A PRELIMINARY ASSESSMENT OF RIO BONITO FORMATION (PARANÁ BASIN, BRAZIL) SUITABILITY FOR CO_2 STORAGE

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Abstract

Brazil presents a great potential for Carbon Capture and Storage (CCS) projects due to the various exploited oil and gas reservoirs on its coast, with many possibilities to replicate the results of the ongoing commercial project of carbon dioxide (CO_2) injection in the Lula oilfield. However, the distances from main sources of CO_2 emissions and the lack of sufficient transport infrastructure impose significant barriers for CCS deployment related to power plants and industrial activities. The Paraná Basin has a strategic location for onshore geological carbon storage in Brazil due to the proximity to a large concentration of CO_2 stationary sources. This work presents an initial assessment of Rio Bonito Formation sandstones suitability for CO_2 storage. Main parameters and properties related to reservoir quality, sealing quality and other leak risks, data coverage, regional proximity analysis, and social context analysis were compared to desirable characteristics for site selection. The analysis suggests a good potential of petrophysical available data for storage capacity and indications of effective containment of the injected CO_2 due to the presence of mudstone layers. However, it is required further characterization of the geological system and trapping mechanisms and assessments of public perception on CCS in the region.

Keywords: *Geological carbon storage, CO_2 storage site characterization, Rio Bonito Formation, Parana Basin*

1. Introduction

Brazil has several sedimentary basins with promising potential for CO_2 storage [1] [2] [3]. Offshore basins such as Campos and Santos Basins are vastly explored due to the intense upstream activity of petroleum industry. Its oil and gas depleted reservoirs are relevant candidates for CO_2 injection – whether for Enhanced Oil Recovery (EOR) or exclusively for carbon sequestration [4]. However, the distance from these sites to the Brazilian coast and especially to areas with large concentrations of stationary carbon sources imposes big logistical challenges to transport the large quantities of CO_2 to be captured. Considering Brazil's dimensions, these long distances impose greater risks to the viability of CO_2 pipelines, with higher costs for implementation and operations, in addition to higher regulatory risks. Previous studies revealed that CO_2 transportation infrastructure to oilfields constitutes a relevant constraint for economic feasibility to the deployment of CCS projects [5] [6].

In this sense, onshore sedimentary basins offer great opportunities to reduce these risks, favouring the viability of CO_2 transport by shorter routes, close to the stationary sources. Currently, one technical challenge to the development of CCS with onshore geological carbon storage in Brazil is the low level of knowledge regarding CO_2 injection capacity potential and related safety aspects. One of the most promising onshore sedimentary basins for CO_2 storage in the country is the Paraná Basin. It comprises an area that can be considered strategic for the implementation of CCS due to the presence of large concentrations of CO_2 emissions stationary sources and deep sandstone layers in the Rio Bonito Formation. In addition to industries with intensive use of fossil fuels, the regions comprised by the Paraná Basin also have a great activity of bioenergy production, which provides opportunities for the development of BECCS, with potential for negative emissions.

The present work proposes an assessment of the suitability for CO_2 storage in Rio Bonito Formation and its geological context in the Paraná Basin (Fig. 1), in order to strengthen the comprehension of critical aspects that may favour or impose challenges to CCS deployment. In addition, it is aimed to identify the main lacks in critical data and information and prior research needs to a further characterization of Rio Bonito Formation as a potential geological CO_2 storage site.

The assessment was based on literature reviews regarding: (i) main parameters related to site screening and reservoir characterization for CO_2 storage; (ii) other relevant non-geological parameters involving CCS activities; and (iii) Rio Bonito Formation and Paraná Basin available data and previous studies published.

2. Basic geological criteria for CO_2 storage suitability

Reservoir properties criteria for CO_2 storage comprises [7]:

- Sufficient depth to ensure the CO_2 supercritical phase.
- Sealing integrity to contain the CO_2 in the designated reservoir, avoiding undesirable migrations.
- Sufficient storage capacity to receive CO_2 from its stationary sources.
- Effective petrophysical reservoir properties (porosity and permeability) to ensure that CO_2 injection can be economically viable and that sufficient CO_2 can be retained.

Several previous works that include the pre-feasibility stage of geological characterization for CO_2 storage propose new workflows and methodology [8] [9] [10] and present studies focused on regional or field scale site assessment [11] [12] [13] [14] [1] [16] [17]. Most of these works show similar macro arrangements, comprehending the evaluation of geological features that indicate the reservoir potential quality of storage capacity, injectivity and containment of the injected fluid. Some publications add non-geological aspects to the evaluation requirement, mentioning logistics of the whole CCS chain and regional proximity information, and social context.

To this present proposal of a primary assessment of Rio Bonito Formation suitability to CO_2 storage, the selected site screening criteria considered the limitations of geological data availability. The analysis was focused on an initial regional site assessment in a pre-feasibility stage, aiming at finding the suitability of the geological formation for CO_2 sequestration as well as the main required data and research needs for further evaluations.

Halland et al. presented a methodology for characterization of aquifers and structures with a classification of main properties as follows [18]:

- Reservoir properties: aquifer structuring, traps, pore pressure, depth, reservoir homogeneity, net thickness, average porosity, and permeability.
- Sealing properties: sealing layer, seal thickness, seal composition, faults, and other breaks.
- Other leak risks: the presence of exploration or production wells drilled through the seal.
- Data coverage: seismic and wells.

In this context, specific reservoir properties of interest and their typical high scores parameters [18] were listed as the basis for comparison with Rio Bonito Formation data. In addition, it was included a tectonic activity in the "other leak risk" category.

Other non-geological parameters and criteria for assessing sedimentary basins for CO_2 geological sequestration presented in Bachu [8] were also considered in the present work. These additional topics for comparison include logistics issues related to accessibility to the injection site, infrastructure availability and concentration of CO_2 sources.

3. Evaluation of Rio Bonito Formation suitability to CO_2 storage

The assessment of Rio Bonito Formation characteristics for each site screening criteria formerly presented is described in the following subsections. Table 1 summarises the results compared to the desirable characteristics for geological CO_2 long-term storage.

3.1 Reservoir quality

The Rio Bonito Formation consists of interbedded orthoconglomerates, sandstones, mudstones, and coals, deposited in fluvial, deltaic, estuarine, and shallow marine environments during the early Permian [19] [20] [21]. The stratigraphic succession is subdivided into three major members, labelled from base to top: Triunfo (coastal and fluvial sandstones), Paraguaçu (marine mudstones and fine-grained sandstones) and Siderópolis (coastal and fluviatile sandstones) [21]. The Rio Bonito sandstones present promising permoporous properties, with peaks of 20% of porosity in some portions [22], favouring Rio Bonito as a CO_2 sink candidate. The total thickness varies from 60 to 135 m [20], which agrees with the 20 m minimum recommended by international guides [23] [24].

However, the Rio Bonito sandstones are quite heterogeneous, and when considering a mineral trapping for CO_2 storage, we must analyse in detail the mineralogical cementation composition of these sandstones, which can vary from calcitic, dolomitic, sideritic, kaolinitic, and pyritic, as described by Ketzer et al. [20] [25].

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 Rio Grande do Sul State, in the southern portion of Paraná Basin [26]. However, more data and studies are still needed to delimit the spatial continuity and extension of these saline aquifers.

Geological environments considered for CO_2 storage were categorized into five major systems: oil and gas reservoirs, saline formations, unmineable coal areas, shale, and basalt formations. In these systems, four trapping mechanisms are considered [27]: structural and stratigraphic trapping (physical), residual CO_2 trapping (physical), solubility trapping (geochemical), and mineral trapping (geochemical). The Rio Bonito Formation presents most of these geological systems with a high potential for CO_2 geological storage. The sandstones of the Triunfo and Siderópolis members could be considered in possible structural and stratigraphic traps where the mudstones of Paraguaçu member and Palermo Formation would act as sealing rocks. The cement with carbonatic composition in some sandstones of the Rio Bonito Formation could present an interesting potential for mineral trapping. The occurrence of saline aquifers in the Rio Bonito Formation could be better studied considering solubility trapping. Coal deposits of the Rio Bonito Formation in the southern Paraná Basin area comprise Brazil's largest coal reserve [18].

Unmineable coal areas in this region could be focused on site locations that meet the specifications for CO_2 storage.

3.2 Sealing quality

The Rio Bonito Formation has its upper contact with mudstones of Palermo Formation or Tatuí Formation, both of which are stratigraphically equivalent, having an average thickness of 100 m [21]. The base of the Rio Bonito Formation overlies the sequence of Itararé Group, commonly with sandstones superimposed over the Taciba Formation shales. Thus, the Rio Bonito sandstones are in contact with sealing rocks both at the top and at the base. Mudstones from Paraguaçu Formation can also act as local sealants depending on their occurrence, which is erratic along the basin, and may sometimes be absent [21].

A comprehensive characterization of the sealing quality requires studies relative to the reactivity of the mineral content reactions of each of these sealing candidates, considering that some preliminary sample tests have indicated the creation of preferential pathways due to dissolution process [28].

3.3 Other leak risks

The Paraná Basin is tectonically related to a divergent margin with no relation with fold belts [29], thus being in a tectonically favourable location for CO_2 reservoir and is subject to the low level of seismic activity typical of intra-plate regions [30], as recommended by IEA-GHG [24].

Although the Paraná Basin has a high potential for hydrocarbons, there are currently no active oil or gas production fields.

3.4 Data coverage

The Paraná Basin presents an extensive data set with 123 hydrocarbon exploration well data, carried out by Petrobras Company during the 1950s until the 2000s, and 2D seismic surveys covering most of its extension, as well as some local electromagnetic, magnetic and gamma surveys (http://geo.anp.gov.br/mapview). The database has already been provided by the Brazilian National Petroleum Agency (ANP) including petrophysical data of all wells and will be analysed together with seismic surveys in the next steps of this research to generate an integrated 3D geological model to better characterize specific locations with potential for CO_2 storage, mainly in the region of the state of São Paulo.

3.5 Regional proximity analysis

An initial regional approach of the Rio Bonito Formation as source-sink was conducted by Rocket et al. [33] considering only the optimal depths for CO_2 storage (800 – 2,000m) and CO_2 stationary sources location in the entire Paraná Basin (Fig. 2). The map highlights the central-northern portion of the state of São Paulo as the most favourable region for selecting CO_2 storage sites.

This region accounts for one the highest concentration of stationary CO_2 emitting sources in Brazil, which could reduce risks and costs for CO_2 transportation. In addition, the presence of bioenergy production in São Paulo can lead to opportunities to implement chains for negative emissions with BECCS. In 2020, 149 production installations in the state generated around 52 thousand cubic meters of ethanol, which represented 8% of national production [31] [32].

On the other hand, existing infrastructure in the region does not present a dense pipeline network that could be considered to find synergies for CO_2 transportation.

3.6 Social context analysis

Public perception studies regarding CCS in Brazil are still at an initial stage and none is focused specifically on the region that concerns Rio Bonito Formation potential sites for CO_2 injection. Commercial CCS activities in Brazil are conducted in oil and gas reservoirs in the Lula field [34], aiming to improve petroleum production with Enhanced Oil Recovery (EOR) technique, and present no significant impacts on public perception since it is an offshore project.

A primary approach to social factors with potential influence on public acceptance of CCS with onshore CO_2 storage was conducted by Netto et al.[35]. The study was applied to Recôncavo Basin, a sedimentary basin with intensive oil production in Brazil's Northeast region. Although this studied basin is far from Rio Bonito Formation, Netto et al. [35] indicate relevant points that could be applied to other onshore potential CO_2 injection sites. The outcomes of the research conducted with communities located in the prospective areas for CCS in Recôncavo Basin point to: (i) the lack of knowledge regarding the concept of CCS; (ii) the relevance of the previous relationship with oil and gas companies to the comprehension of benefits and advantages of CCS activities; and (iii) the trust in government and private companies can improve the community's support for CCS projects [35].

Table 1: Rio Bonito Fm. available data compared to desired reservoir properties for CO_2 storage (after Bachu [8], Halland et al.[18] and Rodosta et al. [10]).

Criteria	Properties of interest	Desirable characteristics	Rio Bonito Fm.
Reservoir quality	Aquifer structuring	Possible closures	n/a
	Traps	Defined sealed structures	Mapped layers of mudstones
	Pore pressure	Hydrostatic or lower	n/a
	Depth	800- 2500 m	800 - 4000 m
	Reservoir homogeneity	Homogeneous	High heterogeneity
	Net thickness	> 50 m	100 m (formation average)
	Average porosity	> 25 %	20%
	Permeability	> 500 mD	n/a
Sealing quality	Sealing layer	More than one seal	Some portions with more than one seal
	Seal thickness	> 100 m	100 m
	Seal composition	High clay content, homogeneous	High clay content, homogeneous
	Faults	No faulting of the seal	n/a
	Other breaks	No fracture	n/a
Other leak risks	Wells (exploration/production)	No drilling through seal	Few drillings through seal
	Tectonic activity	Low level of seismicity	Low level of seismicity
Data coverage	Availability of data from seismic and wells	3D seismic, wells through the actual aquifer/structure	2D seismic, 123 hydrocarbon exploration well data
Regional proximity analysis	Accessibility to injection site	Easy	Easy / onshore reservoir
	Infrastructure availability	Extensive	Minor
	CO_2 sources concentration	Major	Major
Social context analysis	Assessments of public perceptions on CCS	Regional assessments with indications of public support	No regional or national level assessment

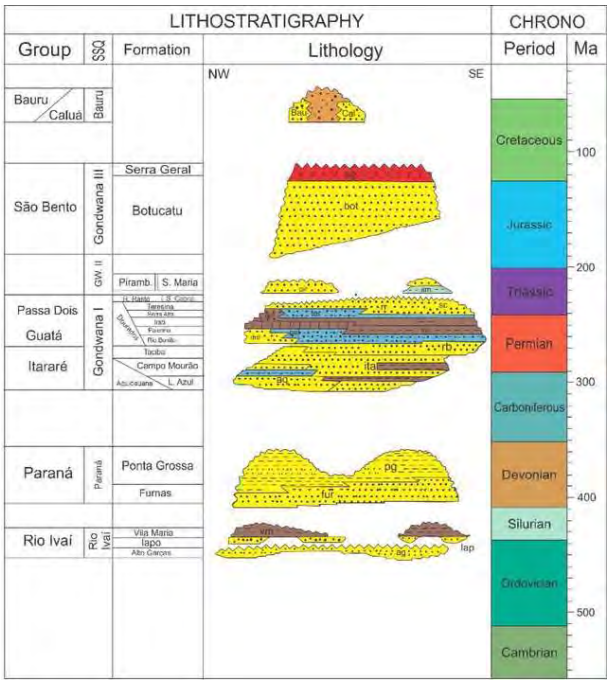

Fig. 1: Stratigraphic chart of Paraná Basin (simplified from Milani et al. [36] and Teramoto et al. [36])

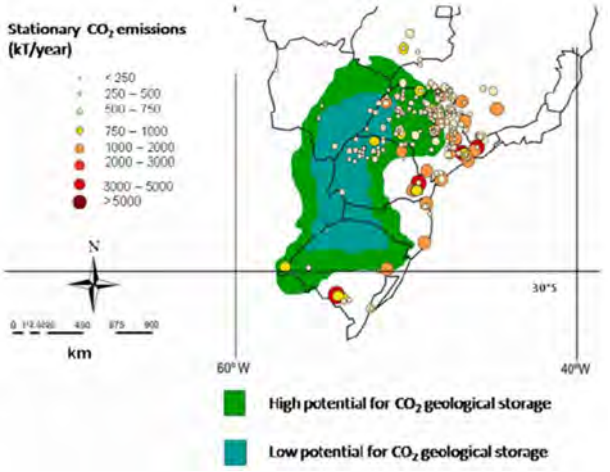

Fig. 2: CO_2 geological storage potential in Rio Bonito Fm., Paraná Basin, considering a minimum of 800 m and maximum of 2,000 m depth and CO_2 stationary sources (after Rockett et al. [33].

Conclusions

The proposed initial assessment of the Rio Bonito Formation suitability for long-term carbon storage has indicated some relevant positive geological characteristics and qualitative analysis regarding the potential region for CO_2 injection. Four geological environments favourable to CO_2 storage should be further assessed in detailed studies considering: (i) structural and stratigraphic trapping in the sandstones of the Triunfo and Siderópolis members, considering the mudstones of Paraguaçu member and of Palermo Formation as sealing rocks; (ii) potential for mineral

trapping with the carbonate cement of some sandstones. (iii) saline aquifers; and (iv) unmineable coal areas.

The reservoir quality of the Rio Bonito sandstones presents good potential for sufficient storage capacity and petrophysical reservoir properties, especially due to average depth and thickness. Also, the presence of mudstone layers above the Rio Bonito Formation suggests a promising sealing quality, with low seismicity activity. Regional proximity analysis showed good accessibility to potential sites for CO_2 injection, considering its onshore location and the great concentration of stationary CO_2 emitting sources.

Despite the considerable availability of data from seismic and exploration wells in the Paraná Basin, the site selection for long-term CO_2 injection must consider local geological structures and properties that require further studies and analysis, e.g. permoporous conditions, pore pressure, and the presence of faults and natural fractures. The evaluation of the sealing effectiveness is also critical to determine the best portions of the formation to assure the containment of the injected CO_2. In addition, public perception of CCS assessments also play a relevant role in the identification of regions with higher risks of strong opposition to CO_2 injection activity deployment. So far, there is no related assessment focused on the region nor at the national level.

Finally, for initial evaluations and analysis of Rio Bonito Formation potential for CO_2 storage capacity, injectivity and containment, we suggest that priority research efforts should be addressed to:

- Further characterization of the geological system – reservoir and sealing layers – through the refinement of geological properties and identification of faults and fractures.
- Site selection of best portions of Rio Bonito Formation for CO_2 injection.
- Analysis of reservoir simulations for potential plume migration and evolution of trapping mechanisms.
- Public perception on CCS assessment focused on targeted regions.

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References

[1] Machado, C. X., Rockett, G. C., Ketzer, J. M. M. (2013) Brazilian renewable carbon capture and geological storage map: Possibilities for the Paraná Basin. Energy Procedia 37:6105-6111. doi: https://doi.org/10.1016/j.egypro.2013.06.539

[2] 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. doi: https://doi.org/10.1002/ghg.1476

[3] 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, Porto Alegre.

[4] Rockett, G. C., Ketzer, J. M. M., Ramírez, A., van den Broek, M. (2013). CO_2 Storage Capacity of Campos Basin's Oil Fields, Brazil. Energy Procedia 37:5124-5133. doi: https://doi.org/10.1016/j.egypro.2013.06.427

[5] Merschmann, P. R. C., Szklo, A. S., Schaeffer, R. (2016). Technical potential and abatement costs associated with the use of process emissions from sugarcane ethanol distilleries for EOR in offshore fields in Brazil, International Journal of Greenhouse Gas Control, Volume 52, 2016, Pages 270-292, ISSN 1750-5836, https://doi.org/10.1016/j.ijggc.2016.07.007.

[6] da Silva, F.T.F., Carvalho, F. M., Corrêa, J.L.G., Merschmann, P.R.C., Tagomori, I. S., Szklo, A., Schaeffer, R. (2018). CO2 capture in ethanol distilleries in Brazil: Designing the optimum carbon transportation network by integrating hubs, pipelines and trucks, International Journal of Greenhouse Gas Control, Volume 71, 2018, Pages 168-183, ISSN 1750-5836, https://doi.org/10.1016/j.ijggc.2018.02.018.

[7] Vosgerau, H., Kirk, K. L., von Dalwigk, I., and Vangkilde-Pedersen, T. (2008). Site Selection Criteria. EU GeoCapacity deliverable D23 (2008) 13.

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

[9] Raza, A., Rezaee, R., Gholami, R., Bing, C. H., Nagarajan, R., Hamid, M. A. (2016). A screening criterion for selection of suitable CO_2 storage sites. Journal of Natural Gas Science and Engineering, Volume 28, 2016, Pages 317-327, ISSN 1875-5100. https://doi.org/10.1016/j.jngse.2015.11.053.

[10] Rodosta, T. D., Litynski, J. T., Plasynski, S. I., Hickman, S., Frailey, S., Myer, L. (2011). U.S. Department of /energy's site screening, site selection, and initial characterization for storage of CO_2 in deep geological formations. Energy Procedia 4:4664-4671. doi: https://doi.org/10.1016/j.egypro.2011.02.427

[11] Bachu, S., (2000). Sequestration of CO_2 in geological media: criteria and approach for site selection in response to climate change. Energy Conversion Management 41, 953-970.

[12] Bradshaw, J., Bradshaw, B.E., Allison, G., Rigg, A., Nguyen, V., Spencer, L., (2002). The potential for geological sequestration of CO_2 in Australia: preliminary findings and implications for new gas field development. Australian Petroleum Production and Exploration Association Journal 42, 25e46. part 1.

[13] Gibson-Poole, C.M., Root, R.S., Lang, S.C., Streit, J.E., Hennig, A.L., Otto, C.J., Underschultz, J.R., (2005). Conducting comprehensive analyses of potential sites for geological CO2 storage. In: Rubin, E.S., Keith, D.W., Gilboy, C.F. (Eds.), Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies, 5e9 September, Vancouver, Canada. Elsevier, Oxford, pp. 673-681.

[14] Varma, S., Underschultz, J., Dance, T., Langford, R., Esterle, J., Dodds, K., van Gent, D., (2009). Regional study on potential CO2 geosequestration in the Collie

Basin and the southern Perth Basin of Western Australia. Marine and Petroleum Geology 26, 1255e1273.

[15] Dance, T. (2013). Assessment and geological characterisation of the CO2CRC Otway Project CO_2 storage demonstration site: From prefeasibility to injection. Marine and Petroleum Geology, Volume 46, 2013, Pages 251-269, ISSN 0264-8172, https://doi.org/10.1016/j.marpetgeo.2013.06.008.

[16] Anthonsen, K. L., Aagaard, P., Bergmo, P. E. S., Gislason, S. R., Lothe, A. E., Mortensen, G. M., Snæbjörnsdóttir, S. O. (2014). Characterisation and Selection of the Most Prospective CO_2 Storage Sites in the Nordic Region. Energy Procedia, Volume 63, 2014, Pages 4884-4896, ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2014.11.519.

[17] Sun, L., Dou, H., Li, Z., Hu, Y., Hao, X. (2018). Assessment of CO2 storage potential and carbon capture, utilization and storage prospect in China, Journal of the Energy Institute, Volume 91, Issue 6, 2018, Pages 970-977, ISSN 1743-9671, https://doi.org/10.1016/j.joei.2017.08.002.

[18] Halland EK, Gjeldvik IT, Johansen WT, Magnus C, Meling IM, Pedersen S, Riis F, Solbakk T, Tappel I.(2011). CO2 Storage Atlas Norwegian North Sea. Norwegian Petroleum directorate; 2011.

[19] 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. doi: https://doi.org/10.1016/S0037-0738(03)00156-8

[20] 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. doi: 10.1046/j.1365-3091.2003.00586.x

[21] 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 29:381-399. doi: https://doi.org/10.1016/j.jsames.2009.04.004

[22] ANP - Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (2017). Bacia do Paraná: sumário geológico e setores em oferta. Superintendência de Definição de Blocos. Available at: <http://rodadas.anp.gov.br/pt/>.

[23] 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. British Geological Survey Occasional Publication, 14. Keyworth, Nottingham

[24] IEA-GHG – International Energy Agency Greenhouse Gas R&D programme (2009). CCS Site characterisation criteria In: Bachu S, Hawkes C, Lawton D, Pooladi-Darvish M, Perkins E (eds). Cheltenham, United Kingdom, pp 112.

[25] 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. doi: https://doi.org/10.1016/j.apgeochem.2009.01.001

[26] Machado, J. L. F., Freitas, M. (2005). Projeto mapa hidrogeológico do Estado do Rio Grande do Sul – Relatório final. CPRM, Porto Alegre, Brasil, pp 65.

[27] Metz, B., Davidson, O., De Coninck, K., Loos, M., Meyer, L., eds. (2005), IPCC special report on carbon dioxide capture and storage, p. 431.

[28] de Lima, V., 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. doi: https://doi.org/10.1016/j.egypro.2011.02.521

[29] Milani, E. J., Thomaz Filho, A. (2000). Sedimentary basins of South America In: Cordani UG, Milani EJ, Thomaz Filho A, Campos DA (eds) Tectonic Evolution of South America. In-Fólio Produção Editorial, Rio de Janeiro, Brazil, pp 389-449.

[30] Berrocal, J., Fernandes, C., Bassini, A., Barbosa, J. R. (1996). Earthquake hazard assessment in southeastern Brazil. Geofísica Internacional 35:257-272.

[31] ANP – Agência Nacional do Petróleo, Gás Natural e Biocombustíveis. Mapa Dinâmico: Produtores de Etanol. Available at: https://app.powerbi.com/view?r=eyJrIjoiZWU1MTc0ZjYtMjVhYi00YTEwLWJhODMtODQ0MDdhNmJiMWYwIiwidCI6IjQ0OTlmNGZmLTI0YTYtNGI0Mi1iN2VmLTEyNGFmY2FkYzkxMyJ9&pageName=ReportSection8aa0cee5b2b8a941e5e0%22.

[32] ANP – Agência Nacional do Petróleo, Gás Natural e Biocombustíveis. Painel Dinâmico: Produção de Etanol. Available at: https://app.powerbi.com/view?r=eyJrIjoiZWU1MTc0ZjYtMjVhYi00YTEwLWJhODMtODQ0MDdhNmJiMWYwIiwidCI6IjQ0OTlmNGZmLTI0YTYtNGI0Mi1iN2VmLTEyNGFmY2FkYzkxMyJ9&pageName=ReportSection8aa0cee5b2b8a941e5e0%22.

[33] Rockett, G. C., Machado, C. X., Ketzer, J. M. M., Centeno, C. I. (2011). The CARBMAP project: Matching CO2 sources and geological sinks in Brazil using geographic information system. Energy Procedia 4:2764-2771. doi: https://doi.org/10.1016/j.egypro.2011.02.179

[34] 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 (2) (2015), pp. 119-130, https://doi.org/10.1002/ghg.1476.

[35] Netto, A. N. A., Câmara, G., Rocha, E., Silva, A. L., Andrade, J. C. S., Peyerl, D., Rocha, P. (2020). A first look at social factors driving CCS perception in Brazil: A case study in the Recôncavo Basin, International Journal of Greenhouse Gas Control, Volume 98, 2020, 103053, ISSN 1750-5836, https://doi.org/10.1016/j.ijggc.2020.103053.

[36] Teramoto, E. H., Gonçalves, R. D., Chang, H. K. (2020) Hydrochemistry of the Guarani Aquifer System modulated by mixing with underlying and overlying hydrostratigraphic units. Journal of Hydrology: Regional Studies 30:100713. doi: https://doi.org/10.1016/j.ejrh.2020.100713

[37] Milani, E. J., França, A.B., Medeiros, R.A. (2007) Roteiros Geológicos Boletim de Geociências da Petrobras, 15 (1), pp. 135-162