Overview Of Lullemmeden Basin For Co_2 Sequestration Potential In North-Western Nigeria

I. Yusuf, N.G Obaje, B.Jibrin, M.T Tsepav, H.M Liman

Abstract: Sedimentary basins are suitable to a different degree for CO_2 geological sequestration as a result of various intrinsic and extrinsic characteristics. This paper screened and ranked the Iullemmeden Basin of Nigeria sector based on Bachu (2003) ranking and screening criteria; evaluating factors such as tectonic setting, basin size and depth, geology, hydrogeology, hydrocarbon potentials, climate, geothermal, existing resources and industry maturity in respect to these criterion. The results shows to rank the Basin to have R^k score value of 0.41 against the $f_{i,\,n}$ = max (f_i) value equal to 1 as highest value of the function characterize the best in terms of suitability for the criterion in which this ranking are based upon. The paper also reveals as findings of some intrinsic characteristics such as; poor intercalated geologic formation, shallow aquifer systems within sedimentary pile in the basin which make the basin not suitable CO2 sequestration and when other parameters in future are favoured; it would possess the risk of CO_2 leakages and groundwater contaminations in the geological storage media. Regional screening and ranking of the adjoining basins are recommended, while detailed local site characterisation of the basin is needed to assess its overall suitability for CO_2 sequestration potentials in Nigeria.

Keywords: Iullemmeden, CO_2 sequestration, Criterion, Ranking and Screening

1.1 INTRODUCTION

The search for earthly minerals for source of energy or energy development; Biomass, Solid minerals, Fossil fuel, Hydrocarbon and the solution to natural and man-made phenomenal affecting the earth; Earth quake, Greenhouse gases by the Geologist, Geophysicist and other Scientist is now a global issue to save the planet. Geoscientist have been looking for way forward for an alternative sources of energy (Renewable Energy) that is safer for about less to non emission of carbon dioxides (CO_2), Methane (CH_4), and other related greenhouse gases into the atmospheres other than nuclear energy that will greatly reduces the measure of continuous raising in temperature of the earth we lived; The Global Warming! As a result of anthropogenic carbon dioxide (CO_2) emissions, atmospheric concentrations of CO_2, a major greenhouse gas, have risen from pre-industrial levels of 280 to 360 ppm, primarily as a consequence of fossil fuel combustion for energy production (Bryant 1997). Increasing concentrations of CO_2 affect the Earth–atmosphere energy balance, enhancing the natural greenhouse effect and thereby exerting a warming influence at the Earth's surface.

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Because of uncertainties regarding the Earth's climate system, there is much public debate over the extent to which increased concentrations of greenhouse gases have caused or will cause climate change, and over potential actions to limit and/or respond to climate change. Planetary cooling forces that are intensified by warmer temperatures and by strengthening of biological processes, which would be enhanced by the same rise in atmospheric CO_2 concentrations, may cancel the predicted climate warming (Idso 2001). Carbon dioxide can be sequestered in geological media by geological (stratigraphic and structural) trapping in depleted oil and gas reservoirs, solubility trapping in reservoir oil and formation water, adsorption trapping in uneconomic coal beds, cavern trapping in salt structures, and by mineral immobilization (Figure 1) (Blunt et al. 1993; Gunter et al., 1993, 1997; Hendriks and Blok 1993; Dusseault et al.; 2002). Use of CO_2 in enhanced oil and gas recovery (EOR and EGR; Holtz et al., 2001; Koide and Yamazaki 2001) and in enhanced coalbed methane recovery (ECBMR; Gunter et al., 1997; Gale and Freund 2001), and hydrodynamic trapping in deep aquifers (Bachu et al., 1994) represent actually forms of CO_2 geological storage with retention times of a few months to potentially millions of years, depending on flow path and processes. In all cases of enhanced recovery of hydrocarbons, CO_2 ultimately breaks through at the producing well and has to be separated and recirculated back into the system, thus reducing the storage and sequestration capacity and efficiency of the operation, notwithstanding the additional CO_2 produced during the separation and compression stages. However, the economic benefits of incremental oil and gas production make EOR, EGR, and ECBMR operations most likely to be implemented first. Only sedimentary basins contain geological media generally suitable for CO_2 storage and/or sequestration: oil and gas reservoirs (geological and solubility trapping), deep sandstone and carbonate aquifers (solubility, hydrodynamic and mineral trapping), coal beds (adsorption storage and trapping), and salt beds and domes (cavern trapping). In addition, these media have both the space (porosity) and injectivity (permeability) necessary for CO_2 injection, and, by and large, have the ability to either prevent or delay for geologically significant periods of time the CO_2 return to the atmosphere. Crystalline and metamorphic rocks, such as granite, on continental shields, are not suitable for CO_2 storage and sequestration because they lack the porosity and permeability needed for CO_2 injection, and because of their fractured nature. Volcanic areas and orogenic belts (mountains) are also unsuitable mainly because they lack capacity and are unsafe. Fortunately and serependitously, sedimentary basins are also where fossil energy resources are found, produced and, by and large, used for power generation (Hitchon et al., 1999). The Nigeria sedimentary basin is divided into seven (7) namely; Chad Basin, Sokoto Basin, Bida or Mid Niger Basin, Anambra Basin, Dahomey Basin, Niger Delta Basin and Benue Trough (Upper, Middle and Lower) all are mainly distributed majorly on the inland, while Dahomey and Niger Delta basin are both offshore (Figure 2). Chad basin has the largest basin size and deepest sedimentary piles in Nigeria when looking at the inland basins and Niger Delta basin for offshore respectively.

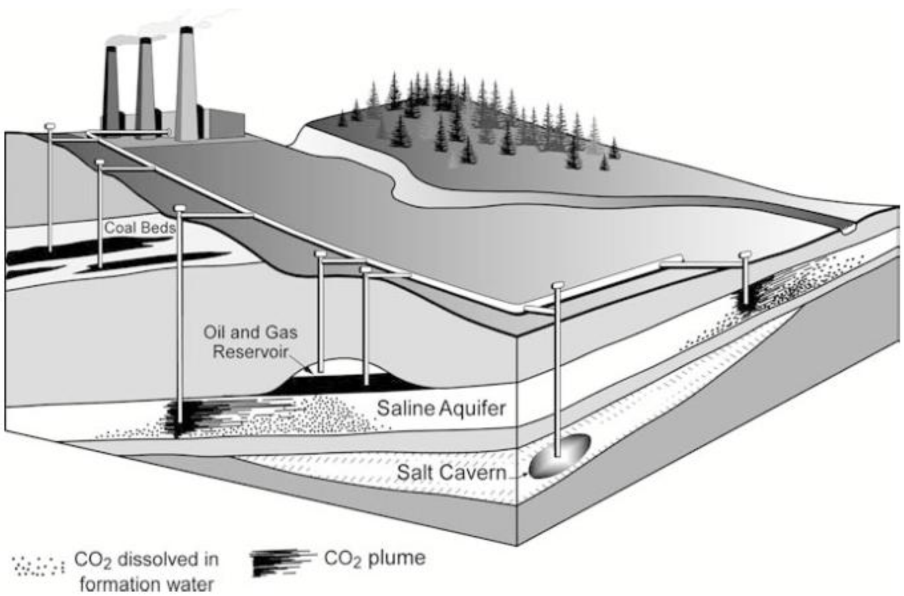

Figure 1: Showing various means of CO_2 sequestration or storage in geological media (after Bachu, 2003)

1.2 LOCATION AND GEOLOGICAL SETTING

The Iullemmeden Basin in north-western Nigeria is known locally as the "Sokoto Basin". It consists predominantly of a gently undulating plain with an average elevation varying from 250 to 400 m above sea-level. The sediments of the Iullemmeden basin were accumulated during four main phases of deposition. Overlying the Pre-Cambrian Basement unconformably, the Illo and Gundumi Formations, made up of grits and clays, constitute the Pre-Maastrichtian "Continental Intercalaire" of West Africa. They are overlain unconformably by the Maastrichtian Rima Group, consisting of mudstones and friable sandstones (Taloka and Wurno Formations), separated by the fossiliferous, shelly Dukamaje Formation. The Dange and Gamba Formations (mainly shales) separated by the calcareous Kalambaina Formation constitute the Paleocene Sokoto Group. The overlying continental Gwandu Formation forms the Post-Paleocene Continental Terminal. These sediments dip gently and thicken gradually towards the northwest, with a maximum thickness of over 1,200 m near the frontier with Niger Republic. The geological map of the Sokoto Basin of northwestern Nigeria is shown on Figure 2 while Figure 3 summarizes the geological sequence in the basin.

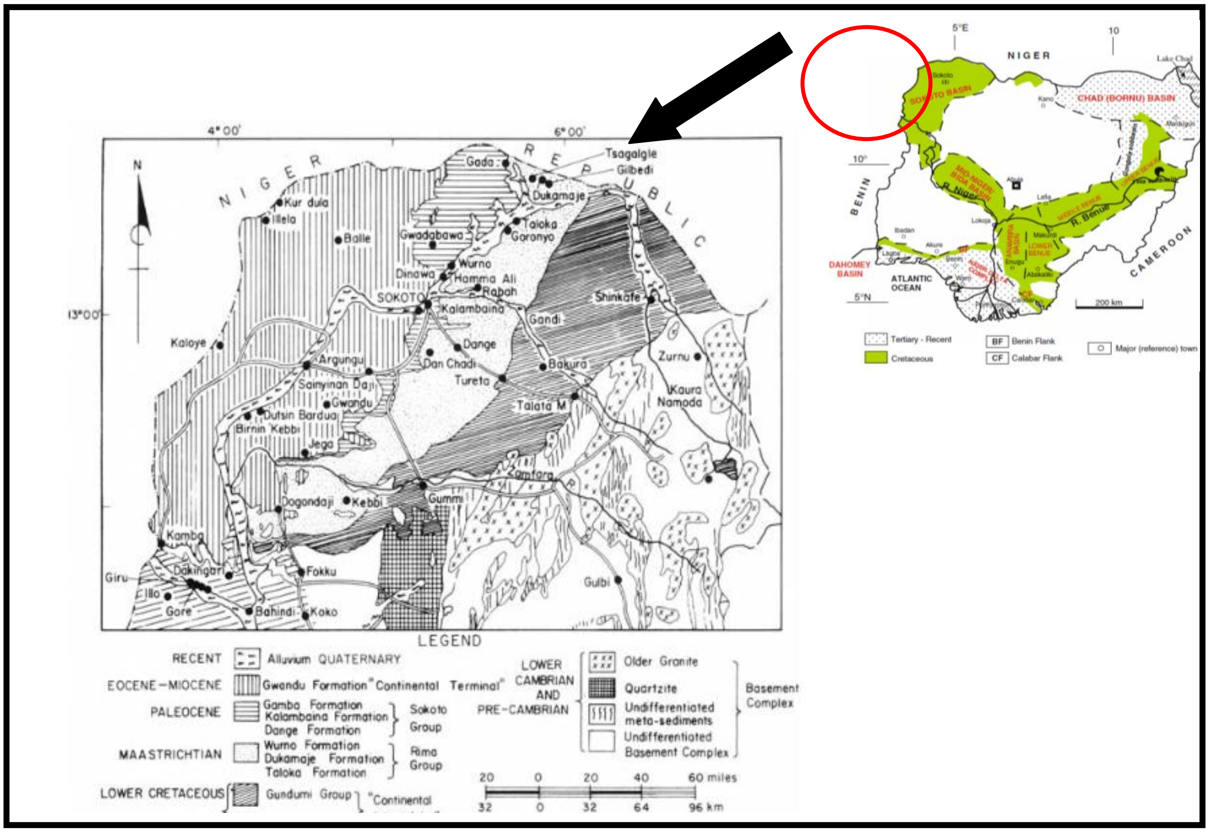

Figure 2: Geological sketch map of the southeastern sector of the Iullemmeden Basin (Sokoto Basin) (After Kogbe, 1981b)

In the Sokoto Basin, the pre-Maastrichtian sediments are of fluviatile and lacustrine origin. They belong to the Illo and Gundumi Formations which extend northwards into Niger Republic. These deposits belong to the upper part of the "Continental Intercalaire" which comprises a group of poorly fossiliferous sediments covering a very extensive area, bounded on the west by the crystalline basement rocks of Niger Republic, and on the east by the Quaternary sands of the Chad Basin. The Gundumi Formation lies unconformably on the basement and consists of basal conglomerates, and gravels with sand and variegated clays increasing upwards; the maximum thickness is about 350 m. The Illo Formation includes interbedded clays and grits, with an intermediate pisolitic and nodular clay member, and attains over 240 m in thickness. The continental period represented by the Gundumi and Illo Formations was terminated by a Maastrichtian marine transgression. The sea penetrated the interior of the continent both from the north (the Tethys), and from the south (Gulf of Guinea), through the mid-Niger Basin. The type section and type locality of the Gundumi Formation are at Dutsin Dambo. The Iullemmeden Basin, as well as many other parts of North and South Africa, experienced extensive periods of continental sedimentation with the accumulation of fluvio-lacustrine nature in pre-Cenomanian times. The northern limits of the continental deposition coincide with the Algeria-Moroccan Sahara and extend eastward into Egypt and the Sudan. The southern limits extend as far as South Africa. The second phase in the depositional history of the sediments of the Sokoto Basin began during the Maastrichtian, when the Rima Group was deposited unconformably on pre-Maastrichtian continental beds. The type sections of the three Maastrichtian formations are at Taloka, Dukamaje and Wurno. The unconformity is well exposed at Wurno. The lower sandstones and mudstones of the Rima Group belong to the Taloka Formation; with a maximum thickness of about 100 m. Gidan Mata. The Dukamaje Formation consists predominantly of shales with some limestones and mudstones. The type section of the formation is exposed on the hill south-west of the village of Dukamaje, while Wurno Formation is very similar to the Taloka Formation; sediments consist of pale friable, fine grained sandstones, siltstones and intercalated mudstones.

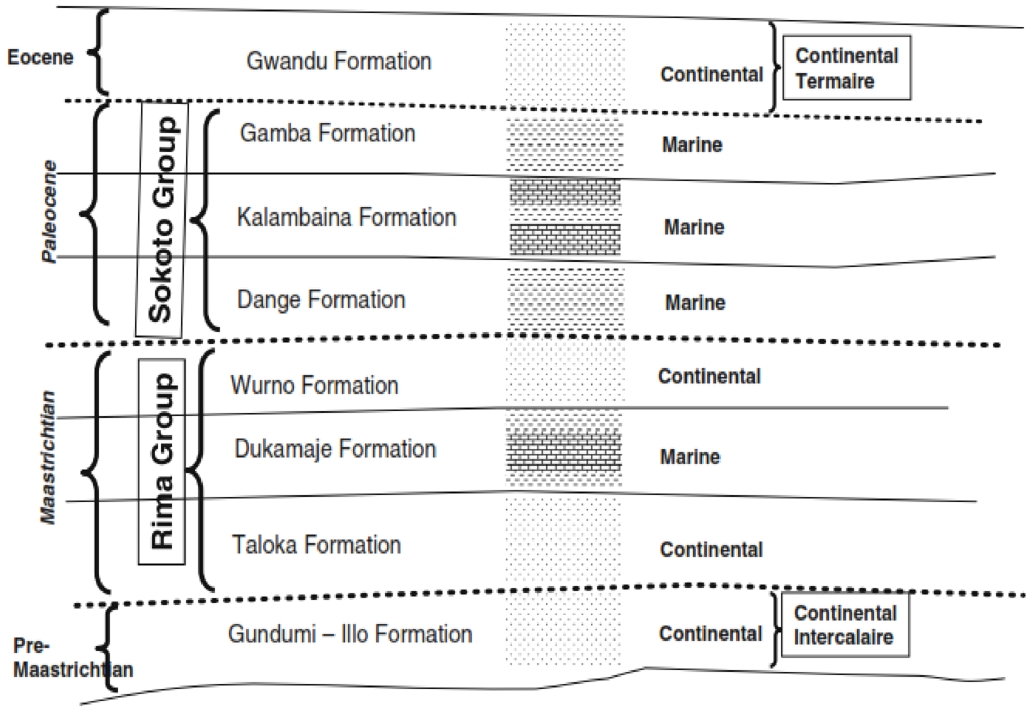

Figure 2: Stratigraphic successions in the Nigerian sector of the Iullummeden Basin (Sokoto Basin) (after Obaje, 2009)

The third phase in the depositional history of the sediments of the Sokoto Basin took place during the Paleocene when the Sokoto Group, comprising the Dange, Kalambaina and Gamba Formations, was deposited unconformably on the Rima Group. The Dange Formation forms the base of the Sokoto Group of sediments of Late Paleocene age. The Dange Formation consists of slightly indurated bluish-grey shale, interbedded with thin layers of yellowish-brown limestone. In surface outcrops, the maximum thickness of the formation is about 22 m near Sokoto, but in subsurface wells, it attains a thickness of over 45 m. The shales include bands of fibrous gypsum with numerous irregular phosphatic nodules. There is a conformable contact with the overlying Kalambaina Formation. Geological Survey borehole No. 3512, drilled at Dange village, reveals the thickness of the formation to be over 23 m. South of Birnin Kebbi, the Dange Formation is about 15 m thick in Geological Survey borehole No. 2483. The Kalambaina Formation consists of marine white, clayey limestones and shales. The thickness of the formation is quite variable, because of the subsurface dissolution of the limestone. The maximum thickness in the boreholes is over 20 m, but usually only about 12 m of section is exposed in the quarry near the village of Dange. The Kalambaina Formation is reduced to about 5 m, but at Birnin Kebbi, further south, the formation is approximately 18 m thick. The formation is rich in invertebrate fossils, mainly echinoids, corals, nautiloids, lamellibranchs and gastropods. Foraminifera and ostracods have also been described from the formation by Reyment (1965), Kogbe (1976) and Petters (1978). The Gamba Formation consists of grey laminated shale overlying the calcareous Kalambaina Formation. The shales appear to be “folded” due to the removal by solution of the underlying limestone and the slumping of the overlying beds. Except when overlain by the Gwandu Formation, the formation is covered by a mantle of loose sand and laterite. The laterite, usually 1.5–3 m thick, often passes down into oolitic ironstone 3–5 m thick. The fourth phase in the depositional history of the sediments of the Sokoto Basin took place during the Eocene when the Gwandu Formation of the Continental Termial was deposited. Throughout the sedimentary basin of north-western Nigeria, the Tertiary marine sediments of the Sokoto Group are overlain disconformably by a thick series of deposits consisting predominantly of red and mottled massive clays, with sandstone intercalations. These sediments belong to the Gwandu Formation, with the type section and the type area in the Gwandu Emirate of northern Nigeria (Kogbe, 1972). Outcrops of the formation cover almost 22,000 km2 in north-western Nigeria.

1.3 METHODOLOGY FOR BASIN-SCALE SCREENING AND RANKING OF CO_2 GEOLOGICAL STORAGE POTENTIAL

A preliminary overview of the geological successions, integrity would be use to establish the potential of the basin for CO_2 geological storage potential in Nigeria before detailed site characterisation would be carried out. Sedimentary basins can be screened and ranked as to their overall suitability for CO_2 storage, based on geological, geographical and industrial characteristics. This study has adapted screening and ranking criteria developed by Bachu (2003), which includes factors such as tectonic setting, basin size and depth, geology, hydrogeology, geothermal regimes, hydrocarbon potential, maturity, on/off shore, climate and accessibility among others. Table 2 documents the criteria that were used to assess the basin-scale suitability of Nigerian sector Iullemmeden basin studied for geological storage of CO_2

	Criterion	Classes				
		1	2	3	4	5
1	Tectonic setting	Convergent oceanic	Convergent intramontane	Divergent continental shelf	Divergent foredeep	Divergent cratonic
2	Size	Small	Medium	Large	Giant	
3	Depth	Shallow (<1,500 m)	Intermediate (1,500–3,500 m)	Deep (>3,500 m)		
4	Geology	Extensively faulted and fractured	Moderately faulted and fractured	Limited faulting and fracturing, extensive shales		
5	Hydrogeology	Shallow, short flow systems, or compaction flow	Intermediate flow systems	Regional, long-range flow systems; topography or erosional flow		
6	Geothermal	Warm basin	Moderate	Cold basin		
7	Hydrocarbon potential	None	Small	Medium	Large	Giant
8	Maturity	Unexplored	Exploration	Developing	Mature	Over mature
9	Coal and CBM	None	Deep (>800 m)	Shallow (200–800 m)		
10	Salts	None	Domes	Beds		
11	On/Off Shore	Deep offshore	Shallow offshore	Onshore		
12	Climate	Arctic	Sub-Arctic	Desert	Tropical	Temperate
13	Accessibility	Inaccessible	Difficult	Acceptable	Easy	
14	Infrastructure	None	Minor	Moderate	Extensive	
15	CO_2 Sources	None	Few	Moderate	Major	

Table 1: Criteria for Sedimentary basins for CO_2 geological sequestration (after Bachus, 2003)

For each criterion, the classes are arranged from least favorable to most favorable left-to-right across the table. The criteria relate to either the containment security, the volume of storage capacity achievable, or consider the economic or technological feasibility. The present-day tectonic setting of a basin gives an indication as to the likely tectonic stability of the region, which is an important consideration for containment risk (i.e. tectonically-active areas, such as subduction zones, are the least favorable due to their increased susceptibility to natural earthquake risk and attendant fault seal failure). The basin size and depth reflects the possible storage capacity achievable, as the larger and deeper the basin is, the greater the likelihood of having laterally extensive reservoir and seal pairings, possibly in more than one stratigraphic interval. The depth of the sedimentary fill of the basin is also relevant to the phase state of the CO_2 (i.e. depths greater than ~800 m result in dense supercritical CO_2 and hence significantly increased storage capacity) and also impacts on the likely economic feasibility, as the greater the depth to the injection target the larger the associated costs of drilling. The stratigraphy of the area is reviewed to identify possible geological formation that may provide reservoir and seal pairs. The reservoir-seal pair criteria (geology) are a qualitative assumption about the likely abundance, lateral extent, thickness and depth of possible reservoir-seal horizons. While, faulting intensity as component of geology view both containment and capacity issue. The more extensively fractured that an area is, the greater the risk for containment breaches, and the lower the likely storage volume achievable due to the need to inject within individual fault blocks. The geothermal conditions of the basin has an impact on the storage capacity, as within colder basins; more CO_2 can be contained within the same unit volume of rock due to the increased density of the CO_2, while verse-verse in warm basin. The hydrocarbon potential of a region gives an indication of the suitability of the area for CO_2 storage, on the assumption that if the rocks are suitable for containing and storing oil and gas, then it is likely that they are also suitable for storing CO_2. Maturity of the extractive industries in the region reflects the likely database available that is the more developed an area is the greater amounts of data available for CO_2 storage assessment. The climate of the region affects the likely surface temperatures (and hence the geothermal conditions) and likewise, accessibility and infrastructure reflect the variability in condition in terms of getting the captured anthropogenic CO_2 from source to point of sequestration.

1.3.1 Fundamental of Screening and Ranking Sedimentary Basins

According to Bachus, 2003; there are no large-scale operations for the geological sequestration or storage of CO_2, and whatever operations exist, they were driven by other considerations, such as increasing oil production, avoiding a carbon tax, or complying with regulations regarding sulfur emissions. However, if CO_2 geological sequestration or storages are to be implemented on a large scale, then there is need for a systematic, quantitative analysis of sedimentary basins in terms of their suitability to serve as enhanced CO_2 sinks. A method for such a quantitative analysis based on parametric normalization and ranking, is proposed here, which can be further developed or adapted to more specific conditions. For each criterion *i* (*i* = 1,…5) in Table 1 for evaluating a basin suitability, monotonically – increasing numerical function F_i is assigned, which can be continuous or discrete, to describe a value placed on a specific class *j* for that criterion. The lowest and the highest functions of this function characterize the worst and best class in terms of suitability for that criterion, i.e. $F_{i,1}$ = min (F_i), where and $F_{i,n}$ = max (F_i), where (n = 3, 4 or 5). If the classes have a relatively equal importance assigned o them, then a linear function is probably the best for F_i. If the increasing value (or importance) is placed on increasingly favorable classes, then geometric or exponential function are probably better. Table 3 presents the numerical values assigned here to the various classes for the criteria in Table 1. For any sedimentary basin k that is evaluated in terms of its general suitability for CO_2 sequestration or storage, the corresponding class *j* for each criterion *i* s identified as in Table 1, resulting in a corresponding score $F_{i,j}$ as in Table 2, because the function f_i has different ranges of values for each criterion, making comparison and manipulation difficult, the individual scores $F_{i,j}$ are normalized according to

$$P_i^k = \frac{F_{i,j} - F_{i,1}}{F_{i\,n} - F_{i\,1}}$$

Such that P_i = 0 for the least favorable class and P_i = 1 for the most favorable class for all the criteria *i* = 1,…15. As a result of this process, each sedimentary basin k being evaluated is characterized by individual scores P^k_i.

	Criterion	Scores					Weight
		j=1	j=2	j=3	j=4	j=5	
i=1	Tectonic setting	1	3	7	15	15	0.07
i=2	Size	1	3	5	9		0.06
i=3	Depth	1	3	5			0.07
i=4	Geology	1	3	7			0.08
i=5	Hydrogeology	1	3	7			0.08
i=6	Geothermal	1	3	7			0.10
i=7	Hydrocarbon potential	1	3	7	13	21	0.06
i=8	Maturity	1	2	4	8	10	0.08
i=9	Coals and CBM	1	2	5			0.04
i=10	Salts	1	2	3			0.01
i=11	On/offshore	1	4	10			0.10
i=12	Climate	1	2	4	7	11	0.08
i=13	Accessibility	1	3	6	10		0.03
i=14	Infrastructure	1	3	7	10		0.05
i=15	CO_2 Sources	1	3	7	15		0.09

Table 2: Scores and weight assigned to criteria and classes for accessing sedimentary basins in terms of their suitability for CO_2 sequestration in geological media (after Bachus, 2003)

The effect of parameterization and normalization is that it transforms various basin characteristics, which have differing meanings and importance, into dimensionless variables that vary between 0 and 1. These can subsequently be added to produce a general score R^k, used in basin ranking, which is calculated using:

$$R^k = \sum_{1}^{15} w_i P_i^k$$

Where W_i are weighting function that satisfy the condition:

$$\sum_{1}^{15} w_i = 1$$

The weights w_1 assigned in this study to the various suitability criteria are shown in Table 3. The number of criteria (currently 15), the functions F_i (i=1,..15) and weights w_i the can be changed and/or adapted to changing conditions and priorities. Using this methodology, sedimentary basins, or parts thereof, within a given jurisdiction or geographic region can be assessed and ranked in terms of their suitability for the geological sequestration or storage of CO_2. This ranking can be then used in making decisions for the large-scale implementation of such operations.

1.3.2 Screening and Ranking of the Iullemmeden Basin

The Iullemmeden basin was evaluated against criteria for assessing sedimentary basins for CO_2 geological sequestration Table 1 adapted from Bachu (2003). Table 3 summarizes the results of the screening criteria for the basin studied. A brief discussion of some of the key features of each basin is presented below.

	Criterion	Characteristics	Class	$w_i P_i^k$
1	Tectonic Stability	Divergent continental shelf	3	0.03
2	Size	Medium	2	0.02
3	Depth	Shallow	1	0.00
4	Geology	Limited faulting and fracturing	3	0.08
5	Hydrogeology	Shallow short flow system & Compaction flow	1	0.00
6	Geothermal	Cold basin	3	0.10
7	Hydrocarbon Potential	Small	2	0.01
8	Maturity	Unexplored	1	0.00
9	Coal & CBM	None	1	0.00
10	Salts	None	1	0.00
11	Onshore/Offshore	Onshore	3	0.10
12	Climate	Tropical	4	0.05
13	Accessibility	Acceptable	3	0.02
14	Infrastructure	None	1	0.00
15	CO_2 Source	None	1	0.00
	$R^k = \sum_{1}^{15} w_i P_i^k$			**0.41**

Table 3: Results of ranking of the Iullemmeden in terms of suitability for CO_2 geological sequestration

1.4 CRITERION POTENTIAL EVALUATION

Injecting carbon dioxide, generally in supercritical form, directly into underground geological formations like oil and gas fields, saline formations, unmineable coal seams, and saline-filled basalt formations have been suggested as storage sites. Various types of physical trapping; structural: anticline and fault; stratigraphic: unconformity and change in type of rock, or a particular formation thinning out, highly impermeable rock, geochemical trapping mechanisms would prevent the CO_2 from escaping to the surface. Sedimentary basins are considered suitable targets for storing large volumes of CO_2, having characteristics that favour effective storage over hundreds of thousands to millions of years (geological time periods), as demonstrated by the widespread existence of natural CO_2 accumulations as occurred in Colorado Plateau and Rocky Mountain region of the USA (IPCC 2005) as well as hydrocarbons trapped in reservoirs. The following below nine (9) criterions are evaluated in view of Bachus, 2003 criteria for assessing sedimentary basins for CO_2 geological sequestration (Table 1).

1.4.1 Tectonic Stability, Basin Size and Depth

The sediments of the Iullemmeden Basin were accumulated during four main phases of deposition as reviewed earlier in geological setting above. There are no tectonic episodes affecting the basin as weather compressionally folds, faults, or an upliftments as experienced in Benue Trough of Nigeria that resulted into the Abakaliki anticlinorium and the Afikpo syncline in the Lower Benue, the Giza anticline and the Obi syncline in the Middle Benue, and the Lamurde anticline and the Dadiya syncline in the Upper Benue Trough. Sedimentary basin needs to be deep enough to store CO_2 in a supercritical phase (a depth of approximately 800 m is needed for this); the basin contains sedimentary piles of depth greater or less than 500 m of Pre-Maastrichtian to Paleocene sediments deduced covering a total area of 22,000 km^2 from Gwandu formation coverage extent overlying directly the Gamba formation. These sediments dip gently and thicken gradually towards the northwest, with a maximum thickness of over 1,200 m near the frontier with Niger Republic. The basin can be termed “medium” in terms of size and “shallow” when considering the depth as criteria to estimate the storage volume of the basin.

1.4.2 Geology

Many studies reveal that the natural underground geological formations can provide adequate CO_2 storage for a very long period of time, considering the nature of geologic storage potential. The Stratigraphic sequences of the trough, as related to CO_2 sequestration potentials are reviewed as follows:

Geological Formation: Taloka Formation

The second phase in the depositional history of the sediments of the Sokoto Basin began during the Maastrichtian, when the Rima Group was deposited unconformably on pre-Maastrichtian continental beds. The type sections of the three Maastrichtian formations are at Taloka, Dukamaje and Wurno. The lower sandstones and mudstones of the Rima Group belong to the Taloka

Formation; with a maximum thickness of about 100 m. The formation consists essentially of white, fine-grained, friable sandstones and siltstones, with thin intercalated mudstones and carbonaceous mudstones or shales.

Wurno Formation
The Wurno Formation is very similar to the Taloka Formation. The sediments consist of pale friable, fine grained sandstones, siltstones and intercalated mudstones. In boreholes, the sediments of the Wurno Formation are dark-coloured, which is due to the presence of carbonaceous material and finely disseminated iron sulphides. Good outcrops of this formation can be observed at Gada near the frontier with Niger Republic. The loosely-consolidated nature of the sediments makes them susceptible to weathering. Small-scale load-cast, bio-turbation structures and flaser bedding noted in the Taloka Formation are also abundant in the Wurno Formation, which is evidence of identical origin of both formations. The geological formations show that, the both consist essentially of white, fine-grained, friable sandstones and siltstones, with thin intercalated mudstones and carbonaceous mudstones or shales. This intercalation within the formations deters their potentiality of serving as a good geological media when to consider its reservoir quality, geometry and connectivity (injectivity). These formations can both be termed "poor" according to Bachus, 2003 basin-scale suitability criteria.

1.4.3 Hydrogeology
The principal water-bearing beds in the Sokoto sediments are the surface laterites, sandstones and grits in the Gwandu Formation, limestone beds in the Kalambaina Formation, sandstones in the Wurno and Taloka Formations as well as grits and sandstones in the Gundumi Formation/Illo Formations (Jones, 1948). Groundwater occurs under water table conditions throughout the area Table 4. Moreover, the association of inclined impervious beds alternating with water-bearing horizons gives rise to pressure-water conditions in some parts of the Sokoto Basin. Perched bodies of groundwater also exist in the area. In the valley depressions along the watercourses, alluvial aquifers up to 20 m thick can be found consisting of intercalations of gravels, sands silt and clay causing locally confined conditions. The depth to groundwater in the alluvium of Wurno area is about 1-3 m, but reaches several tens of meters under topographic highs. Some of the tube wells provided for irrigation purposes in the study area have been sampled for both physical and chemical parameters. Analyses of pumping tests carried out in the shallow aquifer yielded transmissivities in the range of 200 to 5000 m/d and storage coefficients of 10^{-2} to 10^{-5} indicating semi unconfined to confined conditions. Based on these results, the hydraulic conductivity varies between 10^{-4} to 10^{-3} m/sec. The yield of tube wells up to 20 m depth is generally 0.2 L/s. The fluctuation of the water table in the fadama areas is about 2-3 m throughout the year. The water table is lowest in June and highest in September, during the rainy season (Adelana *et al.,* 2006).

AGE	GROUP	ENVIRONMENT	FORMATION	HYDROLOGICAL SIGNIFICANCE
QUATERNARY		Continental	Sandy drifts, laterites	Aquiferous
EOCENE-MIOCENE	"Continental Terminal"	Continental	Gwandu Formation	Prolific Aquifer
UPPER PALEOCENE	Sokoto Group	Marine	Gamba Formation	Aquiclude
			Kalambaina Formation	Aquifer in outcrop area
			Dange Formation	Aquiclude
MAASTRICHTIAN	Rima Group	Brackish water with brief Dukamaje marine Intercalation	Wurno Formation	Moderate Aquifer
			Dukamaje Formation	Aquiclude
			Taloka Formation	Good Aquifer
TURONIAN	"Continental Intercalaire"	Continental	Gundumi Formation	Moderate Aquifer Locally flowing
			Illo Formation	
PRECAMBRIAN			Basement Complex	Isolated Aquifers But mostly aquiclude

Table 4: Summary of geological sequence in Sokoto Basin, Northwestern Nigeria (after Adelana *et al.,* 2006)

The hydrodynamic studies of the Sokoto basin reveal the aquifer system as can be termed 'shallow and short flow systems' from the literature review and summary of hydrological significance in table 4 above. The geological setting review above also reveals that almost all the formations have their respective type locality where they all outcrop. Looking at the Turonian era; the Gundumi formation serves as a water bearing formation in which water locally flows and Wurno formation at the Maastrichtian era where depth to groundwater in the alluvium of Wurno area is about 1-3 m. These confirm that hydrological systems in the Sokoto basin can be termed and ranked to be generally shallow.

1.4.4 Geothermal Regime

Geothermal regime of sedimentary basin is one of the most important elements to be considered as criteria for suitability assessment of a geological storage; as result of phase behavior and variation of CO_2 properties with temperature, pressure and depth. At normal atmospheric conditions; CO_2 is thermodynamically very stable gas heavier than air and also at temperature greater than Tc = 31.1^{o}C and pressures greater than Pc =7.38 MPa (critical point), CO_2 is in a supercritical state. Bachus, 2003 indicated that basin < 30^{o}C/km is termed as cold basin. The data from Borno Basin included also information form several deep oil wells. The data base shows that temperature gradient in Sokoto Basin ranges from 0.9 to 7.6 °C/100m. The zone of highest gradients in Sokoto basin is elongated in SW-NE direction, parallel to general strike of major sedimentary formations which are very thin in that area (about 200 m). This suggests that a significant source of geothermal heat is located below sedimentary complex, in Precambrian basement and perhaps is related to some deep tectonic active structure. The values of geothermal gradients found to the north of Nigeria, within the other part of Iullemmeden basin in Niger, are even higher than in Sokoto basin (Kurowska, 2010).

1.4.5 Hydrocarbon Potential/Maturity

Rocks that are suitable for containing and producing oil and gas are likely to be suitable for storing CO_2. The potential for storing CO_2 will be dependent on the timing of possible hydrocarbon production. If there is a mature oil/gas industry in the area, there will be a larger amount of available information about the site. Most of the hydrocarbon and coal would have been discovered and there are likely to be depleted oil and gas reservoirs. Such areas are likely to have good infrastructure such as roads, pipelines and wells. In Sokoto Basin, hydrocarbon potential prospectivity is at preliminary assessment stage. Recently in the basin, a geochemical analysis shows that 90% of the samples examined have equal or more than minimum limit of TOC value (0.5wt%) required to initiate hydrocarbon generation from the source rock (Obaje *et al;* 2013). The source rocks are said to be generally sub- mature through marginally mature to mature within the oil window. On this note, the hydrocarbon potential in the basin by time of the compilation of this paper can be considered to be "small", while in terms of maturity it can be considered in the phase of "unexploration" for now pending discovery would be confirm

1.4.6. Coal and CBM

Methane is natural gas or methane (CH4) that occurs in coal beds and has been generated during the conversion of plant material to coal (the process known as coalification).Coal bed methane can be produced from low rank sub bituminous/ bituminous coal. There are no occurrences of coal beds reported in the basin.

1.3.6. Climate

Climate affects the surface temperatures, the depth of the water table and the ease of development of storage facilities. Similarly to Chad Basin, the Basin also embraces a great range of tropical climates.

1.4 FINDINGS

Many studies reveal that the natural underground geological formations can provide adequate carbon dioxide storage for a very long period of time, considering the nature of geologic storage potential in the Iullemmeden basin of Nigeria sector as deduced from this paper, as follows: In line with prospects, a sedimentary basin needs to be deep enough to store CO_2 in a supercritical phase; in this case the basin contains sediments pile of depth greater or less than 500 m of Pre-Maastrichtian to Paleocene sediments deduced covering a total area of 22,000 km^2 from Gwandu formation coverage extent overlying directly the Gamba formation. These sediments dip gently and thicken gradually towards the northwest, with a maximum thickness of over 1,200 m near the frontier with Niger Republic. The basin can be termed "medium" in terms of size and "shallow" when considering the depth as criteria to estimate the storage volume of the basin The geological formations above show that, the formations essentially consist of white, fine-grained, friable sandstones and siltstones, with thin intercalated mudstones and carbonaceous mudstones or shales. This intercalation within the formations deters their potentiality of serving as a good geological media when to consider its reservoir quality, geometry and connectivity (injectivity). However, the hydrodynamic review of the Iullemmeden basin can be termed as 'shallow and short flow systems' from the literature review and summary of hydrological significance in table 5 above. Looking at the Turonian era; the Gundumi formation serves as a water bearing formation in which water locally flows and Wurno formation at the Maastrichtian era where depth to groundwater in the alluvium of Wurno area is about 1-3 m. These confirm that hydrological systems in the Iullemmeden basin can be termed and ranked to be generally shallow. The values of geothermal gradients found to the north of Nigeria, within the other part of Iullemmeden basin in Niger, are even higher than in Sokoto basin (Kurowska, 2010). These would enable the researcher to rank the basin as "cold" basin which would favour the injectivity of CO_2 when other criterion considerably favoured. In Sokoto Basin, hydrocarbon potential prospectivity is at preliminary assessment stage. Recently in the basin, a geochemical analysis shows that 90% of the samples examined have equal or more than minimum limit of TOC value (0.5wt%) required to initiate hydrocarbon generation from the source rock (Obaje et al; 2013). The source rocks are said to be generally sub- mature through marginally mature to mature within the oil window. On this note, the hydrocarbon potential in the basin by time of the compilation of this paper can be considered to be "small", while in terms of maturity it can be considered in the phase of "unexploration" for now pending discovery would be confirm. Coal bed methane can be produced from low rank sub bituminous/ bituminous coal. There are no occurrences of coal beds reported in the basin.

1.5 DISCUSSION

The results in Table 3 shows that R^k score value of 0.41 against the $f_{i,n}$ = max (f_i) value equal to 1 as highest value of the function characterize the best in terms of suitability for the criterion in which this ranking is based upon. These score values characterize Iullemmeden basin to have tropical climatic condition having deposited on a stable divergent continental shelf, with medium basin size. The Nigeria sector of Iullemmeden basin is not faulted neither possibly fractured by any tectonic events as in not documented in any literature, but characteristic "limited" faulting and fracturing is assigned since it carries the most favorable value. The basin geothermal gradient is low and is rated cold, with shallow and short system flow hydrogeological systems. The hydrocarbon potential in the basin is rank for now "small" and its maturity rated under unexplored. There is none evidence of coal and salt deposit in the basin. By this ranking and screening criteria, the basin can be compared with SW Ontario basin in the Canada's sedimentary basin in terms of its suitability for CO_2 geological storage with R^k value of 0.52 as assessed by Bachu, 2003. It is not yet possible to conclude its overall suitability in spite of stated findings as outlined above, but in Nigeria sector of the basin its storage suitability to the background geological formation is deterred as against texture and fabric of the formation; others like sequestration integrity, and fate of injected CO_2 over long periods in the basin can be said not to be visible.

1.6 CONCLUSION

The Iullemmeden basin of the Nigeria sector has been preliminarily screened and ranked to overview its potentials for CO_2 sequestration opportunities in Nigeria. The results shows that Iullemmeden basin has R^k score value of 0.41 against the $F_{i,n}$ = max (F_i) value equal to 1 as highest value of the function characterize the best in terms of suitability for the criterion in which this ranking is based upon. The criterion individual scores P^k_i for hydrogeology and depth is zero, while for geology, size and hydrocarbon can be said to be poor; medium and small respectively. These conditions in favour of CO_2 potentials in the basin can in future be subjected to amendment as when further discoveries are made to score the criterion more favorable or better than present ranking score R^k value of 0.41. In conclusion, by this overview; the basin in Nigeria sector lacks for now every key criterion in favour of its suitability for CO_2 sequestration potential; ranging from poorly sorted geological formation; poor structural and stratigraphic fabric; and shallow aquifer flow system which are the main structure in CO_2 storage rest upon for sustainability.

1.7 RECOMMENDATIONS

A detailed regional and local site characterisation of geological storages are needed to fully screen and rank the basin for its overall suitability for CO_2 storage potentials in the region, since country like Niger share part of the Iullemmeden.

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