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Density and Vertical Stress Variation across the Niger Delta Depobelts: Implications for Geopressure Prognosis

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Abstract

Accurate model of the vertical stress is important for precise prediction of pre-drill formation pore pressure, and hence fracture pressure, whether at the well location or on a regional scale. This has the overall effect of a safe, cost effective and successful drilling through the high pressure, high temperature targets which currently form part of the Niger Delta main exploration frontiers. In this study, we modeled density and vertical stress in the Niger Delta from twenty-five (25) wells, spanning the six (6) depobelts in the Niger Delta. The aim is to study variation in the vertical stress across the Niger Delta, with the underlying implication for proper well planning, exploratory and developmental drilling specific to the respective areas. The study shows variation in vertical stress gradient between 0.40 and 0.94 psi/ft in the northern Delta depobelt, and between 0.40 and 0.90 psi/ft in the deep offshore depobelt, indicating a slight overall decrease in the gradient from the onshore towards the Niger Delta deep offshore. The variation is attributable to changes in lithology which result in variations in bulk density with depth and spatially across the Niger Delta as a result of differences in the rate of sediment compaction. Average vertical stress gradient across the Niger Delta is 0.94 psi/ft ±0.02 psi/ft. Bulk density varies with depth from 1.87 to 2.48 g/cm^3, and 1.84 to 2.36 g/cm^3 in the northern Delta and deep offshore depobelts, respectively. Analytical model between bulk density and vertical stress has been derived for the respective depobelts to aid real-time pore and fracture pressure predictions, including formation strength estimates in the specific depobelts, especially where relevant data are not available or data quality is questionable.

Keywords: vertical stress, vertical stress model, vertical stress variation, bulk density model Niger Delta

1. Introduction

Some of the related works previously carried out in the Niger Delta have largely bothered on sediment compaction studies on sandstones and/or shales to relate their porosity to depth. For example, Olowokere and Ojo (2008) derived porosity-depth trends for sands and shales of the Agbada Formation, Weden Field, establishing that porosity decrease with depth in a parabolic and non-parabolic fashion for sandstones and shales, respectively. Olowokere and Ojo (2011) also derived compaction trends for sands and shales to predict lithology at various depths in the Eve Field, south-west of the Niger Delta offshore. Benjamin and Nwachukwu (2011) derived porosity-depth relationship to model the degree of compaction in hydrostatic sandstones in some wells in the southeastern part of the Niger Delta. Mode *et al* (2013) used sandstone porosity versus depth relationships in some wells to predict pore pressure in Cappe Field, offshore part of the Coastal Swamp. Tamunosiki *et al.* (2014) derived porosity-depth relation for some reservoirs in the Molog Field for possible application in petroleum evaluation and overpressure prediction. These rock mechanical compaction studies aim to aid geopressure and geomechanical predictions, as well as assist in quantitative interpretation. In the present work, we modeled density and vertical stress to study their variation across the Niger Delta depobelts. The variation has implicit effect on pore and fracture pressure prediction, geomechanical characterization and wellbore stability studies, and data obtained from this study could guide business decisions in exploration and development specific to the depobelts.

The vertical stress is the pressure exerted by the rock mass and fluids in the pore spaces of the rocks, plus the weight of the water column from the surface to the seabed in offshore areas. The importance of accurate estimate of the vertical stress cannot be over-emphasized. For a safe, cost effective and successful drilling, wellbore stability analysis and successful well placement, the predicted pore and fracture pressure, and rock mechanical properties must be accurate. Vertical stress plays a major role in this accuracy. Unfortunately, in most cases of geopressure and *in situ* rock mechanical characterization, the vertical stress is not calculated, rather a vertical stress gradient approximation of 1.0 psi/ft is often used for Tertiary deltas (Tingay *et. al*., 2003). We show in this study that there is variation in the vertical stress across the Niger Delta depobelts, and the 1 psi/ft approximation for the vertical stress is an over-estimation which, if applied anywhere in the Niger Delta would inherently introduce errors that could significantly impact business decisions.

The vertical stress at a given depth in the subsurface is the result of gravitational loading by sediments vertically above the depth. It is one of the three (3) principal stresses acting on the point at any given instance, and is the largest of the stresses in tectonically relaxed sedimentary basins. The vertical stress is estimated by integrating the bulk density log with depth. Ideally, to provide stability in the vertical stress estimation and to reduce uncertainties, the bulk density log needs to be integrated from the surface. Unfortunately, the log is hardly acquired at shallow depths, but at deeper depths through targeted reservoirs or plays. Tingay *et al*. (2003) described a procedure to estimate average density from the surface to the top of the density log.

Given bulk density ρ_b as a function of depth Z, the geostatic load S_V at Z is given by the integral:

$$S_V(z) = \rho_{atm} + \int_0^Z \rho_b(z) g\, dz \qquad (1)$$

where g is acceleration due to gravity and ρ_{atm} is atmospheric pressure acting on the surface. The water column has a considerable influence in modeling of the vertical stress in offshore areas. Hence, in offshore areas, the vertical stress model is given by:

$$S_V(z) = \rho_{atm} + g\int_0^{D_w} \rho_w\, dz + g\int_{D_w}^{Z} \rho_b(z)\, dz \qquad (2)$$

where D_w is the depth of the water column and ρ_w is the density of seawater.

Success in the vertical stress model is dependent on accuracy of the bulk density model and as such, accurately modeling the density and hence vertical stress is therefore desirable for reasons mentioned above.

2. Materials and Methods

2.1 Geology of the Study Area

The study area is the Niger Delta basin, Nigeria. Areal extent of the basin is about 75,000 km^2, with maximum sediment thickness of about 12 km. Burke (1972) and Evamy et al. (1978) adduce sub-division of the structural styles of the Niger Delta into six mega units, also called depobelts, each having a distinct stratigraphy, structural deformation, sedimentation, oil and gas generation, migration and distribution. These are namely the Northern Delta, Greater Ughelli, Central Swamp, Shallow and Deep Offshore depobelts, respectively.

Three lithostratigraphical units have been identified for the Niger Delta, which include the Benin, Agbada and Akata Formations. The Benin Formation lies topmost and is composed mainly of massive continental, fluviatile sands and gravels, reaching a maximum thickness of about 6,500 ft in its deepest part. The Agbada Formation is made up of interbedded, fluviatile coastal fluviomarine sands and shales (Aliu and Novelli, 1974). The sands in the Agbada Formation form the main reservoirs in the Niger Delta. The Akata Formation is the basal unit, and comprises thick marine shales with stringers of sands and silt. It is believed to be the main source rock in the basin. The distribution of the thickness of sediments in the Niger Delta is influenced by basement faulting (Weber and Daukoru, 1975; Evamy et al., 1978; Nwachukwu and Odjegba, 2001).

The present data delta has the largest thickness of sediments, mainly of the continental sands at its centre, trending in the NW-SE direction. This is believed to be caused by the downwarping at the continental-oceanic crust interface which result in more sediment infill (Ejedawe, 1990). This has strong influence on vertical stress and hence pore and fracture pressure prediction, and geomechanical characterization.

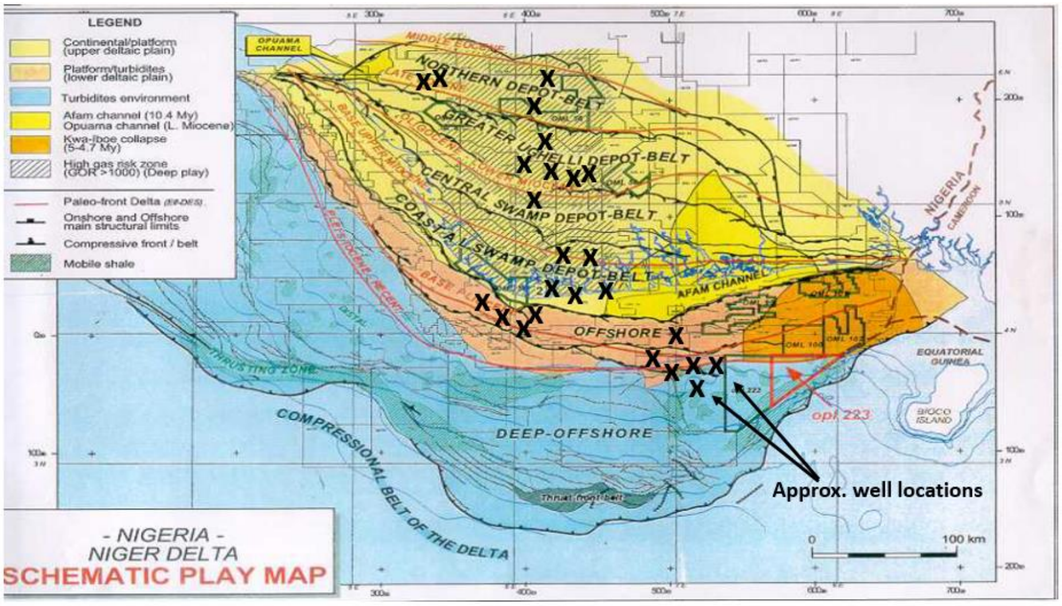


Figure 1: Niger Delta schematic play map showing depobelts and well locations

2.2 Materials

Bulk density logs from twenty-five (25) wells distributed across the six (6) depobelts in the Niger Delta constitute the main dataset used for this study. These include four (4) wells from the northern Delta depobelt, and five (5), one (1), five (5), five (5) and five (5) wells from the Greater Ughelli, Central Swamp, Coastal Swamp, Shallow Offshore and Deep Offshore depobelts, respectively. The acquired density log varied in thickness from well to well and across the depobelts. Apart from the bulk density data, other data include wellbore deviation data for measured to true vertical depth conversion and shale volume data. GR log was used to derive approximate shale volume for wells that did not have the shale log provided, and caliper log provided a measure of identification of borehole washouts.

The density log measures the bulk density of formation. The logging tool emits low energy, focused gamma rays which interact with electrons in the formation and in the process, lose energy mainly by Compton scattering. Density logging is based on measurement of the intensity of the gamma rays which are scattered back into the wellbore and detected by the logging device (sonde). Compton scattering depends on the electron density which, in turn, is dependent on the bulk density of the formation. The density tool requires firm contact with the borehole wall to give reliable measurements (Asquith and Gibson, 1982). The measurements are affected by hole rugosity as contact with the borehole wall is not firmly established in such sections, and as such, the log potentially measures the drilling mud density instead of the formation bulk density in the washout zones, reading abnormally low density in the process. To avoid errors in the density modeling, the bulk density logs were corrected for borehole washouts after the logs were carefully de-spiked.

2.3 Methods

The bulk density of a formation depends on the density of the rock matrix, ρ_m, density of pore fluids, ρ_f and porosity, φ, as well as other factors such as the vertical stress and pore pressure. It is given by:

$$\rho_b = \rho_m - (\rho_m - \rho_f)\varphi \qquad (3)$$

Substituting, the vertical stress model in the offshore areas, for example, becomes:

$$S_V(z) = \rho_{atm} + g\int_0^{D_w} \rho_w \, dz + g\int_{D_w}^{Z} \left[\rho_m - \left(\rho_m - \rho_f\right)\varphi\right] dz \qquad (4)$$

Geostatic load results in porosity loss with depth. The loss in porosity with depth has been described by the widely used Athy's relation (Athy. 1930) given in Eqn. (5), where C is a constant describing the porosity loss, also called compaction coefficient, and φ_0 is initial or surface porosity.

$$\varphi = \varphi_0 \, e^{-CZ} \qquad (5)$$

whereby taking the natural logarithm of both sides, $C = [(Ln\varphi_0 - Ln\varphi)/Z]$.

Using the Athy's model (Eqn. 5), the density model (Eq. 3) is obtained by fitting a density versus depth trend to the data and optimizing the model by varying the surface porosity and compaction coefficient while keeping the other parameters constant to obtain the vertical stress model. However, the use of the Athy's model in density and/or vertical stress modeling could introduce errors in the model(s) since the calibration constants, rather than being formation dependent, could become dependent on depth as lithologic changes become significant. This is particularly important when carrying out a regional density/vertical stress modeling as is the case in this study. For example, there is massive variation in the thickness of the various straitigraphic units across the Niger Delta; whereas intercalated sand/shales sequences are prevalent in the shallow and deep offshore depobelts; the onshore depobelts have significant thickness of continental sands.

In this work, we eliminate the depth dependence of the calibration parameters by using the more fundamental relationship between vertical effective stress, , and porosity, given by:

$$\varphi = \varphi_0 e^{-\frac{\sigma}{K}} \qquad (6)$$

where K is a formation, rather than depth dependent parameter.

The vertical effective stress is generally related to the vertical stress by:

$$\sigma = S_V - \alpha PP \qquad (7)$$

where PP is pore fluid pressure and α is the Biot's poro-elastic coefficient.

By assuming a constant ratio between the vertical stress and pore pressure, the explicit dependence on pore pressure can be eliminated. Following from this, we modeled the density trend for the onshore and offshore depobelts using Eqn. (8) and

(9), respectively, and using sea water density of 1 g/cm^3 (equivalent of 0.435 psi/ft), we used Eqn. (10) and (11) to model the vertical stress in psi.

$$\rho_b = \rho_m - (\rho_m - \rho_0)e^{-C.Z} \qquad (8)$$

$$\rho_b = \rho_m - (\rho_m - \rho_0)e^{-C.Zbml} \qquad (9)$$

$$S_V = P_{atm} + 1.422[\rho_m * Z_{BML} - (\rho_m - \rho_0)(1 - e^{-C*Z_{BML}})/C] \qquad (10)$$

$$S_V = (P_{atm} + 0.435 * 3.28 * D_w) + 1.422[\rho_m * Z_{BML} - (\rho_m - \rho_0)(1 - e^{-C*Z_{BML}})/C] \qquad (11)$$

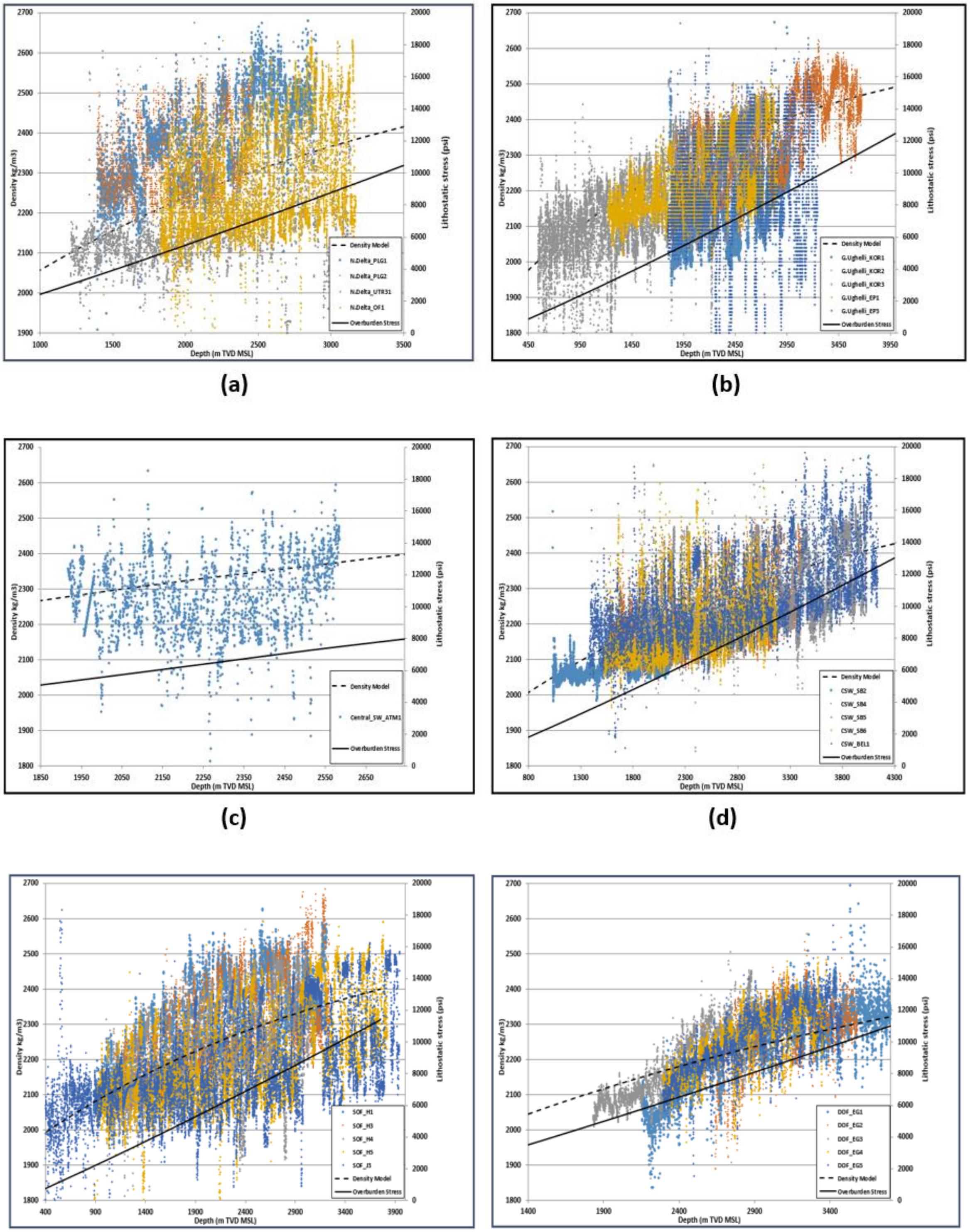
where $Z_{BML} = Z - D_w$ is sediment depth below the seabed, ρ_0 is bulk density at $Z = 0$ and $P_{atm} = 14.7$ psi/ft.

3. Results and Discussion

Albeit rock composition such as density of the mineral grains and pore fluids, including porosity, vertical stress and the pore fluid pressure can influence the bulk density of the sediments, the method adopted for this study which integrates the bulk density with depth from the surface, provides a form of stability in the vertical stress modeling by averaging out detailed variations in the bulk density.

Several geopressure prediction methods, such as the Eaton (Eaton, 1972) and Equivalent Depth, for example, require accurate model of the vertical stress as pore pressures would be over-estimated if the vertical stress model is higher than the actual value (Tingay *et. al.*, 2003).

Figure 2 shows the density and vertical stress trends modeled for wells in the respective depobelts in the Niger Delta. The large spread in the density values in each plot is due to frequently varying lithology, for example, from sands to shales; the spread and uncertainties disappear after integration while deriving the vertical stress as indicated by the modeled trends.



(a) **(b)** **(c)** **(d)** **(e)** **(f)**

Figure 2: Modeled density and vertical stress versus depth trends in the respective depobelts: (a) Northern Delta; (b) Greater Ughelli (c) Central Swamp (d) Coastal Swamp (e) Shallow Offshore and (f) Deep Offshore. The points indicate the density values; dotted lines are the density trend and straight lines show the overburden trends.

Variations in the density and vertical stress models across the depobelts are shown in Figure 3. Density varies across the Niger Delta from 1.87 to 2.48 g/cm^3, and 1.84 to 2.40 g/cm^3 in the Northern Delta and Deep Offshore depobelts, respectively, with average variation of 1.90 to 2.44 g/cm^3 with depth. In Figure 4, we show the vertical stress variation in gradient for ease of comparison across the depobelts. It is evident, also seen in Figure 3b, that the vertical stress varies with depth and spatially across the Niger Delta.

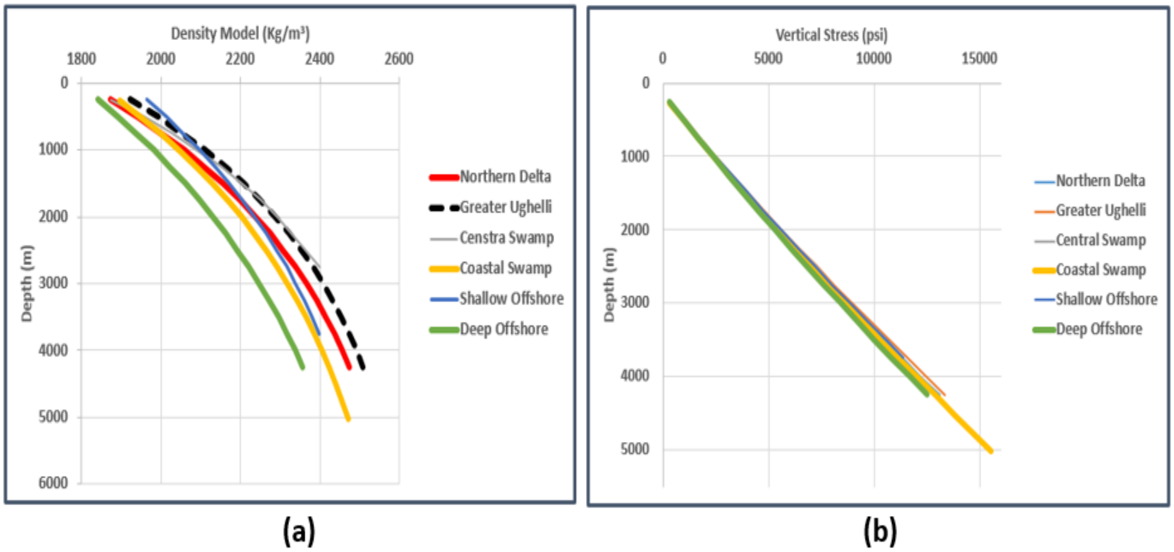


Figure 3: Density and vertical stress variations across the Niger Delta depobelts: (a) variation in density (b) variation in vertical stress.

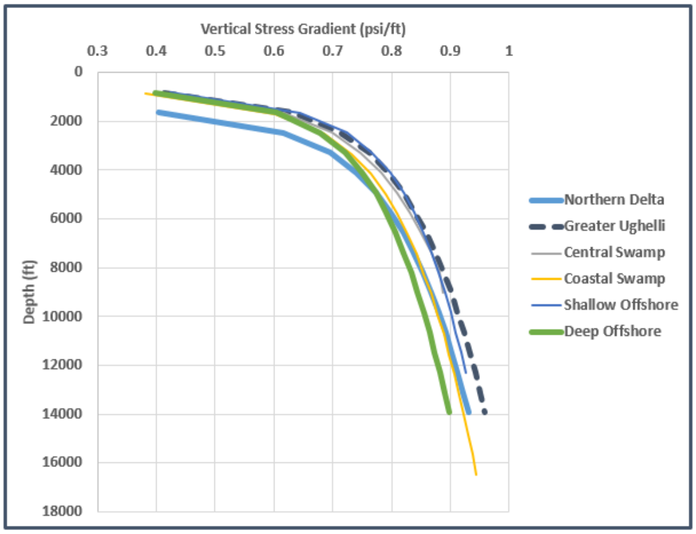


Figure 4: Vertical stress gradients across the Niger Delta depobelts.

Variation in vertical stress with depth slightly decrease spatially across the Niger Delta from the onshore towards offshore depobelts, being 0.40 to 0.94 psi/ft in the Northern Delta to 0.40 to 0.90 psi/ft in the Deep Offshore depobelt. The decrease may not be un-related to the significant change in lithology with the corresponding density change from the onshore to offshore depobelts. Apart Average variation in the vertical stress at 1 km, 2 km, 3 km and 4 km across the Niger Delta is 0.74, 0.84, 0.89 and 0.92 psi/ft, respectively. The result shows that maximum vertical stress gradient in the Niger Delta is about 0.96 psi/ft, modeled for the Greater Ughelli depobelt. Considering the much lower vertical stress gradients in the rest of the Niger Delta depobelts, it is safe to assume that the average maximum vertical stress in the Niger Delta is 0.94 psi/ft ±0.02 psi/ft. In view of this finding, assumption of 1 psi/ft for the vertical stress anywhere in the Tertiary Niger Delta is an over-estimation and would result in over-prediction of pore and fracture pressures, and errors in estimation of rock mechanical parameters. This could result in misguided well planning, and is capable of causing devastating effects during exploratory and developmental drilling such as influx of formation fluids into the wellbore, loss of the drilling mud, kicks, blow outs or even abandonment of the well before drilling to targets, as well as problems in well placements. Table 1 gives a summary of the variation in density and vertical stress, as well as sediment compaction coefficient across the individual depobelts.

Compaction coefficient determines the degree of compaction of sandstones. Low values are indicative of sandstone under-compaction (Benjamin and Nwachukwu, 2011). As shown in Figure 5, sediment compaction increases from the Northern Delta towards the Central Swamp, and decreases afterwards to the offshore depobelts. The values are higher on the average in the onshore areas probably due to the significant thickness of continental sands in these areas, where porosity reduction with depth is expected to be much faster. The result agrees with Weber and Daukoru (1988) that compaction in the Niger Delta varies from one depobelt to the other.

Table 1: Density and vertical stress variation with depth and modeled compaction coefficients across the Niger Delta

Depobelt	Density (gcm^{-3})	Vertical Stress (psi)	Vertical Stress Gradient(psi/ft))	Compaction Coefficient (ft^{-1})
Northern Delta	1.874 - 2.475	331 – 13,086	0.40 – 0.94	1.06312E-4
Greater Ughelli	1.923 – 2.508	340 – 13,360	0.41 – 0.96	1.18394E-4
Central Swamp	1.892 – 2.399	331 – 7,998	0.40 – 0.89	1.33745E-4
Coastal Swamp	1.896 – 2.471	335 – 15,530	0.38 – 0.94	9.08443E-5
Shallow Offshore	1.965 – 2.400	348 – 11,390	0.42 – 0.93	8.73006E-5
Deep Offshore	1.842 – 2.357	326 – 12,512	0.40 – 0.90	5.70273E-5

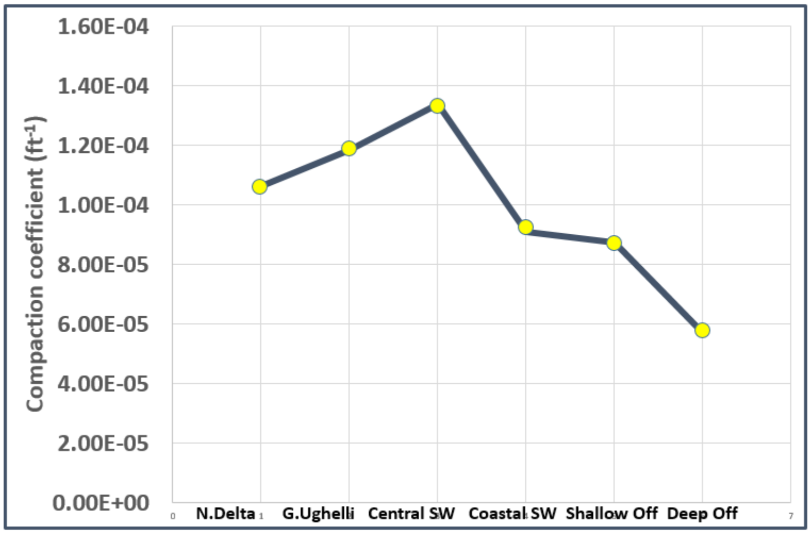


Figure 5: Variation in sediment compaction coefficient across the Niger Delta

Figure 6 shows cross-plot of modeled vertical stress versus bulk density for the Niger Delta. The figure shows two distinct vertical stress versus density trends in the Niger Delta, where vertical stress increases steeply over a small range in density and then a slow increase in vertical stress with density over a wide range in density. Interpreted in terms of sediment depth, the section with the steep increase in vertical stress is the shallow section thought to be within the Benin Formation which comprises mainly thick, unconsolidated continental sands with thin streaks of shale. Analytical models between vertical stress and density have been derived for the respective depobelts for real-time application at well locations (Figure 7): Results of comparison of the modeled vertical and vertical stress derived by regression for the Northern Delta and Greater Ughelli depobelts are shown in Table 2 and Table 3, respectively. The low percentage error margins from the regression give credence to the analytical equations for their use in the specific areas in the Niger Delta.

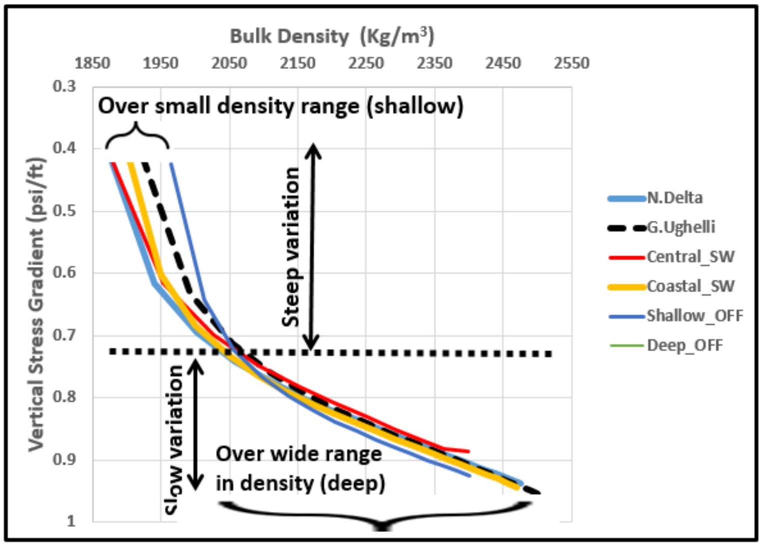


Figure 6: Cross-plot of vertical stress and density across the Niger Delta

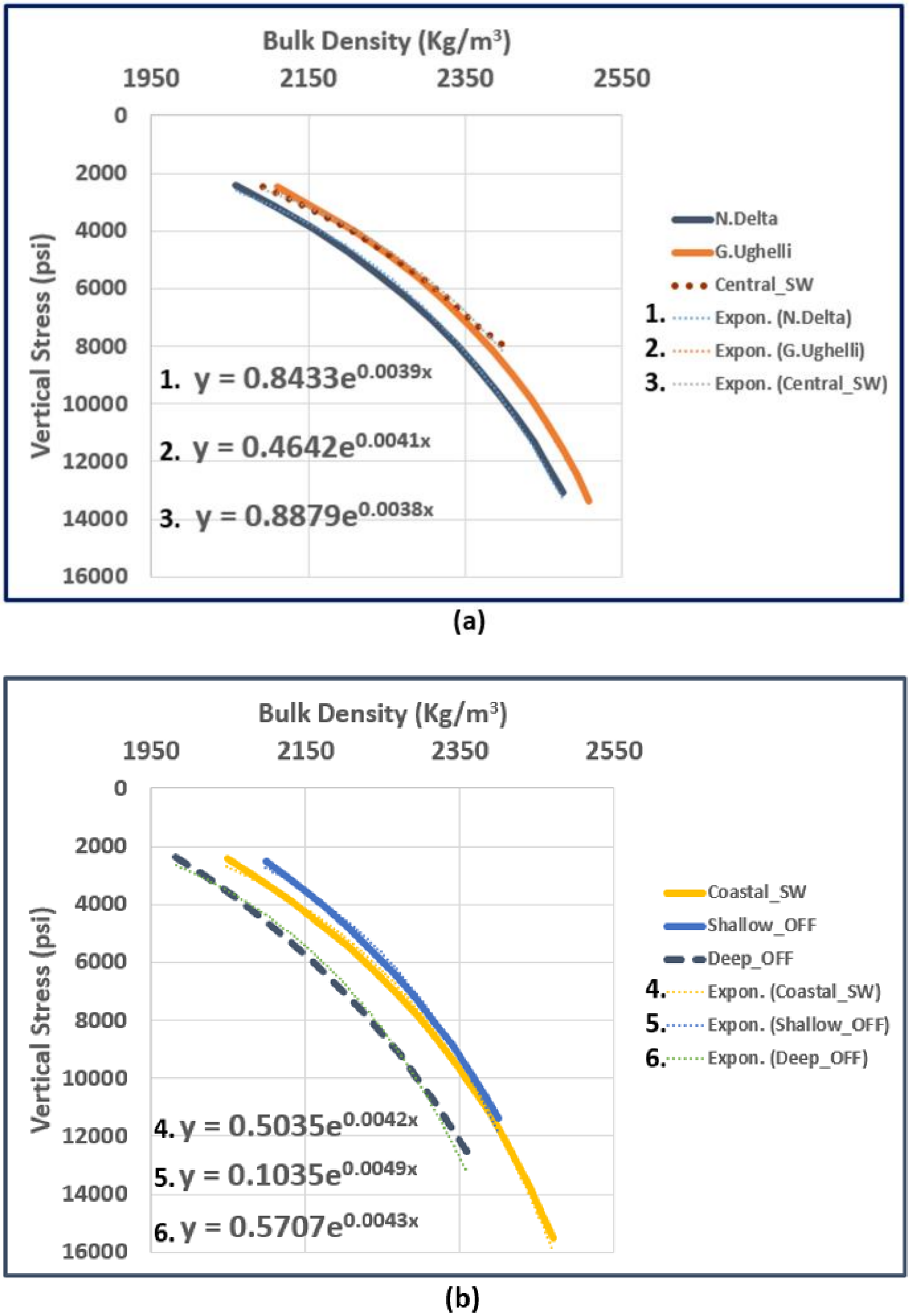
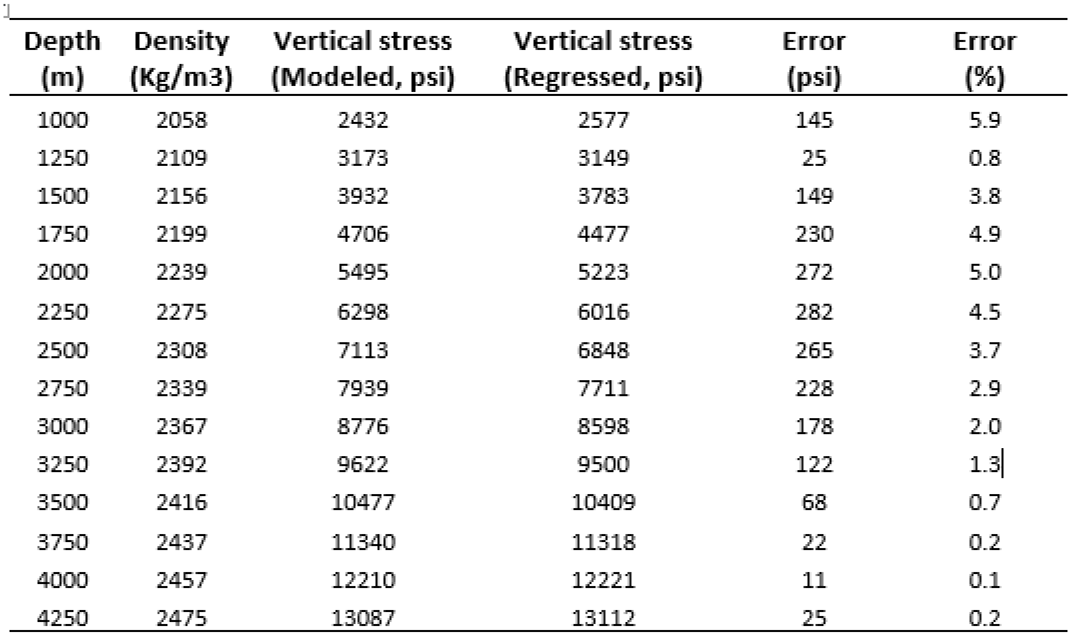


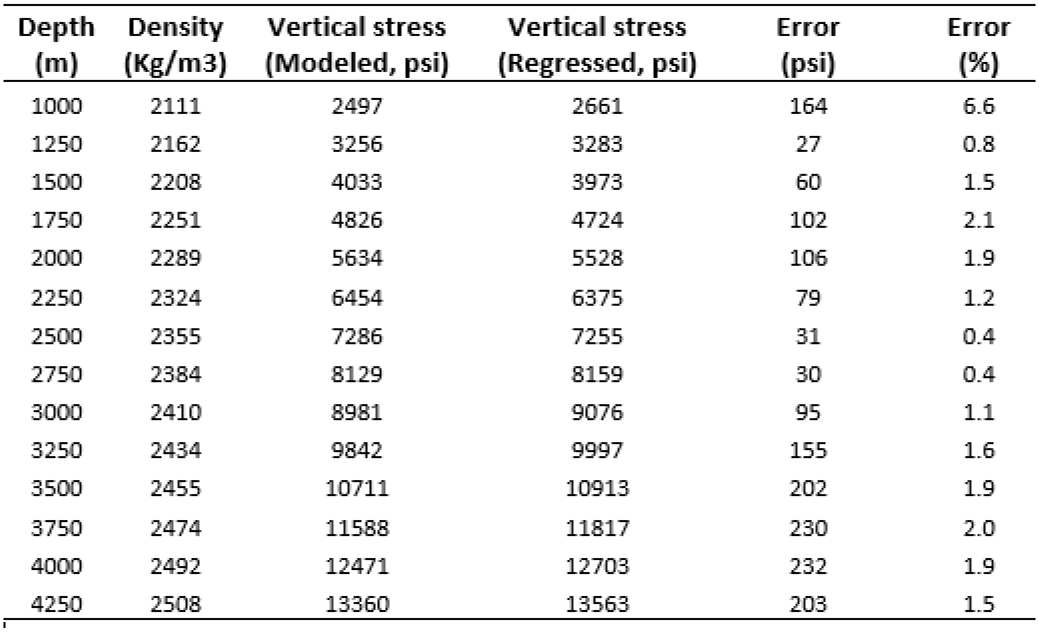
Figure 7: Analytic models between the formation bulk density and vertical stress across the Niger Delta Northern Delta, Greater Ughelli and Central Swamp depobelts Coastal Swamp, Shallow Offshore and Deep Offshore depobelts

Table 2: Comparison of modeled vertical stress with vertical stress obtained by regression with density for the Northern Delta depobelt



Depth (m)	Density (Kg/m3)	Vertical stress (Modeled, psi)	Vertical stress (Regressed, psi)	Error (psi)	Error (%)
1000	2058	2432	2577	145	5.9
1250	2109	3173	3149	25	0.8
1500	2156	3932	3783	149	3.8
1750	2199	4706	4477	230	4.9
2000	2239	5495	5223	272	5.0
2250	2275	6298	6016	282	4.5
2500	2308	7113	6848	265	3.7
2750	2339	7939	7711	228	2.9
3000	2367	8776	8598	178	2.0
3250	2392	9622	9500	122	1.3
3500	2416	10477	10409	68	0.7
3750	2437	11340	11318	22	0.2
4000	2457	12210	12221	11	0.1
4250	2475	13087	13112	25	0.2

Table 3: Comparison of modeled vertical stress with vertical stress obtained by regression with density for the Greater Ughelli Delta depobelt



Depth (m)	Density (Kg/m3)	Vertical stress (Modeled, psi)	Vertical stress (Regressed, psi)	Error (psi)	Error (%)
1000	2111	2497	2661	164	6.6
1250	2162	3256	3283	27	0.8
1500	2208	4033	3973	60	1.5
1750	2251	4826	4724	102	2.1
2000	2289	5634	5528	106	1.9
2250	2324	6454	6375	79	1.2
2500	2355	7286	7255	31	0.4
2750	2384	8129	8159	30	0.4
3000	2410	8981	9076	95	1.1
3250	2434	9842	9997	155	1.6
3500	2455	10711	10913	202	1.9
3750	2474	11588	11817	230	2.0
4000	2492	12471	12703	232	1.9
4250	2508	13360	13563	203	1.5

Conclusion

Geophysical well logs from different depobelts in the Niger Delta have been evaluated to determine variations in density and vertical stress in the Niger Delta. The results show that density and vertical stress vary with depth locally and spatially across the Niger Delta. The variation is mainly the result of lithologic changes with depth and across the Niger Delta. Assumption of 1 psi/ft for the vertical stress for the Tertiary Niger Delta is an over estimation since the results show the maximum vertical stress across the Niger Delta depobelts is on the average, 0.94 ± 0.02 psi/ft. Pore and fracture pressure, and rock mechanical properties suitable for determination of well stability for drilling and completion may all be over-estimated if 1 psi/ft is utilized for their derivation anywhere in the Niger Delta. Analytical models for the determination of the vertical stress from bulk density derived in this study is reliable and can be applied in areas with lack of suitable data or where data quality is in doubt. The error margins resulting from the analytical models are low and fall within safe drilling margins.

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