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Reservoir Containment Characterization for Carbon Dioxide (CO_2) Geo-Sequestration in the Niger Delta

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Abstract:

Considering its history of producing and exploring hydrocarbon since the late 1950s, leading to the depletion and abandonment of some reservoirs which could be useful in the storage of carbon dioxide, Nigeria, especially the Niger Delta, could be a front runner in the geological storage of carbon dioxide in Africa. There would however be a need to carry out extensive site characterization and selection procedures for the reservoirs of interest. Hence, this study was designed to geophysical assess the reservoir containment potential of a depleted oil and gas reservoir in the Niger Delta for purposes of keeping sequestered carbon dioxide in place. To this end, 5 well logs and a suite of 3D seismic data were analysed to characterize the containment potential of reservoir-seal pairs in the study area. This led to further characterizing the lateral extent and depth of the sealing and reservoir units within the study area. This led to identifying 2 sets of reservoir-seal pairs at depths of 9,450-12,450ft and 9,750-13,500ft respectively, which were shown to exhibit lateral continuity across the area of interest. Findings from this study, in connection with findings from previous researchers that showed that the sealing units for reservoir rocks are predominantly shaley, led to suggestions that the reservoir and sealing units within the study area have enough containment potential to keep sequestered carbon dioxide in place.

***Keywords* — Carbon Dioxide, Geo-Sequestration, Lateral Continuity, Containment, Depth.**

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I. INTRODUCTION

Due to the challenge of global warming, one globally considered technological solution aimed at the reduction of emitted carbon dioxide (CO_2) is carbon capture and storage (CCS) [1, 2, 3]. This technology involves capturing CO_2 from large stationary sources (e.g. fossil fuel power plants, major CO_2-emitting industries such as cement and steel production, etc.) and storing it in an underground formation [4, 5].

Evidently, one of the options readily available for the storage of captured carbon dioxide is depleted oil and gas reservoirs. According to Bachu [6] and Funnell et al. [7] this can be attributed to the facts that;

i. These reservoirs have contained oil and gas for a while, providing sufficient storage capacity and a safe cap rock.
ii. Prospecting for oil and gas in the past have provided large amounts of geological and engineering data for detailed site characterization.
iii. Equipment available for the exploration of oil and gas can come in handy during carbon dioxide storage.
iv. The injection of carbon dioxide during enhanced oil and gas recovery leads to concurrent sequestration.

There are however certain possible drawbacks in storing carbon dioxide in depleted oil and gas reservoirs [8, 9, 10] in that;

i. The physical size of the stratigraphic or structure trap may not be large enough, limiting the storage potential of the reservoir.
ii. There is a possibility of pore collapse because of pore-pressure depletion, a consequence of past exploration of oil and gas.
iii. The timing of the availability of depleted reservoirs may not just be right relative to the availability of a carbon dioxide source.

Geological storage options include deep saline aquifers, depleted oil and gas reservoirs, enhanced oil and gas recovery, and enhanced coal bed methane recovery, etc. [11, 12, 13].

Relative to its history of producing and exploring hydrocarbon since the late 1950s, leading to the depletion and abandonment of some reservoirs which could be useful in the storage of carbon dioxide, Nigeria, especially the Niger Delta, could be a front runner in the geological storage of carbon dioxide in Africa.

There would however be a need to carry out extensive site characterization and selection procedures for the reservoirs of interest. Ideally, these procedures could involve regional characterization, geoscience characterization, engineering characterization and socioeconomic characterization as described by Kaldi et al. [14] and Griffiths et al. [15]. However, carrying out a geoscience characterization, one needs to determine the storage capacity, injectivity and containment of the reservoirs [16].

In other words, the successful commercial scale deployment of carbon dioxide geo-sequestration requires assurance of the containment/confinement of the injected CO_2 at each potential storage site, with the most critical element of the containment system being the top seal, or caprock confining the storage formation and faults or fractures which pass through it [17]. Kaldi et al. [18] emphasized the significance in determining the probability of containment (or risk of leakage) by evaluating various properties of the caprock, the faults and fractures as well as the effects of hydrodynamics and of potential geochemical reactions of the caprock properties in the presence of sequestered carbon dioxide.

There is every likelihood for a rock unit that already traps hydrocarbons at depth, especially natural gas, to conveniently trap carbon dioxide [19]. The more confining units of the reservoir present, the greater their thickness and extent, the better engineered the wells, and the higher the confidence in the reservoir's ability to store sequestered carbon dioxide [19]. There is a high likelihood of leakage of sequestered carbon dioxide if the seal of the storage volume is compromised by fractures or faults, or if there are gaps in the seal [20]. Differentiating between good and poor reservoir seals, Christopher et al.[21] described the characteristics of a good reservoir seal to be laterally continuous, laterally and vertically homogenous, thick enough to reduce the number of pathways, presence of petrophysical small pores throats without large connected pores, while those of a poor reservoir seal was described to be lithological variable, thin beds, fractured and faulted, hydrocarbon wet and larger pore throats.

This study is therefore focused on determining the containment capabilities of a typical Niger Delta depleted oil and gas reservoir relative to its potential of keeping sequestered CO_2 in place.

II. METHODOLOGY

The principal data used for this study was a suite of well logs from five oil wells, check shot data, well information (well coordinates, well deviation) and seismic section. The suite of well logs includes Gamma Ray, Resistivity, Spontaneous Potential and Neutron log. These, whose locations are shown in Figure 1, have been given generic names (Well 1, Well 2, Well 3, Well 4 and Well 5). The data from these well logs were analysed using specialized reservoir modelling software (Petrel and Interactive Petrophysics). The seismic section contains traces of seismic amplitudes recorded for 6004ms. It covers an area of approximately 21225×11025m within the study area. It is a high-resolution 3D data, obtained from 849 inlines and 441 crosslines spaced at 25m interval. Additionally, Figure 2 contains details of an inline, a crossline and a time section, accompanied with the details of the seismic section. The data from the seismic section was analysed using Petrel proprietary software.

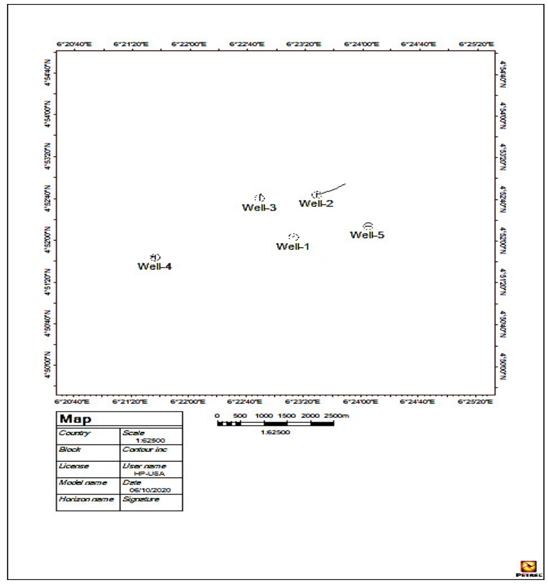

Fig. 1: Map of Location of Well Logs in The Study Area

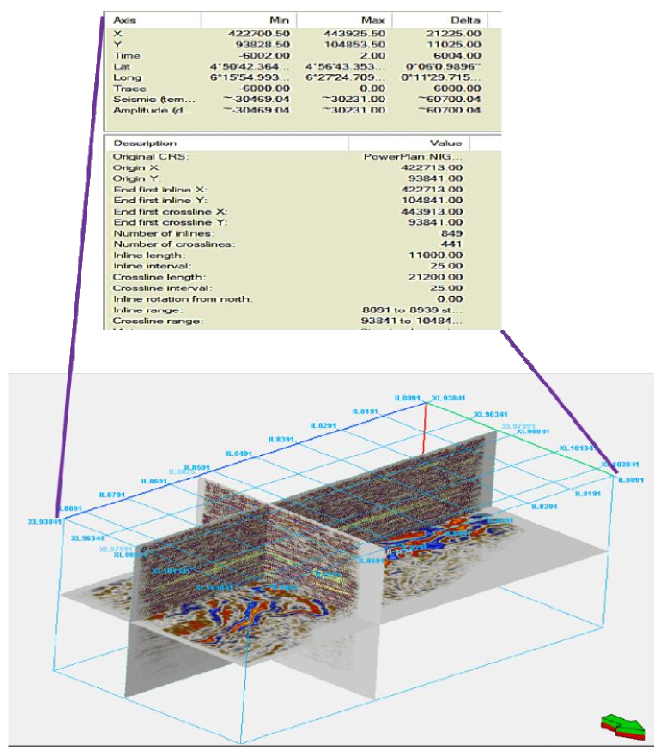

Fig. 2:Seismic Section Showing an Inline, Crossline and a Time Slice

In this study the focus was to estimate the depth, lateral continuity and thickness of the seal column (alongside the lateral continuity and depth of the reservoir column) as determined from the well log correlation in order to determine the containment capability of the reservoir of interest. The thickness was taken to be the average of the different thicknesses identified on the well logs.

To do this, petrel software was used to analyse suites of well logs and its accompanying seismic session.

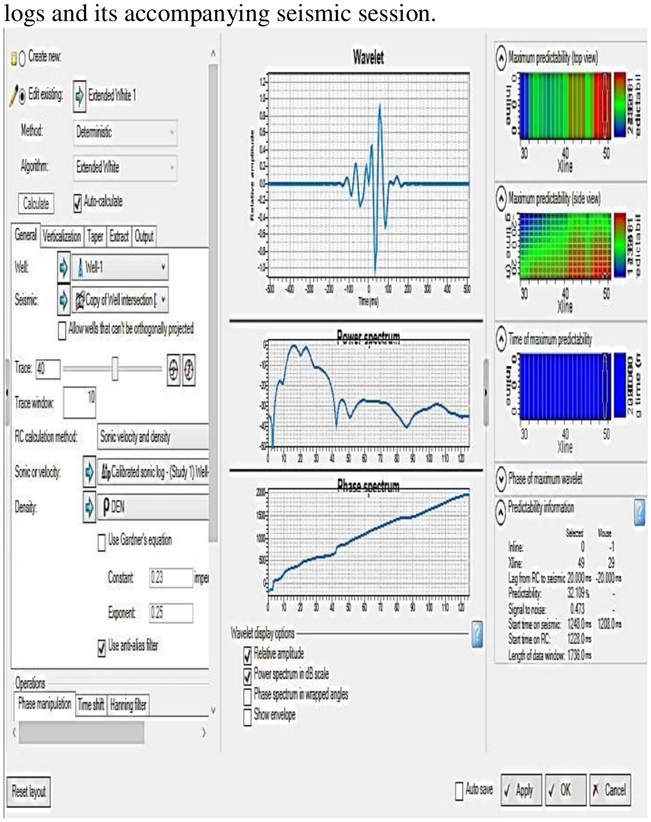

Figure 3: Parameters Used for Modelling the Synthetic Seismogram

The procedure began by loading the 5 well logs into petrel software. Since the main interest was to estimate some petrophysical parameters for reservoir-seal pairs within the area of study, a well log correlation had already been carried out by identifying these reservoir-seal pairs relative to the response of gamma ray log (to identify sandy and shaley formation) and resistivity log (to identify the presence of hydrocarbons within the sub-surface formation). Additionally, the sonic log on Well 1 (since it is the only well containing a sonic log response) was calibrated with the checkshot to account for any anomalous reading that could be present in the sonic log.

A seismic section needed to be analysed to quantitatively describe the lateral continuity, structure and fault system of these reservoir-seal pairs within the study area. Hence, after loading a 3D seismic section into Petrel, a seismic-to-well tie was executed to generate a time-depth relationship. To do this, a synthetic seismogram was created by extracting a wavelet from the seismic section which was convolved with acoustic impedance log estimated from density log and the calibrated sonic log. The other parameters that were used for this purpose are shown in Figure 3.

With the seismic-to-well tie in place, it became easier to map the identified reservoir and seal tops and bottoms (as defined from the well log correlation process) unto the seismic section, by correlating synthetic traces to real seismic traces. Modelling at 10 inline and crossline intervals, the reservoir and seal tops and bottoms, were mapped out, from which a time map was generated. The time map, together with the time-depth function generated from the seismic-to-well tie, were used to generate a depth map that was useful in describing the structure, lateral extent and depth range of the identified-reservoir-seal pairs. Additionally, the faulting structure was quantitatively mapped, by also modelling at 10 inline and crossline intervals.

Additionally, the International Energy Agency [22] prescribed certain structural and stratigraphic thresholds that must be met before depleted oil and gas reservoirs could be considered to shave sufficient containment capability to hold sequestered CO_2. These thresholds are shown in Table 1.

Table 1: Structural and Stratigraphic Selection Threshold for Reservoir Containment Potential Relative to CO_2 Geo-Sequestration for depleted Oil and Gas Reservoirs [22]

RESERVOIR PARAMETERS	SELECTION THRESHHOLD
Reservoir Lithology	Sandstone, Dolomite, limestone & Siltstone for oil and gas reservoirs
Depth to Top	≥800m
Reservoir Thickness	>10m
Caprock Lithology	Salt, Anhydrite, Shale or Claystone
Caprock Thickness	≥10m
Reservoir-Seal Pairs	Intermediate and excellent; many pairs

III. RESULTS

Relying on gamma ray and resistivity responses, 5 well logs were used to identify reservoir and seal pairs of interest. Two reservoir-seal pairs were identified relative to their lateral continuity as identified on the logs. The identified reservoir and seal pairs are shown in Figure 4, with their estimated thicknesses shown in Table 2.

Figures 5 and 6 shows the sonic log, before and after it was calibrated with the available check shot in Well 1. The synthetic seismogram modelled from the calibrated sonic log and density log is shown in Figure 7, with the time-depth function produced from this process shown in Figure 8.

Additionally, Figure 9 shows the correlated reservoir-seal pairs from the well logs as seen on the seismic section. Furthermore, major faults in the vicinity of the reservoir-seal pairs that were modelled are shown in Figure 9.

Also, the mapped seismic horizons of the tops of reservoir-seal pairs are shown in Figure 9. The resulting time grid for the tops of all the seismic horizons of interest are shown in Figure

10, with the Figures 11, 13, 15 and 17 showing the time maps produced from these time grids, while Figures 10, 12, 14 and 16 are depth maps of the identified seismic horizons as generated from the time maps and the time-depth function. Table 3 shows the ranges of depth of the reservoir-seal pairs of interest within the study area as seen from the depth maps.

Summarily, all the relevant results obtained to determine the CO_2 geosequestration containment potential of the reservoir-seal pairs within the study area are summarized in Table 4, relative to the benchmark set for depleted oil and gas reservoir that would be considered viable to hold sequestered CO_2.

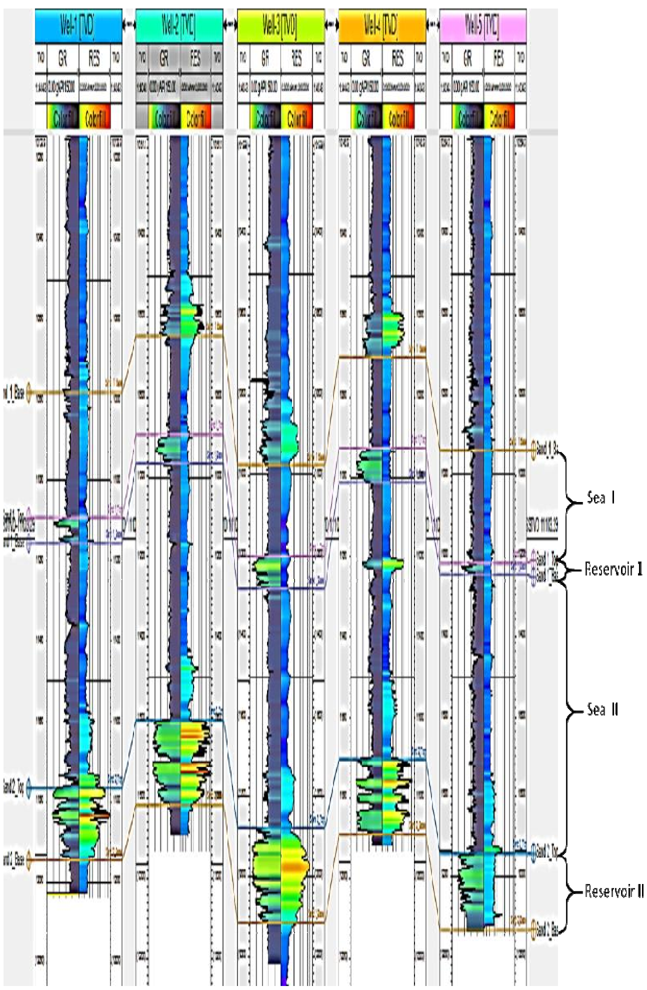

Fig. 4: Correlated Well Logs Showing 2 Seal Rocks and 2 Reservoir Rocks

Table 2 Reservoir-Seal Pair Thicknesses in the 5 Analysed Wells

WELL	ROCK TYPE	TOP (ft)	BASE (ft)	THICKNESS (ft)
Well 1	Seal I	10779.00	11103.00	324.00
	Reservoir I	11103.00	11166.00	63.00
	Seal II	11166.00	11778.00	612.00
	Reservoir II	11778.00	11958.00	180.00
Well 2	Seal I	10848.00	11221.00	373.00
	Reservoir I	11221.00	11301.00	80.00
	Seal II	11301.00	11997.00	696.00
	Reservoir II	11997.00	12225.00	228.00
Well 3	Seal I	10974.00	11253.00	279.00
	Reservoir I	11253.00	11336.00	83.00
	Seal II	11336.00	11949.00	613.00
	Reservoir II	11949.00	12172.00	223.00
Well 4	Seal I	10702.00	10944.00	242.00
	Reservoir I	10944.00	11030.00	86.00
	Seal II	11030.00	11720.00	690.00
	Reservoir II	11720.00	11908.00	188.00
Well 5	Seal I	10937.00	11218.00	281.00
	Reservoir I	11218.00	11245.00	27.00
	Seal II	11245.00	11940.00	695.00
	Reservoir II	11940.00	12120.00	180.00

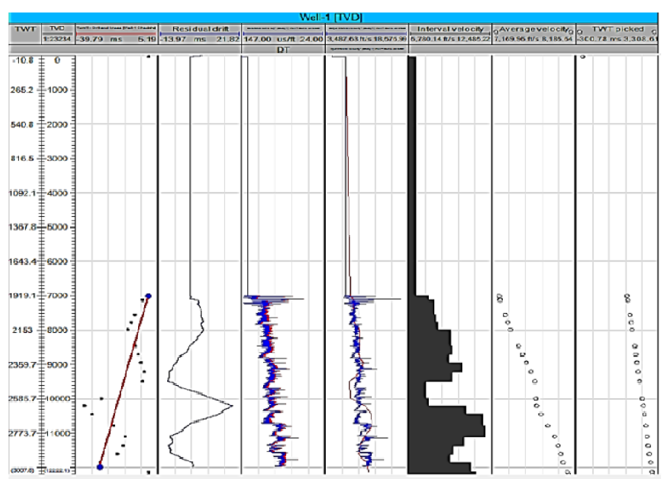

Fig. 5: Before the Correlation of the Sonic Log with the Check Shot

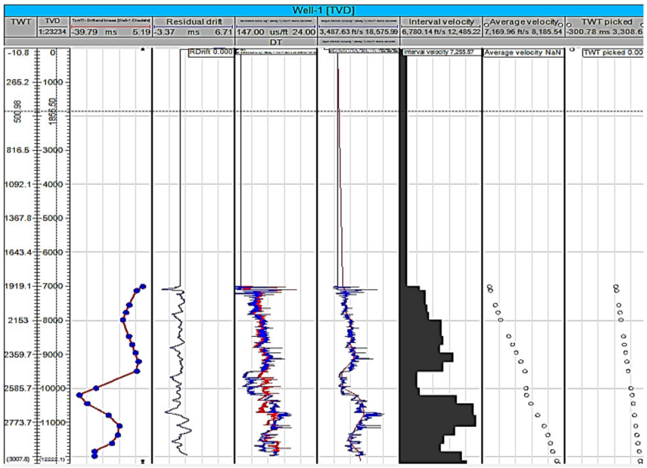

Fig. 6: After the Correlation of the Sonic Log Check Shot

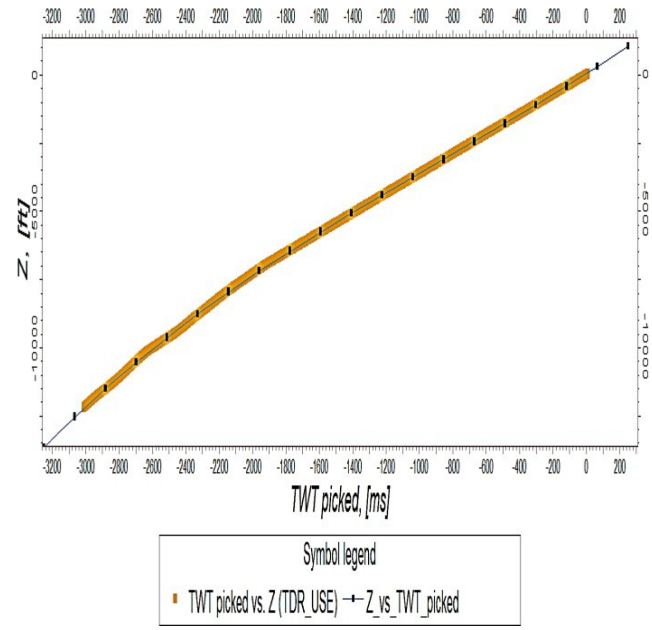

Fig. 8: Plot of Time-Depth Relationship

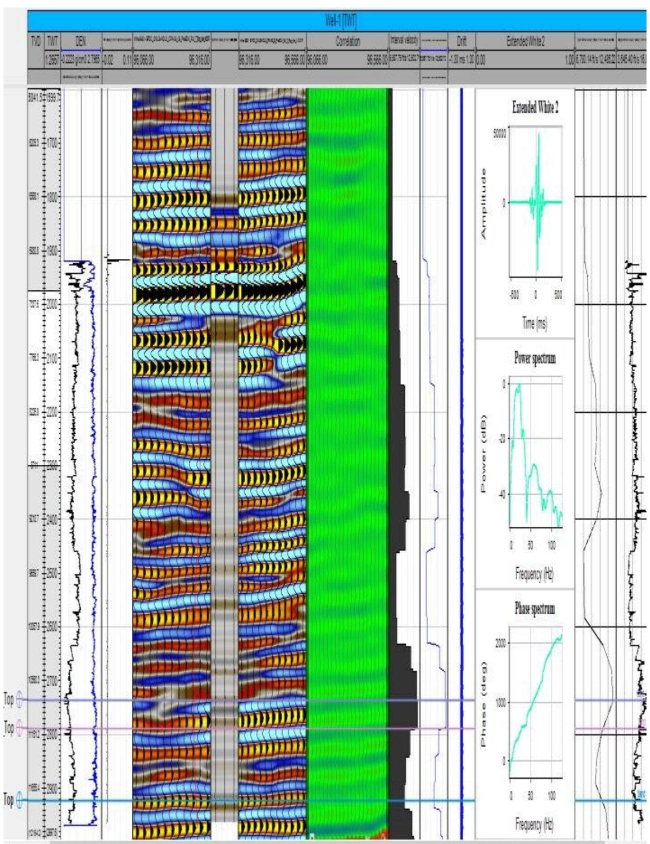

Fig. 7: Generated Synthetic Seismogram for Seismic-to-Well Tying Process

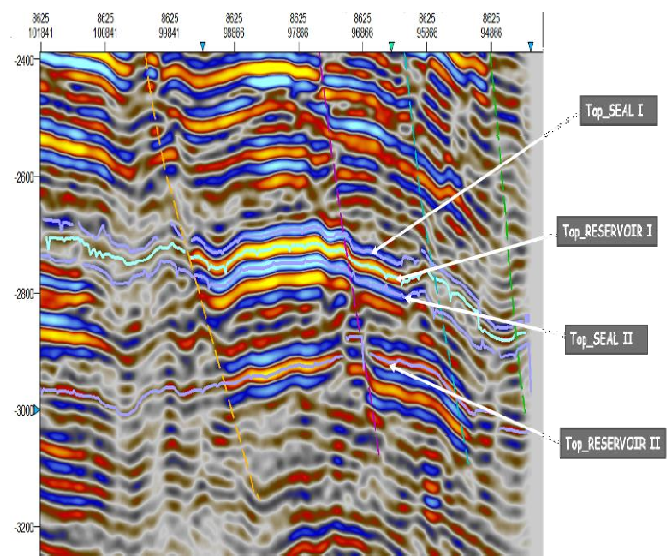

Fig. 9: Seismic Section Showing Identified Reservoir-Seal Pairs, Mapped Horizons and Modelled Faults

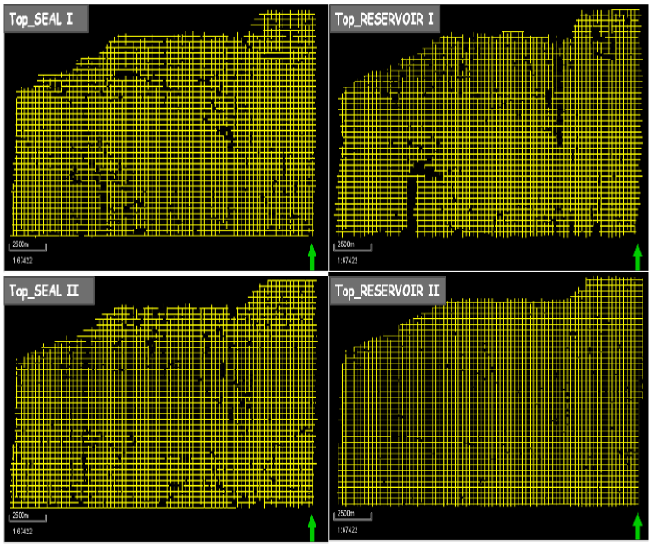

Fig. 10: Time Grids for Modelled Horizons

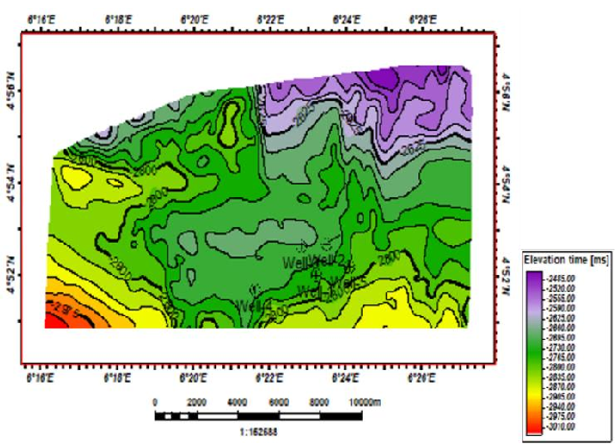

Fig. 11: Time Map for Top of SEAL I

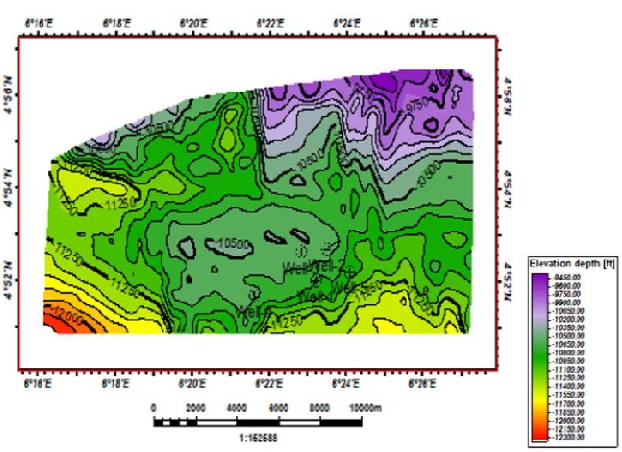

Fig. 12: Depth Map for Top of Seal 1

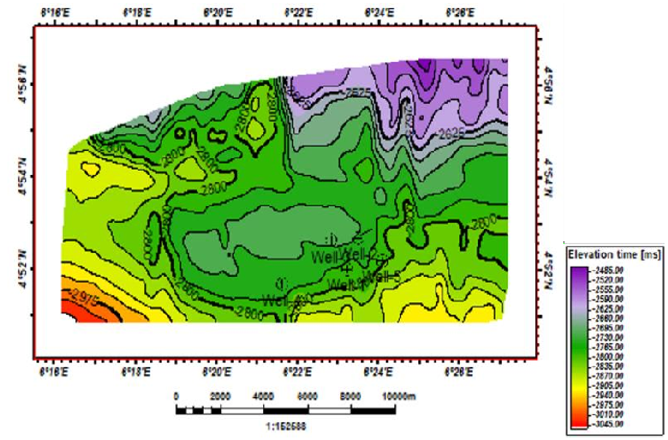

Fig. 13: Time Map for Top of RESERVOIR 1

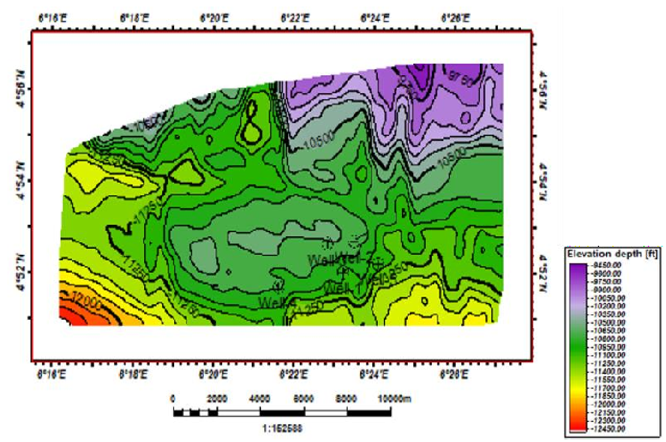

Fig. 14: Depth Map for Top of RESERVOIR 1

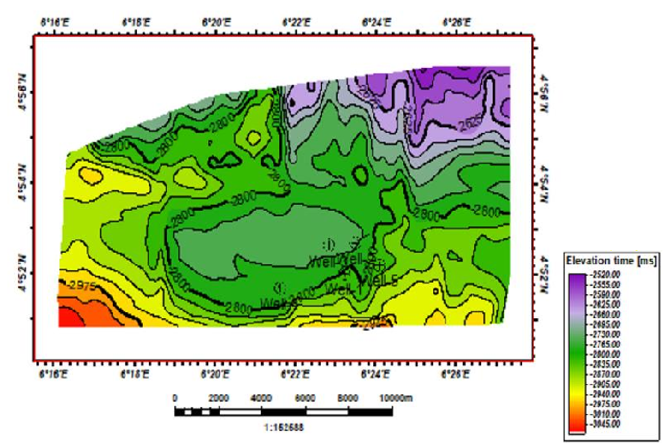

Fig. 15: Time Map for Top of Seal II

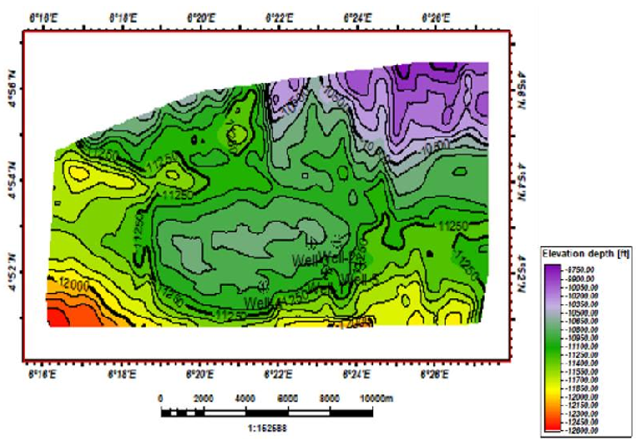

Fig. 16: Depth Map for Top of SEAL II

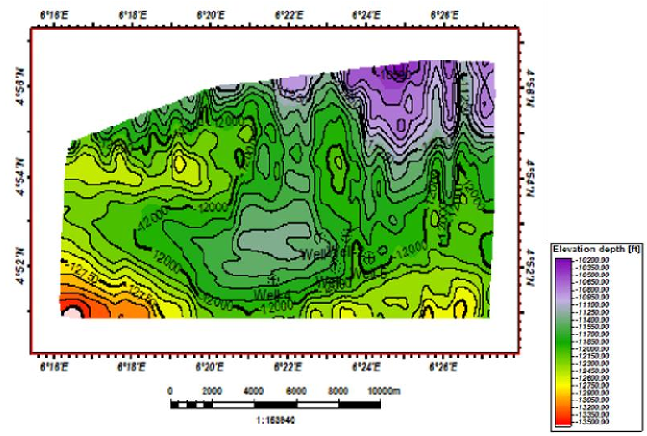

Fig. 18: Depth Map for Top of RESERVOIR II

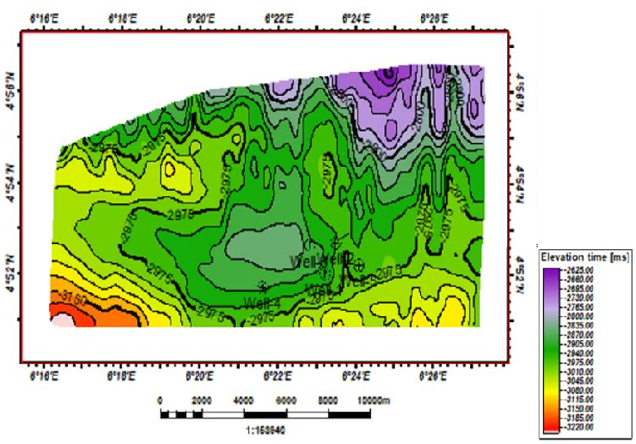

Fig. 17: Time Map for Top of RESERVOIR II

Table 3: Depth Ranges of Reservoir and Sealing Units of Interest Within the Study Area

ROCK TYPES	DEPTH RANGE (ft)	DEPTH RANGE (m)
SEAL I	9450-12300	2880-3749
RESERVOIR I	9450-12450	2880-3795
SEAL II	9750-12800	2972-3901
RESERVOIR II	10200-13500	3109-4115

Table 4: Summary of Findings to Determine the CO_2 Geo-Sequestration Containment Potential of the Reservoir-Seal Pairs Within the Study Area

RESERVOIRS	RESERVOIR PARAMETERS	SELECTION THRESHHOLD [22]	THIS STUDY
I	Reservoir Lithology	Sandstone, Dolomite, limestone & Siltstone for oil and gas reservoirs	Sandstone
	Depth to Top	≥800m	2880-3795m
	Reservoir Thickness	>10m	20.67m (Average)
	Caprock Lithology	Salt, Anhydrite, Shale or Claystone	Shale
	Caprock Thickness	≥10m	91.38m (Average)
II	Reservoir Lithology	Sandstone, Dolomite, limestone & Siltstone for oil and gas reservoirs	Sandstone
	Depth to Top	≥800m	3109-4115m
	Reservoir Thickness	>10m	61.81m (Average)
	Caprock Lithology	Salt, Anhydrite, Shale or Claystone	Shale
	Caprock Thickness	≥10m	200.62m (Average)
COMBINED	Reservoir-Seal Pairs	Intermediate and excellent; many pairs	Many Pairs

IV. DISCUSSION

According to Shipton et al. [20], the likelihood of leakage of sequestered CO_2 is a function of the structure of the sealing unit of the reservoir unit. In describing this structure, there arises a need to look at the lateral continuity, lateral and vertical homogeneity, thickness and structure of the pore throat and pore connectivity of the sealing unit [21]. Knowing that the sealing unit for the reservoirs in the Niger Delta are predominantly shaley [23, 24] and knowing that shales could be quite porous by almost impermeable [25, 26], this study is focused on describing the lateral extent and depth of the sealing and reservoir units within the study area. The results obtained showed that the sealing and reservoir units are laterally continuous (as shown in Figures 11 to 18) existing at depth ranges shown in Table 3.

According to the International Energy Agency [22], these results, as summarized in Table 4, are suggestive of the fact that the reservoir and sealing units within the study area have enough potential to keep sequestered CO_2 in place.

V. CONCLUSION

With an aim to characterize the containment potential, for purposes of CO_2 geo-sequestration, of reservoir-seal pairs in a depleted oil and gas reservoir in the Niger Delta, this study was carried out by analysing well log data to estimate the lateral continuity and depth of the identified reservoir-seal pairs. The following conclusions were arrived at;

i. Two sets of reservoir-seal pairs were identified in the storage area.
ii. The first reservoir-seal pair was identified at a depth range of 9,450-12,450ft, while the second reservoir-seal pair was located at depth range of 9,750-13,500ft.
iii. The identified reservoir-seal pairs were also shown to be laterally continuous across the field, existing everywhere within the field of interest in the study area.
iv. The identified reservoir-seal pairs were adjudged to have sufficient containment potential to keep sequestered CO_2 in place.

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REFERENCES

[1] Davidson, O., H. de Coninck, M. Loos, and L. Meyer, *IPCC special report on carbon dioxide capture and storage. Prepared by working group III of the intergovernmental panel on climate change*. 2005, Cambridge University Press, Cambridge, UK.

[2] Bennaceur, K., D. Gielen, T. Kerr, and C. Tam, *CO_2 capture and storage: a key carbon abatement option*. 2008: OECD.

[3] Haszeldine, R.S., *Carbon capture and storage: how green can black be?* Science, 2009. **325**(5948): p. 1647-1652.

[4] Orr Jr and F. M, *CO_2 capture and storage: are we ready?* Energy Environmental Science, 2009. **2**(5): p. 449-458.

[5] Smit, B., J.A. Reimer, C.M. Oldenburg, and I.C. Bourg, *Introduction to Carbon Capture and Sequestration*. 2014: World Scientific.

[6] Bachu, S., *Sequestration of Carbon Dioxide in Geological Media: Criteria and Approach for Site Selection in Response to Climate Change.* . Energy Conversion and Management, 2000. **41**(9): p. 953-970.

[7] Funnell, R., P. King, S. Edbrooke, K. Bland, and B. Field, *Opportunities for underground geological storage of CO_2 in New Zealand-Report CCS-08/1–Waikato and onshore Taranaki overview*. GNS Science Report, 2008. **53**: p. 70.

[8] Bradshaw, J. and A.J. Rigg, *The GEODISC program: Research into geological sequestration of CO_2 in Australia.* Environmental Geosciences, 2001. **8**(3): p. 166-176.

[9] Rigg, A., A. Bowden, and M. Watson. *Risk Assessment of Long-term Containment of CO_2 in Geological Storage Projects*. in *Proceedings of the AAPG 2006 International Conference and Exhibition*. 2006. Perth, Australia.

[10] Bradshaw, J., B.E. Bradshaw, G. Allinson, A.J. Rigg, V. Nguyen, and L. Spencer, *The potential for geological sequestration of CO_2 in Australia: Preliminary findings and implications for new gas field development.* The Australian Petroleum Production and Exploration Association (APPEA) Journal, 2002. **42**(1): p. 25-46.

[11] Benson, S.M. and D.R.J.E. Cole, *CO_2 sequestration in deep sedimentary formations.* Elements, 2008. **4**(5): p. 325-331.

[12] Gaus, I., *Role and impact of CO2–rock interactions during CO_2 storage in sedimentary rocks.* International journal of greenhouse gas control, 2010. **4**(1): p. 73-89.

[13] Plasynski, S.I., J.T. Litynski, H.G. McIlvried, D.M. Vikara, and R.D. Srivastava, *The critical role of monitoring, verification, and accounting for geologic carbon dioxide storage projects.* Environmental Geosciences, 2011. **18**(1): p. 19-34.

[14] Kaldi, J.G., C.M. Gibson-Poole, and T.H. Payenberg, *Geological input to selection and evaluation of CO_2 geosequestration sites.* in M. Grobe, J. C. Pashin, and R. L. Dodge, eds., Carbon Dioxide Sequestration in Geological Media—State of the Science. AAPG Studies in Geology, 2009. **59**: p. 5-16.

[15] Griffiths, M., P. Cobb, and J. Marr-Laing, *Carbon Capture and Storage: An arrow in the quiver or a silver bullet to combat climate change.* A Canadian Primer. The Pembina Institute, 2005. **13**: p. 77.

[16] Davies, O.A., C. Israel-Cookey, E.D. Uko, and M.A. Alabraba, *Reservoir Capacity and Injectivity Characterization for Carbon Dioxide (CO_2) Geo-Sequestration in the Niger Delta.* International Journal of Research and Innovation in Applied Science, 2020. **5**(10): p. 19-26.

[17] Kaldi, J., R. Daniel, E. Tenthorey, K. Michael, U. Schacht, A. Nicol, J. Underschultz, and G. Backe, *Containment of CO_2 in CCS: Role of Caprocks and Faults.* Energy Procedia, 2013. **37**: p. 5403-5410.

[18] Kaldi, J., R. Daniel, E. Tenthorey, K. Michael, U. Schacht, A. Nicol, J. Underschultz, and G. Backe, *Caprock systems for CO_2 geological storage.* IAEGHG Report, 2011. **1**: p. 149.

[19] Hawkes, C.D., P.J. McLellan, U. Zimmer, and S. Bachu. *Geomechanical factors affecting geological storage of CO_2 in depleted oil and gas reservoirs: risks and mechanisms*. in *Gulf Rocks 2004, the 6th North America Rock Mechanics Symposium (NARMS)*. 2004. American Rock Mechanics Association.

[20] Shipton, Z.K., J.P. Evans, D. Kirschner, P.T. Kolesar, A.P. Williams, and J.J. Heath, *Analysis of CO_2 leakage through 'low-permeability' faults from natural reservoirs in the Colorado Plateau, east-central Utah.* Geological Society, London, Special Publications, 2004. **233**(1): p. 43-58.

[21] Christopher, C.A., J. Iliffe, and B. Americas. *Reservoir seals: How they work and how to choose a good one*. in *CO_2 SC Symposium, Lawrence Berkeley National Laboratory, Berkeley, California*. 2006.

[22] International Energy Agency, *Development of Storage Coefficients for CO_2 Storage in Deep Saline Formations*, in *International Energy Agency Greenhouse Gas Programme Report 2009/12*. 2009, IEA GHG.

[23] Okwoli, E., D. Obiora, O. Adewoye, J. Chukudebelu, and P. Ezema, *Reservoir Characterization and Volumetric Analysis of " LONA" Field, Niger Delta, using 3-D Seismic and Well Log Data.* Petroleum & Coal, 2015. **57**(2): p. 108-119.

