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Structural Capability And Spillage Analysis Of Depleted Oil Reservoirs For CO_2 Storage, In An Onshore Niger Delta Field, Nigeria.

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Abstract
Depleted hydrocarbon reservoirs are often referred to as one of the most preferred options for geological carbon sequestration (GCS). The Nigeria Niger Delta can become the next carbon storage hub if some reservoirs of the region which are already entering depletion are put to use. In practice, however, preliminary re-assessment of these reservoirs must be carried out to ascertain their suitability to store CO_2. In this study, reservoirs of a depleted oilfield in onshore Niger Delta were assessed for their structural capability to keep sequestered CO_2 in place, using suite of well logs and 3D seismic data. The study identified two reservoir-seal pairs within the depth range of 2500m and 3800m, and mapped corresponding horizons intersected by a series of both regional, synthetic and antithetic faults. Generated surface maps showed evidence of rollover anticlinal structures within fault-enclosed areas. Migration pathways of one of the reservoirs were also analysed employing the MRST_CO2lab open-source code via an input geological model. The results showed that the delineated spill point is useful for designing injection strategy that can be adopted not to impose hazard. The findings in this study generally suggest that the reservoirs are potentially capable of holding sequestered CO_2 in place as inferred by recommended standard parameters and results of previous studies.
Key Words: *Carbon Dioxide; CO_2 Containment; Spill Point Analysis; Carbon Sequestration; Niger Delta.*

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I. Introduction

The sudden rise in the average atmospheric concentrations of CO_2 to unprecedented parts per million in recent years is largely attributed to the increase in burning of the fossil fuels and cement production (Ritchie *et al*, 2020). The global greenhouse gas emissions from energy-related sources takes up over 73% of total emissions while those from agriculture, industry waste and land use take the remaining 27% (Ritchie *et al*., 2020; IEA, 2021). CO_2 being the most abundant of the released gases, constitute about 64% of the enhanced greenhouse effect and can remain for hundreds of years in the atmosphere. This effect of global warming is undeniably being felt by both human and the environment as we now experience noticeable fluctuation in weather conditions and general increase in environmental temperatures. And, in fact, most of the damage observed so far is irreversible and will persist for up to 1000 years even after emissions stop (Akpanika *et al*., 2015).

Projections indicate that global CO_2 emissions will rise by 55% between 2004 and 2030, equivalent to an annual increase of 1.7% based on the report of the U. S. Energy Information Administration (EIA)'s world energy outlook 2006 (Birol, 2009). To stabilize atmospheric CO_2 concentrations at less than twice pre-industrial levels, significant reductions in emissions must be achieved within the next 50 years (Pacala and Socolow, 2004). Going by the level of technology development today, there are four main options to achieve this goal on a massive scale; (i) adopt energy-conserving technology, (ii) transition to carbon-free or carbon-neutral energy sources, (ii) capture and store carbon emissions in engineered sinks, or (iv) enhance natural sinks (Pacala and Socolow, 2004). Although all the options mentioned are currently feasible, achieving the necessary emissions reductions and resolving the issue of carbon emissions requires a significant increase in the scale of operations. Furthermore, the magnitude of the problem necessitates the implementation of a broad range of strategies, as no single approach on its own could realistically achieve the required target emissions reduction to achieve the desired net-zero (IPCC, 2005; IEA, 2021). However, geological carbon capture and storage (CCS) has often been regarded as the technology of highest repute for reducing CO_2 emissions from the combustion of fossil fuels in the short-to-long term (IEAGHG, 2009). This involves the capturing, transporting and storing of CO_2 in subsurface geological formations such as the deep saline aquifers, depleted oil/gas reservoirs and unminable coal seams. Of all the available storage options, depleted oil and gas reservoirs are most suitable due to reasons such as their well-known geological characteristics, already existing infrastructures and wells which can easily be adapted for use to reduce costs, and also, the economic consideration of enhance oil/gas recovery (Benson and Cook, 2005; Agartan *et al.,* 2018). Additionally, there is also the assumption that since these reservoirs were able to accumulate hydrocarbons, which are of higher carbon content chemical, in traps for millions of geological years then they are also capable of house CO_2 in those traps (Gallo *et al.,* 2002).

In the Niger Delta region, carbon emission from gas flaring surpasses all other emission sources and this contributes a major quota to the sectoral global greenhouse gas emission. In light of the above, Nigeria is considered a major polluter contributing over 100 million tons of CO_2 per annum emission into the atmosphere ranking 45th in world and 4th in Africa after South America, Egypt and Algerian (World Bank. 2021). A recent report gathering revealed that about 500 fields have so far been discovered in the area, with about 1481 wells currently producing from 156 of those fields including both on-shore and off-shore fields. The rest have either been abandoned due to depletion or other reasons while some are still at various stages of appraisal and development (Akpanika *et al*., 2015). With most of the fields entering depletion and subsequent abandonment, it becomes advantageous to look into them as potential CO_2 sinks.

When CO_2 is injected into a target subsurface formation, it is securely stored in the formation through four main trapping mechanisms: structural and stratigraphic trapping under the seal caprock; capillary trapping by immobilizing CO_2 in the rock pores by capillary forces; dissolution trapping through gravitational forces acting on denser dissolved CO_2; and mineral trapping occurring via dissolution of primary minerals due to the reaction between dissolved CO_2 and the host rock resulting to the formation of secondary carbonate minerals (Aminu and Manovic, 2020). Notably, structural and stratigraphy traps are the first forces to rely upon, especially in depleted hydrocarbon reservoirs, before other mechanisms set in (Bachu *et al.*, 2007). Actually, and in most cases, the hydrocarbon reservoirs are structural or stratigraphic traps at the top of aquifers that have been charged with oil and/or gas during the process of hydrocarbon generation, migration and accumulation. These structures already have caprock (or seal); usually a low-permeability rock (aquitard or aquiclude) that overlies a reservoir and retains the hydrocarbons and/or other gases is believed to also keep the injected CO_2 in place and prevent them from leaking to the surface. The processes involved in capturing and storing CO_2 including determination of storage capacity of the reservoirs, injectivity rate to the reservoir and containment to prevent it from migrating or leaking out of the storage have been extensively discussed (Griffiths et al, 2005; Shaw and Bachu, 2002; IPCC, 2005; IEAGHG, 2009). In practice, usually, an initial preliminary geological assessment must be carried out to re-establish suitability of the target geological formations and their ability to properly contain sequestered CO_2 without migrating upwards to the ground surface (Kaldi et al., 2013; Godec *et al.*, 2013). The key elements of the containment system are usually the top seal or caprock confining the storage formation and faults or fractures penetrating it (Kaldi et al., 2013). The probability of containment (or risk of leakage) is determined by evaluating the various properties of the reservoir rock, caprock, faults and fractures as well as the effects of hydrodynamics, and can include the assessment of possible geochemical reactions of the caprock components with sequestered carbon dioxide (Shaw and Bachu, 2002, Kaldi et al., 2013). In the work of Mkpese *et al*. (2024), they analysed the reservoirs of interest in the study area and suggested their properties are good enough for CO_2 storage operation based on Etu-Efeotor's classification of reservoirs (Etu-Efeotor, 1997) and the International Energy Agency's recommended minimum site selection criteria (IEAGHG, 2009). In the present work, we attempt the use of well logs and seismic data to characterize and analyse the structural capability of these reservoirs to hold in place sequestered CO_2 as well as analyse their spill point indicative for a long-term CO_2 storage and migration.

Location of Study Area and Geological Setting

The studied field is a depleted oil and gas exploration field code named 'CRK' field and situated within the coastal swamp depositional belt of the onshore Niger Delta. The approximate location of the study area is shown in Figure 1.

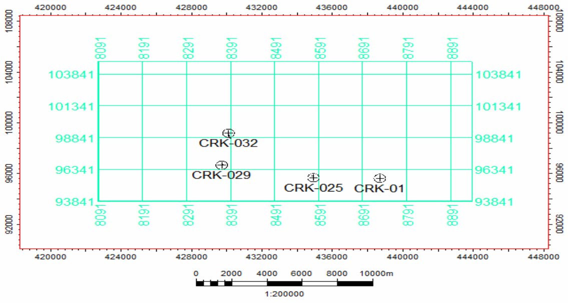

Fig. 1: Approximate location of study area with well positions, plotted from Petrel software

The Niger Delta Basin is one of the largest sub-aerial basins in Africa. It is a prolific petroleum province ranked 13th in world in terms of basin size (Akpanika et al., 2020). However, the region is not a single gigantic field but is composed of thousands of individual reservoirs most of which are sandstone pockets trapped within oil-rich shales. Growth faults and antithetic faults play an essential role in trap configuration. The sediment fill has a depth of between 9 to12km (Orife and Avbovbo, 1982) and composed of several different geologic formations that indicate how this basin could have formed, as well as the regional and large-scale tectonics of the area. Three major lithostratigraphic units have been defined in the subsurface of the Niger Delta based on a description of the stratigraphy of the joint development zone namely; the *Akata*, *Agbada* and *Benin* Formations (Ozumba 2013). These formations decrease in age basinward, reflecting the overall regression of depositional environments within the Niger Delta clastic wedge. The basal Akata Formation is predominantly marine prodelta shale and overlain by the paralic sand/shale sequence of the Agbada Formation. The Benin Formation which is the uppermost stratigraphic unit of the Delta, characterized by fine to coarse sands and sandstone, was deposited during the late Tertiary and early Quatenary period (Doust and Omatsola, 1990). The Delta is characterized mainly by normal faults triggered by the movement of deep-seated, overpressured, ductile, marine shales that have deformed much of the Niger Delta clastic wedge forming simple, as well as complex structures which are known to be hydrocarbon traps (Doust and Omatsola, 1990). Understanding the nature and properties of faults as well as faulting style in the study area is key predicting fluid migration behaviours in the area. The different types of faults and structures typical of the Niger Delta have been illustrated in Figure 2. Studies have shown that major traps for hydrocarbons in the region are predominantly that of the rollover anticlines and fault closures (Oluwajana *et al.*, 2017). Nonetheless, some stratigraphic traps have also been recognized (Orife and Avbovbo, 1982).

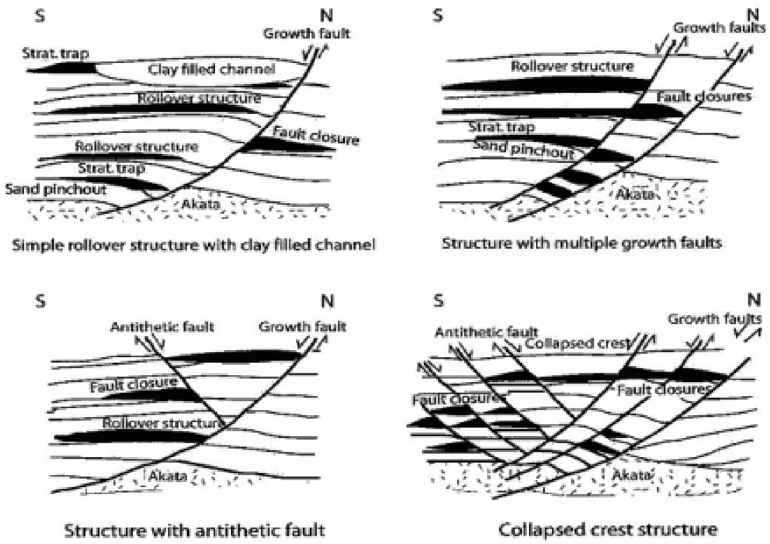

Fig. 2: Typical oil field structures and associated traps in the Niger Delta (Doust and Omatsola, 1990)

II. Materials And Methods

The main focus of this study was to delineate/analyse reservoir structures capable of securing sequestered carbon dioxide and to analyse the migration spill paths of the buoyant fluid within the storage domain. Hence, the principal data used in the study were a suite of well logs from four oil wells, formation tops, check shot data, deviation data and a 3D seismic section. The four wells were codenamed CRK-01, CRK-025, CRK-029 and CRK-032 with appreciable spacing between them (Figure 1). Logs available in the wells were mainly gamma ray, neutron density, resistivity and spontaneous potential logs. The study began with a reservoir characterization workflow using the Schlumberger Petrel 2021.2 software. First, the log data were analyzed to delineate the reservoirs of interest and their corresponding top seals. This was followed by a seismic-to-well tie which was conducted to establish the exact position of the reservoir-seal pairs on the seismic section. Reservoir tops and bottoms were picked on the logs and then interpreted along the seismic lines which then became a guide for fault and horizon mapping. The structural interpretation of the field involved mapping of faults and horizons of interest which corresponds to the delineated reservoir top markers to reveal the structural framework of the field. The process involved manually picking of traces which represents the structural features with the aid of one or combination of visualization tools available in the Petrel software. Although this process can sometimes be automated, however, it was done manually in the present study to avoid some form of mismatch that may arise from the automated approach. Finally, the mapped horizons were then used in generating reservoir surfaces in time and thereafter converted to depth maps used for interpreting the structural patterns and nature of active traps in the area.

Spill point analysis was conducted in this study using the *CO2lab* module of the Matlab Reservoir Simulation Toolbox (MRST) 2023a version, an open-source code by SINTEF Digital. To carry out the spill point analysis, an input geological model built from Petrel software was used. In building a static reservoir model, the reservoir properties were first determined from analyses of the well logs and then distributed on the reservoir surface applying commonly used geostatistical tools (Adeoti *et al*. 2014). The model was then loaded into the *MRST_CO2lab* where it was digitized and processed for the spillage analysis. A more detailed procedures for building the static reservoir models are presented in Mkpese *et al*. (2024). The idea of spill point analysis was to map out the possible migration paths and spill regions associated with traps within the reservoir domain. The spill region of a trap encompasses all reservoir locations where CO migrates into the trap via gravity-driven migration. An apt analogy can be drawn with hydrology, where the spill region of a trap is likened to the catchment area of a lake (SINTEF ICT, 2023). In order to study CO_2 migration in the reservoir, a percolation-type approach, which assumes infinitesimal injection rate can be used (Lie *et al*., 2015). The algorithm recognizes the buoyant nature of supercritical CO_2 and works with the idea that CO_2 injected at a specific point within a catchment area will gradually accumulate and fill up the associated trap until the lower boundary of the CO_2 extends to the spill point (Nilsen *et al*., 2015). The resulting migration model is such that can be used to make informed decisions such as placement of injection wells and the right injection strategy that can be applied to study long-term storage and migration of carbon dioxide.

III. Results

The results of the study presented here are mainly those of the structural interpretation and spillage/migration models. The reader might want to refer to Mkpese *et al*. (2024) for the results of log analysis. Result of the structural interpretation of CRK field include interpreted seismic section showing mapped faults and horizons, time grids for modelled horizons, generated time maps and depth contour maps. Fault interpretation was aided by the application of structural smoothening attribute and variance edge to the seismic volume. Figure 3 is the interpreted inline seismic section showing some of the major faults and the two horizons that were mapped. A total of 27 faults were observed and mapped across the entire seismic sections. The interpreted faults include one major fault and a series of other minor synthetic and antithetic faults. The exact horizons for the tops of the reservoirs were picked and this ensured that the process was consistent. Horizons corresponding to the tops of reservoir D10C0 and reservoir D6200 were identified and manually picked along their seismic continuity at an interval of 10ms having tied the wells to seismic reflections. Figure 4 & 5 are the time grids for the modelled horizons showing that the mapped horizon covered the entire seismic section and, therefore, served as good inputs for generating the time and depth surfaces in Figure 6-9.

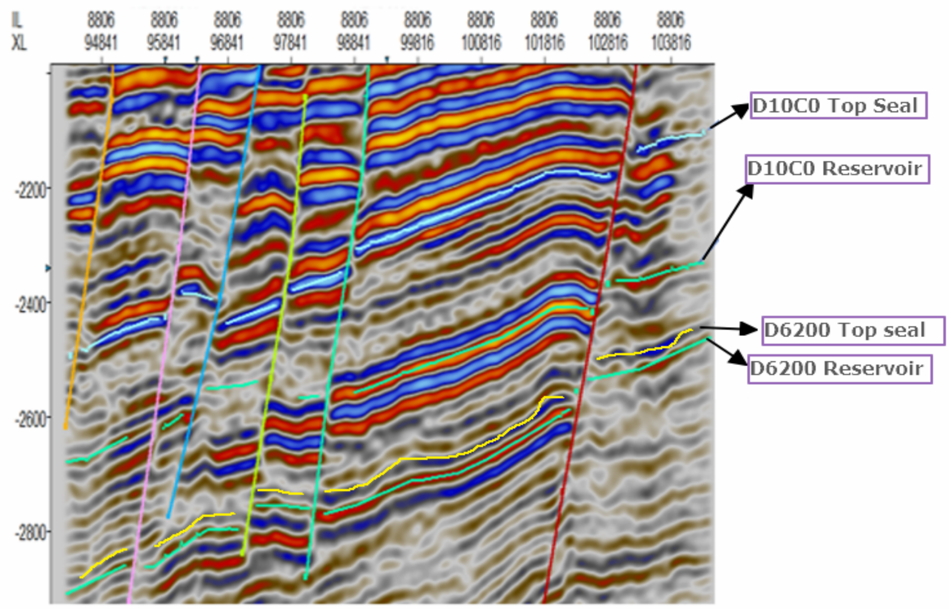

Fig. 3: Interpreted Seismic Inline section showing faults and horizon picks

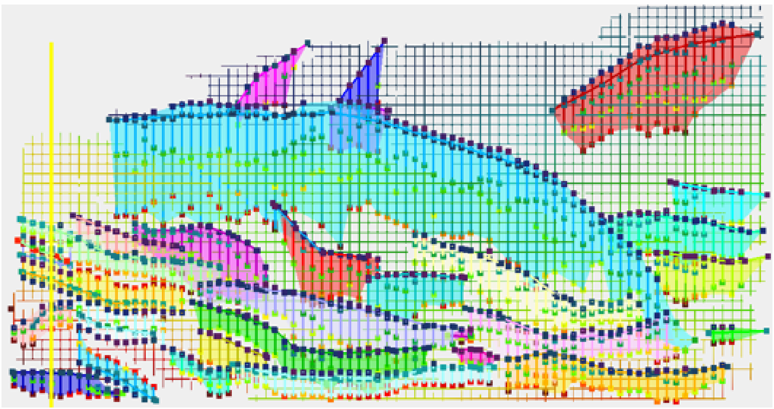

Fig. 4: Manual Horizon Pick D10C0 Reservoir

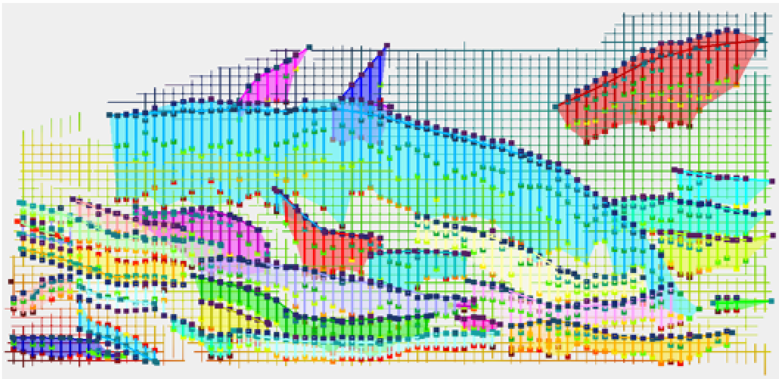

Fig. 5: Manual Horizon Pick D10C0 Reservoir

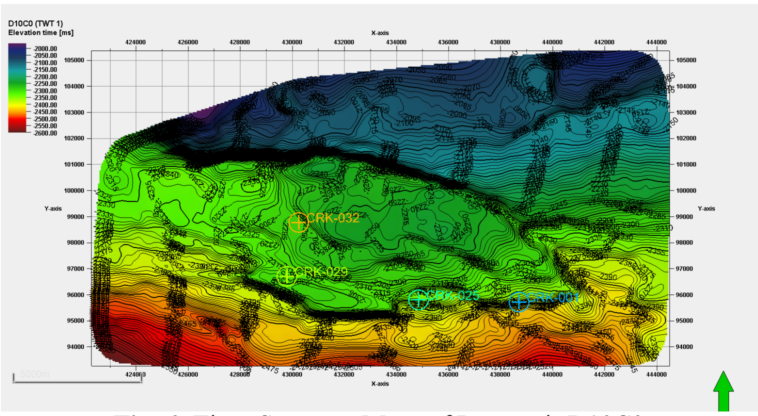

Fig. 6: Time-Structure Maps of Reservoir D10C0

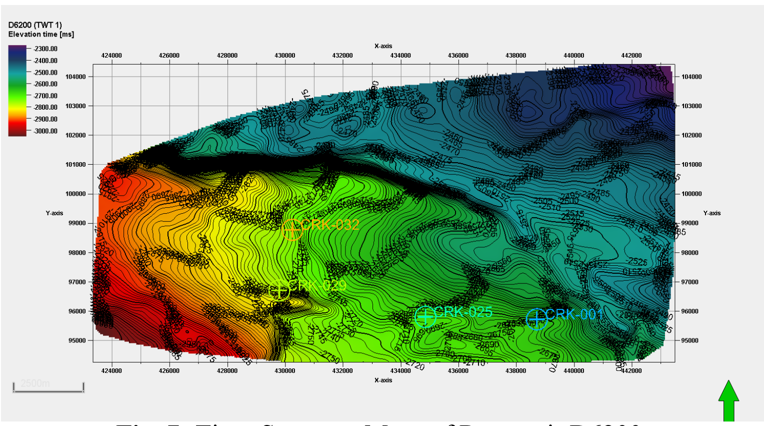

Fig. 7: Time-Structure Maps of Reservoir D6200

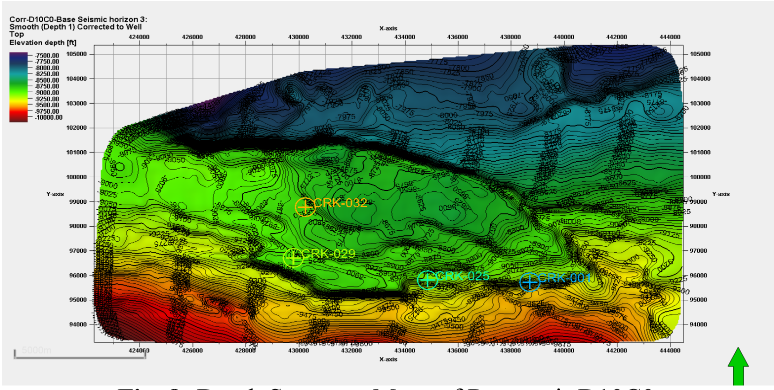

Fig. 8: Depth Structure Maps of Reservoir D10C0

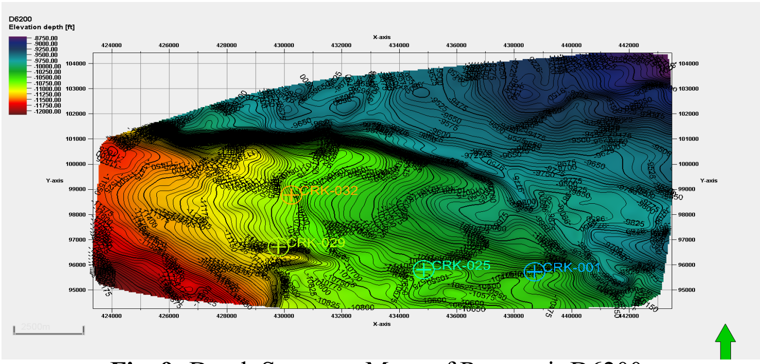

Fig. 9: Depth Structure Maps of Reservoir D6200

The spill point analysis conducted in this work started with visualizing the various structural traps within the modelled domain. Figure 10 (a & b) provides a clear view of the major structural traps within the model as represented by the various colour spots of varying sizes depending on the size of the trap.

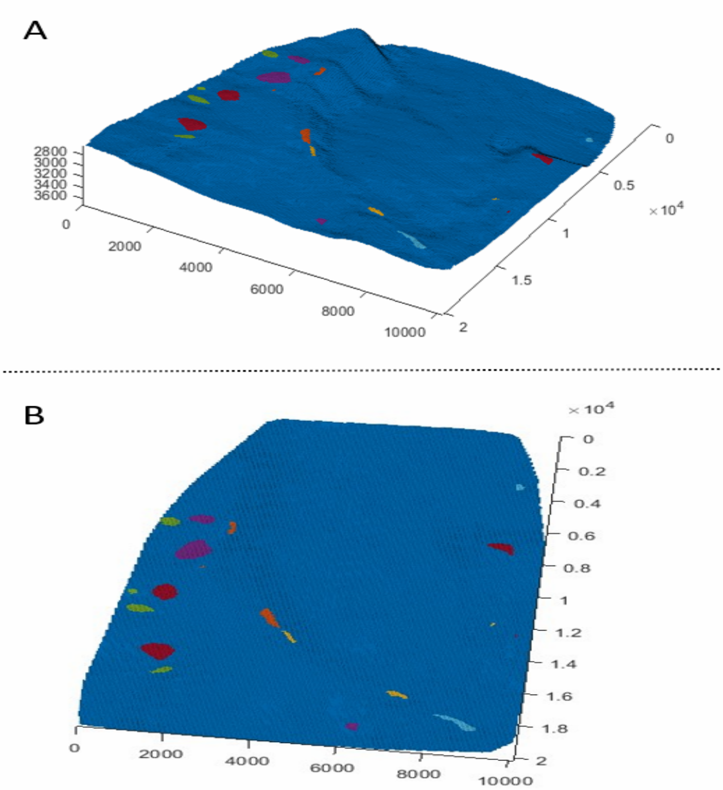

Fig. 10: Structural traps of the reservoir model (a) Oblige view (b) Top view

Furthermore, the term spill regions are typically used to represent regions which function as conduits, gathering buoyant fluids within their coverage area and directing them toward the highest point. Each spill region is topographically isolated from neighbouring spill regions or regions that spill the buoyant fluid out of the model's boundaries, similar to a perimeter in hydrology known as a drainage divide or watershed. Figure 11 (a and b) is an illustration of the major spill regions in the modelled domain. The spill regions are plotted as semi-transparent, with colours matching their associated traps. Nodes positioned above the highest point on the perimeter, referred to as the spill point, are categorized as part of a structural trap, which holds the potential for safe CO_2 storage. Conversely, the remaining portion of the spill region is designated as the catchment area of the associated trap.

And the last step was to analyse the reservoir model for revealing the various spill paths connecting the different traps from downslope to upslope. Figure 12 (a and b) illustrates the various spill paths through which CO can follow when migrating between traps. The spill paths are represented by semi-dotted blue lines interconnecting the traps represented by varying sizes of coloured spots depending on the size of the trap. The spill-paths map is primarily useful for choosing the best location for placing inject well. For a single injector well simulation of long-term CO_2 storage and migration, the red ring in the north-eastern part of the model represents the best injection location since we expect the buoyant CO_2 to naturally spill from the very limited traps in that area and to migrate up slope through the spill-paths to the other traps in the western part of model upslope.

IV. Discussion

CO_2 containment in a storage reservoir is primarily determined by the presence of a competent sealing unit above the reservoir unit and structural traps capable of holding the sequestered CO_2 in place to prevent it from leaking out. The results in Mkpese et al. (2024), as summarized in Table 1, shows the candidate reservoirs has sealing pairs with thicknesses surpassing the recommended minimum of the International Energy Agency (IEAGHG, 2009).

Table 1: Average reservoir and caprock thicknesses (Mkpese *et al*., 2024)

Reservoir Zone	Depth to top (m)	Thickness (m)	Caprock thickness (m)
D10C0	2816	16	29
D6200	3289	40	109

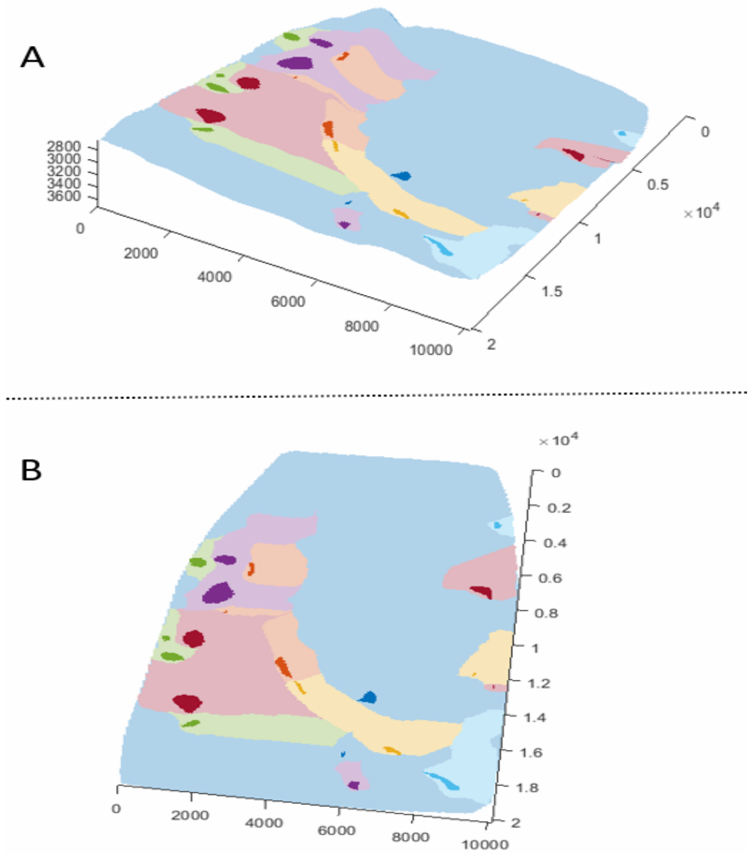

Fig. 11: Spill regions of the reservoir model (a) Oblige view (b) Top view

In the present study, seismic analysis revealed a regional fault and a series of other synthetic/antithetic which forms part of the trapping system. The faulting pattern in the study area are mostly northwest- southeast (NW-SE) trending growth faults typical of the Niger Delta. Although it is assumed the minor faults only make part of the entire network of faults but will have no major impact on the reservoirs within the entire mapped area (Kura *et al.*, 2021). It was observed, however, that the network of faults divides the field into upthrown and downthrown blocks with the downthrown blocks slightly thicker than the correlative counterpart of the upthrown blocks.

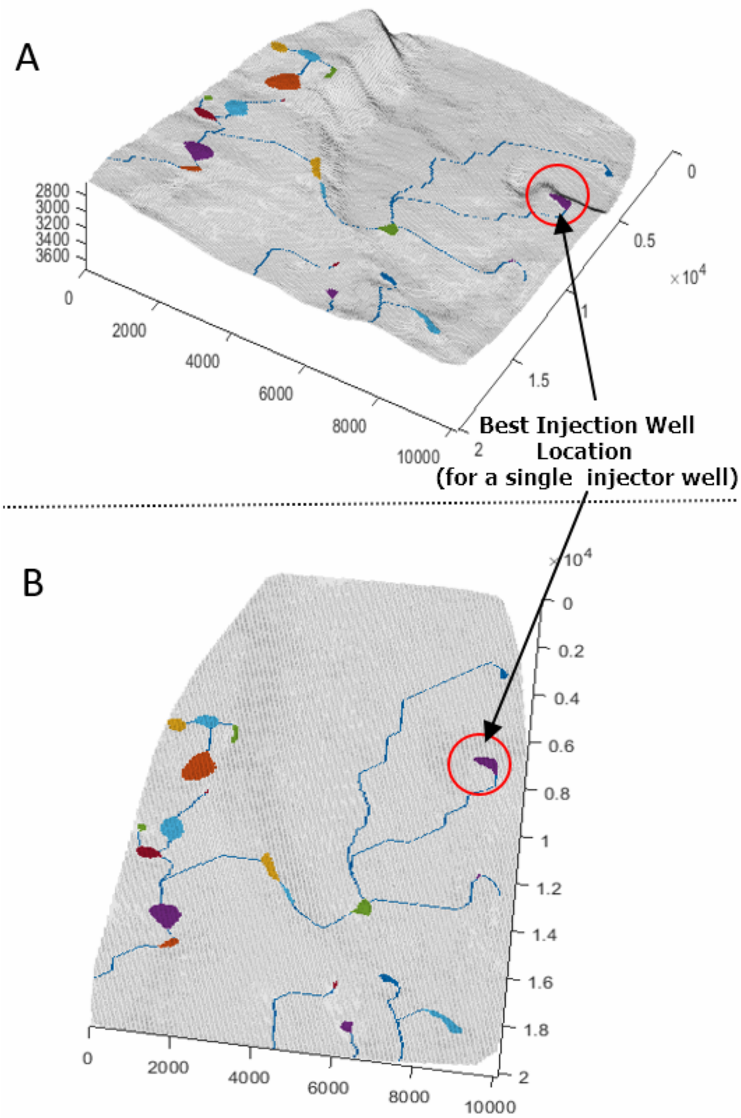

Fig. 12: Migration spill paths or rivers (a) Oblige view (b) Top view

According to Childs *et al.* (2003), such occurrence might be attributed to successive stages of growth which goes further to confirm the proposition of Doust and Omatsola (1990), that the rock volume or strata in the Niger Delta were formed contemporaneously and continuously as deposition progresses. The interpreted seismic section also showed identifiable rollover structures, collapse crests and fault closures within the interplay of faults mapped. Also, clearly, there are observable closures on the depth structure maps especially around the intensely faulted zones indicative of fault enclosed traps which is typical of the Niger Delta hydrocarbon bearing reservoirs as these traps prevent the migration of hydrocarbons (Doust and Omatsola, 1990). On the depth structural map of reservoir D10C0, for instance, there's a near perfect enclosure defining an anticline with a crest around 9100 ft which corresponds to what was measured on the well logs (well CRK-25), as reported in Mkpese *et al*. (2024). Such type of closures, usually the anticlinal structures, which form part of a network of faults observable on depth maps are known to be efficient hydrocarbon traps (Fagbemigun *et al.*, 2021) and as such, can serve as suitable traps for sequestered CO_2 in the candidate reservoirs.

Results of the spill point analysis revealed that there are very scanty spill regions in the lowermost portions of the modelled domain compared to a handful of them observable in the upper regions. Obviously, this is an indication that a viable CO_2 injection operation will only be achievable if the injector wells are placed in the lower portion of the reservoir (Figure 12) within which there are limited number of traps but connected by the spill-paths to many traps in the southern part of model upslope. This is so since it is naturally expected of the buoyant CO_2 to migrate upslope through the interconnected spill-paths after filling up the nearest traps close to the injection point. Also, by injecting the CO_2 in the lower portion of the model, this will buy more migration time for the injected CO_2 while being acted upon by different trapping mechanisms. This is likely to increase the storage performance as well as reduce the risk of leakage. Furthermore, the trapping structure influences other trapping mechanisms. Structural traps, for instance, impede plume migration, while plumes spreading beyond their injection catchment areas require sufficient energy to push CO_2 downward and across the nearest spill point or perimeter (Nilsen et al., 2016). Consequently, catchment areas with significant funnelling effects are likely to diminish global sweep efficiency, which is crucial for ensuring residual effects serve as a viable trapping mechanism.

V. Conclusion

We studied the depleted oil reservoirs of an onshore Niger Delta field for their structural capability to store CO_2 and to also reveal the potentials for leakage via spillage analysis. Structural interpretation of the field shows that features such as rollover anticlinal structures and collapsed crests within fault closures are most likely the structures responsible for fluid retention in the reservoirs. On the other hand, the spillage analysis shows that these structural traps are interconnected such that sequestered CO_2 flowing through the migration paths will gradually fill up the traps from the lower portion of the reservoir moving upslope before it is filled to spill. This process tends to impede plume migration and thus very likely to increase the storage performance as well as reduce the risk of leakage. The study therefore suggests that the identified structural features have sufficient containment potential to secure sequestered CO_2. It also proposes the delineated spill point can be adopted as a guide to future CO_2 injection project in the study area so as not to impose hazard.

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