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Sequestration of CO_2 in Depleted Reservoirs: A Case Study of a Niger Delta Field

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***Abstract*— *The primary purpose of CO_2 sequestration in depleted reservoirs is to lessen rising levels of CO_2 emission considering its negative impact on the environment. However, before a reservoir could be considered as a potential site for CO_2 sequestration, a number of eligibility tests and criteria must be satisfied. In this study, 3-D seismic and a suite of wireline logs (Gamma Ray GR, Spontaneous Potential SP, Resistivity and Neutron log) for six wells in a Niger Delta field in Nigeria, West Africa codenamed UTI. The wells were accessed, digitized, analyzed and discovered to have three reservoirs UTI-1, UTI-2, UTI-3 with unique properties. It was discovered that for every given storage efficiency, reservoir UTI-2 showed the highest storage capacity. Although reservoir UTI-2 possesses the greatest storage capacity of about 9.5 times reservoir UTI-1 & 3, it did not pose to be the most viable candidate for CO_2 sequestration. This is because it did not satisfy other criteria such as minimum miscibility pressure of CO_2, reservoir temperature and permeability. In concluding it is not appropriate to select a reservoir for CO_2 sequestration only based on storage capacity. Due consideration must be given to factors such as miscibility pressure of CO_2, reservoir temperature and permeability.*

***Keywords*— *Sequestration, Depleted reservoirs, storage capacity*.

I. Introduction

Basically, sequestration of CO_2 could be in the form of surface (biological) application (absorption by plants and vegetative covers) or subsurface (geological) application. Geological sequestration of CO_2 is a physical process that deals with capturing CO_2 from its sources, transporting it (usually by pipeline) and injecting it into a suitable sub-surface formation. The primary purpose of geological CO_2 sequestration is to mitigate the adverse effects of greenhouse gases released to the atmosphere (Bilardo and Panvini, 2007). The emission of CO_2 and other greenhouse gases have been identified to be the potential cause of the global climate change. The capture of CO_2 is best at large point source such as fossil fuel power plants, fuel processing plants, and other industrial plants (particularly plants for the manufacture of iron, steel, cement and bulk chemicals). The three options for CO_2 geological sequestration involve storing CO_2 in: 1) depleted oil and gas reservoirs; 2) deep unused saline water-saturated reservoir rocks and 3) unmineable deep coal seams.

For the purpose of this study, we considered geological sequestration involving depleted oil and gas reservoirs. The key advantage of isolating CO_2 in depleted reservoirs is that the reservoir rocks are well characterized in terms of rock type, faults, porosity and permeability (Yann, 2002). Usually, data from seismic to core are available. Also, it is cost effective to workover an oil well converting it to a CO_2 injection well for geological sequestration. Depleted reservoirs have demonstrated the structural integrity for long time storage of original oil and gas. Though, the saline aquifer and unmineable coal bed are poorly characterized but usually have large storage capacity when compared to the depleted reservoir.

Geology of the Niger Delta

The Niger delta is located in the Gulf of Guinea in a rift triple junction which relates to the opening of the southern Atlantic which started in the later Jurassic to the Cretaceous. It is situated between latitudes 4^o and 6^o N and longitudes $4^o30'$ and $8^o00'$E. The Niger Delta is recognized as one of the world's most prolific oil and gas producing Tertiary deltas (Ojo and Tse, 2016).

The three lithostratigraphic units that form the internal structure of the Niger Delta are: the Benin Formation which is fluvial sand unit and occupies the uppermost section, the sand-shale intercalated Agbada Formation, and the marine shale Akata Formation. A clay unit of the sandy Benin Formation called Afam is found in the Port Harcourt area. Generally, structural traps are predominant over stratigraphic traps. These include traps associated with simple rollover structures such as channels filled with clay, multiple growth faults structures, structures with antithetic faults, and collapsed crest structures.

The rollover anticlines which occur in front of growth faults are the target of oil exploration. The Agbada Formation is the major reservoir from which oil is produced primarily from gas expansion. These reservoirs have average porosity of 40% and permeability of 200mD. Reservoir thickness ranges from less than 15m to 10% of reservoir having greater than 45m thickness although thicknesses of 100 meters may be encountered (Edwards and Santogrossi 1990).

The sandy Benin Formation consists of coarse grained, gravelly, poorly sorted, sub-angular to well-rounded sand. It is the most prolific aquifer in the region and comprises over 90% massive, porous sands with localized clay/shale inter-beds. Niger Delta aquifers range from localized, shallow unconfined aquifers up to 400m in the subsurface to deeper, laterally more extensive ones. The deeper aquifers may contain several clay layers which subdivide them into series of aquifers/sub-aquifers which are essentially independent units without hydraulic interconnection. These intermediate and regional-scale flow characteristics are desirable qualities for CO_2 sequestration.

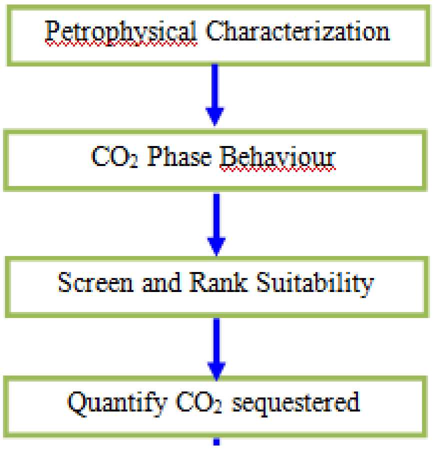
II. Methodology

In this study, 3-D seismic and a suite of wireline logs (Gamma Ray GR, Spontaneous Potential SP, Resistivity and

Neutron log) for six wells in three reservoirs in a field codenamed UTI were accessed, digitized and analyzed. The objective was to assess the quantity of CO_2 which can be stored in a potential sequestration reservoir and to demonstrate that the reservoir is capable of meeting required storage performance criteria.

The Gamma-Ray and Spontaneous-Potential logs were employed in combination with the resistivity logs to discriminate and delineate the reservoirs lithologically.

The geological sequestration of CO_2 in depleted oil and gas reservoirs is dependent on the petrophysical suitability of the reservoir and the phase behaviour of the interaction of CO_2 with oil and gas that enabled it to be geologically sequestrated. Therefore the procedure for CO_2 geological sequestration adopted by this research is outlined as follows:



Petrophysical Characterization of Depleted Reservoirs

The characterization process involves the determination of the reservoir's:

1. Porosity to ascertain its capacity to store the intended volume of CO_2 over the lifetime of the operation.
2. Permeability required to measure the injectivity required to take the CO_2 at the rate that it is supplied from the sources and containment which ensures that it will not migrate or leak out of the storage.

Data gotten from the logs were used to determine the porosity, permeability, volume of shale, water saturation, hydrocarbon saturation, net-to-gross and fractional total pore volume filled with hydrocarbon using the methods stated below:

Porosity:

The method presented by Darling (2005) was used to determine the petrophysical properties of the UTI field. The determination of absolute porosity from the density log is given thus:

Absolute Porosity:

$$\varphi_a = \frac{\rho_{ma} - \rho}{\rho_{ma} - \rho_{fluid}} \qquad (1)$$

where

ρ_{ma} = the density of matrix

ρ = the bulk density measured by the log at a specified well depth

ρ_{fluid} = the density of fluid.

Effective Porosity:

$$\varphi = (1 - V_{sh})\varphi_a \qquad (2)$$

Where: Volume of Shale V_{sh} is derived from

$$V_{sh} = 0.083\left(2^{3.7IGR}\right) - 1 \qquad (3)$$

And Gamma Ray Index (IGR) is gotten from the combined density and Gamma ray log with the equation

$$IGR = \frac{GR - GR_{sa}}{GR_{sh} - GR_{sa}} \qquad (4)$$

where

IGR = the Gamma-ray index

GR = the Gamma-ray deflection reading at the specified well depth

GR_{sa} = the Gamma-ray deflection reading for clean sand

GR_{sh} = the Gamma-ray deflection reading for shale.

Permeability:

The permeability of the reservoirs was determined using the porosity-permeability model proposed by Amaefule et al (1993). This model is based on a modified Kozeny-Carmen equation and the concept of mean hydraulic radius as:

$$K = 1014(FZI)^2\left[\frac{\varphi^3}{(1-\varphi)^2}\right] \qquad (5)$$

To apply Amaefule et al (1993) model to any region, the Niger Delta in this case, the flow zone indicator (FZI) is evaluated with nonlinear optimization algorithm using data set from the Niger Delta.

Screening and Ranking of Depleted oil and gas Reservoirs for CO_2 Sequestration.

Not all depleted reservoirs are suitable for CO_2 sequestration for various technical and economic reasons. Preliminarily, the depleted reservoir is first screened for suitability based on some criteria gleaned from the adequate knowledge of the reservoir characteristics and the CO_2/crude-oil phase behaviour. Suitable reservoirs are then ranked in accordance with performance.

There are many complicated and intricate numerical models to assess the suitability of a depleted reservoir for CO_2 sequestration. Even analytical models require a momentous amount of data preparation and input, and considerable amount of computer resources for running each suitability check.

Screening:

The study adopted a series of criteria recommended for the application of CO_2 sequestration from Shaw and Bachu (2002). (see Table 1)

The table of criteria indicated that depths that vary between 2,000 and 9,800 ft were considered as suitable for CO_2 sequestration and EOR. However, depending on the geothermal and hydrodynamic regimes in a basin, the conditions for supercritical CO_2 are reached at various depths, from very shallow to very deep depths. Therefore, instead of applying a blanket depth threshold as recommended by Shaw and Bachu (2002), the geological space can be transformed into the CO_2 P-T space for screening depleted reservoirs suitable for CO_2 sequestration because CO_2 is subcritical at the respective reservoir conditions.

TABLE 1. Screening Criteria for CO_2 Sequestration.

Reservoir Parameter	Geffen[16] (1973)	Lewin et al.[17] (1976)	NPC[18] (1976)	McRee[19] (1977)	Iyoho[20] (1978)	OTA[21] (1978)	Carcoana[22] (1982)	Taber & Martin[23] (1983)	Taber et al.[24] (1997a)
Depth (ft.)		> 3,000	> 2,300	> 2,000	> 2,500	i) > 7,200 ii) > 5,500 iii) > 2,500	< 9,800	> 2,000	i) > 4,000 ii) > 3,300 iii) > 2,800 iv) > 2,500
Temperature (°F)		NC	< 250				< 195	NC	
Original pressure (psia)	> 1,100	> 1,500					> 1200		
Permeability (mD)		NC		> 5	> 10		> 1	NC	
Oil gravity (°API)	> 30	> 30	> 27	> 35	30-45	i) < 27 ii) 27 – 30 iii) > 30	> 40	> 26	i) 22 – 27.9 ii) 28 – 31.9 iii) 32 – 39.9 iv) > 40
Viscosity (cP)	< 3	< 12	< 10	< 5	< 10	< 12	< 2	< 15	< 10
Fraction of oil remaining	> 0.25	> 0.25		> 0.25	> 0.25		> 0.30	> 0.30	> 0.20

A maximum temperature of 250°F was recommended by the National Petroleum Council (NPC), although a temperature limit as low as 199°F has also been used to ensure miscibility (Edwards, 2000). Reservoir pressure at the start of CO_2 sequestration is recommended to be greater than 1,100 psia and even greater than 1,500 psia, which exceeds the CO_2 critical pressure of 1071 psia.

An additional screening criterion is that the reservoir pressure at the start of a CO_2 flood should be at least 200 psia above the minimum miscibility pressure (MMP) to achieve miscibility between CO_2 and reservoir oil. The MMP depends on the oil composition, gravity, and reservoir temperature. The minimum reservoir pressure requirement means that the ratio between reservoir pressure and minimum miscible pressure (P/MMP) should normally be greater than 1. In reality, CO_2-flood EOR is still possible for P/MMP = 0.95. Thus, P/MMP > 0.95 is another screening criterion for reservoirs suitability for CO_2 flooding (Shaw and Bachu, 2002).

A very important screening criterion is oil gravity, generally recommended to be greater than 27°API but less than 48°API, because extremely light oil such as condensate is not conducive to the development of multicontact miscibility for miscible (MCM) flooding. Oil viscosity is not a necessary screening parameter, since it is dependent on the oil gravity and reservoir temperature.

To ensure an economic outcome for CO_2 EOR, the fraction of remaining oil before CO_2 flooding should be a limiting factor greater than 0.25. Finally, reservoir permeability is recommended to be greater than 5mD, its not a critical screening criterion because most oil reservoirs that have sufficient production should also have adequate CO_2 injectivity.

Ranking:

The raking algorithm employed by this study was adopted from the procedure developed by Rivas et al (1994). It is based on determining for each property (j) of the reservoir (i), $P_{i,j}$, a corresponding normalized parameter $X_{i,j}$, defined by the following equation:

$$X_{i,j} = \frac{\left|P_{i,j} - P_{o,j}\right|}{\left|P_{w,j} - P_{o,j}\right|} \tag{6}$$

where $P_{i,j}$ is the magnitude of property (j) in the reservoir (i) being ranked. $P_{o,j}$ is the magnitude of property (j) in a fictitious reservoir, called the optimum reservoir, in which the magnitudes of the characteristic parameters have been defined such as to give the best response to CO_2 sequestration among the reservoirs to be ranked. On the other hand $P_{W,j}$, is the value of the property in another fictitious reservoir, called the worst reservoir, which is defined such as to give the worst response to the CO_2 sequestration among the reservoirs to be ranked.

The variable $X_{i,j}$, changes linearly between 0 and 1. In the extremes, it will be zero if the magnitude of a property in a given reservoir exactly coincides with the value of that property in the optimum reservoir, while it will be one if it coincides with the worst reservoir. The normalized linear parameters, $X_{i,j}$ are transformed to exponential varying parameters, $A_{i,j}$, using the following heuristic equation:

$$A_{i,j} = 100\exp\left(-4.6X_{i,j}^{\ 2}\right) \quad (7)$$

The actual grading of reservoirs (i) is done using the elements of matrix $A_{i,j}$, instead of $X_{i,j}$, since it is considered that an exponential function is more adequate than a linear function, for comparing different elements within a set.

The relative importance of each reservoir parameter is taken into account using assigned weighting factors w_j for each property (j), such that a final score S_i is obtained for each reservoir (i), according to

$$S_i = \sum_j A_{i,j} w_j \quad (8)$$

The weighting factors as well as the optimum and worse values of each property are summarized by Rivas et al. (1994) as shown in Table 2.

TABLE 2. Parameters for Ranking CO_2 Sequestration.

Parameters	Optimum	Worse	Weight
API Gravity	37	20	0.24
Temperature [oF]	160	130	0.14
Permeability [mD]	3000	18	0.07
Oil Saturation [%]	60	30	0.2
Pressure/MMP	1.3	0.089	0.19
Porosity [%]	20	9	0.02
Sand Thickness [ft]	50	5	0.11
Dip [degree]	20	5	0.03

Quantification of Sequestered CO_2

On the basis of reservoir-by-reservoir analysis, the volume of sequestered CO_2 is evaluated from database of reserves and production. The initial reserve is given by:

$$N = \frac{7758Ah\varphi\left(1-S_{wc}\right)}{B_{oi}} NTG \quad (9)$$

Where: N = Stock tank oil initially in place, ϕ = porosity, S_{wc} = connate water saturation, NTG = Net to gross ratio, h = thickness of the reservoir, A = area of the reservoir and B_{oi} = Initial oil formation volume factor

It follows that the volume of the hydrocarbon that was produced from the reservoir is then determined by

$$N_p = 7758Ah\varphi\left(\frac{1-S_{wc}}{B_{oi}} - \frac{1-S_w}{B_o}\right) NTG \quad (10)$$

Where: S_{wc} = Water saturation and B_o = Oil formation volume factor.

The hydrocarbon production from the reservoir represents the pore volume that would be occupied by sequestered CO_2. And in hydrocarbon reservoirs with little water encroachment, the injected CO_2 will generally occupy this pore volume previously occupied by the produced hydrocarbon. However, not all the pore volume previously occupied by the produced hydrocarbon will be available for CO_2 because some residual water may be trapped in the pore space due to capillarity, viscous fingering and gravity effects. In active water drive reservoir, in addition to the capacity reduction caused by capillarity and other local effects, a significant fraction of the pore space will be invaded by water, reducing the pore volume available for CO_2 sequestration.

If the storage efficiency is defined by ε then the volume of CO_2 stored in a depleted reservoir is given by

$$V_{CO_2} = 7758Ah\varphi\left(\frac{1-S_{wc}}{B_{oi}} - \frac{1-S_w}{B_o}\right) NTG \times \varepsilon \quad (11)$$

And the mass of CO_2 stored is

$$m_{CO_2} = V_{CO_2}\rho_{CO_2} \quad (12)$$

Storage efficiency, ε, is a critical parameter obtained from volumetric and reservoir performance parameters that reflect what portion of the reservoir will actually be occupied by CO_2. CO_2 storage efficiency takes into account three factors: gross thickness to net thickness, total porosity to effective porosity, and total area to net area in the reservoir that has a suitable formation for injection. Ojo and Tse (2016) suggested CO_2 storage efficiency has a range of values between 1 to 4%. However, to incorporate a substantial decrease in uncertainty through consideration of net thickness, porosity, and area calculated from specific wells and regional patterns in the reservoir quality rock, values of efficiency factors between 10% and 15% are recommended.

III. RESULTS DISCUSSION

The UTI field was identified and mapped into three reservoir sands: UTI-1, UTI-2 and UTI-3 whose wells were correlated across the entire field. This was done using seismic continuity and seismic to well correlation. The reservoirs were located at depths of between 10889ft and 11611ft across the wells with thicknesses varying from 45.93ft to 98.95ft and the corresponding cap rock thicknesses fall between 88.32 ft and 223.33ft. The derived petrophysical properties of the reservoirs are also shown in Table 3.

TABLE 3. Geologic Characteristics of Reservoirs in UTI Fields.

	Reservoirs		
Average Properties	**UTI-1**	**UTI-2**	**UTI-3**
Thickness [ft]	45.93	203.41	98.95
Cap Rock thickness [ft]	135.01	88.32	223.33
Area [acre]	601	1645	488
Net-to Gross	0.48	0.64	0.67
Water Saturation	0.58	0.42	0.38
Connate Water Saturation	0.24	0.21	0.19
Porosity	0.17	0.23	0.21
Permeability [mD]	782.27	1437.75	1381.92

The computed porosity values of the reservoirs range from 0.17 to 0.23 while net to gross ratio ranged from 0.48 to 0.67 signifying reservoir sands of excellent quality. The water saturation ranged from 0.42 to 0.58 indicating that if all oil is depleted from the reservoir, the saturation of CO_2 to be sequestered will not exceed 58%. The entire reservoir is observed to have exceedingly good flow capability with permeability values ranging from 782.27mD to 1437.75mD.

The petropysical properties were used to estimate the volume of hydrocarbon in place and hydrocarbon produced as given in Table 4.

TABLE 4. Computed Oil in Place and Oil Produced.

	Reservoirs		
Properties	**UTI-1**	**UTI-2**	**UTI-3**
Initial Oil FVF [rb/Stb]	1.2416	1.3145	1.1984
Oil FVF after Depletion [rb/Stb]	1.0579	1.1208	1.0103
Initial Oil in Place [MMStb]	10.70	229.65	35.63
Oil Produced [MMStb]	3.76	31.91	3.28
Oil Recovery Factor	35.14	13.90	9.21

Results in the Table indicate that the stock tank oil in place for reservoirs UTI-1, UTI-2 and UTI-3 are 10.70 MMStb, 229.65 MMStb and 35.63 MMStb while the oil produced are 3.76 MMStb, 31.91 MMStb and 3.28 MMStb respectively. The importance of this is that UTI-2 has the highest storage capacity (229.65 MMStb) and the voids available for CO_2 sequestration (31.91MMStb). This follows from the fact that sequestered CO_2 is meant to replace the depleted voids in the reservoir. However, if the voids to be sequestered by CO_2 are normalized with the initial oil in place, it is seen that UTI-1 with the recovery factor of 35.14% has the highest CO_2 storage capacity.

The theoretical storage capacity represents the mass of CO_2 that can be stored in the hydrocarbon reservoirs. Following this method, the storage capacity was estimated on the assumption that not all the depleted pore spaces of the reservoirs are occupied by CO_2. The resultant values for the total storage capacity as a function of storage efficiency factors are shown in Table 5.

TABLE 5. CO_2 Storage Capacity for Different Storage Efficiency.

	Reservoirs CO_2 Capacity [MM tons]		
Efficiency [%]	**UTI-1**	**UTI-2**	**UTI-3**
1	0.26	2.24	0.24
10	2.58	22.4	2.35
20	5.16	44.8	4.71
30	7.74	67.2	7.06
40	10.33	89.6	9.41
50	12.91	112.01	11.76
60	15.49	134.41	14.12
70	18.07	156.81	16.47
80	20.65	179.21	18.82
90	23.23	201.61	21.17
100	25.82	224.01	23.53

It can be seen from Table 5 that CO_2 storage capacity increases with storage efficiency attaining maximum at 100%. That is, at 100% storage efficiency, all the freed pore spaces of the reservoir are occupied by CO_2. However, for every given storage efficiency, reservoir UTI-2 showed the highest storage capacity as seen in Figure 1 indicates that there is no practical difference in the storage capacity of reservoirs UTI-1 and UTI-3 for all depletion conditions even up to 100% depletion. But, UTI-2 showed a very significant storage capacity of about 9.5 times that of UTI-1 & 3.

Selecting Candidate UTI Reservoirs for CO_2 Sequestration

It is not enough to select a reservoir with the highest storage capacity as a candidate for CO_2 sequestration. This is because other factors influence sequestration of CO_2. The optimum and worst reservoirs, and the parameter weights were determined; they were used to rank the three reservoirs of UTI field. Scores were assigned to each reservoir based on their weighted performance of CO_2 sequestration as shown in Table 6.

TABLE 6. Rank of Reservoirs in UTI Field.

	Reservoirs		
Parameters	**UTI-1**	**UTI-2**	**UTI-3**
API Gravity	33	35	36
Temperature [^oF]	157	147	150
Permeability [mD]	782.27	1437.75	1381.92
Oil Saturation [%]	42	58	62
Pressure/MMP	1.2	0.35	0.466
Porosity [%]	17	23	21
Sand Thickness [ft]	45.93	203.41	98.95
Dip [degree]	16	8	12
Score	68.93	52.67	58.35
Rank	**1**	**3**	**2**

It can be seen from Table 6 that reservoir UTI-1 ranked first with the highest score of 68.93% despite being ranked second on the basis of storage capacity. The implication of this is that although reservoir UTI-2 has the highest storage capacity of about 9.5 times reservoir UTI-1 & 2, it is not the most viable candidate for CO_2 sequestration given other conditions such as minimum miscibility pressure of CO_2, reservoir temperature and permeability.

IV. CONCLUSION

Analysis of the properties of the UTI field Niger Delta of Nigeria, West Africa to ascertain its potential for CO_2 sequestration presents the following conclusions:

1. The reservoir characterization showed that the computed porosity values of the reservoirs range from 0.17 to 0.23 while entire reservoir is observed to have exceedingly good flow capability with permeability values ranging from 782.27mD to 1437.75mD, making it a desirable field for CO_2 sequestration.
2. Although reservoir UTI-2 has the highest storage capacity of about 9.5 times reservoir UTI-1 & UTI-3, it is not the most viable candidate for CO_2 sequestration given other conditions such as minimum miscibility pressure of CO_2, reservoir temperature and permeability.
3. Storage efficiency should never be neglected since not all the void created by hydrocarbon production is available for CO_2 sequestration.

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