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Subaqueous basaltic rocks of the Boa Vista Basin (Paraíba, Brazil): A petrographic and morphological characterization

Rochas basálticas subaquosas da Bacia de Boa Vista (Paraíba, Brasil): uma caracterização petrográfica e morfológica

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ABSTRACT

This study provides a morphological and petrographic characterization of subaqueous volcanic rocks from the upper unit of the Boa Vista Basin, a Cenozoic volcano-sedimentary basin in northeastern Brazil. Located within the Borborema Province, the basin is defined by the NE-SW Serra do Monte shear zone (SMSZ) and the NW-SE main fault (MF). The upper unit, which overlies an intermediate unit with deposits of bentonite and fossiliferous sandstone, consists of massive olivine basalt flows that grade into pillow lavas and pillow breccias. Detailed analysis of the pillow lavas reveals features characteristic of subaqueous eruption, including glassy rims, multiple crusts, radial cooling joints, vesicles, and amygdales. Petrographically, these pillows exhibit a distinct crystallinity, changing from a glassy crust to a hypohyaline core. Hyaloclastites are present in interpillow spaces and as the matrix for pillow breccias, which separate elongated and inclined (averaging 30°) pillow lava tubes oriented with a westward trend. The combination of these features, including paleochannels filled by volcanic deposits and the transition from pillow lavas to massive flows, supports a depositional model of a lava delta prograding into a lacustrine environment. Evidence of invasive lavas also suggests direct interaction between the basalt lava flows and the unconsolidated to partially consolidated siliciclastic sediments of the underlying intermediate unit. Given the scarcity of such well-preserved outcrops in Brazil, this study provides a crucial analogue for understanding non-outcropping volcanic sequences, such as those encountered during hydrocarbon exploration in sedimentary basins.

Keywords: pillow lavas, hyaloclastite, pillow breccia, lava delta.

RESUMO

Este estudo apresenta uma caracterização morfológica e petrográfica de rochas vulcânicas subaquosas da unidade superior da Bacia de Boa Vista, uma Bacia Cenozoica vulcano-sedimentar localizada no nordeste do Brasil. Inserida na Província Borborema, a bacia é delimitada pela zona de cisalhamento Serra do Monte (NE-SW) e pela falha principal (NW-SE). A unidade superior recobre uma unidade intermediária composta por depósitos de bentonita e arenito fossilífero e é constituída por derrames de basaltos maciços que gradam para lavas em almofada (pillow lavas) e brechas de almofada (pillow breccias). A análise detalhada das lavas em almofada revela feições típicas de erupção subaquosa, como crostas vítreas, múltiplas crostas, juntas de resfriamento radiais, vesículas e amígdalas. Petrograficamente, essas almofadas exibem uma diferença de cristalinidade, mudando de uma crosta vítrea para um núcleo hipohialino. Hialoclastitos ocorrem nos espaços interpillow e como matriz das brechas de almofada, separando tubos de lava em almofada alongadas e inclinadas (média de 30°), orientadas com uma tendência para oeste. O conjunto dessas características, incluindo paleocanais preenchidos por depósitos vulcânicos e a transição de lavas em almofada para derrames maciços, sustenta um modelo deposicional de um delta de lava progradando em ambiente lacustre. Evidências de lavas invasivas indicam interação direta entre os fluxos de lava basáltica e os sedimentos siliciclásticos não consolidados a parcialmente consolidados da unidade intermediária subjacente. Diante da escassez de afloramentos tão bem preservados desse tipo no Brasil, este estudo fornece um análogo fundamental para a compreensão de sequências vulcânicas não aflorantes, como aquelas encontradas durante a exploração de hidrocarbonetos em bacias sedimentares.

Palavras-chave: lavas de almofada, hialoclastito, brecha de almofada, delta de lava.

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1. INTRODUCTION

The Cenozoic Boa Vista Basin, an approximately 250 km² volcano-sedimentary depocenter in northeastern Brazil, 40 km from Campina Grande, Paraíba (Figure 1). The volcano-sedimentary sequence is part of the Cariri Paraibano Geopark, owing to its sedimentary deposits and basaltic flows (27-22 Ma; Souza et al., 2013), known as the Pillow Lavas Geosite (Lages et al., 2018).

The basin is tectonically controlled by reactivated faults of the Transversal Zone of the Borborema Province which channeled the mantle-derived magmas to the surface (Souza et al., 2005). The main depocenter of the basin was filled with three distinct units, culminating in an upper unit characterized by subaqueous volcanics, including pillow lavas, pillow breccias, and hyaloclastites (Barbosa and Souza, 1999a, b; Souza et al., 2005; 2013; Lages et al., 2018). This basin is a key locality within the broader Cenozoic Magmatic Province of Northeastern Brazil. This magmatism, active from the Paleocene to the Miocene, is now interpreted as the continental expression of a remnant, aborted mid-ocean ridge system that developed between the South American and African plates (Souza et al., 2025).

The importance of studying these deposits is underscored by the pronounced scarcity of comparable, well-exposed subaqueous volcanic successions throughout Brazil. While occurrences are noted in locations like the Paraná Basin (Ferreira, 1985; Moraes and Seer, 2017; Famelli et al., 2021a), the outcrops in the Boa Vista Basin offer a rare and accessible natural laboratory for investigating lava-water interaction processes (Barbosa and Souza, 1999a, b; Dias, 2004; Souza et al., 2005, 2013). The description of the subaqueous volcanic rocks of the Boa Vista Basin is important for enhancing the understanding of these deposits and for contributing to the recognition of this area as a potential site for subaqueous volcanism research on a national scale. This makes the area an analogue for interpreting subsurface volcanic sequences encountered during hydrocarbon exploration in offshore sedimentary basins, where such rocks can significantly impact reservoir quality and geometry (e.g. de Luca et al., 2017). A detailed characterization of the Boa Vista deposits can therefore provide a predictive framework for these economically important, yet poorly understood, subsurface settings.

The objective of this study is to provide the morphology and petrographic characterization of the subaqueous volcanic deposits (pillow lavas, hyaloclastites, and pillow breccias) of the Boa Vista Basin and to investigate these rocks in the areas surveyed near the bentonite mining close to Serra do Monte.

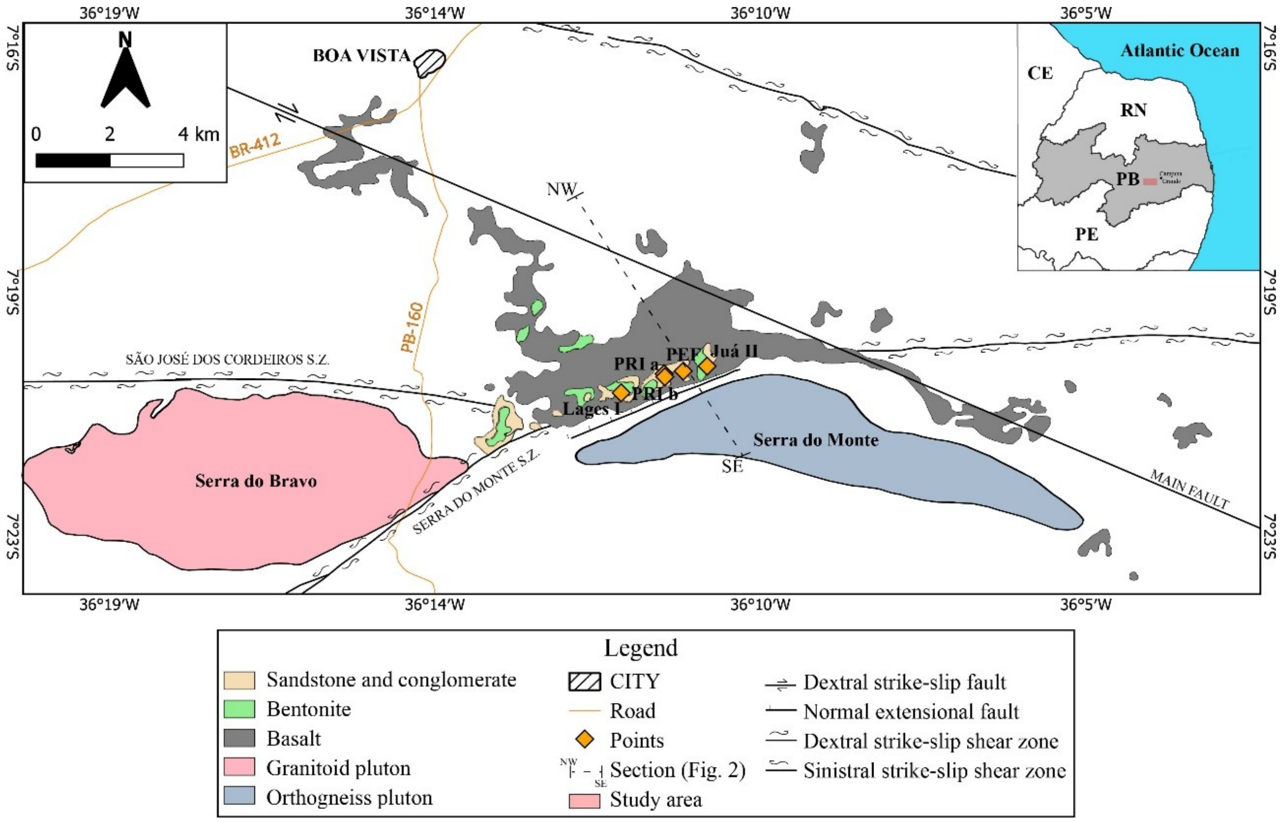

Figure 1. Location map of the points investigated in the study area. The names of the points studied Juá II, Lages I, Pedra do Fogo (PEF), and Primavera (PRI a and PRI b) correspond to the names of the mines at the time of the first fieldwork in November 2014. Serra do Monte Shear Zone according to Souza et al. (2005) (the same as the Boa Vista-Cabaceiras Shear Zone according to Lages and Marinho, 2012). Modified from Lages and Marinho (2012) and Souza et al. (2005).

2. REGIONAL GEOLOGY

The Boa Vista Basin is in the central portion of the Transversal Zone within the Borborema Province, situated in the Cariris Velho region and the central portion of the Boqueirão Sheet (Souza et al., 2005). This province, of Archean to Neoproterozoic age, achieved tectonic stabilization at the end of the Precambrian, following the development of a complex system of continent-scale ductile shear zones (Vauchez et al., 1995). This study focuses exclusively on the upper unit, the Macau-Queimadas volcanic alignment. The volcanic flows of the Boa Vista Basin exhibit chemical compositions and ages similar to Macau-type basalts (Souza et al., 2025). The Neoproterozoic-aged Precambrian basement in the study area is composed of migmatite gneisses, mica schists, and granite plutons from the Serra do Monte, associated with the Carnoió intrusive suite, and the Serra do Bravo, linked to the Itaporanga intrusive suite (Sial, 1976; Almeida et al., 1988; Souza et al., 2005).

Subsequent reactivations of Precambrian structures in the Borborema Province controlled the tectonic evolution of local sedimentary basins since the Paleozoic. Part of these structures were reactivated during the breakup of Gondwana, resulting in a compressional and extensional stress regime within the Borborema Province. This tectonic activity produced NE-SW-oriented normal dip-slip faults, which shaped the half-graben geometry of the Boa Vista Basin (Souza et al., 2005; Figure 2).

During the Cenozoic, the ancient crust was affected by widespread, intraplate, alkaline magmatism. The geochemistry and isotopic signatures (Sr-Nd-Pb) of these volcanic rocks indicate an origin from mantle plumes (OIB-like source) linked to a major plate-tectonic reorganization (Souza et al., 2025). According to Souza et al. (2025), this magmatic event represents the continental trace of a failed oceanic spreading center, making the region a key area for understanding the final stages of Gondwana's breakup. The volcanism manifested along distinct alignments, including the Macau-Queimadas volcanic alignment, which encompasses the Boa Vista, Cubati, and Queimadas volcanic centers.

Some of the faults delineating the Boa Vista Basin include the reactivated Serra do Monte Shear Zone (SMSZ), oriented NE-SW, which defines the southern boundary of the basin in contact with the Serra do Monte pluton, and the Main Fault (MF), oriented NW-SE. The primary depocenter of the basin is embedded within the SMSZ along the Serra do Monte contact, with the deepest areas located near the intersection of the SMSZ and the MF (Figure 2) (Caldasso, 1965; Caldasso and Andrade, 1979; Souza et al., 2005; 2013).

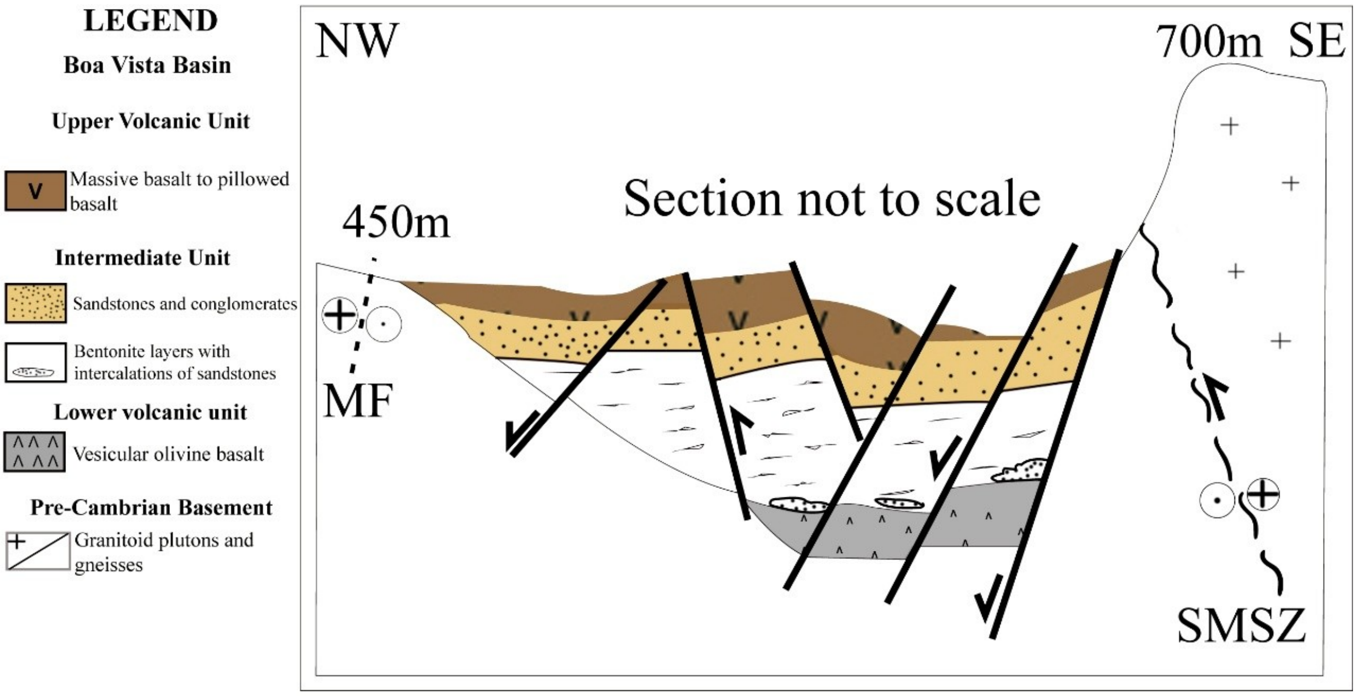

Figure 2. NW-SE geological cross-section of the Boa Vista Basin as shown in Figure 1. The deepest portion of the basin reaches a depth of 35 meters. Legend: SMSZ: Serra do Monte Shear Zone; MF: main fault (black dashed line). Compiled from Souza et al. (2005).

The sedimentary and volcanic components of the basin, as well as the Cenozoic thermal reactivation of the Borborema Province, evidenced by relatively voluminous basaltic magmatism, demonstrate that the SMSZ and associated faults were deeply rooted and acted as conduits for mantle-derived magmas (Souza et al., 2005). The basin formed during the Cenozoic era and was infilled with volcano-sedimentary deposits (Lages et al., 2018).

2.1. Stratigraphic framework of the Boa Vista Basin

The stratigraphic column of the Boa Vista Basin consists of three main units overlying the Neoproterozoic crystalline basement:

- **Lower Unit**: Deposits of basalts and basaltic andesites, overlying the Precambrian crystalline basement (Souza et al., 2005; 2013).
- **Intermediate Unit (Volcano-Sedimentary)**: The Campos Novos Formation (Holder Neto and Silva, 1974), consisting of bentonite deposits, fossiliferous sandstones, and conglomerates.
- **Upper Unit**: Characterized by massive olivine basalt flows transitioning to pillow lavas, lapillitic pillow breccias (Souza et al., 2005; 2013), and pyroclastic rocks (Barbosa, 1999) (Figure 2).

The lithostratigraphy of the Boa Vista Basin correlates with the stratigraphic sequence of the Cubati Basin based on petrographic characteristics and sedimentary structures, as detailed in the regional mapping by Dias (2004). The intermediate and upper units of the Boa Vista Basin correspond to those of the Cubati Basin, due to the presence of bentonite and sandstone sequences overlain by basaltic flow deposits in both basins (Souza et al., 2005). The Cubati Basin is located approximately 47 km north of Boa Vista Basin.

2.1.1. Lower unit

The age of the volcanic lower unit ranges from 29.3 ± 0.4 to 29.8 ± 0.8 Ma, has a 1 to 5 m thickness, and lies above the crystalline basement and below the bentonite layer (Souza et al., 2013). This unit comprises massive to vesicular olivine basalt and andesitic basalt. These basalts are locally exposed and weathered (Souza et al., 2005).

2.1.2. Intermediate unit

The intermediate unit, classified as the Campos Novos Formation by Holder Neto and Silva (1974), is the most volumetrically and economically significant. It consists of a 4 to 30 m thick bentonite package overlain by 1.5 to 5 m siliciclastic deposits. At the base of the bentonite package, decimeter- to meter-thick layers of massive sandstone and conglomerates (with centimeter-sized volcanic clasts) are occasionally present. The bentonite displays a range of colors (gray, brown, green, and white), is laterally continuous over tens to hundreds of meters, and features intercalations of sandstone and chalcedony at its top (Souza et al., 2005).

The origin of the bentonites is directly linked to compaction, diagenesis, and alteration of volcanic ash deposits produced by violent explosive eruptions (Bardintzeff, 1992). Mineralogical and stratigraphic characteristics suggest that bentonite originated from highly homogeneous volcanic ashes deposited in a calm aqueous environment, later compacted and altered into smectite clay minerals (Fisher and Schminke, 1984; Gopinath et al., 1988; 2003). However, the absence of coarse pyroclastic fragments such as bombs or blocks suggests that the pyroclastic event was not highly violent or that the bentonites represent distal deposits (Souza et al., 2005; 2013).

The siliciclastic portion of the intermediate unit consists of siltstones, sandstones, and conglomeratic sandstones. These are arkose to subarkose, immature sandstones and matrix-supported conglomerates. Fossilized tree trunks, petrified stems, and leaves found within the sandstone and bentonite layers indicate a continental origin for these sediments (Souza et al., 2005).

2.1.3. Upper unit

The volcanic deposits of the upper unit, comprising olivine basalt flows (notably pillow lavas and volcaniclastic rocks), have an age of 22.0 ± 0.2 Ma and cover approximately 10 km^2 of the basin area (Souza et al., 2013). These deposits fill paleochannels within the sandstone layer, with thicknesses ranging from 1.5 to 6 m (Barbosa and Souza, 1999a, b). The geometry of pillow lava lobes varies from spherical to ellipsoidal, frequently shows fragmentation of their vitric, and commonly palagonite rims, forming lapillitic pillow breccias (Souza et al., 2005).

The petrography of the upper unit basalts is described as fine-grained (occasionally tachylitic at pillow margins) to medium-grained (in pillow interiors) with porphyritic to glomeroporphyritic textures. Microphenocrysts of augite, olivine, and labradorite are present alongside intersertal, pilotaxitic, hyalophitic, and variolitic textures. Olivine phenocrysts display cavities infiltrated by glassy groundmass, indicative of lava supercooling. Plagioclase microlites, olivine, and silica-filled amygdales are also present (Souza et al., 2005; 2013).

2.2. Environment of deposition

The extrusion of basaltic lavas of the upper unit occurred in a lacustrine to fluvio-deltaic environment (Barbosa and Souza, 1999a, b). Supporting evidence includes: i) high lava fluidity indicated by pilotaxitic and hyalophitic/vitrophyric textures; ii) massive domains in the upper sections transitioning downward and laterally into pillow lavas or pillow breccias; and iii) associated sedimentary units.

Souza et al. (2005) attribute the occurrence of pillow breccias to lava extrusion along steep fluvial channels. In contrast, Petta and Barbosa (2003) and Lages et al. (2018) suggest these deposits formed exclusively in a lacustrine environment.

3. MATERIALS AND METHODS

For this study, two field expeditions were conducted in the Boa Vista Basin. A total of 22 petrographic thin sections were prepared from the collected samples, and their analyses were performed using a ZEISS AXIOSCOP transmitted light petrographic microscope. Three different morphologies were identified within this context and described in detail: pillow lava, pillow breccia, and hyaloclastite. The photographs were edited using Adobe Illustrator™ 2020.

The identified rocks were classified based on the guidelines proposed by Le Maitre (2002) for coherent rocks and by McPhie et al. (1993) for fragmented rocks. The volcanic deposits were analyzed by the interpretation of volcanic facies and their internal structure (lithofacies; sensu Rossetti et al., 2025).

4. RESULTS

4.1. General characteristics of the subaqueous deposits of the upper unit of the Boa Vista Basin

The quarries visited during this research represent the best available outcrops of the volcano-sedimentary section of the Boa Vista Basin. Subaqueous deposits identified in the upper unit of this basin include the following facies: pillow lavas, pillow breccias, and hyaloclastites. A detailed description of each facies and their respective lithofacies is presented below.

4.1.1. Pillow lavas facies

The pillow lavas facies of the Boa Vista Basin exhibit diameters ranging from 14 to 80 cm, with distinct morphologies such as circular/rounded, flattened/elongated, and irregular shapes. Notable features of these facies include glassy crusts, multiple crusts (contraction cracks), radial cooling joints, interpillow material, and vesicles/amygdales.

The glassy margins were observed on most edges of the pillow lavas, characterized by black coloration and typically exhibiting contraction fractures of the "bread crust" type (figures 3A and 3B). The multiple crusts, which occur locally, vary from black to brown, indicating different alteration levels. These crusts are approximately 12 cm thick, with a visible gap representing the spacing between the two crust layers (Figure 3C).

Pillow lavas may exhibit irregular internal fractures or radial joints. Radial fracture patterns are generally associated with more rounded pillows, which range from 54 to 60 cm in diameter.

Interpillow material occurs locally among pillow lavas, displaying colors ranging from brown to gray (Figure 3D).

Vesicles were also observed in some pillow lavas. The empty cavities represent the vesicles (Figure 3E), while cavities filled with an orange-brown coloration are classified as amygdales (Figure 3F).

4.1.2. Hyaloclastites facies

Hyaloclastites facies were identified within interpillow spaces or as the matrix of pillow breccias. In general, it is composed of massive vitreous fragments, with conchoidal fractures and grain sizes of up to 6 cm. These deposits predominantly exhibit a black coloration. However, intervals with brown to yellow hues are also present, indicating the formation of palagonite (Stroncik and Schmincke, 2002; Figure 3G). Some glassy fragments are vesicular.

4.1.3. Pillow breccias facies

Pillow breccias (Figure 3H) facies are characterized by fragments of pillow lavas embedded in a hyaloclastite-rich matrix. Typically, these rocks are black, with zones ranging from light brown to orange-brown. Glass fragments reach sizes up to 10 cm, while pillow lava fragments can be as large as approximately 25 cm.

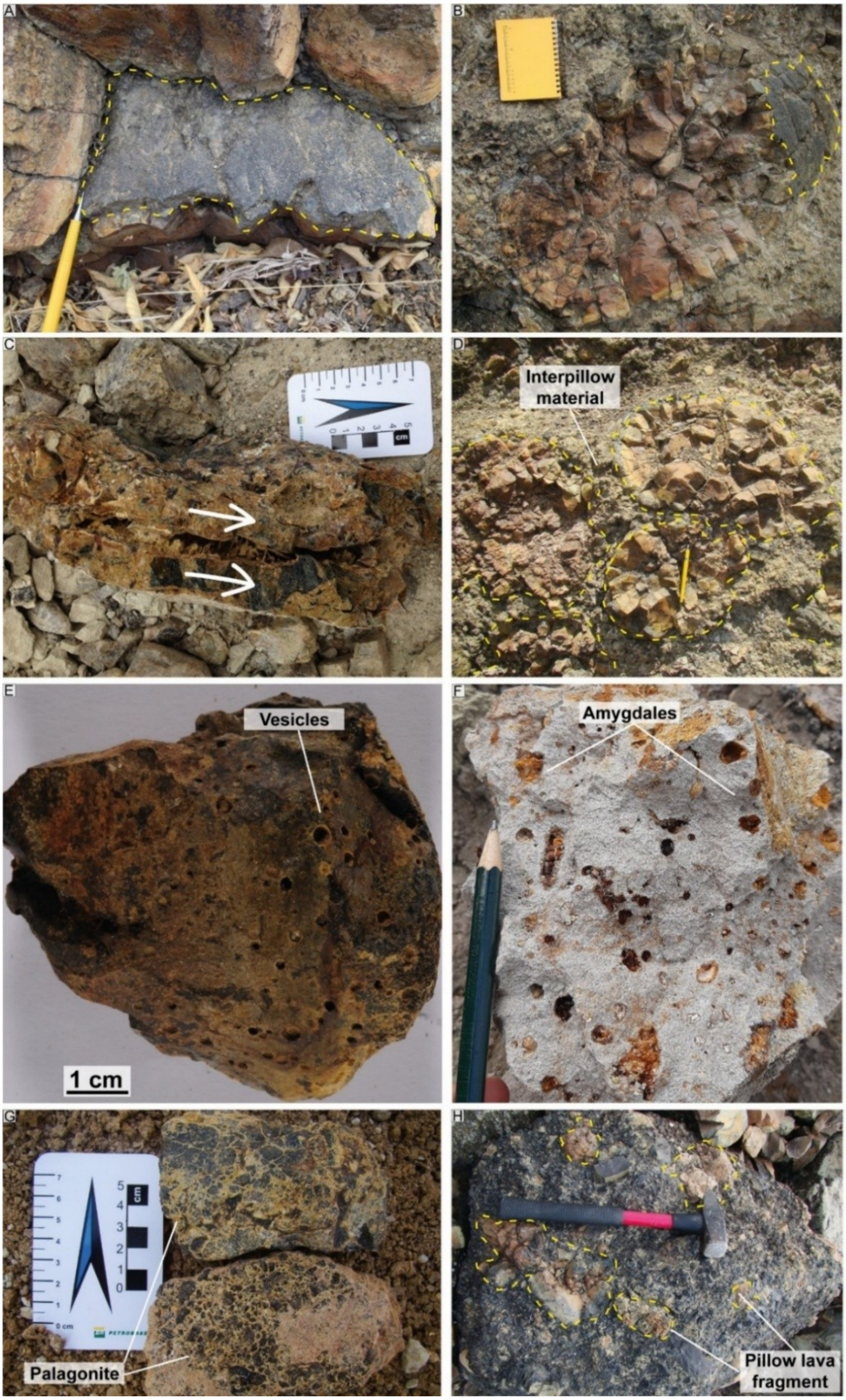

Figure 3. Mosaic of field photographs of structures of subaqueous facies identified in the upper unit. **A.** Represents vertical view, letter **B** and **D** a horizontal view, while letter **C**, **E-H** are block samples. **A-B.** Glassy crust with a bread-crust texture highlighted by a dashed yellow line. **C.** Multi-crust block associated with pillow lava, with white arrows indicating the two crust layers. **D.** Altered interpillow material with a gray coloration and an approximate thickness of 5 cm. **E.** Sample of vesiculated pillow lava. **F.** Altered pillow lava with orange-brown amygdales. **G.** Block of hyaloclastite with palagonite alterations. **H.** Pillow breccia block, with the dashed yellow line highlighting pillow lava fragments.

4.2. Outcrops and profile

Among the studied sites, only the Primavera (PRI), Pedra do Fogo (PEF), and Juá II mines exhibit exposures of subaqueous basaltic deposits. At the Lages I mine, only the bentonite sequence of the intermediate unit was observed.

The Primavera site (PRI) represents the NE-SW section in the middle portion of the basin. The outcrops are exposed in the area closest to the main depocenter of the basin (Figure 2) and are composed of pillow lavas, interpillow material (hyaloclastite), and pillow breccias are exposed. The pillow lavas are shown as elongated tubes dipping 30°, oriented from E to W. These elongated tubes are embedded within pillow breccias (Figure 5) and are deposited concordantly with the orientation of the SMSZ.

The diameter of the pillow lavas ranges from 20 to 60 cm. The pillow lobes are brown, with glassy margins that are typically black. Characteristic structures observed in the pillow lavas include cuspate features at the basal portion of the lobes, radial joints, glassy margins, and multiple crusts (figures 3C and 4). The interpillow material is altered, gray, and has an approximate thickness of 5 cm (Figure 3D). Additionally, hyaloclastites were observed in the interpillow spaces, with black coloration and altered portions displaying orange-brown hue, indicative of palagonite.

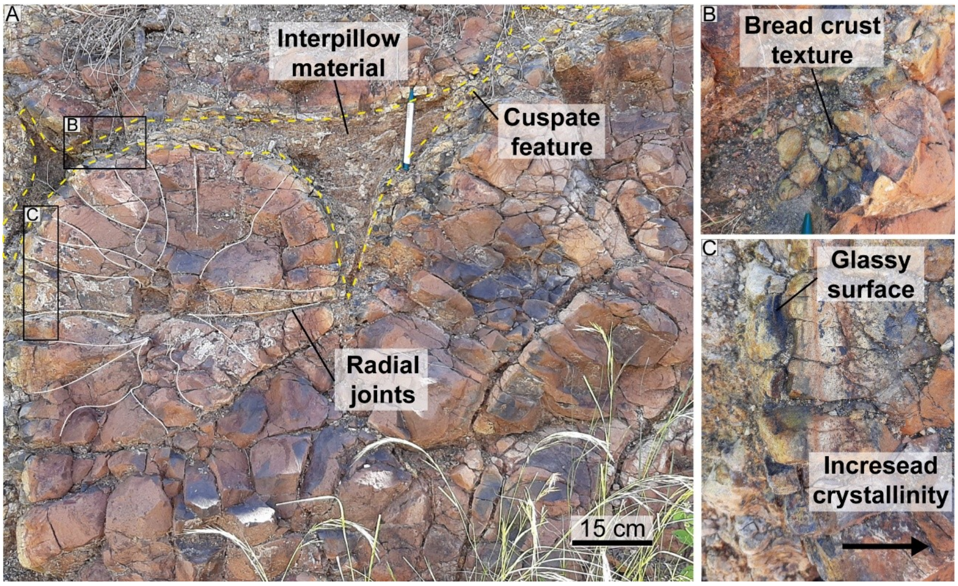

Figure 4. Pillow lava outcrop in PRI mine. **A** and **C** represent horizontal view, while **B** has a vertical view. **A.** Cusp feature (yellow dashed line) and radial joints (white line). **B.** Bread crust texture. **C.** Glassy surface and increased crystallinity. The black rectangle represents the images in detail (B and C).

Figure 5. Outcrop showing a vertical view of elongated pillow lavas, sloping 30° and heading E-W, isolated from each other by pillow breccias. The yellow dashed line represents the elongated pillow lavas. The black arrow on the map points out the location of the outcrop.

Another important feature observed at the Primavera mine (PRI) is the contact between the pillow lavas and the sandstone of the intermediate level of the Boa Vista Basin (Figure 6A). This contact is generally curvilinear in the southwest-facing outcrop. Additionally, in the southwest-facing exposure, a portion of lava was observed surrounded by the sandstone of the intermediate unit, directly beneath the basaltic flows of the upper unit (figures 6B and 6C).

At the Pedra do Fogo (PEF) mine, the contact between pillow lavas and sandstone is also observable. The pillow lavas range in diameter from 28 to 80 cm, with interpillow material varying in thickness from 5 to 25 cm. The basalts range from black to reddish, with local variations from light to dark brown, highlighting altered portions. The structures observed at this mine include cooling fractures and glassy crusts. The interpillow material exhibits colors ranging from white to gray. Below the pillow lavas, the sandstone has greater hardness compared to areas farther from the contact, which may suggest some form of thermal effect.

Unlike the other mines, at the Juá II mine, the observed pillow lavas are light brown, with interpillow material exhibiting a brown hue (Figure 7A). The interpillow material measures approximately 3 to 5 cm in thickness at the basal and central portions (figures 7B and 7C), with the thickness decreasing and eventually disappearing toward the top (Figure 7D). The diameter of the pillow lavas at this mine ranges from 56 to 60 cm. At the upper part of the observed sequence of pillow lavas (Figure 7), a hyaloclastite deposit containing pillow lava fragments (pillow breccia; Figure 3H) was found. Additionally, fossilized tree trunk blocks covered by sandstone crusts were discovered at this mine.

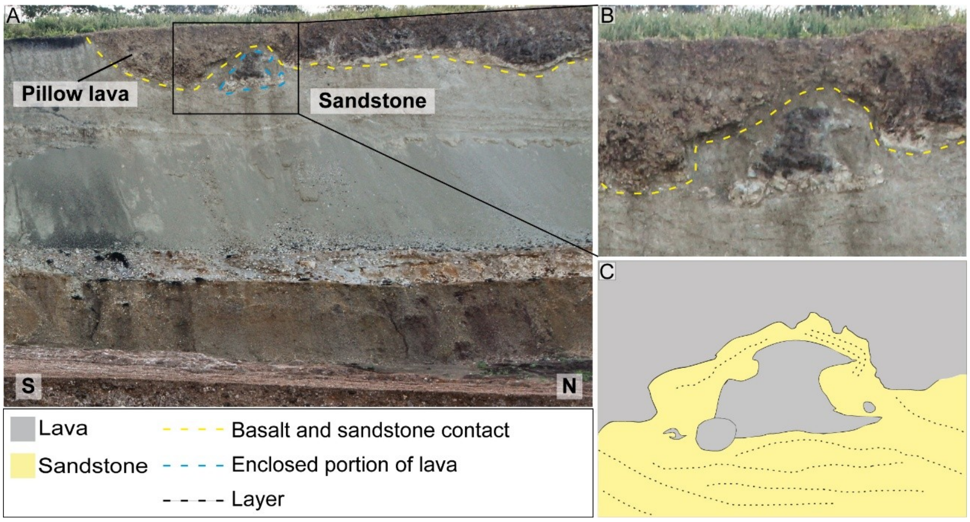

Figure 6. Outcrop of the S-N contact between pillow lavas and sandstone. **A.** General view. The contact is represented by the yellow dashed line and the portion of the lava surrounded by the sandstone of the intermediate unit by the blue dashed line. **B.** This is an enlarged representation of Figure A, highlighting the portion of the lava surrounded by the sandstone. **C.** Schematic illustration of the volcanic body immersed in the sandstone deposits of the intermediate unit.

Figure 7. Outcrop of the Juá II point of approximately 15 m. **A.** General view. **B.** Interpillow material at the base with 5 cm thickness. **C.** Interpillow material in the central portion with an average thickness of 3 cm. **D.** View of the top of the outcrop with an absence of interpillow material. The yellow dashed lines represent the pillow lavas. The yellow arrows indicate the interpillow material.

The main morphological and dimensions characteristics of pillow lavas identified at each investigated site is summarized in Table 1.

4.3. Petrography

The analysis of 22 petrographic thin sections revealed significant variations in the crystallinity and structural features of volcanic samples from the Upper Unit of the Boa Vista Basin. The primary textures identified include vitrophyric, amygdaloidal/vesicular, and massive basalts. The crystallinity ranges from hypocrystalline (glass-dominated relative to crystals) to hypohyaline (crystal-dominated relative to glass) and can also exhibit vitrophyric textures (MacKenzie et al., 1982).

4.3.1 Pillow lavas and pillow breccias

The petrographic characteristics of pillow lavas and pillow breccias are similar, as pillow breccias represent the fragmented tip portions of pillow lavas. Therefore, the petrographic characterization of these two facies is presented as a single category.

The basalts at the edges of the pillow lavas are vitrophyric, hypocrystalline, and range in color from beige to reddish-brown. The beige coloration under parallel polarizers is indicative of a high concentration of volcanic glass (Figure 8A), while the reddish-brown coloration reflects devitrification textures (Figure 8B) with spherulites. This portion of the pillow lavas consists of volcanic glass (~60%), plagioclase (~25%), and olivine (~15%). The grain size is fine (<1 mm), with the presence of olivine crystal aggregates. The plagioclase crystals are subhedral, acicular to lath-shaped, with a fine grain size (0.1 mm) and a gray/colorless hue (Figure 8A). Additionally, plagioclase crystals displaying a swallow-tail texture were observed (Figure 8C). The olivine crystals are euhedral to subhedral, prismatic and fine-grained (<0.2 mm). In the reddish-brown (devitrified) portions, olivine crystals display high interference colors with a yellowish alteration. The beige-colored portions of the thin sections are moderately fractured, with irregular fractures filled with palagonite and unidentified clay minerals, representing cooling fractures at the crust.

The central portions of the pillows are composed of massive basalts with a hypohyaline texture (Figure 8D). The grain size is fine (<1 mm), the relative granulation is inequigranular and microporphyritic, and the rock is composed of plagioclase (~85%) and opaque minerals (~15%). Glass is less common in these rocks, and when present, it is found in the interstices of plagioclase crystals. The plagioclase crystals are subhedral, tabular, with sizes ranging from 0.09 to 0.2 mm, and exhibit a gray/colorless hue. The opaque minerals are anhedral and fine-grained. These rocks contain microphenocrysts of plagioclase, augite, and olivine. The microphenocrysts of olivine are subhedral to euhedral, prismatic, fine-grained (0.3 to 0.7 mm), turning reddish-brown when altered to iddingsite. The microphenocrysts of plagioclase are subhedral to euhedral, tabular, and fine-grained (mean size 0.6 mm in diameter).

Some pillows exhibit vesicles that are partially or fully filled, termed amygdales (Figure 8E). These cavities account for up to 5% of the total volume, with diameters ranging from 0.40 to 4.1 mm (Figure 8F). Locally, textures such as pilotaxitic (alignment of plagioclase microlites within the glassy groundmass) are associated with vesicles (Figure 8G).

Alteration features observed in the thin sections include olivine dissolution and alteration, as well as the carbonation of certain basalts, particularly those from the Juá-II mine, imparting a light brown appearance to the rocks.

Table 1. Summary of morphological and dimensional characteristics of pillow lavas by investigated site in the Boa Vista Basin.

Site	Diameter (cm)	Main morphology	Key structures
Primavera (PRI)	20-60	Elongated pillows	Glassy crusts, multiple crusts, radial joints, hyaloclastite (~ 5 cm thick) and palagonite.
Pedra do Fogo (PEF)	28-80	-	Glassy crusts, cooling fractures and interpillow material (5-25 cm thick)
Juá II	56-60	Rounded pillows	Glassy crusts, minor interpillow hyaloclastite and pillow breccia.
Lages I	-	-	Pillow lavas are not exposed, only bentonite is observed.

4.3.2 Hyaloclastites

Hyaloclastite samples consist of fragments of vitrophyric basalt. The groundmass of these vitrophyric fragments is composed of volcanic glass (~70%), plagioclase (~20%), and olivine (~10%). Crystallinity is hypocrystalline. The thin section in Figure 8H displays two distinct color areas under parallel polarizers: light brown and dark brown. The light brown areas have a higher concentration of glass than the dark brown areas. The dark brown areas show subtle indications of devitrification textures with the presence of plagioclase microlites. This rock is fine-grained (<1 mm). The plagioclase crystals are subhedral, lath-shaped, fine-grained (<0.2 mm), and exhibit a gray/colorless hue. The olivine crystals are subhedral, prismatic and fine-grained (mean size 0.16 mm). When altered, these crystals change to yellow or brown hues. Vesicle presence is low (<2%), with diameters ranging from 0.1 to 0.4 mm. Additionally, in the light brown portions of the hyaloclastite, fractures filled with palagonite are prominent.

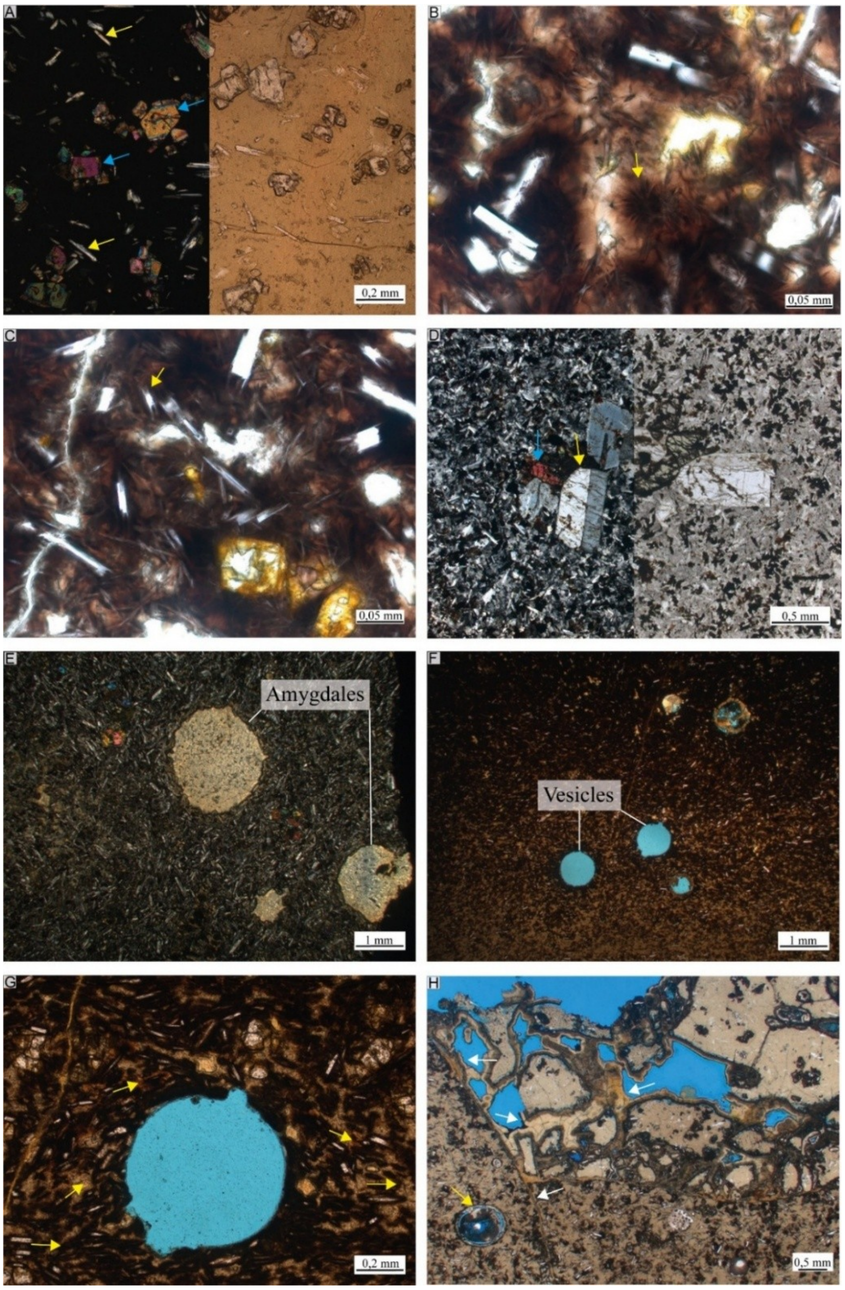

Figure 8. Photomicrographs of volcanic samples from the upper unit of the Boa Vista Basin. **A.** Hypocrystalline basalt, with plagioclase crystals (yellow arrow) and olivine crystals (blue arrow) visible under crossed (left) and parallel (right) nicols. **B.** Devitrification textures with spherulites are highlighted by a yellow arrow under parallel nicols. **C.** Plagioclase microlites with a swallow-tail texture are indicated by a yellow arrow under parallel nicols, with enhanced light exposure emphasizing the rock groundmass. **D.** Hypohyaline basalt features microphenocrysts of plagioclase (yellow arrow) and olivine (blue arrow) under crossed (left) and parallel (right) nicols. **E.** Amygdales are observed under crossed nicols. **F.** Vesicles visible under parallel nicols. **G.** Pilotaxitic texture, marked by a yellow arrow, and devitrification textures are also evident under parallel nicols. **H.** Hyaloclastite with fracture filled with palagonite (white arrow) and a vesicle (yellow arrow) under parallel nicols.

5. DISCUSSION

The basalts of the Upper Unit of the Boa Vista Basin studied in this work exhibit characteristic features of pillow lavas, including elliptical or circular morphology, glassy crust, multiple crusts, radial cooling joints, vesicles/amygdales, cuspate features at the basal portion of the lobes, and interpillow material. These features are consistent with descriptions by various authors (McPhie et al., 1993; Gill, 2010; Jerram, 2011; Famelli et al., 2021a, b) as diagnostic of pillow lavas.

Additionally, despite the fine to very fine grain size of the rocks studied, the petrographic analysis revealed significant variations in crystallinity from the margins to the centers of the pillows. The pillow edges exhibit a glassy texture, hypocrystalline in nature, with a higher proportion of glass relative to crystals. Conversely, the pillow centers exhibit more crystals than glass, reflecting a hypohyaline texture. According to Gill (2010), hypocrystalline textures indicate lavas subjected to a high degree of supercooling, typically associated with subaqueous lava flows.

Another noteworthy observation is the presence of palagonite in the studied samples, generally associated with pillow edges, interpillow spaces, and fracture fillings. According to Stroncik and Schmincke (2002), palagonite forms through the interaction of volcanic glass with water, and its presence in the samples strongly supports the interpretation of a subaqueous depositional environment.

Hyaloclastite deposits were primarily identified as components of the interpillow material, while pillow breccias predominated in the spaces between isolated pillow lavas. In outcrops with hyaloclastites, variations in quantity were observed in the interpillow spaces, particularly at the Juá II mine. In the upper portion of this outcrop, interpillow spaces are absent, while in the basal portion, the hyaloclastite interpillow material reaches a thickness of up to 5 cm. According to Walker (1992), increased hyaloclastite within interpillow spaces may result from steeper slopes at the original depositional site of the lavas.

In the Boa Vista Basin, pillow lavas at the PRI mine are associated with pillow breccias. In the S-N section of this site, both deposits fill concave paleo reliefs (Figure 6), which, according to some authors, represent paleochannels in the sandstone layers (Barbosa and Souza, 1999a, b; Souza et al., 2005; 2013). In the E-W section, the pillow lavas are elongated (Figure 5), with a 30° inclination, oriented with a westward trend, and are isolated from one another by pillow breccia deposits.

The presence of paleochannels rules out the hypothesis of an exclusively lacustrine system, as proposed by Petta and Barbosa (2003) and Lages et al. (2018), and supports the idea that the basalts of the Upper Unit were deposited from steep fluvial channel flanks within a lacustrine environment (Souza et al., 2005; 2013). The deposits that best reflect the lacustrine and fluvial aspects of the basin are the thick bentonite and sandstone layers, respectively (Barbosa and Souza, 1999a, b). However, the absence of siliciclastic material, such as sand, associated with the effusive and volcaniclastic deposits filling the channels at the PRI site, prevents confirmation of an active fluvial channel (transporting water and sediments) during lava flowage. This hypothesis requires further investigation, as the sampling in this study focused primarily on pillow lavas.

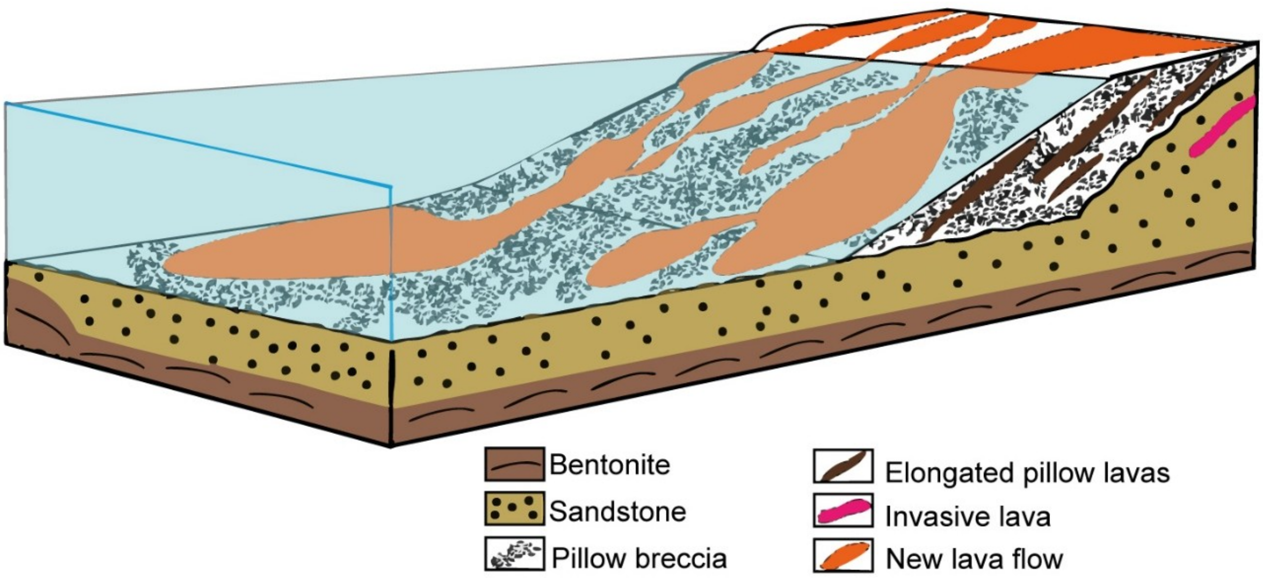

Figure 9. Illustration of a potential lava delta formed on the slope of a lake in the Boa Vista Basin with associated invasive lavas (not to scale).

Based on these observations, volcanic activity in the study area may be related to the formation of lava deltas, which represent volcanic architectures formed when subaerial lavas flow into the water, prograding over steep subaqueous slopes (Moore et al., 1973; Furnes and Fridleifsson, 1979; Watton et al., 2013). In such environments, the formation of pillow breccias is common, with gravity acting on steep subaqueous slopes (30° to 45°; Moore et al., 1973) contributing to the disaggregation of pillow lavas. Moore et al. (1973), in their studies of Hawaiian lava deltas, describe a depositional sequence similar to that observed in Figure 5. The elongated pillow lavas are emplaced on steep slopes (30° to 45°), oriented in the same direction as the delta progradation, and are isolated by pillow breccia deposits. The inclination (30°) and orientation of the elongated pillow lavas (which come from E and move to W), isolated by pillow breccias (Figure 5), are similar to those observed in lava deltas (Moore et al., 1973; Figure 9). Watton et al. (2013) identified channelized structures, comparable to those observed in this study, in Icelandic lava deltas. The subaerial expression of lava deltas, although not identified in this study, may correspond to the massive flows that grade into pillow lavas described by Souza et al. (2005; 2013) in the Upper Unit of the basin.

The presence of a basaltic body embedded within the sandstones of the intermediate unit at the PRI mine, located directly below the flows of the Upper Unit (Figure 6), may suggest: (i) basaltic flows from the intermediate unit later covered by sands after their deposition; (ii) shallow intrusion; or (iii) invasive lava. The sandstone layers observed in this section are conformable to the irregularities of the volcanic body, showing evidence of deformation (Figure 6C). This characteristic is more consistent with lava interaction with unconsolidated or partially consolidated sediments (McPhie et al., 1993) than with new sand deposition following lava solidification.

Another noteworthy observation is that the volcanic body embedded in the sandstone and the overlying flow from the Upper Unit of the basin exhibit complementary shapes that appear to fit together. In this case, it is more likely that the volcanic body embedded in the sands represents an invasive lava flow associated with the Upper Unit flows rather than a shallow intrusion.

Examples of invasive lavas have been identified in Brazil and worldwide (Schmincke, 1967; Beresford and Cas, 2001; Dostal and MacRae, 2018; Famelli et al., 2021a, b). These deposits form due to density differences between lava and unconsolidated or partially consolidated sediments. When lava invades unconsolidated sediments, peperite deposits can form around the volcanic body (Famelli et al., 2021b). Although this outcrop was not directly accessed and could only be observed through distant photographs, the shape of the volcanic body and the small detached basaltic clasts suggest peperite formation (Figure 6C). One basaltic clast has a globular shape, while another exhibits a fluidal, irregular morphology (a single clast with fluidal and sub-planar margins), similar to the main volcanic body embedded in the sands. Skilling et al. (2002) note that volcanic fragments with such shapes embedded in sediments are indicative of peperites.

6. CONCLUSION

This study provides a comprehensive morphological and petrographic analysis of the subaqueous volcanic rocks from the Upper Unit of the Boa Vista Basin, leading to an interpretation of their depositional environment. The combination of characteristic features, including pillow lavas with multiple crusts (contraction cracks), glassy crusts and radial cooling joints, associated hyaloclastites in the interpillow material, and pillow breccias, confirms eruption and rapid cooling in a subaqueous setting.

The primary conclusion of this research is that these volcanic deposits formed as part of a lava delta system prograding into a lacustrine environment. This interpretation is supported by key architectural evidence: 1) the presence of paleochannels filled with effusive and volcaniclastic deposits; 2) the consistent inclination of elongated pillow lavas (averaging 30°) isolated by pillow breccias; and 3) the observed transition from massive basalt flows into pillow lavas.

A significant and novel finding of this work is the identification of invasive lavas, which demonstrates a direct interaction between the basaltic flows of the Upper Unit and the underlying unconsolidated to partially consolidated siliciclastic sediments of the intermediate unit. This provides new insight into the complex emplacement dynamics within the basin.

The characterization of the Boa Vista Basin is of considerable national importance due to the scarcity of such well-exposed subaqueous volcanic outcrops in Brazil. The findings presented here establish this site as a critical reference for studying lava-water interactions. Moreover, these deposits serve as an invaluable surface analogue for interpreting subsurface volcanic sequences encountered during oil and gas exploration in sedimentary basins. While this study establishes a strong depositional model, future work, including detailed stratigraphic sections, will further refine our understanding of the volcanic evolution within the basin.

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Bruna Vale de Oliveira: Writing - original draft, Conceptualization. Gabriel Medeiros Marins: Writing - review and editing, Resources, Investigation. Natália Famelli: Writing - review and editing, Resources, Investigation. Leandro Arrais Bevilaqua: Writing - review and editing, Resources, Investigation.

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