Study of the diabase sills in the Parnaíba basin on the basis of openhole well logs, drilling cuttings, x-ray diffraction and x-ray fluorescence

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Abstract

The study of the intrusions is extremely important to understand the petroleum system of the Parnaíba Basin since they acted as a heat source for the immature generators and at the same time are the trappers and sealers of the gas reservoirs. Correlations using X-Ray Fluorescence (XRF), X-Ray Diffraction (XRD), well logs and seismic data, as well as the detailed description of drilling cutting samples proved effective in understanding the physicochemical characteristics and mineralogical variations of these igneous bodies. The studied sills show variations in well logs along their section, as well as variations in Titanium, Aluminum, Potassium, Magnesium, Iron, Calcium, Rubidium, Nickel, and Chromium values, evidencing a large textural and mineralogical variation, allowing the characterization of these sills in distinct electrofacies and chemiofacies. Three electrofacies and four chemiofacies were identified, which determined a higher concentration of magnesian minerals at the base and felsics at the top of the sill, showing a probable crystallization order, as proposed in the Bowen Series. In addition, with the upscale to seismic data, it was possible to identify more precisely the top and the bottom of the sill, demonstrating a strong relation between mineralogy, acoustic impedance and amplitude.

Introduction

In the Brazilians Paleozoic Basins, the petroliferous system is closely related to magmatic events as mentioned by Thomaz Filho et al. (2008), where the authors define them as favorable aspects to the processes of generation, migration and accumulation of hydrocarbons.

The Parnaíba Basin highlights the importance of igneous rocks due to its atypical petroleum system, where the intrusions act as a heat source for the organic-rich shales from Pimenteiras Formation and are the main trap and seal for commercial gas accumulations (Araújo, 2015; Trosdtorf Junior et al., 2014; Miranda et al., 2018).

The Parnaíba Basin is characterized by the occurrence of two mafic magmatism episodes, which generated a great variety of intrusive igneous bodies in its sedimentary section, evidenced in the form of dikes and sills divided into *Mosquito* Formation and *Sardinha* Formation (Aguiar, 1971; Trosdtorf Junior et al., 2014).

Trosdtorf Junior et al. (2014) and Oliveira et al. (2022) used well logs to identify the presence of igneous intrusive rocks in the sedimentary section of Brazilian basins, given that these rocks present characteristic features in the most varied well logs, enabling the distinction between sills and dikes.

The intrusions were identified using the "igneability feature" (Oliveira et al., 2022) and further they were classified into the *Caixote* feature, characterized by constant values in the GR curve, which can be interpreted as a rapid crystallization event, and the *Barriguda* feature, marked by an increase in the GR curve in the upper third of the intrusion, consequence of the rapid crystallization at the edges of the intrusion, when compared to the upward percolation of volatiles (Trosdtorf Junior et al., 2014). According to Oliveira (2023) the *Caixote* and *Barriguda* features are not restricted to the Parnaíba Basin and have also been observed in the Santos and Paraná Basins.

The recognition and understanding of this atypical igneous–sedimentary petroleum system could be used to unlock the potential of analogue basins worldwide and also to expand the exploration successful cases in the Parnaíba Basin itself (Miranda et al., 2018).

The study was developed based on geochemical analysis, geophysical well logs and drilling cutting samples from wells located in production fields that are part of the Parque dos Gaviões area, the main gas producing area in the Parnaíba Basin (Figure 1).

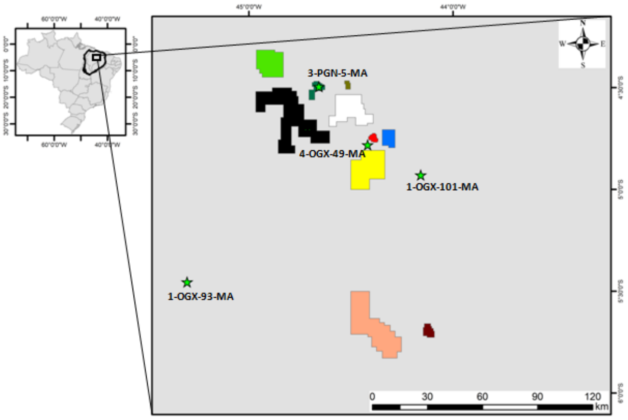

Figure 1: Location map of the studied wells made in ArcGIS software. The shapefiles used were obtained from the ANP and CPRM libraries

Parnaíba Basin igneous rocks

The intrusions of the Parnaíba Basin are associated with the occurrence of Mesozoic events fundamental for the evolution of the South American Platform, marked by distension episodes, remobilization of ancient faults, emergence of fractures and intense magmatism. The duration of magmatic activity persisted much longer than in other Brazilian Paleozoic basins, presenting two principal events of magmatic activity, seen in outcrops and in subsurface (Daly et al., 2018).

The igneous records of the Parnaíba Basin were mainly caused by the Jurassic rifting of the Pangaea supercontinent, which established in South America a new tectonic stage that would lead to the opening of the Atlantic Ocean during the Cretaceous (Almeida & Carneiro, 2004; Zalán, 2004; Vaz et al., 2007). Intrusive igneous rocks (dikes and sills) and extrusive rocks of basic composition were accommodated in the basin, which, from a stratigraphic point of view, were divided into two units: the Mosquito Formation of Eojurassic age and the Sardinha Formation, Eocretaceous, exposed in the western and eastern portions of the basin, respectively (Vaz et al., 2007; Oliveira et al., 2018).

According to Oliveira & Mohriak (2003), these two units are distinct in: form of occurrence in subsurface, chemical, and isotopic nature, age and location. In subsurface, the dikes and sills are mostly presented in the Mesodevanian-Earboniferous Sequence, also occur in the Silurian Sequence and are rarely present in the Neocarboniferous-Eotriassic.

Method

Four exploratory wells in the Parnaíba Basin were studied, where an integration of geochemical, geological, and geophysical data was carried out. The first step was the identification and the characterization of intrusions through openhole well logs. Initially, the igneous bodies were individualized using the Igneability feature, proposed by Oliveira et al., (2022). In this methodology, Density (RHOB) and Photoelectric Factor (PEFZ) well logs are set on the same track, on a scales of 2 to 3 and 12 to 2, respectively. In the sections that the PEFZ log is on the left of the RHOB log, are zones with strong evidence of basic igneous rock or anhydrite (Oliveira et al., 2022). Later, the intrusions were classified into *Barriguda* Feature and Caixote feature based on the shape of the Gamma-Ray (GR) log, according to Trosdtorf Junior et al., (2014).

The second stage of the research consisted in the interpretation of the well logs, where it was observed that the *Barriguda* features have a similar pattern in all studied wells: in the upper third of all intrusions, the GR values increase and the RHOZ values decrease. Just below this zone the values of the RHOZ are higher, despite similar values of GR, and in the rest of the sill the values of the logs remain practically constant. Therefore, crossplots of GR x RHOB were made, clearly showing the electrofacies in the studied sills.

Description of the drilling cuttings and geochemical analyzes were used in order to understand the cause of these variations in the well logs. We selected cutting samples corresponding to the Barriguda *("Paunchy")* igneous intrusions, that were collected at intervals of 3 meters during drilling. The description was carried out using a Stemi 508 Binocular Stereomicroscope, which allowed the identification of specific characteristics of each interval. The igneous rocks were analyzed by describing the following parameters: color, composition, structure, granulometry, cohesion and mineralogy.

After this step, samples were separated for X-ray fluorescence (XRF) analysis using the EPSILON 1 from Malvern Panalytical, a fully integrated energy dispersive instrument, analyzing chemical elements from Sodium (Na) to Americium (Am), represented by percentage or ppm. It uses an X-ray tube with an anode of Ag (silver) and a 50 Kv generator for the excitation of the elements. The instrument was set up for readings from the loose powder method with 10 minutes analyses. For this process, samples were washing with neutral detergent and drying at 40ºC, were ground in agate graal and placed uniformly in plastic capsules to be taken to the equipment.

To support and improve the data obtained from the well logs, XRF and sample description, X-ray diffraction (XRD) analyses were performed using a Bruker's D2 PHASER equipment, a benchtop powder diffractometer that operates in Bragg-Breton geometry. For the preparation of this procedure, the washed and dried samples were ground using a Tungsten (W) ball mill to reduce the particle size and homogenize the samples, allowing more crystalline phases determination. The samples were disposed in the sample holder in such a way that they were flush with its upper plane and with non-rough surface. The measurements were done using the following parameters: range 3º to 100º, 0.02º step size and a 3 seconds acquisition time.

As quality control for the XRF data, analyses containing pure calcite and duplicate analyses were performed once every 10 samples. The methodology is summarized in Figure 2, in the form of a simplified workflow, which identifies the main activities/steps and their sequence.

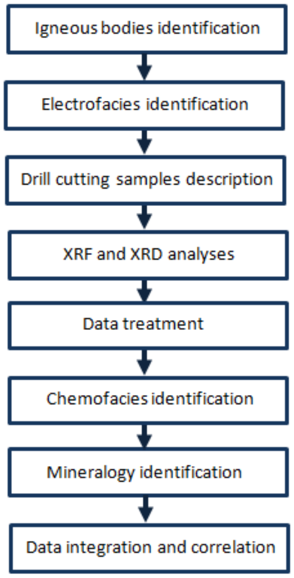

Figure 2: Proposed methodology workflow.

Results and discussions

The proposed methodology was applied in four wells and the results were generated using the softwares Excel, IP (Interactive Petrophysics) and APPy (Avaliação de Perfis em Python), which is been developed by the Universidade Federal Fluminense. This work will illustrate the application of the methodology for the Barriguda Feature in well 1-OGX-101-MA.

The intrusion of this well, as also observed in the other studied wells, has GR values between 15 and 85 gAPI and density between 2.92 and 3.1 g/cm³. The crossplot of Gamma Rays x Density (Figure 3) allowed the identification of 3 distinct electrofacies, named as: GR anomaly zone, where GR values increase (from 40 to 85 gAPI) and RHOB values decrease; High Density zone, where density values are higher (above 3 g/cm³); and the Standard zone with constant values, averaging 35 gAPI in GR and 2.94 g/cm³ in RHOB.

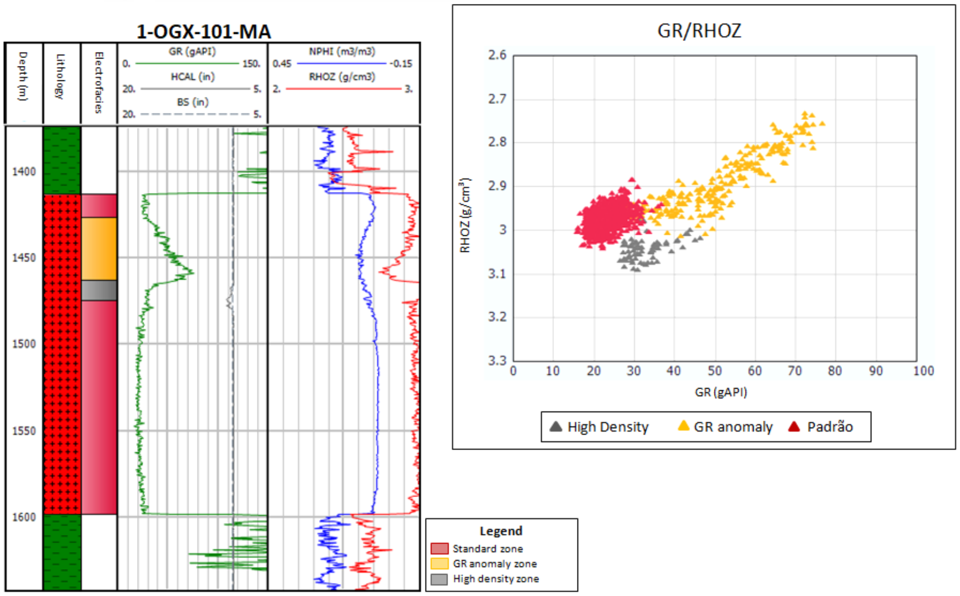

Figure 3: On the left, openhole logs from well 1-OGX-101-MA, showing the Barriguda "Paunchy" feature at ca. 1450m; on the right, a crossplot GR x RHOZ prepared in the Software IP, pointing out the three electrofacies identified.

Cuttings from this intrusion were described to identify their characteristics and mineralogical variations. In the upper part, extending to the entire sill, crystals characterized by subhedral grains and vitreous luster were observed, separated into mafic (dark coloration) and felsic (light), interpreted as pyroxene/amphibole and plagioclase, respectively. In this zone, occasionally, tabular crystals were also found, when not broken, subhedral and greenish, occasionally disaggregated and others coupled to the mafic fragments, interpreted as olivine. The hyaline fragments identified in many samples along the sill were also interpreted as plagioclase, since it was possible to identify typical characteristics of this mineral, such as tabular crystals and cleavage. In this part of the sill, the cutting samples from well 1-OGX-101-MA are composed of approximately 60% to 70% plagioclase and 30% to 40% pyroxene/amphibole.

In the GR anomaly zone there were no great mineralogical variations, and fragments with the same characteristics of the top of the sill were observed. In the region below the Barriguda feature, where an increase in density occurs, besides the basic mineralogy of plagioclase and pyroxene/amphibole, several oxides were found, mostly small, on the order of 100-200 µm. These fragments show glassy luster and predominantly crystalline form, with rare subhedral crystals, apparently octahedral interpreted as magnetite.

In the lower half of the sill, in addition to the plagioclase and pyroxenes/amphiboles, was observed a gradual and abundant increase of green to yellowish green crystals, also interpreted as olivine, representing about 30% of the fragments in the samples. Therefore, the descriptions allowed the separation of the sill into 3 specific intervals, according to their majority characteristics: top of the sill up to the GR anomaly zone, rich in plagioclase, pyroxene/amphibole with sporadic olivine crystals; zone below the GR anomaly rich in oxides, associated with high density values; and the base, very rich in olivine.

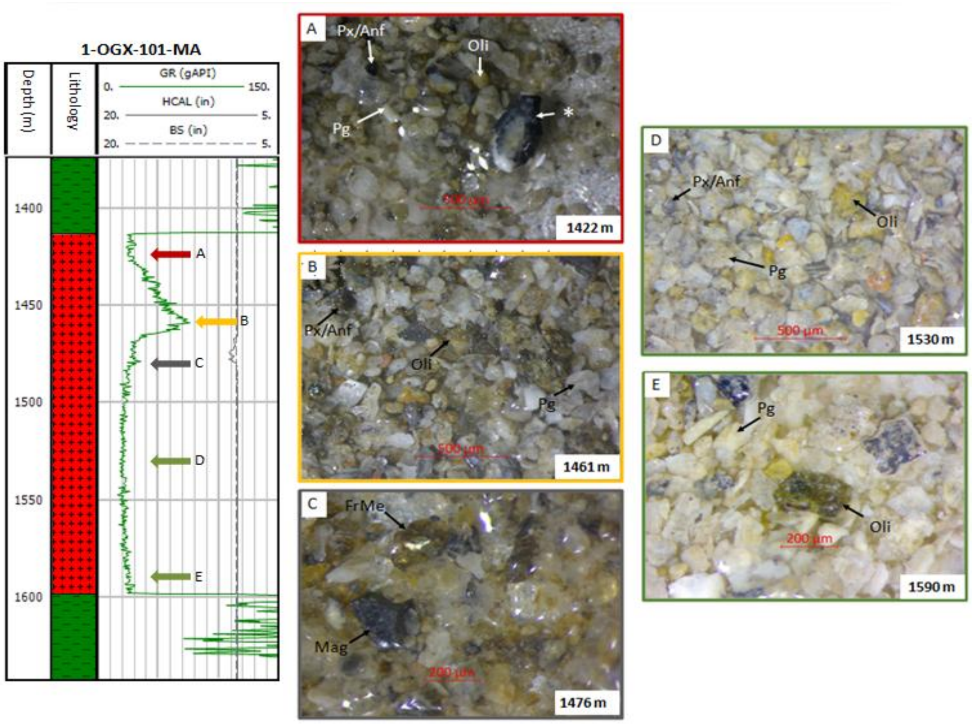

Figure 4: Photos of drilling cutting samples from well 1-OGX-101-MA, and their respective depths. Legend: Px/Anf: Pyroxene/Anfibole; Pg: Plagioclase; Oli: Olivine; FrMe: Metallic fragment; Mag: Magnetite.

Another interpretation of the diabase sills was based on the geochemical behavior, obtained through XRF and XRD analyses. Using the XRF data, the APPy software plotted the curves of the most significant chemical elements found in the diabase and in the minerals observed in the cutting samples. Therefore, it was possible to separate the igneous bodies with a *Barriguda* feature into four distinct chemiofacies described below, delimited by the colors red, yellow, gray, and green (Figure 5), equally identified in all analyzed wells.

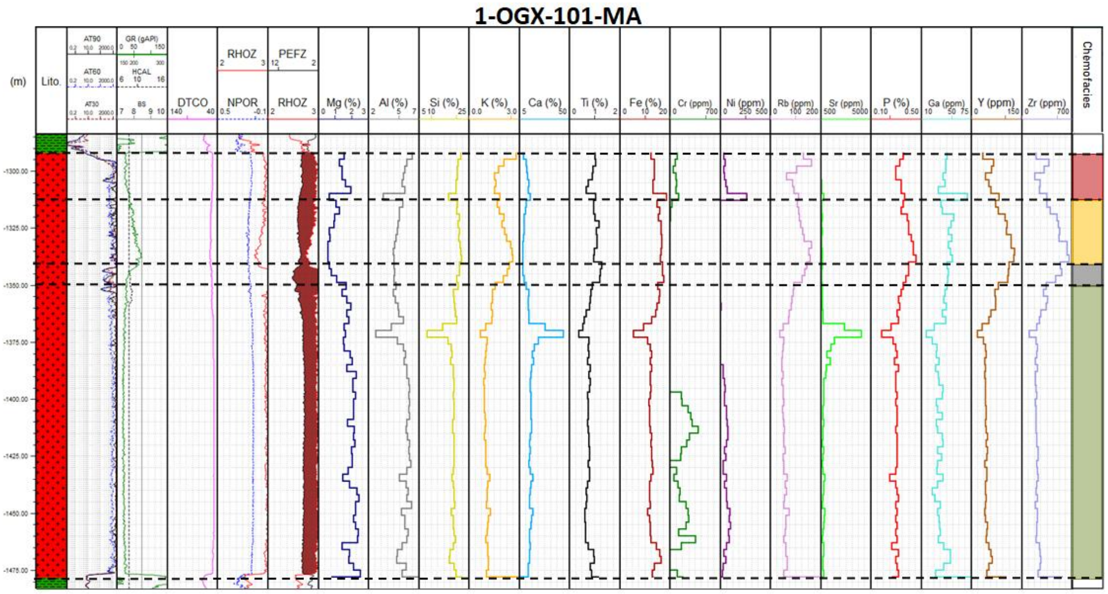

Figure 5: In the last track, chemiofacies division based on chemical element behavior along the diabase sill in the well 1-OGX-101-MA.

Green zone: Rich in Magnesium (Mg), probably associated with the increase of magnesian olivine at the base of the sill, as recommended by the Bowen's Serie, in which minerals that have a higher melting point are crystallized at first, submerging into the rest of the magma that is still in the pasty state. The increase in Chromium (Cr) and Nickel (Ni) values in this same interval occurs, possibly, due to the occurrence of magnesian varieties, enriched by divalent Cr^{2+} and Ni^{2+} ions replacing Mg^{2+} in the olivine. The high Calcium (Ca) values indicate a likely increase in calcium plagioclase, corroborated by the increase in Aluminum (Al) values. Marsh (2015) suggests that the increase of these elements in diabase sills may be related to the presence of orthopyroxene or olivine, the last one observed in the cutting samples. This magmatic differentiation can occur in sills in two situations: the first is when the sill, during its crystallization beginning, receives a new magmatic contribution, and the second is when this magma is already allocated with the presence of phenocrysts (Marsh, 2015).

Gray zone: This region, marked by high RHOZ values, is characterized by a higher concentration of Iron (Fe) and Titanium (Ti), suggesting the occurrence of oxides rich in these elements, such as magnetite (seen in samples) and ilmenite.

Yellow zone: In the Barriguda feature, where the GR increases and the density decreases, is observed a incompatible elements crystallization zone, marked by the increase of Potassium (K), Rubidium (Rb), Phosphorus (P), Yttrium (Y) and Zirconium (Zr) values. According to Sial & McReath (1984), K and Rb suggest the presence of anti-pertite in the more sodic plagioclase, while P indicates the occurrence of apatites. When associated with increased Y they may denote the existence of xenothymium. Zr is linked to the presence of Zircon, suggesting, coupled with increased Silicon (Si) values, a zone of magmatic differentiation, probably crystallized in a final cooling phase. The lower concentration of Mg and Ca are possibly linked to the presence of more sodic plagioclase.

Red zone: At the top of the sill, moderate values of all elements indicate a zone without mineralogical variation, associated with plagioclase and pyroxenes/amphiboles.

The XRD data supported the interpretations obtained with the cutting samples description and X-ray fluorescence, where the main minerals identified were the same: plagioclase, pyroxene, amphibole, magnetite, and olivine. The interpretation of the diffractogram presented in Figure 6 was done in EVA Software using the RIR method for mineralogical quantification.

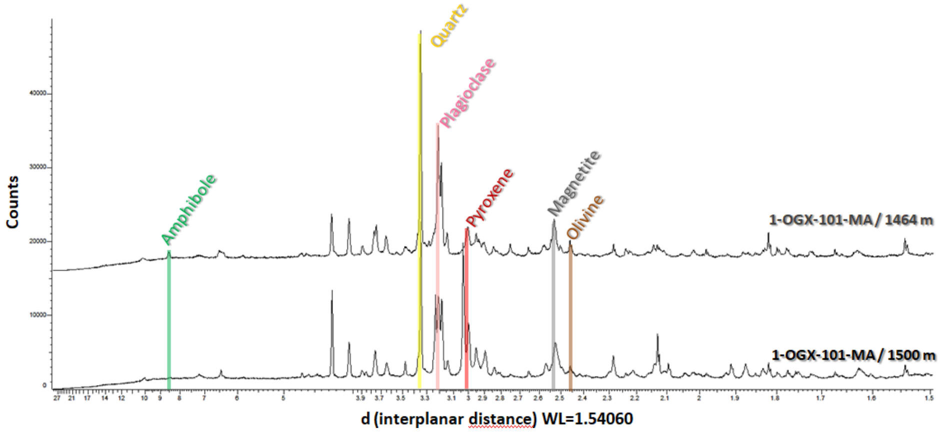

Figure 6: Interpreted diffractogram of the well 1-OGX-101-MA.

Using all data presented above, Leaubon et al., 2022 correlated geochemical and well logs with seismic data. Through well-seismic tying, it was possible to identify more accurately the top and bottom of the sill, as horizons can be damaged due to the imaging instability that sills complexities can cause in seismic (Leaubon et al., 2022).The minerals that form the entrance of the sill, identified in cuttings, XRF and XRD analysis, have a higher density than the minerals that form the surrounding rock. This results in a highly positive amplitude because of the impedance response between the sedimentary layer (generally less dense) and the top of the sill. In the Barriguda feature, there is the presence of incompatible minerals associated with the drop in density values (seen in the RHOZ log). With this, the impedance response between the top and the GR anomaly zone generates an extremely negative peak. At the base of the sill, there is a higher concentration of Olivine, giving an impedance contrast between the GR anomaly and the base of the sill, and between the base and the lower surrounding rocks, generating a positive amplitude, but not as positive as at the entrance (Leaubon et al., 2021).

Conclusions

Data from geochemical measurements linked to openhole well logs and the description of cutting samples allowed the identification of the igneous intrusions and their characterization based on compositional differences along the thicker diabase sills, classifying them into correlated electrofacies and chemiofacies.

It was possible to analyze that the Gamma Ray and Density logs present variations along the studied diabase sills. With this, it was observed that the behavior of these curves is the response to a mineralogical and compositional variation along the intrusions, probably related to the Bowen crystallization series. Four chemiofacies were identified, which determined a higher concentration of magnesian minerals at the base and more felsic minerals at the top. In the Barriguda feature, the presence of incompatible minerals is evidenced, suggesting that it was the last portion of the sill to crystallize, proving the intrusive character of these rocks, in which a slow and gradual cooling occurred.

The sill show an increase of olivine at the base, culminating in an increase of Mg, Cr and Ni, and the presence of oxides in the high-density portion below the GR anomaly, marked by an increase of Fe and Ti. In addition, data from GR and RHOZ logs proved effective in separating the Barriguda feature sills into different electrofacies, characterized by three zones with distinct physical properties.

The integration of all these data allowed us to identify and explain the internal differentiation observed in the seismic data of the main sill in the Parque dos Gaviões area, explaining the amplitude peaks that possibly represent the internal differentiation of the sill and its contact with the sedimentary layers.

This work exposes a methodology that allowed obtaining, interpreting, and integrating several data, contributing to a better understanding of the heterogeneities related to the physical and geochemical characteristics along the diabase sills with Barriguda features. In this way, this methodology and the variations observed along these sills can be applied to other wells in the Parnaíba basin and in other regions of similar domain, to understand the principle behind the similar variations along the most varied igneous intrusions and to support the correlation between wells.

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