisms are thought to be responsible for generating the extreme overpressures, which approach, or even exceed the fracture gradient at great depths in the Niger Delta. In summary, results have demonstrated that compaction disequilibrium is not the sole cause of overpressures in the Niger Delta basin as widely believed. Fluid expansion mechanisms also play a major role in overpressure generation in the Niger delta.

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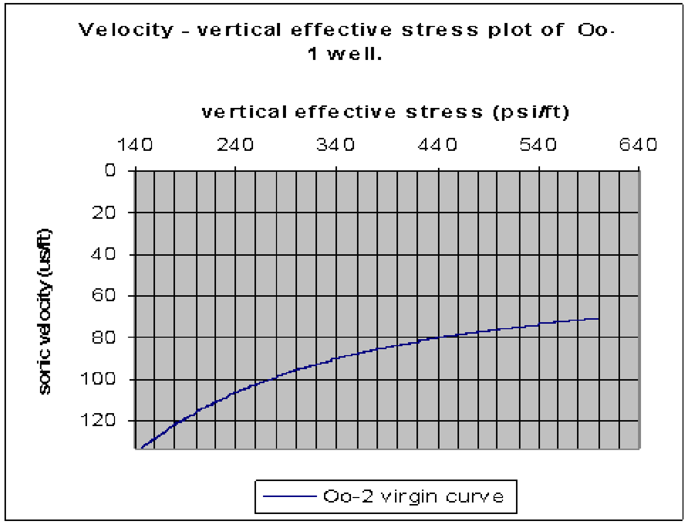

Figure 3. A typical loading (virgin) curve showing absence of unloading in Oo-02 well

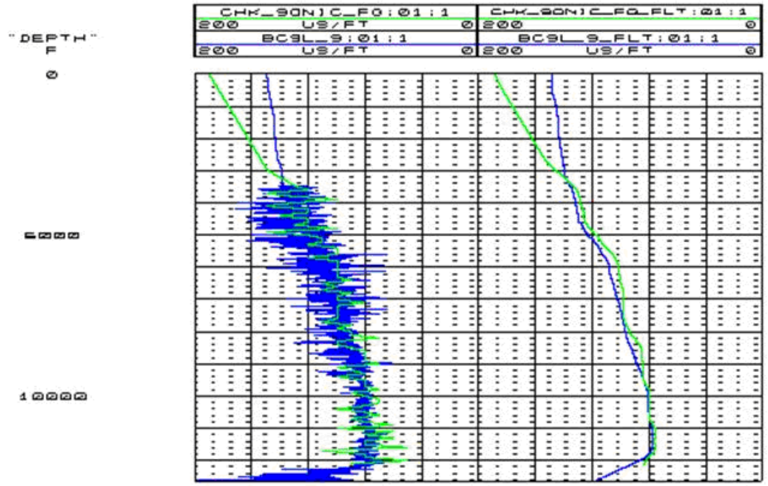

Figure 4. Checkshot data inverted to sonic data in Ah-01 well showing velocity reversal at deeper intervals

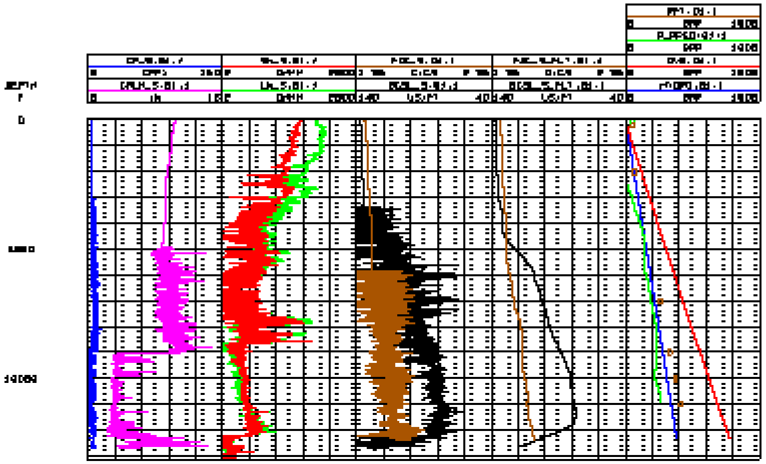

Fig. 5. Cross plot of predicted versus measured pressure for a set of wells in Onshore, Niger delta showing off trend wells

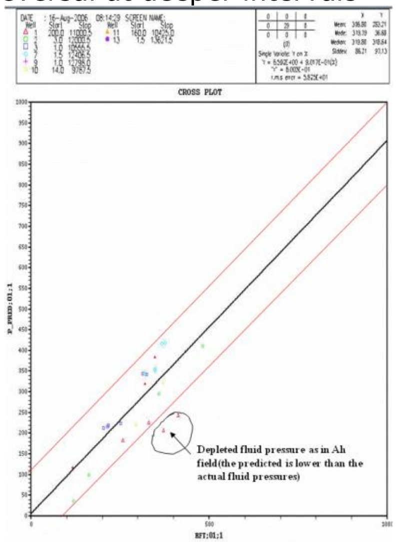

Fig. 6. Pore pressure prediction of Ah - 1 from sonic velocities showing under-prediction in the lower over pressured section of the well

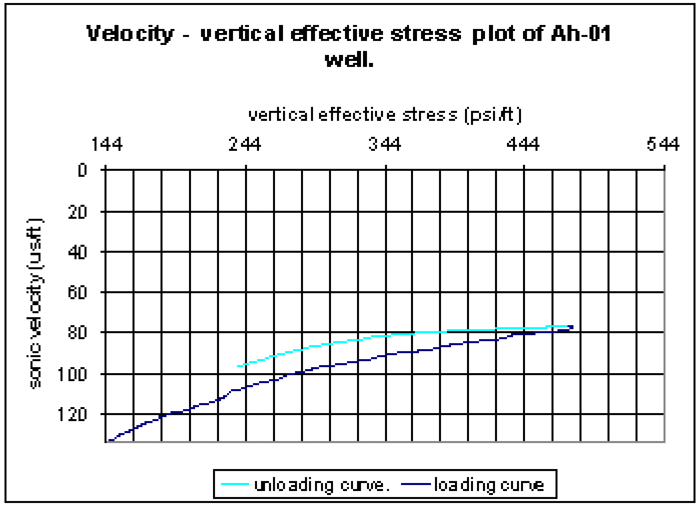

Fig. 7. Sonic velocity – effective stress cross plot showing velocity hysteresis (unloading) within the velocity reversal zone in Ah-01

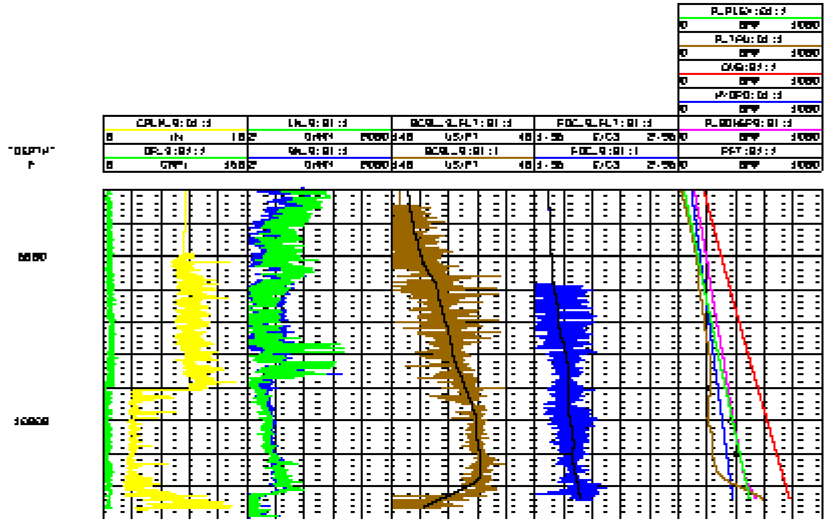

Fig. 8 Pressure Prediction in Ah -1 well using three different effective stress models (Tau, Bowers and 'New' Model

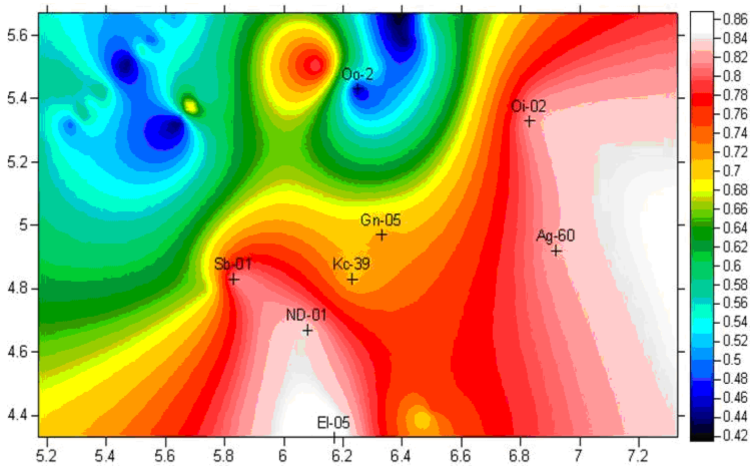

Fig. 9. Overpressure map of the Niger delta showing pore pressure gradient in psi/ft.

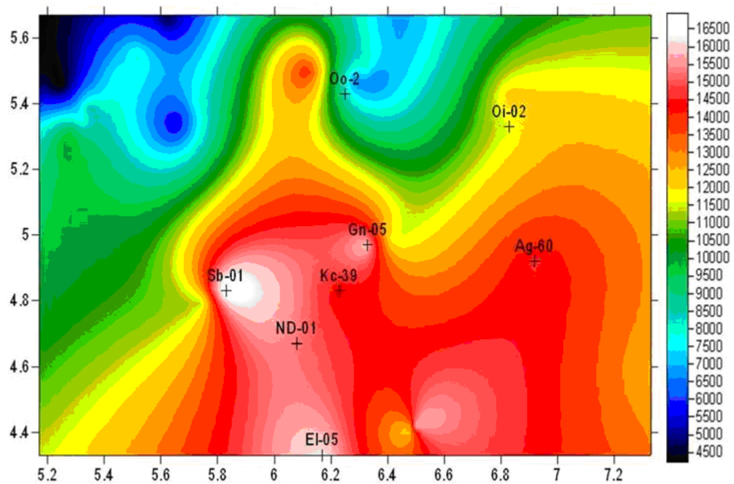

Fig. 10. Overpressure map of the study area showing depth to hard overpressures in the study area in feet subsea (ft ss)