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Geomechanical Characterization of a Reservoir in Part of Niger Delta, Nigeria

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ABSTRACT

Geomechanical characterization of a reservoir in the Niger Delta basin, using geophysical well-logs was adequately evaluated. The deformability and strength of delineated unconsolidated sandstone and compacted shale were investigated by determined elastic moduli (Poisson ratio, Young modulus, Bulk modulus, Shear modulus and Compressibility) and the unconfined compressive strength (UCS), cross plots of the parameters were done for validation. Sand production prediction was used to adequately analyse sanding. The results show average parameters of weakly cemented sand to have lower Poisson ratio, Young, Bulk, Shear modulus and Unconfined compressive strength of magnitudes of 0.28, 2.4GPa, 10.5GPa, 6.83GPa, 14.44MPa respectively, high compressibility (0.1 GPa-1), and porosity (0.25) the compacted shale have higher Poisson ratio, Young, Bulk, Shear modulus and rock strength as (0.35, 8.93GPa, 18.08GPa, 21.01GPa, 56.17MPa respectively, lower compressibility (0.06 GPa-1) and porosity (0.06). The shale has maximum average rock strength value of 56.17MPa.These results can be useful in the planning of well drilling and sanding prediction in the study area.

Keywords: Elastic moduli, Geomechanical characterization, Niger Delta, Petro physical properties, Sand production prediction and geophysical well logs.

1. INTRODUCTION

Geophysics in reservoir exploration and exploitation has evolved in role with Rock mechanics assuming center stage in energy resources development and sustainability. Rock mechanics related problems such as prediction of pore pressure, fault/seal integrity, well stability, prediction of permeability heterogeneity, prediction sand production benefits from the accurate measurement and evaluation of Geomechanical properties.

Such challenges like, sand production which depends largely on the strength and to predict sanding the awareness of the compressive strength of the formation, especially young formation (tertiary age) is vital [21]. Sanding prediction is necessary because some sand control techniques such as downhole solidification, emulsification, and gravel packing are very costly hence, it is better to predict the possibility of a formation to produce sand rather than applying sand control techniques without knowledge. The crucial step to effective rock mechanics solutions is hidden in obtaining rock mechanical parameters data like elastic moduli and estimating the strength of rock formation [5]. Therefore an economic production in such reservoirs will require a good understanding of the reservoir geomechanics.

In spite of all the information on regional stress field made handy by the world stress map project [32], the local stress field of reservoirs is often not homogeneous as temporal and spatial variation in lithologies, sedimentation rates and structural patterns form compartments and induce heterogeneities which are capable of causing time [dependent and non-time dependent anisotropies in rock strength, elastic properties and in situ stresses [6, 32]. Relying on the world stress map in geomechanically characterizing a reservoir will over simplify the deformability and rock strength of the reservoir of interest, therefore the Geomechanical evaluation, rock strength and its application built for other regions of the world do not yield accurate results when used for the Niger Delta region, an alternative approach of using well logs where core sample is unavailable for laboratory test can geomechanically describe reservoirs , predict and manage sand production.

Rock mechanical laboratory test method has made great stride in establishing Geomechanical information of the deformability and strength of rock materials [22]. These tests usually measure several parameters including elastic, plastic, and strength properties of the rock samples. However, there are acceptable reasons why laboratory test is not very reliable, the fact that the core samples analyzed in the lab are not under the influence of exact in-situ conditions experienced underground. The type of fluid, its compressibility, and pore pressure have significant influences on the mechanical behavior of rocks. Several of these laboratory measurements are performed at dry conditions. Even for saturated samples, it is very difficult to perform a test with the exact fluid properties in the field, especially for the hydrocarbon-bearing formations. Another major issue is the effect of in-situ stresses on the rock samples. Even though it is usually tried to apply the best estimates of the in-situ stresses during testing, it is almost impossible to do it perfectly due to the difficulty of measurement of in-situ stresses in the field and limitations of the lab apparatuses for applying the full stress tensor. Another major discrepancy between the lab results and the field behavior of rocks is caused by the effect of sampling size. It is difficult to core a wide area of the reservoir especially fractured and weak zone hence the samples used in the lab are small compared to the sampling sizes of geophysical measurements in the field. Geophysical measurements are easily available and also produce reliable results [7, 10,19].

Given the demerits of rock mechanical laboratory test approach, this research will reveal the merit of indirect measurement method of rock properties; an alternative approach using well log data to obtain rock strength and deformation property predictions of the reservoir. The rock strength and other parameters are computed from data obtained from well logs, since most of the factors that affect rock strength also affect elastic modulus and other parameters such as petrophysical parameters which could be deduced from geophysical measurement [8,9]. The aim of this work, therefore, is to use well-log data to determine Poissons ratio, Bulk modulus, Young modulus, Shear modulus, compressibility, unconfined compressive strength (UCS) porosity, volume of shale and predict sand production in the reservoir. The results of this work can improve process efficiency, enhance overall production, and to increase the return rate of economic assets.

2. THEORETICAL BACKGROUND

There are four major constitutive law governing rock deformation in response to applied stress [28,32].The four generic types of constitutive laws for homogeneous and isotropic materials are; Linear elastic, Poroelastic, Elastic-plastic and Viscoelastic behavior. While linear elastic material is when stress and strain are linearly proportional and deformation is reversible, in Poroelastic material, the stiffness of the fluid saturated in a rock depends on the rate at which the external force is applied. Elastic-plastic materials behave elastically to the stress level at which it yields and then deforms plastically without limit and viscoelastic materials exhibits permanent deformation after application of load.

The components of the second-order strain tensor in Figure 1 of elastic deformation, defines the constitutive laws more precisely. Principal stresses and principal strains, in a homogeneous and isotropic material act in the same direction [32].

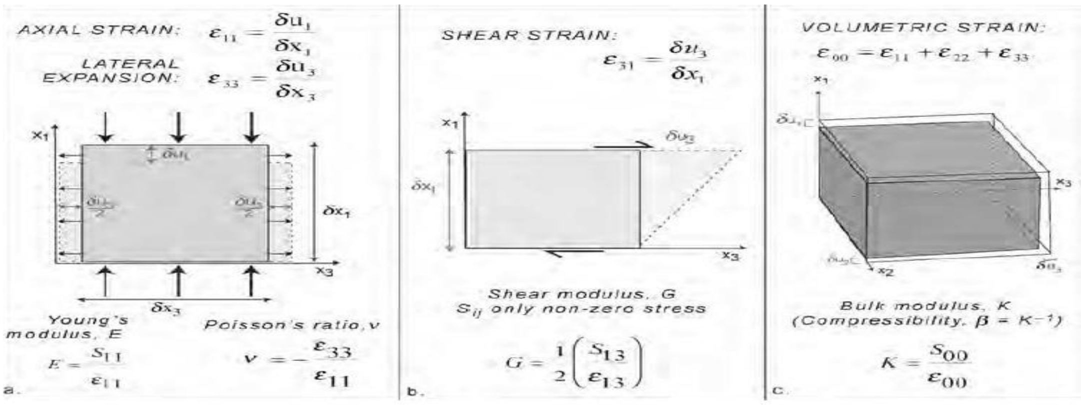

Figure 1: An illustration of the relationship between stress, strain and the physical meaning of frequently used elastic moduli in different kinds of idealized deformation [32].

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\delta u_i}{\delta x_j} + \frac{\delta u_j}{\delta x_i}\right) \qquad (1)$$

Where ε_{ij} is a component of the second-order strain tensor, $\frac{\delta u_i}{\delta x_j}$ and $\frac{\delta u_j}{\delta x_i}$ are principal stress and principal strain acting in the same directions respectively as shown in Figure 1.

The theory of elasticity, where no significant damage or alteration of rock results from an applied stress and the assumption that stress and strain are linearly proportional and fully reversible is often be valid. In such a material, stress can be expressed in terms of strain by the following relation

$$S_{ij} = \lambda \delta_{ij} \varepsilon_{00} + 2G\varepsilon_{ij} \qquad (2)$$

Where ε_{00} is the volumetric strain, Kronecker delta, δ_{ij} is given by δ_{ij} = 1, I = j, δ_{ij} = 0,

Expanding equation 2, it yields:

$$S_1 = (\lambda + 2G)\varepsilon_1 + \lambda\varepsilon_2 + \lambda\varepsilon_3 = \lambda\varepsilon_{00} + 2G\varepsilon_1 \qquad (3)$$

$$S_2 = \lambda\varepsilon_1 + (\lambda + 2G)\varepsilon_2 + \lambda\varepsilon_3 = \lambda\varepsilon_{00} + 2G\varepsilon_2 \qquad (4)$$

$$S_3 = \lambda\varepsilon_1 + \lambda\varepsilon_2 + (\lambda + 2G)\varepsilon_3 = \lambda\varepsilon_{00} + 2G\varepsilon_3 \qquad (5)$$

Where equation 3 represents axial strain and lateral expansion in a sample compressed uniaxially, equation 4 represents shear strain resulting from application of a simple shear stress and equation 5 represents volumetric strain resulting from compressing a body under isostatic mean stress.

Where λ = Lame's constant, K = bulk modulus and G = shear modulus; all are elastic moduli. In this work the following elastic moduli assuming homogeneous isotropic rock; Bulk modulus, Shear modulus, Young modulus, Poisson ratio, Compressibility. One of the most common is the bulk modulus, *K*, which is the stiffness of a material in hydrostatic compression $\frac{S_{00}}{\varepsilon_{00}}$ as shown in equation 2 and given by

$$K=\frac{S_{00}}{\varepsilon_{00}} \quad (6)$$

While compressibility of the rock, β is given by $\beta = K^{-1}$ and Young modulus, E, is simply the stiffness of a rock in ($\frac{S_{11}}{\varepsilon_{00}}$) unconfined compression (S_{11} is the only non-zero stress) as shown in equation 5

$$E=\frac{S_{11}}{\varepsilon_{00}} \quad (7)$$

Poisson's ratio, υ, is the ratio of lateral expansion (ε_{33}) to axial shortening (ε_{11})as shown in equation 3

$$\upsilon=\frac{\varepsilon_{33}}{\varepsilon_{11}} \quad (8)$$

Shear modulus, is the ratio of an applied shear stress (S_{13}) to corresponding shear strain (ε_{13}) as in equation 4

$$G=\frac{1}{2}\left(\frac{S_{13}}{\varepsilon_{13}}\right) \quad (9)$$

According to [2,8,9,12,14] nearly all proposed formulae for determination of rock strength and elastic moduli from geophysical logs utilize either compressional velocity (V_p), transit time (μs/ft) or porosity (∅). Seismic velocities are affected by several factors such as lithology, interstitial fluid, porosity, clay content, depth, density, temperature and so on. Lithology is an obvious factor affecting velocity (P-wave and S-wave). Pores is one of the weakest and the most deformable elements in rocks; hencePorosity affects the velocity of the acoustic waves penetrating the rocks [8, 9]. Wyllie *et al*. (1950) developed equations showing the relationship between velocity and porosity.

$$\Delta t = \phi \Delta t_f + (1-\phi)\Delta t_{ma} \quad (10)$$

Where $\Delta t, \Delta t_f, \Delta t_m$ = specific transit time (slowness), pore fluid, rock matrix respectively, ϕ = Porosity

In terms of velocity, equation (10) can be re-written as:

$$\frac{1}{v}=\frac{\phi}{v_f}+\frac{(1-\phi)}{v_{ma}} \quad (11)$$

Where, v = Bulk velocity v_f = Velocity of the fluid v_{ma} = Velocity of rock matrix.

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3. PETROLEUM GEOLOGY OF THE STUDY AREA

The study area which is the oil-rich Niger Delta region is located within the offshore depo belt of Niger delta basin, Nigeria (Figure 2).This sedimentary basin is a clastic environment dominated by sands and shales. Niger Delta Province contains only one identified petroleum system [27] referred to as the Tertiary Niger Delta (Akata -Agbada) Petroleum System. The area is geologically a sedimentary basin, and consists of three basic Formations: Akata, Agbada and the Benin Formations. The Akata is made up of thick shale sequences and it serves as the potential source rock. It is assumed to have been formed as a result of the transportation of terrestrial organic matter and clays to deep waters at the beginning of Paleocene. According to [4], the thickness of this formation is estimated to about 7,000 meters thick, and it lies under the entire delta with high overpressure. Agbada Formation is the major oil and gas reservoir of the delta, It is the transition zone and consist of intercalation of sand and shale (paralic siliciclastics) with over 3700 meter thick and represent the deltaic portion of the Niger Delta sequence. Agbada Formation is overlain by the top Formation, which is Benin. Benin Formation is made of sands of about 2000m thick (Kulke, 1995).

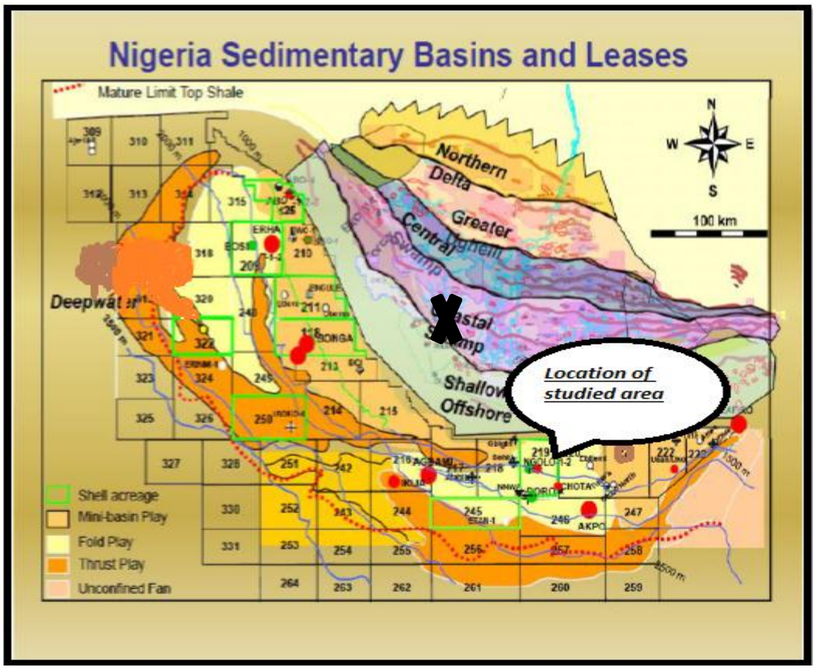

Figure 2: Map of the Niger Delta Basin showing Study Area (Onuorah *et al.*, 2014).

4. MATERIALS AND METHODS

Quality Checks of Well Logs

In order for the Well logs to be used to compute the geomechanical parameters, pre-processing was carried out. Primary processing included despiking, normalization, and splicing. The logs were normalized to eliminate all differences in the various log signatures that are not a direct function of reservoir properties to enable accurate determination of appropriate ranges and cutoffs for porosity, and shale-sand contents. The Petrel software was also used to check data at the point of entry to see if it falls within minimum and maximum ranges of the dataset. Availability and consistency of the GR and Sonic logs for all five wells were identify as these logs are paramount

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in lithological delineation and compression velocity generation, logs were scaled to standard to avoid erroneous readings.

4.1 Determination of Rock Geomechanical Properties

Mechanical properties of the field were determined using wireline logs. The Elastic properties include poisson ratio Young modulus (E) Shear/rigidity modulus (G), Bulk and matrix/grain moduli (K_b and K_m) Bulk and grain compressibility (C_b and C_r) Biots coefficient (a) and inelastic prosperity, unconfined compressive strength (UCS). Rock sample from the reservoir can also be measured effectively in the laboratory using the major three rock deformation test, hydrostatic, uniaxial, and tri-axial technique.

4.1.1 Shear modulus (G) or modulus of rigidity is the ratio of applied shear stress to shear strain, it is given by:

$$G = \frac{strearstress}{shearstrain} = \frac{\tau}{\gamma} \quad (12)$$

Bulk Modulus (K_b) represents the ratio of changes in the average of the three principal stresses to the changes in rock volume. Or is the ratio of change in hydrostatic stress to the corresponding volumetric strain:

$$K = \frac{\Delta P \Delta V}{V_O} \quad (13)$$

Where ΔP the change is in hydrostatic pressure, ΔV is the change in volume, and V_O is the original volume. The bulk modulus is the inverse of rock matrix compressibility, C_r:

$$C_r = K^{-1} \quad (14)$$

For a rock that has similar properties and identical in all direction, homogenous, and elastic the bulk modulus is by:

$$K_b = a\rho_b\left(\frac{1}{\Delta Tc^2} - \frac{4}{3Ts^2}\right) \quad (15)$$

Poisson's ratio (v) can be defined as the ratio of the lateral strain to longitudinal strain when a longitudinal stress is applied

$$V = \frac{\varepsilon_{lat}}{\varepsilon_{ax}} = \frac{\Delta d/d_o}{\Delta l/l_o} \quad (16)$$

Where d_o = original diameter of the cylindrical core sample, Δd = change in diameter, L_o = original length of core, ΔL = change in length, ε_{lat} = strain in the lateral direction and ε_{ax} = strain in the axial direction.

Young's modulus (E) is a measure of the property of the rock to resist deformation. It is the ratio of compressive/ tensile strength to compressive/tensile strains which for a rock that has similar properties and identical in all direction, homogenous, and elastic the modulus is given as:

$$E = \frac{9GK_b}{3K_b + G} \qquad (17)$$

Biot Constant (a) is given as:

$$a = 1 - \left(\frac{K_b}{K_m}\right) \qquad (18)$$

4.1.2 Poisson Ratio (ν)

The log derived Poisson ratio was computed from acoustic measurements such as sonic log usually displayed in terms of slowness, the reciprocal of velocity called interval transit times, (ΔT) in units of microseconds per foot. The Slowness of compressional wave (ΔV_p) and slowness of the Shear wave (V_s) ratio is used to determine the Poisson ratio (Moos, 2006).

$$\upsilon = 0.5\frac{\left[\left(\frac{V_P}{V_S}\right)^2 - 1\right]}{\left[\left(\frac{V_P}{V_S}\right)^2 - 1\right]} \qquad (19)$$

The theoretical maximum value of v is 0.5

Where V_P =compression wave velocity and V_S =shear wave velocity

4.1.3 Shear Modulus (G)

The Shear modulus is the ratio of the Shear stress to the Shear strain which for a homogeneous and elastic rock is given by equation (13) [Schlumberger, 1989].

$$G = \frac{a\rho_b}{v(\Delta T_s)} \qquad (20)$$

Where coefficient a = 13464, ρ_b = Bulk density in g/cni3, ΔT_s = Shear sonic transit time in us/ft. v = Poisson ratio. The unit of G is 10^6 MPa.

4.1.4 Bulk Modulus (K_b **)** is a static modulus but an equivalent dynamic modulus can be computed from the sonic and density logs. The relationship is given in below:

$$K_b = a\rho_b \left(\frac{1}{\Delta T_c^{\ 2}} - \frac{4}{3T_s^{\ 2}} \right) \quad (21)$$

Where coefficient a =13464, ρ_b =Bulk density in g/cm^3, ΔT_c and ΔT_s = change in compression and shear wave respectively in us/ft . The unit of K_b is 10^6 MPa.

4.1.5 Matrix/Grain Bulk Modulus (K_m)

$$K_m = \frac{K_s \rho_{ma}}{\left(\frac{1}{\Delta T_{c\,ma}^{\ 2}} - \frac{4}{3T_{s\,ma}^{\ 2}} \right)} \quad (22)$$

where K_S is constant and equals to1000m , ΔT_{cma} and ΔT_{sma} = change in compression and shear wave respectively of the rock matix in us/ft and ρ_{ma} = Matrix density in g/cm^3

4.1.6 Young Modulus (E)

Young modulus or modulus of elasticity was determined from the relationship between Young modulus, Shear modulus and Poisson ratio.

$$E = 2G(1+v) \quad (23)$$

Where G = Shear modulus and v =Poisson ratio. E is in MPa.

4.1.7 Biot Constant was determined using the expressions in equations (21) and (22).

$$a = 1 - \left(\frac{K_b}{K_m} \right) \quad (24)$$

in term of bulk and grain modulus where K_b and K_m are skeleton bulk and solid grain moduli respectively (Crain 2000) in terms of compressibility it is expressed as

$$a = 1 - \left(\frac{C_r}{C_b} \right) \quad (25)$$

Where, C_r/C_b is grain and bulk compressibility respectively.

4.1.8 Unconfined compressive Strength (UCS)

Among the several empirical relationships proposed for application in sandstone, shale and Carbonate rocks, the [15] equation (21) for fine grained both consolidated and unconsolidated sandstones with all porosity ranges Is most suited for the Niger Delta basin while [13] equation (22) for shales was used for comparison.

$$UCS = 1200 \exp^{(-0.036\Delta T_c)} \quad (28)$$

$$UCS = 10\left(\frac{304.8}{\Delta T_c - 1}\right) \quad (29)$$

Where, UCS = unconfined compressive strength. ΔTc =change in compressional wave transit time matix in us/ft

4.1.9 Volume of Shale

The volume of shale is the Bulk volume of the reservoir composed of clay minerals and clay hound water. V_{shale} was determined using Larinov (1962) equation (30)

$$V_{shale} = 0.083(2^{3.71_{gr}} - 1)[Larinov, 1962] \quad (30)$$

Where 1_{gr} is the shale index (gamma ray index) which is defined in (31)

$$1_{gr} = \frac{GR_{\log} - GR_{\min}}{GR_{\max} - GR_{\min}} \quad (31)$$

Where, GR_{log}= measured gamma ray log reading at depth (z), GR_{min} minimum gamma ray log in clean sand, GR_{min}= maximum gamma log reading (in clean shale) V_{shale} volume of shale in the formation at depth z.

4.1.10 Porosity and effective Porosity

Porosity is the total volume of a rock occupied by pores both connected and unconnected. It is the ratio of the pore volume to the Bulk volume expressed as fraction %. Porosity is determined from density, sonic, neutron logs.

The total porosity was determined from density log data which are weighted average densities of the rock and pore fluid using equation

$$\theta_D = \frac{(\rho_{ma} - \rho_b)}{(\rho_{ma} - \rho_{fl})} \quad (32)$$

Where θ_D = total density porosity, ρ_{ma} density of rock matrix, ρ_b = measure density and ρ_{fl} = density of fluid.

Effective porosity was calculated by application of volume of shale equation

$$\theta_{eff} = \frac{(\rho_{ma} - \rho_b)}{(\rho_{ma} - \rho_{fl})} - \frac{V_{sh}(\rho_{ma} - \rho_{sh})}{(\rho_{ma} - \rho_{fl})} \quad (33)$$

Where θ_{eff} shale corrected density porosity, V_{sh} is volume of shale and ρ_{sh} is density of shale, ρ_{ma} is density of rock matrix and ρ_{fl} is density of fluid.

4.1.11 Sand Production Prediction

Prediction of sanding in the reservoir was done using the following listed methods.

Sand production index method (B): In this method the sand production index was derived using

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$$B = \frac{E}{3(1-2v)} + \frac{4}{3} \times \frac{E}{2(1+v)} \quad (34)$$

Where E=Elasticity modulus, v = Poisson's ratio.

Schlumberger sand production index method (S/I): This index was determined using the relationship between Shear modulus and Bulk density

$$S.I = K \times G \quad (35)$$

Where K = Bulk modulus, G = Shear modulus

Shear modulus to Bulk compressibility ratio: The value was derived from

$$G / C_b \quad . \quad (36)$$

where G = Shear modulus, C_b = Bulk compressibility.

4.1.12 Elastic Combined modulus (E_c) This method was achieved based on acoustic time and density logging information.

$$E_c = \frac{9.94 \times 10^8 \rho_r}{\Delta t_C^2} \quad (37)$$

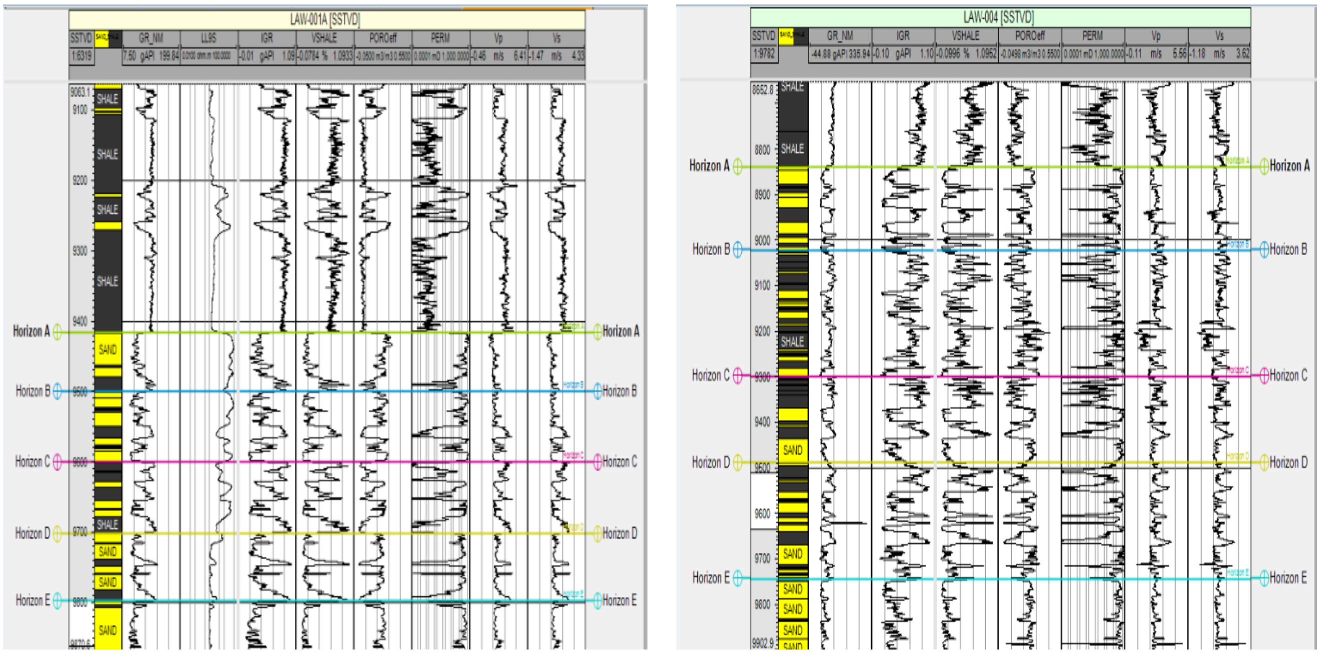

Fig. 3: Petrophysical logs of Law 1A and Law 004 showing the physical properties of the reservoir rock as delineated with Gamma ray (GR), Resistivity (lls) volume of shale (V_{sh}), compressional (V_p) and Shear velocity (V_s), Effective porosity and permeability**.**

5. RESULTS AND DISCUSSION

5.1. Reservoir Mapping

The lithological and stratigraphy study of the reservoir using GR log shows that the geological units are predominantly sand and shale with increasing trend of high sand/shale ratio, confirming the area of interest to be within Agbada formation of the Niger delta [4], as shown in Fig. 4. The correlation revealed five stacks of sand units in the reservoir namely; horizon A,B,C,D,E,F across the five wells with thickness of approximately 84m,100m,102m,96m,133m respectively, the lateral variation in reservoir thickness which tends to be thickest at Law 004 is strongly controlled by differential subsidence variation from compaction of sediments and the presence of growth faults as indicated in Niger delta [26].Comparisons drawn between the correlation derived and other existing correlations in the industry fits the lower part of the Agbada formation in the Niger Delta region [4,11,17].

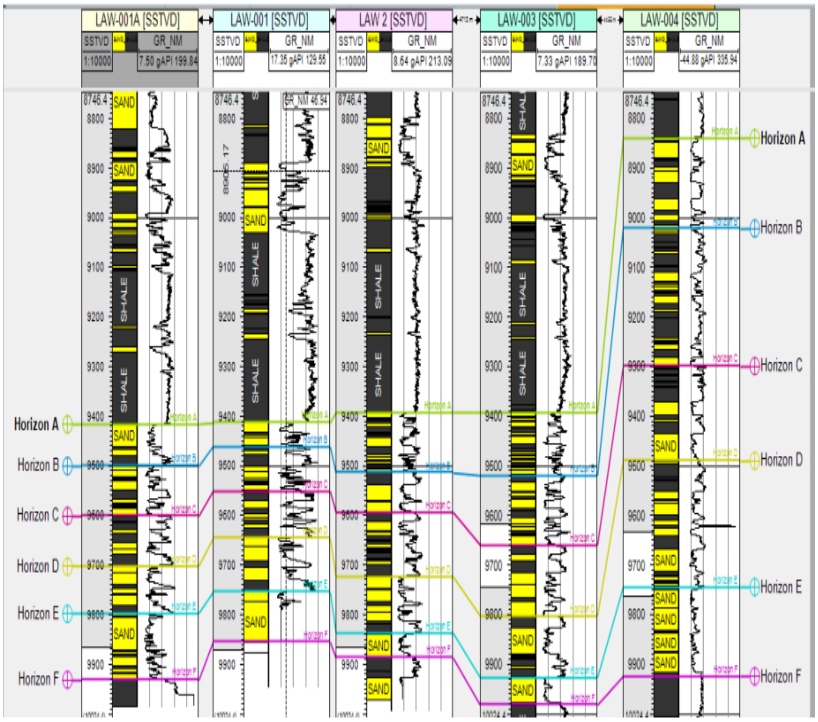

Fig. 4: Well logs from law 1A, 001, 2, 003, 004 showing delineated horizon of the studied reservoir using GR log

Table 1 and Fig. 5, show the elastic properties, petrophysical parameters, rock strength (UCS), as well as logs of Law 001A derived using empirical relation to characterise the sands and the shale of the various units of the studied reservoir. Results in all wells show significant variation in properties between the shale and the sand. In Table 1, average sand parameters show lower Poisson ratio (0.28), Young, Bulk, Shear modulus and unconfined compressive strength (2.4GPa, 10.5GPa, 6.83GPa, 14.44MPa respectively), higher compressibility and porosity (0.1 GPa^{-1}, 0.25) making it more brittle with high potential to tensile failure. On the other hand the shale have higher Poisson ratio, Young, Bulk, Shear modulus and rock strength (0.35, 8.93GPa, 18.08GPa, 21.01GPa, 56.17MPa respectively) lower compressibility and porosity (0.06 GPa^{-1}, 0.06) making it more ductile as a result of its clay content, stiffer (high moduli), less compressible than the unconsolidated sand. Rock strength (UCS) is a function of elastic modulus, hence the higher the elastic modulus of a material the higher the Rock strength [3].

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The shale has maximum average rock strength value of 56.17MPa, which is the force that can be applied to the shale unit without breaking or causing the rock to fail completely under compression.It means larger vertical stress or pressure is needed to achieve deformation in the shale than the sand (14.44MPa).These properties also make the shale fracture stimulation barriers, thus the sandstone of the studied reservoir will fracture before the shale in a hydraulic fracture process under the same fracture gradient while the shale will form a seal to the fracture growth. This is one of the primary causes of separate reservoir compartmentalization, where series of permeable sands are separated by impermeable shales [19]. The result also shows porosity to be high in sand and very low in shale making shale denser and stiffer. Pores are one of the weakest and the most deformable elements in rocks, thus increase in porosity resulted to decrease Rock strength and elastic moduli of the units.

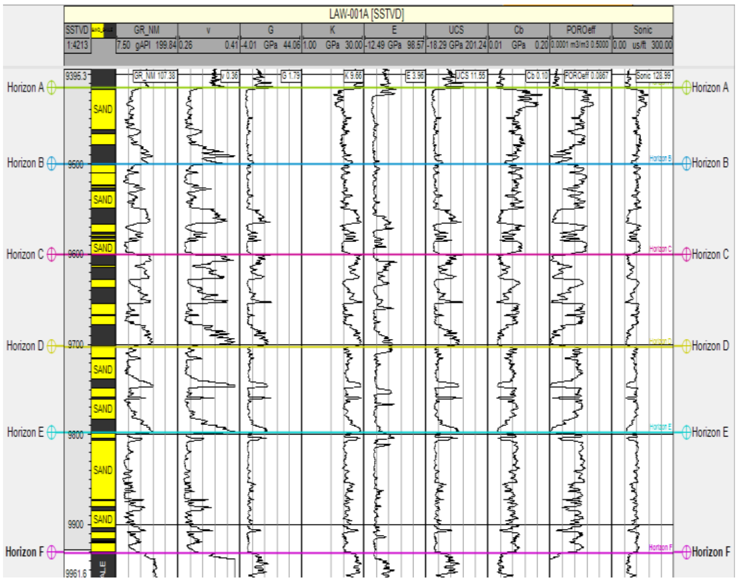


Fig. 5: Geomechanical properties logs showing lithology, poisson ratio (v), Bulk modulus(K), Shear modulus (G), Young modulus (E), the unconfined compression strength (UCS), Bulk compressibility (C_b), effective porosity, compression velocity (V_p) of the Law 001A.

Table 1: Showing Average of Elastic Parameters, Porosity and Unconfined Compressive Strength for Sand and Shale Units of the Five Well of the Studied Reservoir.

WELL	LITHOLOGY	GR API	Poro Eff	V	G Mpa	K_bMpa	E Mpa	C_b Mpa^{-1}	UCS Mpa
LAW	SAND	45.57	0.25	0.28	2.24	10.24	6.84	0.10	9.45
001A	SHALE	105.29	0.07	0.36	10.42	19.14	17.32	0.06	47.30
LAW 001	SAND	40.76	0.24	0.27	1.65	9.27	4.64	0.109	10.71
	SHALE	96.76	0.06	0.33	7.7	17.07	20.02	0.062	47.743
LAW 2	SAND	41.46	0.23	0.28	1.53	9.01	4.29	0.11	11.87
	SHALE	97.30	0.06	0.34	8.35	17.62	21.48	0.06	52.12
LAW 003	SAND	37.07	0.23	0.27	1.79	9.52	9.52	0.1	14.57

	SHALE	91.71	0.05	0.33	9.61	18.52	24.28	0.05	61.87
LAW 004	SAND	36.05	0.21	0.28	4.58	12.24	8.87	0.09	25.62
	SHALE	109.06	0.04	0.37	8.58	18.05	21.95	0.06	69.34
RESERVOIR SAND AVERAGE		40.18	0.25	0.28	2.4	10.05	6.83	0.1	14.44
RESERVOIR SHALE AVERAGE		100.02	0.06	0.35	8.93	18.08	21.01	0.06	54.17

5.4. Relationship between Geomechanical Parameters, Rock Strength and Properties with Depth

Despite the considerable scatter in data for each elastic modulus in the formation as a result of anisotropic effect, there is marked increase of unconfined compressive strength with elastic properties. The cross plots shows that higher values of elastic moduli are a function of a more consolidate or compacted unit, which denotes the shale units in the studied formation. Cross plots of unconfined compression strength were also carried out against petro physical parameters (porosity and acoustic travel time), this is to confirm the relationship according to [8,9], where increase in unconfined strength is a function of decrease in porosity and acoustic travel time. There is also an appreciable increase in elastic and inelastic properties with depth as shown in Fig.8a and b, The observation is as a result of compaction due to overburden loading under effective stress conditions resulting in fluids expulsion, increase in grain contacts, density, Biot's coefficient.

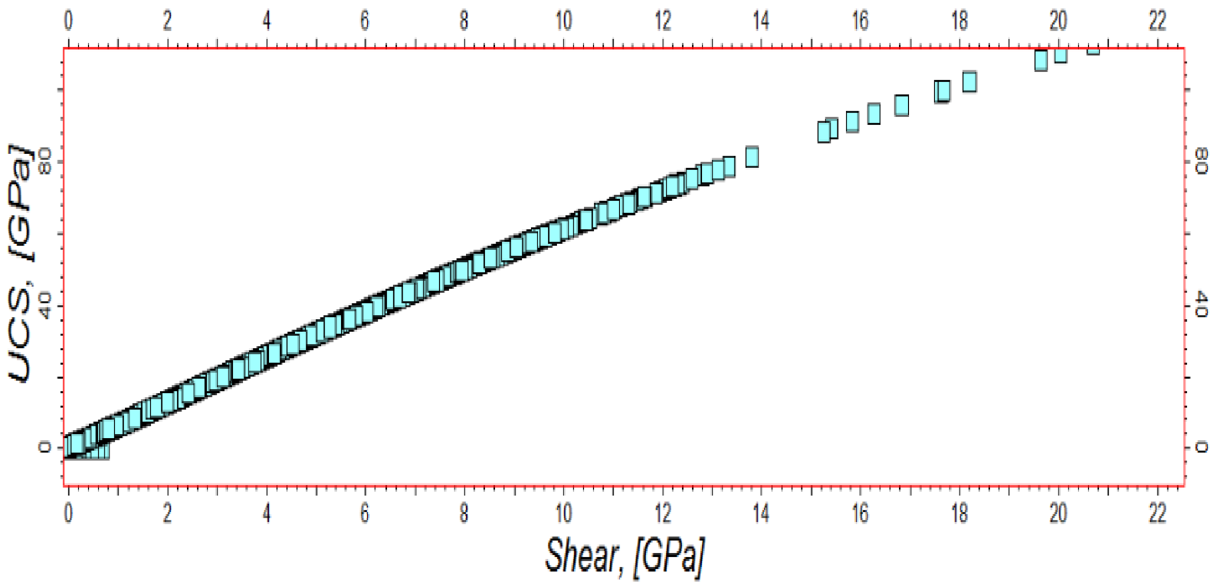


Fig. 6a: Relationship between Unconfined Compressive Strength (UCS) of the Reservoir Sand Units and Shear Modulus [G] for Well Law 001.

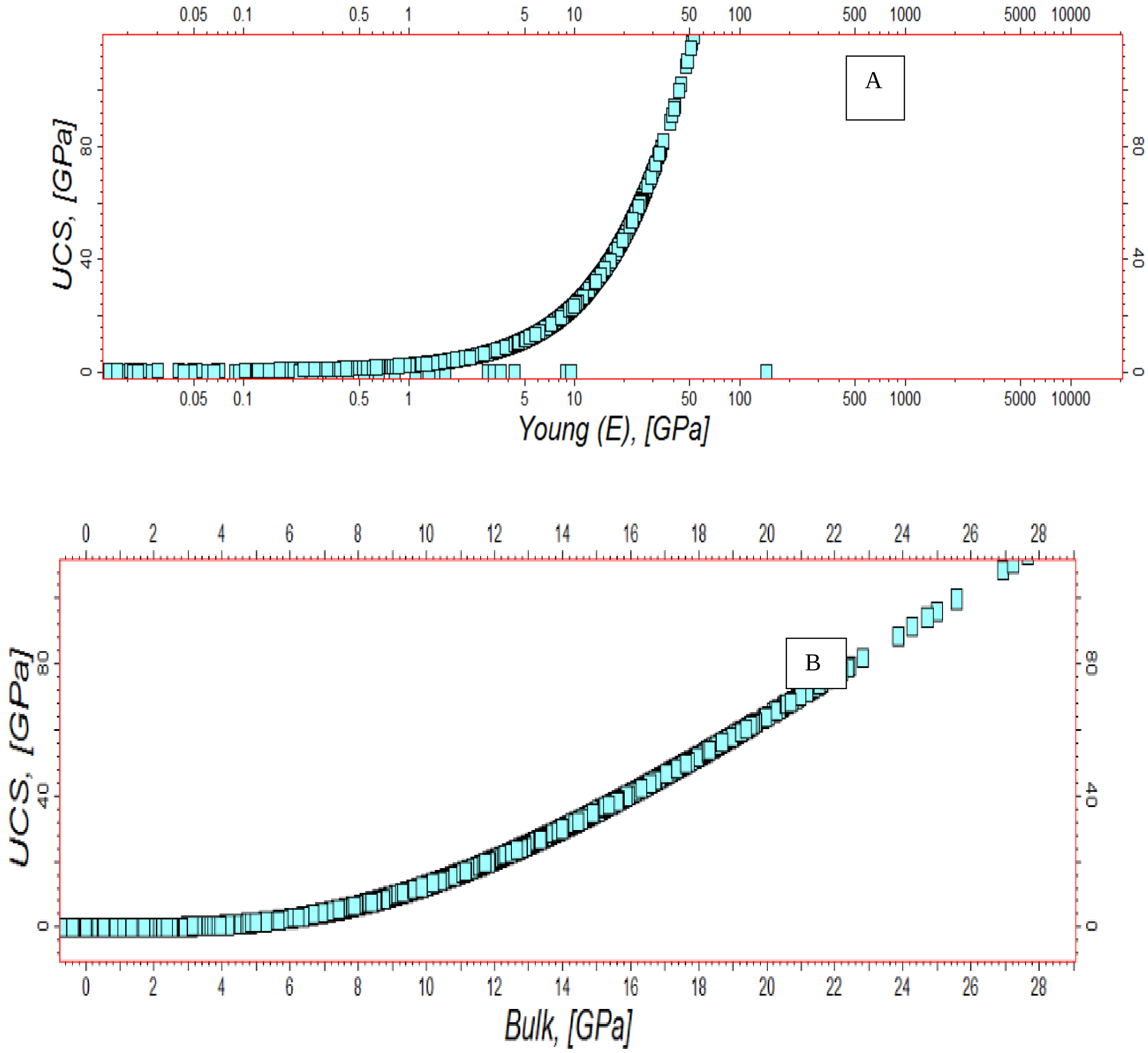
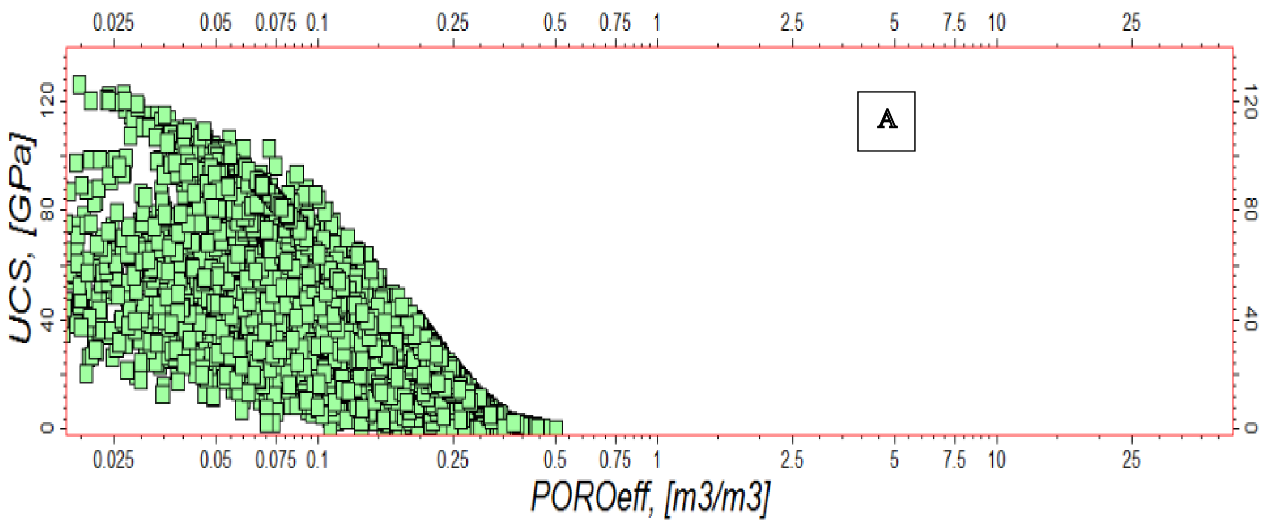


Fig. 6b: Relationship between Unconfined Compressive Strength (UCS) of the Reservoir Sand Units (A) Young Modulus [E] (B) Bulk Modulus [K] for Well Law 001.



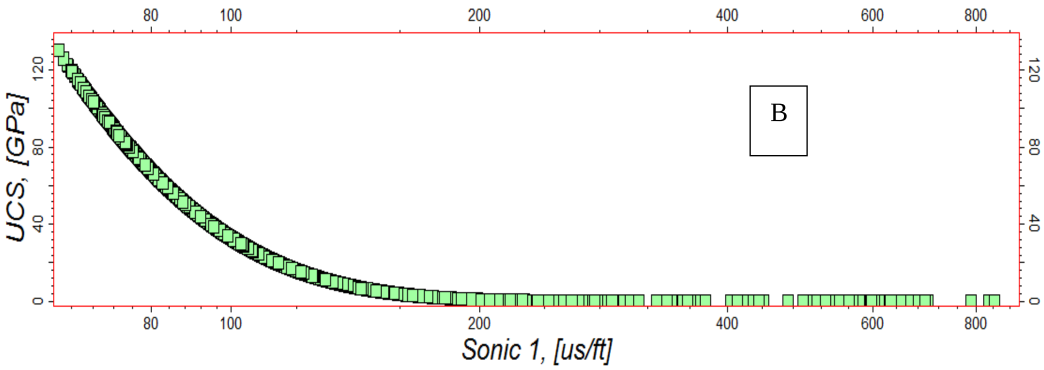


Fig. 7: Relationship between Petrophysical Parameters (porosity and acoustic sonic) Against Unconfined Compressive Strength (UCS) of Law 4; (A) Porosity and (B) Acoustic Sonic.

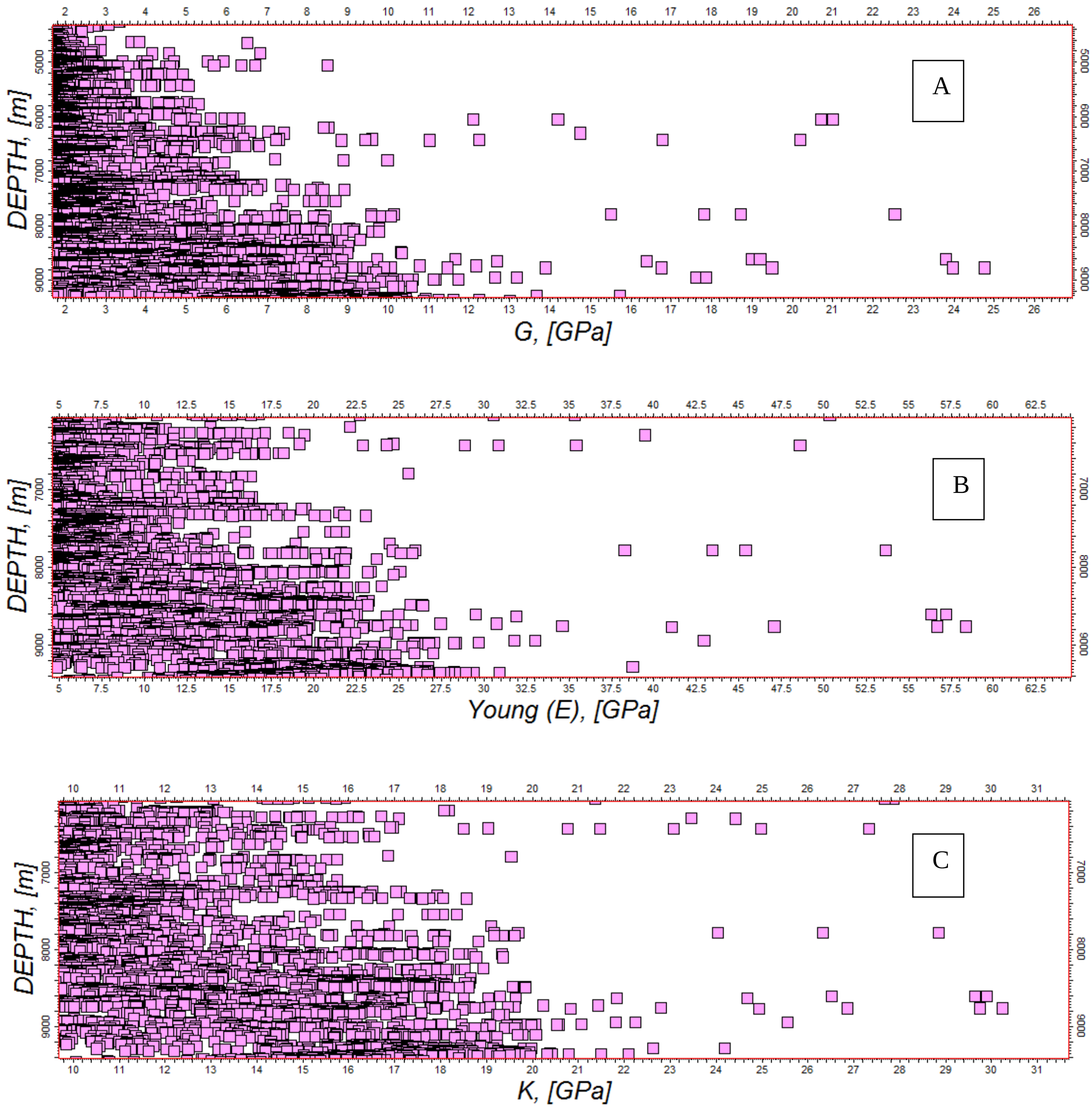


Fig 8a: Relationship between depth and the elastic and inelastic properties of the reservoir for Well Law2; (A) Shear Modulus [G] (B) Young Modulus [E] (C) Bulk Modulus [K] .

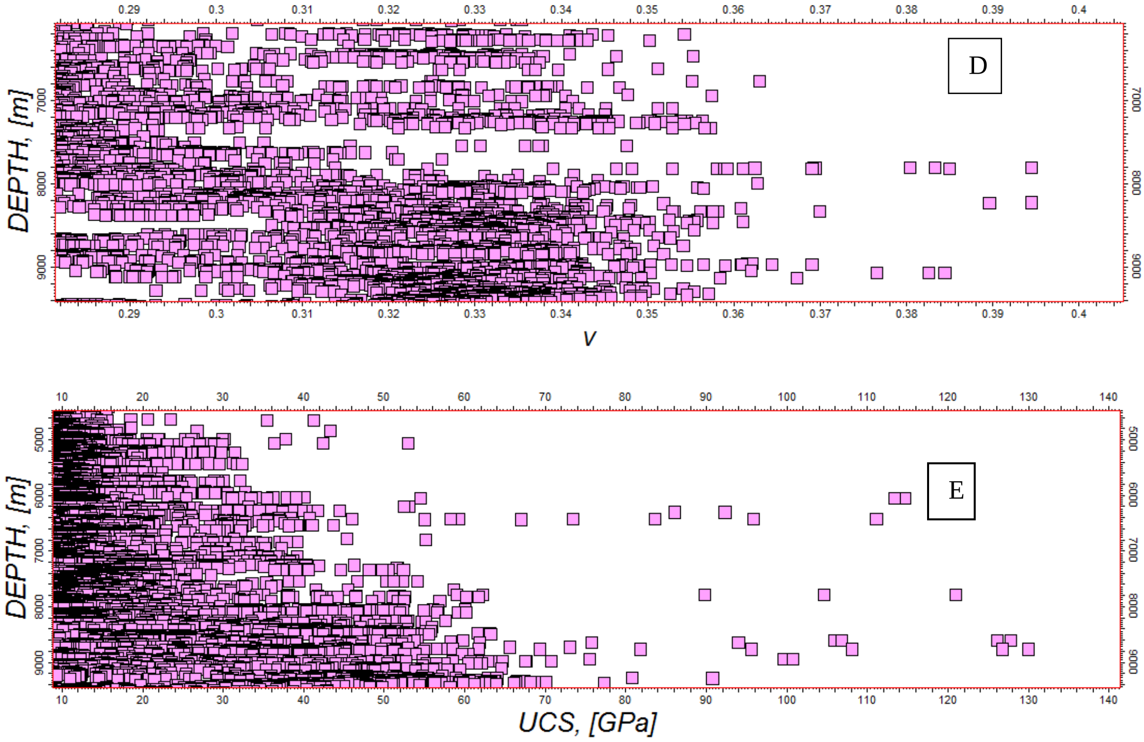


Fig 8b: Relationship between depth and the elastic and inelastic properties of the reservoir for Well Law 2; (D) Poisson's Ratio [v] (E) Unconfined Compressive Strength [UCS]

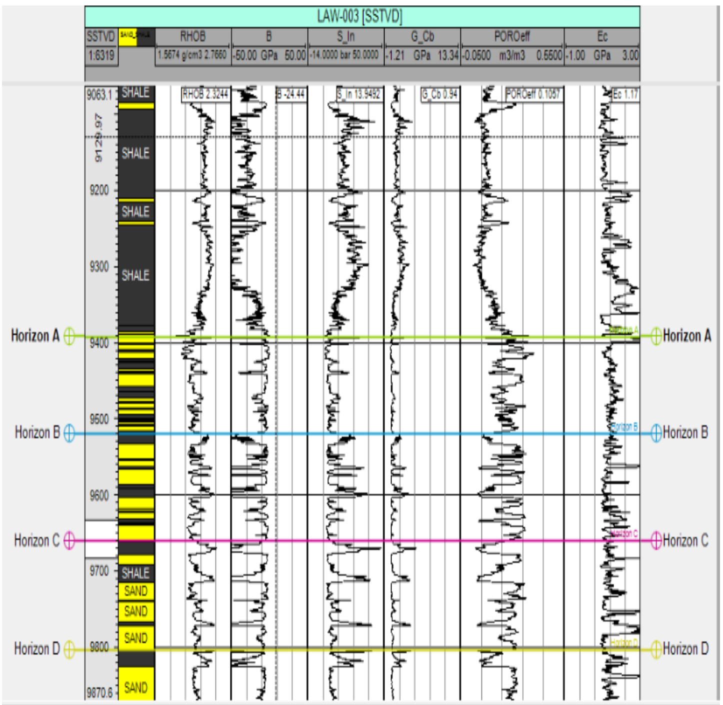


Fig. 9: Correlation of Sand Production Prediction Logs (Schlumberger sand Production Index Sand (S/I), Production Index (B), the Ratio of Shear Modulus to Bulk Compressibility (G/C_b), Combined Modulus Method (E_c) with Effective Porosity of Law 003.

5.5. Sand Production Prediction and Critical Drawdown Pressure

The calculated Geomechanical parameters were used to generate the prediction of sanding parameters as well as the critical drawdown pressure of the studied reservoir. According to [5], Geomechanical parameters such as elastic moduli and rock strength are needed in order to have an effective mechanical evaluation of rocks. The prediction was carried out from generated logs of five sand production methods; Schlumberger sand production index, sand production index, the ratio of Shear modulus to Bulk compressibility and combined modulus method were calculated from Geomechanical parameters of all the wells as shown in Fig. 9 and Table 2.

Table 2: Summary of Sand Production Prediction Methods of the Studied Reservoir and the critical drawdown pressure (CDD).

WELL	G/C_b $10^{12}{}_{psi}{}^2$	B $10^6 psi^2$.	S/I $10^{12} psi^2$	E_c $10^6{}_{psi}{}^2$.	CDD MPa
LAW 001A	0.41	1.98	1.53	2.89	23.56
LAW 001	0.9	1.08	1.13	2.32	16.76
LAW 2	1.02	1.43	1.32	2.27	17.12
LAW 003	0.72	1.22	1.06	2.07	14.48
LAW 004	0.65	1.13	0.98	1.98	13.61
SAND PRODUCTION PREDICTION INDEX AVERAGE	0.74	1.36	1.19	2.3	17.1

5.5.1. Shear modulus to Bulk compressibility ratio (G/C_b)

This was used for prediction of sanding in the five wells of the reservoir of interest, from the study the value of G/C_b fell between $0.41\times10^{12}psi^2$ and $1.02\times10^{12}psi^2$ with an overall average of $0.74\times10^{12}psi^2$. According to [25],this empirical correlation implied that a threshold for sanding existed at $G/C_b= 0.8\times10^{12} psi^2$ whereas values less than $0.8\times10^{12}psi^2$ suggest a high probability of sanding.

5.5.2. Sand production index (B) method

This has its values between $1.08\times10^6 psi^2$ and $1.98\times10^6 psi^2$ as shown in Table 2 with an overall average of $1.36\times10^6 psi^2$ When the sand production index *(B)* increases ,it indicates that the rock elastic modulus is high, thus rock is stiffer and has good stability. When *B* is less than $2.0\times10^6 psi^2$, exploitation will produce the high reservoir sand [1].

5.5.3. Schlumberger sand production index Method (S/I)

From Table 2 the values ranges between $0.98\times10^{12}psi^2$ and $1,53\times10^{12}psi^2$ with an average of $1.19\times10^{12}psi^2$.When the Schlumberger sand production index of a formation is less than $1.24\times10^{12}psi^2$ the formation is likely to produce sand and sand control may be necessary [1].

5.5.4. Elastic Combined modulus (E_c)

In this method, the prediction of sand is based on acoustic travel time and density logging data and its values fell between $1.98\times10^6 psi^2$ and $2.89\times10^6 psi^2$ with a gross average of $2.3\times10^6 psi^2$.According to [1], when *Ec* is greater than $2.608\times10^6 psi^2$, formation may require sand control.

The sand production prediction methods carried out in the studied reservoir shows that the formation falls below the threshold of the cutoffs of the four sand prediction techniques using elastic parameters and physical rock properties (acoustic time and density), as shown in Table 3, the Shear modulus to Bulk compressibility ratio (G/C_b) method predict the highest potential of sand influx of the reservoir. These validate that the delineated sandstone is highly unconsolidated.

5.5.5. Critical drawdown pressure

The Critical drawdown pressure (CDD) of the wells which can attenuate sand production rate was also evaluated, the values fell between 14.48 MPa and 23.56 MPa with an average of 17.1 MPa. Generally, as reservoir fluids are being produced pressure differential and frictional drag forces are created that can combine to exceed the formation compressive strength, however if the critical flow rate of production is maintained below 17.1MPa then the pressure differential and frictional drag forces will not be strong enough to exceed the rock compressive strength to cause sand production. According to [1], when the critical drawdown pressure (CDD) is smaller than the reservoir unconfined compressive strength (UCS) by half, it can keep the reservoir to a great extend from sanding.

6. CONCLUSION

Geophysical measurement, an alternative and reliable approach in the absence of core data was used to successfully achieve the ultimate deliverables of this paper which is to study the deformability and strength of a studied reservoir in the Niger Delta. This entails the evaluation of mechanical parameters (Poisson ratio, Young modulus, Bulk modulus, Shear modulus, compressibility) and unconfined compressive strength (UCS), correlate the determined parameters to petro physical properties of interest and prediction of sanding of the studied reservoir during production.

The evaluated reservoir is predominantly unconsolidated sandstone and compacted shale, shows reservoir sand units having lower Poisson ratio, Young, Bulk, Shear modulus and Unconfined compressive strength as (0.28, 2.4GPa, 10.5GPa, 6.83GPa, 14.44MPa respectively) higher compressibility and porosity as (0.1 GPa^{-1}, 0.25) making it more brittle with high potential to tensile failure,the reservoir shale showed higher value of Poisson ratio due to its ductility which is controlled primarily by clay content, higher Young modulus , Bulk modulus , Shear modulus and unconfined compressive strength as (0.35, 8.93GPa, 18.08GPa, 21.01GPa, 56.17MPa respectively) with lower compressibility and porosity as (0.06 GPa^{-1}, 0.06 respectively) making it stiffer (due to high moduli), more resistive to overburden stress, less compressible than the unconsolidated sand. These properties make the shale fracture stimulation barriers, thus the sandstone of the studied reservoir will fracture before the shale in a hydraulic fracture process under the same fracture gradient while the shale will form a seal to the fracture growth. It also causes reservoir compartmentalization, where series of permeable sands are separated by impermeable shales [19].

The deformability and rock strength were calibrated and justified in the studied reservoir by a correlation of the mechanical properties and petro physical property (porosity and acoustic sonic), since factors affecting rock strength, elastic modulus and petrophysical properties (porosity, volume of shale etc.) are the same. Pores are one of the weakest and the most deformable elements in rocks, hence increase in porosity resulted to decrease Rock strength and elastic moduli with respect to porosity of the units were recorded. The cross plots confirm a marked increase of unconfined compressive strength with elastic properties and relative decrease in porosity and acoustic travel time [8,9]. The compacted Shale units in this study, therefore have higher rock strength than the highly porosity unconsolidated sandstone units.

The results from the mechanical property evaluation were applied to sand production prediction analysis, and it confirms the Schlumberger sand production index [28-30] Sand production index [29,30] , Shear modulus to Bulk compressibility ratio [25] and Combined modulus method all predict high potential sanding of the studied reservoir during production but then, if the critical flow rate of the production is maintained below 17.1MPa then the pressure differential and frictional drag forces might not be strong enough to exceed the rock compressive strength and cause sand production.

Based on the observation in this work, the sand production evaluation and Geomechanical analysis results are consistent with the unconfined compressive strength (UCS) derived from well logs and the highly porous and unconsolidated sand units of the studied reservoir. Therefore it is concluded that Geomechanical evaluation built for other regions of the world for optimal production do not yield accurate results when used for the Niger Delta region, as heterogeneity can cause time dependent and non-time dependent anisotropies in rock strength, elastic properties and in situ stresses [6].

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