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Characterization of subsurface geological reservoir for safe carbon dioxide storage in the mitigation of climate change

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ABSTRACT

This research work characterized subsurface geological reservoir for long-term and safe carbon dioxide storage as an exigent feat to fight climate change and its mitigation. The objectives of the study include but not limited to analyzing seismic and well data to characterize a depleted oil reservoir to determine its suitability as a potential reservoir for CO_2 storage and subsequent emplacement of long-term monitoring, valuation and accounting system to map and observe the position where the CO_2 is injected. The reservoir is Eocene sands of the Agbada Formation of the Niger Delta, at depths 2,702 m – 2,745 m across the field, reaching up to 102 m in thickness with large vertical oil columns, with average porosity 14 – 24 %, and permeability 300 – 2,240 mD, reservoir pressure 2600 psi as well as temperature 169 oF. The average oil gravity is 38o API, and cumulative production from the field reached 1.968 bbls in 2012, and daily production peaked 108,214 b/d in 1984, but dropped to 1064 b/d in 2014 with a 98 % water cut. Results of the analysis of the reservoir properties shows that it is a candidate for dedicated storage of CO_2 where the injected CO_2 could be permanently stored. This research is pivotal for achieving the anticipated reduction of CO_2 emissions and fostering a more sustainable future for Nigeria while striving to achieve global climate goals.

1. INTRODUCTION

Nigeria is predominantly reliant on fossil fuels for revenue and power generation, producing huge emissions of carbon dioxide (CO_2) which amass in the atmosphere contributing to global warming and weather change. Balancing energy demand and reducing atmospheric CO_2 emissions is a significant challenge [1–3]. Anthropogenic CO_2 emissions into the atmosphere traps heat, preventing its escape to the atmosphere and sends it back to the Earth, increasing the temperature of the Earth, leading to global warming and climate change. This causes ice to melt leading to a rise in sea level, glacial shrinkage, ice shelf collapse, flooding, drought, subsidence, coastal erosion resulting to land instability and a possible threat to submergence of communities. Obviously, there is need to mitigate the impacts of climate change, by combating climate change and other geohazards in line with United Nations Sustainable Development Goal 13, by monitoring with geophysical techniques any changes that could increase the risk [4–8].

This research support fuel shifts to natural gas to reduce greenhouse gas emissions and other air pollutants. Priority should be given to the identification, study and development of prospects with lower carbon footprints. Important concepts to reduce greenhouse gas emissions include carbon capture utilization and storage (CCUS), use of renewable energy such as wind, geothermal energy, hydrogen and solar, the use of nuclear energy, energy efficiency improvements, and switching from coal fire power plants to gas fired power plants among others [9-10]. There is a focus on integrating carbon capture and storage (CCS) systems to sequester CO_2 in deep geological formations rather than releasing it into the atmosphere. This is because central to the success of CCS project is the safe and permanent storage of CO_2 in subsurface geological reservoirs. Storage of CO_2 in deep subsurface geologic formations permanently stores the CO_2 in either deep saline aquifers or depleted oil and gas reservoirs, capable of reducing the CO_2 concentration in the atmosphere. This is known as a component of CCUS, and its success depends on our ability to mitigate its risk [11]. This is achieved by either capturing CO_2 released to the atmosphere or by capturing CO_2 directly at the source instead of discharging it to the atmosphere, potentially lowering CO_2 emissions from major point sources which include coal and gas-fired power plants, chemical industries, natural gas processing plants, steel manufacturing factories, ethanol production facilities, cement producing factories, and other industrial operations. The captured CO_2 is then compressed to become a dense fluid which is transported through pipelines or trucks or sea going vessels and injected into deep subsurface geologic formation(s) for either enhanced oil recovery (EOR) or permanent storage [6], [10], [12].

Utilization of CO_2 for EOR operations and subsequent storage in geological formations has been well known for some decades. Where CCUS begins as a measure of CO_2-EOR project, to boost oil output, the supercritical phase CO_2 is usually injected into an existing oil-bearing reservoir. Injecting the electrically resistive supercritical CO_2 through injection well pushes the CO_2 outward from the well where it displaces and mixes with the electrically conductive brine and pore fluids and any crude oil it encounters, significantly increasing the bulk resistivity of the rock, while swelling and assembling extra crude oil for production. However, a fraction of the CO_2 released to the surface with the crude oil is recaptured and injected again into the reservoir. In the long span, almost hundred percent (100 %) of the injected CO_2 perpetually remains in the reservoir. Successful subsurface storage of CO_2 in deep saline aquifers, or as the use of CCS process or as part of CO_2-EOR operation entails cautious monitoring of the CO_2 concentration inside the subsurface reservoir, using seismic or electrical and electromagnetic (EM) methods. This is necessary because of regulatory and environmental apprehensions in CCUS and for optimization of EOR operations [6], [9-10], [13-16].

Large point sources of CO_2 include power plants, furnaces, industrial boilers and calcining plants. General, the concept of CCS involves capture of CO_2 directly from source(s) and/or from the atmosphere by physical and chemical separation methods. Basically, CO_2 capture processes could be categorized into three, (1) postcombustion processes in power plants where CO_2 is captured from a flue gas at low pressure, (2) precombustion processes where CO_2 is captured from a gas mixture with predominantly hydrogen gas at high pressure or produced directly from fossil fuel, (3) denitrogenation where a concentrated stream of CO_2 is produced by the exclusion of nitrogen before or during the combustion/conversion process, targeting the production of oxygen from air. Decarbonization processes involve absorption process using solvents that are absorption liquids to separate gases, membranes using selective barriers to separate gases, adsorption by sorbents using selective particles to separate gases and cryogenic separation using difference in points of condensation to separate gases. Biological processes involving algae production could be used to convert CO_2 to biomass which could be used as fuel. Furthermore, by carbon extraction fuel could be directly decarbonated and converted to inert carbon and hydrogen avoiding the use of carbon in the combustion process. Importantly, the energy conversion technologies and separation technologies for CO_2 and O_2 are usually integrated to achieve low cost and high efficiency in the

capture process [2], [6], [9], [17-19].

This is followed by compression at high pressure and liquefaction to achieve the right transport and storage conditions on land and sea respectively. Transport is needed because CO_2 emitting stations may not necessarily be at the same location as the storage site. On land, transport could be achieved through construction of pipelines or the use of trucks. Marine transport could be done using marine vessels (tankers or ships) or pipelines; thus, a transport system is needed to link CO_2 source(s) to the sink(s). Storage of CO_2 in deep geological formations is such that CO_2 remains isolated from the atmosphere for a very long period, say 1000 years. CO_2 might react with other fluid or be chemically bound to rock materials within the storage system, which is the means of CO_2 containment over geologic time. Proven trapping mechanisms are residual, structural, mineral trapping and solubility, which enhance storage safety over geologic timescales [6], [9], [12], [19-20].

Hydrocarbon discovery and production in Nigeria dated back to 1957 with the first discovery at Oloibiri in Bayelsa State. Since then, Nigeria has become a great hydrocarbon producer and greenhouse gas emitter because most of the gases produced earlier were flared. Thus, hydrocarbon discovery and exploitation since 1957 to date has resulted in reduction and abandonment of some reservoirs in the Niger Delta which could now be used for dedicated geological storage of anthropogenic CO_2 to reduce CO_2 emissions into the atmosphere in line with the UN SDG 13 which is climate action [2], [20]. For the purpose of this research, assessment of geological storage of CO_2 in a depleted hydrocarbon reservoir of the Niger Delta is considered. The field was initially identified by a 2D seismic survey in 1959 followed by a discovery well in 1962 and subsequently occupied by a long cable 3D seismic survey to obtain high resolution images. In 2015, injection of CO_2 into this oil field using it to produce additional oil through CO_2-EOR, which also provides a bridge to a low carbon energy future, was envisaged but not implemented ([14], [16], [21].

However, after the global covid-19 pandemic, in 2024, the decision to permanently store captured anthropogenic CO_2 emissions in this field, through a dedicated CCS project was reached, which warranted this study. This research work is aimed at characterizing the depleted oil reservoir for long term and safe carbon dioxide storage in the mitigation of climate change. The objectives of the study include but not limited to characterizing the depleted oil reservoir to determine its suitability as a potential reservoir for CO_2 storage, assess the quantity of CO_2 that could be stored and emplacement of long-term monitoring, valuation and accounting system to map and monitor the location of injected CO_2. This research highlights cutting-edge, multidisciplinary breakthroughs across the CCUS chain and tackle challenges of managing emissions, social acceptance, environmental stewardship and industrial competitiveness.

1.1. Location and Geology of the Study Area

Ambeme field is a hydrocarbon field located in the Central Swamp of the Nigerian Delta, and the geology of the field follows that described by [22-28]. This field (see Figure 1) is chosen for this work because both seismic and well data are available, and its reservoir rocks, fluids, porosity, permeability, faults, stratigraphy, etc, have been well characterized by the energy company that discovered and produced it. Furthermore, the field has demonstrated structural and stratigraphic integrity for long time storage of original hydrocarbon and is cost effective to convert an oil/gas well to a CO_2 injection well for geological storage [1], [21], [29-32]. It is a 268 km^2 oil field which has been producing primarily and subsequently by waterflooding for over 62 years. Production was from the Eocene sands of the Agbada Formation of the Niger Delta, at depths 2,702 m – 2,745 m, reaching up to 89.002 m in thickness with large vertical oil columns, with average porosity 14 – 22 %, and permeability 300 – 2,240 mD, reservoir pressure 2600 psi and temperature 169 ^oF. The oil gravity is 38^o API on the average, and accumulative production from the field peaked 1.968 billion barrels in 2012, and daily production peaked 108,214 barrels per day (b/d) in

1984, but reduced to 1064 b/d in 2014 by a 98 % water cut [2], [14], [21], [29-31].

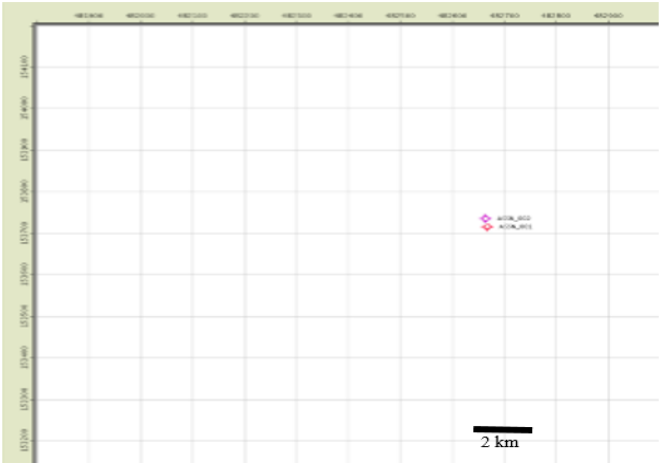


Figure 1. *Base map of the of the study area showing some of the wells in the field.*

The reservoir sands at the crest of the field are segmented by a series of northeast trending faults that dip to the southeast, dividing the reservoir into semi-continuous blocks truncated by northwest-trending sealing faults that dip to the northeast [32-33].

2. MATERIALS AND METHOD

2.1. Materials

Materials used in this research work include long cable (6 km) anisotropic 3D prestack seismic data, processed into three partial angle stacks of near (10^o-20^o) middle (20^o-30^o) and far (30^o-40^o), and a suite of wireline logs (gamma ray, resistivity, density, spontaneous potential, neutron, sonic, etc) obtained from five wells on the field. Other materials include interpreted horizons and low frequencies (0^o-10^o) hertz obtained from the wells and velocity model. Softwares such as Ikon Science Rokdoc, Techlog, Petrel and Jason Geoscience Workbench were used for the analysis and interpretation of data. The well logs were used to discriminate and delineate reservoir fluids and lithologies, determine porosity, assess the quantity of CO_2 that can be stored in the potential storage reservoir and demonstrate the reservoir's competence to meet required storage performance criteria.

2.2. Method

Seismic technology as applied to hydrocarbon exploration, due to its high resolution and high-fidelity images, is also, the imaging tool for subsurface depth and resolution required for CCUS projects. Analysis of the hydrocarbon potential of a geological formation entail characterizing the hydrocarbon in terms of quality and quantity, assessing the stage of its thermal evolution, determining the type of hydrocarbon generated, determining the mineralogical, geometric and volumetric properties of the formation rocks, etc. This is critical for selecting appropriate method for CO_2 storage and the reservoir's capacity for a dedicated CCUS project [2], [4], [7-8], [10], [12], [15-16], [19-20].

Geological storage of CO_2 in depleted hydrocarbon reservoirs is dependent on its petrophysical suitability and the phase behaviour of the interaction of CO_2 with the brine, oil and gas in it. The method follows that described by [1], [12], [20-21], [29-31]. Uncertainties associated with reservoir integrity, injectivity and long-term containment of geologically stored CO_2 present technical and societal risks that must be systematically derisked to promote large scale implementation. In principle, any fuel containing carbon could be used in the CCS systems [14]. For a successful subsurface CO_2 storage, certain geologic conditions are required, irrespective of the source and purpose. These include but not limited to identifying the right reservoir by having a good understanding of the subsurface rocks and proper monitoring of the reservoir because CO_2 leakage could lead to severe environmental consequences if it gets to near surface formations [2], [10], [12]. Usually, various methods such as seismic surveys, computational modelling, sorption isotherms, insitu measurements, organic petrology and geochemistry techniques, well data analysis, are employed in assessing the potential of geological formations for use as CO_2 storage reservoirs. In CCS projects, CO_2 is extracted at the point of emission or from the atmosphere, it is then compressed to a supercritical liquid and transported through pipelines, vehicles or sea vessels to where it is stored in suitable geological formations. Usually, at the storage site, monitoring, verification, and accounting activities

are performed before, in the course of active injection, and subsequently after closure of CO_2 injection operations [9], [13], [15-16].

3. RESULTS AND DISCUSSION

Since the purpose of CCS is to diminish anthropogenic CO_2 emissions to the environment, in the light of this truth, it is not the amount of CO_2 captured per production that is important but the amount of CO_2 emission prevented or avoided. Because plants with CO_2 capture produce the same output but generate more CO_2, the amount of CO_2 produced per unit production increases, and the amount of CO_2 avoided is less than the amount of CO_2 captured [16].

3.1. Finding of research

Derisking the subsurface reservoir for CO_2 storage began with rigorous site characterization using well log data, petrophysical analysis and high-resolution seismic imaging to understand reservoir heterogeneity, structural and stratigraphic patterns and cap rock integrity, injectivity and long-term containment. These would help predict reservoir quality, thickness, lateral extent, pressure and temperature, porosity, permeability, potential leakage pathways, etc, which is essential to select reservoirs with excellent proven trapping mechanisms, which enhance storage security over geologic timescales [1-2], [6], [20].

Figure 2 is the panel showing well log data from well 01 in the field, column 1 is the true vertical depth subsea (TVDSS) in feet (ft), column 2 is the horizon H1000 showing the reservoir interval, column 3 shows gamma ray log (black) and caliper log (red), column 4 shows water saturation, column 5 is edited density log, column 6 is edited sonic log and column 7 is acoustic impedance (AI) log. The gamma ray log pattern shows serrated/irregular shape, connoting fluvial marine dominated environment of deposition, with tidal flat, canyon fill, marine slope, channel, shoreface sands [29], [34]. The reservoir is found at depths of 8,865 ft (tvdss) – 9006 ft (tvdss) across the field, with maximum thickness of 292 ft, approximately 89.002 m (8865 - 9157 ft tvdss), large vertical oil columns, with average porosity 14 – 24 %, and permeability 300 – 2,240 mD, reservoir pressure 2600 psi and temperature 169 ^oF. There is also a huge thick overburden of shale packages above the reservoir which serves as effective low permeability cap rock and side seals of thick laterally continuous shale exist. These results reveal plausible criteria for the prospective CCS programme [2], [6], [12], [14], [20], [29].

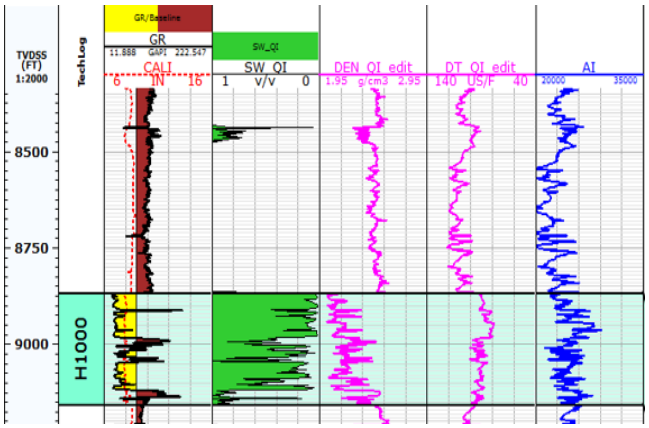


Figure 2. *Panel showing well log data from well 01*

Recall, that the oil gravity was 38° API, and cumulative production from the field heightened to 1.968 bbls in 2012, and daily production peaked 108,214 b/d in 1984, but reduced to 1064 b/d in 2014 by a 98 % water cut and estimated 20 % oil saturation. Figure 3 displays rock physics crossplots of P-impedance versus S-impedance (left) and lambdarho versus murho (right) colour coded by volume of shale (V_{shale}) and porosity, from well logs. The hydrocarbon sands, brine sands, and shale could be clearly differentiated in the lambdarho versus murho crossplot that the P-impedance space. Cut-off for sand was 0.5 from the V_{shale} and porosity of the hydrocarbon sands vary from 14 – 24 % [7-8], [29-30].

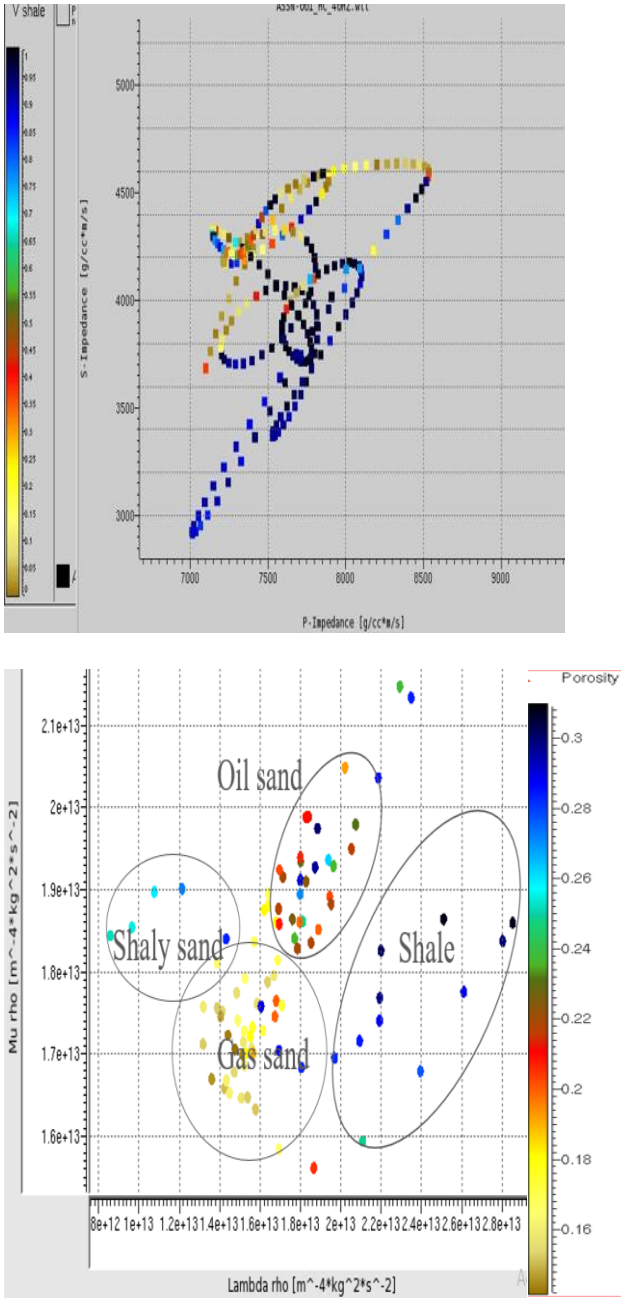


Figure 3. *Rock physics crossplots of P-impedance versus S-impedance (left) colour coded with volume of shale (V_{shale}) and Lambda-rho versus Mu-rho (right) colour coded with porosity for a quick lithology identification and fluid discrimination*

Understanding the hydrocarbon potential of a geological formation is critical for investigating its suitability for a CCUS project because there is a direct relationship between hydrocarbon potential and its suitability for CO_2 storage. This research follows the dynamics of other countries such as Norway, Canada and the USA, while focusing on the Niger Delta Basin due to the region's geological characteristics, significant potential, and extensive reach. Potential CO_2 permanent storage operations in Ambeme field is currently being studied for a dedicated CCS project designed to inject CO_2 from several wells at the flank of the structure and pressurize the sands [2], [4], [10], [12].

Figure 4 shows a seismic line passing through well 01 in the field, with well markers (red), gamma ray log (black) and horizon (green) displayed on the seismic section. The reservoir top was a trough, encountered at 2203 ms two-way traveltime.

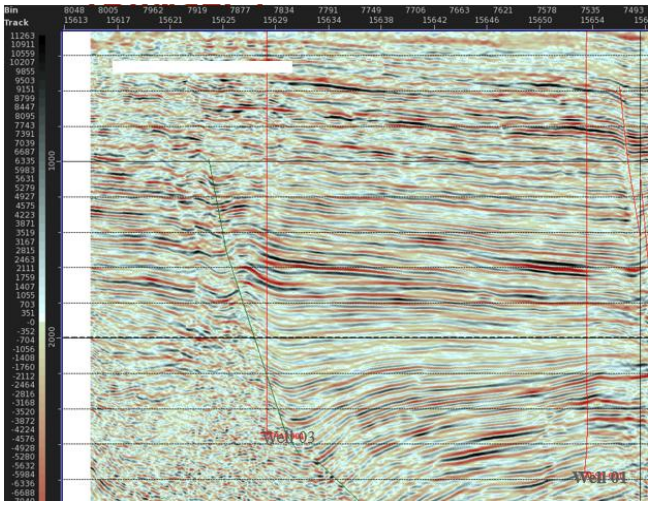


Figure 4. *Seismic line passing through well 01 showing horizon, well markers and gamma ray log*

The sequestration reservoir is at a depth of 2,702.01 m extending to approximately 12.6 km. The top of reservoir sandstone is a very clear seismic event and impedance contrast with the seal create a trough at the top reservoir and within the reservoir there are no mappable features due to acoustic properties of the reservoir. The full seismic section was subdivided into three partial angle stacks of 10°, 20° and 30° [2], [12], [29], [31].

Figure 5 is the well-to-seismic tie of the field, with the correlation legend in column 1, column 2 is the seismic wavelet, and column 3 is seismic section, column 4 is the synthetic seismogram, column 5 is drift, column 6 has well logs of gamma ray (red), P-impedance (blue), sonic (green). The tie is a good one with no stretch/squeeze as the horizons matched in both seismic and synthetic panels. Average wavelets were extracted for the simultaneous inversion of the three partial angle

stacks to porosity, net-to-gross and impedance properties for quantitative estimation of reservoir properties [4], [12], [14], [21], [31].

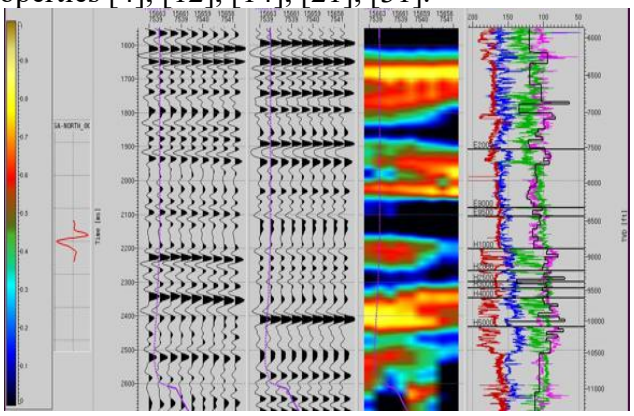


Figure 5. *Well-to-seismic tie*

Figure 6 is the inversion result showing P-impedance volume overlain with well markers, gamma ray log, P-impedance volume and logs from the wells in the field and colour coded by P-impedance values. The inversion result produced impedance volume as a layer property that could be used for interpretation and reservoir characterization [35]. The reservoir is laterally extensive and continuous [4], [7-8], [20-21], [31].

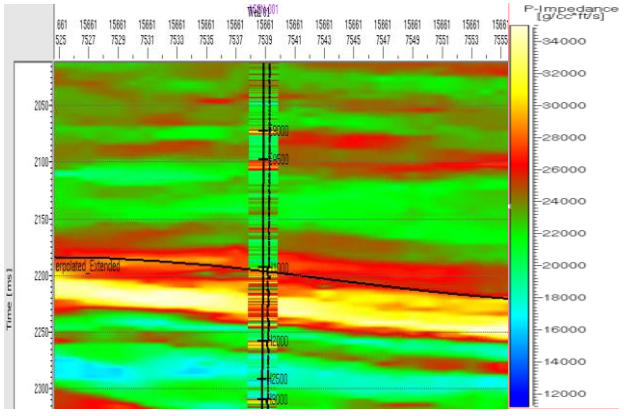


Figure 6. *Inversion volume showing reservoir layer properties*

The reservoir sandstones are channel sands with high P-impedance values and a high net-to-gross of about 90 %, and porosity 14 – 24 %, which identifies this reservoir as a large tank. The risk in containment is usually leakage through existing wells, geologic leakage through open faults/fractures, and induced faults/fractures. But reservoir structure shows thick layers of impermeable sealing shale and shale cap rock that guaranteed adequate containment for in-place hydrocarbon that was produced. However, lateral migration out of the reservoir could occur if barriers are laterally extensive and where such occur, CO_2 could be trapped beneath impermeable sealing shale layers that extend beyond the spill point. Conformance is important for continued safe injection and prediction of future migration patterns [2], [12], [15], [21], [31-32].

The challenge in the CCS project is to develop CO_2 capture/separation technologies that will recover CO_2 from sources at an acceptable energy penalty and costs. The best option is the use of absorption technologies using amine-based solvents. This would require a technology matrix of different technologies linking all capture processes with different technological platforms is recommended. Also, priority should be given to institutional, national and international collaborative climate action efforts across the globe. Knowledge sharing, international collaboration and accelerating pilot projects to commercial scale deployment would aid closing the emissions gap. The operation of CCS plants is governed by existing regulations on health, safety and environment (HSE) and aspects such as safety related to the handling of CO_2 and the treatment of waste products have already been dealt with through existing oil and gas regulations. Existing planning procedures according to existing best practices including environmental impact assessment report are followed in terms of technology implementation [1], [9], [36]. Continuous monitoring using timelapse (4D) seismic surveys, pressure sensors and geomechanical tracers are known to help early detection of anomalies and ensure regulatory compliance. Integrating real time data with predictive models could improve management and reduce operational uncertainties [4].

4. CONCLUSION

Ambeme field has been assessed as an excellent candidate for CO_2 storage and potentially decarbonization opportunity due to its reservoir properties, position, depth, extensive seal. The deployment of CCS is a critical pathway to

achieving decarbonization and mitigating climate change. Derisking subsurface geologic reservoirs is a prerequisite for climate resilience with attendant technical challenges, and with renewable energy expansion an essential option. Convincingly, CCS has evolved into a reliable and scalable solution for long term CO_2 storage by integrating advanced characterization and monitoring techniques, stakeholder engagement, and good policy and robust regulatory frameworks. CCS altogether reduces or limits the release of CO_2 into the atmosphere, so, CCS together with energy efficiency, renewable energy and low carbon fuels can lead to reductions in global CO_2 emissions. It is possible to sustain the use of fossil fuels (coal, oil and gas) while pursuing net zero carbon emission by drastically reducing CO_2 emissions. Deployment of this geological reservoir for future CO_2 storage presents viable options for reducing and lowering CO_2 emissions and concentrations aligning with global targets set for 2050. Thus, implementation of such storage solution could significantly contribute to mitigating climate change and its associated impacts. The urgency of climate change calls for urgent action, as such, urgent, swift and coordinated action is imperative for climate risks mitigation and achieving global climate targets. Continual research and improvement in the understanding of these geological reservoirs would enhance our knowledge of their suitability for CO_2 storage. Detection and monitoring of the injected CO_2 over time is very important for the lasting success of the CCUS project to image the expected injection pattern of CO_2, reservoir geologic layering and show how increase and decrease in resistivity or velocity over time inside the reservoir could be linked to variations in reservoir CO_2 saturation as a result of injection. Interpretation of the results could be enhanced through integration of production data, electrical and (EM) data, fluid models, known geology and timelapse (4D) seismic data. Public trust and project approval could be facilitated through transparency in risk communication, environmental stewardship plans and clear liability structures. Research should be intensified in developing reliable and cost-effective techniques for monitoring the CO_2 saturation and migration within the reservoir, modelling and applications. Several leading energy companies and nations including Nigeria, are actively engaged and engaging in the study, development, deployment as well as implementation of green energy technologies such as geothermal energy, solar, wind, electric, green hydrogen energy systems, photovoltaics, etc. The government of Nigeria should support investment in CCS infrastructure through national interests and economic instruments such as incentives and carbon pricing among others.

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