Original Research Article

CompressibilityAnalysis and Geomechanical Characterization for CO_2 Sequestration and Storage for Advancement of Health and Environment Protection. A Case of 'Jxt' Field, Niger Delta, Nigeria.

ABSTRACT:

CO_2 sequestration and storage areparts of the approaches to mitigate the effect of global warming through the reduction and stabilization of CO_2 emitted in the atmosphere. In the Niger Delta, several depleted and abandoned wells can be utilized as geologic storage for CO_2 to assist economic growth and environmental protectionThis study aimed at identifying suitable reservoirs for CO_2 storage to prevent its from leaking to the surface. Logs from two wells from the 'JXT' field, onshore, Niger Delta were used for the studies. Petrophysics computation and Rock physics analysis such as Geomechanics, fluid sensitivity and compressibilitywere carried out. Potential reservoirs were delineated and correlated, elastic parameters were generated from pseudo logs, cross plotted for comparison, and evaluated for physical strength. Fluid sensitivity was carried out using Gassmann's equation to understand dry rock sensitivity to fluid changes. Finally, a compressibility study was done to measure the drained and undrained properties of each reservoir and its resistance to compressive forces. Results of the petrophysical analysis for the three potential reservoirs (A, B, C) delineated revealed values ranging from a high thickness of reservoir (20-109m), moderate porosity (17-23%), and good permeability (128-1251mD). The geomechanical analysis for the two wells shows the range of values for Young modulus (E) as (20.5-27.5GPa), bulk modulus (k) as (21.3-25.3GPa), Shear modulus (μ) as (8.01-11.2GPa) and Poisson ratio (σ) as (0.25). Results from the compressibility analysis indicated the average drained and undrained compressibility for both wells as ($0.048GPa^{-1}$, $0.044GPa^{-1}$) and ($0.044GPa^{-1}$, $0.044GPa^{-1}$) respectively. Conclusively, the results indicated that the 'JXT' field is suitable for CO_2 storage and can be considered to reduce the emission of this greenhouse gas into the atmosphere and aid positive global climate change.

Keywords: Reservoir Characterization, CO_2 Sequestration, Rock Physics, Geomechanics, Petrophysics

INTRODUCTION

CO_2 and other greenhouse gases emitted daily into the Earth''s atmosphere pose a great challenge to our existence as humans and the adverse effects in the form of climate change increasing every year. The environment is becoming almost inhabitable for us with the rise in average temperatures reaching critical points.Melting glaciers are destroying natural habitats of endangered animals and causing a rise in sea levels. This in turn leads to flooding and poor quality of life. Flooding leads to the loss of lives and, the destruction of homes, farms, infrastructure, etc. Cold regions of the world are becoming warmer, and warm regions are becoming hotter, natural habitats are gradually disappearing. The environment is the worst hit but we are the most affected. The presence of these destructive substances is anthropogenic and can be attributed to human activities, and the desire to generate energy for self-sustainability and community development.

Nigeria is the principal producer of ~~O~~oil and gas in Africa, and the Niger Delta basin is the predominant basin from which most of ~~her ~~itscrude oil is produced. According to the ~~w~~World ~~d~~Development ~~i~~Indicator (World Bank 2015, Maju-Oyovwikowhe and Lucas.2019), Nigeria is ranked 39th in the world for CO_2 emissions from all ~~springs/~~sources, with emissions/discharges rising from 3,406.6kt in 1960 to 88,026kt in 2011, and contribute adding 0.3% of the worldwide/global emissions. In the exploration and production division or sector, Nigeria ranks in the top 1% for the emission of greenhouse gases in Africa, splaying 1.4 billion cubic feet of accompanying gas daily. This is equivalent to approximately 40% of ~~produced ~~the gas produced from over 120 flaring~~/~~ sites (Onyekonwu 2008).

These events can hardly be reversed but can be mitigated, and the process slowed down. The Kyoto ~~Practice/p~~Protocol and the United Nations (UN) Context Convention on Climate Change were set up to achieve the objective of mitigating the effects of global warming and climate change by reducing the amount of CO_2 present in the atmosphere (Ojo et al. 2018).

CO_2 capture and sequestration ~~is ~~area processes that have~~s~~ been identified and adopted to mitigate and slow down the rate of CO_2 emission into the atmosphere. It involves the capture of CO_2 before its emission into the atmosphere, and injection into deep subsurface formations for lengthy periods of storage and sequestration (IEA 2008). The geologic sequestration of CO_2 into the subsurface, which includes depleted Oil and gas reservoirs, ~~S~~salt domes, and coal seam beds, requires initial characterization of the site where the CO_2 is to be sequestered, in terms of the geology, structural framework, and geomechanical properties. This is done to determine~~;~~ the volume capacity of the reservoir, optimum conditions present for the long-term storage and containment of the CO_2, and the ~~I~~injectivity (permeability of the reservoir), for fluid flow (IPCC 2005).

Nigeria is a major player in the hydrocarbon exploration sector in Africa and globally,~~ and the world in general, and ~~with several reservoirs explored, produced, depleted, and abandoned since the inception of the exploration industry of Nigeria in 1957.~~,i~~It is expected that these brownfields in the Niger Delta can be utilized for the geologic sequestration of CO_2. To better understand the physical properties of these reservoirs~~,I~~in terms of storage capacity, containment capacity, and injectivity, feasibility studies must be carried out (Ojo et al. 2018).

This work aims to study the compressibility and geomechanical properties of a reservoir ~~with~~ usingrock physics to analyze the suitability of the reservoir for CO_2 sequestration and storage in the future after the well has been depleted through production, and abandoned.

LOCATION AND GEOLOGY OF THE STUDY AREA

Situated in the Gulf of Guinea~~,~~ and extending ~~all over~~throughout the Niger Delta domain~~/province~~, is the Niger Delta (Klett*et al*, 1997~~,~~). Delta prograde southwestward from the Eocene to the present, creating depo-belts that signify the most active percentage of the delta at each phase of its expansion (Doust and Omatsola, 1990). These depo-belts become one of the major regressive deltas globally. One petroleum system ~~had been ~~identified in the

Niger Delta province ~~which~~ is the Tertiary Niger Delta. (Ojo et al. 2019). The main source rock remains in the upper Akata~~f~~Formation,consisting of the marine-shale facies, ~~with~~ probably ~~the~~ influenced~~of~~ byinterbedded marine shale in the lowermost Agbada Formation.Agbada ~~f~~Formation sandstone accommodates hydrocarbons, whereas~~,~~ the upper Agbada~~f~~Formation turbidite sand units serve as potential reservoirs in deep water offshore (Okpoli and Arogunyo. 2020). **Figure 1** shows the location map of the Niger Delta and the base map of the study area.**Figure 1**Base map of the study area.

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METHODOLOGY

Two wells in the “~~"~~JXT field”~~"~~, JXT_03 and JXT_04, equipped with suites of wireline logs, including lithology log (gamma ray), resistivity, and porosity logs (neutron, sonic, and bulk density), were utilized for this study. The methodology adopted for this study is grouped into two major sections. These include Petrophysical analysis and Rock physics analysis (Geomechanical and Compressibility analysis)

Petrophysical analysis

This section assists in conducting the compressibility analysis and elastic property characterization of the reservoir, as well as the sensitivity analysis of each elastic parameter utilized in this study (Ojo *et al.* 2021). The lateral variations and vertical thickness of delineated reservoir units were investigated by correlating the formation tops and lithology units across the field. Six petrophysical parameters were evaluated for the three delineated reservoir formations (Lyaka and Mulibo, 2018). The parameters are, reservoir thickness, shale volume, porosity (effective), permeability, water saturation, and hydrocarbon saturation (Lyaka and Mulibo, Ojo et al. 2019, Khalid 2021~~.~~).

Reservoir thickness

The gamma-ray log was handy in identifying the reservoirs in the ‘~~'~~JXT’~~'~~ field. The reservoir thickness (h) was calculated using the following relationship (Ruiz 2011).

$$h = \text{Base of reservoir} - \text{Top of reservoir} \quad (1)$$

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Shale volume (V_{sh})

For the shale volume estimation, Larionov’~~'~~s (1969) equation for tertiary formations was used (Szabó and Dobróka 2017).

$$Vsh = 0.083\left(2^{3.7*Igr} - 1\right) \quad (2)$$

$$Igr = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}} \quad (3)$$

Where $Igr$is the gamma ray log index, GRlogis the gamma ray log appraisal at the depth of concentration, $GR_{min}$is the gamma ray log appraisal /reading in the clean zone, $GR_{max}$is the gamma ray log appraisal/reading in the shale zone.

Porosity

Porosity aids estimation of compaction trends and differentiating the hydrocarbon zones using Neutron, and Density logs ((Dvorkin *et al.*, 2002 , Bosch et al., 2014).

$$\Phi = \sqrt{\frac{\Phi^{2}_{density} + \Phi^{2}_{neutron}}{2}} \qquad (4)$$

The effective porosity is given by Eq. 5 (Cluff and Cluff, 2004)

$$\Phi_{eff} = \Phi_{Total}(1\text{-}V_{sh}) \qquad (5)$$

Water saturation

Water saturation is obtained using the Archie (1942) equation.

$$Sw = \sqrt[n]{\frac{a * Rw}{\varphi^{m} * Rt}} \qquad (6)$$

Hydrocarbon saturation

For hydrocarbon saturation (S_h) was obtained using an equation defined by Shepherd, (2009).

$$S_h = (1 - Sw) \qquad (7)$$

Rock physics investigation

Rock physics analysis is used to establish the relationship between reservoir properties (porosity, volume of shale, and water saturation) and elastic properties (velocity, impedance, and density)(Ojo et al. 2021). Hence the primary focus of rock physics investigation is to meet the need to quantify and improve the interpretation of amplitudes for hydrocarbon discovery, reservoir characterization, and reservoir monitoring, especially with the recent improvements and developments in seismic data acquisition, and processing (Avseth, 2010; Avseth*et al.*, 2009; Sharma 2020, Ojo et al. 2021). Rock physics analysis is carried out to estimate the elastic properties/assets of the reservoir rocks identified in the 'JXT' field. The estimation of these elastic parameters aided the characterization of the reservoirs in terms of their lithology, fluid content, and Geomechanical properties, figure 2- (Abe et al., 2018, Idowu and Ojo 2022)

Calculation of Rock Physics parameters

Vp estimation

Vp, known as compressional wave velocity, and the equation below was used to estimate Vp from the compressional wave sonic transit time log (DT_c).

$$Vp = \left(\frac{1000000}{DTc}\right) * 0.3281 \qquad (8)$$

Vs estimation

Shear wave velocity (Vs) is estimated from Vp using the following empirical relationships (Castagna *et al.*, 1993)

$$Vs = 0.804Vp - 0.856 \qquad (9)$$

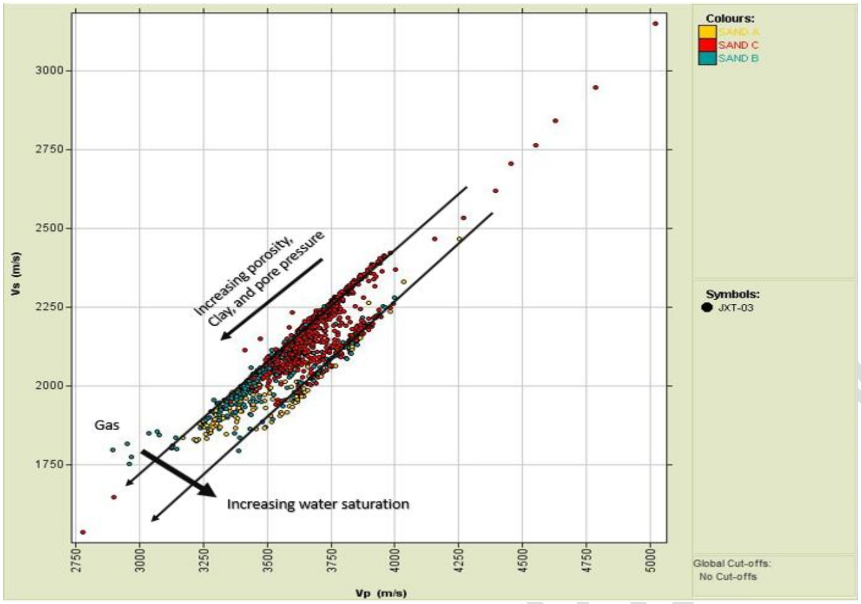

Figure 2: Cross-plot of Vs against Vp in JXT 03, digitized after Avseth et al., (2005).

2.2.2 Geomechanics

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This deals with the behavior of rocks under the influence of different forces, with respect to their physical properties, and interaction under different stress regimes. Reservoir geomechanics is an area of rock mechanics that integrates the study of the stresses of the earth with the knowledge of the principles of rock mechanics across various disciplines to solve problems that may arise during the life cycle of a reservoir, from exploration to abandonment (Zoback, 2007, Idowu and Ojo 2022).

Estimation of Geomechanical parameters

Bulk modulus (K)

The bulk modulus denotes the volumetric alteration/changes of a material under the influence of normal stresses (W. Lowry, 2007, Ojo et al. 2021). The dynamic bulk modulus of a reservoir formation describes the volume changes of the formation with respect to the fluid bulk modulus, under the influence of normal stresses. The equation below was used to derive the dynamic bulk modulus (K), in this study.

$$K = \rho * \left(Vp^2 - \frac{4}{3}Vs^2\right) \quad (10)$$

Shear modulus (μ)

The shear of a formation describes the resistance of the formation to shearing stress (Telford *et al.* 1990).

$$\mu = \rho * (Vs)^2 \qquad \text{Oo} \qquad (11$$

Lambda (λ)

Lambda (λ) is among the class of elastic parameters known as Lame’s parameters. In this study, it was used in the characterization of other Geomechanical parameters.

$$\lambda = \rho * (Vp^2 - \frac{2\mu}{\rho}) \qquad (12)$$

Young modulus (E)

Young modulus describes the longitudinal strains when uniaxial normal stress is applied to a material. In this study, E was derived using the relationship between Lambda (λ) and Mu (μ) (W. Lowry 2007, Ojo et al. 2021).

$$E = \mu * \left(\frac{3\lambda+2\mu}{\lambda+\mu}\right) \qquad (13)$$

Poisson ratio (σ)

The Poisson ratio measures the deformability of a rock formation and its ability to resist compressive forces. It is in the range of 0.05 to 0.5, with the former representing very hard materials, and the latter representing very soft materials.

$$\sigma = \frac{\lambda}{2(\lambda+\mu)} \qquad (14)$$

Gassmann’s model

Gassmann's model applied in this study is given in equation 15.

$$\frac{K_{sat}}{K_{mineral} - K_{sat}} = \frac{K_{dry}}{K_{dr\,y} - K_{dry}} + \frac{K_{fluid}}{\phi(K_{min} - K_{fluid})} \qquad (15)$$

$$\mu dry = \mu sat \qquad (16)$$

where K_{sat} is the saturated bulk density, K_{dry} is the dry bulk density, K_{min} is the mineral bulk density, K_{fluid} is the fluid bulk density, μ_{dry} is the shear modulus of dry rock, μ_{sat} is the shear modulus of saturated rock, and ϕ is the effective porosity of the reservoir formation. (Khalid 2021.

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Compressibility analysis`

The compressibility analysis describes the physical properties of the reservoir, in terms of its density. A rock with low porosity tends to have a high density, which translates to the bulk modulus of the rock frame. The compressibility is the inverse of the bulk modulus of the formation and is affected by the fluid contained in the pores of the formation (Avseth et al., 2005: Marvko et al., 2009). A weak formation with high porosity is expected to be highly compressible, while a stiff formation with low porosity is expected to be less compressible. (Idowu and Ojo, 2022)

The compressibility analysis carried out in this study was carried out in two phases, using the Gassmann equation, and the Berryman (1995) form of the Hashin-Shtrikman-Wadpole (1966) equation.

Gassmann’s equation for compressibility analysis

The compressible form of equation 15 was adopted for the compressibility analysis carried out in this study (Avseth et al., 2005: Marvko et al., 2009).

$$(C_{sat} - C_{min})^{-1} = (C_{dry} - C_{min})^{-1} + [\emptyset(C_{fl} - C_{min})]^{-1} \quad (17)$$

Where:

$$C_{sat} = \frac{1}{K_{sat}}, \quad C_{dry} = \frac{1}{K_{dry}}, \quad C_{fl} = \frac{1}{K_{fl}}, C_{min} = \frac{1}{K_{min}}. \quad (18)$$

Where $\frac{1}{K_{dp}}$is the dry pore compressibility, $\frac{1}{K_{sp}}$is the saturated pore compressibility, and $\frac{1}{K_{\phi}}$is the pore space compressibility.

Hashim-Shtrikman-Wadpole bounds for elastic moduli

According to Hashim-Shtrikman (1963), and Wadpole (1966), the effective elastic moduli of a mixture of mineral grains and pores can be predicted. Figures 3 and 4. This can be achieved without specifying the geometric details of the phases' arrangements relative to each other (Avseth et al., 2005: Marvko et al., 2009, Idowu and Ojo, 2022).

$$K^{HS\pm} = K_1 + \frac{f_2}{(K_2 - K_1)^{-1} + f_1\left(K_1 + \frac{4}{3}\square_m\right)^{-1}} \quad (22)$$

$$\mu^{HS\pm} = \mu_1 + \frac{f_2}{(\mu_2 - \mu_1)^{-1} + f_1[\mu_1 + \frac{\mu_m}{6}\left(\frac{9K_m + 8\mu_m}{K_m + 2\mu_m}\right)]^{-1}} \quad (23)$$

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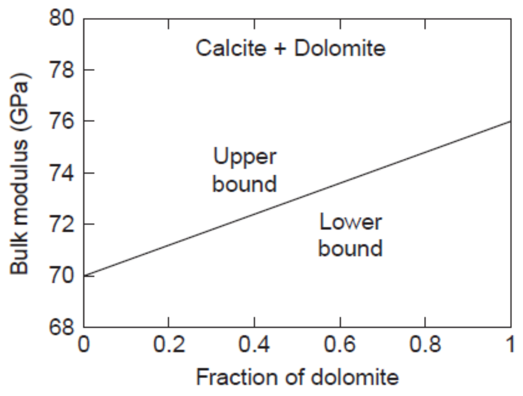

Figure 3: Plot of bulk modulus against volume fraction of mineral mixture in the Hashim-stickman bounds for elastic moduli (Avseth*et al.*, 2005).

The Berryman (1995) general method of the Hashim-Shtrikman-Wadpole model for a mixture greater than two phases was adopted to predict and envisage the effective elastic moduli

of each reservoir identified in this study. The upper and lower bounds of the compressibility of each reservoir formation were estimated using this model.

$$K^{HS+} = \Lambda(\Box_{max}) \quad (24)$$

$$K^{HS-} = \Lambda(\Box_{min}) \quad (25)$$

$$\mu^{HS+} = \Gamma(\zeta(K_{max}, \Box_{max})) \quad (26)$$

$$\mu^{HS-} = \Gamma(\zeta(K_{min}, \Box_{min})) \quad (27)$$

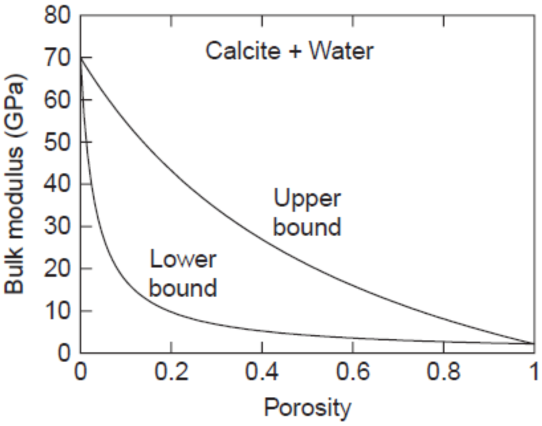

Figure 4: A plot of Bulk modulus against volume fraction of mineral and fluid mixture in the Hashim-shtrikman bounds for elastic moduli (Avseth*et al.*, 2005).

Properties of the individual components (subscripts "1" and "2"). Equations (22) and (23) produce the upper bound, maximum bulk, and shear moduli of the individual constituents and the lower bound are $K_m$and $\Box_m$, while the minimum bulk and shear moduli of the constituents are K_m and $\Box_m$. (Afif 2020, Nishank 2021)

$$\Lambda(z) = \left\langle \frac{1}{K(r) + \frac{4}{3}z} \right\rangle^{-1} - \frac{4}{3}z$$

$$\Gamma(z) = \left\langle \frac{1}{\mu(r) + z} \right\rangle^{-1} - z$$

$$\zeta(K, \mu) = \frac{\mu}{6}\left(\frac{9K + 8\mu}{K + 2\mu}\right)$$

The brackets specify an average over the medium similar to an average over the constituents weighed using their volume fractions

Modified Hashim-Shtrikman-Wadpole bounds for compressibility analysis

To ~~find~~ determinethe the upper bounds and lower bounds on the effective compressibility of a mixture of more than two phases, the Hashim-Shtrikman-Wadpole bounds model was adopted and modified in this study. The upper bound of the effective compressibility is equivalent to the inverse of the lower bound on the effective elastic moduli of the mixture, while the lower bound of the effective compressibility is equivalent to the upper bound on the effective elastic moduli Avseth et al, 2005, Saenger, 2006, Schreyer et al., 2021)

$$C^{HS+} = \frac{1}{K^{HS-}} \quad (28)$$

$$C^{HS-} = \frac{1}{K^{HS+}} \quad (29)$$

RESULTS AND DISCUSSION

Petrophysical analysis

The stratigraphy of the two wells in the JXT field shows an intercalation of shale and sandstone layers. Three reservoirs were delineated and correlated across the two wells, 'JXT' 03 and 'JXT' 04. The three reservoirs are SAND A, SAND B, and SAND C. The delineation and correlation of these lithologic units were achieved by using the gamma-ray and resistivity logs (~~f~~Figure 5). The summary of the results from the petrophysical analysis carried out is shown in Tables 1 and 2.

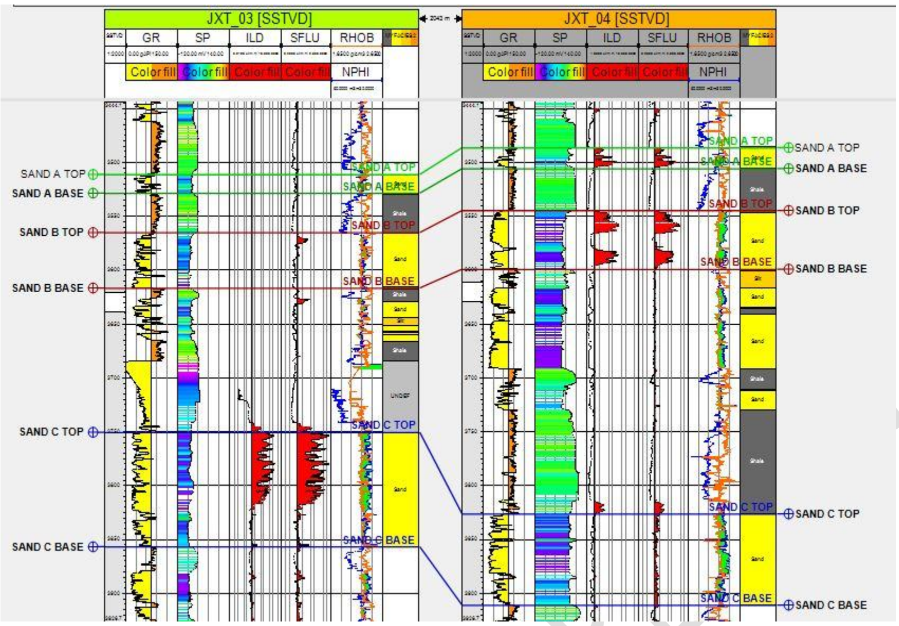

Figure 5: Reservoirs correlated across JXT 03 and 04.

Table 1: Summary of petrophysical evaluation of the reservoirs in JXT 03

PARAMETER	**JXT-03**		
Reservoirs	**SAND A**	**SAND B**	**SAND C**
MD (m) -Top	3510.13	3565.23	3750.25
-Base	3530.71	3618.28	3858.61
THICKNESS (m)	20.58	53.05	108.36
Vsh (%)	0.15	0.14	0.08
POROSITY (%)	0.2	0.2	0.23
PERMEABILITY (mD)	469.1	367	1251

Sw (%)	0.9	0.8	0.2
Sh (%)	0.1	0.2	0.8

SAND A ranges from a depth of 3510m to 3531m in JXT 03. The depth range of this reservoir gives it a thickness of about 20m. In JXT 04, this reservoir has an estimated thickness of about 20m and a depth range of 3485m to 3506m. The shale volume of SAND A has an estimated value of 15% in JXT 03 and 21% in JXT 04. Across the two wells, the effective porosity was estimated to be 20% and 17% respectively. The permeability of this reservoir ranges from 128mD in JXT 04 and 469.1mD in JXT 03. The reservoir is highly saturated with water in JXT 03 at 90%, while in JXT 04, the water saturation reduces to 30%.

SAND B ranges from a depth of 3565m to 3618m in JXT 03. The depth range of this reservoir gives it a thickness of about 53m. In JXT 04, this reservoir has an estimated thickness of about 55m and a depth range of 3545m to 3600m. The shale volume of SAND A has an estimated value of 14% in JXT 03 and 12% in JXT 04. Across the two wells, the effective porosity was estimated to be 20% respectively. The permeability of this reservoir ranges from 310mD in JXT 04 and 367mD in JXT 03. The reservoir is highly saturated with water in JXT 03 at 80%, while in JXT 04, the water saturation reduces to 30%. In this regard, the hydrocarbon saturation across both wells ranges from 20% in JXT 03 to 70% in JXT 04.

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Table 2: Summary of petrophysical evaluation of the reservoirs in JXT 04

PARAMETER	**JXT-04**		
Reservoirs	**SAND A**	**SAND B**	**SAND C**
MD (m) -Top	3485.27	3545.27	3827.63
Base	3505.69	3600.69	3910
THICKNESS (m)	20.42	55.42	82.37
Vsh (%)	0.21	0.12	0.12
POROSITY (%)	0.17	0.2	0.2
PERMEABILITY	128.1	310.2	310.2

(mD)			
Sw (%)	0.3	0.3	0.8
Sh (%)	0.7	0.7	0.2

SAND C ranges from a depth of 3750m to 3859m in JXT 03. The depth range of this reservoir gives it a thickness of about 108m. In JXT 04, this reservoir has an estimated thickness of about 82m and a depth range of 3828m to 3910m. The shale volume of SAND A has an estimated value of 8% in JXT 03 and 12% in JXT 04. Across the two wells, the effective porosity was estimated to be 23% and 20%respectively. The permeability of this reservoir ranges from 310mD in JXT 04 and 1251mD in JXT 03. The reservoir is highly saturated with hydrocarbons in JXT 03 at 80%, while in JXT 04, the water saturation increases to 80%. In this regard, the hydrocarbon saturation across both wells ranges from 20% in JXT 04 to 80% in JXT 03.

Rock physics

The Vp across the SAND A interval in JXT 03 is 3489.1 m/s, while in JXT 04, it is 3402 m/s (Tables 3 and 4). In the SAND B interval, the Vp increases with values ranging from 3473 m/s to 3686.1 m/s. The lower Vp values for SAND A and B were estimated from JXT 04, while the higher values are from the JXT 03 well. The Vp values in the SAND C reservoir interval were estimated to have higher values in JXT 04, than in JXT 03. The increase and decrease in values of Vp across both wells can be attributed to changes in fluid saturation in the reservoirs. There is an observed increase when water saturation increases and a decrease when gas saturation increases.

The Vs across the reservoirs are unaffected by fluid because shear sonic waves do not travel through fluids (Telford 1990; Avseth, 2005). The results from Vs estimation can be used to show the cementation properties in each of the reservoirs. The estimated Vs values from the SAND A interval across both wells range from 1887.5m/s to 1967m/s, with the higher values observed in JXT 03. The estimated values in SAND B show an increase in depth, and range from 2019.4m/s to 2170m/s, with the values increasing from JXT 03 to JXT 04. Vs values in SAND C range from 2214.4m/s to 2248m/s. The increase in Vs values across both wells indicates the direction of increasing cementation in the JXT field. For SAND A, cementation increases from SE to NW, while SAND B and C show an increase from the NW to SE direction. Cementation is important in understanding pore volume compressibility because it reduces the effect of compressive forces on the formation matrix. Studies have shown that formations with high cementation and low clay volume have higher effective porosities while undergoing diagenetic processes (Han, 1986; Avseth 2005).

Table 3: Calculated rock physics parameters of JXT 03

JXT 03				
	Vp	**Vs**	**Porosity**	**Rho**
SAND A	3489	1967	0.2	2.27
SAND B	3473	2019.4	0.2	2.26
SAND C	3746.2	2214.4	0.23	2.177

Table 4: Calculated rock physics parameters of JXT 04

JXT 04				
	Vp	**Vs**	**Porosity**	**Rho**
SAND A	3402.1	1887.5	0.17	2.25
SAND B	3686.1	2170	0.17	2.146
SAND C	3809.5	2248.3	0.19	2.209

Estimation of elastic parameters

The estimated bulk modulus of the reservoirs in the JXT field ranges from 21.3GPa to 25.3GPa, while the shear modulus ranges from 8GPa to 11.2GPa. Quartz being the major mineral in a clastic reservoir setting has a bulk modulus of 36.6GPa, therefore, the estimated bulk modulus of the reservoirs in the JXT field gives a good indication of its strength. The young modulus estimated also indicates the strength of the reservoirs. The values range from 20GPa to 28GPa, while the Poisson ratio ranges from 0.23 to 0.28. A detailed look at these results reveals that in terms of bulk modulus and young modulus, SAND A registered the lowest values across both wells, while SAND C registered the highest values. A summary of the estimated parameters is shown in Tables 5 and 6.

Table 5: A summary of the estimated reservoir elastic parameters in JXT 03

JXT 03				
	K(GPa)	**μ(GPa)**	**E(GPa)**	**Σ**
SAND A	22.5	8.8	22.3	0.27
SAND B	21.8	9.2	23	0.24
SAND C	24	10.67	26.3	0.23

Table 6: A summary of the estimated reservoir elastic parameters in JXT 03

JXT 04				
	K(GPa)	**μ(GPa)**	**E(GPa)**	**Σ**
SAND A	21.3	8	20.5	0.28
SAND B	22.9	10	25	0.23
SAND C	25.3	11.2	27.5	0.23

Compressibility Analysis

This involved using Gassmann's model and Modified Hashim-Shtrikman-Wadpole bounds for compressibility analysis

Gassmann's model

Gassmann's modelestimation of saturated bulk modulus, mineral modulus, undrained pore modulus, drained pore modulus, fluid modulus, and dry rock modulus was implemented (Figures 6,7, 8 ,9 and 10). This aided the estimation of the corresponding saturated rock compressibility, mineral compressibility, undrained pore compressibility, fluid compressibility, drained pore compressibility C(dp), and dry rock compressibility. From Tables 6 and 8, the drained pore compressibility C(dp), which is the pore volume compressibility of the reservoir formations ranges from 0.06GPa^{-1} to 0.13GPa^{-1}. The values of the limits of compressibility derived from the Gassmann model were used to measure the pore volume compressibility relative to the mineral compressibility. Based on the obtained results, the SAND C reservoir has the least compressible pore volume. It is 2.2 times more compressible than quartz mineral. SAND A has the most compressible pore volume and is approximately 5 times more compressible than quartz mineral.

Table 7: Results for Ksat, Kmin, Ksp, Kdp, Kf, and Kdry, from the Gassmann compressibility analysis of JXT 03

		K(sat)	**K(min)**	**K(sp)**	**K(dp)**	**K(f)**	**K(dry)**	**Por**
	SAND A	22.5	36.6	11.7	8.91	2.77	20.1	0.2
WELL 3	**SAND B**	21.8	36.6	10.8	8	2.77	19.13	0.2
	SAND C	24.01	36.6	16.1	16	0.069	24	0.23

Table 8: Results for Csat, Cmin, Csp, Cdp, Cf, and Cdry, from the Gassmann compressibility analysis of JXT 03

		C(sat)	**C(min)**	**C(sp)**	**C(f)**	**C(dp)**	**C(dry)**
	SAND A	0.044	0.027	0.086	0.36	0.11	0.05

WELL 3	**SAND B**	0.046	0.027	0.093	0.36	0.13	0.052
	SAND C	0.042	0.027	0.062	14.5	0.063	0.042

Table 9:~~showing~~ results for Ksat, Kmin, Ksp, Kdp, Kf, and Kdry, from the Gassmann compressibility

analysis of JXT 04

Comment [JY4]: Please pay attention to formatting issues.

		K(sat)	**K(min)**	**K(sp)**	**K(dp)**	**K(f)**	**K(dry)**	**Por**
WELL 4	**SAND A**	21.3	36.6	8.7	8.6	0.069	21.23	0.17
	SAND B	22.9	36.6	11.6	11.6	0.069	22.85	0.19
	SAND C	25.3	36.6	15.6	12.8	2.77	23.72	0.19

Table 10:~~showing~~ results for Csat, Cmin, Csp, Cdp, Cf, and Cdry, from the Gassmann compressibility analysis of JXT 04

		C(sat)	**C(min)**	**C(sp)**	**C(f)**	**C(dp)**	**C(dry)**
WELL 4	**SAND A**	0.047	0.027	0.12	14.5	0.12	0.047
	SAND B	0.044	0.027	0.086	14.5	0.087	0.044
	SAND C	0.04	0.027	0.064	0.36	0.08	0.042

3.2.2.2 Modified Hashim-Shtrikman-Wadpole bounds for compressibility analysis

The modified Hashim-shtrikman-wadpole model for compressibility is used in this research to predict the pore type within the allowable range (Avseth et al., 2005). The pore types fall within the range of soft pore shapes and stiff pore shapes. Stiffer pore shapes made the compressibility values to be lower within the permissible range, while softer pore shapes caused the values to be higher. The results obtained from the application of this model are in the range of 0.04GPa^{-1} to 3GPa^{-1}. Where the lower bound of compressibility (C^{HS-}) measured in the JXT field is 0.04GPa^{-1}, while the upper bound of compressibility (C^{HS+}) is 3GPa^{-1}. In JXT 03, SAND A falls within the range of stiffer pore shapes (0.042GPa^{-1} to 0.38GPa^{-1}), SAND B falls within the range of stiffer pore shapes to moderately stiff pore shapes (0.042GPa^{-1} to 0.95GPa^{-1}), while SAND C falls within the range of softer pore shapes to stiffer pore shapes (0.042GPa^{-1} to 3GPa^{-1}). In JXT 04, SAND A falls within the range of stiffer to softer pore shapes (0.043GPa^{-1} to 2GPa^{-1}), SAND B falls within the range of stiffer to softer pore shapes (0.04GPa^{-1} to 2.14GPa^{-1}), while SAND C falls within the region of stiffer pore shapes (0.04GPa^{-1} to 0.74GPa^{-1}) These values imply that the compressibility of a reservoir is highly influenced by lithology and mineral type, as well as fluid type. The results for each well are displayed in Tables 11 and 12.

Table 11: Results of the Hashin-Shtrikman-Wadpole compressibility analysis of JXT 03 highlighting the upper and lower boundaries.

WELL 3			
PARAMETER	**SAND A**	**SAND B**	**SAND C**
K(quartz)	36.6	36.6	36.6
K(shale)	11.4	11.4	11.4
K(gas)	0.069	0.069	0.069
K(water)	2.77	2.77	2.77
µ(quartz)	45	45	45
µ(shale)	3	3	3
µ(gas)	0	0	0
µ(water	0	0	0
K(SH+)	23.9	23.9	23.3
K(SH-)	2.605	1.054	0.34
C(SH+)	0.38	0.95	2.97
C(SH-)	0.042	0.042	0.043
µ(SH+)	23.4	23.8	24.6
µ(SH-)	0	0	0
Por	0.2	0.2	0.23
(1-Por)	0.8	0.2	0.8
Vquartz	0.85	0.86	0.92
Vsh	0.15	0.14	0.08
Sw	0.9	0.7	0.2
Sg	0.1	0.3	0.8
ζ(Kmax,µmax)	40.8	40.8	40.8

Table 12: Results of the Hashin-Shtrikman-Wadpole compressibility analysis of JXT 04 highlighting the upper and lower boundaries.

WELL 4			
PARAMETER	**SAND A**	**SAND B**	**SAND C**
K(quartz)	36.6	36.6	36.6
K(shale)	11.4	11.4	11.4
K(gas)	0.069	0.069	0.069
K(water)	2.77	2.77	2.77
µ(quartz)	45	45	45
µ(shale)	3	3	3
µ(gas)	0	0	0
µ (water)	0	0	0
K(SH+)	23	24	24.8
K(SH-)	0.5	0.47	1.35
C(SH+)	2.0	2.14	0.74
C(SH-)	0.043	0.04	0.04
µ(SH+)	22.5	25	25.
µ(SH-)	0	0	0
Por	0.17	0.19	0.19
(1-Por)	0.83	0.81	0.81
Vquartz	0.79	0.88	0.88
Vsh	0.21	0.12	0.12
Sw	0.3	0.3	0.8
Sg	0.7	0.7	0.2
ζ (Kmax, µmax)	40.84	40.84	40.84

CONCLUSION

There is a ~~major~~ crucialneed to mitigate~~/reduce~~ the adverse effects of CO_2 emissions in the atmosphere which cause~~s~~ global warming,~~which generally has adverse effects on~~impacting both health and the environment negatively. This can be done through possible reduction and stabilization of CO_2 emitted in the atmosphere. In this study, CompressibilityAnalysis and Geomechanical Characterization were carried out for ~~P~~potential~~ssible~~ CO_2 Sequestration and Storage. This, in turn, will ~~assist in~~ provid~~e~~ing positive indications for the advancement of health and environmental protection. This study ~~assisted~~ facilitatedin the identification of the availability of suitable reservoirs for CO_2 storage to prevent this gas leakage to the surface. Logs from two wells from the ‘‘JXT’’ field, onshore, Niger Delta were used for the study. Due to ~~long~~ manyyears of hydrocarbon production in the Niger Delta, several depleted and abandoned wells that can be utilized as geologic storage for CO_2,~~to assist~~ supportingeconomic growth and environmental protection, are available. Results from Petrophysics and Rock physics (Geomechanics, fluid sensitivity, compressibility) analysis for comparison and evaluation of physical strength, rock sensitivity to fluid changes, the drained and undrained properties of each reservoir, and its resistance to compressive forces indicated that the ‘‘JXT’’ field is suitable for CO_2 storage. It can therefore be considered for safe storage of CO_2 to reduce the emission of this greenhouse gas into the atmosphere. The study has shown that the availability of adequate, non-leaking reservoirs in the field can assist in health and environmental protection as it will aid positive global climate change.

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