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EVALUATION OF RESERVOIR ROCKS IN GABO FIELD, NIGER DELTA FOR CO_2 STORAGE AND RETENTION

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ABSTRACT

The study was conducted to evaluate the reservoir rocks for carbon storage and retention using seismic and well log data. A multidimensional sequence stratigraphic framework was constructed, estimated the spatial and lateral continuity of reservoir sands, deduced petrophysical properties of offshore sands and interpreted gross depositional settings and processes. Well-to-seismic tie analysis was performed to verify the accuracy of seismic data, while well correction analysis was carried out to adjust well data for errors and inconsistencies. Fault and horizon interpretations were conducted, revealing regional faults, major counter-regional faults, and reverse faults. A comprehensive 3D analysis was performed to assess the facies composition, porosity distribution, and water saturation in the field reservoirs. Sand facies dominated the reservoir, indicating favourable conditions with high porosity and permeability. The results significantly showed the reservoir's geological characteristics, fluid dynamics and potentials for hydrocarbon accumulation, carbon storage and retention. Sands A, B, C and D were found to exhibit favourable characteristics for CO_2 storage.
Keywords: carbon sequestration, reservoir, storage and retention

INTRODUCTION

One of the main causes of climate change is carbon dioxide (CO_2) (Ismail *et al*., 2019). Steel manufacture and the use of electricity obtained from coal are just two of the many processes that release CO_2 into the environment (Bhattacharyya *et al*., 2021). A layer of invisibility created by the CO_2 emissions prevents heat from escaping the Earth's atmosphere. We refer to this phenomenon as global warming (Ogwu *et al*., 2023). As a result, it is important to investigate potential scientific treatments for reducing the effects of global climate change.

Long-term storage of anthropogenic CO_2 by either geologic or terrestrial sequestration is referred to as carbon sequestration. In order to store CO_2 in geologic layers for protracted periods of time, a mix of cutting-edge technologies is needed for geologic carbon sequestration (Li *et al*., 2009). By using these new technologies, human kind will be able to reduce the negative consequences that burning fossil fuels has on the environment and the rate of climate change. The need for energy as a result of the world's growing industrialization and urbanization is the primary source of the excess of CO_2 in the atmosphere (Xu & Lin, 2015). Coal is the primary source of energy utilized globally. When coal is heated to a high temperature, energy is produced that powers massive turbines that create electricity, (Akpabio *et al* (2012). Large amounts of carbon dioxide are released into the atmosphere during this process, increasing anoxia and having an impact on biological life. Before or after production, CO_2 is captured as part of the capture and storage/sequestration process, and then it is permanently deposited beneath the surface of the Earth in geological formations (Jayeola & Olusola, 2022). The first stage in CCS is to identify suitable sites for carbon storage (Leung *et al*., 2014). This study will identify and demarcate suitable basin-wide locations for potential carbon storage. The objective of this study was to evaluate reservoir rocks with emphasis on CO_2 storage and retention.

This research is relevant in various ways. It addresses the important global issue of climate change by investigating CO_2 sequestration which helps in reducing greenhouse gas emissions. Carbon dioxide capture and storage (CCS) is a technique aimed at reducing the emission of greenhouse gases into the atmosphere (Cao *et al*., 2022). The process involves capturing CO_2 from several sources. The captured CO_2 is then transported to a storage site, usually underground, and securely stored within the earth's geology (Plasynski *et al*., 2009). This process is designed to reduce the negative effects of CO_2 emissions from burning fossil fuels, which are known to contribute to climate change.

The atmospheric concentrations of CO_2 have increased dramatically over the past two centuries (Ayani & Grana, 2020). This increase is primarily due to human activities, such as the burning of fossil fuels and deforestation (Cao *et al*., 2022). In the late 18th century, atmospheric CO_2 concentrations were estimated to be around 280 parts per million (ppm). However, in recent years, the concentration levels have increased significantly, reaching approximately 380 ppm and continuing to rise (Zhang *et al*., 2013). Typically, fossil fuel power plants release large amounts of CO_2 into the atmosphere, but with CCS, this carbon dioxide is captured before it is released. The captured CO_2 is compressed and transported to a storage site, where it is injected deep into geological formations such as depleted oil and gas reservoirs, saline aquifers, or deep unmineable coal seams (Ighalo *et al*., 2022). In addition to CO_2 capture and storage, there are other options available for reducing CO_2 emissions. These options include reducing the use of carbon-rich fuels and transitioning from coal-based energy to more renewable energy sources (Zhang *et al*., 2013). Although CO_2 capture and storage is considered one of the most effective ways to reduce atmospheric CO_2, its implementation requires a significant effort (Ayani and Grana, 2020). Industries heavily rely on the burning of fossil fuels, with over 85% of the energy used in these industries coming from fossil fuel combustion. Coal is a major source of energy, and it is projected to provide 28% of the world's energy by 2030. The objective of CCS technology by 2050 is to equip all coal and gas power plants with the ability to capture CO_2. If this goal is accomplished, emissions from energy production would decrease by 20%.

Geological Features for CO_2 Storage

The types of rock formations and geologic structures that are suitable for the long-term storage of carbon dioxide include (Ighalo *et al*., 2022; Cao *et al*., 2022):

i. **Saline Aquifers**: are large underground water-bearing rock formations that have a high salt content. They are considered ideal for CO_2 storage because the high pressure and variations in temperature (Akpabio and Ejedawe (2001)) of the CO_2 can cause the salt to dissolve, creating a secure seal that prevents the CO_2 from escaping.

ii. **Depleted Oil and Gas Reservoirs**: are reservoirs that have been depleted of their hydrocarbons and are no longer in use for oil or gas production. They are ideal for CO_2 storage because the rock formation is already permeable and porous, allowing for easy injection and storage of CO_2.

iii. **Unmineable Coal Seams**: are coal seams that are too deep or otherwise unmineable for commercial extraction. They are considered suitable for CO_2 storage because they are typically under high pressure and temperature, which can help keep the CO_2 stored securely.

iv. **Deep Saline Formations**: are large underground rock formations with high salt content that are located at great depths below the earth's surface. They are ideal for CO_2 storage because of the high pressure and temperature conditions, as well as the secure sealing properties of the salt.

v. **Enhanced Oil Recovery (EOR) Reservoirs**: are oil reservoirs that have been depleted of their hydrocarbons and are now used for enhanced oil recovery. In EOR, CO_2 is injected into the reservoir to increase pressure and displace the remaining oil, making it easier to extract. This process also allows for the long-term storage of CO_2 in the reservoir.

It is important to note that not all geological features are suitable for CO_2 storage, and careful consideration must be given to factors such as the depth, pressure, temperature, (Akpabio and Ejedawe, 2010) and permeability of the rock formation before selecting a site for CO_2 storage.

Storage of CO_2 in Reservoirs

CO_2 storage in the subsurface of the earth is considered a safe method for disposing of unwanted CO_2. A subsurface sandstone reservoir with high porosity and low faulting can serve as an ideal storage space for CO_2, especially if it is capped by a shale deposit (Ighalo *et al*., 2022). This is because faults could cause the CO_2 to escape from the storage reservoir if the faults are non-sealing and cut through the seal above the reservoir rock. In addition, CO_2 storage in active oil and gas reservoirs can help improve the recovery rate of oil or gas. By adding pressure to the system, the stored CO_2 can increase the extraction of hydrocarbons and force them to the surface. The process of Carbon Sequestration with Enhanced Gas Recovery (CSEGR) was simulated on the Rio Vista Gas Field in California (Oldenburg, 2001). This process involves injecting CO_2 into a gas reservoir to help recover the remaining gas as well as store the CO_2.

Oil and gas reservoirs, which are spread over a vast area in smaller units, limit the storage capacity as their volumes are relatively small. In contrast, saline aquifers have much larger storage volumes and can store larger amounts of CO_2 (Ozotta *et al*., 2021). One advantage of storage in either active or depleted oil or gas reservoirs over saline aquifer storage is that these reservoirs already have exploration and production wells, which provide the necessary geological data and access to these deep underground reservoirs for CO_2 storage. Additionally, the pipelines and well equipment are already in place, making the CO_2 project cost-effective and time-efficient. Depleted hydrocarbon fields have successfully kept the previously present hydrocarbons in place, indicating that the reservoir has a good sealing capacity. However, this sealing capacity may deteriorate as CO_2 replaces the hydrocarbons. The surface tension of the CO_2-water system in the reservoir is much lower than the hydrocarbon-water system that was previously there (Ighalo *et al*., 2022). This replacement process reduces the capillary sealing pressure of the caprock, which means that the sealing capacity must be tested before the CO_2 is injected to ensure the reservoir pressure will not cause migration to other formations above the caprock.

Geology of the Study Area

The Niger Delta Province is made up of Nigeria, Cameroon, and Equatorial Guinea and is located in the Gulf of Guinea. So far, only one petroleum system has been identified in the region, which is known as the Tertiary Niger Delta (Akata-Agbada) petroleum system in Nigeria. The delta formed at a rift triple junction in the Late Jurassic and continued into the Cretaceous as the southern Atlantic opened up. The delta proper started to develop in the Eocene and has accumulated sediments that are over 10 km thick. The primary source rock is the upper Akata Formation, which is a marine shale, and the interbedded marine shale of the lowermost Agbada Formation may also contribute (Osuji *et al*., 2014). The Niger Delta covers an area of over 70,000 km² in Nigeria and makes up about one-fourth of the country's total land mass. It was originally made up of the Bayelsa, Delta, and River States but was expanded in 2000 to include other states.

The geologic history of the Niger Delta Province ranges from the Eocene period to the present day and is the youngest of the three depositional cycles that led to the formation of the coastal sedimentary basin in Nigeria. The deposition of sediments took place from 56 to 34 million years ago and continues to the present day, resulting in three stratigraphic subdivisions: the Benin formation, the Agbada formation, and the Akata formation. The Niger Delta Province is located in the Gulf of Guinea and spans Nigeria, Cameroon, and Equatorial Guinea. It has an area of over 70,000 km² and is made up of the Tertiary Niger Delta Petroleum System in Nigeria. The geologic history of the region dates back to the Eocene period, and it is the youngest of three depositional cycles that led to the development of the coastal sedimentary basin of Nigeria.

Lithologically, the upper portion of the Niger Delta, known as the Benin formation, is composed of sand, while the middle Agbada formation is made up of alternating sandstone and shale, and the lower Akata formation is primarily shale. The Tertiary section of the Niger Delta is divided into three litho-stratigraphic formations, each with varying sand-shale ratios. The hydrocarbon potential of the Niger Delta and found that petroleum is produced from sandstone and unconsolidated sands in the Agbada Formation. The characteristics of the reservoirs in the formation are controlled by the depositional environment and depth of burial. As of 1999, the Niger Delta was estimated to hold recoverable oil and gas reserves of 35 billion barrels and 94 trillion standard cubic feet, respectively, with production primarily from the sandstone facies within the Agbada Formation, Figure 1.

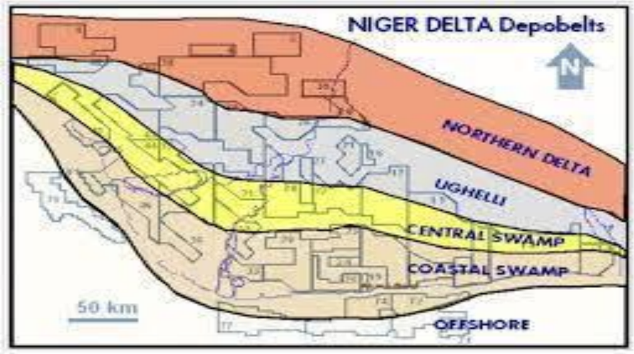

Figure 1: Niger Delta Basin

MATERIALS AND METHODS

Materials

Data collected from the Department of Petroleum Resources; an arm of the Nigerian National Petroleum Corporation were seismic in SEG-Y and well log in LAS. The Gabo Field offshore deposits' multidimensional sequence stratigraphic framework was built using well log data. In addition, well log and seismic data were utilised to evaluate the spatial and lateral continuity of reservoir sands.

Methodology Flowchart

These data were incorporated into the Petrel software and utilized to build 3-D geological static models, such as structural, lithofacies, and petrophysical property models, as well as to calculate the volume of the reservoir. An uncertainty analysis of the constructed reservoir geological models was performed to compute the CO_2 storage capacity. Additionally, the CO_2 sequestration capacity was established based on a specific formulation introduced by previous studies (Umunna *et al*., 2019). Figure 2 shows the flow chart for the methodology

Integration and Correlation of Data

Schlumberger Petrel software was used for the analysis of seismic and well data. The 3D seismic data was loaded in SEG-Y format. Inlines, crossline and time slices were generated and quality control performed on them. Well header information file containing co-ordinates was loaded into Petrel software before well logs were loaded in order to display the wells within their proper co-ordinates. Deviation surveys were also imported into the Petrel software. The deviation survey measures the deviation of the wells from vertical. Well log data were imported after proper quality control was carried out on the data. A base map of the study area was generated after loading the various data types enumerated above. Posamentier & George, (1994) identified the first step in sequence stratigraphic interpretation as determination of the general paleogeographic setting for the database in question.

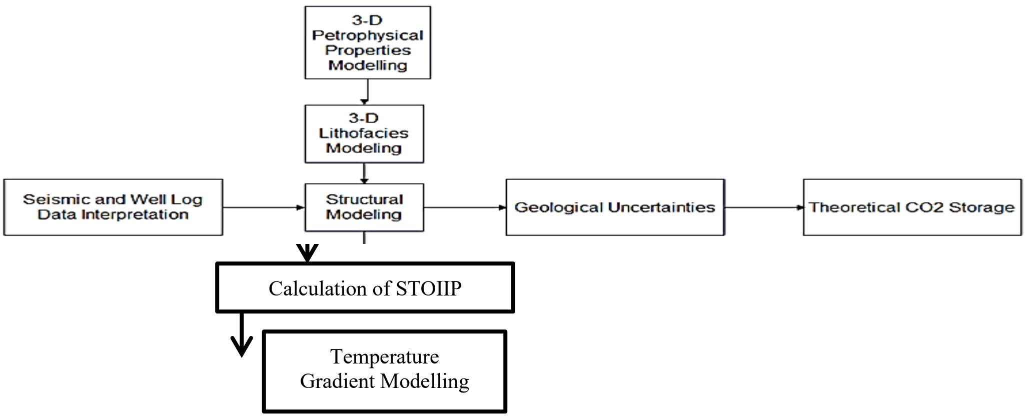

Figure 2: Flow chat

Determination of physiographic setting for this dataset was accomplished using 2-D and 3-D seismic data. These data provide continuous imaging of the subsurface in a way not possible with other forms of data because they enable the interpretation of the overall geologic and tectonic setting of the basin (Vail *et al.*, 1977). The second step was to interpret depositional systems and facies using all available data. Different parasequence stacking patterns (coarsening upward, fining upward, blocky, symetrical and serrated patterns) noticed were analyzed in relationship with those below and above individual parasequences to determine depositional systems. These range of patterns compares with those described by Abbasov (2022), (Alcolea Rodriguez *et al.,* 2018). The third step was to subdivide the stratigraphic succession through the identification of maximum flooding surfaces and sequence boundaries (Mahmoud, 2001). Gamma ray logs were examined for highest peaks that could signify flooding surfaces, maximum flooding surfaces and sequence boundaries were identified afterwards.

Checkshot data was used for well log to seismic tie, this was necessary in order to be able to locate and mark information from the well data in the form of geologic tops on the time (seismic) section. Well logs were used to identify different lithofacies present within the study area. Gamma ray logs were used as the primary tools for lithology identification and delineations. A range of 0 API to 150 API was used for GR logs and 0 ohm m^2/m to 200 ohm m^2/m for resistivity. Also, a scale of 0 g/cm^3 to 60 g/cm^3 was used for bulk density while 1.5 neutron porosity unit (p.u) to 2.6 p.u was used for neutron porosity. Lithology interpretation was done for all the wells and through careful study of log patterns. Well correlation for the Freeman field was done after lithology interpretation based on well logs.

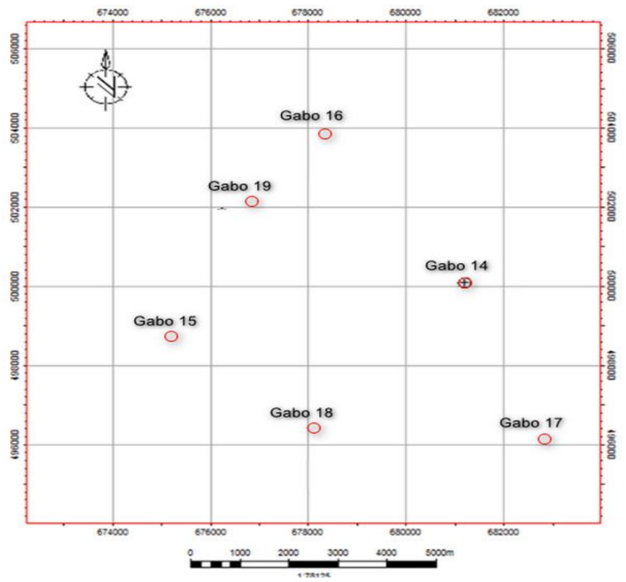

Figure 3: Base map showing well log locations in the study

Figure 3 shows the base map that depicts the locations of well logs, specifically Gabo 14, 15, 16, 17, 18, and 19. The formation is a sedimentary rock formation consisting of sandstones, shales, and clays and is located in the Gabo Field within the Northern Depobelt of the Niger Delta Basin in Nigeria. The well logs shown on the map are records of geological formations that were encountered during drilling activities. They provide valuable information about the physical properties of the formation, such as rock type, porosity, permeability, and other characteristics that are crucial for the exploration and production of hydrocarbons.

METHODS

These results are achieved through the following steps:
Step One: Correlation of well log data
Step Two: Identification of key bounding surfaces on correlated results on step one
Step Three: High-resolution sequence stratigraphic framework with respect to depth reflecting the correlated results
Step Four: Seismic to well tie which converts time slide to depth slide

Well to Seismic Tie

Well-to-seismic tie was carried out on the well that is either within the area of seismic survey or closest proximity with the seismic survey line (that is well that were drilled within the seismic coverage) to enhance the seismic trace signal obtained from each acoustic interface. It is known that seismic data measures velocity contrast in acoustic impedance interface. Synthetic seismic traces are used for well-to-seismic tie (matching of wavelets from synthetic seismic trace or seismogram with seismic data).

Seismic Facies Analysis

Well to seismic tie enable conversion of seismic slice in time to depth since well log (sonic and density) information is given in depth. This makes the suites of data coherent such that each surface identified in well log data can be mapped across seismic section since seismic section gives the regional subsurface geology of an area (Kufre *et al*., 2017). Various seismic attributes were also analyzed using seismic section so that clearer view on the depositional settings can be interpreted.

Seismic Facies Interpretation Techniques

The attributes used to define facies include reflection configuration, continuity, amplitude and frequency spectra, internal velocity, internal geometrical relations and external 3D form. Most of these are best seen in sections parallel to the dip. Parallel or subparallel reflections indicate uniform rates of deposition; divergent reflections result from differential subsidence rates, such as in half graben or across a shelf–margin hinge zone. Prograding clinoform reflections are particularly common on continental margins where they represent deltaic or continental slope outgrowth. Variations in patterns of progradation reflect different combinations of depositional energy, subsidence rates, sediment supply, water depth and sea level position. Sigmoid clinoforms tend to have low depositional dips, typically less than 1^o, whereas oblique clinoforms may show depositional dips up to 10^o. Parallel oblique clinoform patterns show no topsets which implies deposition in shallow water, with wave or current scour and sediment bypass to deeper water, perhaps down a submarine canyon that may be revealed on an adjacent seismic cross-section. Many seismic sequences may show a very complex prograding stratigraphy, e.g., as illustrated by the complex sigmoid-oblique clinoform in

RESULTS

The results and discussions are presented using Gabo 14 as a representative. Figure 4 shows the petrophysical parameters of Gab14.

Gabo 14 Sand A

The Sand A reservoir was identified as having a depth between 2033.93 and 2050.69 meters, and a net thickness of 16.92 meters in Gabo 14 well as shown in Figure 5. The characteristics of the Sand A reservoir were determined by various measurements, indicating that the formation encountered is a Sand A reservoir. The bit size used during drilling was 12.25 inches. The bulk volume of water present in the Sand A reservoir varied between 0.074 and 0.122 dec, with an average value of 0.102 dec. The caliper measurements showed that the Sand A reservoir has varying thicknesses ranging from 14.666 to 23.004 inches, with an average value of 17.416 inches. The density measurements indicate that the Sand A reservoir has a density range of 1.62 to 2.35 g/c3, with an average value of 2.128 g/c3. The gamma ray measurements showed a range of values between 29.627 and 76.177 gAPI, with an average value of 42.417 gAPI. The neutron measurements indicated a range of values between 0.138 and 0.451 v/v, with an average value of 0.251 v/v. The porosity measurements showed a range of values between 0.184 and 0.6 dec, with an average value of 0.317 dec.

Gabo 14

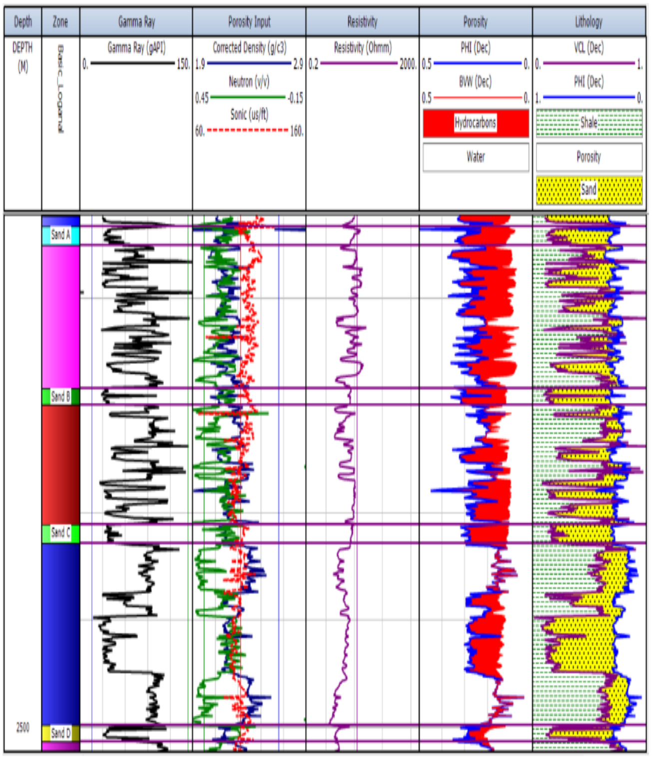

Figure 4: Basic and petrophysical parameters of Gab14, Source: Field Data (2023)

The photoelectric log measurements indicated a range of values between 1.343 and 1.994 B/E, with an average value of 1.679 B/E. The resistivity measurements showed a range of values between 6.761 and 18.291 Ohmm, with an average value of 10.24 Ohmm. The self-potential measurements showed a range of values between 60.892 and 67.396 mV, with an average value of 64.368 mV. The sonic measurements indicated a range of values between 96.288 and 117.922 us/ft, with an average value of 107.104 us/ft. The water saturation measurements showed a range of values between 0.156 and 0.559 dec, with an average value of 0.33 dec. The true vertical depth below sea level of the Sand A reservoir was found to be between 1954.464 and 1970.643 meters, with an average value of 1962.549 meters. The volume of shale present in the Sand A reservoir varied between 0.108 and 0.472 dec, with an average value of 0.208 dec.

Gabo 14 Sand B

Figure 6 shows that the Sand B reservoir in Gabo 14 well has a depth range of 2183.892m to 2199.284m, with a net thickness of 15.545m. The characteristics of the Sand B reservoir were determined using various measurements, indicating that the formation encountered is a Sand B reservoir. The bit size used during drilling was 12.25 inches. The bulk volume of water present in the Sand B reservoir varied between 0.111 and 0.132 dec, with an average value of 0.12 dec. The caliper measurements showed that the Sand B reservoir has varying thicknesses ranging from 12.23 to 15.565 inches, with an average value of 13.69 inches. The density measurements indicate that the Sand B reservoir has a density range of 0.002 to 0.115 g/c3, with an average value of 0.031 g/c3. The gamma ray measurements showed a range of values between 24.664 and 106.36 gAPI, with an average value of 39.729 gAPI. The neutron measurements indicated a range of values between 0.196 and 0.351 v/v, with an average value of 0.261 v/v. The porosity measurements showed a range of values between 0.182 and 0.363 dec, with an average value of 0.304 dec. The photoelectric log measurements indicated a range of values between 1.557 and 2.999 B/E, with an average value of 1.802 B/E. The resistivity measurements showed a range of values between 5.739 and 8.056 Ohmm, with an average value of 7.021 Ohmm. The self-potential measurements showed a range of values between 56.821 and 64.936 mV, with an average value of 60.067 mV. The sonic measurements indicated a range of values between 99.193 and 114.006 us/ft, with an average value of 107.7 us/ft. The water saturation measurements showed a range of values between 0.321 and 0.72 dec, with an average value of 0.4 dec. The true vertical depth below sea level of the Sand B reservoir was not reported. The volume of shale present in the Sand B reservoir varied between 0.069 and 0.709 dec, with an average value of 0.187 dec.

DISCUSSION

Gabo 14

The identification of the Sand A reservoir with a depth range between 2033.93 and 2050.69 meters and a net thickness of 16.92 meters confirms its suitability as a target for CO_2 storage, retention and sequestration. The various measurements conducted, including density, porosity, and resistivity, indicate that Sand A possesses favorable characteristics for CO_2 storage. The average water saturation value of 0.33 dec suggests a significant potential for CO_2 storage within this reservoir. These findings highlight Sand A as a promising candidate for CO_2 sequestration in the Agbada Formation. Similarly, the characteristics of the Sand B reservoir, with a depth range of 2183.892m to 2199.284m and a net thickness of 15.545m, indicate its suitability for CO_2 sequestration. The average water saturation value of 0.4 dec suggests a relatively higher potential for CO_2 storage compared to Sand A. However, the absence of reported true vertical depth below sea level for Sand B requires further investigation to fully assess its sequestration capacity. Additional analysis and modeling efforts are necessary to determine the extent of CO_2 storage potential in Sand B.

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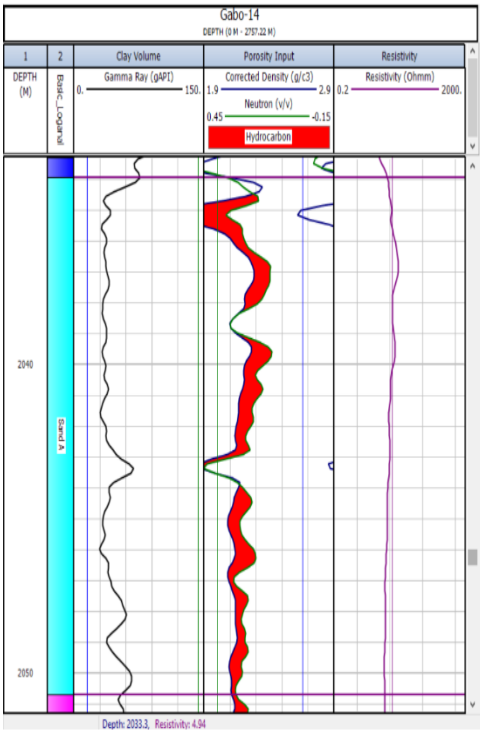

Fig. 5 Gabo 14 Sand A

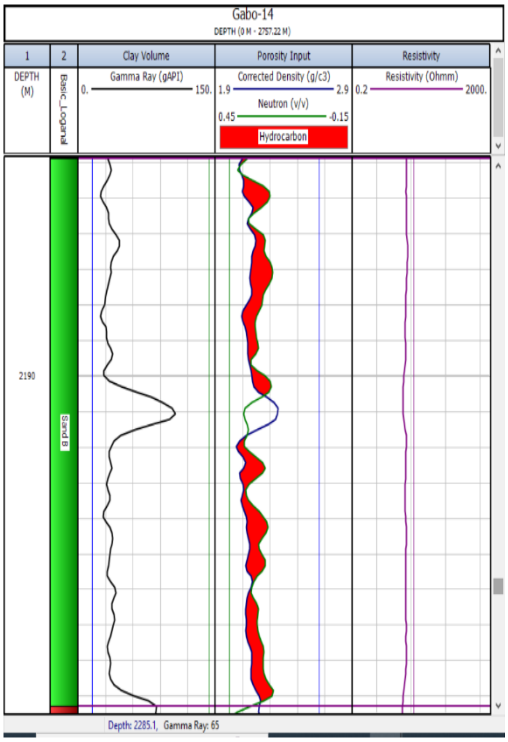

Fig. 6: Gabo 14 Sand B

The analysis of the properties of Sand C and Sand D reservoirs reveals their potential for CO_2 sequestration. The Sand C reservoir, with a depth range of 2310.536m to 2328.977m and a net thickness of 18.593m, exhibits characteristics that make it a favorable candidate for CO_2 sequestration. The relatively higher porosity values and lower water saturation values compared to Sand A and Sand B indicate favorable conditions for CO_2 storage. Similarly, the properties of Sand D, with a depth range of 2497.531m to 2512.619m and a net thickness of 15.24m, suggest its potential for CO_2 sequestration. The lower resistivity values and higher water saturation values in Sand D indicate suitable storage conditions.

The measurements of gamma ray, neutron, sonic, and photoelectric log provide valuable insights into the lithology and formation characteristics of the reservoirs. These data contribute to understanding the rock properties and their response to CO_2 injection and storage. The integration of well log and seismic data in this study enhances the accuracy and reliability of the assessments, offering a comprehensive evaluation of the subsurface conditions, reservoir properties, and the potential for CO_2 storage in the Agbada Formation. The findings of this study significantly contribute to the understanding of the Agbada Formation in the Gabo-Field and its potential for CO_2 sequestration. The identified reservoirs, including Sand A, Sand B, Sand C, and Sand D, offer promising opportunities for storing CO_2, which can play a crucial role in mitigating greenhouse gas emissions and combating climate change. However, it is essential to acknowledge that further analysis and modeling efforts are necessary to assess the storage capacity, reservoir performance, and long-term viability of CO_2 sequestration in these formations.

CONCLUSION

The results obtained from this study provide valuable information about the Sand A, Sand B, Sand C, and Sand D reservoirs in the Agbada Formation. These findings emphasize the potential of these reservoirs for CO_2 storage, retention and sequestration based on various measurements and properties. The porosity analysis revealed significant variations across the reservoir, reflecting different lithologies, depositional environments, diagenetic processes, and structural features. Understanding porosity distribution is vital for well placement, reservoir management, and production optimization. It helps identify areas of higher porosity and permeability, which serve as preferential flow paths for hydrocarbons. Furthermore, the analysis provides insights into diagenetic processes and reservoir quality evolution, enabling predictions of enhanced porosity and permeability areas. The water saturation analysis contributes to assessing fluid movement potential and the effectiveness of hydrocarbon recovery processes. By understanding the distribution of water saturation, regions with potential hydrocarbon accumulations can be identified, and challenges related to water saturation can be addressed in reservoir characterization and development planning.

The findings from these analyses collectively provide a comprehensive understanding of the reservoir's geological characteristics, fluid dynamics, and potential for hydrocarbon accumulation. This knowledge supports effective reservoir management, production optimization, and informed decision-making in hydrocarbon exploration and development activities in the Gabo Field. It enhances the success rate of exploration efforts, improves hydrocarbon recovery processes, and aids in resource estimation.

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