Favorability mapping for carbon storage in basaltic rocks of the Paraná Basin

This manuscript is a non peer-reviewed preprint submitted to EarthArXiv. This manuscript was submitted to International Journal of Greenhouse Gas Control for peer review and is currently under consideration.

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December 19, 2024

Abstract

Carbon capture and storage (CCS) is a critical technology to mitigate climate change by reducing atmospheric CO_2. The Paraná Basin, with its extensive basaltic formations, offers potential for large-scale CO_2 storage. However, determining the most favorable areas for CCS remains challenging due to the complex interplay of geological, geochemical, and logistical factors. This study addresses this gap by developing a favorability map for CO_2 storage in the Serra Geral Group basalts within the Paraná Basin, focusing on the western region of the State of Santa Catarina, Brazil. Using the Fuzzy Analytic Hierarchy Process (Fuzzy AHP), we integrated multiple criteria, including geological, geochemical, and emissions sources data. Key findings indicate that the northern and eastern areas of the region exhibit the highest favorability for CO_2 storage, driven by optimal porosity-permeability values and proximity to significant CO_2 emitters. This study provides a detailed favorability map highlighting optimal areas for CCS, offering valuable insights for future exploration and investment. The results advance CCS technology in basaltic formations and contribute to climate change mitigation by identifying the most promising sites for effective carbon storage.

Keywords: Carbon Capture and Storage · Carbon fixation in basalt · Fuzzy AHP · Serra Geral · Climate Change

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) set the goal of limiting global temperature rise to 1.5°C above pre-industrial levels to avoid the impacts of climate change (IPCC et al., 2018). However, current global greenhouse gas emissions, primarily from human activities, are driving the planet toward a future with more frequent and intense extreme weather events, rising sea levels, and damage to ecosystems.

Carbon dioxide (CO_2) is the main contributor to climate change, accounting for over 75% of total greenhouse gas emissions (Ritchie et al., 2020). As CO_2 accumulates in the atmosphere, it traps heat, causing global temperatures to rise. In this context, carbon capture and storage (CCS) is a key technology to combat climate change by capturing CO_2 emitted from stationary sources, storing it underground, and preventing large amounts of CO_2 from reaching the atmosphere (IPCC et al., 2018).

CO_2 can be stored in various geological formations, such as sedimentary rocks, mafic and ultramafic rocks, saline reservoirs, as well as oil, gas, and coal reservoirs. Among these options, basalts stand out due to their unique chemical and physical properties, making them an attractive option for carbon storage due to their abundance and capacity for carbon mineralization (Cartier, 2020; Snæbjörnsdóttir et al., 2020). These rocks are rich in calcium and magnesium, which react with CO_2 to form minerals like calcite and magnesite, securely sequestering carbon (Oelkers et al., 2008; Snæbjörnsdóttir et al., 2020).

The Paraná Basin in Brazil, particularly the Serra Geral Group, represents one of the largest basaltic provinces in the world, with significant potential for carbon storage (Piccirillo & Melfi, 1988). The thick, extensive flows of basalt in this region offer suitable conditions for CCS due to their permeability, porosity, and mineral composition. However, a comprehensive site evaluation is necessary to identify the most favorable areas for carbon fixation in basaltic rocks. By integrating geological, geochemical, and logistical factors, this study aims to provide a detailed favorability map to guide future CCS initiatives in the Paraná Basin.

1.1 Carbon capture and storage in basalts

Carbon fixation in basaltic rocks involves a series of processes that allow the permanent storage of carbon dioxide (CO_2) through mineralization. This mechanism is particularly relevant in the context of carbon capture and storage, which aims to mitigate climate change.

CO_2 injection into basalts can occur in two main ways: (i) injection of CO_2 in a supercritical state and (ii) injection of CO_2-dissolved fluids (Snæbjörnsdóttir et al., 2020). In the first method, CO_2 is injected in a supercritical state, where it exhibits both gas and liquid properties, allowing it to permeate the rock more effectively. This method enhances the interaction between CO_2 and basaltic minerals and was used by the Big Sky Carbon Sequestration Partnership (BSCP) in the northwestern USA, near Wallula, Washington (Gislason & Oelkers, 2014).

In the second method, CO_2 is dissolved in water (creating CO_2-dissolved fluids) and then injected into the basalt. This method can lead to faster mineralization rates as the dissolved CO_2 reacts with the rock's minerals and does not require a caprock. This approach was used by the CarbFix project in southwestern Iceland (Snæbjörnsdóttir et al., 2020).

1.2 Chemical reactions involved in carbon fixation

The chemical reactions responsible for carbon fixation in basaltic rocks play a pivotal role in the long-term sequestration of CO_2, forming the foundation for secure and stable carbon storage solutions. This process is primarily driven by carbonation and hydrolysis reactions, which convert CO_2 into solid carbonate minerals such as calcite ($CaCO_3$), magnesite ($MgCO_3$), and siderite ($FeCO_3$) (Matter & Kelemen, 2009; Snæbjörnsdóttir et al., 2020). The initial stage begins with the dissolution of CO_2 in formation water, producing carbonic acid (H_2CO_3), which subsequently dissociates into bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), and hydrogen ions (H^+) as represented in reaction (1):

$$\mathrm{CO_2\,(aq) + H_2O = H_2CO_3 = HCO_3{}^- + H^+ = CO_3{}^{2-} + 2\,H^+} \tag{1}$$

Bicarbonate and carbonate ions, critical intermediates, react with divalent metal cations like calcium (Ca^{2+}), magnesium (Mg^{2+}), and iron (Fe^{2+}), abundant in basaltic rocks. These interactions result in the precipitation of stable carbonates through reactions (2) and (3):

$$\mathrm{(Ca, Mg, Fe)^{2+} + HCO_3{}^- \longrightarrow (Ca, Mg, Fe)CO_3 + H^+} \tag{2}$$

$$\mathrm{(Ca, Mg, Fe)^{2+} + CO_3{}^{2-} \longrightarrow (Ca, Mg, Fe)CO_3} \tag{3}$$

The release of hydrogen ions during these reactions introduces a potential challenge by increasing the acidity of the surrounding solution, which could hinder mineralization rates. This issue is mitigated by the dissolution of other minerals in basalt, such as calcium plagioclase, which reacts with the excess of hydrogen ions, maintaining pH stability and promoting continuous reaction progress. Reaction (4) illustrates this buffering mechanism:

$$\mathrm{CaAl_2Si_2O_8 + 2\,H^+ + H_2O \longrightarrow Ca^{2+} + Al_2Si_2O_5(OH)_4} \tag{4}$$

This interplay between carbonate formation and hydrogen ion consumption exemplifies the dynamic equilibrium that sustains efficient carbon fixation. The effectiveness of these reactions is influenced by environmental factors such as temperature, pressure, pH, and the mineralogical composition of the basalt. These variables collectively dictate the rate and extent of CO_2 immobilization within the rock matrix, ensuring its stability over geological time scales.

Understanding the nuances of these chemical processes is fundamental to evaluating the viability of basaltic formations for carbon storage. This study focuses on assessing the suitability of basaltic rocks in the Serra Geral Group for carbon capture and storage using a multi-criteria decision-making framework. By employing the Fuzzy AHP method, this research integrates geological, geophysical, and geochemical data to develop a favorability map, identifying optimal locations for CO_2 storage. The findings aim to advance CCS technologies in basalts, contributing to climate change mitigation through robust and sustainable carbon storage strategies.

2 Material and Methods

2.1 Study area

The Paraná Basin in Brazil hosts extensive basaltic rock flows, collectively referred to as the Serra Geral Group (SGG) (Piccirillo & Melfi, 1988). These rocks erupted during the Early Cretaceous period (Renne et al., 1992; Turner et al., 1994), forming a sequence up to 1.7 km thick and covering an area of approximately 1.6 million km², with a volume of 800,000 km³ (De Almeida, 1986; Eyles & Eyles, 1993; Piccirillo & Melfi, 1988; Renne et al., 1992). This extensive volume and area make the SGG one of the largest magmatic provinces globally, with significant potential for carbon dioxide fixation.

This study focuses on the basalts located in the western portion of the state of Santa Catarina (Figure 1). These basaltic rocks display significant compositional variations (Nardy et al., 2008; Wildner et al., 2014) and are situated near stationary sources that could benefit from carbon storage (Ketzer et al., 2016). Furthermore, the area has good data coverage, making it an ideal candidate for prospective research.

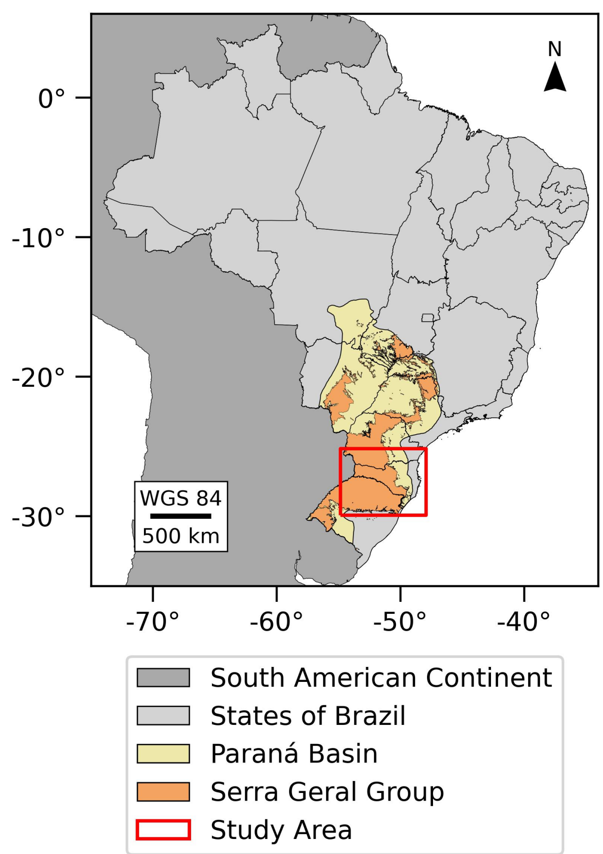

Figure 1: Location map of the study area. The focus is the basaltic rocks in the Serra Geral Group area at the Paraná Basin in the State of Santa Catarina.

2.2 Multi-criteria decision method

There are several ways to determine the potential for exploration in an area. Bonham-Carter (1994) categorizes the various potential mapping techniques into two distinct approaches: knowledge-driven, where the model criteria are defined by an expert, and data-driven, where the model is calculated based on existing data (known occurrences).

Since there is not yet a dataset on carbon injection and storage in the Paraná Basin to calibrate a data-driven model, the approach used in this case was knowledge-driven. The fuzzy analytic hierarchy process (Fuzzy AHP) method was chosen for this study due to its ability to manage uncertainties and subjective judgments (Kahraman, 2008). This multi-criterion decision-making method allows for the comparison and ranking of different alternatives based on a set of criteria, facilitating the selection of the most suitable option for carbon storage.

The Fuzzy AHP method was selected over the traditional AHP because it provides a more realistic representation of the uncertainties and subjectivities inherent in the decision-making process. Traditional AHP uses exact numbers, while Fuzzy AHP employs fuzzy numbers to better capture the nuances of human judgments (Buckley, 1985; Chang, 1996; Wang & Elhag, 2006).

The application of Fuzzy AHP begins with structuring the problem and defining the final objective, criteria, and alternatives. Next, a pairwise comparison matrix is created for the criteria, assigning relative importance weights. These weights are transformed into fuzzy weights, which are then calculated using the geometric mean. Finally, the fuzzy weights are defuzzified and normalized to produce the final weights (Buckley, 1985; Chang, 1996).

This methodology assigns weights to different criteria layers, which are then overlayed to create a decision map. This map identifies the most suitable locations for carbon storage based on the combined influence of all criteria (Malczewski & Rinner, 2015; Zadeh, 1965). This approach has proven successful in various applications, including land suitability analysis and environmental planning (Eastman et al., 1993; Şener et al., 2006).

2.3 Criteria for favorability

To construct a favorability map for carbon storage, it is essential to identify relevant criteria. Snæbjörnsdóttir et al. (2014) proposed criteria for selecting areas in Iceland, including water availability for injection, temperature, partial pressure of CO_2, porosity, permeability, depth, and water contamination risk. Raza et al. (2022) expanded the criteria to 20 factors, such as igneous rock type, porosity, fracture presence, depth, CO_2 density, rock composition, pressure, temperature, water type, injection fluid composition, rock wettability, thickness, permeability, well type, water availability, seal capacity, seal geometries, distance to emission sources, and CO_2 emissions near storage sites. Rodosta et al. (2011) provided a broader set of criteria, not limited to basalts, including formation depth, containment system, storage resources, protected areas, population centers, development resources, gas pipelines, demographic trends, and land use. These criteria were adapted for this study based on available data.

The criteria used were (Figure 2): elevation of the Serra Geral Group base, thickness, density, porosity, permeability, distance from emission sources, intensity of emission sources, distance to geological lineaments, water well flow rate, and concentrations of CaO, MgO, and Fe_2O_3t.

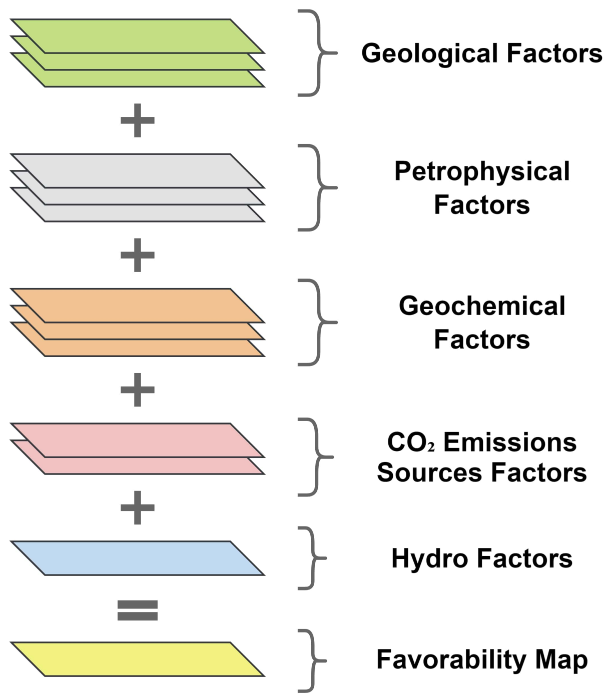

Figure 2: Flowchart illustrating the generation of the favorability map. The original interpolated maps are normalized, fuzzy weights are applied, and the maps are summed to create the final map.

2.4 Data sources

To create the layers used to generate the favorability map, it was necessary to use different data sources. Figure 3 presents the location maps of the data used. To generate the base elevation and thickness maps (Figure 3a), data from Descovi Filho (2015) were used.

The lineament data (Figure 3b) were derived from the regional structural map of Soares et al. (2007), in which the lineaments were delineated from the overlay of gravimetric, magnetometric, radar, and satellite image data.

Exploratory wells data from the Paraná Basin (Figure 3c) (ANP-SGB, 2023) were used by Alves and Riccomini (2024) along with machine learning models to predict density, porosity, and permeability. The data were interpolated using regularized splines with tension.

Data from SIAGAS-SGB (SGB-CPRM, 2023) (Figure 3d) were used to generate the flow rate map of tubular wells in basaltic rocks of the Serra Geral Group.

CO_2 emission intensity and distance maps were generated using data on stationary CO_2 emission sources in Santa Catarina, from MapBiomas (2023). These data included fossil and biomass thermal power plants with at least 1 MW of power (Figure 3e). Emissions were estimated assuming 152 days per year of operation at maximum efficiency (Ketzer et al., 2016), and multiplied by an emission factor based on fuel type (FGV-PBGP, 2023).

Geochemical data of the basalts (Figure 3f) used to generate the interpolated maps of concentrations of CaO, MgO and Fe_2O_3t were compiled from Garland et al. (1996), Peate and Hawkesworth (1996), Piccirillo et al. (1989), Petrini et al. (1987), Fodor et al. (1985), Bellieni et al. (1984), Nardy et al. (2008, 2011), Mantovani, Cordani, and Roisenberg (1985), Mantovani, Marques, et al. (1985), Peate et al. (1999), Chmyz et al. (2020), Rämö et al. (2016), Pinto et al. (2011), Pinto and Hartmann (2011), Besser et al. (2018), Marques et al. (1989), Ruegg (1976), Frozza (2015), Sartori and Bortolotto (1982). In the case of Fe, authors reported data as FeO (ferrous iron), Fe_2O_3 (ferric iron), FeOt (when all Fe has been mathematically converted to FeO), or Fe_2O_3t (when all Fe has been mathematically converted to Fe_2O_3). Thus, the data were standardized as Fe_2O_3t (Le Maitre et al., 2005; Winter, 2014) using equations (5), (6), and (7):

$$\mathrm{F_2O_{3/}FeO} = 0.15 \quad \text{to} \quad 0.5 \tag{5}$$

$$\text{FeOt} = \text{FeO} + 0.8998(\text{Fe}_2\text{O}_3) \tag{6}$$

$$\text{Fe}_2\text{O}_3\text{t} = \text{Fe}_2\text{O}_3 + 1.113(\text{FeO}) \tag{7}$$

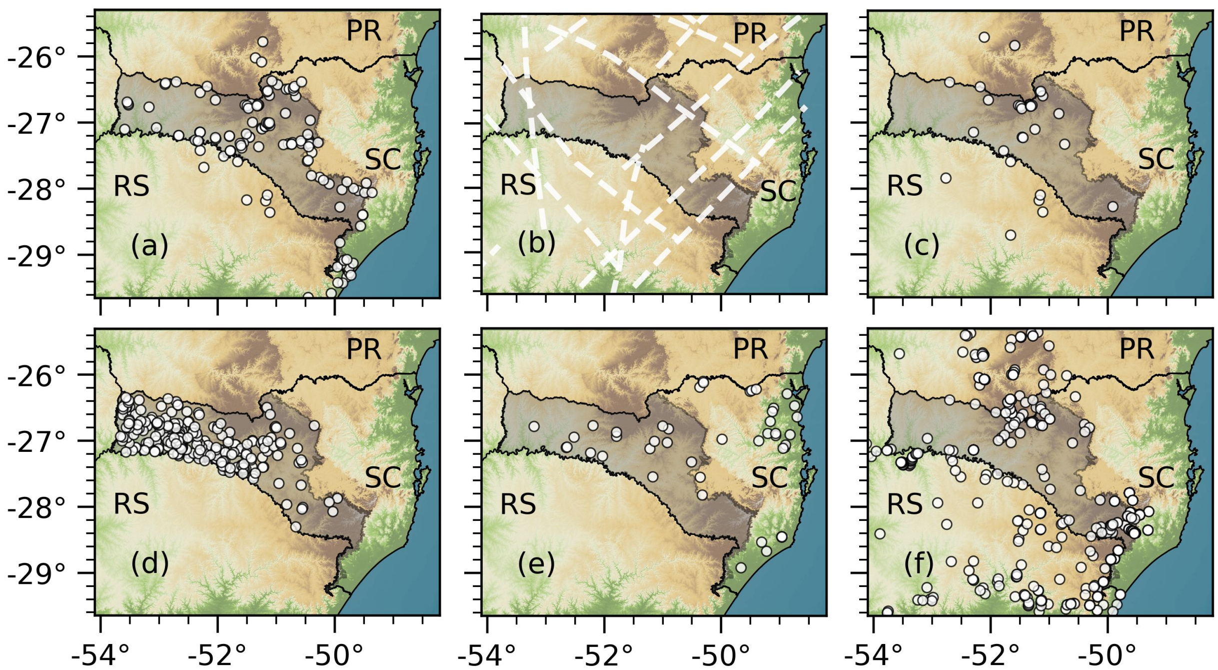

Figure 3: Location maps of data used to generate favorability map. The shaded area represents the location of the Serra Geral Group in the State of Santa Catarina, Brazil. (a) Elevation of the base and thickness of the Serra Geral Group. (b) Lineaments associated with geological faults. (c) Exploratory wells used for density, porosity, and permeability maps. (d) Flow rate data from hydro wells in the Serra Geral layer. (e) Stationary emission sources data. (f) Geochemical data of the basalts (CaO, MgO, and Fe_2O_3t).

Figure 4 illustrates CO_2 emission intensity from stationary sources in Santa Catarina. Most sources are of low to medium intensity. The highest emissions are in the northeast and southeast, with the northeast source being a natural gas power plant emitting 248.7 KtCO_2/yr, and the southeast sources being three coal power plants (Jorge Lacerda Thermoelectric Complex) emitting a total of 1138.9 KtCO_2/yr.

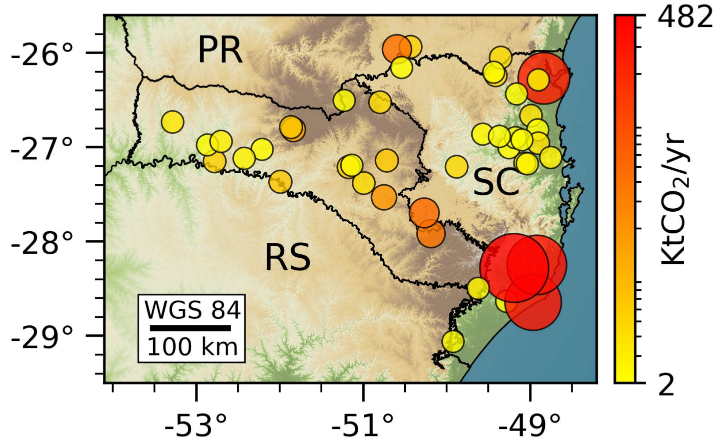

Figure 4: Map of CO_2 emissions from stationary sources in Santa Catarina, Brazil. The data includes fossil and biomass thermoelectric plants with at least 1 MW of power. Larger circles indicate higher emissions. Sources are shifted from their original locations to avoid overlapping.

2.5 Storage capacity

Assessing the CO_2 storage capacity in basalts is critical for evaluating their potential for carbon capture and storage. Vishal et al. (2021) listed various methods for this assessment. For this study, the method proposed by Snæbjörnsdóttir et al. (2014) was employed, which considers net thickness, porosity, storage efficiency (ranging from 18.8 to 48.7 kg/m³), and area.

Since the Serra Geral Group (SGG) is an outcropping formation, the first top 100 meters were excluded from the calculation as a safety margin to ensure the accuracy and reliability of the storage capacity estimates.

3 Results

This study integrates 12 different maps to generate a favorability map for CO_2 storage in basaltic rocks of the Serra Geral Group within the Paraná Basin. To create the final map, Fuzzy AHP analysis was applied to rank and attribute weights to the layers based on their importance.

Figure 4 presents the compilation of all the maps (layers) used to generate the favorability map. To realistically assess the feasibility of a region for carbon capture and storage, the analysis considers geological, petrophysical, geochemical, emission sources, and hydro factors. The elevation of the base map (Figure 4a) illustrates the trend rising from west to east, while the thickness map (Figure 4b) indicates a very deep region northwest, consistent with the deep part of the Paraná Basin in the northwest of the State of Santa Catarina. The average thickness of the Serra Geral Group in the state, obtained from the interpolated map, is 707.3 m.

The distance to lineaments map (Figure 4c) is a crucial factor to integrate into the analysis to mitigate risks and ensure long-term storage. The northern region is the furthest from any lineament (87.3 km). Closer regions can still be used for CCS, as evidenced by the Carbfix project in Iceland, which is located within the active rift zone of the Mid-Atlantic Ridge (Matter & Kelemen, 2009; Snæbjörnsdóttir et al., 2014).

The petrophysical properties maps (Figures 4d, 4e, 4f) are important for evaluating the capacity of CO_2 storage. The density map indicates a high-density region in the southeast, near the largest stationary sources in the state (Jorge Lacerda Thermoelectric Complex), with an average density of 2.7 g/cm³. The porosity and permeability maps present similar patterns, with high areas in the north and a low NE-SW trend in the middle (average porosity 3.2%, average permeability 3.5 μD). The high area on the porosity map is larger, and the low trend line on the permeability map is more intense.

The flow rate of hydro is important because, during the injection process, CO_2 is dissolved in water and interacts with reactive basalts (Gislason & Oelkers, 2014). The flow rate map (Figure 4g) shows a high variability pattern, indicating sufficient water for CCS in most regions, with a minimum of 0.1 m³/h, an average of 16.3 m³/h, and a maximum of 53.6 m³/h.

Emission source data are crucial for assessing the feasibility of a geological storage project. Ideally, a project should be located near several stationary sources that emit enough CO_2 to make it economically viable. In Figures 4h and 4i, despite the proximity to sources within the Serra Geral area, these sources exhibit medium to low intensity, with major emitters located outside the area, along the state's coast.

CaO, MgO, and Fe_2O_3t are essential for carbon storage in basalts, as they react with CO_2 to form stable carbonate minerals, effectively sequestering carbon dioxide and enhancing the rock's capacity for long-term storage. Figures 4j, 4k, and 4l indicate different propitious areas: the high concentration area of the CaO map is in the extreme west, in the MgO map it is in northwest, and in the Fe_2O_3t map it is in the center-south.

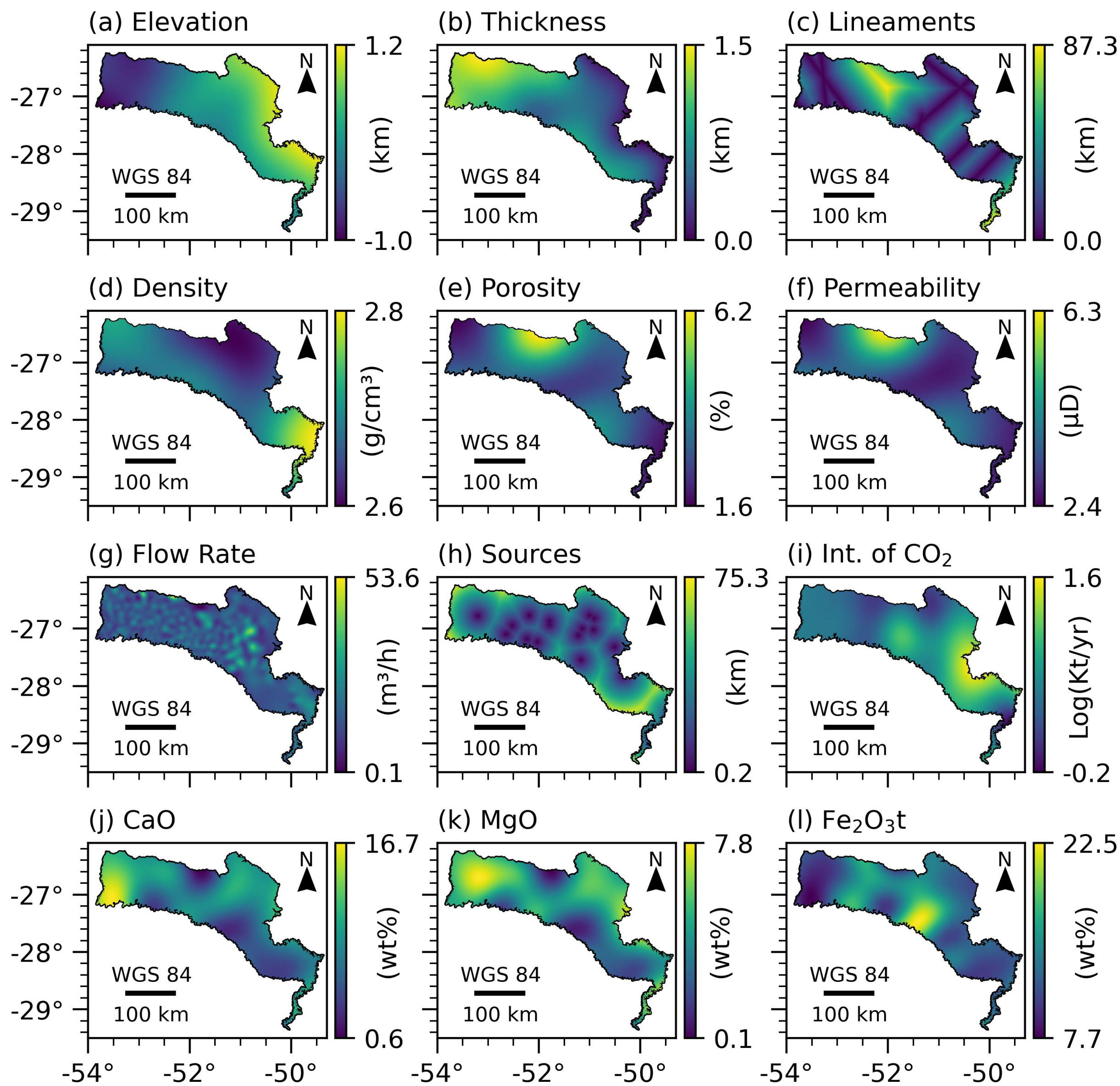

Figure 5: Maps used to generate the favorability map. (a) Elevation of the base map. (b) Thickness map. (c) Distance to lineaments map. (d) Density map. (e) Porosity map. (f) Permeability map. (g) Flow rate of hydro wells map. (h) Distance to stationary sources map. (i) Intensity of CO_2 emissions map. (j) CaO map. (k) MgO map. (l) Fe_2O_3t map.

To integrate these diverse factors and create a comprehensive favorability map, appropriate weights were assigned to each parameter based on their relative importance to CO_2 storage. This process ensures that the final map accurately reflects the combined influence of geological, petrophysical, geochemical, and logistical considerations.

Figure 5 presents the ranking of the layers used to generate the favorability map, where the greater the normalized weight, the more that layer impacts the final map. Factors related to stationary sources have the most impact on the final map, with a sum of normalized weights of 0.401 (40.1% influence). The two major petrophysical parameters follow with 0.117 each (total 23.4% influence). Geochemical parameters contribute 0.075 (total 22.5% influence), and other parameters considered less important for CO_2 storage in basalts contribute 13.9% influence.

The consistency ratio evaluates the acceptability of the consistency of comparisons. The obtained CR of 0.04 (< 0.1 or 10%) indicates that the judgments made in the pairwise comparison matrix are highly consistent and reliable for decision-making purposes.

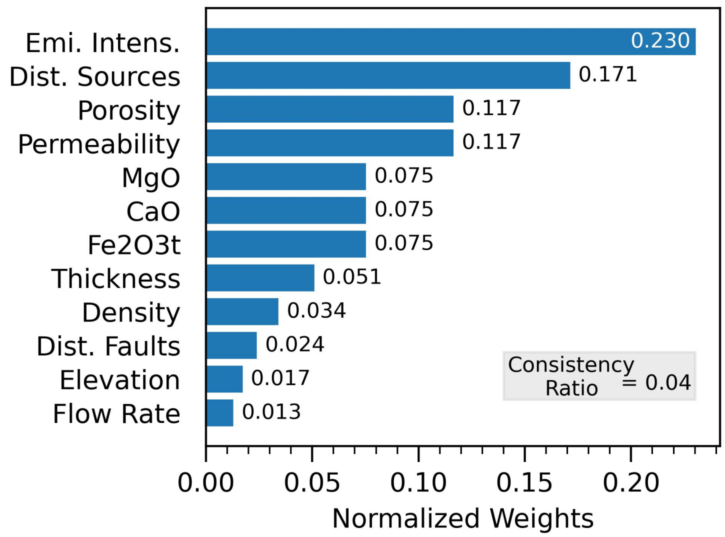

Figure 6: Final fuzzy weights from the Fuzzy AHP analysis. The consistency ratio of 0.04 is well below the upper limit of 0.1, indicating that the judgments made in the pairwise comparison matrix are highly consistent.

The 12 maps represent different properties and indicate various favorable areas for CO_2 storage, necessitating their integration for a robust and comprehensive analysis. Fuzzy weights were assigned to the normalized maps based on the Fuzzy AHP analysis. The integration of these weighted maps resulted in the favorability map.

Figure 7 presents the areas identified by their favorability potential for CO_2 storage in the basaltic rocks of the Serra Geral Group. The most favorable areas are in the north and east. The northern area is associated with the highest porosity-permeability values, while the eastern area is closer to the largest stationary sources in the state's coastal region. Most other areas are identified as moderate to high in favorability. The area with very low favorability is situated in the south.

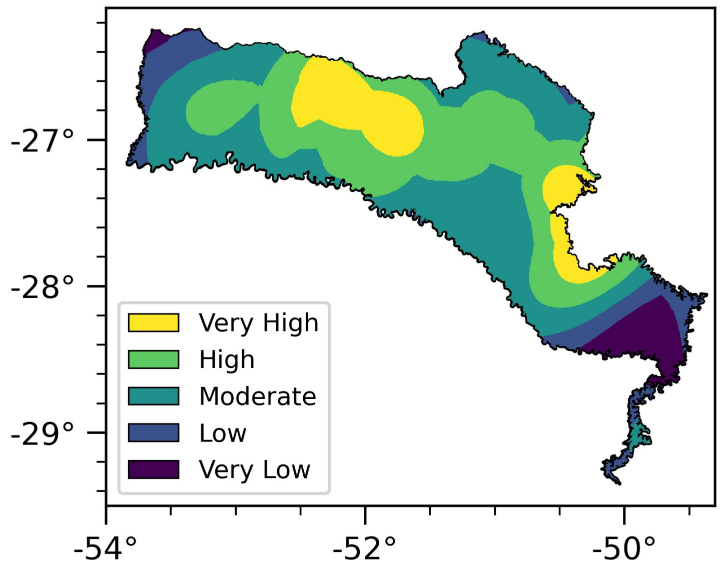

Figure 7: Favorability map for CO_2 storage in basalts. The final map was created through the integration of 12 maps with weights attributed using a Fuzzy AHP analysis.

The State of Santa Catarina contains 45 fossil and biomass thermoelectric plants, each with at least 1 MW of power, emitting approximately 1,653 KtCO_2 annually. The very high favorability area is near seven low to medium emission sources, collectively emitting approximately 126.5 KtCO_2 annually (7.7% of total emissions). The very high favorability area has the capacity to store 3 to 8 GtCO_2, while the total Serra Geral area can store between 17 to 44 GtCO_2.

4 Discussion

The favorability map integrates different maps to indicate suitable regions for CCS in basalts. The northern very high favorability area contains high porosity-permeability properties, allied with other favorable geological and logistical conditions. In contrast, the eastern area has weaker geological conditions but is closer to major stationary sources. The fact that the northern area is far from major geological lineaments makes it an appropriate place to prevent CO_2 leakage, ensuring structural integrity and long-term stability.

The economic viability of a CCS project is critical; being in a region with optimal geological conditions and proximity to sufficient anthropogenic sources directly impacts the project's success. Although the most favorable area is not close to the Jorge Lacerda Thermoelectric Complex (the largest stationary source of CO_2 in the state), it is near seven sources that emit 126.5 KtCO_2 annually. This amount may be sufficient for a viable project, considering that the Carbfix demonstration plant at Hellisheidi has been operational since 2014, injecting about 12 KtCO_2 and 6 KtH2S annually (von Strandmann et al., 2019; Ratouis et al., 2022).

To achieve a possible breakeven in a CCS project, other factors must be considered, such as attractive carbon prices, robust governmental incentives (research, subsidies, tax credits), and a well-defined legislative framework that provides clarity and stability for long-term investments.

5 Conclusions

To assess the favorability of a region for carbon capture and storage in basalts, a comprehensive analysis of various features is necessary. The overlapping of 12 different maps, with weights provided by a Fuzzy AHP analysis, generated a favorability map for CCS in basaltic rocks of the Serra Geral Group in the Paraná Basin, Brazil.

The favorability map indicates areas with very low to very high potential. The very high favorability areas are in the west and north parts of the map. The northern area is driven by high porosity and permeability values, while the eastern area is influenced by high-intensity sources along the state's coast. These areas have the capacity to store 3 to 8 GtCO_2, sufficient for the 126.5 KtCO_2/yr emitted by surrounding stationary sources.

The findings of this study have significant implications for future research and industry. Identifying high-potential areas for CO_2 storage can guide targeted exploration and development efforts, optimizing resource allocation and reducing costs. Additionally, this favorability mapping approach can be applied to other regions with similar geological settings, enhancing global CCS strategies. This work contributes to the advancement of carbon capture and storage technologies, promoting sustainable practices and supporting efforts to mitigate climate change.

6 Acknowledgments

The authors are grateful for the financial support from the Human Resources Program of the National Agency of Petroleum, Natural Gas, and Biofuels (PRH-ANP), supported with resources coming from the investment of qualified oil companies in the R&D Clause of ANP Resolution No. 918/2023 (PRH 33.1 - Regarding the announcement No. 1/2018/PRH-ANP; FINEP/FUSP/USP Agreement Ref. 0443/19). C. Riccomini is funded by the Research Productivity Grant #307471/2022-5 of CNPq-Brazil.

7 Supplementary data

The supplementary materials include the Excel sheet containing the Fuzzy AHP matrix, and the Jupyter Notebook with the Python code for fuzzy weight calculations. Additionally, the materials provide the raster files used to generate the favorability maps, including the favorability map itself, as well as the data sources required for generating the interpolated maps.

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