3D structural and stratigraphic characterization of X field Niger Delta: implications for CO₂ sequestration

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Abstract

Carbon capture and sequestration technology has been a ground-breaking tool in tackling carbon dioxide (CO₂) emissions worldwide but has limitedly been researched and practised in Africa at present. Considering the vast growth and developmental level in the continent, there is a need to consider this option of mitigating global climate change. In this study, a systematic and process-based incorporation of seismic and well logs datasets was used to characterize the structural and stratigraphic framework of sandstone reservoirs within the field in order to determine their capacities for effective CO₂ sequestration. Petrophysical analysis, fault modelling as well as geostatistical techniques were used to build facies and property models which enabled a qualitative assessment of the sealing potential of faults associated with the reservoirs based on prediction of key properties such as shale gouge ratio, lithological juxtaposition, fault permeability and fault transmissibility across the fault faces. Nine water-bearing sandstone reservoirs (reservoirs A–J) with varying reservoir quality were identified in the field. The dominance of high SGR, low permeability, higher fault throws and low fault transmissibility values at the lower parts of the faults indicates the deeper structural traps of the field are low-risk zones and might serve as good storage areas for CO₂.

Keywords Climate change · Sealing potential · Niger Delta · Fault face · Lithological juxtaposition · CO₂ sequestration

Introduction

The sharp surge in Africa's population from about 257 million to about 1.2 billion (Sankoh 2016) in the last few decades, coupled with technological advancement in Africa, has resulted in large-scale industrialization and an upscale in anthropogenic activities (such as power generation, cement and petrochemical production, transportation emissions, industrial processes and agricultural practices) which has invariably impacted on its atmosphere in terms of its carbon dioxide (CO) intake (Herzog 2001).

Virtually, all the gas generated during oil production in Nigeria's Niger Delta oil-rich region is flared into the atmosphere. As a result, Nigeria ranks as the second highest gas flaring nation behind Russia (Hansen 2004). The greenhouse gas (GHG) mitigation is becoming a stronger legislative priority in Nigeria as renewable generation technologies (e.g. wind and power) are still unable to provide dispatchable electric power in the country, therefore fossil fuels are likely to remain the principal source of energy. Emissions from oil extraction and energy use will continue to drive atmospheric concentrations of CO₂ upwards unless energy conversion systems can be designed to otherwise dispose CO₂ generated from combustion and flaring.

The technology of carbon capture and sequestration (CCS) is fast becoming very common and effective method in storage of carbon dioxide (CO₂) in subsurface reservoirs (Czarnogorska et al. 2016). In fact, this method has been termed as a waste management strategy that has helped in curbing down the release of CO₂ into the atmosphere thereby mitigating the negative effects associated with climate change (Bachu et al. 2007; Akpanika et al. 2015; Umar et al. 2019a).

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To achieve the goal of sequestration of CO₂ in subsurface reservoir however, it is imperative that geologic units suitable for storing CO₂ must have the effective trapping mechanisms, injectivity and capabilities that can confine the CO₂ gas and impede its horizontal migration and/or vertical leakage to other subsurface strata, shallow portable groundwater and/or atmosphere over geologically long periods of time (Stefan 2007; Yang et al. 2014). Consequently, geo-modelling of the structural and stratigraphic disposition as well as the petrophysical attributes (porosity and permeability) of the reservoir units is to be evaluated to determine its potential for CCS. Genuine research into CCS only started in the early 1990s. Since then, significant progress has been made in the technologies available for predicting the fate of injected CO₂. This has allowed a large body of work to be produced and the feasibility of CO₂ disposal in several reservoir systems to be determined. Three classical studies have been performed on structures in the Sleipner project in Norway, the Weyburn Project in Canada and the In Salah Project in Algeria. These field-scale injections of CO₂ into suitable formations have provided more insight into the processes and technologies involved in geologic sequestration and on the effective monitoring tools. The Sleipner project in Norway is the first case of large-scale commercial CO₂ storage in the world (Torp and Gale 2004). The project began in 1996, with over 10 million tonnes of CO₂ stripped from the produced natural gas and injected into the sands of the Utsira Formation which is about 900 m below the bottom of the North Sea. There have not been any significant operational problems observed in the capture plant or in the injection well so far. (Torp et al. 2003). Geo-modelling studies have been carried out extensively on this project and this demonstration project is expected to provide a better understanding of the relative effectiveness of competing migration and sequestration processes for optimal sequestration performance in term of safety (Goel 2012). The Weyburn field project in Canada (Malik and Islam 2000) was the first to study CO₂ storage as both an Enhanced Oil Recovery (EOR) technique and a storage method. The Weyburn project is a good example to prove that oil reservoirs are attractive candidates for subsurface CO₂ storage. Another CCS project already in operation is The In Salah gas project in Algeria, which comprises a phased development of eight gas fields located in the Ahnet-Timimoun Basin in the Algeria Central Sahara (Riddiford et al. 2003). CO₂ removed from the produced gas is injected into the formation, which provides storage of 1.2 million tonnes per year. Ringrose et al. (2013) analysed the need for characterization of the overburden and the reservoir prior to injection, continuous risk assessments of the identified storage sites and the significance of flexibility in the design of capture, compression and injection systems at the In Saleh CCS gas project. However, CCS is yet to be implemented on a local or regional

scale in Nigeria. Previous studies on CCS in Nigeria have, so far, mainly focused on the fundamental science of CCS, the present status of global CCS development, terrestrial sequestration and the benefits/potential risks of its future implementation (Galadima and Garba 2008; Akpanika et al. 2015; Yelebe and Samuel 2015; Ibrahim et al. 2019). The stratigraphic and structural competence of some reservoir units within the Niger Delta for carbon storage has also been carried out by a few authors (Ojo and Tse 2016; Umar et al. 2019a). However, their work was restricted to the Central Swamp depobelt I and limited to carbon storage capacity using reservoir and seal properties such as porosity, permeability, thickness and depth. Whereas, the presence of excellent reservoir–seal pair, large areal extent, matured oil and gas field and availability of giant hydrocarbon pools generally makes the Central Swamp II depobelt of the Niger Delta basin an ideal potential for storage of anthropogenic carbon dioxide.

The study area in this research is typically characterized by several growth faults associated with rollover anticlinal structures typical of the Niger Delta extensional zone (Doust and Omatsola 1990). Oil fields situated nearby the study area reported high amount of hydrocarbon leakages from shallow reservoirs intervals within the Agbada Formation which was largely attributed to the limitations imposed by the previous fault analysis of the field in which one-dimensional fault shale gouge ratio (SGR) analysis solely was employed using the Yielding et al. 1999 method to characterize the faults seal potential of the field. However, to better define the architecture of the fault planes as well as effectively capture the sealing attributes of faults in three dimensions in terms of lithological juxtaposition, fault permeability, SGR and transmissibility, the sealing potentials of the faults affecting the reservoirs in 3 Dimension was investigated in this research. This is of crucial importance in determining the integrity and effectiveness of geologic formations or underground CO₂ storage units of the study area. We also recognize that while some authors have worked on the applications of 3D fault seal attributes to characterize fault planes, hydrocarbon predictions and prospectivity in the Niger Delta basin (Ifeonu, 2015; Ejeke et al. 2017; Adagunodo et al. 2017), few have commented on the implications of these on CO₂ storage as well as highlighted the importance of seismic data conditioning by applications of structure-orientated filtering seismic attributes which takes account of bed estimated orientations and thereby reduces the noise content without losing information related to edges of geologic units (Azevedo 2009; Qi 2018) before determining the framework of faults within the field.

Geology of the study area

Sequel to the breakup of African plate from South American plate, the Niger Delta (Fig. 1) was formed in the Paleogene (Obafemi et al. 2020). The sedimentary succession of the basin is mostly obtained from the Precambrian crystalline basement complex and the Cretaceous and Cenozoic basement-derived sedimentary rocks (Adegoke et al. 2017). From

the Cenozoic era through the middle Miocene, the Niger Delta basin developed via various episodes of events which led to sediment deposition into the Gulf of Guinea from the Cenozoic to Middle Miocene (Reijers 2011). According to Obafemi et al. 2020, the stratigraphic fill of the Niger Delta basin is primarily composed of three lithostratigraphic units. These units include the lowermost marine pro-delta Akata Formation, the middle shallow-marine delta-front Agbada

Fig. 1 Schematic map of the Niger Delta showing the distribution of depositional and structural belts (modified after Whiteman (1982), Damuth (1994) and Cohen and McClay (1996))

Formation and, the overlying youngest continental, delta plain Benin Formation (Doust and Omatsola 1990; Adojoh et al. 2020). These three formations extend across the whole delta (Fig. 2).

The lowermost Akata Formation is Paleocene to Recent in age. It primarily consists of pro-deltaic lithofacies composed mainly of marine shales with turbidite sands and

continental slope channel fills (Doust and Omatsola 1990), estimated to be up to 7 km in thickness and generally considered as the source rock of the Niger Delta.

The middle paralic Agbada Formation is Eocene to Recent in age (Avbovbo 1978). It is primarily composed of delta-front lithofacies characterized by intercalations of sand and shale. The sandstone reservoir facies within

Fig. 2 Simplified stratigraphic fill of the Niger Delta modified after Doust and Omatsola (1990)

this formation are mostly shoreface and channel sands with minor shales in the upper part, and alternation of sands and shales in the lower part (Doust and Omatsola 1990; Sanuade et al. 2017). The Agbada Formation sand members serve as the reservoir units within the basin (Doust and Omatsola 1990).

The uppermost Benin Formation is Oligocene to Recent in age and composed of continental fluvial sands (Avbovbo 1978; Doust and Omatsola 1990; Owolabi et al. 2019). The 2 km thick unit is generally friable and consists of white, fine to coarse and pebbly, poorly sorted sands (Avbovbo 1978; Adegoke et al. 2017).

There are three main structural extensional zones in the delta; the Extensional zone, the intermediate zone and the compressional zone (Damuth 1994; Umar et al. 2019b). The study area is characterized by growth faults and lies within the extensional zone (Fig. 3) which are formed by the movement of deep-seated, over-pressured, ductile, marine shale of the lowermost Akata Formation that deformed much of the Niger Delta clastic wedge (Doust and Omatsola 1989).

Dataset and methodology

Dataset

The dataset used for this study includes 3D seismic data and three wells which has a composite suite of geophysical wireline logs and check shot data. The seismic data are post-stacked and time-migrated. It covers an area of approximately 271.68 km² and comprises of 863 in-lines and 1068 cross lines.

Methodology

Reservoir identification and petrophysical analysis

The different reservoir units within the field were delineated from the available gamma-ray logs from the given wells. The identified storage units were subsequently correlated across the different offset wells based on flooding surfaces (i.e. abrupt deepening) and marker shales within the Agbada Formation. The gamma-ray logs were then integrated with the resistivity and neutron density logs to identify the distribution of different reservoir fluids (i.e. water and hydrocarbon) across the wells.

Fig. 3 Structural style of the extensional area of the Niger Delta (modified after Doust and Omatsola, 1990)

Fig. 5 Seismic section highlighting the vivid enhancement of faults after applying the structural smoothing attribute

Fig. 6 Variance map, **a** uninterpreted and **b** interpreted showing complex fault distribution across the field

volume of shale (Vsh), NTG and permeability estimated from petrophysical analysis were then upscaled into the mesh-like cellular framework of the three-dimensional structural model. 3D models of facies as well as properties estimated from well logs were built using geostatistical techniques. To extrapolate estimates at unknown locations away from well locations, standard geostatistical techniques rely on known data points from multiple locations (e.g. drilled wells) to reduce uncertainties associated with

the estimated unknown data values. Another alternative is to use a secondary property, e.g. a seismic attribute which shows good relationship with defined properties from well logs in addition with well information to estimate data values at unknown locations especially if there are very limited number of wells (Pyrzcz and Deutsch 2014). Due to the availability of limited numbers of drilled wells (three) used for this study, uncertainties were reduced by using a seismic attribute (minimum amplitude) which shows

Fig. 7 Diagram depicting fault transmissibility in a pair of grid cells with fault permeability and thickness

strong correlation with facies from logs at different reservoir levels. Variogram models as well as standard geospatial extrapolation techniques such as sequential indicator simulation and sequential Gaussian simulation used in capturing inherent uncertainties in spatial continuity (Pyrz and Deutsch 2014) were used to build facies model and the rock properties models, respectively.

Table 1 Average petrophysical results for the reservoirs

Reservoirs	Porosities	Sw	NTG	Vsh	Permeabilities (mD)
A	0.34	0.96	0.80	0.20	312
B	0.32	0.98	0.68	0.32	209
C	0.30	1.00	0.82	0.18	223
D	0.24	0.99	0.65	0.35	124.5
E	0.28	0.97	0.61	0.39	345
F	0.24	0.99	0.79	0.21	321
H	0.12	0.96	0.47	0.53	32.3
I	0.15	0.99	0.79	0.21	12.2
J	0.11	0.97	0.90	0.15	10.4

3D fault seal analysis

The three-dimensional facies and property models generated using geostatistical analysis were consequently used to generate fault seal attributes including lithological

Fig. 8 Well logs interpretation showing identified reservoirs. Notice the significantly low resistivity signature within the reservoirs

Fig. 9 **a** Arbitrary seismic line (see Fig. 6b for location) showing identified faults (F1–F9) offsetting the mapped reservoirs. **b** Seismic dip line showing fault throw anisotropy that has affected the different horizons corresponding to the reservoir tops. The faults have smaller throws at the shallower parts and relatively larger throws at the deeper parts of the faults

juxtapositions (sand and shale), shale gouge ratio (SGR) and fault permeability distributions across the fault faces of the faults associated with the structural traps at the different reservoir levels. Fault transmissibility distribution is a key property of faults and a potential flow indicator that depends on the modelled geometry of the 3D grid geometry (Abdullah et al. 2019). In this study, fault transmissibility was determined using permeability values from the 3D permeability model assigned to cells of the 3D structural grid of the reservoirs and transmissibility multipliers from the varying fault thickness in the 3D structural grid (see Fig. 7).

Pore volume estimation and uncertainty analysis

Pore volumes were estimated for the reservoirs associated with zones across the fault faces where there are indications of good fault sealing potentials, i.e. areas of

favourable fault properties (such as high SGR and low permeability) as well as areas with low fault transmissibility. This is to access the volume of CO₂ that can be stored within the reservoirs pore volume which was estimated using;

$$\text{Pore volume} = \text{Area} * \text{thickness} * \text{NTG} * \text{porosity}.$$

To capture uncertainties in the pore volume estimates, the various inputs in this formula were varied and Monte Carlo simulation was used to determine P10, P50 and P90 pore volume estimates, respectively.

Results and discussion

Reservoir identification and petrophysical analysis

Nine reservoirs (A–J) comprising shallow reservoir (A–C), middle reservoirs (D–F) and deep/lowermost reservoirs (H–J) are identified from wireline logs interpretation (Fig. 8). The deep resistivity logs indicate all the storage units are water-bearing. Estimated porosities range from 0.11 to 0.39, NTG ranges from 0.47 to 0.90, Vsh ranges from 0.15 to 0.53 and permeabilities range from 10.4 to 345 mD (Table 1). However, the estimated water saturation has an average value of 1.00 across all reservoirs giving indication of little to low hydrocarbon accumulations which are probably due to leakages or migration of hydrocarbon out of these storage units. The petrophysical estimates suggest that the reservoirs have varying properties of high to low porosities, high to low NTG, high to low Vsh and varying permeabilities. However, the shallow reservoirs have better reservoir properties than the middle and lowermost reservoirs.

Seismic interpretation

Twenty different faults (F1–F20) were identified and mapped across the seismic data. The prominent faulting styles include growth faults with associated rollover anticlinal structures. The faults have a north-west south-east orientation as well as a north-east–south-west direction. Observations from a seismic arbitrary line A–A' indicate that most of the faults have affected all the storage units (Fig. 9a). It was also observed that the faults that are deeper have higher throws than the shallower faults (Fig. 9b). The variance time slice reveals that the faults are curved (listric) and the seismic in-lines indicate the faults have listric planes. The depth structural map of reservoir E (middle reservoir) is shown as a representative depth map showing the dominant

Fig. 10 Representative depth structural map (reservoir E) of the field. Structural closures observed on the map are typical of all the reservoirs. A and B represent the locations of the prospects observed across all reservoir levels

Fig. 11 Representative minimum amplitude map (across reservoir E) showing typical amplitude variation across the reservoirs

Fig. 12 Constructed 3D fault models of the X field

Fig. 13 3D structural model of the field

structural trapping styles associated with each of the reservoirs (Fig. 10). Minimum amplitude attribute map (Fig. 11) of reservoir E also gives insight into the distribution of fluid types across all the storage units. High minimum amplitude was observed mostly within the major and extensive faulted

areas and low amplitude within the structural traps (closures). This gave rise to the identification of two prospects A and B which extends across all the reservoirs. The seismic attribute shows good consistencies with well logs information at the drilled points in terms of facies and fluid type.

Fig. 14 Facies model showing the distribution of sands and shales across all the mapped reservoirs

3D structural and reservoir modelling

The 3D fault models of the mapped faults reveal their three-dimensional distribution and orientation across the field (Fig. 12). The faults towards the north central part of the field are associated with stacked rollover anticlines as revealed by the 3D structural model of the field (Fig. 13). The facies model and Vsh model (Figs. 14 and 15) show the distribution of sands and shale and the corresponding shale volume across all the mapped reservoirs. The models showed good quantity of sands across the reservoirs. The permeability model and NTG models (Figs. 16 and 17) suggest high permeability within sands and low permeability

within shales while sand-prone regions appropriately have high NTG and shale-prone areas have low NTG.

3D fault seal analysis

Faults seal attributes including lithological juxtapositions, shale gouge ratio, fault permeability and fault transmissibility distributed across the fault faces are shown in Figs. 18, 19, 20 and 21. Lithological juxtapositions across the faults are mostly characteristics of sand-sand juxtaposition and few shale-sand and shale-shale juxtapositions indicating the faults in the field generally have poor to fair sealing potentials (Fig. 18). Sands that are permeable can act as ‘thief zones’ in which fluid would migrate to overlying beds at sand-sand contacts.

Shale gouge ratio values and fault permeability (Figs. 19 and 20) distributed laterally and vertically across the fault faces revealed that the faults have very high number of permeable zones and low SGR zones. However, the deeper parts of the faults have relatively higher SGR and lower permeability values suggesting good sealing potentials at the lower parts of the faults. The SGR and permeability fault

Fig. 15 Vsh model showing the distribution of volume of shale across all the mapped reservoirs

distribution are consistent with the 3D models as well as well logs.

Though the water-bearing nature of the reservoirs as indicated by the integration of resistivity and GR logs as well as the low amplitudes observed on the structural highs suggest possible hydrocarbon leakages and tertiary migration of hydrocarbon out of faulted reservoirs which perhaps had resulted from ineffective trapping systems and structurally compromised top seals, the lower parts of the faults are likely sealing with low permeability and high SGR values. This would suggest that possibly migration of hydrocarbon had emanated from shallower structures. The possibility of a good sealing potential of the lower/ deeper faults is also evident by larger fault throws at depth (see Fig. 10). The fault transmissibility distributions on the fault faces indicated that the deeper parts of the faults which tends to be more prevalent towards the south-western and north-eastern part of the field mostly showed very lower fault transmissibility as depicted in Fig. 21. Some occurrences of areas with relatively low fault transmissibility values observed at some shallow parts of the faults are attributed to regions of relatively high fault thickness and large 3D grid cell lengths

at these regions. However, regions with low fault transmissibility occur predominantly at the lower part of the faults in the field (see Fig. 14). Hence, the faulted and rollover structural traps associated with the lower reservoir levels (i.e. reservoirs HIJ) would constitute low-risk zones and serve as good storage areas for CO₂.

Pore volume estimation and uncertainty analysis

Pore volume estimates for the drilled structural highs at the three lower reservoirs which are associated with higher proportions of sealing potentials across the faults in the field are shown in Fig. 22. The pore volume estimates give insights into the CO₂ storage capacity of the drilled structures associated with the lower reservoir intervals (H, I and J). The summed pore volume estimated for the three lowermost reservoirs (H, I and J) includes a P10 estimate (low case/pessimistic scenario) of 10.8 Gbbl (1.73×10^9 m³), P50 (mid-case/realistic scenario) estimate of 13.1 Gbbl (2.07×10^9 m³) and P90 (high case/optimistic scenario) estimate of 13.9 Gbbl (2.21×10^9 m³).

Fig. 16 Permeability model showing the distribution of volume of shale across all the mapped reservoirs

Limitations

The limitations of the comprehensive fault seal analysis carried out in this study are the unavailability of production data and pressure data to determine the sealing nature of the lower zones of the faults in the field under production conditions. However, overall, the integration of the wells and seismic information is relevant for future studies in the field.

Conclusion

The faults associated with ten reservoirs were identified and analysed in this study. Heterogeneity and anisotropy of properties critical to sealing potentials of faults such as shale gouge ratio, fault permeability, lithological juxtapositions and fault transmissibility suggest that the faults

have good sealing properties at the lower/deeper parts as compared to the shallower parts of the faults hence indicating that the structures at the lower parts north-eastern parts of the field are likely good storage units for CO₂ in the study area. It also indicates the lower reservoirs are of low risk in terms of CO₂ storage as compared to the shallow and middle reservoirs.

Recommendations

It is recommended that a storage capacity assessment of the X field using numerical injectivity and a geomechanical analysis should be conducted in the future. Also, the prospective cluster areas A and B identified across all the reservoirs should be appraised using more seismic coverage to better define the structure.

Fig. 17 Net to gross model showing the distribution of volume of shale across all the mapped reservoirs

Fig. 18 Lithological juxtapositions across the faces of the faults. The sand-on-sand juxtapositions zones are areas which could lead to possible migration of stored CO₂

Fig. 19 Shale gouge ratio distributions across the faces of the faults. Observe that the deeper parts of the fault faces have relatively high SGR as compared to the shallower parts

Fig. 20 Fault permeability distributions across the faces of the faults. Also, observe that the deeper parts of the fault faces have relatively high permeability as compared to the shallower parts

Fig. 21 Fault transmissibility distributions across the faults. Observe low fault transmissibility occurring predominantly at the lower part of the faults. Signifying the lower structural traps associated with the lower reservoirs (HIJ) constitute low-risk zones for CO₂ storage

Fig. 22 Summed pore volume estimation for the lower reservoirs (HIJ) showing the P10, P50 and P90 estimates

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Declarations

Conflict of interest I write to acknowledge that this manuscript is my work and the content therein has not been copied from elsewhere. The manuscript is unpublished and is not currently under review with another journal. This research was done in Seismic Laboratory at the

University of Nigeria, Nsukka, Enugu State. There is no conflict or potential conflict of interest on this work. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: None.

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Consent to participate All authors consent to participate.

Consent for publication All authors consent to the publication of this research if accepted by the journal.

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