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SENSITIVITY ANALYSIS OF GEOMECHANICAL PROPERTIES OF HYDROCARBON RESERVOIRS USING CROSS PLOT METHOD IN X-FIELD SOUTHEAST NIGER DELTA.

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ABSTRACT

The sensitivity analysis of geomechanical properties of production-induced compaction of reservoirs in X-Field deploying well log data has been investigated. The study aims to utilize the estimated geomechanical properties to evaluate the relationships and sensitivity of cross-plotted properties to probable failure mechanisms, and to infer compaction due to production within the reservoir interval. The petrophysical analysis of this study reveals that the selected reservoir-3 interval across the three study wells exhibits better reservoir thickness, porosity, hydrocarbon saturation, net-to-gross, and a lower volume of shale and water saturation. The reservoir interval is predominantly sandstone with varying intercalation of shale. The geomechanical properties results from the selected reservoir-3 interval reveals relatively low elastic moduli and UCS, as well as relatively high compressibility and Poisson's ratio. This suggests that the dominant porous reservoir sands are unconsolidated and friable. The cross plot results reveal that the dominant reservoir sands are unconsolidated, friable, highly deformable, and brittle with very low mechanical strength as a result of low elastic moduli and high compressibility, while the less porous and better consolidated shale is ductile. This depicts that the dominant reservoir sands are susceptible to mechanical failure due to the low elastic moduli, high deformation rate, brittleness, as well as low mechanical strength exhibited by the reservoir. Under overburden, this will give rise to increased compaction of the pore spaces of the reservoir due to the withdrawal of subsurface fluid during production.

Keywords: Geomechanics, Petrophysics, Reservoir, Compaction, Brittleness

1. INTRODUCTION

In the Niger Delta region of Nigeria, there are several environmental challenges and geohazards resulting from the exploration and production of hydrocarbons from subsurface reservoirs in the oil fields. Land subsidence (resulting from the compaction of subsurface reservoirs), wellbore instability, increase in flooding, and other geohazards are some of the resulting challenges [4]. The causative factors of land subsidence include compaction (arising from the withdrawal of underground fluid), sea level rise, and other tectonic activities. According to [21], the Niger Delta basin is sinking between 66.67mm and 200.0mm annually. This could be attributed to the withdrawal of subsurface fluids, resulting in the compaction of the reservoir intervals and the deformation and displacement of the ground surface with attendant environmental and socio-economic impacts. This withdrawal of hydrocarbon is accompanied by

pore pressure and fluid depletion, thereby increasing the effective stress on the grain structure of the reservoir, since the overburden stress (pressure) remains unchanged [16].

Reservoir compaction due to withdrawal of underground fluid (like hydrocarbons and water) and its resulting land subsidence, leading to catastrophic damages to the surface infrastructure, environmental hazards (like flooding), and technical challenges in the oil and gas industry, has been mentioned in the study area [1, 4, 17, 21]. The foundation to evaluating the compaction of reservoirs lies in the deployment of petrophysics and geomechanics for the estimation and evaluation of the relevant properties used for reservoir characterization.

[8, 18, 20] estimated and evaluated the geomechanical properties of Niger Delta oil fields using well logs. The findings of their investigations show that the unconsolidated reservoir sands with a high Poisson's ratio and low elastic moduli are likely to fracture easily under uniaxial stress drilling and production of hydrocarbons from such reservoirs. Again, it was established that the strength of the reservoirs depends on the general disposition of these properties. Recently, [4] estimated the geomechanical properties of the Y oil field in the area for the geomechanical characterization of the field. Unlike the previous studies, the study used the cross plot method to evaluate relationships of the evaluated geomechanical properties. However, this study colour-coded the cross-plotted geomechanical properties with porosity instead of the rock's strength and only utilized one well log for the geomechanical analysis.

Thus, this study intends to close some of these identified gaps by deploying three wells of X-Field to estimate and evaluate the relevant petrophysical and geomechanical properties of the field. The evaluated petrophysical properties within the correlated reservoir intervals were used for the selection of the best reservoir interval for geomechanical properties estimation and further analysis. From the selected reservoir, the relevant geomechanical properties were estimated dynamically using relations found in literature (Table 2) and cross plotted using UCS as the third dimension. The cross plots were done to

evaluate relationships and sensitivity of cross plotted geomechanical properties to probable failure mechanisms and to infer compaction within the reservoir interval.

2. LOCATION AND GEOLOGY OF THE STUDY AREA

The study area is located in the South East Niger Delta, delineated by latitude 4.15°N - 7.17°N and Longitude 5.00°E - 8.68°E (Figure 1), with the inline (70000-76000) and x-line (460000-466000) given by the base map (Figure 2). The Niger Delta basin is located at the peak of the Gulf of Guinea and was given rise to by the rifting of the South American and African plates during the last stage of the Jurassic era [22]. Geologically, the study area is a complex sedimentary basin, and it is characterized by progradational cycles of sedimentation and fault growth [19]. The Akata, Agbada, and Benin formations are the major lithographic units, underlying an area of about $256,000\text{km}^2$ [2]. The field's structure comprises extensional faults that provide the pathways for the migration and accumulation of hydrocarbons, and it covers a vast area of wetlands and riverine environments [15].

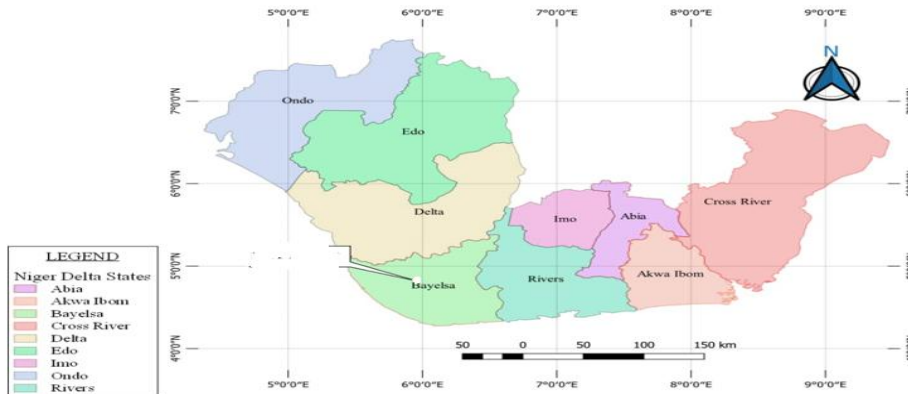


Fig. 1 Study Area Map [16]

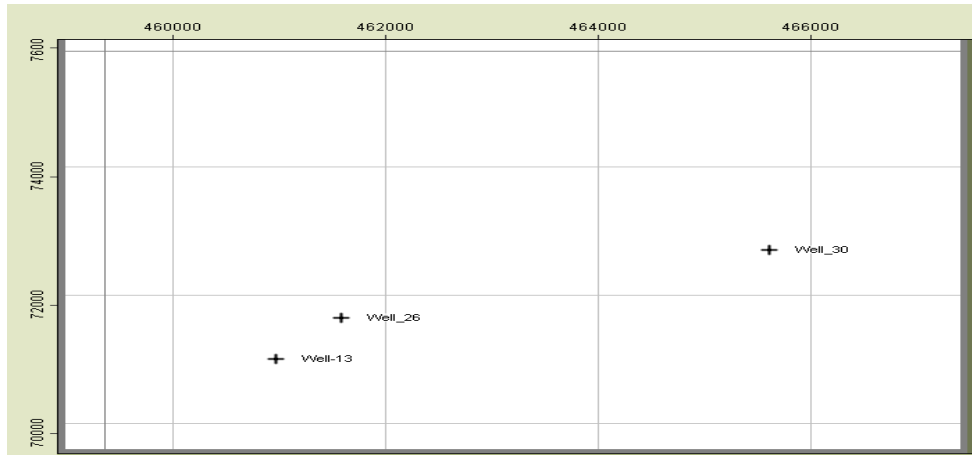


Fig. 2 Base Map of the Study Area

3. MATERIALS AND METHOD OF STUDY

Suit of well logs comprising gamma ray, resistivity, density, neutron, and sonic logs, and RokDoc (2.0 Ikon Science) software are the major materials used for the study. The gamma ray and resistivity logs were integrated for the reservoir delineation and correlation. The relevant petrophysical properties were estimated within the correlated reservoir intervals for analysis. From the selected reservoir interval, the relevant geomechanical properties were estimated using established relations (Table 1) and cross plotted to evaluate relationships and sensitivity of the estimated properties for reservoir compaction investigation.

Table 1. Relevant Geomechanical Properties

Geomechanical Properties	Relationship	Measured Parameter
Young's Modulus (E)	$G = \frac{E}{2(1+\nu)}$	Rigidity of the Rock
Shear Modulus (G)	$E = 2G(1+\nu) = 3K(1-2\nu)$	Stiffness of the Rock
Bulk Modulus (K)	$K = \frac{E}{3(1-2\nu)}$	Volume Change/ability of the Rock to resist compression
Poisson's Ratio (ν)	$\nu = \frac{3K-2G}{2(3K+G)}$	change in shape/deformation of the Rock
Compressibility (β)	$\beta = \frac{E\nu}{(1+\nu)(1-2\nu)}$	Compression/Squeezing of the Rock
Unconfined Compressive Strength (UCS)	$UCS = 2.28 + 4.1089E$	Strength of the Rock

4. PRESENTATION OF RESULTS

4.1 Petrophysical Properties Results and Analysis

Three probable hydrocarbon-bearing zones were delineated and correlated across the wells (Figure 3). The well correlation was done to reveal the general stratigraphic continuity and to identify equivalent reservoirs of the oil field. The delineated reservoir intervals are made up of the intercalation of sand and shale lithofacies. From the three correlated reservoir intervals, Porosity (ϕ), permeability (K), shale volume (VSH), water saturation (SW), hydrocarbon saturation (SH), Net-to-gross (NTG), and density (ρ) were estimated (Table 2). The estimated properties indicate a low gamma ray and consequently low shale volume [5], low water saturation, high resistivity, high hydrocarbon saturation, high Net-to-gross, relatively high porosity, and permeability. The analysis of these results (Table 2) shows that the reservoir-3 interval across the wells has better reservoir thickness, porosity, hydrocarbon saturation, Net-to-Gross, and less volume of shale and water saturation. Thus, the reservoir-3 interval was selected for further analysis in the study.

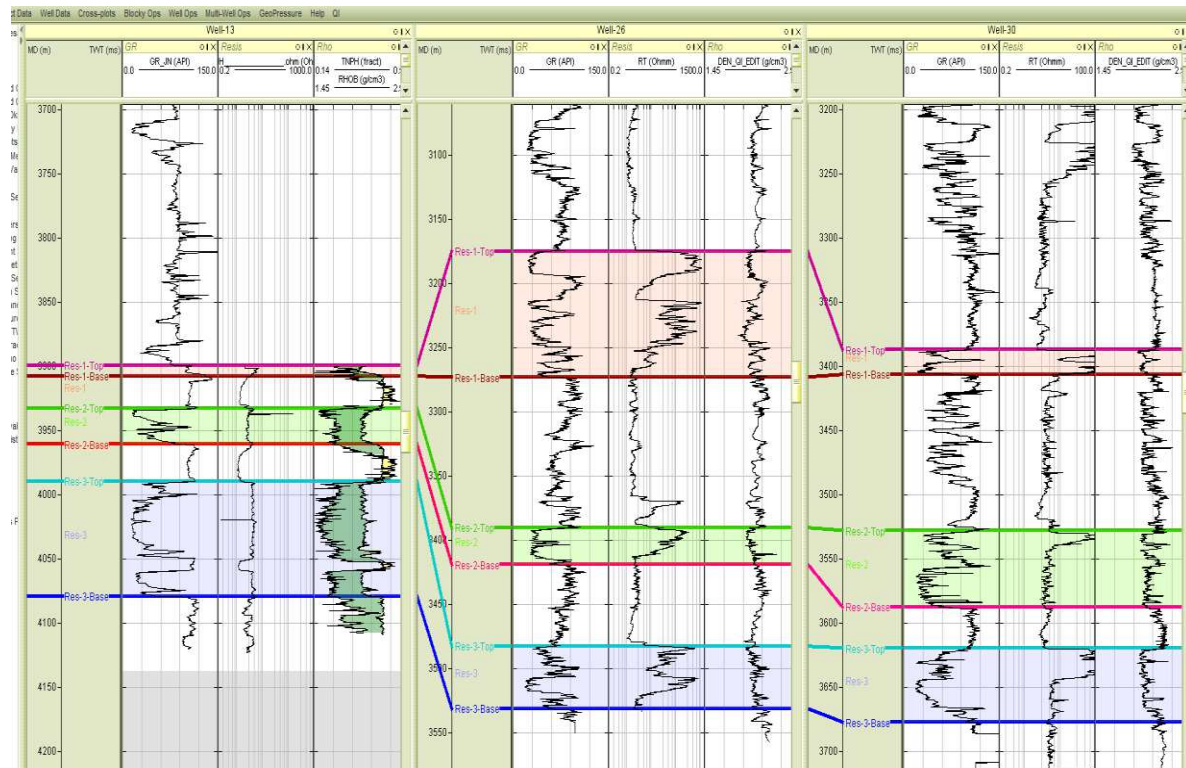


Fig. 3. Correlated Reservoir Log Section

Table 2. Estimated Petrophysical Properties

Properties	Reservoir 1	Reservoir 2	Reservoir 3
Thickness (m)	41.9	38.9	65.3
ϕ (%)	25.6	20.1	26.7
K (mD)	420.6	520.0	375.8
V_{SH} (%)	25.8	10.2	6.8
S_w (%)	14.3	18.8	12.5
S_H (%)	85.7	81.2	87.5
NTG (m)	74.2	89.8	93.2
ρ (kg/m ³)	2213	2178	2239

4.2 Geomechanical Properties Results and Analysis

From the selected reservoir-3 interval, compressional wave velocity (V_P), shear wave velocity (V_S), Poisson's ratio (ν), bulk modulus (K), shear modulus (G), Young's modulus (E), compressibility (β), and unconfined compressional strength (UCS) were estimated (Table 3). The relatively low values of elastic moduli and UCS, and relatively high compressibility and Poisson's ratio observed in the table, suggest that the dominant porous reservoir sands are unconsolidated and friable with intercalation of shales.

Table 3. Estimated Geomechanical Properties for Reservoir-3

Property	Well-13	Well-26	Well-30
V_P (m/s)	3506.9	3088.4	3166.5
V_S (m/s)	1868.7	1587.4	1637.9
G (GPa)	8.9	5.7	6.3
E (GPa)	22.6	14.9	16.4
K (GPa)	17.2	13.7	14.7
ν	0.28	0.32	0.32
β (GPa ⁻¹)	0.059	0.075	0.072
UCS (GPa)	20.5	17.9	21.6

As observed in the geomechanical log section (Figure 5), an increase in V_p and V_s corresponds to a proportionate increase in the elastic moduli (E , G and K) and UCS, as well as a decrease in β and ν for the less porous shale and sorted sands within the reservoir interval. The weight of the overlying rocks (overburden) which results to increase in compaction and reduction in porosity of the reservoir rock is attributed to this increase in V_p and V_s [8], while the increase in compaction resulting to the increase in elastic velocities, rigidity, and stiffness of the rock are fingered as causative factors for the increase in elastic moduli and UCS [13].

Conversely, a decrease in the V_p and V_s corresponds to a decrease in the elastic moduli and UCS, as well as an increase in β and ν for the porous sands. This decrease in the porous reservoir sands interval could be attributed to the weight of the overlying rocks (overburden) which compresses the formation and thereby reduces the pore spaces (and thus porosity), resulting in increase in compaction and compressibility of the rock [11]. This suggests that the dominant reservoir sands are unconsolidated, friable, less resistant to compression (and thus, highly compressible), with low mechanical strength and possible high deformation rate under stress. This discovered nature of the reservoir necessitated a further sensitivity analysis of the estimated geomechanical properties using cross plot method to evaluate relationships. This is aimed at using the sensitivity analysis for probable mechanical failure mechanism investigation and compaction inference of the reservoir interval.

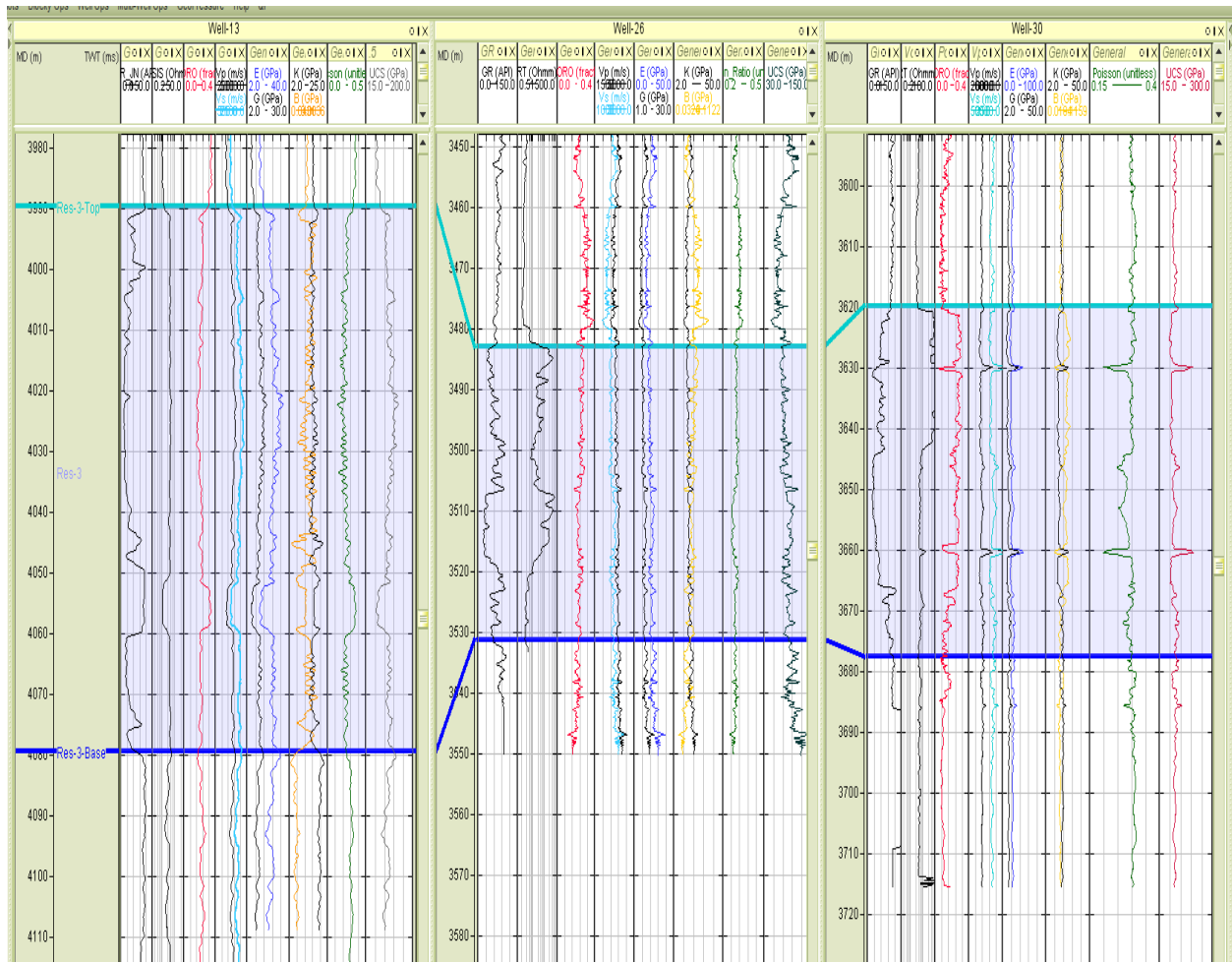


Fig. 5 Geomechanical Property Log Section

4.3 Geomechanical Properties Cross Plots and Analysis

The evaluated geomechanical properties from the selected reservoir-3 interval were cross plotted and colour-coded with UCS. These cross plots were done to evaluate relationships and sensitivity of geomechanical properties to probable failure mechanisms within the reservoir [14, 16]. The cross plot of E versus G (Figure 6) shows a linear relationship. Low E corresponds to low G and low UCS in the porous reservoir sands, and low to moderately high values for the less porous shale. This pattern also appears in plots of Young's modulus versus bulk modulus (Figure 7) and shear modulus versus bulk modulus (Figure 8). Low elastic moduli (E, G, and K) indicate that the porous reservoir sands are less stiff, less rigid, and less compression-resistant. Moderately high elastic moduli indicate that the less porous shale and sorted sands are stiffer, more rigid, and more compression-resistant. This suggests the dominant reservoir sands are friable, unconsolidated, have low mechanical strength, and are brittle.

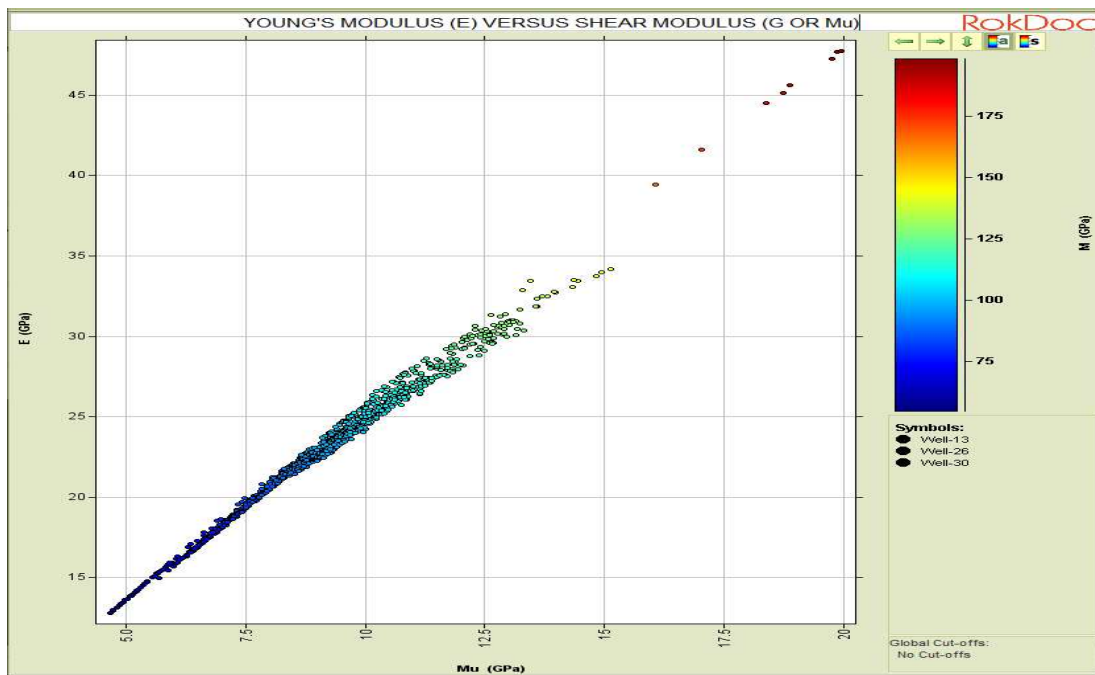


Fig. 6. Cross plot of Young's Modulus versus Shear Modulus

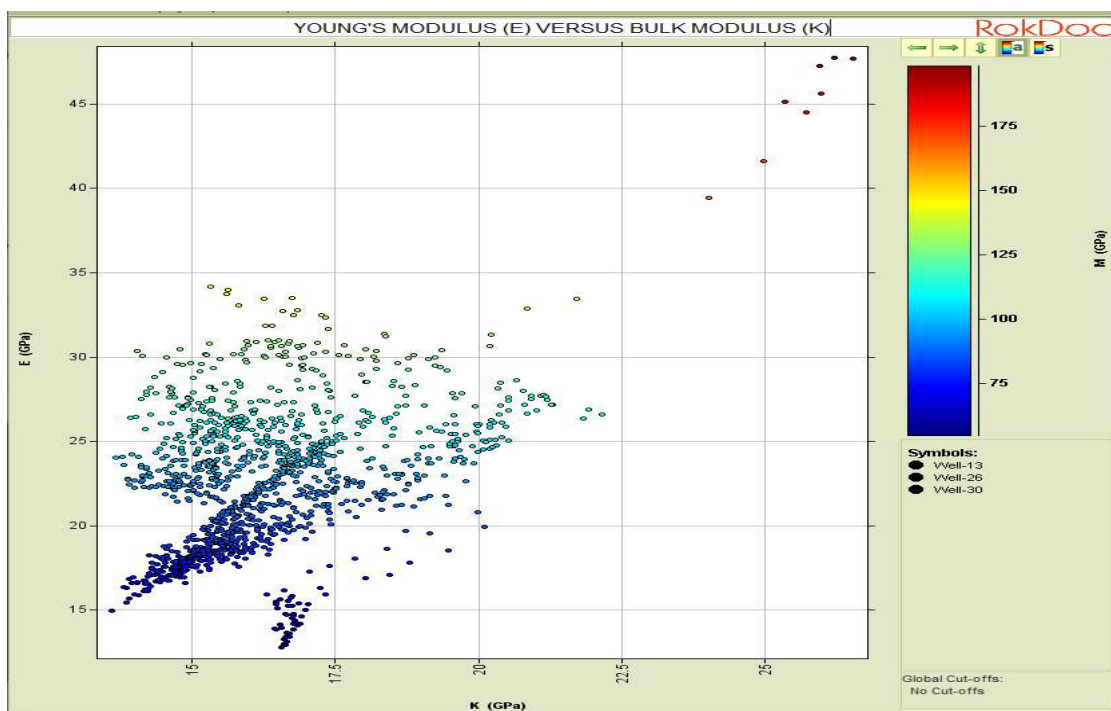


Fig. 7. Cross Plot of Young's Modulus versus Bulk Modulus

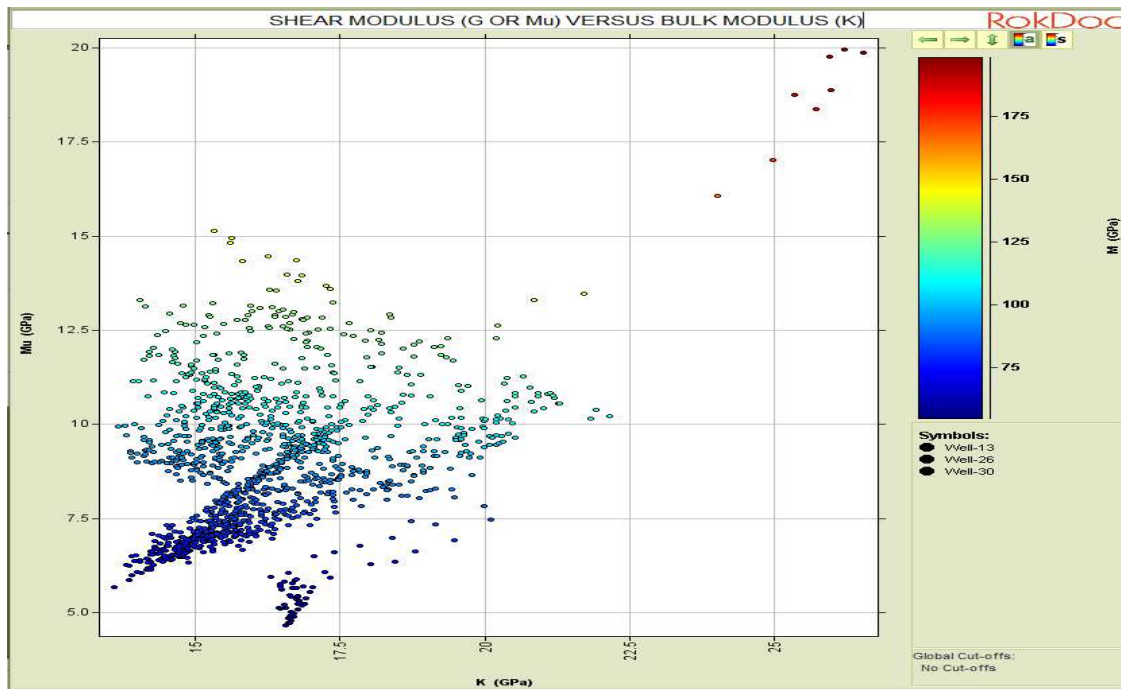


Fig. 8. Cross plots of Shear Modulus versus Bulk Modulus

The result of the cross plot of Poisson's ratio (ν) versus Young's modulus (E) (Figure 9) shows an inverse relationship between the properties, with high ν exhibiting low E and low UCS for the porous reservoir sands, while low ν and moderately high E for the shales. This same result was observed in the cross plots of ν versus shear modulus (G) (Figure 10) and ν versus bulk modulus (K) (Figure 11). High ν with low elastic moduli (E, G, & K) for the dominant reservoir sands implies that the reservoir interval is highly deformable and unconsolidated with low stiffness, rigidity, as well as low resistance to compression and low UCS. These suggest that the dominant porous reservoir sands are highly deformable, unconsolidated, and friable with very low mechanical strength.

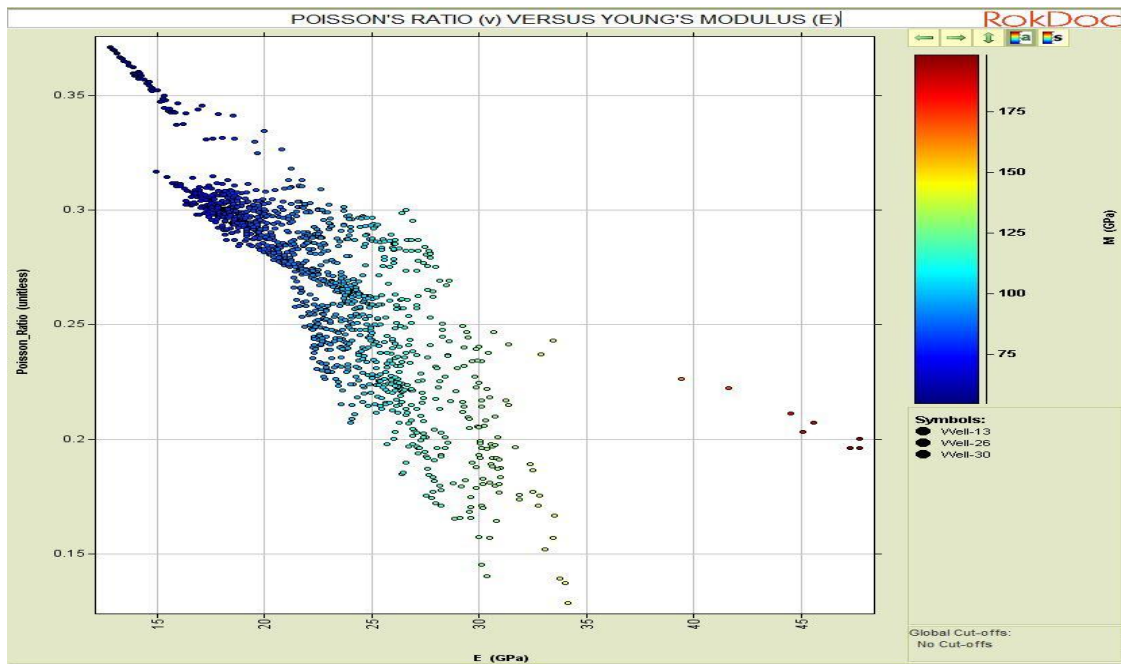


Fig. 9. Cross plot of Poisson's Ratio versus Young's Modulus

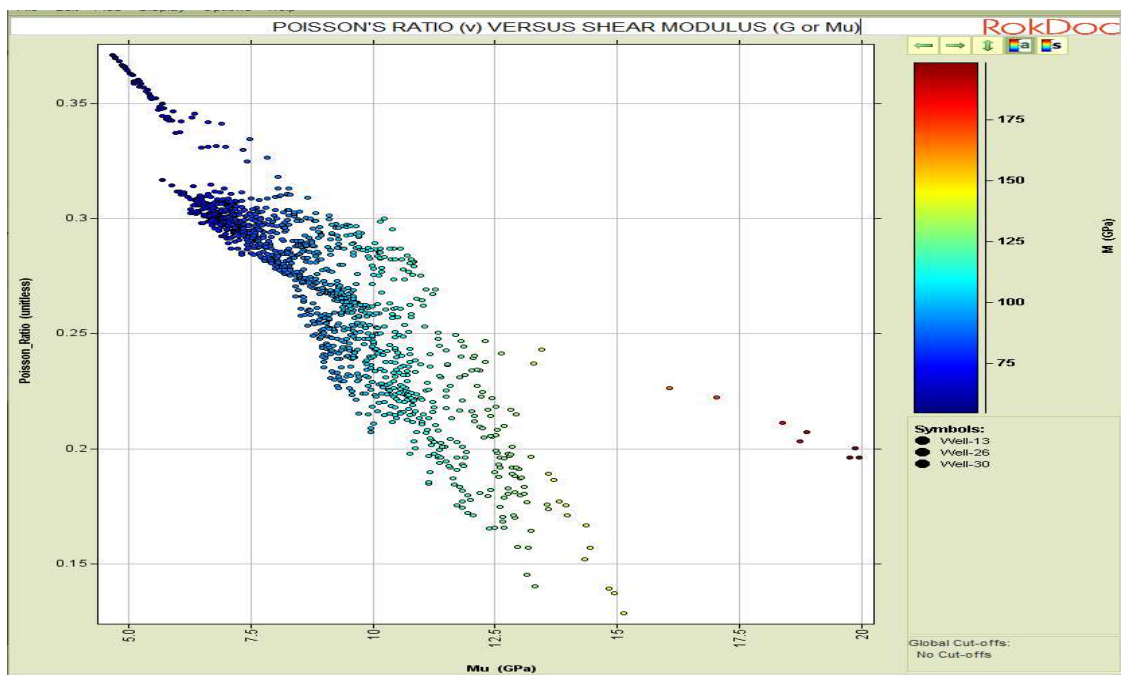


Fig. 10. Cross plot of Poisson's Ratio versus Shear Modulus

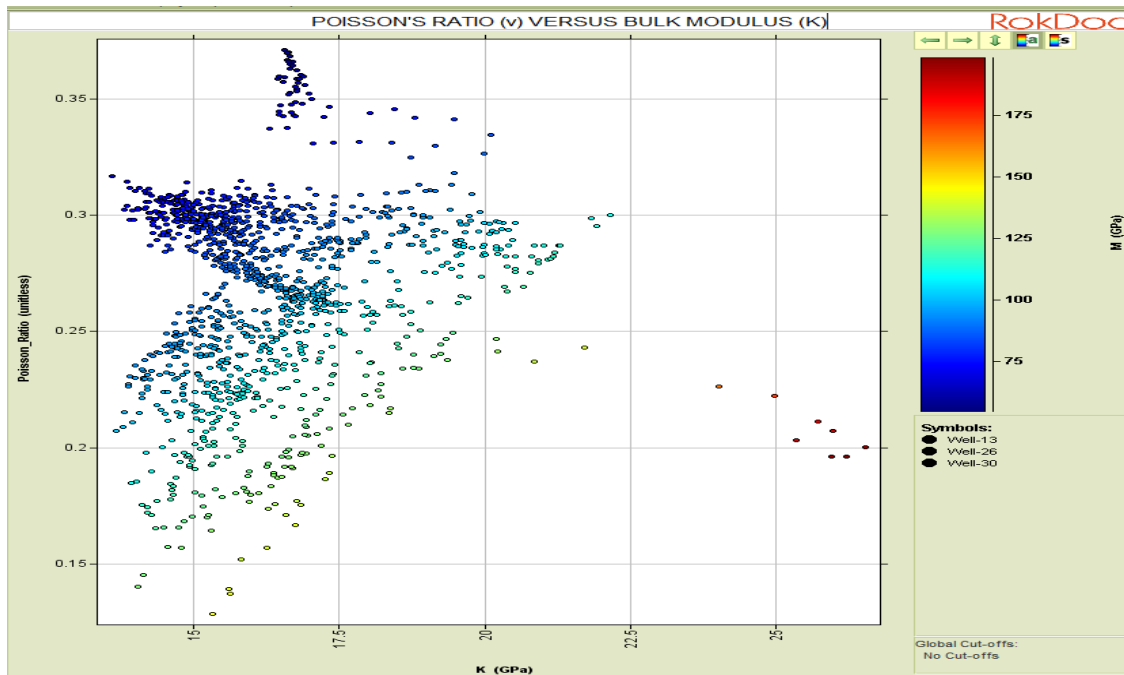


Fig. 11. Cross plot of Poisson's Ratio versus Bulk Modulus

The cross plot of the Young's modulus (E) versus compressibility (β) (Figure 12) shows an inverse relationship between the properties, with low E corresponding to high β for the porous and unconsolidated reservoir sands, while moderate to high E and low β for the less porous shales. The same result was observed in the cross plot of shear modulus versus compressibility (Figure 13). High β implies that the reservoir is highly compressible (with low resistance to compression), unconsolidated, and friable, while low β depicts that the reservoir is less compressible (with high resistance to compression) and consolidated. This suggests that dominant reservoir sands are unconsolidated, friable, highly deformable, and brittle with very low mechanical strength as a result of low elastic moduli and high β , while the less porous and better consolidated shale is ductile.

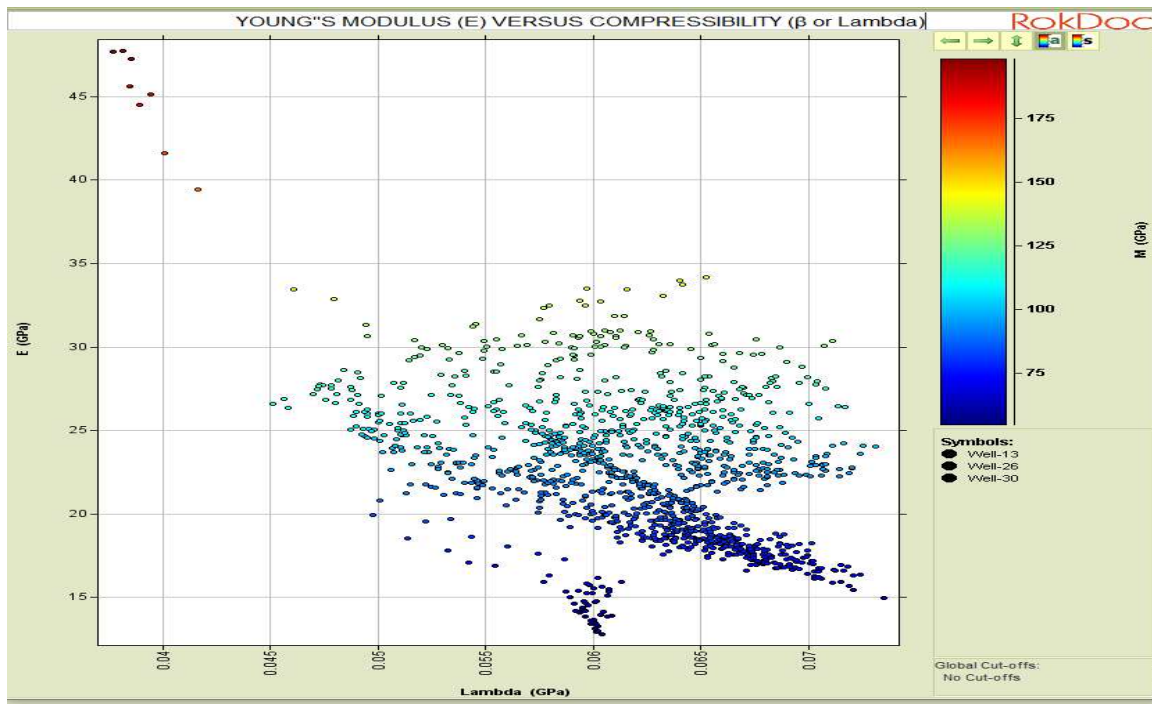


Fig. 12. Cross plot of Young's Modulus versus Compressibility

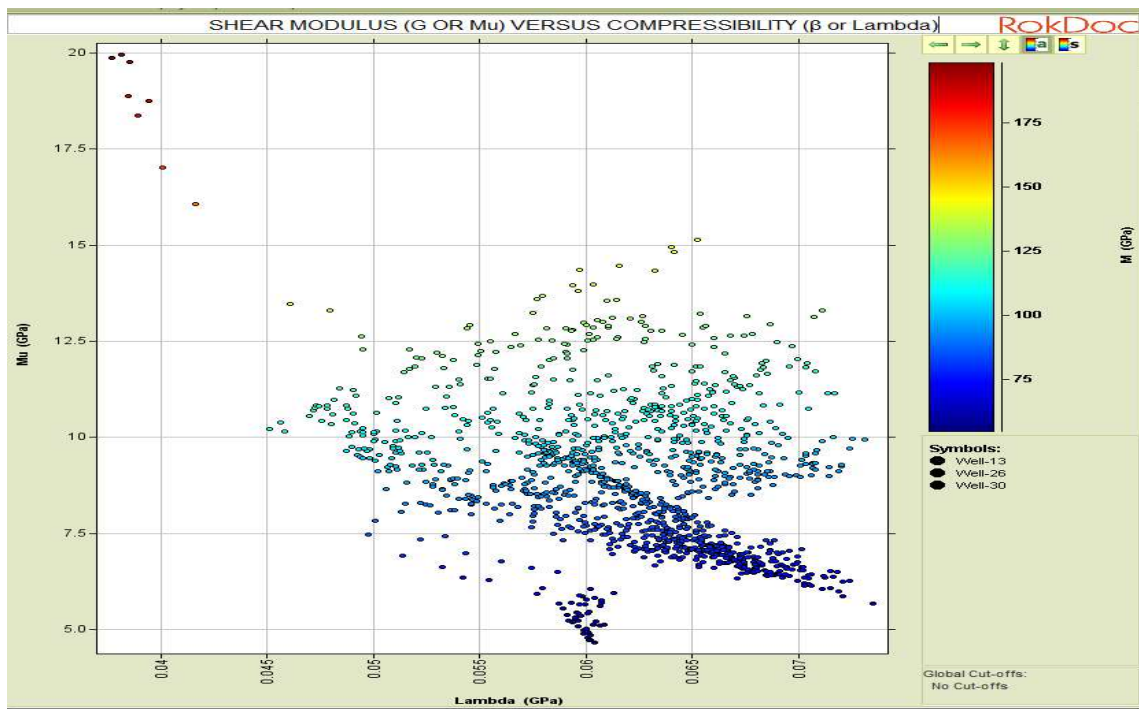


Fig. 13. Cross plot of Shear Modulus (G or Mu) versus Compressibility

5. DISCUSSION OF RESULTS

Results show that the reservoir-3 interval is classed as clean sands based on the high net to gross ratio ($>70\%$) and the low shale volumes ($<30\%$) [12, 17]. Thus, the reservoir is of economic and commercial quality. It is important to note that porous and unconsolidated reservoir intervals with high Poisson's ratio and low elastic moduli tend to be brittle, while the less porous intervals with high ν and high elastic moduli tend to be ductile [3]. It follows that the stiffness, rigidity, and compressibility of reservoirs are influenced by the material's underlying structure (fault pattern) and bonding (compaction) [11].

Due to the brittleness and low mechanical strength exhibited by the dominant porous and unconsolidated reservoir sands, there is a high risk of increased compaction and its resulting land subsidence due to production and withdrawal of hydrocarbons from the subsurface. This is because the compaction of subsurface formations can be transferred to vertical and lateral ground surface displacements, whose magnitude is directly related to the compaction in lateral and depth-wise extents [7]. Again, the primary indicator of reservoir compaction is a lowering and sinking of the ground surface into its surrounding environment [1, 9]. This is based on the fact that subsidence mechanisms include compaction, shear, consolidation pressure, and consolidation path [6]. These depict that under stress (overburden), the reservoir is prone to suffer mechanical failures resulting in the increased compaction of pore spaces and subsequent land subsidence as a result of the low elastic moduli, high deformation rate, brittleness, as well as low mechanical strength exhibited by the selected reservoir. This is because porous reservoirs with low mechanical strength are generally susceptible to compaction and its resulting land subsidence (as a result of brittleness and high deformation rate) [16], wellbore instability, and other technical issues in the oil and gas industry due to the resulting change in the stress fields during and after production [21].

6. CONCLUSION

The geomechanical characterization of a Niger Delta field for sensitivity, relationships, and probable mechanical failure mechanisms of the reservoirs has been investigated using petrophysics and geomechanics. The cross plot results of the evaluated geomechanical properties within the selected

reservoir-3 interval show that the reservoir is unconsolidated and brittle with low mechanical strength, and it is said to be susceptible to mechanical failure as a result of the suspected compaction of the reservoir due to the withdrawal of subsurface fluid during production.

Thus, there is a strong need to investigate the variations of these properties beyond the well control points (at seismic scale) using seismic data sets for a better understanding of the geomechanical properties variation and behaviour of the entire oil field for a better compaction evaluation and analysis. This is because the strength of the reservoir can impart the exploration and production rates of hydrocarbons, leading to compaction and its resulting land subsidence, as well as other mechanical failure mechanisms and environmental geohazards like increased flooding if not properly controlled and mitigated.

Author contributions

Author O.K.M. prepared the manuscript text, took part in the analysis and interpretation of the results. Author E.C.N. took part in the interpretations, analysis, and the proofreading of the manuscript. Author D.T. handled the software analysis and evaluations alongside author O.K.M. The review was done by all authors.

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Data availability

The datasets analyzed during the current study are not publicly available due the confidentiality agreement signed with the oil company operating in the study area that provided the datesets in this study but are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not Applicable.

Consent for publication

Not Applicable.

Competing interests

The authors declare no competing interests.

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