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CO_2 Storage Capacity of Campos Basin's Oil Fields, Brazil.

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Abstract

Large potentials for CO_2 storage were demonstrated in previous studies in Brazil. This study aims to estimate the CO_2 storage capacity in the Campos Basin's oil fields, Southeast Brazil, in order to provide refined values to support CCS planning in the country. The results, based on field/reservoir level data show that there is a large potential for CO_2 storage (ca. 950Mt) in the 17 assessed oil fields in the basin, and 75% of this storage capacity is found in sandstone reservoirs.

Key Words: CO_2 storage capacity, Campos Basin, Oil fields, Geological storage, Enhanced oil recovery, CCS, CO_2-EOR

1. Introduction

A critical point for the development of carbon dioxide capture and storage (CCS) is the availability of CO_2 storage. A thorough understanding of the available CO_2 storage capacity is required for the implementation of CCS. According to Bachu et al [1], CO_2 storage capacity assessment may be conducted at various scales: country, basin, regional, local and site-specific. Even in different assessment-scales, Bradshaw et al [2] state that the estimation of the capacity of a geological reservoir to store CO_2 is not a straightforward or simple process, and lack of data is still one of the major challenges in CO_2 storage capacity estimations.

There are three different ways to assess storage capacity [1] [3], one for each storage option (coalbeds, aquifers, oil and gas fields), based on specific inherent characteristics of each kind of reservoir. Regarding

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CO_2 storage capacity estimation in depleted oil and gas reservoirs, it is straightforward and is based on recoverable reserves, reservoir properties and in situ CO_2 characteristics [1]. The fundamental assumption is that the volume previously occupied by the produced hydrocarbons is available for CO_2 storage. In the case of CO_2-EOR, the CO_2 storage capacity can be more accurately through numerical simulations [1].

1.1. CO_2 storage capacity estimation in Brazil

In the Brazilian National Plan for Climate Change [4], Carbon Capture and Storage has been recognized as an important option to reduce CO_2 emissions, especially for the oil and gas, and industrial sector. The Brazilian oil and gas industry is engaged in CCS research and development, and CO_2 is already being injected for enhanced oil recovery in the country [5]. Preliminary studies on CO_2 storage potential and source-sink matching in Brazilian sedimentary basins (The CARBMAP Project) have been conducted ([6], [7], [8], [9], [10]), and the findings identify some promising basins for CCS development in Brazil.

A previous study [6] estimated the Brazilian potential storage capacity (in saline aquifers, petroleum fields and coalbeds) and opportunities for CCS in the country. In total, the basin scale estimation indicates that Brazil has a large theoretical storage capacity (ca. 2,000 $GtCO_2$). Regarding CO_2 storage in petroleum fields, Campos and Santos Basins appear as good candidates, with theoretical capacities – mostly based on generic basin-scale data (total oil and gas reserves) – of ca. 1,800 and 167 $MtCO_2$ respectively [6] [7].

In this context, the aim of this study was to estimate CO_2 storage capacity of petroleum fields in the Campos Basin, in order to provide refined capacity values based on field/reservoir level data.

2. Methodology

2.1. Study Area: Campos Basin

The Campos Basin is an offshore basin located in southeastern Brazil, between the geographic parallels 21º and 23º South (Fig.1). The basin covers an area of about 100,000 km² [11] [12], and contains 80% of the Brazilian petroleum reserves [11]. The discovered petroleum fields are in water depths ranging from 80 to more than 2,600 meters.

According to PETROBRAS [11], there are 36 petroleum fields in Campos Basin which have already reached peak production and are or will be in the coming years in the mature phase. Because of this and its proximity to large scale stationary CO_2 emission sources, the Campos Basin is considered one of the most promising Brazilian basins for CO_2 storage development [6] [7].

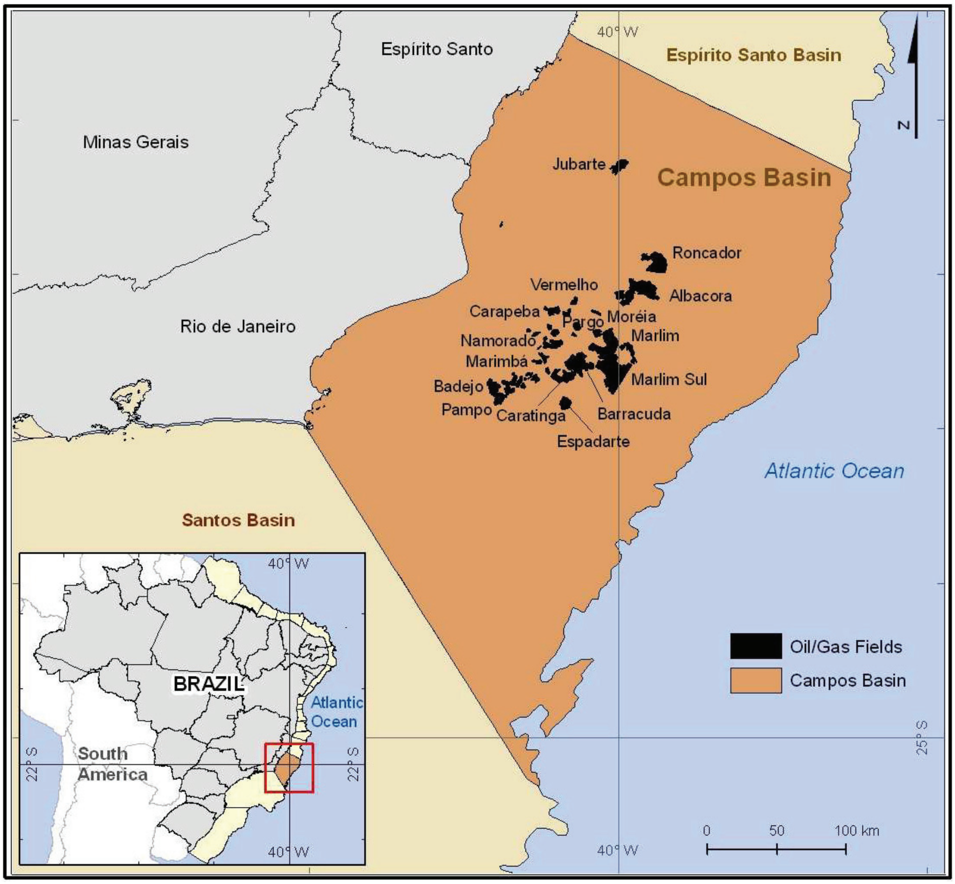

Fig.1: Campos Basin's location

2.1.1. Geological setting

The Campos Basin was formed as a result of the breakup of Gondwana paleocontinent, in the Early Cretaceous (~140 Ma), followed by subsequent infilling of the rift basin with as much as 9,000 m of Early Cretaceous–Holocene sediments [12]. According to Moraes et al [13], the sedimentary package that forms the Campos Basin is divided into five megasequences (Fig.2): continental rift (Neocomian); transitional (evaporitic) (Aptian); shallow marine (Albian); marine transgressive (Cenomanian to Upper Eocene); marine regressive (Upper Eocene to Present) megasequences. The Palaeocene–Eocene reservoirs occur mostly within the transgressive megasequence.

Guardado et al [12] described the most important Campos Basin megasequences, as follows: The nonmarine rift megasequence is composed of lacustrine Barremian sedimentary rocks overlying Neocomian basalts. Rift tectonics had influenced the strata deposition paleoenvironments. This sequence contains the calcareous shales of the Lagoa Feia Formation, the most important source rock in the basin. The transitional megasequence was deposited in Aptian time during a non-tectonic period. It represents the beginning of the drift phase and contains a lower sequence (mostly composed of conglomerates and carbonates), and an upper sequence (consisting of evaporites). The marine megasequence is made up of Albian shallow-water carbonates, mudstones, and marls (Macaé Formation) at its base. This basal sequence grades upward into an Upper Cretaceous–Paleocene bathyal sequence consisting of shales, marls, and sandstone turbidites. A progradational siliciclastic sequence characterizes the remaining Neogene section.

Reservoir rocks with good to excellent permeability and porosity are widespread in the Campos Basin both in time and space [12].

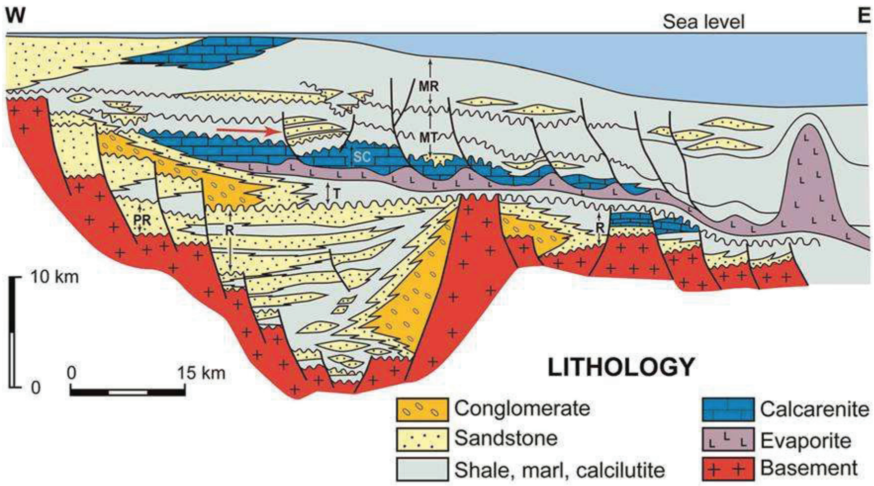

Fig.2: Generalized geological section for the Eastern Brazilian continental margin basins, showing the main megasequences: PR, pre-rift (which does not occur in the Campos Basin); R, rift; T, transitional (which includes the evaporate section); SC, shallow carbonate; MT, marine transgressive; MR, marine regressive (modified from Bruhn [14]).

2.2. Geological Reservoir Data

Campos Basin oil fields were selected for this study, because of their well-known structure, proven traps and availability of reservoir data. Specific oil/gas field data were obtained through extensive literature survey. Public available data are very limited, and because of this, the total number of fields analyzed in this study is 17 (from more than 50 oil fields in the basin). The fields included are: Carapeba, Linguado, Marimbá, Marlim, Vermelho, Barracuda, Roncador, Caratinga, Jubarte, Namorado, Badejo, Pampo, Enchova/Bonito, Garoupa, Albacora, Corvina and Malhado. These fields contain about 36% of the Campos Basin's oil reserves (excluding new pre-salt reserves; based on data from ANP [15], Rangel et al [16], Assis et al [17] and Horschutz et al [18]). The assessed reservoirs in these fields are mainly Cretaceous and Tertiary sandstones, and some Cretaceous limestones. For storage capacity estimation purposes, the following data was collected:

- **Reservoir:** For each oil/gas field, data on the type of rock, age and Formation were collected. The reservoirs considered in this study are listed in Table 1.

Table 1. Reservoirs considered in this study, per Oil Field

Oil Field	Reservoir type	Age/Stratigraphic Unit
Carapeba	Turbidite sandstones	Eocene/Carapebus Mb.
	-	Cretaceous/Carapebus Mb.
Linguado	Calcirudites	Barremian/Lagoa Feia Fm.
	Calcarenites and calcirudites	Albian/ Macaé Fm.
	Turbidite sandstones	Maastrichian/Campos Fm.
Marimbá	-	Cretaceous/Campos
Marlim	Turbidite sandstones	Oligocene/Carapebus Mb.
Vermelho		Oligocene
	Medium-grained sandstones	Eocene/Carapebus Mb.
Barracuda	-	Oligocene/Campos
	Turbidite sandstones	Eocene/Campos
Roncador	Sandstones	Maastrichian/Carapebus Fm.
Caratinga	Turbidites	Oligocene
Jubarte	Sandstones	Maastrichian
Namorado	Sandstones (Namorado sandstone)	Cenomanian-Turonian/Macaé Fm.
Badejo	Coquines	Lagoa Feia Fm.
Pampo	Neritic carbonates	Albo-Cenomanian/Macaé Fm.
	Coquines (calcirudites/carcarenites)	Lagoa Feia Fm.
Cherne	Turbidite sandstones	Cretaceous
Enchova/Bonito	Turbidites	Eocene/Carapebus Mb.
Albacora	Turbidite sandstones	Cretaceous-Terciarious
Garoupa	Carbonates	Albian/Macaé Fm.
Albacora Leste	Sandstones	Miocene/Carapebus Fm.
Corvina	Turbidite sandstones	Eocene/Carapebus Mb.
Malhado	Turbidite sandstones	Eocene/Carapebus Mb.

- **Depth:** Reservoir depth data was not always available at the field level, and therefore it is estimated (for each field) by one of the following four indicators: (i) average depth of specific reservoirs in an oil field (ex. Carapeba, Linguado, Vermelho, Namorado, Pampo); (ii) average depth of the reservoir layers in the field (ex. Marlim, Roncador, Caratinga, Jubarte, Badejo, Albacora, Malhado); (iii) average field depth extracted from geological sections (iv) oil-water contact depth extracted from geological sections and articles (ex. Enchova/Bonito, Corvina). All the 17 reservoirs are over 800 meters deep, which is required for CO_2 geological storage in supercritical conditions [19].
- **Original Oil in Place (OOIP):** Recent data on oil reserves are only publicly available at basin level or per federal state and not for specific fields. However, older data on the original oil in place were available in scientific literature dating from 1992 to 2006.

The figures available in the literature and used in this study are from the references in Appendix A.

2.3. CO_2 Storage Capacity Estimation

CO_2 storage capacities were estimated based on the methodology proposed by Bachu et al [1], which assumes that the volume previously occupied by the produced hydrocarbons is available for CO_2 storage (Eq. 1).

$$MCO_2 = \rho CO_2\, r\, [(Rf \times OOIP/Bf) - Viw + Vpw] \qquad \text{(Eq.1)}$$

Where MCO_2 stands for the theoretical CO_2 storage capacity (in tonnes), ρCO_2 r is the CO_2 density under reservoir conditions (in kg/m³), Rf the recovery factor, OOIP the original oil in place (in m^3), Bf the formation volume factor, Viw the injected water volume and Vpw the produced water volume.

Note that the analysis in this study is at the field level and some assumptions had to be made when data were only available from specific reservoirs within an oil/gas field.

- **CO_2 Density at Reservoir Condition:** Average CO_2 density of each oil field was determined based on temperature and pressure data. When data were not available, the average temperature was calculated based on its depth and the Campos Basin's average geothermal gradient data (from Jahnert [20]). Furthermore, 4ºC was added to each field's average temperature to take into account the sea floor temperature [21]. The average pressure was estimated based on the oil field's depth, assuming hydrostatic pressure of 100 bar per kilometer.
- **Recovery Factor and Original Oil in Place:** The recovery factor is defined as the ratio of the planned oil production and the original oil in place. Since this data is not publicly available, in this study, oil reserve values were used instead. For the oil fields for which also oil reserves data were unavailable (i.e., Badejo, Enchova/Bonito, Albacora, Corvina and Malhado), the original oil in place data were multiplied by a recovery factor of 35.4% (the average recovery factor in Campos Basin with the new technologies application), according to Bosco [22].
- **Formation Volume Factor, Injected Water Volume and Produced Water Volume:** The formation volume factor, which converts the oil volume in normal conditions to the reservoir condition, was assumed to be 1.2 [23] and the sum of injected water volume and produced water volume was assumed to be zero.

3. Results and Discussions

The results show that Campos Basin has a storage capacity of approximately 950 $MtCO_2$, in the 17 analyzed oil fields. The Roncador field appears as the one with the large storage capacity (~265 $MtCO_2$), followed by Marlim, Albacora and Barracuda oil fields with storage capacities of 174, 163, and 118 $MtCO_2$, respectively. These 4 oil fields bear more than 75% of the Campos Basin's potential CO_2 storage capacity as it is shown in Fig.3. Some of the analyzed oil fields have limited CO_2 storage capacity (less than 6 $MtCO_2$), such as Linguado, Garoupa, Malhado and Badejo.

Figure 4 shows the CO_2 storage capacities contribution to the different assessed reservoirs in the oil fields. Sandstones reservoirs in Roncador field (Carapebus Fm.) contribute with about 28% of Campos Basin's storage capacity, while the siliciclastic reservoirs in Marlim field (Carapebus Mb./Campos Fm.) match about 18%. The Albacora field represents 17% of Campos Basin CO_2 storage capacity, Cretaceous and Tertiary reservoirs are turbidite sandstones from Macaé and Campos Formations, respectively. The Barracuda field's capacity is 50% in Eocene reservoirs (turbidite sandstones) and 50% in Oligocene reservoirs. 100% of Jubarte and Namorado fields storage capacity corresponds to Crataceous sandstones.

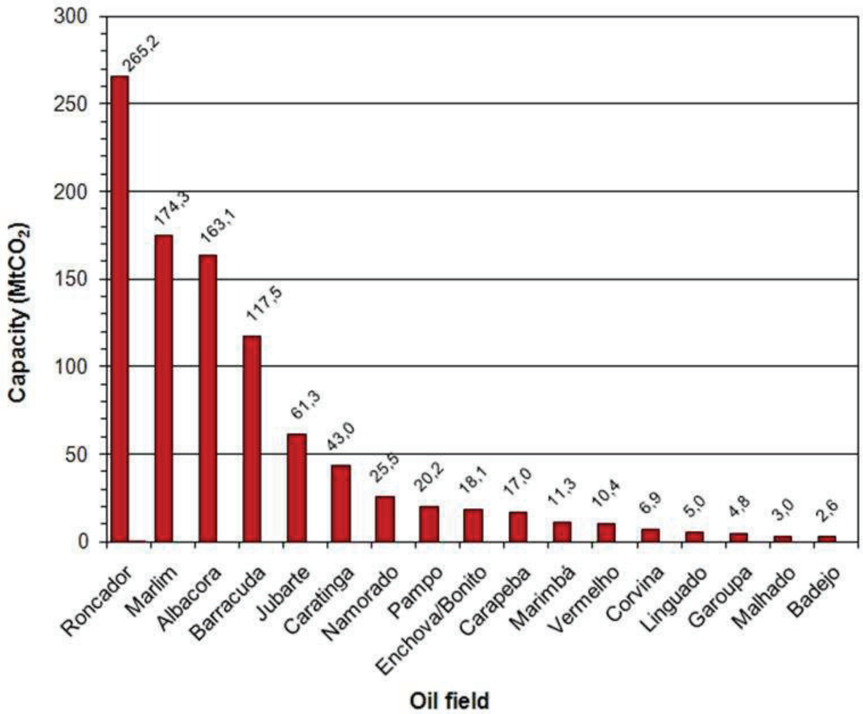

Fig.3: CO_2 storage capacity in Campos Basin oil fields

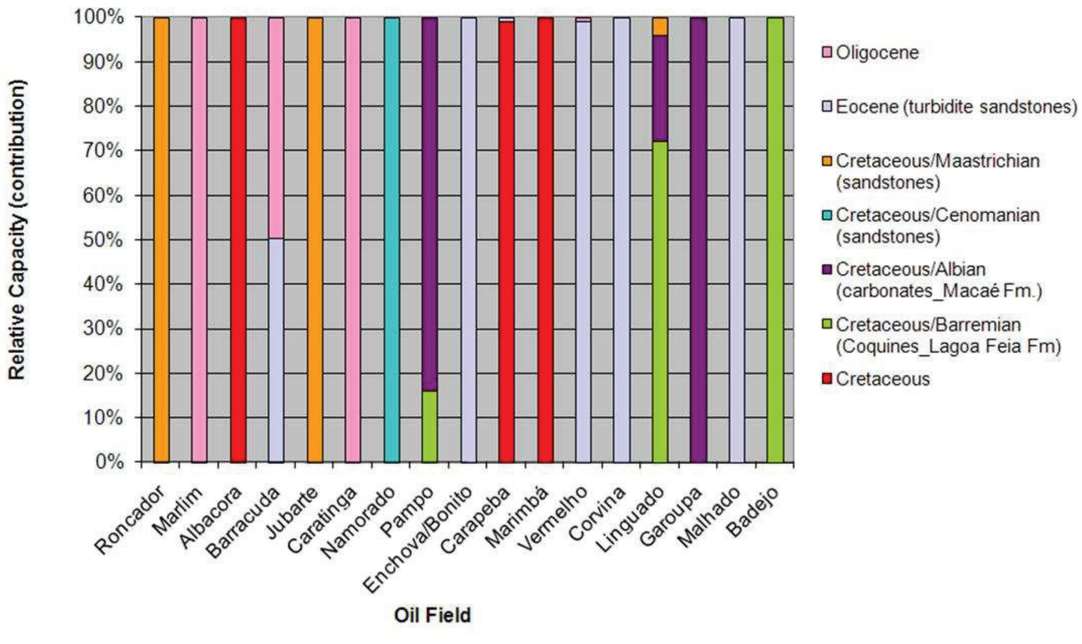

Fig.4: CO_2 storage capacity in the different reservoirs of Campos Basin's oil fields

In Pampo field's storage capacity corresponds to limestone reservoirs (84% in Macaé Formation carbonates and 16% in Lagoa Feia Formation coquines).

Estimated storage capacities of Enchova/Bonito, Carapeba, Marimbá, Vermelho and Corvina oil fields are in sandstones reservoirs. In Carapeba field, turbidite sandstones from Carapebus Fm. were assessed. Sandstones from Campos Fm. were assessed in Marimbá Field. Linguado's storage capacity is divided into limestone reservoirs and sandstone reservoirs (96% and 4%, respectively). Garoupa's storage capacity corresponds to carbonate reservoirs and Badejo's capacity corresponds to coquine reservoirs. Malhado oil field's storage capacity corresponds to turbidite sandstones reservoirs.

4. Conclusion

In this research, Carbon dioxide storage capacity estimation based on field/reservoir level data was carried out. The findings of this research indicate a CO_2 storage capacity of about 950 Mt in the 17 assessed oil fields in Campos Basin. More than 75% of the storage capacity is in sandstone reservoirs of Roncador, Marlim, Albacora and Barracuda oil fields. These reservoirs can play a significant role for CCS implementation in Brazil due to the large CO_2 storage capacities and because most of them are already mature fields or will be mature in the near future. It is important to note that Campos Basin's storage capacity is potentially larger than the estimated value in this research, since the theoretical storage capacity estimated in this study corresponds to data from only 17 out of 50 oil fields (at least) in Campos Basin, and most data are not updated.

Enhanced Oil Recovery combined with CCS (CO_2-EOR) is a promising opportunity in Campos Basin, considering that it is a mature basin with a significant amount of data and infrastructure. Further, CO_2 storage capacity, in this case, might be larger due to the oil produced by EOR. A preliminary cost modelling for CO_2 storage in Campos Basin's oil fields was conducted [24] and the results showed a great potential for store CO_2 at low costs (storage costs of about 4 €/t CO_2 – not considering capture and transport) in this sedimentary basin.

Currently, planned investment in CO_2 storage are focusing in the pre-salt reservoirs (discovered in Santos, Espírito Santo and Campos Basins), considering that in some fields CO_2 content might be >2% vol. and the injection of this amount can be an option to produce residual oil from these fields.

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Appendix A. Available figures on Campos Basin's reservoirs/oil fields - References used in this study

Figures collected from literature and used in this study (available/published data on depth, original oil in place, oil reserves and reservoir temperature) are from the following references:

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