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Petrophysical properties and physical characteristics of lava flows from Serra Geral Group in Paraná State, Brazil and its relevance for CO2 storage

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Abstract Summary

Volcanic reservoirs represent strong candidates for CO_2 storage. This research investigates the volcanic lithofacies in the Paraná state focusing on their petrophysical properties and microstructural characteristics. Outcrop analogs are used to support the interpretation of the subsurface well log data and to characterize volcanic stacking patterns providing insights into the reservoir architecture. Outcrop samples were collected for petrophysical analysis (density, porosity and permeability under different pressure). Fifteen wells were interpreted using gamma-ray, sonic, density, neutron porosity and photoelectric factor. Those methods combined allows the identification of lithofacies with the greatest potential to act as reservoirs and seals, the assessment of microstructures controlling porosity and permeability, and provides critical information of the potential of Serra Geral Group as a CO_2 storage and offers a practical framework for interpretation in areas lacking data.

Introduction

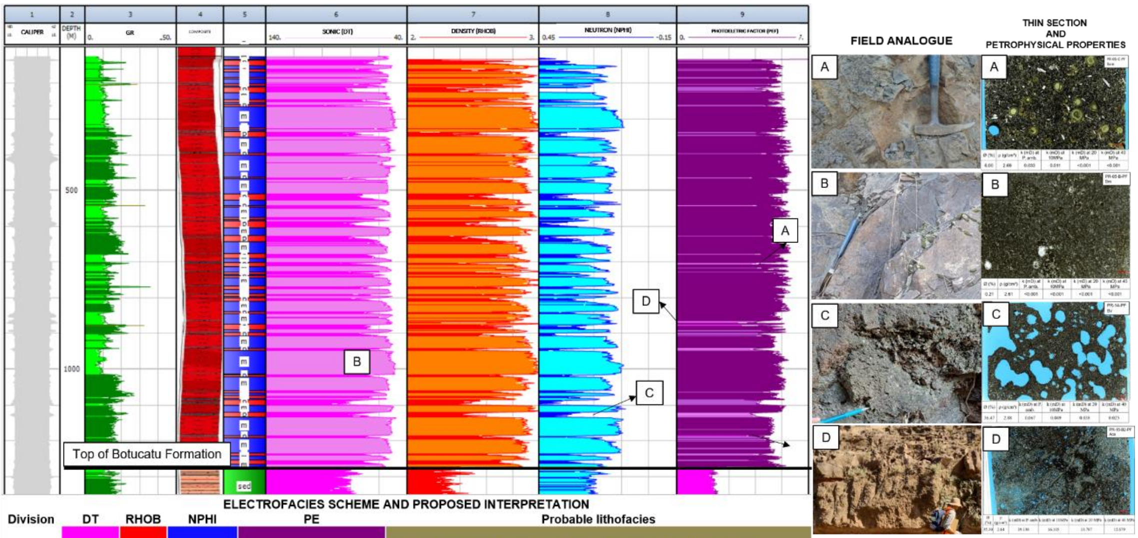
One of the major challenges today faced by society is the global warming (IPCC, 2018). Carbon capture and storage (CCS) is proposed as one the main strategies to reduce CO_2 emissions (IPCC, 2018; Global CCS Institute, 2022). In this context, Large Igneous Provinces (LIPs) has emerged as potential candidate for carbon storage due to their large volumes and extensive areal coverage (Millet et al., 2024). Additionally, basalts are rich in elements such as Ca^{2+}, Mg^{2+}, and Fe^{2+}, which react with dissolved carbon dioxide to form stable carbonate minerals, providing a permanent and secure form of CO_2 sequestration (McGrail et al., 2003; Oelkers et al., 2008; Matter and Kelemen, 2009). The Paraná-Etendeka Igneous Province (PEIP) classified as a LIP, originated within the rifting and opening of the South Atlantic Ocean during the Early Cretaceous (Bellieni et al., 1984a; Piccirillo et al., 1988; Peate, 1990). The Brazilian segment of the PEIP is represented by the Serra Geral Group (SGG), which spans an area of approximately 917,000 km², with an estimated volume exceeding 1,400,000 km³ (Abdelmalak et al., 2025, and is located near major CO_2 emission centers (Ketzer et al., 2016). To better assess the potential of the SGG as a target for CO_2 storage, a detailed subsurface characterization of the present lithofacies and their stacking patterns is necessary Few researches were dedicated to understand Serra Geral Group in subsurface through petrophysical data. Rossetti et al. (2025) integrates well logs, cuttings samples, seismic data, and geochemical analyses to propose a regional stratigraphic framework composed of an alternating succession of porous and massive volcanic units potentially acting as reservoirs and seals. The present study adds to the new volcanic interpretation of the Serra Geral Group using a multi-scale approach including the petrographic, petrophysical and well log data to describe subsurface lithofacies and their associations, integrating with porosity and permeability and the microstructures controlling the reservoir properties. This data can support subsurface geological interpretations in areas lacking core data.

Method

To characterize potential reservoirs and seals at the local scale within the Serra Geral Group (SGG), this study first involves the description of outcropping volcanic rocks in order to identify the lithofacies, their vertical stacking patterns, and lateral continuity. These surface exposures serve as analogs for subsurface rocks and provide a basis for petrophysical interpretation. During the fieldwork, representative samples of different lithofacies were collected and coreplugs were extracted from hand specimens. These plugs underwent (i) routine petrophysical analyses, including measurements of bulk density, porosity, and permeability under different confining pressures (ambient pressure, 10 MPa, 20 MPa, and 40 MPa), and (ii) thin sections preparation for petrographic description of lithofacies and identification of pore types and microstructures that may control porosity and permeability. Finally, well logs (caliper, gamma ray, sonic, density, neutron, and photoelectric factor) were used to characterize lithofacies stacking patterns and to propose electrofacies to aid interpretation. The sonic log proved as a valuable tool to porosity variation. The density and neutron logs are also useful, although they can be influenced by compositional variations, such as alteration minerals. The photoelectric log, which is sensitive to variations in atomic composition, was therefore used to help distinguish between volcanic and sedimentary rocks.

Results

Based on outcrop descriptions, ten lithofacies were identified: brecciated basalt (bB), vesicular basalt (vB), amygdaloidal basalt (amB), massive basalt (mB), columnar basalt (cB), massive basalt with a vesicular segregation zone (vsB), basalt with horizontal vesicular sheets (hvsB), peperites (Pep), cross-bedded sandstones (cbS), and siltstones (Sl). These facies are organized into different facies associations as 1) simple pahoehoe lava flows, 2) rubbly pahoehoe flows, 3) ponded pahoehoe flows,) intertrap sandstones, and 7) volcanoclastic rocks. Laboratory petrophysical results indicate porous facies are cross-bedded sandstones (13.1–35.3%), vesicular basalts (15.7–36.4%), peperites (13.25–25.3%), and amygdaloidal basalts (6.0–24.4%). The most permeable lithofacies are cross-bedded sandstones (0.001–19.1 mD), amygdaloidal basalts (0.02–0.43 mD), and peperites (0.01–10.0 mD). The massive basalt lithofacies exhibits low porosity (0.2–5.8%) and low permeability (<0.001–0.024 mD). Petrographic descriptions show two types of porosity: primary, represented by vesicles and intergranular porosity, and secondary, represented by moldic and sieve porosity. In the more permeable rocks, such as the intertrap sandstones dominate intergranular and moldic porosities, with a high degree of pore connectivity. In volcanic rocks, those with high porosity typically exhibit a large number of vesicles ranging from 1 to 7 mm in diameter. Well log data reveal a cyclic pattern within the volcanic rocks of the Serra Geral Group, characterized by alternation between intervals with high sonic transit time (DT ≥59 μs/ft), high neutron porosity (NPHI ≥0.24), and low bulk density (RHOB ≤2.8 g/cm³), interpreted as porous intervals, and intervals with low DT (<59 μs/ft), low NPHI (<0.24), and high RHOB (>2.8 g/cm³), interpreted as massive intervals. The volcanic rocks of the SGG display photoelectric factor (PE) values predominantly within the range of 5.0–5.4 barn/electron, with thin interbedded intervals showing PE peaks lower than 4.9 barn/electron. The sedimentary rocks overlying the Serra Geral Group exhibit significantly lower PE values (mostly <3.8 barn/electron). A crossplot of density versus photoelectric factor reveals a trend of decreasing density associated with decreasing PE values. Additionally, intervals interpreted as volcanic tend to exhibit PE values above 4.2 barn/electron, whereas sedimentary rocks generally show values below 3.8 barn/electron. Volcanic and sedimentary rocks appear to overlap within the 3.8–4.2 barn/electron range, characterizing this interval as a transitional zone.



ELECTROFACIES SCHEME AND PROPOSED INTERPRETATION

Division	DT	RHOB	NPHI	PE	Probable lithofacies
Porous	>=57	=<2.8	>=0.24	>=4.9	Unaltered vesicular basalt, unaltered brecciated basalt, unaltered, volcanoclastic, hybrid rocks
				4.2<PE=<4.9	Altered vesicular basalt, altered brecciated basalt, altered, volcanoclastic, hybrid rocks
				3.8<PE<4.2	Altered volcanic, volcanoclastic, hybrid rocks, sedimentary
				<3.8	Seidmentary rocks
Massive	<57	>2.8	<0.24	>=4.9	Unaltered massive core
	<57	=<2.8	<0.24	4.2<PE=<4.9	Unaltered massive core

Figure 1: Interpretation and classification of 3-ELPS-7-PR The choice of the well took into account representativeness and the available tools. Electrofacies scheme showing color divisions and the respective cutoffs, with several possibilities of interpretation. Due to the ambiguous nature of the profiles, more than one possibility was considered. Field analogues and corresponded thin section with porosity, density and permeability values.

Conclusions

The description of surface outcrops was essential for identifying lithofacies, their association, and stacking patterns, there by supporting the interpretation of petrophysical logs in regions lacking detailed subsurface core-based lithological descriptions. Laboratory petrophysical analyses of permo-porous properties, make it possible to identify which lithofacies are most suitable to act as reservoirs and which are better suited to serve as seals. Petrographic descriptions provide insights of microstructures affecting the permo-porous characteristics. The integration of petrographic, petrophysical and geophysical data offers a robust approach for recognizing volcanic lithologies at depth, and to delineate porous (potential reservoirs) and massive zones (potential seals) essential knowledge for identifying potential CO_2 storage targets.

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