MODEL COMPACTION EQUATION FOR HYDROSTATIC SANDSTONES OF THE NIGER DELTA.

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ABSTRACT

Compaction is one of the diagenetic processes that have an enormous impact on the reservoir quality of sandstones. It is generally expressed in terms of porosity loss and results mainly from effective pressure. Derivation of an equation that relates porosity and depth in these rocks is useful in estimating their degree of compaction. Well log data of five wells from the South-Eastern part of the Niger Delta, covering a stratigraphic interval of 1704.9-3135.6 m, were analyzed. Petrophysical, Decompaction and Linear Regression techniques were used to investigate overpressure, degree of compaction and to derive a model compaction equation for hydrostatic sandstones. Compaction coefficients obtained range from 0.0003 - 0.0005 m^{-1} (averaging 0.0004 m^{-1}) and percentage compaction ranges from 30 - 48% (averaging 37%). These indicate that the sandstones are undercompacted. A model compaction equation: $_{Av}$ 45.0 - 0.0092Z (where porosity ($_{Av}$) is in percent and depth (Z) is in meters) was obtained. This gives porosity values which are comparable with those from the accepted Gluyas equation and as such are reliable. This equation is easier to use and is therefore recommended for use in predicting porosity and assessing the compaction status of hydrostatic sandstones in the Niger Delta and similar basins.

Keywords: Compaction, Equation, Hydrostatic, Sandstones, Niger Delta.

INTRODUCTION

The quality of a sandstone reservoir is defined by its hydrocarbon storage capacity and deliverability. While the hydrocarbon storage capacity is partly determined by porosity, its deliverability is a function of permeability. Compaction reduces porosity and permeability in sandstones and is generally expressed in terms of porosity loss (Gluyas and Cade, 1997).

Mechanical compaction, chemical compaction and cementation are the three major diagenetic processes that contribute to the loss of pore space in sandstones. Mechanical compaction is however, the dominant process and will usually cause an exponential loss of porosity with depth (Ramm et al., 1997). Compaction coefficient and percentage compaction are two parameters that indicate the degree of compaction in sandstones. When the values are low, the sands are undercompacted, but when they are high the sands are compacted.

A number of equations relating porosity and depth in sandstones have been published (Athy, 1930; Hubbert and Rubey, 1959; Gluyas, 2005; and Olowokere and Ojo, 2008). Athy (1930) and Gluyas (2005) equations hold for hydrostatic sands, while the Hubbert and Rubey (1959) equation holds for sands that are overpressured (Nwachukwu and Odjegba, 2001). Olowokere and Ojo (2008) attempted to use the sonic interval transit time-depth relationship (for sands and shales of the Agbada Formation) to determine compaction trend in the 'Weden' Field of the Niger delta. They stated that the decrease of porosity with depth is approximately parabolic for sandstone and non-parabolic for shale. They also observed that the parabolic function takes into account the physical limits of sonic transit times in sedimentary formations; correctly predicts porosity at greater depths and therefore improves the delineation of sonic anomalies at depth.

The currently proposed model compaction equation was derived from data sourced from the Niger Delta and it relates porosity to depth for sandstones under hydrostatic pressure condition. The equation is useful in predicting porosity and compaction trend in hydrostatic sands of the Niger Delta.

GEOLOGICAL SETTING OF THE NIGER DELTA.

The Niger Delta is located in the southern part of Nigeria (Fig.1) and it is bounded in the south by the Gulf of Guinea and in the north by older tectonic elements such as the Anambra Basin, Abakaliki Uplift and Afikpo Syncline (Ejedawe, 1981; Nwachukwu and Chukwura, 1986). In the West, it is bounded by the Benin Flank and in the East by the Calabar Flank- a subsurface expression of the Oban Massif (Stoneley, 1966; Nwachukwu and Odjegba, 2001).

The Tertiary deltaic fill of the Niger Delta consists of three major lithostratigraphic units; the basal unit called the Akata Formation, the middle unit called the Agbada Formation, and the uppermost unit called the Benin Formation (Fig.2). The formations are of marine, paralic and continental origins respectively (Short and Stauble, 1967).

The three formations are stratigraphically superimposed both in space and time, and range in age from Eocene to Recent. Together they make up a regressive clastic sequence of about 9000-12000 m thick (Evamy et al., 1978) and are strongly diachronous. The thickness distribution of sediments in the delta is affected by basement faulting (Weber and Daukoru, 1975; Evamy et al., 1978; Nwachukwu and Odjegba, 2001).

The Akata Formation is composed of thick shale sequences that are believed to be the principal source of hydrocarbons in the delta. The Agbada Formation consists of interbedded fluviatile, coastal fluviomarine sands and/or sandstones and marine shales (Aliu and Novelli, 1974). The shales of the lower Agbada Formation are thought to contribute partly to the trapped hydrocarbons in sands of the Agbada Formation (Nwachukwu and Chukwura, 1986). The hydrocarbons are trapped mostly in rollover anticlines associated with growth faults (Avbovbo, 1978). The sandstones of Agbada Formation are generally unconsolidated but can be slightly consolidated with calcareous cement (Schlumberger, 1985).

The Benin Formation is the topmost and youngest unit of the Niger Delta complex and is of continental fluviatile origin. Till date, no commercial quantity of hydrocarbon has been found in the formation (Schlumberger, 1985).

MATERIALS AND METHODS

Digital well log data from five wells ('K'015, 'K'016, 'K'021, 'N'001 and 'U'003) located in the southeastern part of the Niger Delta (Fig. 1) were used for this study. The dataset includes Caliper logs, SP log, Gamma Ray (GR) logs, and Porosity logs (Density and Sonic logs). Representative log diagrams of the studied wells are shown in Figures 3a, b, & c.

The analysis of the data was done using the 7.6 version of the Kingdom Suite software. Identification and delineation of sandstone and shale beds were done using the lithologic logs (SP and GR logs). The porosity values of the identified sandstones were computed from porosity logs. The shale volumes of the sandstones, calculated using the Larionov (1969) technique, were used to correct the porosity values for shale effect. The corrected porosity values were then plotted on semi-log paper to investigate overpressure. The locations of the studied wells were also plotted on a map showing the distribution of overpressure zones in the Niger Delta in order to further investigate the overpressure.

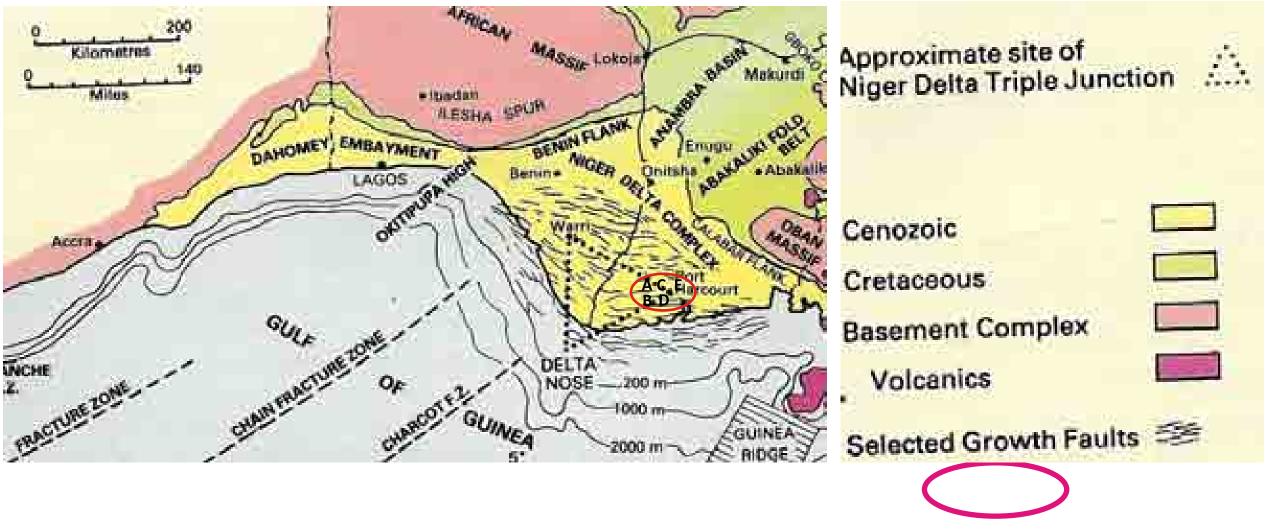
Two parameters were used to evaluate the compaction status of the sands in the study area compaction coefficient and percentage compaction. The Athy (1930) equation was employed in the determination of the compaction coefficients of the hydrostatic sands. For the evaluation of the percentage compaction of the sand beds, their original thicknesses were evaluated from the Einsele (1992) decompaction equation while their zero-depth and total-depth porosities were estimated from linear regression equations of porosity-depth plots for the wells.

The proposed model compaction equation for sandstones was derived from a linear regression plot of average porosity versus top-sand depth and the reliability of the model equation was demonstrated by comparing it with the Gluyas (2005) compaction equation for hydrostatic sandstones. Gluyas (2005) compaction equation is well tested and predicts porosity to within 3 % at 95 .0 % confidence level.

RESULTS AND DISCUSSION

Overpressure

Representative plots of Bulk Density versus depth on semi-log paper for shale beds (Figs.4a, b) showed all the data points falling along a straight line of normal compaction trend which is characteristic of the study area. Similar plot of sonic transit time versus depth (Fig. 4c) showed the same trend. These plots show that the wells did not penetrate the overpressure zones. The locations of the studied wells on a map of the distribution of depth-to-top of overpressure zones in the Niger Delta (Fig.5) further show that the wells did not penetrate the overpressure zone (Table 1).



Location of Studied wells:

A= ‘’K” 021
B= ‘’U” 003
C=”K” 015
D=”K”016
E=”N” 001

Figure 1: A Geological Map Showing the Niger Delta and Location of Studied Wells (Modified from Schlumberger, 1985).

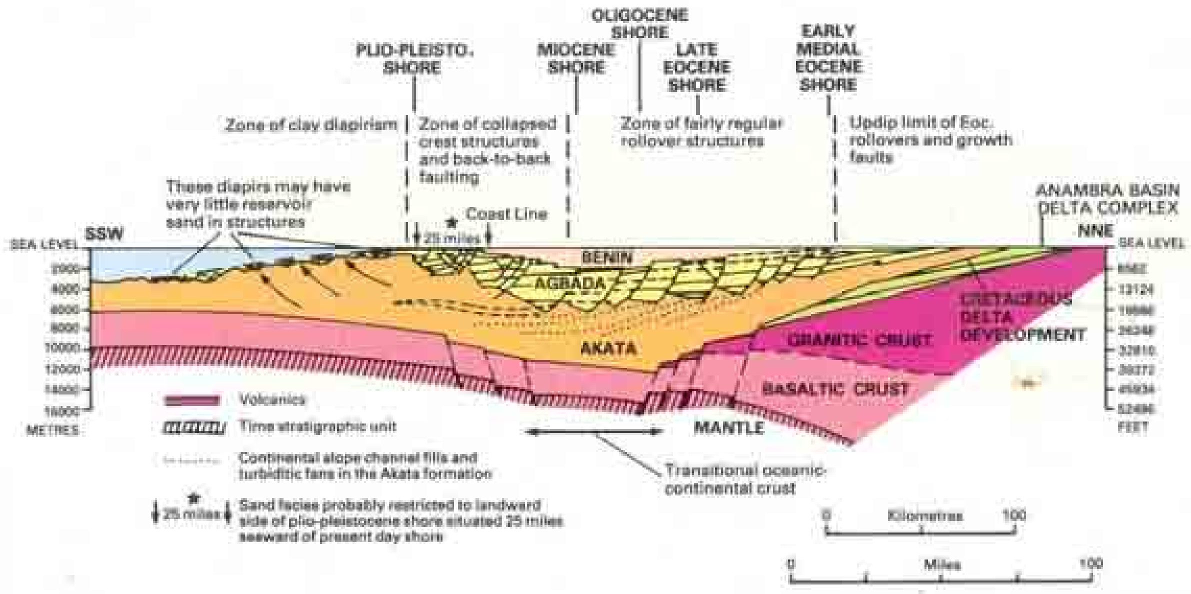


Figure 2: Schematic Dip Section of the Niger Delta Showing it's Stratigraphic Succession (Adapted from Whiteman, 1982).

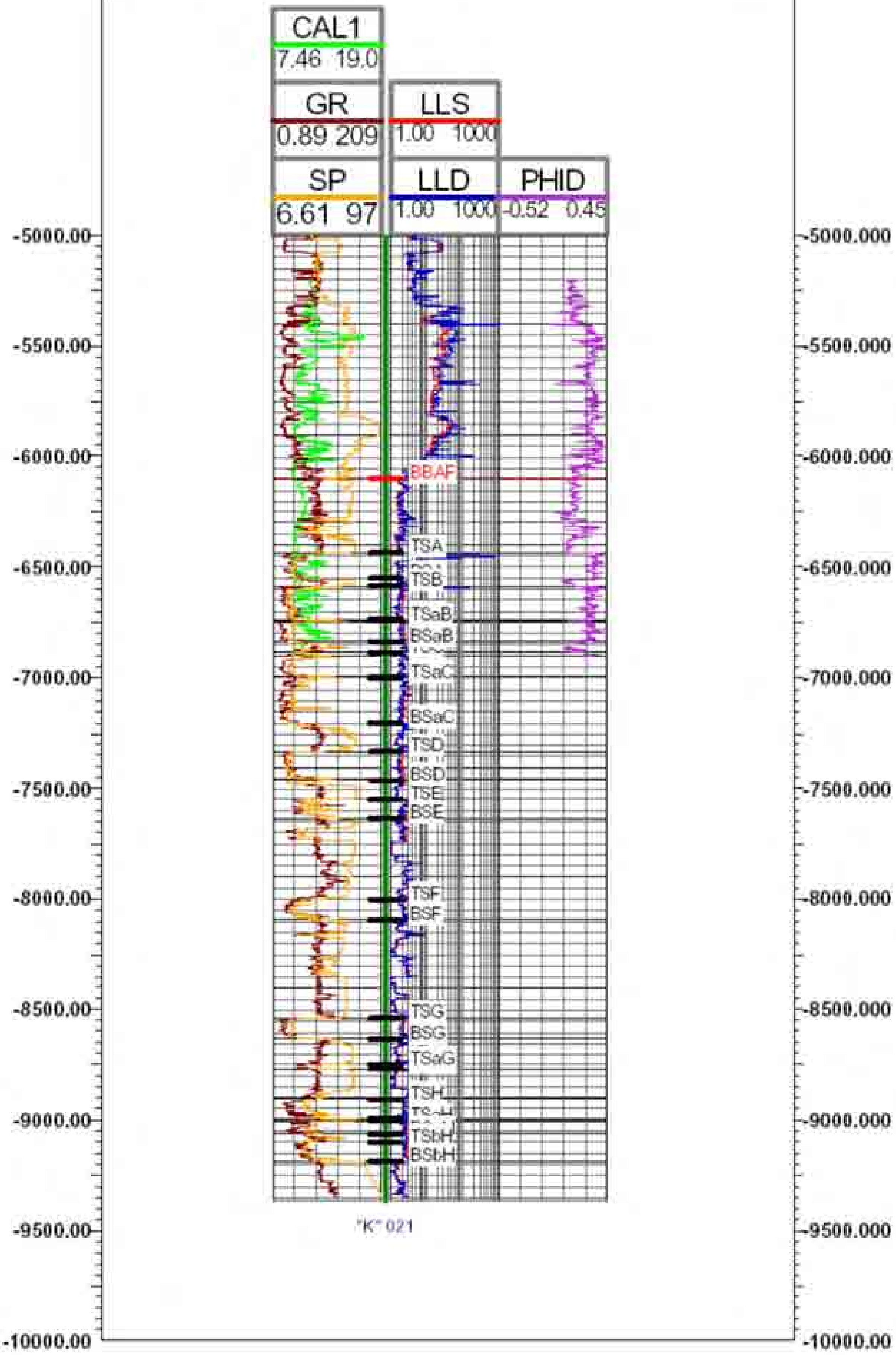


Figure 3a: Log Diagram of Well "K" 021(Subsea Depths are in feet)

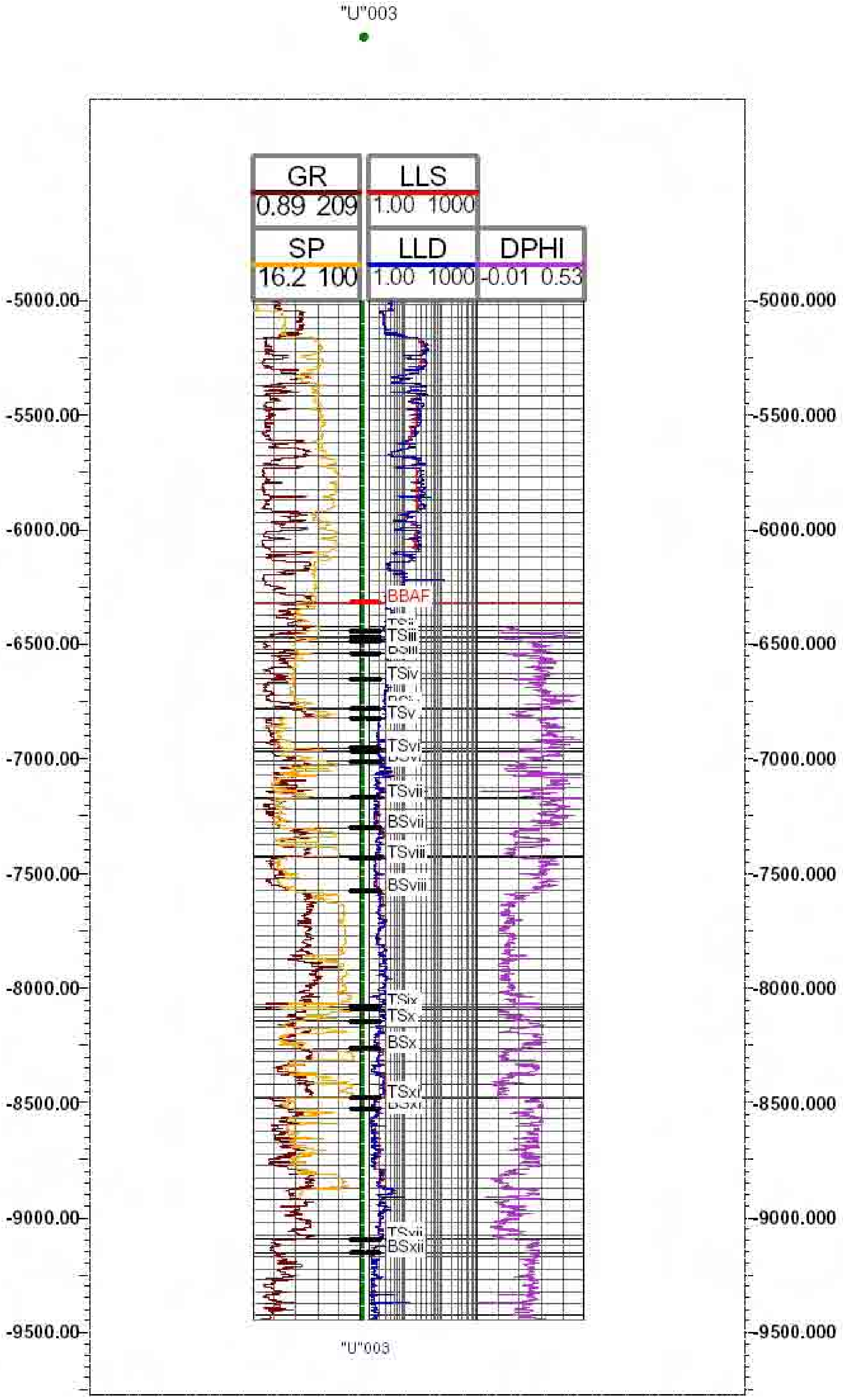


Figure 3b: Log Diagram of Well "U" 003 (Subsea Depths are in feet).

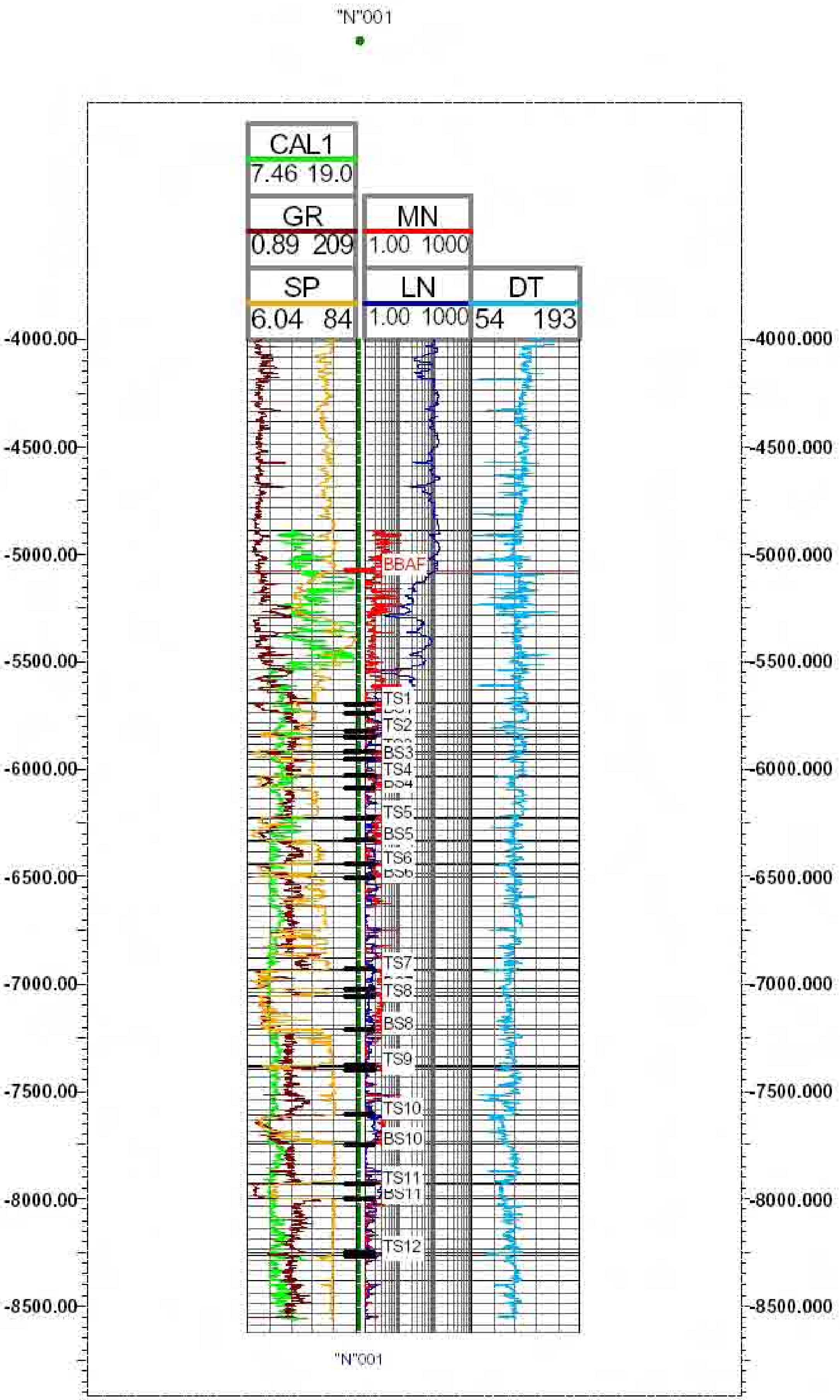


Figure 3c: Log Diagram of Well "N" 001(Subsea Depths are in feet).

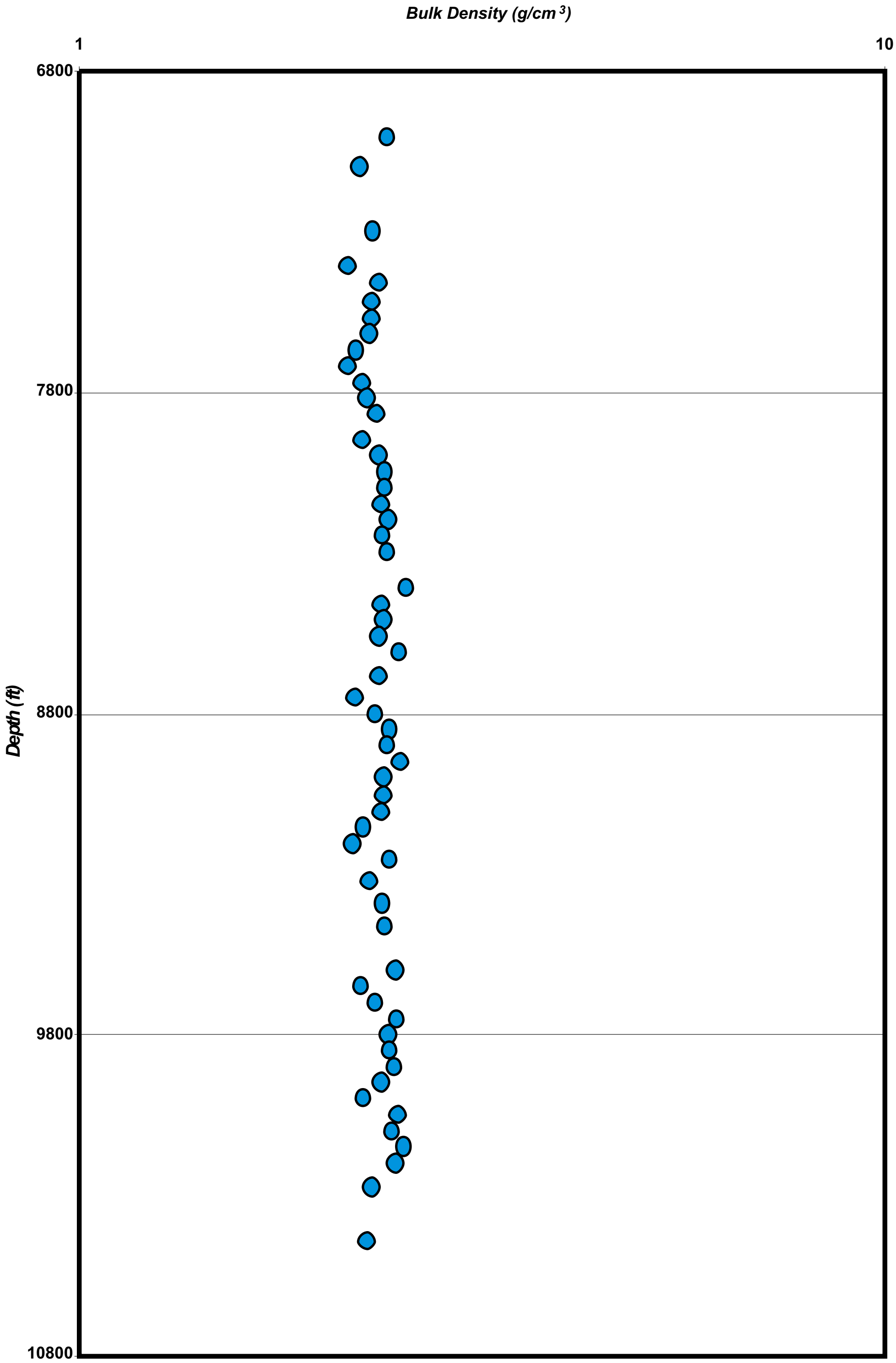


Figure 4a: Bulk Density versus Depth plot for "K"016 Well.

Table 1: Depth to Top of Overpressure Zone at Well Locations.

Well	Total Depth (m)	Depth to Top of Overpressure Zone at Well Location (m) (Schlumberger, 1985)
"K"015	2871.91	3000
"K"016	3165.0	3300
"K"021	2834.17	3000
"N"001	2621.10	2700
"U"003	2856.70	3000

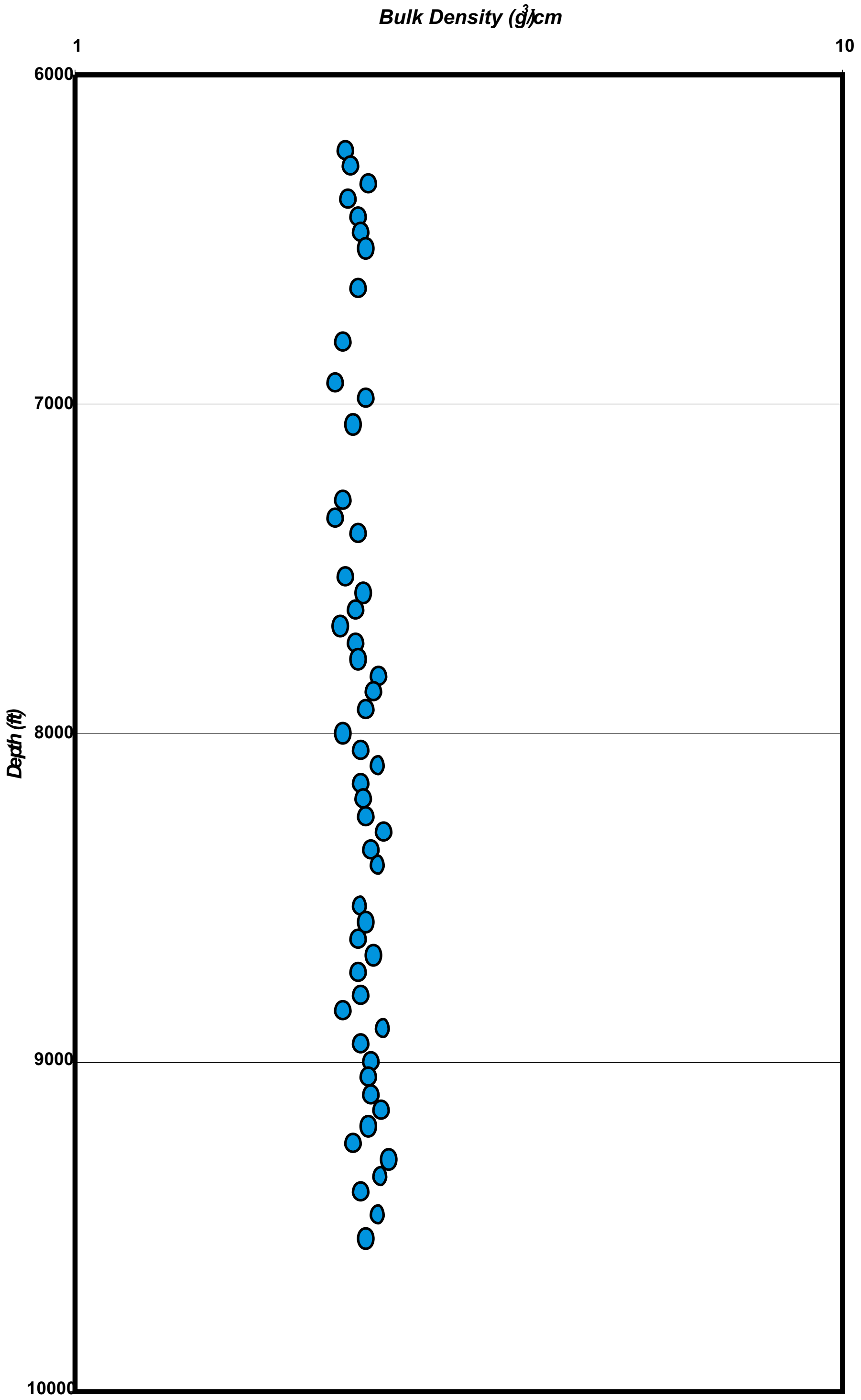


Figure 4b: Bulk Density versus Depth plot for "U"003 Well

Table 2: Compaction Coefficients of Sands in Delta from Earlier and Present Studies.

Earlier Studies.	Compaction Coefficients
Bethke (1986)	0.00014 – 0.0016 (0.000042-0.00048ft^{-1})
Weber & Daukoru (1988)	0.0003 – 0.0006 (averaging 0.0004m^{-1})
Nwachukwu & Odjegba (2001)	0.0004 – 0.0008 (averaging 0.0006m^{-1})
This Study	***0.0003 – 0.0005 (averaging 0.0004m^{-1})***

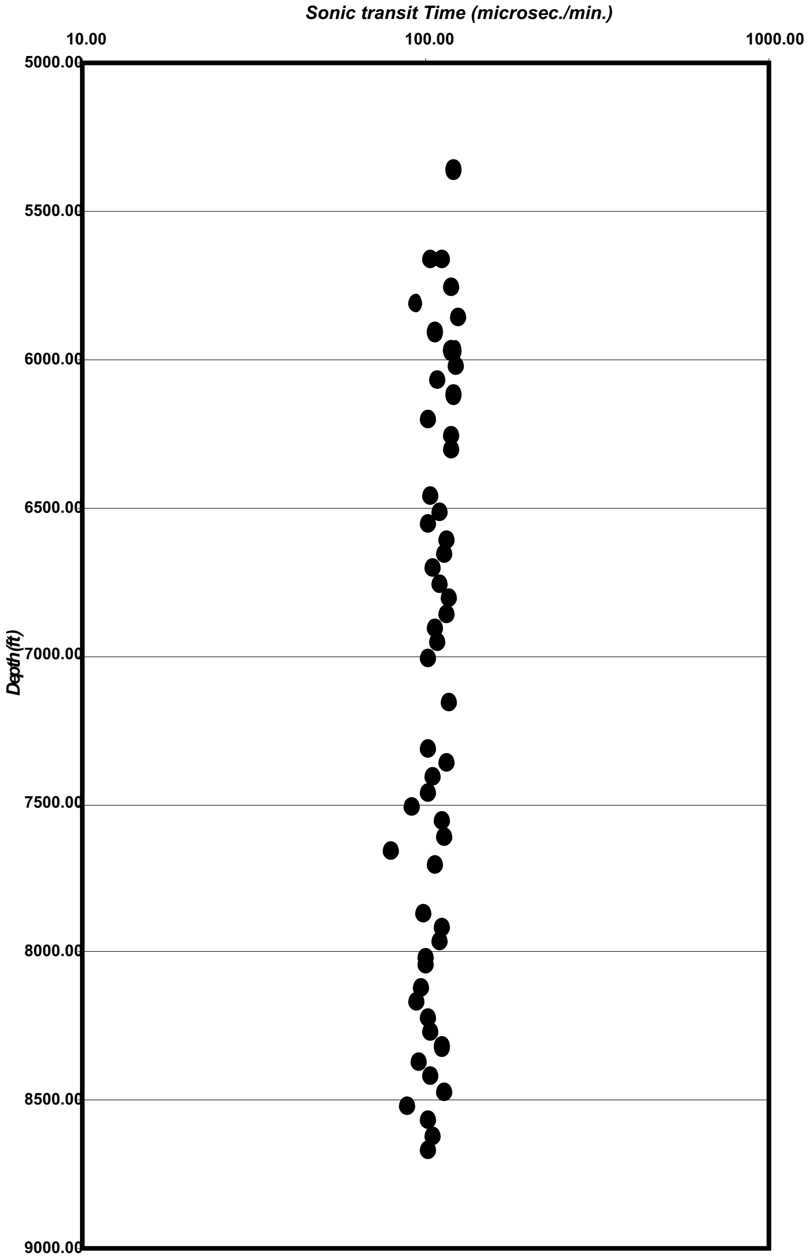
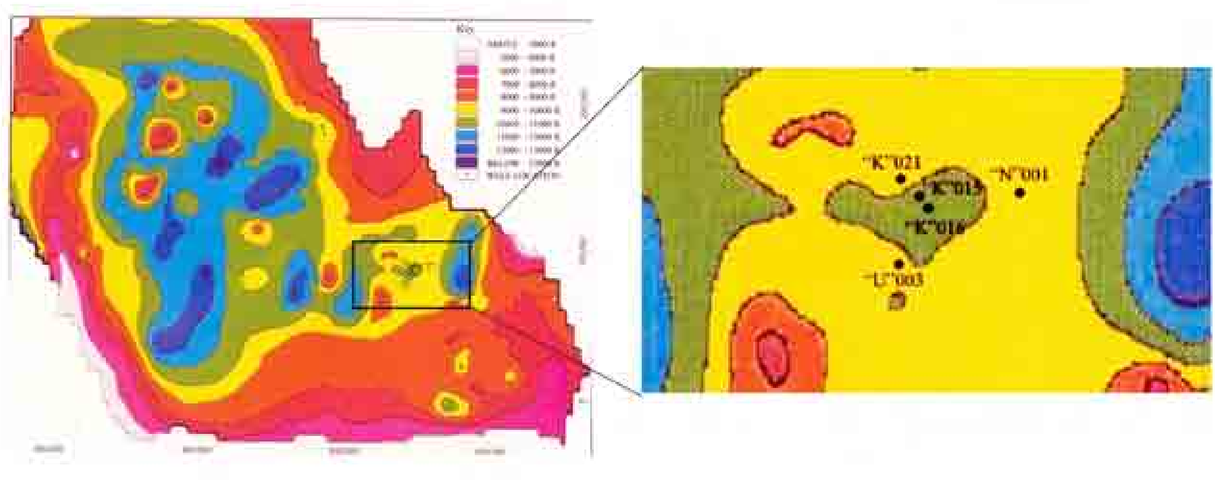


Figure 4c: Sonic Transit Time versus Depth plot for “N”00 Well..



(a)

(b)

Figure 5: **(a)** Map of the Niger Delta Showing Depth-to-Top of Overpressure Zones. **(B)** A Portion in (a) Highlighting the Studied Wells (X5.4) (Modified from Schlumberger, 1985).

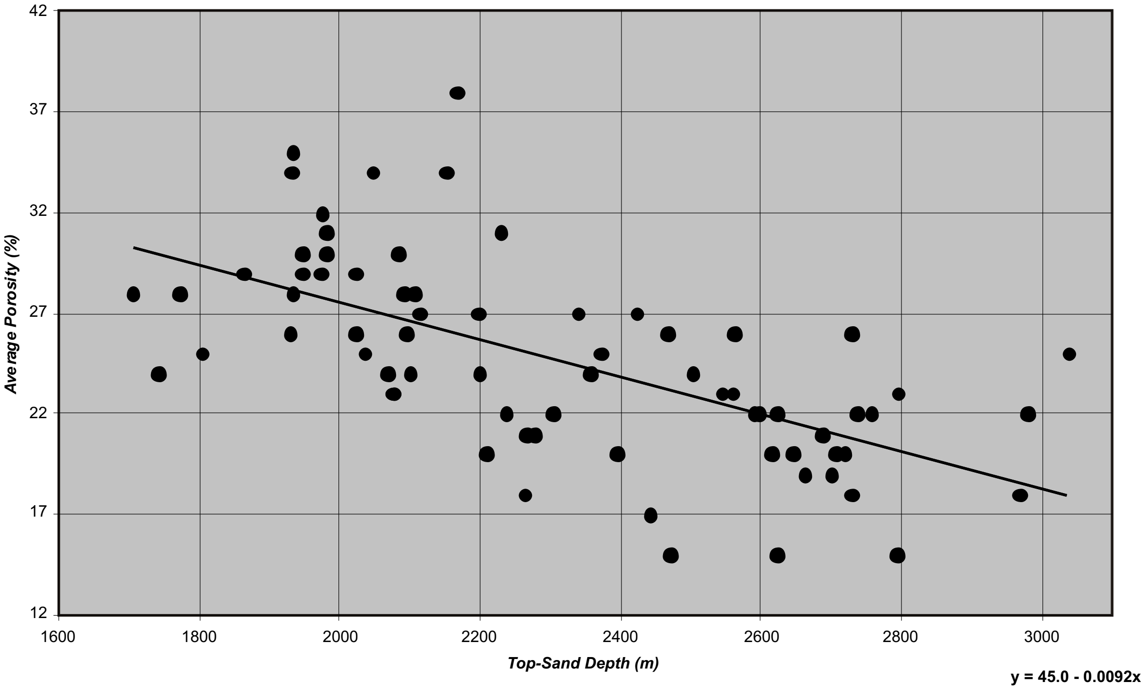


Figure 6: Representative Plot of Porosity Vs Depth.

TABLE 3: Comparison of Porosities from the Model and Gluyas (2005) Compaction Equations.

Depth (m)	**Porosity prediction from Model Comp. Equation (depth in m) (%)**	**Porosity prediction from Gluyas Comp. Equation (depth in m) (%)**	**Acceptance Limit for Gluyas (2005) Equation. (%)**
300	42	44	41 - 47
450	41	42	39 - 45
600	39	39	36 - 42
750	38	37	34 - 40
900	37	35	32 - 38
1050	35	33	30 - 36
1200	34	31	28 - 34
1350	33	29	26 - 32
1500	31	28	25 - 31
1650	30	26	23 - 29
1800	28	25	22 - 28
1950	27	24	21 - 27
2100	26	22	19 - 25
2250	24	21	18 - 24
2400	23	20	17 - 23
2550	22	19	16 - 22
2700	20	18	15 - 21
2850	19	17	14 - 20
3000	17	16	13 - 19
3150	16	16	13 - 19
3300	15	15	12 - 18
3450	13	14	11 - 17
3600	12	14	11 - 17
3750	11	13	10 - 16

Compaction Status of the Sands of the Niger Delta.

The compaction coefficient of the sands ranges from 0.0003 - 0.0005 m^{-1} (averaging 0.0004 m^{-1}) while the average percentage compaction ranges from 30 48% (averaging 37%).These low values indicate that the sands are undercompacted and in agreement with values in the literature (Bethke, 1986; Weber & Daukoru, 1988; Doust & Omatsola, 1990; Nwachukwu & Odjegba, 2001; Table 2).

Model Compaction Equation for Hydrostatic Sandstones.

A linear regression plot was made of porosity versus depth in meters (Fig. 6). The proposed model compaction equation was derived from the linear regression curve of the plot and given as:

$_{Av}$ 45.0 - 0.0092Z (1)

Where: $_{Av}$ Average porosity (%);

Z = Depth(meters).

The Correlation Coefficient (r) of the plot (Fig.6) is -0.56 which indicates a strong negative correlation between the two variables; when depth increases, average porosity decreases and vice versa.

Comparison of Model Compaction Equation with the Gluyas (2005) Equation

In comparing the model compaction equation with the Gluyas (2005) equation, porosity values at twenty-five sample depths were calculated using the two equations. All the results from the model equation fell within the acceptance limits of the Gluyas (2005) equation (Table 3). The respective values of the two equations were also cross plotted in Fig. 7 which has a strong Correlation Coefficient (r) of 0.97. It can therefore be said that the proposed model equation is in very good agreement with the Gluyas (2005) equation.

Comparing Porosities from the Model Compaction Equation with Documented Porosities of Sands from the Niger Delta

The sands of the Niger Delta can be undercompacted, slightly consolidated with calcareous cement, overpressured or hydrostatically pressured. For hydrostatic sands, primary porosity will generally decrease with depth.

The model compaction equation is true for hydrostatic sands with mainly primary porosity. It does not hold for zones with overpressured and cemented sands as these zones show higher porosities (overpressure zones) or lower porosities (cemented zones) than those predicted by the model equation for particular depths. This is illustrated by the porosity values of sands of the delta from previous work (Table 4).

For overpressure zones, however, the depth (Z) in the model equation must be replaced with

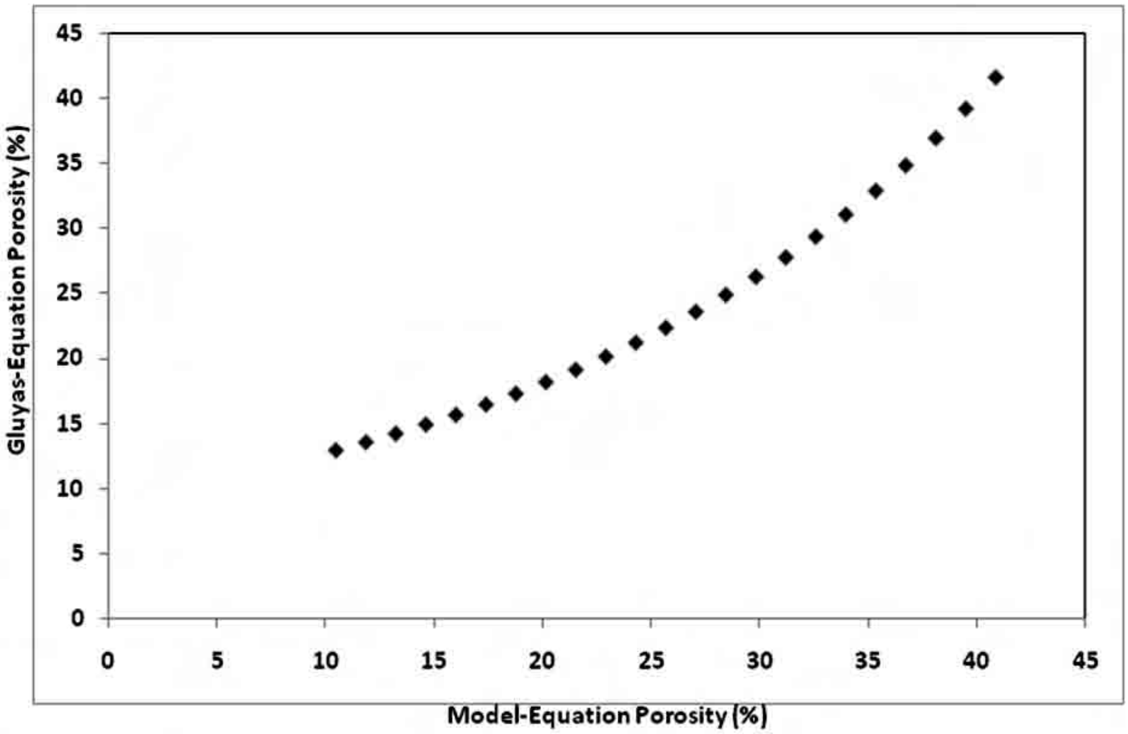


Fig. 7: A Cross-plot of Porosity Values derived from the Model and Gluyas Equations. The correlation coefficient of the plot is 0.97, indicating a strong positive correlation between the two variables

Table 4: Porosities of Sands of the Niger Delta from Research Works.

Depth (m)	**Aminu (2007) Porosity (%)**	**Porosity from Model Equation (%)**	**Difference (%).**	**Likely Reason for Difference**
2870.4	28	18.2	+9.8	overpressure
2936.1	27.6	17.6	+10.0	overpressure
3379.5	34	13.5	+20.5	overpressure
3165.3	26	15.4	+10.6	overpressure
3270.9	30	14.4	+15.6	overpressure
3554.9	31	11.8	+19.2	overpressure
3333.8	27	13.0	+13.2	overpressure
3302.9	27	14.8	+12.8	overpressure
3476.4	29	12.5	+16.5	overpressure
Depth (m)	**Onanuga (1995) Porosity (%)**	**Porosity from Model Equation**	**Difference.**	
1550.7-1553.7	21	30.5	-8.5	overpressure
1743-1749	34	28.7	+5.3	overpressure
2032.2-2035.2	28	26.3	+2	overpressure
2005.5-2008.5	30	26.2	+3.8	overpressure
2067.9-2070.9	22	25.6	-3.6	cementation
2146.2-2149.2	28	25	+3.0	overpressure
2232.6-2233.2	21	24.1	-2.9	cementation
2229-2235	30	24.2	+5.2	overpressure
Depth (m)	**Abegunrin (1996) Porosity (%)**	**Porosity from Model Equation**	**Difference.**	
1943.1-1943.7	26.2	26.8	-0.6	normal
1944.6-1945.2	16.5	26.8	-10.3	cementation
1953.6-1954.2	34.2	26.7	+7.5	overpressure
1956.6-1957.2	35.7	26.7	+9.0	overpressure
1959.9-1960.2	34.2	26.7	-5.7	overpressure
1967.4-1968	12.0	26.6	-14.6	cementation
1984.8-1985.4	32.1	26.4	+6.3	overpressure
2016.6-2017.2	24.33	26.1	-1.17	cementation
2031.9-2032.5	31.44	26.04	+5.4	overpressure
2042.4-2043	21.86	25.9	-4.04	cementation

effective burial depth (Z'). This is because overpressured sands will have an effective stress that is equivalent to that of hydrostatically pressured sand at a shallower depth. This shallower depth is the effective burial depth (Gluyas and Cade, 1997).

CONCLUSION

Plots of Bulk Density and Sonic Transit Time versus Depth, as well as location of the studied wells on a map of depth-to-top of overpressure zones, show that the wells did not penetrate the overpressure zone.

The low compaction coefficients (0.0003 0.0005 m^{-1}) and percentage compaction (30 48%) values of the sands indicate that they are undercompacted and in agreement with earlier published data in the literature.

The developed model compaction equation is valid for hydrostatic sands of the Niger Delta and similar deltaic settings, and compares favorably with the Gluyas (2005) equation for sandstones.

The model compaction equation is therefore useful and easier for predicting porosity and assessing the compaction status of hydrostatic sandstones in the Niger Delta and similar basins as these have implications for well completion operations and optimal hydrocarbon recovery.

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REFERENCES

Abegunrin, O. O. 1996. Petrophysical Evaluation of Two reservoir Sands in Five wells in the western Part of the Niger Delta. *M.Sc. Thesis,* Obafemi Awolowo University, Ile-Ife. 189 pp.

Aliu, U. and L. Novelli, 1974. Outlines of Niger Delta. In : C. Ancel, E. Couve de Murville, C. Dadrian, D. Deines, J. Goetz, A. Misk, J. Moore, D. Parker, J. Trassard, and K .Weiss, *(eds.)*, Well evaluation conference Nigeria, 2^{nd} edition. Schlumberger Publication, p. 1 5.

Aminu, M. B. 2007. Application of Artificial Neural Networks in the Reservoir characterization of "XT-Field" in the Niger Delta, Nigeria. M.Sc thesis, Obafemi Awolowo University, Ile-Ife. 183 pp.

Athy, L. F. 1930. Density, porosity and compaction of sedimentary rocks. *AAPG Bulletin* 14: 1 21.

Avbovbo, A.A. 1978. Tertiary lithostratigraphy of Niger Delta: AAPG Bulletin, 62(2): 295 - 300.

Bethke, C.M. 1986. Inverse hydrologic analysis of the distribution and origin of Gulf coast-type geopressured zones. *Journal of Geophysical Research,* 91: 6535 6545.

Doust, H., and Omatsola, E. 1990. Niger Delta. In Edwards, J.O. and Santogross, P.A., (Eds) Divergent Passive Margin Basins Tulsa, AAPG Memoir, vol. 48: p. 201 - 238.

Einsele, G. 1992. *Sedimentary basins, evolution, facies, and sediment budget.* Springer-Veriag, 628 pp.

Ejedawe, J.E. 1981. Patterns of incidence of oil reserves in Niger Delta Basin. *AAPG Bulletin,* 65: 1574 - 1585.

Evamy, B.D., J. Haremboure, P. Kamerling, W.A. Knaap, E.A. Molloy, and P.H. Rowlands, 1978. Hydrocarbon habitat of Tertiary Niger Delta; *AAPG Bulletin,* 62:1 - 39.

Gluyas, J., 2005. Sandstones, Diagenesis and Porosity Evolution. In, R. C. Selley, L.R.M Cooks and I.R. Plimer (eds): *Encyclopaedia of Geology,* 5. Elsevier Academic press Ltd., 807 pp.

Gluyas, J. And C.A. Cade, 1997. Prediction of porosity in compacted sands. In, J.A. Kupecz, J. Gluyas, and S. Bloch, (Eds.), Reservoir quality prediction in sandstones and carbonates: *AAPG Memoir* 69:19 - 28.

Hubbert, M.K. and W.W. Rubey, 1959. Mechanics of fluid filled porous solids and its application to overthrust faulting, 1, role of fluid pressure in mechanics of overthrust faulting. *Geological Society of America Bulletin,* 70:115 - 166.

Larionov, V.V. 1969. *Borehole Radiometery;* Moscow, U.S.S.R., Nedra, p. 115 - 121.

Nwachukwu, J.I. and P.I. Chukwura, 1986. Organic matter of Agbada Formation, Niger Delta, Nigeria: *AAPG. Bulletin,* 70: 48 - 55.

Nwachukwu, J.I. and E.T. Odjegba, 2001. Compaction in Reservoir sandstones of the Niger Delta, Nigeria. *Journal of Mining and Geology,* 37 (2): 113 - 120.

Olowokere, M.T and J.S. Ojo, 2008. Application of compaction trends in the prediction of porosity distribution in 'Weden Field', Niger Delta. *Journal of Mining and Geology,* 44 (2):161 - 171.

Onanuga, K. O., 1995. Delimitation of Hydrocarbon Reservoir Size from Seismic Velocity-Depth Profiles over Aghigho Oil Field, Niger Delta. *M.Sc. thesis,* Obafemi Awolowo University, Ile-Ife; 162 pp.

Ramm, M., Forsberg, and J.S. Jahren, 1997. Porosity-depth trends in deeply buried Upper Jurassic reservoirs in the Norwegian Central Graben: an example of porosity preservation beneath the normal economic basement by grain-coating microquartz. In, J.A. Kupecz, J. Gluyas, and S. Bloch, (eds.); Reservoir quality prediction in sandstones and carbonates: *AAPG Memoir* 69:177 - 199.

Schlumberger, 1985. *Well Evaluation Conference, Nigeria.* Schlumberger Well Services Inc. 290 pp.

Short, K.C., and A.J. Stauble, 1967. Outline of the Geology of Niger Delta. *AAPG Bulletin*, 51: 761 - 779.

Stoneley, R., 1966. The Niger Delta region in the light of the theory of continental drift. *Geology Magazine*, 105: 385 - 397.

Weber, K.J. And E.M. Daukoru, 1975. Petroleum geological aspects of the Niger Delta. *Journal of Mining and Geology,* 12(1/2): 1 - 22.

Weber, K.J. and E.M. Daukoru, 1988. Niger Delta reservoir geology: Historical growth of the sedimentological model and its application to field development. *Contribution to the 1988 SPE conference,* 03 05 August 1988. Port Harcourt, Nigeria, 49 pp.

Whiteman, A.J., 1982. Nigeria: *Its Petroleum Geology, Resources and Potential,* London, Graham and Trotman, 394 pp.