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Investigating the Feasibility of CO_2-EOR and Storage in Oilfields along the West African Transform Margin

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***Abstract*—Most Oilfields along the West African transport margin are estimated to span close to 20 years of continuous production before abandonment, with some few fields expected to produce close to 40 years. It is important for the local oil companies and operators to investigate means to attain maximum oil production from these fields when they enter middle and late development stages of production life. Moreover, the recent dip in oil prices has arguably brought many discovery operations to standstill worldwide, with majority of oil operators focusing on how to improve oil recovery from already-existing fields. This study is aimed at assessing the future potential of executing Carbon Dioxide Enhanced Oil Recovery, popularly called CO_2-EOR and CO_2 storage in the region based on the available data of known reservoirs along the West African Transform Margin (WATM). This research entails an overview of the regional makeup of the WATM, reservoir screening for CO_2 enhanced oil recovery, EOR potential of the reservoirs and CO_2 storage potential. This work reveals that CO_2-EOR and CO_2 storage has a bright application potential in selected large fields along the Transform Margin and recommends its consideration by decision makers and industry operatives in the sub region. A decision tree is finally designed to assist in the screening of reservoirs for CO_2-EOR and CO_2 storage along the WATM.**

Keywords— Carbon Capture, Anthropogenic CO_2, Enhanced Oil Recovery, Miscibility Pressure Introduction

I. INTRODUCTION

Climate warming and weather changes is greatly influenced by greenhouse gases playing specific roles in a process termed as the greenhouse effect. The greenhouse effect is the process by which radiation from a planet's atmosphere warms the planet's surface to a temperature above what it would be without it's atmosphere. Higher concentrations of greenhouse gases, such as carbon dioxide (CO_2) and methane (CH_4), has the effect of increasing the greenhouse effect, leading to climate changes that are critical to supporting life. Human activities over the years have contributed greatly to the release of high amounts of these gases to critical levels that have become of concern on the global scale. CO_2 is roughly regarded to contribute between ten (10) to twenty-six (26) percent impact to the greenhouse effect. And in this industrialized world, it's continual release into the atmosphere by fossil burning, cement production, tropical deforestation and petroleum extractive plants appears unavoidable. Studies show that Carbon dioxide capture, transport and geological storage (CCS) is a significant greenhouse gas (GHG) mitigation option that could allow the continued use of fossil fuels while providing the time needed by renewable energy to be deployed at large scale [1].

A. Overview of the WATM

One area in Africa that has won the interest of several investors as "the sure Gulf of Mexico" in the few years to come is the West African Transform Margin (WATM). The decade-old discovery of Jubilee Oilfield in an uncompromising deep-water area off the Western coast of Ghana; the giant Agbami oilfield in the Niger delta discovered in 1998 and been on stream since 2008; the Zafiro Complex, another giant oilfield, offshore Equatorial Guinea; are findings that took the world by surprise. Ever since these giants were discovered, the oil industry entered the shores of the West African sub region (Figure 1) and opened new oil provinces stretching across Sierra Leone, Liberia, Cote d'Ivoire and Ghana. The sub region, over the past decade, has seen increased trends of oil discoveries and subsequent production from its offshore resources. The region constitutes approximately 50 percent (that is 64 billion barrels) of Africa's 132.1 billion barrels of proven oil reserves *[2]*.

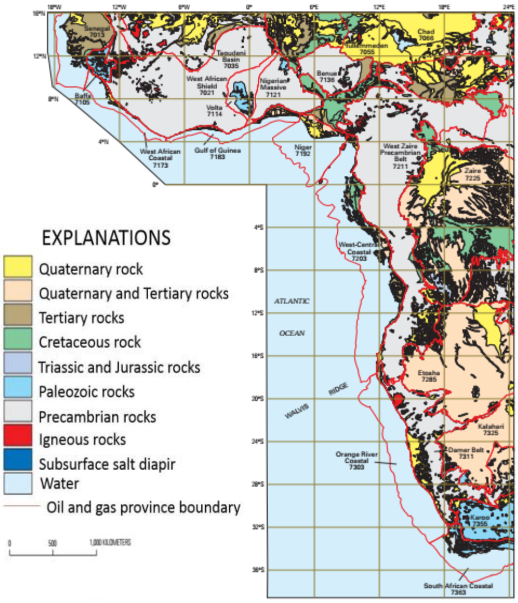

Fig. 1. Geologic map of west Africa. [3]

With this potential upsurge in industrialized oil activity, an overwhelming increase in CO_2 emission in the region is not far-fetched, and could make the region a hub for massive CO_2 emissions in the next few years. Figure 2 shows the regional distribution of annual CO_2 emission per country taken from the United Nations Statistics Division [4]. As previously

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established, massive CO_2 emission is a threat to the earth environment due to its propensity to cause global warming. The intervention method that can be adopted indeed, is CO_2 sequestration. There is therefore the need for a combination of CO_2-EOR and permanent CO_2 storage operations along the region to control the forecasted menace and provide a means for the sub region to contribute solutions to the release of greenhouse gases.

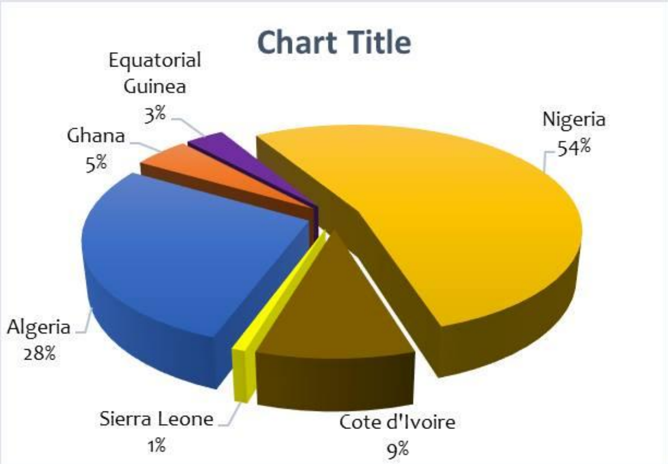

Fig. 2. West Africa's contribution to CO_2 emissions [5]

B. *Overview of CCS*

Sequestrating atmospheric CO_2 released from industrial sources such as petroleum extractive plants involve capturing and transporting CO_2 through pipelines systems to the injection site, compressing CO_2 to achieve the injection pressure, and injecting it into the reservoir [6]. The capture process and method (as shown in Figure 3), the processing, transport and injection methods are well-established technologies that have had excellent safety records in CCS operations. The element of uncertainty has to do with the integrity of CO_2 trapping after injection, which has not yet been fully understood because the subsurface region (SSR) in itself is only partly understood and often processes involving the SSR are described by means of correlated data and information from analogous geological structures. It is imperative therefore to properly assess geological formations before they are sanctioned for long term CO_2 storage. Hydrocarbon bearing reservoirs are appealing as save storage sites since they are best understood to have geologic seals that successfully trap buoyant reservoir fluids for millions of years [6].

The International Energy Agency (IEA) report on Carbon Capture and Storage [7] identifies that highly prospective geological basins for CO_2 storage are mainly found in the United States and Canada, Siberia, the Middle East, and North and West Africa within existing oil and gas regions. The report indicates that in Africa the CO_2 storage capacity in aquifers varies from 6 to 220 Gt and in oil and gas fields from 30 to 280 Gt (Figure 4). North and West Africa were reported to have the highest potential for CO_2 storage in oil and gas fields.

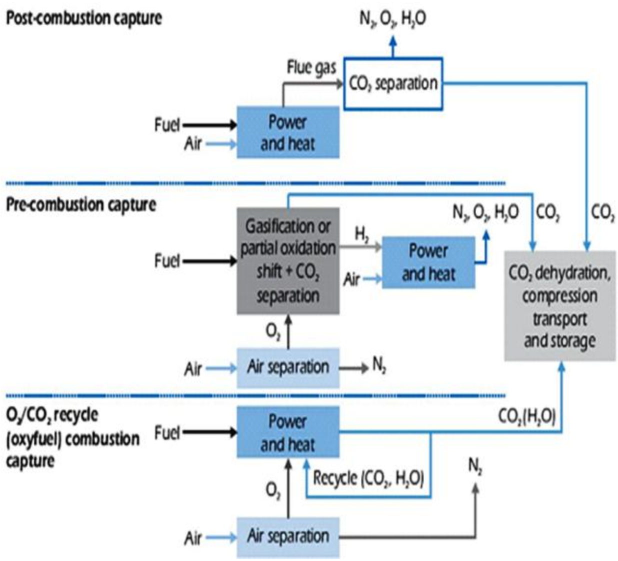

Fig. 3. CO_2 capture process [7]

The trapping of CO_2 can occur in one of three ways elaborated below;

- Physical trapping: These can take two main forms: static trapping where upwards movement of CO_2 is blocked by impermeable layer of shale or clay rock, also called a "cap rock", and residual-gas trapping in a porous structure provided by capillary forces.

- Chemical trapping: This occurs by dissolution or by ionic trapping. Once dissolved, the CO_2 reacts chemically with minerals in the geological formation (mineral trapping) or adsorbs on the mineral surface (adsorption trapping).

- Hydrodynamic trapping: The CO_2 migrates upward at a very low velocity and is being trapped in intermediate layers. Large quantities of CO_2 could be stored using this mechanism, since the migration to the surface would take millions of years.

C. *Overview of CO_2-EOR*

Oil recovery techniques have traditionally been grouped into three categories, based on when they are likely to be implemented in a typical oilfield. Primary, Secondary and Tertiary recovery methods. The successive use of primary recovery and secondary recovery in an oil reservoir produces about 15% to 40% of the original oil in place, depending on the properties of oil and the characteristics of the reservoir rock. Tertiary oil recovery methods aim at altering the flow properties of crude oil and the rock-fluid interactions in the reservoir to improve oil flow; one of these techniques is CO_2-EOR. The term 'tertiary oil recovery' has recently been disfavored in the literature and substituted by the term enhanced oil recovery or EOR [8].

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CO_2-EOR is an enhanced oil recovery method in which carbon dioxide (CO_2) is injected into a reservoir to increase production by reducing oil viscosity and providing miscible or partially miscible displacement of the oil. The applicability of the two main processes developed for CO_2 flooding (miscible and immiscible displacement) will depend on the reservoir conditions. The process, moreover, can also be distinguished based on the type of CO_2 injection method implemented. Here, we discriminate between the Water Alternating Gas (WAG) method and the Gravity Stable Gas Injection (GSGI) method. WAG has an advantage over GSGI in that it can be performed on a small scale; while in general, GSGI is applied in the whole oilfield. Hence GSGI projects are likely to recover more oil and store larger CO_2 volumes [9]. A schematic of the miscible CO_2-EOR operation is shown in Figure 5.

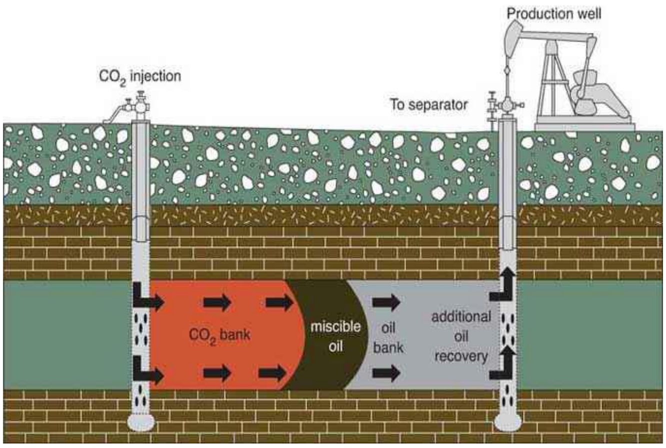


Fig. 5. schematic of the miscible CO_2-EOR operation [10]

EOR by CO_2 is a method that is widely applied in recovery techniques around the world and provides a unique opportunity to gain a considerable financial return for storing anthropogenic CO_2 once oil production declines prior to field abandonment. The relationship between CO_2 storage and CO_2-EOR is important and unique because while the CO_2 serves as an agent for maximizing recovery, the entire EOR operation, in turn, also stores the greenhouse gas away from the Earth's atmosphere by keeping it locked in the geological reservoir formations.

II. METHODOLOGY

Along the WATM there are several oil and gas fields. In this study, the oil fields that were considered are Jubilee field – Ghana; Agbami field – Nigeria; Zafiro Complex – Equatorial Guinea; Baobab – Cote d'Ivoire, the Espoir field - Cote d'Ivoire, Girassol Complex – Angola. The fields were selected to cover the regional margin under study and partly based on available data

A. *Screening of reservoirs suitable for CO_2-EOR*

To merge CCS with oil recovery would first require investigating for field suitability for CO_2-EOR. Theoretically, any type of reservoir formation; carbonate or sandstone, could be suitable for CO_2-EOR but for various technical and economic reasons, not all reservoirs would be good candidate for CO_2-EOR. Several reservoir properties are considered. Broadly speaking, oil viscosity, oil API-gravity, reservoir depth, reservoir oil saturation and reservoir heterogeneity are among the most important [11]. The most critical parameter is the Minimum Miscibility Pressure (MMP) for each reservoir. The MMP is defined as the minimum pressure at which the injected CO_2 will begin to mix with the residual oil in all proportions without the existence of an interface between the fluids. The MMP is a function of oil properties, reservoir temperature, reservoir pressure and the purity of the injected CO_2 [11]. Therefore, it is not an easy parameter to estimate, even with full reservoir data. Due to challenges with obtaining key reservoir data on the fields along the WATM from the operators, we used a two-step approach to estimate the MMP's of the reservoirs. An oilfield was regarded as a successful candidate for CO_2-EOR if the MMP was less than the initial pressure.

B. *Estimating MMP*

A relationship published by Holm and Josendahl (1982) [12] and extended by Mungan (1981) [10], which estimates MMP from molecular weight of the C5+ components of reservoir oil and reservoir temperature (figure 7) was used. First, the molecular weight of carbon factions in the range greater than or equal to five (C5+ components) of the reservoir oil was determined using the correlation between oil API-gravity and C5+ oil molecular weight published by Lasater (1958) [13] in figure 6. The correlated data can be empirically determined by using equation 1.

$$MW = (7864.9/G)^{1/1.0386} \quad (1)$$

Where MW = C5+ molecular weight and G = API oil gravity
The MMP estimation using the extended work of Mungan (1981) [10] was also based on equation 2, derived by using non-linear multiple regression.

$$MMP = -329.558+(7.727*MW*1.005^{T})-(4.377*MW) \quad (2)$$

Where T = Temperature (°F)

These equations were used because they are simple yet accurate, and do not require too much information of the reservoir to estimate the MMP. Fields for which the temperature was not available were estimated using depth correlation with geothermal gradients.

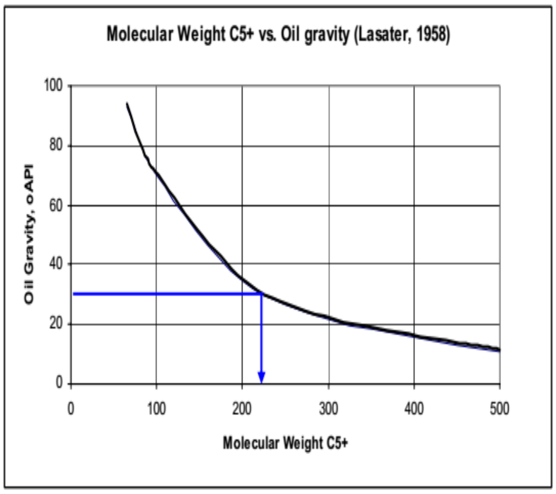


Fig. 6. Correlation between oil gravity and MW of C5+ components [11]

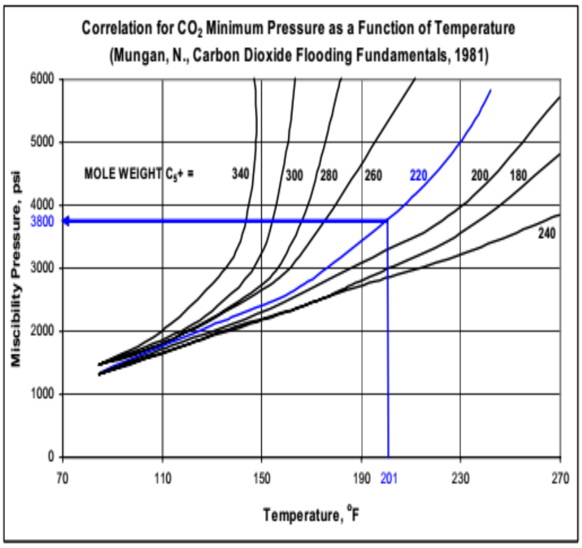


Fig. 7. Nonlinear relationship between temperature, C5+ MW of components and MMP [11]

C. Screening and Assessment of Reservoirs Suitable for CO_2-EOR and CO_2 storage

A critical issue for geological storage of CO_2 is ensuring that the stored CO_2 does not escape from the host reservoir formation. To ensure a robust screening system for the proposed reservoirs along the WATM, we adopted the method published by Shaw and Bachu [14]. It is based on the premise that an oilfield is qualified for CO_2 storage if the geological make-up of the reservoir fulfils some specific required indexes. Further work done by Zeng et. al (2005) [15] also proposed that the main features of assessment of CO_2 storage potential in oil reservoirs included reservoir properties such as depth, permeability, porosity, in-situ temperature, original pressure, trap integrity and inherent fault structures. Suitable formations should have a thick and extensive seal, be sufficiently permeable to permit injection of CO_2 at high flow rates without requiring overly high pressure, have sufficient porosity for large volumes of CO_2 to be stored, and be deeper than 800m. At this depth, CO_2 is most likely in a liquid or supercritical state. Under these conditions, the density of CO_2 is close to density of crude oils, reducing the buoyant forces that tend to drive CO_2 upwards (figure 8)

Per the reservoir conditions of the fields along the WATM thus, the operational screening criterion is made based on the work presented by Zeng et. al. [15]

D. Calculation of Storage Capacity

Based on the evidence that a reservoir is qualified for CO_2-EOR, we adopted a simple volumetric formula to determine the volumetric capacity of the reservoirs to store CO_2. We arrive at equation 3 by assuming that an average of 10% of STOIIP for each field would be recovered using CO_2-EOR and that 0.33 tonnes of CO_2 would be stored for each barrel of oil produced through the flooding method.

$$CO_2 \text{ storage capacity (Mt)} = (STOIIP/10) \times 0.33 \quad (3)$$

$$STOIIP = OOIP/Bo \quad (4)$$

Where STOIIP/10 = 10% of Stock Tank Oil Initially In Place in millions of barrels; OIIP = Oil Originally In Place and Bo = Oil formation volume factor.

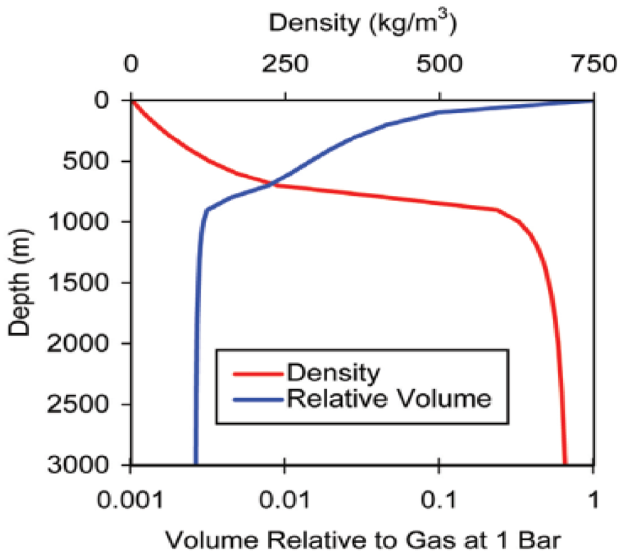
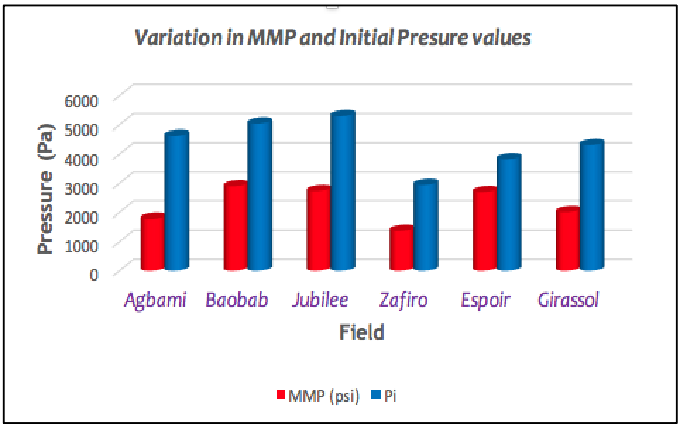


Fig. 8. Density and change in volume of CO_2 as a function of depth below seabed for a typical geothermal gradient [16]

Thus, by knowing the hydrocarbon volume initially in place and the formation volume factors, the CO_2 capacity was then calculated using excel spreadsheet.

III. RESULTS AND DISCUSSION

The results show clearly that all the fields investigated in this study are suitable for CO_2-EOR. This provides a clear indication that these fields can be considered for CO_2-EOR in the context of maximizing the economic benefit of CO_2 storage along the WATM in the future.



For each field scrutinized, the MMP value was way below the initial field pressure. Figure 9 shows the variation in the values for each field.

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TABLE I. MW AND MMP CALCULATED VALUES FOR THE FIELDS

Field	API	MW (C5+)	T (oF)	MMP (psi)	Pi	CO_2-EOR Suitability
Agbami	43	150.71	173	1771	4622	✓
Baobab	23	275.30	147	2894	5035	✓
Jubilee	37	174.17	209	2725	5295	✓
Zafiro	30	213.15	94	1370	2940	✓
Espoir	32	200.31	185	2688	3820	✓
Girassol	32	200.31	146	2000	4315	✓

The total capacity for the selected fields is approximately 369.71Million Metric Tons (Mt). This also reflects a good storage capacity for the region and emphasizes the need for the region to consider implementation of this project (figure 10).

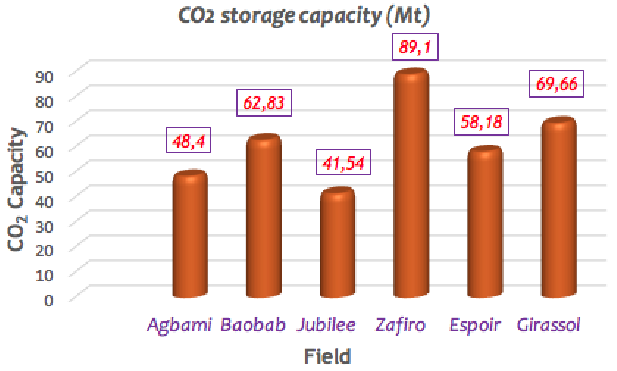

Fig. 10. Bar graph of CO_2 storage capacity for selected fields

Figure 11 is a schematic diagram representing a decision tree that can be used to identify CO_2-EOR candidate fields along the WATM. The process used was entirely based on field geo-makeup and reservoir characteristics, and thus, only reservoir rock and fluid characteristics were considered.

IV. CONCLUSION AND FUTURE WORK

A high potential for increasing oil production lies along the West African Transform Margin through the implementation of CO_2-EOR technique. The results indicate that this will not only increase reserves, but provide the opportunity to safely sequester anthropogenic CO_2 in the matured life of the fields, so the region can provide solutions to the threat of global warming. The revelations of this study calls for further studies to reveal the full potential of the west African region to successfully execute CCS.

The following recommendations are suggested;

- The screening criteria can be modified by considering other techical, engineering geoscience, and economic measures to provide industry with a full tool for field selection for CO_2 storage in EOR operations in the oil reservoirs along the WATM.
- Risk associated to CO_2 storage affects the suitability of a reservoir and consequently affects regional and national capacity estimates. It is important to conduct further work that takes risk into account as it will result in more realistic valuations of total technical CO_2 storage potentials along the WATM.
- Other regional considerations covering environmental, and public issues need to be investigated before full-scale
- implementation of CO_2 storage.

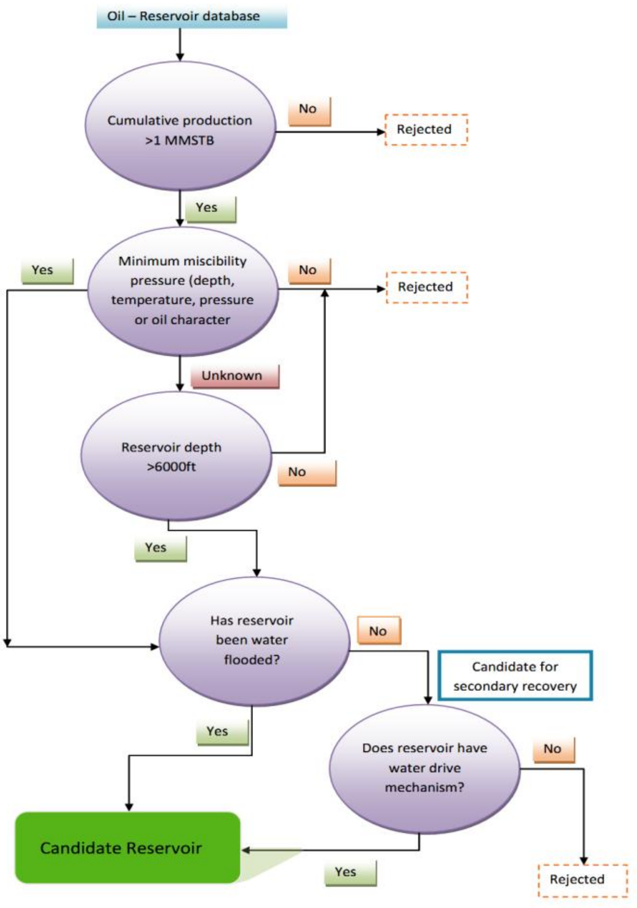

Fig. 11. Decision tree to identify CO_2-EOR candidate reservoirs.

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