World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Research Article)

Check for updates

Modelling of bulk modulus from sand [API <75]-shale [API >75] lithology for X_A field in the Niger Delta Basin

Atat JG [1,*], Essiett AA [1], Ekpo SS [1] and Umar S [2]

[1] *Department of Physics, Faculty of Science, University of Uyo, Uyo, Nigeria.*
[2] *Department of Physics, Faculty of Physical and Computing Sciences, Usmanu Danfodiyo University, Sokoto, Nigeria.*

World Journal of Advanced Research and Reviews, 2023, 18(03), 635–644

Publication history: Received on 02 May 2023; revised on 11 June 2023; accepted on 21 June 2023

Article DOI: https://doi.org/10.30574/wjarr.2023.18.3.1018

Abstract

Modelling of bulk modulus from sand-shale lithology has been researched. This is to come up with a model than relates the bulk modulus with the Lame's first parameter. Data adequate for this finding were obtained from three Niger Delta oil wells A, B and C. Microsoft Excel was used for all stages of analysis. The result indicates the average values of Poisson's ratio and V_p/V_s ratio as 0.5 and 1.637 respectively for all wells. Other results include the depth range of about 5300ft to 6600ft; shear modulus varies from 4.05 x 10^9 to 11 x 10^9N/m^2; the range of result of young modulus varies from 1.21 x 10^{10} to 3.18 x 10^{10}N/m^2; Lame's first parameter range from 2.75 x 10^9 to 7.20 x 10^9N/m^2; bulk modulus values are within 1.08 x 10^{10} to 2.84 x 10^{10}N/m^2; the elastic parameters with peak values are noted at the depth of 6200ft for well A. For well B, the results indicate the depth of investigation as 8300ft to 10000ft; shear modulus varies from 5.76 x 10^9 to 10.00 x 10^9N/m^2; the range of young modulus varies from 1.73 x 10^{10} to 3.04 x 10^{10}N/m^2; Lame's first parameter range from 3.90 x 10^9 to 6.87 x 10^9N/m^2; bulk modulus values are 1.54 x 10^{10} to 2.71 x 10^{10}N/m^2; the elastic parameters with maximum values are recorded at the depth of about 9900ft. For well C, the depth ranges from 5200ft to 8200ft; shear modulus varies from 7.84 x 10^9 to 1.35 x 10^{13} N/m^2; the range of result of young modulus varies from 2.35 x 10^{10} to 4.04 x 10^{13}N/m^2; Lame's first parameter range from 5.32 x 10^9 to 9.14 x 10^{12}N/m^2; bulk modulus values are within 1.05 x 10^{10} to 1.81 x 10^{13}N/m^2; the elastic parameters with peak values are noted at the depth of 8200ft. The relationship between bulk modulus and Lame's first parameter obtained is $K = 3.9455\lambda$ (or $K = 4\lambda$). Lame's first parameter analysis could permit a better resolution of potential hydrocarbon zones; therefore, in a linear relationship with bulk modulus of about 1.0 correlation coefficient would yield a model which is adequate for mapping of hydrocarbon accumulation.

Keywords: Bulk modulus; Lame's first parameter; Lithology; Model; Shear modulus; Velocity

1. Introduction

Bulk modulus is one of the mechanical properties used in several geoengineering problems (Wang et al., 2022; Bock, 1993; Bell, 1996; Andhumoudine, 2021; Yang and Liu, 2021) and it could be obtained by the stress-strain relation (like static measurement) or the propagating elastic wave velocities (such as dynamic measurement) (Wang et al., 2020). The static bulk modulus symbolizes the mechanical firmness of subsurface basins (Zimmer, 2004; Zoback, 2007). The dynamic moduli can be generally obtainable from seismic or well logging data (Fjaer, 2019; Wang et al., 2022). Mechanical properties of rocks include elastic properties (such as E, σ, μ, K, C_b and SPI) and inelastic properties (like UCS, τ, S_v, Sh_{max} and Sh_{min} and H_p) properties. E represents the elastic modulus, σ represents poisson's ratio, μ is the rigidity/shear modulus, the symbol for bulk modulus is K, C_b equals bulk compressibility, SPI is the Sand Production Index, UCS represents the Uconfined Compressive Strength, τ is shear stress, vertical stress is denoted by S_v, Sh_{max} is the maximum horizontal stress, Sh_{min} is the minimum horizontal stress and H_p is the heat production.

* Corresponding author: Atat JG.

The mechanical properties may be assessed using density log, gamma ray log and sonic log. Bulk modulus valuation could be accomplished from wireline logs using empirical relationships (Zoback, 2007; Fjaer 2019; King, 1969). Bulk modulus of mineral matrix (Kmatrix) ranges from 13 to 23 GPa which is within the bounds calculated for sand (that is, quartz and clay mixture) (Han and Batzle, (2004) for upper and lower bounds of different sandstones (Ahmad and Schmitt, 2006).

Many Researchers have worked on bulk modulus; to highlight some findings, Cheng and Johnston (1981) have worked on the static-to-dynamic bulk modulus ratio for dry Navajo and Berea sandstones which differs from about 0.5 at atmospheric pressure to about unity at 200 x 10^6Pa. Also, Jizba and Nur (1990) concluded that the static bulk modulus is nearly the value of the dynamic modulus at high-stress levels and might decrease to about 50% value of the dynamic bulk modulus at low-stress levels from dry tight gas sandstones constituents (Wang et al., 2022).

Modelling of bulk modulus from reservoir sand (API less than 75) and shale (API greater than 75) lithology is the aim of this research. Bulk modulus is the resistance of a material against compression (or measuring the ability of a material to resist variations in volume when under compression). That is, indicates the compressibility of fluids (Ezeh, 2014) or indicates the stiffness in hydrostatic compression (Fjaer et al., 2008; Olotu et al., 2020). At higher pressure, if bulk modulus is disregarded, may compromise response time of a system. The model is about a relationship between bulk modulus and lame's first parameter (λ). λ analysis could permit an improved resolution of potential or future hydrocarbon zones (Ezeh, 2014); moreso, in a linear relationship with bulk modulus of about 1.0 correlation coefficient would yield a model which is adequate for mapping of hydrocarbon accretion. Bulk modulus model could yield lame's first parameter which would combine with lame's second parameter (μ called shear modulus) and density to identify hydrocarbon and reservoir rocks (Ezeh, 2014). However, gas in solution is largely accountable for reducing the bulk modulus of the live oil (that is, gas dissolved into oil). Live oils have lower velocity, density and modulus when compared to dead oil (that is, gas free from oil at room condition). Velocity, density and modulus of oils rise with increasing pressure and decreasing temperature (Han and Batzle, 2000). The model considers the first lame's parameter than second due to the fact that first parameter with density gives a better fluids indicator than second parameter which is a matrix pointer that offers direct geological evidence about reservoirs. The hydrocarbon zone shows low first parameter-density and density responses in oil and the lowest in gas (Ezeh, 2014). A model is an explanation of a system using mathematical ideas and language which physics establish an application field for mathematics. When solving problems, the Physicists attempt to achieve a mathematical model that challenges some aspect of the real situation (Atat et al., 2020a; Atat et al., 2020b).

1.1. Basic Concept

The bulk modulus (K) is the ratio of an infinitesimal pressure increase to the subsequent relative infinitesimal decrease of the volume at constant temperature. It may be determined using either Equation 1 or 2.

$$K = V_p^2\rho - \frac{4\mu}{3} \tag{1}$$

$$K = \frac{2\mu(1+\sigma)}{3(1-2\sigma)} = \frac{E}{3(1-2\sigma)} \tag{2}$$

K is Bulk modulus

μ is Shear modulus

V_p is compressional wave velocity

σ is the Poisson ratio

E is the young's modulus

Equation 1 is not adequate if the lame's second parameter (shear modulus) is not obtained. To compute for this, Equation 3 is recommended for shear modulus estimation (Atat et al., 2012; Atat and Umoren 2016; Akpabio et al., 2023a).

$$\mu = \rho V_s^2 \tag{3}$$

V_s is shear wave velocity

Since our goal is to build a model that relates bulk modulus with lambda (Lame's first parameter), this can be investigated by the use of Equation 4.

$$\lambda = V_p^2\rho - 2\mu \tag{4}$$

λ is the Lame's coefficient

According to Atat et al. (2013), Atat and Umoren (2016) and Atat et al. (2020c), young's modulus may be computed with Equation 5.

$$E = 2\mu(1 + \sigma) \tag{5}$$

σ is Poisson's ratio

Poisson ratio may be determined using Equation 6 (Atat et al., 2020c; Atat and Umoren 2016).

$$\sigma = \frac{(\frac{V_p}{V_s})^2 - 2}{2\left((\frac{V_p}{V_s})^2 - 1\right)} \tag{6}$$

When a compressive or tensile stress is uniformly applied on a body, the relative variation detected in the volume of the body is called bulk modulus. Poisson's ratio may be taken as 0.2 if the situations are drained (sandy soil) or 0.5 when the conditions are undrained (clayey soil) (Bayo et al., 2021).

Lambda is one of the brittleness estimation parameters (others include: young's modulus, Poisson's ratio and Lame's second parameter) that can be directly quantified through extracted rock elastic properties. Organic matter in rock describes its hydrocarbon generation potential. The rock with high organic matter content is a good candidate for production. The areas with high young's modulus and low Poisson's ratio are more productive for hydraulic fracking due to their high brittleness (Abid and Geng, 2020).

1.2. Location and Geology Information of the Niger Delta

X_A Field is in Rivers State in the Niger Delta region, Nigeria. It is separated from the large Cawthorne Channel Field by a major antithetic (counter regional) normal fault (Jev, et al., 1993). The Niger Delta is located between latitudes 3^0N and 6^0N; longitudes 5^0E and 8^0E (Reijers et al., 1996; Atat et al., 2018a; Atat et al., 2020a; Akpabio et al., 2023a). About 80% of the Niger Delta region is made up of the Akata, the Agbada and the Benin formations (George et al., 2017a; George 2017b; Akpabio 2023b).

The area is characterized by two distinct seasons: rainy (or wet) and dry seasons (Akpabio et al., 2023b; Atat et al., 2020b; Atat et al., 2021; George et al., 2010; Atat et al., 2012; Atat et al., 2018b). The mean monthly rainfall during rainy season is approximately 135mm and falls to 65mm in dry season (George et al., 2010). Geologically, the study area has a thick sequence of Neogene-Quaternary deposits. The Niger Delta is the youngest Sedimentary basin within the Benue Trough system. The region began after the Eocene tectonic phase, up to 12.0km of silicic high energy deltaic deposits and shallow marine sediments have gathered in the basin. The Niger and the Benue Rivers are the major suppliers of sediments. Three lithostratigraphic units are notable in the Tertiary Niger Delta. The basal Akata Formation which is predominantly marine prodelta shale is overlain by paralic sand/shale sequence of the Agbada Formation. The topmost section, which overlies the Agbada Formation, is the continental upper deltaic plain sands-the Benin Formation in which the top soil is investigated for elastic constants (Atat and Umoren, 2016).

2. Materials And Method

2.1. Materials

Data obtained for three wells from the onshore Niger Delta oilfield include: well Location, raw well data and Geology. Microsoft Excel was used for data loading, processing, plots/curves, diagrams and other computations.

2.2. Method

Data from the three wells were used to generate suites of log such as depth, gamma ray and density and other necessary information. From the investigation as stated in the workflow (Figure 1), Data were loaded, conditioned and processed.

Sand and shale lithologies were identified. V_p/V_s ratio, Poisson's ratio, shear modulus, bulk modulus, Lame's first parameter and other elastic properties were determined which would yield the model. The dominant lithology at the top of the reservoir was noted as shale with API value greater than 75; the dominant lithology in the reservoir is sandstones with API value less than 75. Software used was Microsoft Excel most suitable package.

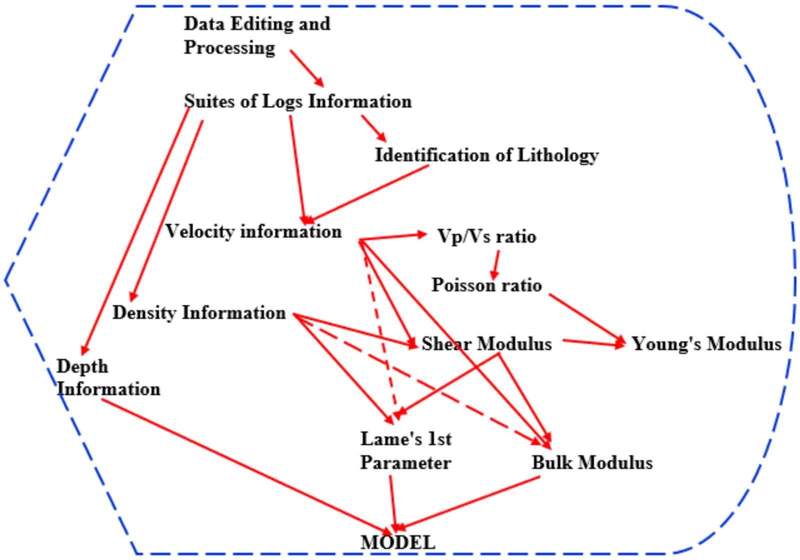

Figure 1 Research Workflow

3. Result

Modelling of bulk modulus from reservoir sand and shale lithology has been researched to achieve a mathematical model that defies some aspect of the real situation. The results of necessary elastic parameters are displayed in Tables 1 to 3 from analysis of wells A, B and C respectively. Figures 2 to 5 have different stages of the graphical presentation of results relating two elastic parameters (bulk modulus and Lame's first parameter) to achieve the model.

Table 1 Elastic parameters from Well A

Depth (ft)	Density (Kg/m^3)	V_p (m/s)	V_s (m/s)	V_p/V_s	σ	μ (N/m^2)	E (N/m^2)	K (N/m^2)	λ (N/m^2)
5300	2104.9	2269.899	1386.995	1.636558	0.5	4.05E+09	1.21E+10	1.08E+10	2.75E+09
5400	2106	2629.799	1606.894	1.636572	0.5	5.44E+09	1.63E+10	1.46E+10	3.69E+09
5500	2261.5	2642.537	1614.677	1.636573	0.5	5.9E+09	1.77E+10	1.58E+10	4E+09
5600	2116.3	2781.964	1699.867	1.636577	0.5	6.12E+09	1.83E+10	1.64E+10	4.15E+09
5700	2094	2628.935	1606.366	1.636572	0.5	5.4E+09	1.62E+10	1.45E+10	3.67E+09
5800	2092.6	2776.581	1696.578	1.636577	0.5	6.02E+09	1.81E+10	1.61E+10	4.09E+09
6000	2105.1	2452.538	1498.588	1.636566	0.5	4.73E+09	1.42E+10	1.27E+10	3.21E+09
6100	2150.2	2850.13	1741.517	1.636579	0.5	6.52E+09	1.96E+10	1.75E+10	4.42E+09
6200	2113.1	3667.68	2241.04	1.636597	0.5	1.06E+10	3.18E+10	2.84E+10	7.2E+09
6300	2165.8	3213.254	1963.386	1.636589	0.5	8.35E+09	2.5E+10	2.23E+10	5.66E+09
6400	2117.5	2968.024	1813.55	1.636583	0.5	6.96E+09	2.09E+10	1.86E+10	4.72E+09
6500	2104.1	2903.98	1774.419	1.636581	0.5	6.62E+09	1.99E+10	1.77E+10	4.49E+09
6600	2104.2	2646.808	1617.287	1.636573	0.5	5.5E+09	1.65E+10	1.47E+10	3.73E+09

Table 2 Well B Elastic parameters

Depth (ft)	Density (Kg/m³)	Vp (m/s)	V_s (m/s)	V_p/V_s	*σ*	μ (N/m²)	E (N/m²)	K (N/m²)	λ (N/m²)
8300	2113	3108.206	1899.201	1.636586	0.5	7.62E+09	2.29E+10	2.04E+10	5.17E+09
8400	2286	3156.488	1928.702	1.636587	0.5	8.5E+09	2.55E+10	2.28E+10	5.77E+09
8500	2317	3072.952	1877.661	1.636585	0.5	8.17E+09	2.45E+10	2.19E+10	5.54E+09
8600	2124	3036.613	1855.458	1.636584	0.5	7.31E+09	2.19E+10	1.96E+10	4.96E+09
8700	2416	3108.206	1899.201	1.636586	0.5	8.71E+09	2.61E+10	2.33E+10	5.91E+09
8800	2218	2966.423	1812.572	1.636583	0.5	7.29E+09	2.19E+10	1.95E+10	4.94E+09
8900	2116	3140.228	1949.247	1.610996	0.5	8.04E+09	2.41E+10	2.09E+10	4.79E+09
9000	2084	2719.899	1661.945	1.636575	0.5	5.76E+09	1.73E+10	1.54E+10	3.9E+09
9100	2425	2995.577	1830.385	1.636583	0.5	8.12E+09	2.44E+10	2.17E+10	5.51E+09
9200	2270	3340.274	2040.995	1.636591	0.5	9.46E+09	2.84E+10	2.53E+10	6.42E+09
9300	2261	3448.939	2107.389	1.636593	0.5	1E+10	3.01E+10	2.69E+10	6.81E+09
9400	2140	3242.553	1981.287	1.636589	0.5	8.4E+09	2.52E+10	2.25E+10	5.7E+09
9500	2161	3292.892	2012.045	1.63659	0.5	8.75E+09	2.62E+10	2.34E+10	5.94E+09
9600	2251	3317.551	2027.111	1.636591	0.5	9.25E+09	2.77E+10	2.48E+10	6.28E+09
9700	2208	3251.2	1986.571	1.636589	0.5	8.71E+09	2.61E+10	2.33E+10	5.91E+09
9800	2237	3372.614	2060.754	1.636592	0.5	9.5E+09	2.85E+10	2.54E+10	6.45E+09
9900	2214	3500.913	2139.145	1.636594	0.5	1.01E+10	3.04E+10	2.71E+10	6.87E+09
10000	2225	3061.378	1870.589	1.636585	0.5	7.79E+09	2.34E+10	2.08E+10	5.28E+09

Table 3 Elastic parameters from Well C

Depth (ft)	Density (Kg/m³)	Vp (m/s)	V_s (m/s)	V_p/V_s	*σ*	μ (N/m²)	E (N/m²)	K (N/m²)	λ (N/m²)
5200	2221.2	10452.67	6386.672	1.636639	0.5	9.06E+10	2.72E+11	1.22E+11	6.15E+10
5300	2104.9	4673.413	2855.543	1.636611	0.5	1.72E+10	5.15E+10	2.31E+10	1.16E+10
5400	2106	3157.895	1929.561	1.636587	0.5	7.84E+09	2.35E+10	1.05E+10	5.32E+09
5500	2261.5	57293.23	35006.25	1.636657	0.5	2.77E+12	8.31E+12	3.73E+12	1.88E+12
5600	2116.3	7161.654	4375.858	1.636629	0.5	4.05E+10	1.22E+11	5.45E+10	2.75E+10
5700	2094	4261.745	2604.013	1.636606	0.5	1.42E+10	4.26E+10	1.91E+10	9.63E+09
5800	2092.6	4867.454	2974.102	1.636613	0.5	1.85E+10	5.55E+10	2.49E+10	1.26E+10
5900	2092.2	4011.582	2451.164	1.636603	0.5	1.26E+10	3.77E+10	1.69E+10	8.53E+09
6000	2105.1	5187.202	3169.468	1.636616	0.5	2.11E+10	6.34E+10	2.84E+10	1.43E+10
6100	2150.2	8634.561	5275.804	1.636634	0.5	5.98E+10	1.8E+11	8.05E+10	4.06E+10
6200	2113.1	4519.573	2761.546	1.63661	0.5	1.61E+10	4.83E+10	2.17E+10	1.09E+10
6300	2165.8	8480.801	5181.857	1.636634	0.5	5.82E+10	1.74E+11	7.82E+10	3.95E+10

6400	2117.5	7555.776	4616.666	1.63663	0.5	4.51E+10	1.35E+11	6.07E+10	3.06E+10
6500	2104.1	8948.914	5467.873	1.636635	0.5	6.29E+10	1.89E+11	8.46E+10	4.27E+10
6600	2104.2	8668.942	5296.811	1.636634	0.5	5.9E+10	1.77E+11	7.94E+10	4.01E+10
6700	2111.3	5415.778	3309.128	1.636618	0.5	2.31E+10	6.94E+10	3.11E+10	1.57E+10
6800	2112.4	17339.86	10594.74	1.636648	0.5	2.37E+11	7.11E+11	3.19E+11	1.61E+11
6900	2118	16877.08	10311.98	1.636647	0.5	2.25E+11	6.76E+11	3.03E+11	1.53E+11
7000	2143.5	19952.87	12191.29	1.63665	0.5	3.19E+11	9.56E+11	4.29E+11	2.16E+11
7100	2235.3	52173.91	31878.35	1.636657	0.5	2.27E+12	6.81E+12	3.06E+12	1.54E+12
7200	2140.7	40585.88	24798.06	1.636655	0.5	1.32E+12	3.95E+12	1.77E+12	8.93E+11
7300	2153	42321.58	25858.57	1.636656	0.5	1.44E+12	4.32E+12	1.94E+12	9.77E+11
7400	2217.8	69780.22	42635.8	1.636658	0.5	4.03E+12	1.21E+13	5.42E+12	2.74E+12
7500	2186.4	69021.74	42172.37	1.636658	0.5	3.89E+12	1.17E+13	5.23E+12	2.64E+12
7600	2275.9	83552.63	51050.74	1.636658	0.5	5.93E+12	1.78E+13	7.98E+12	4.03E+12
7700	2165.2	24934.55	15235.1	1.636652	0.5	5.03E+11	1.51E+12	6.76E+11	3.41E+11
7800	2154.1	79333.68	48472.97	1.636658	0.5	5.06E+12	1.52E+13	6.81E+12	3.43E+12
7900	2254.3	102903.4	62874.09	1.636659	0.5	8.91E+12	2.67E+13	1.2E+13	6.05E+12
8000	2180.5	88092.48	53824.6	1.636659	0.5	6.32E+12	1.9E+13	8.5E+12	4.29E+12
8100	2203.7	120189.3	73435.73	1.636659	0.5	1.19E+13	3.57E+13	1.6E+13	8.07E+12
8200	2286.3	125638.9	76765.46	1.636659	0.5	1.35E+13	4.04E+13	1.81E+13	9.14E+12

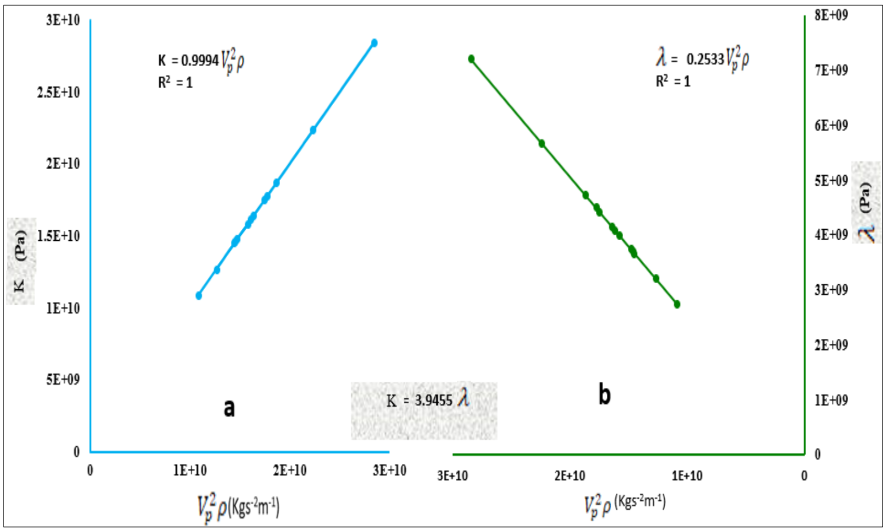

Figure 2 The Bulk Modulus-Lame's first parameter relationship for well A

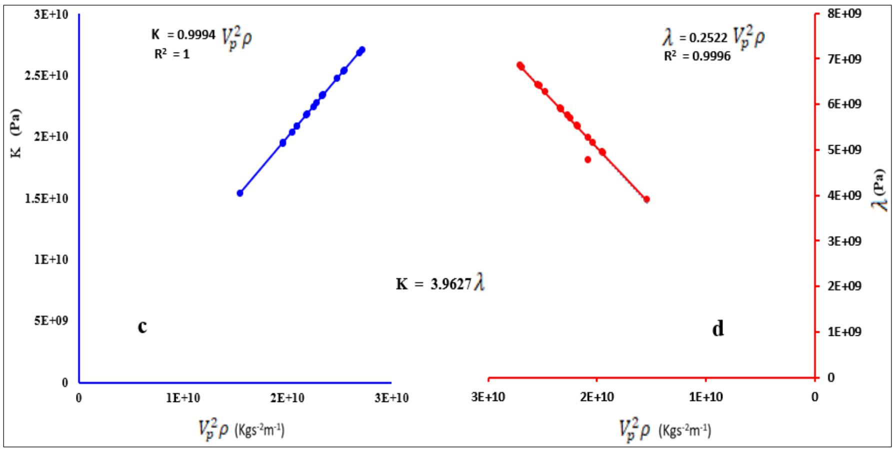

Figure 3 The Bulk Modulus-Lame's first parameter relationship for well B

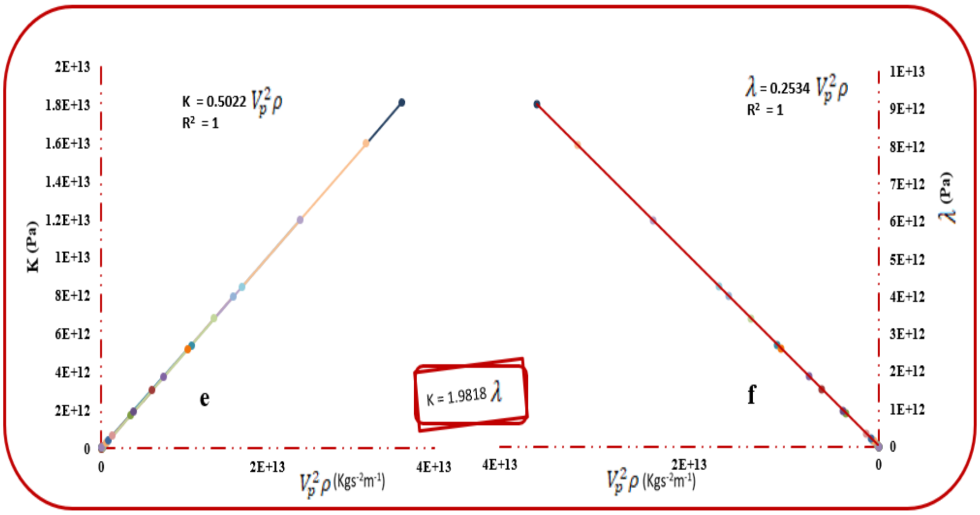

Figure 4 The Bulk Modulus-Lame's first parameter relationship for well C

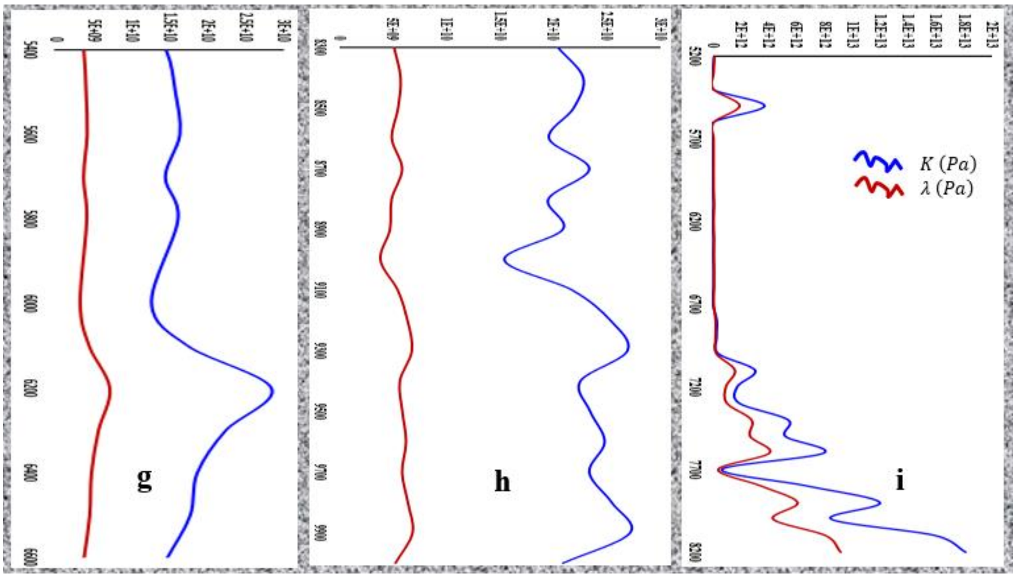

Figure 5 The Bulk Modulus-Lame's first parameter curves showing a linear effect of each on the other (g for well A, h for well B and i for well C)

4. Discussion

From Tables 1 to 3, density information and velocity enabled the achievement of shear modulus by the use of Equation 3. Vp/Vs ratio result leads to Poisson's ratio determination using Equation 6. Equation 5 was adequate for evaluation of young's modulus. Bulk modulus and Lame's first parameter were computed using Equations 1 and 4 respectively. The depth of sand-shale formation identified are 5300 – 6600 ft, 8300 to 10000 ft and 5200 – 8200 ft for wells A, B and C respectively.

The models generated and solved for wells A, B and C from different linear curves (Figure 2 to 4) are Equations 7 to 9 respectively.

$$K_A = 3.9455\lambda_A \quad (7)$$

$$K_B = 3.9627\lambda_B \quad (8)$$

$$K_C = 1.9818\lambda_C \quad (9)$$

The average of these Equations (Equations 7 to 9) yields Equation 10.

$$K = 3.9455\lambda \quad (10)$$

The model is about a relationship between bulk modulus and lame's first parameter (λ). According to Ezeh (2014), λ analysis could permit an improved resolution of potential hydrocarbon zones; therefore, in a linear relationship with bulk modulus of about 1.0 correlation coefficient, would yield a model which is adequate for mapping of hydrocarbon accumulation. Bulk modulus model could yield lame's first parameter which would combine with lame's second parameter (μ called shear modulus) and density to identify hydrocarbon and reservoir rocks (Ezeh, 2014) (Figure 5 clearly presents how increase in Lame's first parameter could influence bulk modulus and bulk modulus effect on lambda). However, gas in solution is largely accountable for reducing the bulk modulus of the live oil as live oil has lower velocity, density modulus than dead oil at room condition. The model considers the first lame's parameter than second due to the fact that first parameter with density gives a better fluids indicator than second parameter which is a matrix indicator that provides a direct geological information about reservoirs.

5. Conclusion

Physicists attempt to achieve a mathematical model that defies some aspect of the real situation to explain a system using mathematical ideas and language. The model achieved in this research is about a relationship between bulk modulus and lame's first parameter (λ) for south eastern part of the Niger Delta basin. The correlation coefficient in the building up of the model is about 1.0. Bulk modulus model could yield lame's first parameter which would (or directly) combine with shear modulus and density to identify hydrocarbon and reservoir rocks. The model considers the first lame's parameter because when combined with density gives an improved fluids indicator.

Compliance with ethical standards

Acknowledgments

The authors thank Professor Idara Akpabio of the Department of Physics, University of Uyo, Nigeria for the availability of the data used in this study. Acknowledgement is made to the competent Reviewers for their inputs. We also thank the Editorial board of World Journal of Advanced Research and Reviews for the acceptance and publication this research article.

Disclosure of conflict of interest

No potential conflict of interest.

References

[1] Abid, M. and Geng, J. (2020). Effective Attributes Quantification to Bridge Gap between Elastic Properties and Reservoir Parameters in Self-Resource Rocks. Scientific Reports, 10:2534.

[2] Ahmad, J. and Schmitt, D. (2006). Reservoir Characteristics of a Quaternary Channel: Incorporating Rock Physics in Seismic and DC Resistivity Surveys. CSPG-CSEG-CWLS Convention.

[3] Akpabio, I. O., Atat, J. G. and Akankpo, A. O. (2023a). Local Fit Parameter Satisfying Shear Modulus Porosity Relation for Southern Z Basin Analysis. Neuroquantology, 21(5), 1385 – 1391.

[4] Akpabio, I. O., Atat, J. G., Umoren, E. B. and Ekemini, J. D. (2023b). The Reservoir Rock Volumetric Concentration and Tortuosity Description of Pore Space of Xa Field, Niger Delta Basin. World Journal of Advanced Science and Technology, 3(1), 1 – 13.

[5] Andhumoudine, A. B., Nie, X., Zhou, Q. et al. (2021). Investigation of coal elastic properties based on digital core technology and finite element method. Advances in Geo-Energy Research, 5(1), 53- 63.

[6] Atat, J. G., Akpabio, G. T., George, N. J. and Umoren, E. B. (2012). Geophysical Assessment of Elastic Constants of Top Soil using Seismic Refraction Compressional Velocities in the Eastern Niger Delta. International Journal of Modern Physics, 1(1), 7 – 19.

[7] Atat, J. G., Akpabio, I. O. and George, N. J. (2013). Allowable Bearing Capacity for Shallow Foundation in Eket Local Government Area, Akwa Ibom State, Southern Nigeria. International Journal of Geoscience, 4 (10), 1491 – 1500.

[8] Atat, J. G., George, N. J. and Atat, A. G. (2020c). Immediate Settlement of Footing using Interpreted Seismic Refraction Geoelastic Data: A Case Study of Eket County, Nigeria. NRIAG Journal of Astronomy and Geophysics, 9(1), 433 – 448.

[9] Atat, J. G., Horsfall, O. I. and Akankpo, A. O. (2020b). Density Modelling from Well Analysis of Fields [Sand API< 75 and Shale API> 75], Niger Delta Basin. IOSR Journal of Applied Geology and Geophysics, 8(2), 1 – 6.

[10] Atat, J. G., Isong, S. M., George, N. J. and Umar, S. (2021). The Local Fit Constants from Near Surface Seismic Measurements for Shear Wave Velocity Estimation in the Eastern Niger Delta. International Journal of Research in Engineering and Science 9 (8), 1 – 10.

[11] Atat, J. G., Uko, E. D., Tamunobereton-ari, I. and Eze, C. L. (2018b). Major Lithology of Tau Field as Defined by Density in the Niger Delta Basin. World Journal of Applied Science and Technology, 10 (2), 268 – 273.

[12] Atat, J. G., Uko, E. D. Tamunobereton-ari, I. and Eze, C. L. (2020a). Site-Dependent Geological Model for Density Estimation in the Niger Delta Basin, Nigeria. Malaysian Journal of Geoscience. 4(1): 1 – 6.

[13] Atat, J. G. and Umoren, E. B. (2016). Assessment of Mechanical and Elastic Properties of Soils in the South Eastern Part of Niger Delta, Nigeria. World Journal of Applied Science and Technology, 8 (2), 188 – 193.

[14] Bayo, A. R., Okiongbo, K. S. and Sorronadi-Ononiwu, G. C. (2021). Determination of elastic moduli and bearing capacity of sediments using geophysical and cone penetration test techniques in Yenagoa, Southern Nigeria, NRIAG Journal of Astronomy and Geophysics, 10(1), 202 – 217.

[15] Bell, J. S. (1996). In situ stresses in sedimentary rocks (part 2): applications of stress measurements. Geoscience, 23, 135 – 153.

[16] Bock, H. (1993). Measuring In Situ Rock Stress by Borehole Slotting. Principles, Practice and Projects, 3, 433 – 443.

[17] Cheng, C. and Johnston, D. H. (1981). Dynamic and static moduli. Geophysical Research Letters, 8(1), 39 – 42.

[18] Ezeh, C. C. (2014). Using Lame's Petrophysical Parameters for Fluid Detection and Lithology determination in Parts of Niger Delta. Global Journal of Geological Sciences, 13, 23 – 33.

[19] Fjaer, E. (2019). Relations between static and dynamic moduli of sedimentary rocks. Geophysical Prospecting, 67(1), 128 – 139.

[20] Fjaer, E., Holt, R. M., Raaen, A. M. and Horsrud, P. (2008). Petroleum Related Rock Mechanics, Second Edition. Developments in Petroleum Science, Vol. 53. Elsevier Science, Elsevier. ISBN: 9780080557090.

[21] George, N. J., Akpan, A. E., George, A. M. and Obot, I. B. (2010). Determination of Elastic Properties of the Over Burden Materials in Parts of Akamkpa, Southern Nigeria using Seismic Refraction Studies. Archives of Physics Research, 1(2), 58 – 71.

[22] George, N. J., Atat, J. G., Udoinyang, I. E., Akpan, A. E. and George, A. M. (2017a). Geophysical Assessment of Vulnerability of Surficial Aquifer in the Oil Producing Localities and Riverine Areas in the Coastal Region of Akwa Ibom State, Southern Nigeria. Current Science, 113(3), 430 – 438.

[23] George, N. J., Atat, J. G., Umoren, E. B. and Etebong, I. (2017b). Geophysical Exploration to Estimate the Surface Conductivity of Residual Argillaceous Bands in the Groundwater Repositories of Coastal Sediments of EOLGA, Nigeria. NRIAG Journal of Astronomy and Geophysics, 6, 174 – 183.

[24] Han, D. and Batzle, M. L. (2004). Gassmann's Equation and Fluid-Saturation Effects on Seismic Velocities. Geophysics, 69, 398 – 405.

[25] Han, D. and Batzle, M. (2000). Velocity, Density and Modulus of Hydrocarbon Fluids – Data Measurement. Society of Exploration Geophysicists.

[26] Jev, B. I., Kaars-Sijpesteijn, C. H., Peters, M. P. A. M., Watts, N. L. and Wilkie, J. T. (1993). Akaso Field, Nigeria: Use of Integrated 3-D Seismic, Fault Slicing, Clay Smearing, and RFT Pressure Data on Fault Trapping and Dynamic Leakage. American Association of Petroleum Geologists Bulletin, 77 (8), 1389 – 1404.

[27] Jizba, D. and Nur, A. (1990). Static and Dynamic Moduli of Tight Gas Sandstones and their Relation to Formation Properties," in the SPWLA 31st Annual Logging Symposium, Lafayette, Louisiana.

[28] King, M. S. (1969). Static and Dynamic Elastic Moduli of Rocks under Pressure. In the 11th U.S. Symposium on Rock Mechanics (USRMS), Berkeley, California.

[29] Olotu, S. J., Alao, O. A. Agbai, P. G., Afolabi, O. and Inaolaji, E. B. (2020). Estimating reservoir geomechanical parameters for enhanced reservoir characterization: case study of "Tobi" field, Niger Delta. SN Applied Sciences, 2:1422.

[30] Reijers, T. J. A. Petter, S. W. and Nwajide, C. S. (1996). The Niger Delta basin: Reijers, T.J.A., ed., Selected Chapter on Geology: SPDC Wa.: LP1O3-118.

[31] Wang, Y., Han, D., Zhao, L., Li, H. and Long, T. (2022). Static and Dynamic Bulk Moduli of Deepwater Reservoir Sands: Influence of Pressure and Fluid Saturation. Geoscience World (Lithosphere), 1 – 11.

[32] Wang, Y., Han, D. H., Li, H., Zhao, L., Ren, J. and Zhang, Y. (2020). A comparative Study of the Stress-Dependence of Dynamic and Static Moduli for Sandstones. Geophysics, 85(4), MR179–MR190.

[33] Yang, C. and Liu, J. (2021). Petroleum rock mechanics: an area worthy of focus in geo-energy research. Advances in Geo-Energy Research, 5(4), 351 – 352).

[34] Zimmer, M. A. (2004). Seismic velocities in unconsolidated sands: measurements of pressure, sorting, and compaction effects, Stanford University.

[35] Zoback, M. D. (2007). Reservoir Geomechanics. Cambridge (UK): Cambridge University Press.