Journal of Maps

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tjom20

Geological screening for onshore CO_2 storage in the Rio Bonito formation, Paraná Basin, Brazil

Saulo B. de Oliveira, Nathália Weber, Christopher Yeates & Colombo C. G. Tassinari

To cite this article: Saulo B. de Oliveira, Nathália Weber, Christopher Yeates & Colombo C. G. Tassinari (2023) Geological screening for onshore CO_2 storage in the Rio Bonito formation, Paraná Basin, Brazil, Journal of Maps, 19:1, 2171817, DOI: 10.1080/17445647.2023.2171817

To link to this article: https://doi.org/10.1080/17445647.2023.2171817

JOURNAL OF MAPS
2023, VOL. 19, NO. 1, 2171817
https://doi.org/10.1080/17445647.2023.2171817

SCIENCE

OPEN ACCESS Check for updates

Geological screening for onshore CO_2 storage in the Rio Bonito formation, Paraná Basin, Brazil

Saulo B. de Oliveira [a], Nathália Weber[a], Christopher Yeates[b] and Colombo C. G. Tassinari[a]

[a]Instituto de Energia e Ambiente, Universidade de São Paulo, São Paulo, Brazil; [b]Geoenergy Department, GFZ Potsdam, Potsdam, Germany

ABSTRACT
A growing number of countries have set ambitious climate targets and recognized the potential of CO_2 geological storage. Brazil's goal is to neutralize carbon emissions by 2050. The Paraná Basin is one of the most favorable onshore sedimentary basins for geological storage of CO_2 in Brazil. This extensive sedimentary basin presents a privileged location in the south and southeast regions, where the largest stationary CO_2 emitters are concentrated. Our results showed Rio Bonito Formation siliciclastic deposits present pairs of reservoir-seal rocks with adequate thicknesses and depths for stratigraphic CO_2 trapping. The screening allowed us to define a favorability map area, which will be the basis for subsequent detailing and characterization studies on the Rio Bonito Formation rocks and the location of CO_2 injection sites, thus contributing to the mitigation of the impacts of this gas in climate change.

ARTICLE HISTORY
Received 29 June 2022
Revised 15 January 2023
Accepted 17 January 2023

KEYWORDS
CO_2 geological storage; Paraná Basin; Rio Bonito Formation; CO_2 site screening; 3D geological analysis

1. Introduction

The increase in the concentration of greenhouse gases in the atmosphere has caused irreversible changes in the climate dynamics of the planet (IPCC, 2021). Geological storage of CO_2, as well as other carbon capture, utilization and storage (CCUS) technologies, has been extensively indicated as a relevant strategy for mitigating greenhouse gas emissions (IEA, 2021; IPCC, 2005; Stephens, 2006). Around 80% of long-term low emission development strategies submitted to the United Nations Framework Convention on Climate Change (UNFCCC) recognize a role for CCUS technologies. The International Energy Agency Roadmap to Net Zero by 2050 predicates CCUS growing to 7.6 billion tons of CO_2 per year by 2050 (IEA, 2021).

In Brazil, the onshore Paraná Basin has shown great potential for CO_2 storage (Iglesias et al., 2015; Ketzer et al., 2016; Pelissari, 2022; Rockett et al., 2011; Weber et al., 2021) largely because of its strategic location, but also due to its rock composition, favorable to different CO_2 trapping mechanisms (IPCC, 2005; Zhang & Song, 2014). The Paraná Basin presents coal seams with potential for CO_2 adsorption (Kalkreuth et al., 2013; Weniger et al., 2010), as well as organic-rich shales (de Oliveira et al., 2021; de Oliveira et al., 2022), and saline aquifers (Ketzer et al., 2009; Lima et al., 2011; Moreira et al., 2016). Although these specific studies of CO_2 storage have been carried out in the Paraná Basin, a systematic basin-scale screening study that spatially identifies areas or regions of favorability is absent in the literature. The objective of this paper is to establish an area of favorability for carbon capture and storage (CCS) projects in Brazil through 3D analysis of drilling data, considering the most industrialized region with the highest CO_2 emissions, and the rocks of the Rio Bonito Formation as possible CO_2 reservoirs.

1.1. Paraná Basin geology

The Paraná Basin is a Phanerozoic intracratonic basin that occurs through an area with continental dimensions (> 1,000,000 km^2), mainly in Brazil's Central-West, Southeast and South regions, but also extending to Paraguay, Uruguay, and Argentina.

The stratigraphic record of the Paraná Basin comprises six supersequences from Late Ordovician to the Cretaceous: Rio Ivaí, Paraná, Gondwana I, Gondwana II, Gondwana III, and Bauru (Milani et al., 1998; Milani & Thomaz Filho, 2000).

The Rio Ivaí Supersequence comprises sandstones of the Alto Garças Formation, diamictites of the Iapó Formation, and shales and siltstones of the Vila Maria Formation (Milani et al., 1998). The Furnas Formation sandstones and the Ponta Grossa Formation shales comprise the Paraná Supersequence (Milani et al., 1998).

CONTACT Saulo B. de Oliveira sauloboliveira@hotmail.com Instituto de Energia e Ambiente, Universidade de São Paulo, São Paulo, Brazil
Supplemental map for this article is available online at https://doi.org/10.1080/17445647.2023.2171817.

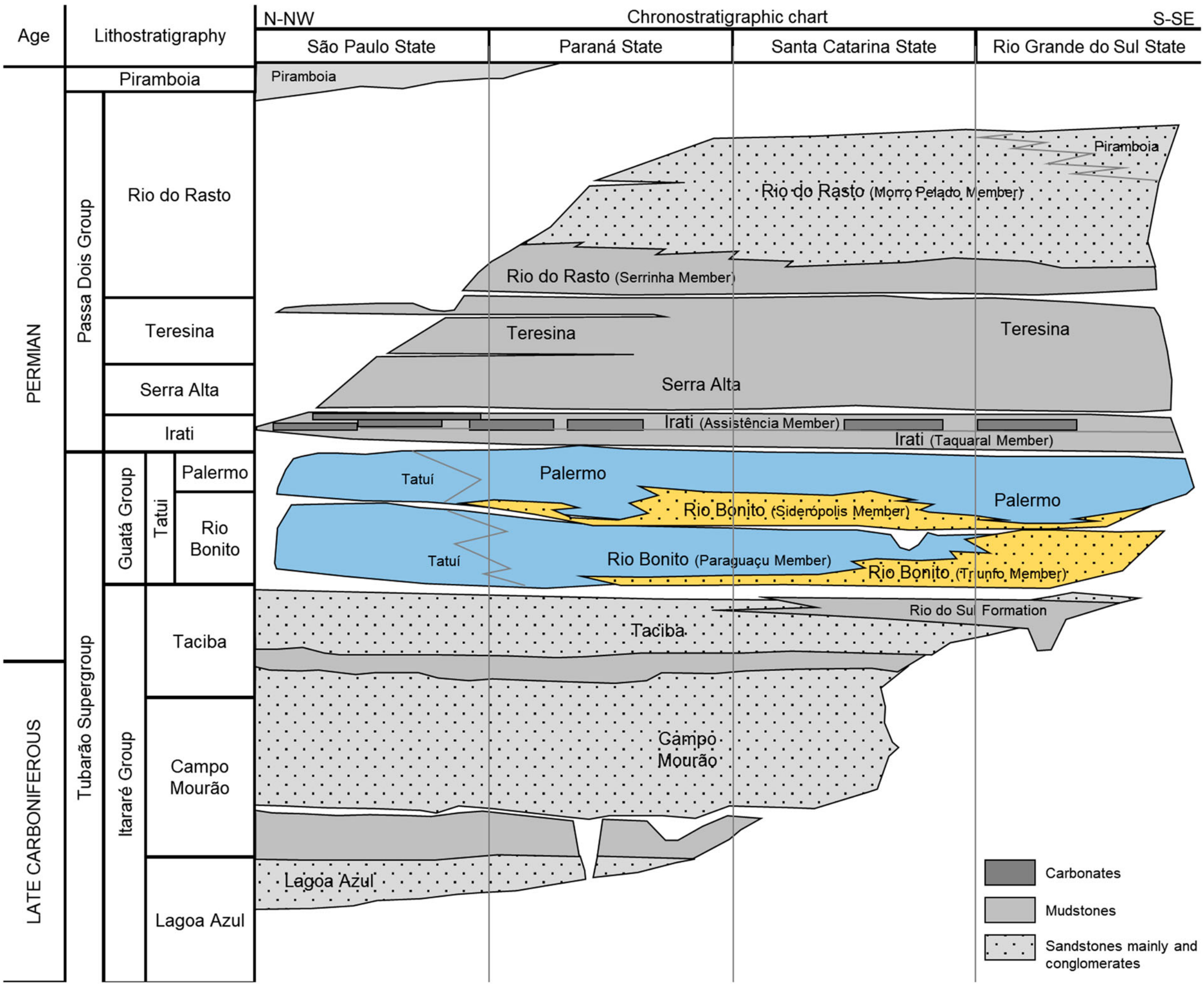

Figure 1. Stratigraphic reference chart of Late Carboniferous-Permian of the Paraná Basin in southern and southeastern Brazil, highlighting the Rio Bonito, Palermo, and Tatuí Formations (modified from Holz et al., 2010).

The Late Carboniferous-Permian Gondwana I Supersequence comprises a basal sequence composed of the Itararé Group glacial sediments and the Guatá Group transitional sediments (Holz et al., 2010) (Figure 1). The Itararé Group is subdivided from base to top into the sandstones, siltstones and mudstones of the Lagoa Azul Formation; sandstones with thin intercalations of siltstones and mudstones of the Campo Mourão Formation; sandstones and pebbly mudstones of the Taciba Formation, and clayey sediments of the Rio do Sul Formation (França & Potter, 1991; Vesely et al., 2007). The Guatá Group is composed of sandstones, siltstones, and coal beds of the Rio Bonito Formation, and siltstones and shales of the Palermo Formation (Milani et al., 1998). The Rio Bonito Formation is subdivided into three major members, labeled from base to top: 1) the Triunfo Member composed of coastal and fluvial sandstones, 2) the Paraguaçu Member composed of marine mudstones and fine-grained sandstones, and 3) the Siderópolis Member composed of coastal and fluviatile sandstones (Holz, 2003) (Figure 1). In some regions, Rio Bonito Formation members are not defined but the succession is equivalent. Tatui Formations (present only in São Paulo State) is time equivalent to the Guatá Group (Figure 1). The Passa Dois Group lies above a regressive sequence composed of the Irati Formation, which consists of bituminous shale and limestone beds with subordinated evaporite layers, the Serra Alta Formation shales, the Teresina Formation marine sediments, and the Rio do Rasto Formation red beds (Milani et al., 1998; Milani & Thomaz Filho, 2000). The topmost formation of the Gondwana I Supersequence refers to continental sequences of the Pirambóia Formation, which occur in the northern portion of the Paraná Basin with several hundred meters in thickness (Milani & Thomaz Filho, 2000).

The Gondwana II Supersequence is exclusive to the Paraná Basin's southernmost portion and is represented by the Santa Maria Formation siltstones, sandstones, and shales (Milani et al., 1998).

The Botucatu Formation sandstones form the lower portion of the Gondwana III Supersequence, while the upper portion comprises a volcanic sequence of the Serra Geral Formation that overlies the other older sequences and intruded them as sills and dikes (Milani et al., 1998).

The Bauru Supersequence is subdivided into the Caiuá and Bauru Groups and is composed of deposits with sandy-conglomeratic composition, with some silty to shaly deposits (Milani et al., 1998).

1.2. Potential of the Paraná Basin for CO_2 geological storage

Among the favorable rocks for conventional CO_2 reservoirs within the Paraná Basin are the sandstones of the Botucatu-Pirambóia, Rio Bonito, Taciba, Furnas, and Alto Garças formations, whose potential caprocks are the Serra Geral, Palermo, Rio do Sul, Ponta Grossa, and Iapó formations. Nevertheless, the Botucatu and Pirambóia formations rocks host the Guarani Aquifer, one of the main water supply sources in the region (Hirata et al., 2011), which disfavors their potential for CO_2 storage. The depth of the basal Furnas and Alto Garças Formations increases in the central region along NNE-SSW fault-bounded basin depocenter, reaching approximately 5,000 m, which would increase significantly the CO_2 storage costs. The occurrence of the Rio do Sul Formation as caprock of the Taciba Formation is very irregular in thickness and does not extend throughout the basin (Holz, 2003) (Figure 1), thus making it a negative factor for carbon dioxide storage. Thereby the Rio Bonito Formation presents benefits in terms of its position along with the stratigraphy of the Paraná Basin, with the presence of reservoir-seal rock sequences, as well as the coal seams (Kalkreuth et al., 2013; Weniger et al., 2010) and saline aquifer occurrences (Ketzer et al., 2009; Lima et al., 2011; Moreira et al., 2016). Rio Bonito Formation sandstones also present promising permoporous properties, with values above 10% of porosity in some portions (Ketzer et al., 2003), favoring Rio Bonito Formation as a CO_2 sink candidate (Weber et al., 2021).

Aquifers in the Rio Bonito Formation with a level of total dissolved solids (TDS) in the water greater than 10,000 ppm are reported in the southern portion of the Paraná Basin (Machado & Freitas, 2005). The Tubarão Aquifer, in the Rio Bonito Formation, is also pointed out as a potential reservoir due to presenting saline anomalies (Moreira et al., 2016). However, more data and studies are needed to precisely delimit the spatial continuity and extension of these saline aquifers.

Besides the Rio Bonito Formation, other beds of the Paraná Basin present some potential for CO_2 geological storage, which include the organic-rich shales of the Irati Formation (Abraham-A & Tassinari, 2021; de Oliveira et al., 2021; de Oliveira et al., 2022), the Ponta Grossa Formation, and the basalts of the Serra Geral Formation (Pelissari, 2022). In terms of depleted oil and gas fields, the Paraná Basin has a high potential for hydrocarbons with two recognized petroleum systems: the Carboniferous-Devonian Ponta Grossa/Rio Bonito-Itararé System; and Permian Irati-Pirambóia System (Araújo et al., 2000; Milani et al., 2006), with oil shale production but no production in conventional fields.

2. Materials and methods

The drillhole database provided by *Agência Nacional do Petróleo, Gás Natural e Biocombustíveis*, Brazil (ANP) (https://reate.cprm.gov.br/anp/) consists of 125 hydrocarbon exploration wells within Paraná Basin (1 well/ ∼10,000 km^2). Of these wells, 123 have stratigraphic data and 113 have lithological data. The stratigraphic dataset comprehends the geological interpretation of lithostratigraphic units (groups, formations and members) of the Paraná Basin. The Rio Bonito Formation is described in 91 out of 123 wells. In the other wells, this formation is not described for different reasons: the drillings have not reached its depth; the well has already started in the underlying Itararé Group rocks; or this formation does not occur in that portion of the basin, where the intervals go from the Palermo Formation directly to Itararé Group. In 51 out of 91 wells, the Rio Bonito Formation is subdivided into three members: Siderópolis, Paraguaçu, and, Triunfo.

Rio Bonito Formation dataset show 17 lithologies interpreted from geological logging. Table 1 shows the number of intervals of each lithology for all logged intervals. The most frequent lithologies in the Rio Bonito Formation are sandstone (n = 1,224), siltstone (n = 995), and shale (n = 643). Sandstone predominates in the Siderópolis and Triunfo members, while shale and siltstone predominate in the Paraguaçu Member.

In 40 of the 91 wells where the Rio Bonito Formation is undivided in members, the dataset analysis was carried out on Leapfrog software (Figure 2). The

Table 1. Lithology data (log intervals) for Rio Bonito Formation.

Lithology	Number of data (*n*)
calcarenite	68
calcilutite	87
calcisiltite	12
clay	1
coal	5
conglomerate	3
crystal limestone	24
diabase	4
diamictite	8
dolostone	1
granite	1
marl	3
meta-siltstone	1
mudstone	3
sand	3
sandstone	1,224
shale	643
siltstone	995

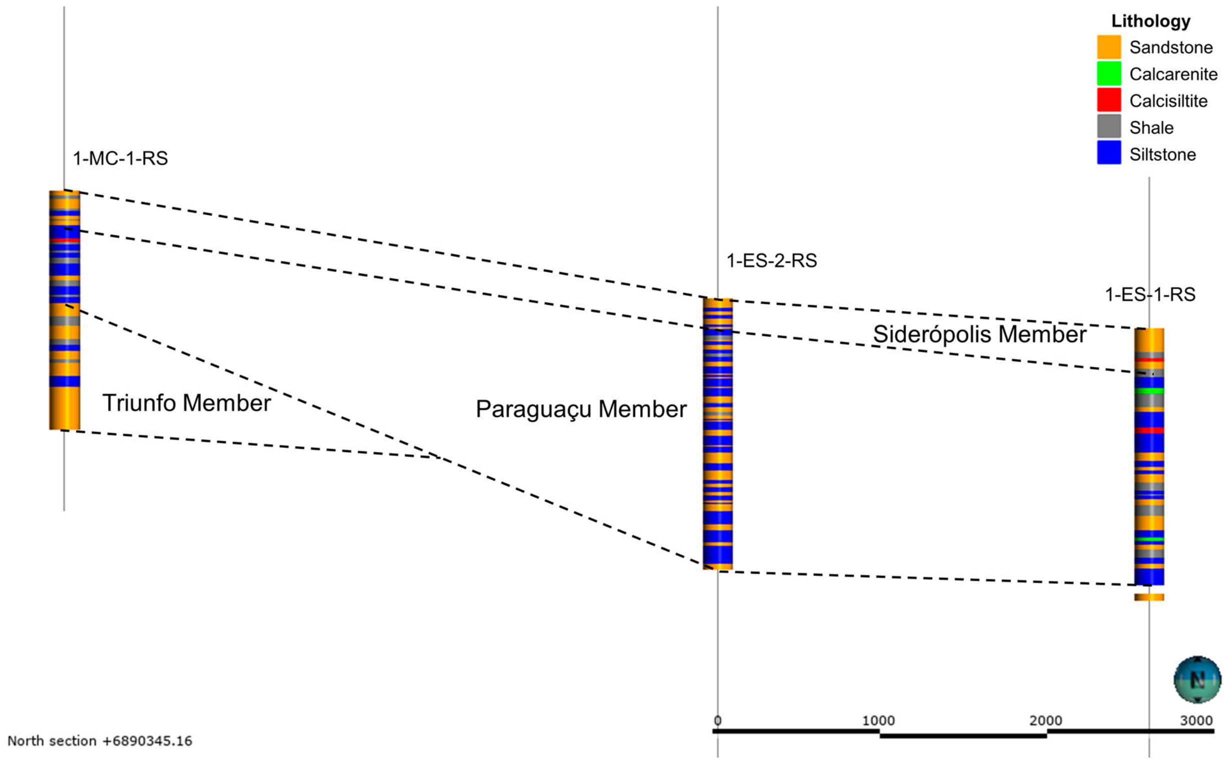

Figure 2. Example of 3D interpretation of the Rio Bonito Formation subdivisions through lithostratigraphic correlation in a geological cross-section, 10x vertical exaggeration.

geological interpretation was based on: 1) proportion of siltstone/shale or sandstone (predominance); 2) the stratigraphic position; and 3) spatial position and lateral continuity (considering other wells nearby), following the basic principles of lithostratigraphic correlation (Boggs, 2011; Brookfield, 2008). Members interpretation and classification in the software were mostly manually correlated, with a few exceptions. Particularly, in the well 1-MC-1-RS an intermediate interval originally classified as Siderópolis is now reclassified to Paraguaçu Member (from 2,141–2,237 m). Well 1-JT-1-PR was previously fully described as a Paraguaçu Member and now the top interval is reclassified to Siderópolis Member (from 102 to 119 m).

To evaluate the potential for CO_2 storage at the basin scale, assuming stratigraphic trapping and a reservoir-sealing rock pair (Gunter et al., 2004; Zhang & Song, 2014), two systems were considered:

1) Palermo Formation (seal) – Siderópolis Member (reservoir),
2) Paraguaçu Member (seal) – Triunfo Member (reservoir).

Initially, maps of the distribution of each of the formations/members were generated from well data (Figures 3 and 4) integrated with the Rio Bonito Formation outcrops from the *Companhia de Pesquisa de Recursos Minerais* (CPRM) geological map (Schobbenhaus et al., 2004).

Several criteria have been proposed in the literature for the characterization and screening of geological CO_2 storage sites (Bachu, 2000; Chadwick et al., 2008; IEA-GHG, 2009; Miocic et al., 2016; Smith et al., 2011). To define the area of favorability for geological storage in the Rio Bonito Formation, the International Energy Agency criteria (IEA-GHG, 2009) were applied in this study (Main Map), where the CO_2 reservoir rock must occur at depths greater than 800 m with a thickness greater than 20 m, being immediately sealed by rock with a minimum thickness of 10 m.

The geological contacts between the reservoir-seal pairs were visually analyzed in 3D case-by-case, considering lithology predominance and thickness. Some notable exceptions are detailed here. When the base of the Paraguaçu Member or Palermo Formation was a sandstone interval, it was not considered seal rock. Calcarenite, calcisiltite, and calcilutite are more common within the Paraguaçu Member. When these lithologies occur in a reservoir-seal contact, they were not considered due to uncertainties regarding the CO_2 reactivity with these carbonate-bearing rocks. In the wells 1-J-1-PR, 1-GB-1-PR; 1-CS-2-PR; 1-PH-1-PR, the total reservoir thickness of the formation was reconsidered due to the occurrence of thick diabase intercalations (some intervals with diabase were disregarded).

All wells with intervals of the Siderópolis Member also exhibit the Palermo Formation immediately above as seal rock with a thickness larger than 10 m.

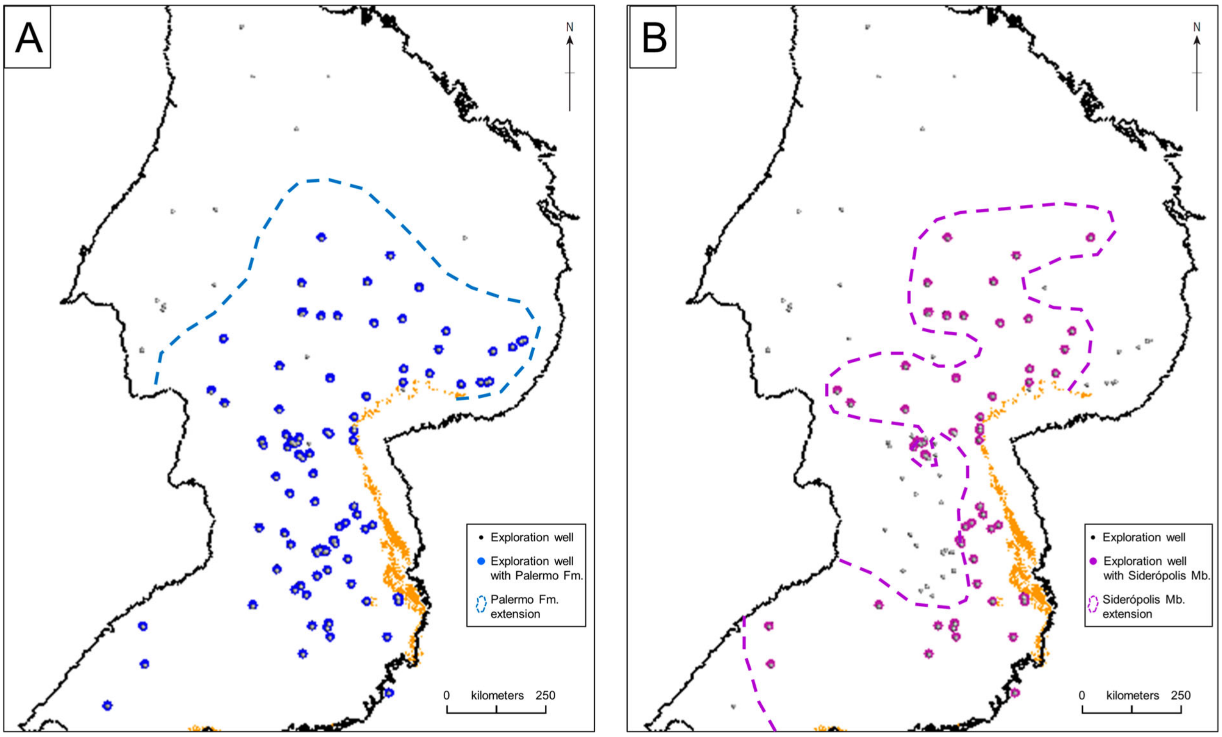

Figure 3. Plan maps with exploration wells (black dots) within the Paraná Basin limits (map contour in black). Rio Bonito Formation outcrops in orange (from Schobbenhaus et al., 2004). A) Palermo Formation extension; B) Siderópolis Member extension (dashed lines).

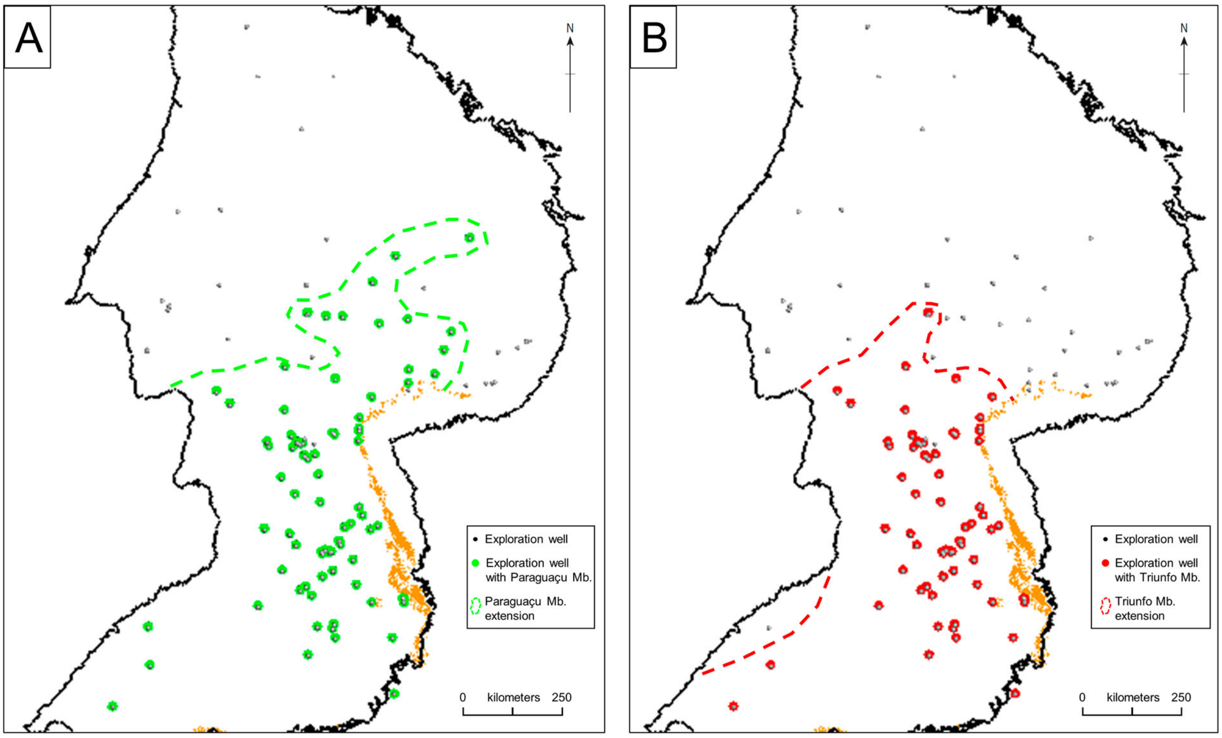

Figure 4. Plan maps with exploration wells (black dots) within the Paraná Basin limits (map contour in black). Rio Bonito Formation outcrops in orange (from Schobbenhaus et al., 2004). A) Paraguaçu Member extension; B) Triunfo Member extension (dashed lines).

In the 1-MA-1-SP well, the Palermo Formation occurs with the lowest thickness (19 m). Exceptions occur in the 1-MO-1-PR well, where the Rio Bonito Formation is the outcropping stratigraphic unit, and in the 2-OL-1-SP well, where the Palermo Formation is absent. Nevertheless, in this last case, the reservoir-seal pair was still considered because the Irati Formation is the upper layer composed mainly of shales with a thickness of 21 m. Wells exhibiting intervals of the Triunfo Member also have the Paraguaçu Member immediately above as seal rock with a thickness higher than 10 m. In the 2-AP-1-PR well, the Triunfo Member occurs with a thickness of 18 m, and this interval was considered inside the area of favorability due to its lateral continuity, verified through 3D spatial analysis. All the wells around it present the Triunfo Member with thicknesses greater than 20 m.

Of the 91 wells with the occurrence of the Rio Bonito Formation, 73 meet the criteria for CO_2 geological storage following the IEA-GHG (2009). The final step consisted of overlaying the distribution maps of the stratigraphic units of the Rio Bonito Formation (Figures 3 and 4), each with its restrictions regarding minimum thicknesses and depth. Then, an area of favorability was drawn encompassing all contours. The two systems of rock-seal pairs were thus integrated and presented as a single area of favorability for the geological storage of CO_2. Thus, inside the red dashed line (Main Map) the Rio Bonito Formation occurs at depths greater than 800 m, with the presence of either the Palermo Formation (seal) – Siderópolis Member (reservoir) pair or the Paraguaçu Member (seal) – Triunfo Member (reservoir) pair or both, with thicknesses of at least 10 and 20 m, respectively.

The contour of the area of favorability drawn around these wells also considers limits of areas with environmental restrictions (Main Map), avoiding Conservation and Sustainable Use units, Indigenous territories, and Integral Protection areas, sourced from the shapefiles obtained from the *Instituto Chico Mendes de Conservação da Biodiversidade* (ICMBio, 2022).

As southern Brazil is the country's region with the highest concentration of stationary CO_2 emitters, the location of thermoelectric power plants (ANEEL-SIGEL, 2022), bioethanol production plants (ANP, 2022), steel industries (IAB, 2021), and cement industries (SNIC, 2019) were also added to the Main Map.

3. Results and discussion

The 3D analysis of stratigraphic data from wells allowed the delimitation of a favorability area of 383,951 km² for CO_2 geological storage within the Paraná Basin (Main Map). This area occurs along the Brazilian states of São Paulo, Paraná, Santa Catarina, Rio Grande do Sul, Mato Grosso do Sul, and Minas Gerais. Within this area, the Palermo Formation, assumed in this study as a caprock, and the Siderópolis Member, assumed as a reservoir rock, occur in 35 wells with an average thickness of 126.3 and 42.0 m, respectively. The other system of reservoir-seal rock pairs, considering the Triunfo and Paraguaçu Members occurs in 61 wells and presents an average thickness of 57.3 and 77.4 m, respectively, within the area of favorability. The considered reservoirs, Siderópolis and Triunfo occur at average depths of 2,213.90 m and 2,240.00 m, respectively. Table 2 shows thickness and depth statistics for well interval data within the area of favorability for the two reservoir-sealing rock pair systems considered in this study.

The criteria from IEA-GHG (2009) adopted in this study in terms of thickness (> 20 m for reservoir rock, and > 10 m for seal rock) are stringent requirements, which seldom are available in a single trap, as also stated by Chadwick et al. (2008). The Rio Bonito Formation sandstones rarely exhibit a continuous thickness of 20 m (only in the 1-BN-2-SC and 1-CA-2-PR wells), with frequent centimetric to metric intercalations with other lithologies. A similar approach to Chadwick et al. (2008) was applied, considering cumulative sandstone bed thickness of 20 m, for reservoirs, and siltstone or shale thickness of 10 m, for caprocks, as minimum values per stratigraphic unit.

In terms of seal rock thickness, Tek (1989) points out that a thin layer of shale of 1.5 m thickness could retain gas. However, the discussion of seal rock thickness often has more to do with the continuity of the caprock. In this study, the spatial continuity between exploration wells was evaluated at the basin scale and the local continuity needs to be better addressed in the subsequent stages of research, as well as other important reservoir parameters such as porosity, permeability, mineralogy, temperature, and pressure regime (Chadwick et al., 2008; IEA-GHG, 2009; Miocic et al., 2016; Smith et al., 2011).

Other trap mechanisms regarding adsorption in coal seams and dissolution in saline aquifers (Bachu et al., 2007; IPCC, 2005; Zhang & Song, 2014), are not covered in this study due to the requirement for a more detailed geological characterization of the reservoir rocks, but they also should be added in future subsequent assessments of the Rio Bonito Formation.

The international criteria recommend that the site for CO_2 geological storage must not adversely affect, directly or indirectly, other resources, including

Table 2. Thickness and depth statistics for well interval data for the two reservoir-sealing rock pair systems considered in this study.

		Thickness (m)			Depth (m)		
Geological Unit	Number of wells	Average	Min.	Max.	Average	Min.	Max.
Palermo Formation	35	126.3	19.0	379.0	-	-	-
Siderópolis Member	35	42.0	21.0	96.0	2,213.9	842.0	3,814.0
Paraguaçu Member	61	77.4	15.0	131.0	-	-	-
Triunfo Member	61	57.3	18.0	122.0	2,240.0	826.0	3,984.0

groundwater (IEA-GHG, 2009). Several potable water aquifers occur in the Paraná Basin, the Guarani Aquifer System being the most extensive and deepest of them, present in the upper layers of Botucatu and Pirambóia Formations (Araújo et al., 1999; Gilboa et al., 1976; Hirata et al., 2011). Inside the area of favorability for CO_2 storage, the Rio Bonito Formation occurs at an average distance of 1,250 m from the bottom of both Botucatu and Pirambóia Formations, considered a safe distance assuming possible geological gas leaks.

The sum of total CO_2 emissions from all stationary sources compiled and plotted on the Main Map, including thermoelectric plants (ANEEL-SIGEL, 2022), ethanol distilleries (ANP, 2022), and cement (SNIC, 2019) and steel industries (IAB, 2021) represents approximately 435 million tons of CO_2 per year. This rate would lead to a total of 12.1 billion tons of CO_2 over a 28-year horizon from the present day to 2050. Thus, doing a reverse calculation based on this emission rate, a minimum areal extent target for a CO_2 reservoir within the Paraná Basin is approximately 7,250 km^2. This overall estimate assumes a reservoir thickness of 20 m, with 10% porosity (Ketzer et al., 2003), and a supercritical carbon dioxide density of 840 km/m^3 (Bachu, 2003; Haghbakhsh et al., 2013), based on the average Rio Bonito depth of 2,200 m (Table 2), hydrostatic pressure gradient of 10 MPa/km (Weniger et al., 2010), and temperature gradients of 24.4 ± 2.1 °C/km (Hamza et al., 2005), which is a highly realistic scenario for the Rio Bonito Formation, considering the potential area presented.

4. Conclusions

The Paraná Basin is a favorable onshore sedimentary basin for the geological storage of CO_2 in Brazil, due mainly to its privileged location in the south and southeast regions, where the largest stationary emitting sources are concentrated. Rio Bonito Formation siliciclastic sequences have shown great potential, as they present pairs of reservoir-seal rocks with adequate thicknesses and depths following international criteria over most of their extent in the subsurface, considering stratigraphic trapping. The screening carried out in this study allowed us to define an area of favorability of 383,951 km^2, which will be useful for future studies to detail and characterize the Rio Bonito Formation rocks and the location of CO_2 injection sites.

Software

QGIS 3.16 and Leapfrog Geothermal 2021.1.3 were used for 3D well data visualization and map analysis purposes. The map is designed to be color printed at A1 (594×841 mm) size for optimum clarity of font, point size, and shading.

Acknowledgments

The authors would like to thank Seequent Limited for providing the Leapfrog academic license. We gratefully acknowledge the support of the Research Centre for Greenhouse Gas Innovation (RCG2I), hosted by the Universidade de São Paulo (USP) and sponsored by Fundação de Amparo à Pesquisa do Estado de São Paulo (Fapesp) (2014/50279-4; 2020/15230-5; 2021/06158-1) and Shell Brasil, and the strategic importance of the support given by Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP) through the R&D levy regulation. We thank the reviewers for their constructive comments, which helped us to improve the manuscript.

Data availability statement

The data that support the findings of this study are openly available in Programa de Revitalização da Atividade de Exploração e Produção de Petróleo e Gás Natural em Áreas Terrestres (Reate) website at https://reate.cprm.gov.br/anp/.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP): [Grant Number 2014/50279-4, 2020/15230-5, 2021/06158-1].

ORCID

Saulo B. de Oliveira http://orcid.org/0000-0002-2149-1297

References

Abraham-A, R. M., & Tassinari, C. C. G. (2021). CO_2 storage algorithms involving the hybrid geological reservoir of the Irati Formation, Parana Basin. *International Journal of Greenhouse Gas Control*, *112*, 103504. https://doi.org/10.1016/j.ijggc.2021.103504

ANEEL-SIGEL. (2022). Data base of the Brazilian Power Sector-SIGEL: https://sigel.aneel.gov.br/Down/.

ANP. (2022). Painel Dinâmico de Produtores de Etanol: https://www.gov.br/anp/pt-br/centrais-de-conteudo/paineis-dinamicos-da-anp/paineis-e-mapa-dinamicos-de-produtores-de-combustiveis-e-derivados/painel-dinamico-de-produtores-de-etanol.

Araújo, L. M., França, A. B., & Potter, P. E. (1999). Hydrogeology of the Mercosul aquifer system in the Paraná and Chaco-Paraná Basins, South America, and comparison with the Navajo-Nugget aquifer system, USA. *Hydrogeology Journal*, *7*(3), 317–336. https://doi.org/10.1007/s100400050205

Araújo, L. M., Trigüis, J. A., Cerqueira, J. R., and Freitas, L. C. D. S., 2000, The atypical Permian petroleum system of the Paraná Basin, Brazil, in Mello, M. R., and Katz, B. J., eds., *Petroleum systems of south Atlantic margins, 73*, American association of petroleum geologists, p. 0.

Bachu, S. (2000). Sequestration of CO_2 in geological media: Criteria and approach for site selection in response to climate change. *Energy Conversion and Management*, *41*(9), 953–970. https://doi.org/10.1016/S0196-8904(99)00149-1

Bachu, S. (2003). Screening and ranking of sedimentary basins for sequestration of CO_2 in geological media in response to climate change. *Environmental Geology*, *44* (3), 277–289. https://doi.org/10.1007/s00254-003-0762-9

Bachu, S., Bonijoly, D., Bradshaw, J., Burruss, R., Holloway, S., Christensen, N. P., & Mathiassen, O. M. (2007). CO_2 storage capacity estimation: Methodology and gaps. *International Journal of Greenhouse Gas Control*, *1*(4), 430–443. https://doi.org/10.1016/S1750-5836(07)00086-2

Boggs, S. (2011). *Principles of sedimentology and stratigraphy*. Pearson Prentice Hall, 583 p.

Brookfield, M. E., 2008, *Principles of stratigraphy*, Wiley-Blackwell, 368 p.

Chadwick, R. A., Arts, R., Bernstone, C., May, F., Thibeau, S., & Zweigel, P. (2008). *Best practice for the storage of CO_2 in saline aquifers*, 14. British Geological Survey Occasional Publication.

de Oliveira, S. B., Rocha, H. V., & Tassinari, C. C. G. (2022). 3D geochemical characterization of organic-rich shales of the Irati Formation, Paraná Sedimentary Basin: New perspective for CO_2 geological storage in southeastern Brazil. *International Journal of Greenhouse Gas Control*, *114*, 103563. https://doi.org/10.1016/j.ijggc.2021.103563

de Oliveira, S. B., Tassinari, C. C. G., Abraham-A, R. M., & Torresi, I. (2021). 3D implicit modeling applied to the evaluation of CO_2 geological storage in the shales of the Irati Formation, Paraná Basin, southeastern Brazil. *Greenhouse Gases: Science and Technology*, *11*, 1024–1042. https://doi.org/10.1002/ghg.2111

França, A. B., & Potter, P. E. (1991). *Stratigraphy and reservoir potential of glacial deposits of the Itararé group (carboniferous-permian), Paraná Basin. AAPG Bulletin*, *75*, 62–85. https://doi.org/10.1306/0C9B273B-1710-11D7-8645000102C1865D

Gilboa, Y., Mero, F., & Mariano, I. B. (1976). The Botucatu aquifer of South America, model of an untapped continental aquifer. *Journal of Hydrology*, *29*(1-2), 165–179. https://doi.org/10.1016/0022-1694(76)90012-3

Gunter, W. D., Bachu, S., & Benson, S. (2004). The role of hydrogeological and geochemical trapping in sedimentary basins for secure geological storage of carbon dioxide. *Geological Society, London, Special Publications*, *233*(1), 129–145. https://doi.org/10.1144/GSL.SP.2004.233.01.09

Haghbakhsh, R., Hayer, H., Saidi, M., Keshtkari, S., & Esmaeilzadeh, F. (2013). Density estimation of pure carbon dioxide at supercritical region and estimation solubility of solid compounds in supercritical carbon dioxide: Correlation approach based on sensitivity analysis. *Fluid Phase Equilibria*, *342*, 31–41. https://doi.org/10.1016/j.fluid.2012.12.029

Hamza, V. M., Dias, F. J. S. S., Gomes, A. J. L., & Terceros, Z. G. D. (2005). Numerical and functional representations of regional heat flow in South America. *Physics of the Earth and Planetary Interiors*, *152*(4), 223–256. https://doi.org/10.1016/j.pepi.2005.04.009

Hirata, R., Gesicki, A., Sracek, O., Bertolo, R., Giannini, P. C., & Aravena, R. (2011). Relation between sedimentary framework and hydrogeology in the Guarani Aquifer System in São Paulo State, Brazil. *Journal of South American Earth Sciences*, *31*(4), 444–456. https://doi.org/10.1016/j.jsames.2011.03.006

Holz, M. (2003). Sequence stratigraphy of a lagoonal estuarine system—an example from the lower Permian Rio Bonito Formation, Paraná Basin, Brazil. *Sedimentary Geology*, *162*, 305–331. https://doi.org/10.1016/S0037-0738(03)00156-8

Holz, M., França, A. B., Souza, P. A., Iannuzzi, R., & Rohn, R. (2010). A stratigraphic chart of the late carboniferous/permian succession of the eastern border of the Paraná Basin, Brazil, South America. *Journal of South American Earth Sciences*, *29*(2), 381–399. https://doi.org/10.1016/j.jsames.2009.04.004

IAB. (2021). Anuário Estatístico: Rio de Janeiro, Instituto Aço Brasil.https://acobrasil.org.br/site/wp-content/uploads/2021/07/Anuario_Completo_2021.pdf.

ICMBio. (2022). Mapa Temático e Dados Geoestatísticos das Unidades de Conservação Federais: https://www.icmbio.gov.br/portal/geoprocessamentos/51-menu-servicos/4004-downloads-mapa-tematico-e-dados-geoestatisticos-das-uc-s.

IEA. (2021). Net Zero by 2050: A Roadmap for the Global Energy Sector: https://www.iea.org/events/net-zero-by-2050-a-roadmap-for-the-global-energy-system.

IEA-GHG. (2009). IEA greenhouse gas R&D programme: CCS Site characterisation criteria. In S. Bachu, C. Hawkes, D. Lawton, M. Pooladi-Darvish, & E. Perkins (Eds.)112). IEA Greenhouse Gas R&D Programme (IEA-GHG).

Iglesias, R. S., Ketzer, J. M., Melo, C. L., Heemann, R., & Machado, C. X. (2015). Carbon capture and geological storage in Brazil: An overview. *Greenhouse Gases: Science and Technology*, *5*, 119–130. https://doi.org/10.1002/ghg.1476

IPCC. (2005). Intergovernmental panel on climate change special report on carbon dioxide capture and storage. In B. Metz, O. Davidson, H. De Coninck, M. Loos, & L. Meyer (Eds.), Intergovernmental Panel on Climate Change, p. 442.

IPCC. (2021). Summary for policymakers. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthew, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate Change* (pp. 3–32). Cambridge University Press.

Kalkreuth, W., Holz, M., Levandowski, J., Kern, M., Casagrande, J., Weniger, P., & Krooss, B. (2013). The Coalbed Methane (CBM) potential and CO_2 storage capacity of the Santa Terezinha coalfield, Paraná Basin, Brazil – 3D modelling, and coal and carbonaceous shale characteristics and related desorption and adsorption capacities in samples from exploration borehole CBM001-ST-RS. *Energy Exploration & Exploitation*, *31* (4), 485–527. https://doi.org/10.1260/0144-5987.31.4.4852

Ketzer, J. M., Holz, M., Morad, S., & Al-Aasm, I. S. (2003). Sequence stratigraphic distribution of diagenetic alterations in coal-bearing, paralic sandstones: Evidence from the Rio Bonito Formation (early Permian), southern Brazil. *Sedimentology*, *50*, 855–877. https://doi.org/10.1046/j.1365-3091.2003.00586.x

Ketzer, J. M., Iglesias, R., Einloft, S., Dullius, J., Ligabue, R., & de Lima, V. (2009). Water–rock–CO_2 interactions in saline aquifers aimed for carbon dioxide storage: Experimental and numerical modeling studies of the Rio Bonito Formation (Permian), southern Brazil. *Applied Geochemistry*, *24*, 760–767. https://doi.org/10.1016/j.apgeochem.2009.01.001

Ketzer, J. M. M., Machado, C. X., Rockett, G. C., & Iglesias, R. S. (2016). *Atlas brasileiro de captura e armazenamento geológico de CO_2*. EDIPUCRS, 95 p.

Lima, V. d., Einloft, S., Ketzer, J. M., Jullien, M., Bildstein, O., & Petronin, J.-C. (2011). CO_2 Geological storage in saline aquifers: Paraná Basin caprock and reservoir chemical reactivity. *Energy Procedia*, *4*, 5377–5384. https://doi.org/10.1016/j.egypro.2011.02.521

Machado, J. L. F., & Freitas, M. A. D. (2005). *Projeto mapa hidrogeológico do Estado do Rio Grande do Sul – Relatório final, 1*. CPRM, p. 65.

Milani, E. J., Faccini, U. F., Scherer, C. M., Araújo, L. M. D., & Cupertino, J. A. (1998). Sequences and stratigraphic hierarchy of the Paraná Basin (Ordovician to Cretaceous), southern Brazil. *Boletim IG-USP*, *29*, 125–173. http://dx.doi.org/10.11606/issn.2316-8986.v29i0p125-173

Milani, E. J., França, A. B., & Medeiros, R. A. (2006). Rochas geradoras e rochas-reservatório da Bacia do Paraná, faixa oriental de afloramentos, Estado do Paraná. Roteiros Geológicos. *Boletim de Geociências da Petrobras*, *15*, 135–162.

Milani, E. J., & Thomaz Filho, A. (2000). Sedimentary basins of South America. In U. G. Cordani, E. J. Milani, A. Thomaz Filho, & D. A. Campos (Eds.), *Tectonic evolution of South America, 31* (pp. 389–449). In-Fólio Produção Editorial.

Miocic, J. M., Gilfillan, S. M. V., Roberts, J. J., Edlmann, K., McDermott, C. I., & Haszeldine, R. S. (2016). Controls on CO_2 storage security in natural reservoirs and implications for CO_2 storage site selection. *International Journal of Greenhouse Gas Control*, *51*, 118–125. https://doi.org/10.1016/j.ijggc.2016.05.019

Moreira, J. R., Romeiro, V., Fuss, S., Kraxner, F., & Pacca, S. A. (2016). BECCS potential in Brazil: Achieving negative emissions in ethanol and electricity production based on sugar cane bagasse and other residues. *Applied Energy*, *179*, 55–63. https://doi.org/10.1016/j.apenergy.2016.06.044

Pelissari, M. R. (2022). Parana Sedimentary Basin's potential for CO_2 geological storage. In R. M. L. M. Musarra, C. C. G. Tassinari, & S. San Martín Cañas (Eds.), *Perspectives to CO_2 geological storage and greenhouse gas negative emissions in south-southeastern Brazil: Paraná and Santos sedimentary basins* (pp. 41–60). Blucher.

Rockett, G. C., Machado, C. X., Ketzer, J. M. M., & Centeno, C. I. (2011). The CARBMAP project: Matching CO_2 sources and geological sinks in Brazil using geographic information system. *Energy Procedia*, *4*, 2764–2771. https://doi.org/10.1016/j.egypro.2011.02.179

Schobbenhaus, C., Gonçalves, J. H., Santos, J. O. S., Abram, M. B., Leão Neto, R., Matos, G. M. M., Vidotti, R. M., Ramos, M. A. B., and Jesus, J. D. A., 2004, *Carta Geológica do Brasil ao milionésimo, Sistema de Informações Geográficas, 46 folhas na escala 1:1.000.000, Programa Geologia do Brasil*: Brasilia, Brazil, Companhia de Pesquisa de Recursos Minerais

Smith, M., Campbell, D., Mackay, E., & Polson, D. (2011). CO_2 aquifer storage site evaluation and monitoring: Understanding the challenges of CO_2 storage: results of the CASSEM project: Heriot-Watt University, Edimburgh, Scottish Carbon Capture and Storage (SCCS). ISBN: 978-0-9571031-0-8.

SNIC. (2019). Relatório Anual: São Paulo, Sindicato Nacional da Indústria do Cimento, 41 p.http://snic.org.br/assets/pdf/relatorio_anual/rel_anual_2020.pdf.

Stephens, J. C., 2006, Growing interest in carbon capture and storage (CCS) for climate change mitigation: Sustainability: Science, Practice and Policy, 2, p. 4-13. https://doi.org/10.1080/15487733.2006.11907979

Tek, M. R. (1989). *Underground storage of natural gas: Theory and practice*. Springer Dordrecht, 472 p.

Vesely, F. F., Rostirolla, S. P., Appi, C. J., & Kraft, R. P. (2007). Late Paleozoic glacially related sandstone reservoirs in the Paraná Basin, Brazil. *AAPG Bulletin*, *91*(2), 151–160. https://doi.org/10.1306/09250605085

Weber, N., de Oliveira, S. B., Meneghini, J. R., & Tassinari, C. C. G. (2021). *A preliminary assessment of Rio Bonito Formation (Paraná Basin, Brazil) suitability for CO_2 storage*. Trondheim conference on CO_2 capture, transport and storage, Trondheim, Norway, p. 304-309.

Weniger, P., Kalkreuth, W., Busch, A., & Krooss, B. M. (2010). High-pressure methane and carbon dioxide sorption on coal and shale samples from the Paraná Basin, Brazil. *International Journal of Coal Geology*, *84*(3-4), 190–205. https://doi.org/10.1016/j.coal.2010.08.003

Zhang, D., & Song, J. (2014). Mechanisms for geological carbon sequestration. *Procedia IUTAM*, *10*, 319–327. https://doi.org/10.1016/j.piutam.2014.01.027