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Volcanic stratigraphy of the high-Ti basalt succession in the northern Paraná Magmatic Province based on geochemistry of detailed field sections in the Jaú-Barra Bonita region

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Abstract

We combined detailed field work with whole-rock geochemistry of samples from both surface exposures and rock chips from a ~300 m pile of basalt retrieved from a groundwater borehole in the Jaú region (central part of the state of São Paulo) to contribute to the stratigraphic knowledge of the northern Paraná Magmatic Province. The P_2O_5 content was used as the first guide to flow identification, always combined with other minor and trace elements (mostly Ti, Zr, Sr, and Cu). This approach allowed the establishment of a stratigraphic column with 16 flows, which were tentatively divided into three sequences. Regional correlations show that the lower portion of these basalt flows (Sequence 1) has good correspondence with the flow-by-flow succession identified at the border of the Paraná Basin by previous regional works. The upper eight flows, occurring at the top of the plateau where the thickness of basalt reaches up to 300 m, should have their continuity westward (toward the center of the Paraná Basin), where the volcanic pile thickens. The local preservation of these upper flows may result from significant (up to 170 m) displacements along the ENE-directed Jaú fault, identified from stratigraphic relations here defined in the basalt pile.

KEYWORDS: volcanic stratigraphy; Paraná Magmatic Province; Serra Geral Group; geochemistry.

INTRODUCTION

The definition of volcanic stratigraphy of basalt flows in large parts of the Paraná Magmatic Province (PMP), especially in its northern portion in Brazil, is hampered by the smooth topography and a small number of good exposures, in part due to widespread cover by the younger Bauru Group sedimentary rocks. Significant findings on the regional PMP volcanic stratigraphy were accomplished when field campaigns and the study of borehole samples were combined, relying on whole-rock geochemistry as a key tool for the correlation of major flow sequences (Peate *et al.* 1988). Stratigraphic correlation on a detailed flow-by-flow basis was applied in key areas of the southern PMP, always using whole-rock geochemistry as a major tool (Pinto and Hartmann 2011, Rosenstengel and Hartmann 2012).

Two recent contributions identified flow-by-flow basalt successions in parts of the state of São Paulo, based on whole-rock geochemistry and either field campaigns and correlation of geologic profiles (Fernandes *et al.* 2018) or the study of rock chips from groundwater exploration boreholes traversing thick packs of the volcanic succession (Machado *et al.* 2018). A combination of these two approaches was also applied with success in a small area near Ribeirão Preto by Fernandes *et al.* (2010). These studies constitute a fundamental step toward the refinement of the volcanic stratigraphy in a region with generally poor exposures.

Fernandes *et al.* (2018) focused on the first flows of the basalt succession, whose spatial distribution is critical for environmental issues, especially the exploration of the Guarani Aquifer, which occurs in the Botucatu Formation and directly underlies the volcanic rocks. However, the lava pile thickness is known to reach hundreds to thousands of meters toward the center of the northern province (Torres *et al.* 2008, Machado *et al.* 2018), where the rock exposures correspond only to the top of a succession that may comprise tens of basalt flows.

Supplementary material

Supplementary data associated with this article can be found in the online version: https://doi.org/10.48331/scielodata.PAHXCW.

Supplementary File 1. Results of whole-rock geochemistry analyses (major and minor oxides and selected trace elements) by X-ray fluorescence.

Supplementary File 2. Results of trace-element analyses by ICP-MS.

Supplementary File 3. Summary of the main characteristics of each flow identified in the Jaú region.

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The purpose of this study is to determine the flow-by-flow stratigraphy of a ~50 × 50 km^2 area of the northern PMP near the city of Jaú (São Paulo state), where the first basalt flows that overlay the Botucatu Formation sandstones are exposed. In this area, the volcanic succession thickness varies significantly to over 300 m, as indicated by data from underground water wells. The lava stratigraphy was defined based on the whole-rock geochemistry of basalt chips obtained from a deep (~380 m) groundwater well that reached the lower contact of the volcanic succession with the sandstones and of basalt samples collected in field campaigns, mainly from six detailed geological profiles along the main rock exposures. Correlations were made considering the regional basalt isopachs recently obtained from borehole data processing (cf. Negri et al., submitted). The proposed column integrated with regional data reveals a total of 16 flows in the Jaú region and greatly improves the previous knowledge of the volcanic stratigraphy of this area, which might be used as a potential reference for regional correlations in the northern portion of the PMP.

THE PARANÁ MAGMATIC PROVINCE IN BRAZIL

The volcanic succession of the PMP in Brazil is mostly located in the Paraná intracratonic basin, succeeding and partly interacting with the desert sands which originated the sandstones of the Botucatu Formation, of the Upper Jurassic-Lower Cretaceous age. In the northern portion of the basin, these volcanic rocks are locally covered by Upper Cretaceous sedimentary rocks of the Bauru Group (Fig. 1).

The extrusive rocks of the PMP are preserved in an area of ~920,000 km^2, with a corresponding volume of 450,000 km^3 (Frank *et al.* 2009), distributed over large portions in the south and southeast of Brazil and extending to neighboring areas in Argentina, Uruguay, and Paraguay. Recent high-precision U-Pb dating of silicic rocks that are interleaved with the basalts confirms a remarkably rapid magmatic event at ~134–133 Ma, with a < 1 Ma duration for the formation of the older low-Ti succession exposed in south Brazil (Rocha *et al.* 2020), possibly extending to ~132 Ma in the case of the younger high-Ti succession which outcrops in the northern and western part of the province (Ernesto *et al.* 1990, Janasi *et al.* 2011).

Tholeiitic basalts and andesite basalts are largely predominant in the volcanic succession and also among the expressive volumes of associated intrusive rocks (estimated preserved volume ~110,000 km^3; Frank *et al.* 2009). The volcanism is bimodal, and silicic (> 63 wt% SiO_2) rocks form voluminous occurrences mostly at the upper portion of the southern low-Ti basalt succession (Palmas-type dacites and rhyolites) and locally at the lower portion of the high-Ti succession (Chapecó-type trachydacites) (e.g., Nardy *et al.* 2008).

As in other Continental Flood Basalt (CFB) provinces, chemical composition was used as a major tool for stratigraphic correlations. The classical work of Peate (1997) distinguished three main basalt magma types in the southern PMP (the low-Ti Gramado and Esmeralda types and the high-Ti, high-Sr Urubici type) and another three in the northern PMP (high-Ti Pitanga, Paranapanema, and Ribeira types; Nardy *et al.* 2002, Squisato *et al.* 2009). The latter are distinguished from each other for their progressively more primitive and lower-Ti contents from Pitanga- to Ribeira-type lavas.

Recent detailed stratigraphy work in the southern part of the province resulted in the proposition of a formal stratigraphic column, promoting the Serra Geral Formation which included the PMP basaltic rocks to the category of Group, subdivided into four formations distinguished by their structural and compositional characteristics (Rossetti *et al.* 2018).

No formal stratigraphic division was proposed for the lavas from the northern PMP, but studies based on field relationships and borehole chemical data indicate a general succession beginning with Chapecó-type trachydacites, followed by the Pitanga basalts and then by the least evolved Paranapanema basalts (Peate 1997, Janasi *et al.* 2007, Machado *et al.* 2018). The stratigraphic position of the Ribeira basalts in this succession is still dubious, as its minor occurrences are scattered in the northern PMP (Peate 1997, Machado *et al.* 2009, 2015, Rocha-Junior *et al.* 2020).

LOCAL GEOLOGY

The study area is in the central region of the state of São Paulo and is constituted, from the base to the top, by the Piramboia, Botucatu, Serra Geral, and Itaqueri formations (Fig. 1). Very locally, the Serra Geral basalts are overlain by the younger sedimentary rocks of the Bauru Group. The Piramboia and Botucatu formations are formed by sandstones that generally outcrop in the Peripheral Depression (lower altitude region) and at the base of the basalts which support escarpments that form the so-called "cuestas." Toward the west and northwest of the cuestas, altitudes gradually decrease and the layers of sedimentary and volcanic rocks dip gently in that direction (Fig. 1). The Permo-Triassic Piramboia Formation consists of medium to fine sandstones, locally thick and conglomeratic, deposited in a fluvio-lacustrine and eolian environment (Soares 1975, Milani 2004), while the Jurassic-Cretaceous Botucatu Formation is formed by well-sorted, eolian, medium- to fine-grained sandstones deposited in a desert environment (Assine *et al.* 2004). The Upper Cretaceous Bauru Group is locally represented by the Vale do Rio do Peixe Formation which consists of reddish fine-grained sandstones, siltstones, and local conglomerates, while the Upper Cretaceous-Paleogene Itaqueri Formation is mostly formed by silicified sands and conglomerates (Riccomini 1995).

In the study area, the basaltic rocks support an E-W elongated cuesta between the cities of Torrinha and Jaú (Fig. 1). The interpolation of lithological data from water wells provides a regional estimate of the basalt thickness in the western part of the cuesta, where it may reach 300–400 m, and the depth of the lower contact with the Botucatu sandstones is found at altitudes as low as 200 m (Fig. 2). South of it, between Bauru and Barra Bonita, the thickness of basalts is much smaller due to the Bauru structural high (Paula e Silva 1988), where the Bauru Group directly covers the Piramboia and Botucatu formations, and the Piratininga Dome, a region with no basalt occurrence (Braga *et al.* 2016). North of the cuesta, in the Brotas region, the Piramboia and Botucatu formations outcrop at altitudes where

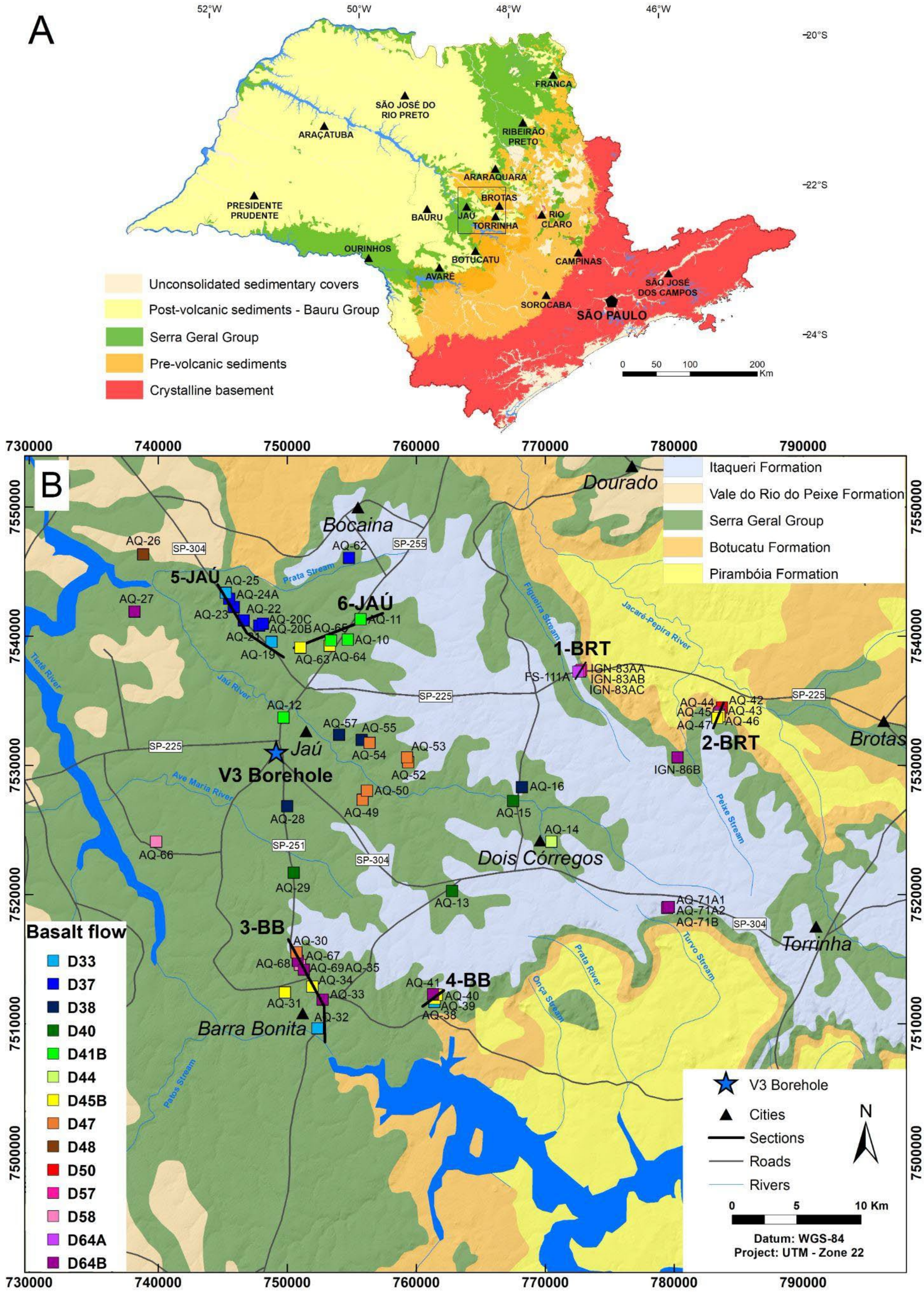

Figure 1. (A) Simplified São Paulo state geological map with the study area location (black square). (B) Geological sketch map of the study area with the location of visited outcrops and identified basalt flows (represented by squares of distinct colors, see the text for details on flow nomenclature). The locations of the six geological sections further described in the article (1-BRT, 2-BRT, 3-BB, 4-BB, 5-JAÚ, and 6-JAÚ) are also indicated.

the basalts should appear. This was observed by Fernandes *et al.* (2018), who identified and defined a large structural high in this region where locally the Itaqueri Formation directly overlies the Botucatu Formation. Fernandes *et al.* (2018) also suggested that several conspicuous structural lineaments, in the E-W, N20W, and N50–60W directions, represent faults with significant vertical offsets, whose activity was posterior to the emplacement of the basalts and prior to the deposition of the Itaqueri Formation.

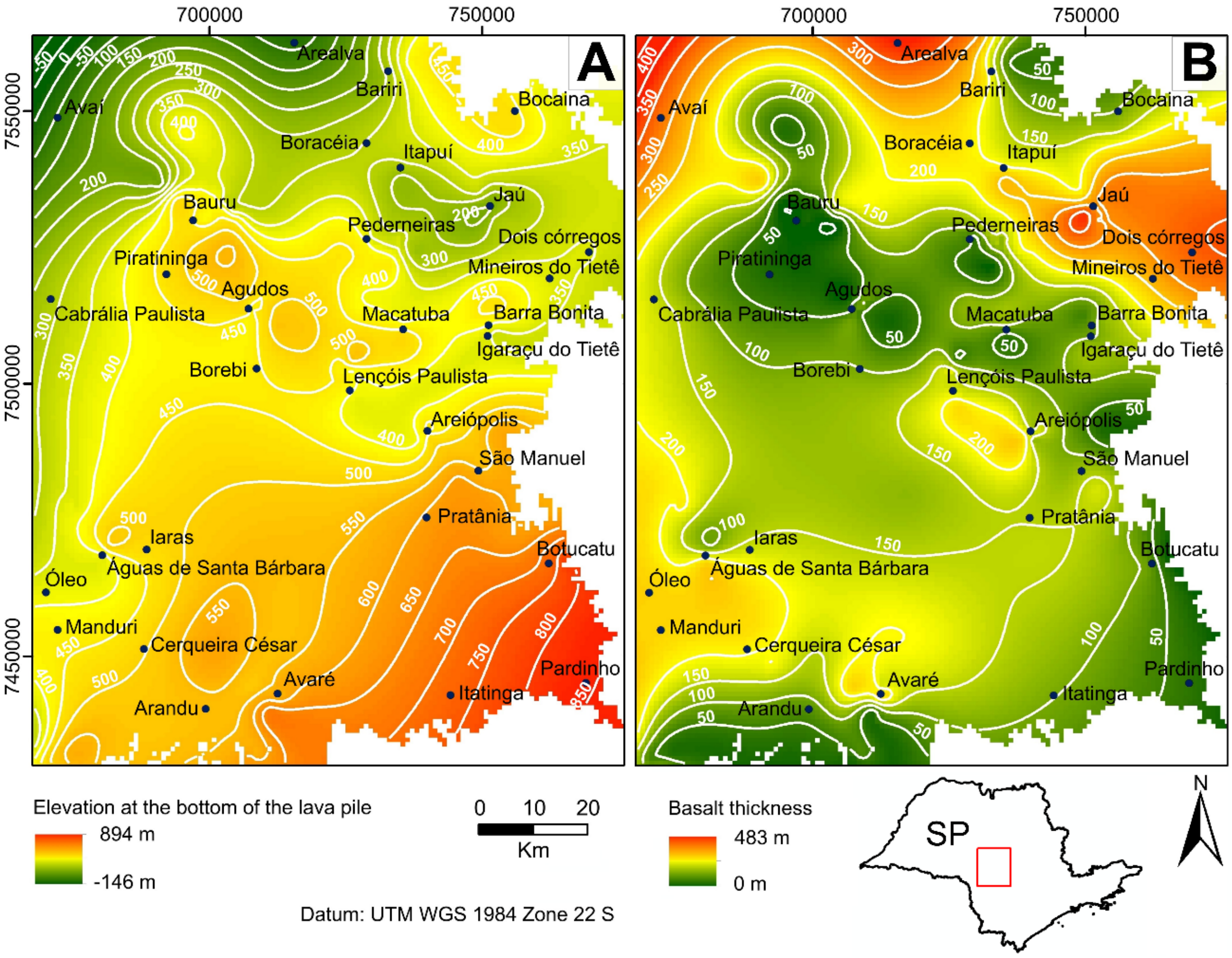

Figure 2. Elevation at the bottom of (A) the lava pile and (B) basalt isopachs estimated from hydrogeological wells data processing. The red rectangle below shows the outline of these maps in the state of São Paulo (SP).

METHODS

Field work was carried out mostly along roads shown in Fig. 1, as the best exposures occur in roadcuts and in a quarry located ~7 km west of the city of Jaú. Circa 75 sites were studied, and fresh samples of basalt were collected in most of them.

A total of 58 fresh basalt samples were analyzed for major, minor, and trace-element analyses by X-ray fluorescence. A subset of 12 samples which represent most of the existing chemical variability observed was analyzed by inductively coupled plasma mass spectrometry (ICP-MS) for additional trace elements, including rare-earth elements (REEs). The details of the analytical procedures are given below.

Strong support for the stratigraphic correlations was given by additional geochemical analysis of rock chip samples from a borehole drilled for water exploitation. In this case, samples were prepared differently to ensure the best quality and representativeness of these analyses, as detailed below.

Sample preparation for geochemical analysis

Samples were prepared at the Geoanalitica Core Facility in the Institute of Geosciences from the Universidade de São Paulo (IGc-USP) following the protocols by Mori *et al.* (1999). In addition to the samples collected during field work, 20 samples from the V-3 borehole, kindly provided by DAEE (Departamento de Águas e Energia Elétrica; the governmental department which keeps material drilled from water exploration wells), were selected for geochemical analyses based on the identification of potentially different flows and avoiding oxidized and/or amygdale-rich horizons. Considering the limited amount of rock chip samples available and possible cross-contamination with fragments of different depths during drilling, samples were carefully examined under the binocular microscope. Secondary materials such as calcite, clay minerals, zeolite, and quartz from amygdales were manually removed, as well as any fragment that had a contrasting textural or compositional aspect with respect to the predominant chips in a sample. The fragments selected for analysis were then submitted to repeated ultrasonic baths to remove any remaining mud from the drilling process. After that, they were dried and ground in an agate mill.

Geochemical analyses

The analyses of major and minor oxides were obtained from fused glass disks, and a set of trace elements was analyzed from pressed powder pellets, both in a PANalytical AXIOS MAX Advanced X-ray Fluorescence Spectrometer at the Geoanalitica Core Facility in IGc-USP, following the protocol described by Mori *et al.* (1999). Quality was controlled by analyzing certified international reference materials basalt

JB1a and granodiorite JG1a, as well as a duplicate for every five samples. The results were considered satisfactory for both major elements (accuracy better than 2% for oxides with contents over 10 wt% and better than 5% for the remaining oxides) and trace elements (accuracy better than 10% when the contents are 10 times greater than the detection limit). Because of the limited amount of material available, only major oxides were determined for the borehole rock chip samples.

For the analysis of a subset of 12 samples by ICP-MS, a 40 mg aliquot of each powdered sample was dissolved by acid attack using HF and HNO_3 in a CETEC microwave oven for 60 min. The solution obtained was dried and dissolved in HNO_3 and analyzed in a Thermo iCapQ ICPMS at the same laboratory, following the procedures described by Navarro *et al.* (2008). For quality control, reference materials BR and JGb-1 were analyzed, as well as duplicates and blanks.

BASALT STRATIGRAPHY

Intensive use of whole-rock geochemistry was necessary to correlate the basalt flows, as their field aspect is very similar, and outcrops are scarce, as typical in most of the northern part of the PMP. We follow approaches already tested in previous work in the province, using the P_2O_5 content as the first guide to differentiate the flows (e.g., Fernandes *et al.* 2018, Machado *et al.* 2018, Pinto and Hartmann 2011, Rosenstengel and Hartmann 2012). All flows identified in the study region belong to the Pitanga type of Peate (1997), which shows the highest P_2O_5 contents among the PMP basalts, and yet the variation is large enough (from 0.3 to 0.7 wt%, see below) to distinguish most of them. Surely, other parameters are needed to identify a clear fingerprint of each flow, as two different flows may have the same P_2O_5 content, and small variations may exist within a single flow. As will be seen in discrimination diagrams, other elements, most importantly Ti, Zr, Cu, and Sr, whose contents are high enough to be analyzed with good precision by XRF, were used to identify the flows. As for the flow nomenclature, because, at least at this stage, the use of geographic names for individual flows has not been adopted in the local nomenclature (as opposed to the case for instance in the classical Columbia River Province; Reidel 2015), we decided to refer to their average P_2O_5 content times 100 (e.g., D67 refers to a flow with average $P_2O_5 = 0.67$; if two different flows have the same P_2O_5 content, they are distinguished by a letter: D67A, D67B). We emphasize that all samples analyzed correspond to fresh portions of the rocks, as attested by petrographic examination and low loss on ignition values; no samples from the upper amygdaloidal portions of the flows were analyzed. Petrographic sections were obtained for all outcrop samples and used for the selection of samples for geochemical analyses.

As typical of the Pitanga-type basalts in the study area at the northern PMP, texture and mineralogy are monotonous. All rocks are aphyric, aphanitic to fine-grained with intergranular to intersertal texture, and constituted of plagioclase of labradorite composition, clinopyroxenes, and magnetite, with apatite and traces of quartz and potassic feldspar as granophyric intergrowths in the interstices of fine-grained intergranular samples. Therefore, we did not dedicate a specific section to present their petrography.

V-3 Borehole

A ~400 m thick sequence of basaltic rocks was sampled at a V-3 borehole, located near the city of Jaú (Fig. 3; UTM 7531050 S 749850 W, zone 22 K, 595 m). Rock chips were originally sampled every 2 m, but considering the high number of samples and their homogeneity, we subsampled at 4-m intervals, obtaining ~100 samples. Samples were named V3-xx, where xx corresponds to the depth of the upper level of the sampled interval. This material was carefully evaluated to identify possible limits of individual flows, marked, for instance, by the presence of discontinuities such as intercalated sediments or vesicular-amygdaloidal levels (VALs) that could be indicative of flow tops. The first-order geochemical proxy to identify different flows was the P_2O_5 content, which was found to be a reliable tracer in this and previous investigations (e.g., Fernandes *et al.* 2018, Machado *et al.* 2018).

A single level of intercalated sandstone is present at 170 m, i.e., above at least 230 m of basalt (Fig. 3). Additionally, 11 VALs were identified. Most are thin and grayish, but a thicker (> 30 m) reddish VAL corresponding to a more oxidized horizon occurs at a depth of 270–300 m. Between VALs, massive basalts have thicknesses of 10–30 m and were interpreted as individual flows. An 80-m-thick sequence of massive basalt with no VAL occurs above the intercalated sandstone from depths 90 to 170 m. Thus, 20 samples considered representative of possible individual flows were selected for chemical analysis.

Results of the chemical analyses, which were performed only for major and minor oxides due to the limited amount of

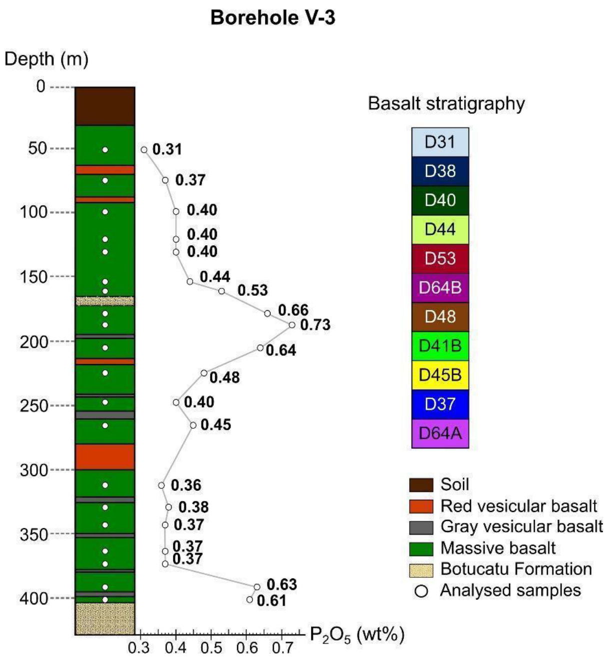

Figure 3. V-3 borehole log with chemical variation of basalt flows illustrated by P_2O_5 contents (wt%) and basalt stratigraphy constrained based on the geochemistry of the analyzed samples. The column with the basalt stratigraphy refers only to the inferred succession of flows and does not have a spatial scale.

material available, are presented in Suppl. File 1 and suggest the existence of 11 flows.

At the bottom of the borehole section, the lower 100 m of basalts are interpreted as two relatively thick flows, despite the presence of four thin gray VAL intervals. The first flow, named D64A, rests directly over the Botucatu sandstones, is ~30 m thick and has high P_2O_5 (0.61–0.62 wt%). It is succeeded by another flow with ~75 m of low P_2O_5 basalt (0.36–0.38 wt%). Although it is possible that this second interval corresponds to more than one flow, no definitive criteria could be found to confirm it. Therefore, this interval was interpreted as an anomalously thick composite flow, as suggested by the presence of a ~30 m red VAL above it, and was named D37.

The second sequence of flows can be identified between the top of the thick red VAL at a depth of 280 m and the intercalated sandstone at 170 m. Based on chemical variations and the presence of VAL, four 20–30-m-thick flows can be identified, and were named, from base to top, D45B, D41B, D48, and D64B. The D41 and D45 flows were named B because there are other D41 and D45 flows identified by Fernandes *et al.* (2018) in a distinct area (referred to as D41A and D45A in this paper), and they cannot be correlated to each other (see Section 6.3 for details).

From the top of the sandstone at 170 m until the soil horizon at the top of the borehole sequence, the P_2O_5 contents of the basalts drop steadily from 0.53 to 0.31 wt%. This is tentatively defined here as the third basalt sequence (see discussion). There is an ~80-m-thick basalt package immediately overlying the sandstone, topped by a thin VAL. Most of it is formed by a basalt with 0.40 wt% P_2O_5 (D40), but in the lower 20 m, the two samples analyzed have, from top to bottom, 0.44% and 0.53 wt% P_2O_5. The more differentiated character of these samples and the absence of VAL suggest that they correspond to thin flows that immediately preceded the eruption of the voluminous D40. The upper two flows, separated by a red VAL, have lower P_2O_5 and were named D38 and D31.

Geological sections

As typical of the northern part of the PMP, rock exposures are sparse and mostly restricted to road cuts and a few active and abandoned quarries. By integrating field data with geochemistry, six main geological sections were elaborated to help infer key stratigraphic relationships between lavas. These sections were grouped into three main areas and are described below.

Brotas Sections

Two sections were described between Jaú and Brotas, in the eastern part of the study area. Section 1-BRT refers to an extensive road cut at km 154 of the BR-369 Road (section 1; Fig. 4A), where the basalt sequence rests directly over the Botucatu sandstone and consists of two flows. The lower flow is ~30 m thick and has a massive portion at the bottom resting directly over the Botucatu sandstone shaped according to its wavy (dune) surface; a thin (~5 cm) laminated layer of aphanitic basalt appears at the contact with the sandstone. This massive basalt is scarcely porphyritic, with mm-sized plagioclase phenocrysts and occasionally plagioclase and pyroxene glomerocrysts. Upward in the section, thin discontinuous strings of vesicular basalt are found within the massive basalt. This flow has a thick (~3 m) vesicular-amygdaloidal top with cm-sized vesicles filled with calcite, quartz, and zeolites, separated from the massive basalt below by a 3–5 m transitional fine-grained to aphanitic microamygdaloidal basalt. A ~10–20-cm-thick layer of hardened sandstone overlays the VAL. It is evident that this layer was thermally affected and interacted with the flow below, as fragments of sandstone are locally involved by the vesicular-amygdaloidal basalt and part of it began to sink into the flow. These features suggest that the sandstone layer floated over the denser basalt flow.

The second flow sits on top of the sandstone layer. It has a clear zonation, with a lower level of fine-grained, platy basalt with horizontal jointing, and an upper level of black aphanitic microamygdaloidal basalt with thinly spaced and irregular vertical jointing, corresponding to an entablature structure. The upper part of this flow is not exposed, and as such, the minimum flow thickness is ~10 m.

Chemical analyses were performed in samples from this outcrop in this and previous studies (e.g., Fernandes *et al.* 2018). The upper flow is chemically homogeneous, with high P_2O_5 content (0.63 wt%), whereas the lower flow is zoned, with a porphyritic portion at the bottom which has higher MgO and lower P_2O_5 (0.51 wt%) than the main part of the flow (with ~0.58 wt% P_2O_5), apparently resulting from accumulation of crystals during solidification, as no contacts are seen in the outcrop. These flows were named D64A and D57, respectively.

Another section (2-BRT; Fig. 4A) was described along an unpaved road climbing the basalt plateau from the lowermost contact with the Botucatu sandstone, 11 km southeast of section 1. Despite poorer exposures, this section is more complete and comprises at least five flows. The first flow, sampled at elevation 585 m, has 0.48 wt% P_2O_5 (D50) and is succeeded by two flows that can be correlated with lavas exposed in section 1-BRT (D57 at 630–650 m and D64A at 650–670 m, the latter with aphanitic basalt and entablature structure). At elevation 680–690 m and above an expressive VAL, another flow, named D45B, was identified based on samples that have 0.44–0.45 wt% P_2O_5. The uppermost flow at this section is D64B, at elevation 700 m and with 0.63 wt% P_2O_5 content.

Barra Bonita sections

In the southern part of the area, section 3-BB (Fig. 4B) starts in the lowermost elevations of the entire studied region (~430 m) at the Tietê River, which separates the towns of Barra Bonita and Igaraçu do Tietê. Extensive exposures of a ~50-m-thick flow exist on both sides of the river along the SP-251 Road and were sampled by Fernandes *et al.* (2018) and again in this study. All samples are chemically similar and are part of a relatively primitive flow with MgO = 5.5–5.8 wt%, 80–95 ppm Cr, and low P_2O_5, here named D33.

This section follows SP-251 northward, taking advantage of a ~220 m relief up to elevation 680 m (Fig. 4). A good exposure of D45B massive basaltic flow at elevation 510 m has 0.45 wt% P_2O_5 and can be correlated with the lavas that outcrop ~2 km to the west in a neighborhood north of Barra Bonita (sample

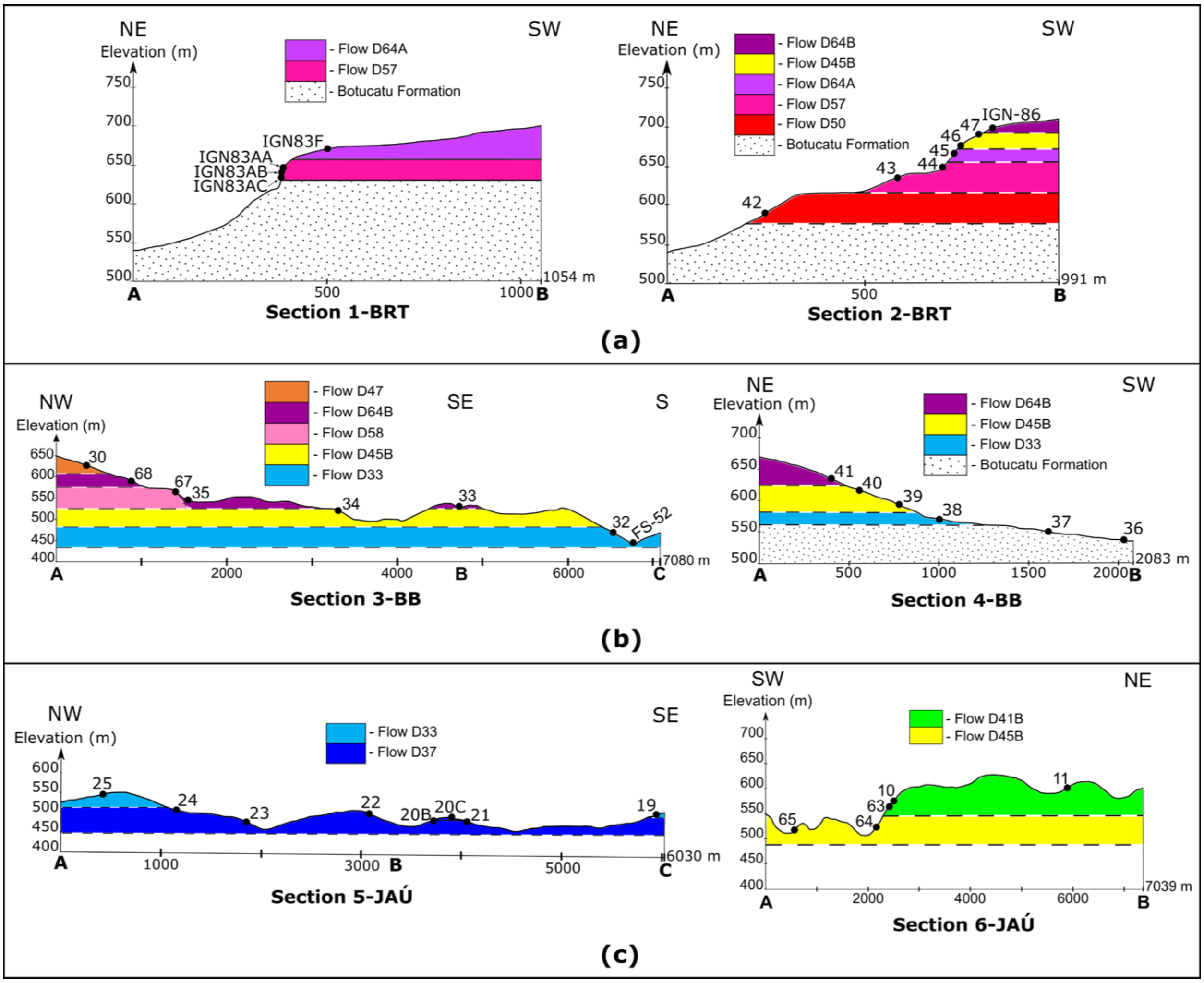

Figure 4. Flow stratigraphy in (A) Brotas sections 1-BRT and 2-BRT; (B) Barra Bonita sections 3-BB and 4-BB; and (C) Jaú sections 5-JAÚ and 6-JAÚ, showing that there are local correlations between flows which are observed in more than one section. Points along sections correspond to samples and their respective codes. See Fig. 1B for section locations.

AQ-31). At higher elevations (520–540 m), a D64B flow with high P_2O_5 is exposed in extensive, but mostly weathered outcrops sampled at sites AQ-33 and AQ-35. Exposures up-section are poor, but small non-weathered samples were collected at elevations 550 (AQ-67) and 580 m (AQ-68). AQ-68 is chemically similar to D64B, which could indicate that a single D64B flow crops out from elevations of 520 to at least 580 m. However, sample AQ-67 has lower P_2O_5 (0.57 wt%) and might correspond either to a D58 flow separating two D64 flows of similar chemistry or to the lateral limit of a previous flow (also represented by sample AQ-66, Fig. 1) that was overlapped by D64, our preferred interpretation (Fig. 4B).

Section 4-BB is ~9 km E of 3-BB and was made with the purpose of checking the lateral continuity of the flows identified in the latter. The Botucatu sandstones outcrop up to elevation 550 m, and the first basalts appear at ~ 570 m, over 100 m above the basalts exposed at the bottom of section 3-BB. The basalt exposures are of poor quality, and the flow succession begins with D33 overlain by D45B (at 590 and 610 m, respectively) and D64 at elevation 630 m. Therefore, 4-BB exposes the same sequence identified on 3-BB, minus D58 (Fig. 4B). D33 can be demonstrated to be the first flow in 4-BB, as it is in direct contact with the Botucatu sandstones. However, it is unclear whether previous flows exist below the expressive occurrence of D33 in section 3-BB because its lower contact is not exposed.

Jaú sections

In the northern part of the study area, section 5-JAÚ follows the SP-304 Road from NW of Jaú toward Bariri. Outcrops occur at low elevations (460–525 m) where the road follows the valley of the Pouso Alegre Creek. All sampled basalts are relatively primitive (MgO = 5.1–5.5 wt%; Cr = 80–100 ppm). At elevations below 500 m, they have 0.35–0.37 wt% P_2O_5 and correspond to flow D37, and samples above this have ~0.32 wt% P_2O_5 and were classified as D33 (Fig. 4C). The best exposures are in site AQ-24, where black, aphanitic microamygdaloidal basalt with entablature structure is observed, and site AQ-25, where massive basalt with sparse flattened amygdales occurs. These outcrops might represent, respectively, exposures of the upper part of a D37 flow and the lower part of a younger D33 flow. No outcrops are found NW of these in SP-304 up to Bariri, so this section is limited to these two flows.

Section 6-JAÚ is located to the NE of the urban area of Jaú along SP-255 Road and consists of three outcrops of fresh, massive basalt exposed at elevations from 520 to 600 m (Fig. 4C).

These three samples have similar composition, with 0.41 wt% P_2O_5 and 3.4 wt% TiO_2. Despite the wide topographic interval, they probably correspond to the same D41B flow, which can be inferred to be located above those exposed in section 5-JAÚ based on their elevation.

As no contacts between the flows exposed in 5-JAÚ and 6-JAÚ were observed in the sections, the stratigraphy of the northern part of the area relies on exposures in the slopes of neighboring hills between these two sections (Fig. 1). These reveal that, between D33 and D41B, there is another flow, exposed at sites AQ-64 and 65 (elevation ~520 m). Samples from both outcrops have 0.45 wt% P_2O_5 and 3.7 wt% TiO_2 and correspond to flow D45B. This intermediate flow can be correlated with lavas exploited in a quarry located west of the city of Jaú in the Jaú River valley, correspondent to site FS-150 sampled by Fernandes *et al.* (2018). This quarry exploits a thick level of massive basalt with spaced, curved jointing.

Outcrops in unpaved roads east of Jaú were sampled and represent two flows: an upper D47 (at elevations above 550 m) resting above a D38 flow (outcropping at 525–545 m). Further east toward Dois Córregos and Mineiros do Tietê, samples from sites AQ13 and AQ15 have 0.40–0.41 wt% P_2O_5 and correspond to D40; site AQ16 with 0.38 wt% P_2O_5 is at a topographic level (640 m) above AQ-15 (from a creek in the urban area of Dois Córregos, at elevation 600 m), suggesting that D40 is below D38. D47 flow is not present in V-3, possibly because it was located above the 550 m elevation below which fresh samples could be recovered. This upper D47 flow is the youngest identified in this area and can be found in rare outcrops at the top of some hills (e.g., AQ-30 at the top of section 3-BB) and it is apparently in contact with flows from different successions, which is suggestive that it was emplaced as part of a distinct, younger sequence.

Geochemistry

Geochemistry was used as the main tool in the stratigraphic correlations presented in the previous item, especially P_2O_5 and TiO_2 contents. All data are available as Suppl. Material.

Figure 5 shows variation diagrams using MgO as a differentiation index. MgO varies from 5.8 to 3.6 wt%, and Ti and P behave as incompatible elements over this whole range, but a significant spread of TiO_2 and P_2O_5 contents exists for a given MgO content, suggesting that the lavas are not part of a single liquid line of descent. Most compositions fall in the small range between 4 and 5 wt% MgO, where their P_2O_5 ranges from 0.4 to 0.6 wt% and TiO_2 varies from 3.4 to 4.0 wt%. More primitive basalts (>5 wt% MgO) have lower contents of incompatible elements (P_2O_5 < 0.4 wt%; TiO_2 < 3.4 wt%; Zr < 220 ppm; Nb < 20 ppm; flows D33, D37, and D38), while the highest contents of these elements are found in basalts with < 4 wt% MgO (P_2O_5 = 0.61–0.65 wt%; TiO_2 = 3.8–4.1 wt%; Zr = 280–310 ppm; flows D64A and D64B).

The distribution of a few trace elements in the variation diagrams (Fig. 5) is more complex compared with the others. For instance, Sr and Cu do not have a clear correlation with MgO but can be used to discriminate several flows. For example, D57 from the lower flow sequence has distinctively higher Sr and lower Cu contents. The youngest D47 flow can also be easily distinguished from flows with similar P and Ti for its relatively high Cu or low Sr. In fact, a progressive decrease in the Sr content can be devised from the early to the late flows with intermediate (4–5 wt%) MgO. It is remarkable that contrastingly low Cu (< 60 ppm × 120–300 ppm) is a feature of the two first flows of the column (D50 and D57).

The results of trace-element analyses by ICP-MS for selected samples are presented in Suppl. File 2. Strongly incompatible elements such as the REE, Th, U, Nb, Ta, and Hf show a steady enrichment, and their contents almost double from more primitive D33 to more evolved D64B (Fig. 6). D57 stands out for its higher contents of multiple incompatible elements compared with other flows with similar MgO content.

The increase in all incompatible elements is nearly linear with decreasing MgO, as also shown by the virtually parallel primitive-mantle normalized incompatible element patterns of all samples analyzed by ICPMS (Fig. 6E). Positive Ti and negative Sr anomalies, as well as depletions in Th-U and Nb-Ta relative to neighbor elements, are common to all samples and typical of the high-Ti Paraná basalts (Bellieni *et al.* 1984, Peate 1997). The variations observed in the patterns of distinct samples for Cs and to a lesser degree of Rb and K might be a reflection of secondary alteration. A slightly negative Eu anomaly (Eu/Eu* = 0.89) and a stronger negative Sr anomaly in D64B reflect more significant plagioclase fractionation affecting these differentiated magmas.

In their recent study of Platinum Group Elements (PGE) and Te, As, Bi, Sb, and Se (TABS+) distribution in the Paraná basalts, Mansur *et al.* (2021) included samples from our collection from the Jaú region. It is remarkable that the Pt, Pd, and Au contents of the two initial flows (D50 and D57) are consistently lower compared with all the other flows, in consonance with their already noticed low Cu.

DISCUSSION

Local and regional correlations

An attempt to correlate the stratigraphic columns built from the Brotas sections with the V-3 borehole is presented in Fig. 7. Individual flows were also preliminarily grouped into sequences based on the presence of features indicative of depositional hiatuses, such as sedimentary layers between flows, thick and oxidized vesicular top layers, and abrupt breaks in the observed trends of chemical variation in lavas. Flow D64A is clearly located below D45B in 2-BRT, and this part of the sequence is inferred to correlate with the lower portion of V-3, where these two flows are separated by a thick D37 flow whose upper VAL might mark the top of the first volcanic sequence (Sequence 1). The absence of D37 in the BRT sections can be explained by non-deposition or erosion. D57 and D50 flows below D64A are not present in V-3, but are clearly at lower stratigraphic positions, as they rest directly in contact with the Botucatu sandstone. Even though D50 is only present in section 2-BRT, it may be correlated to the first flow in the Ribeirão Preto region

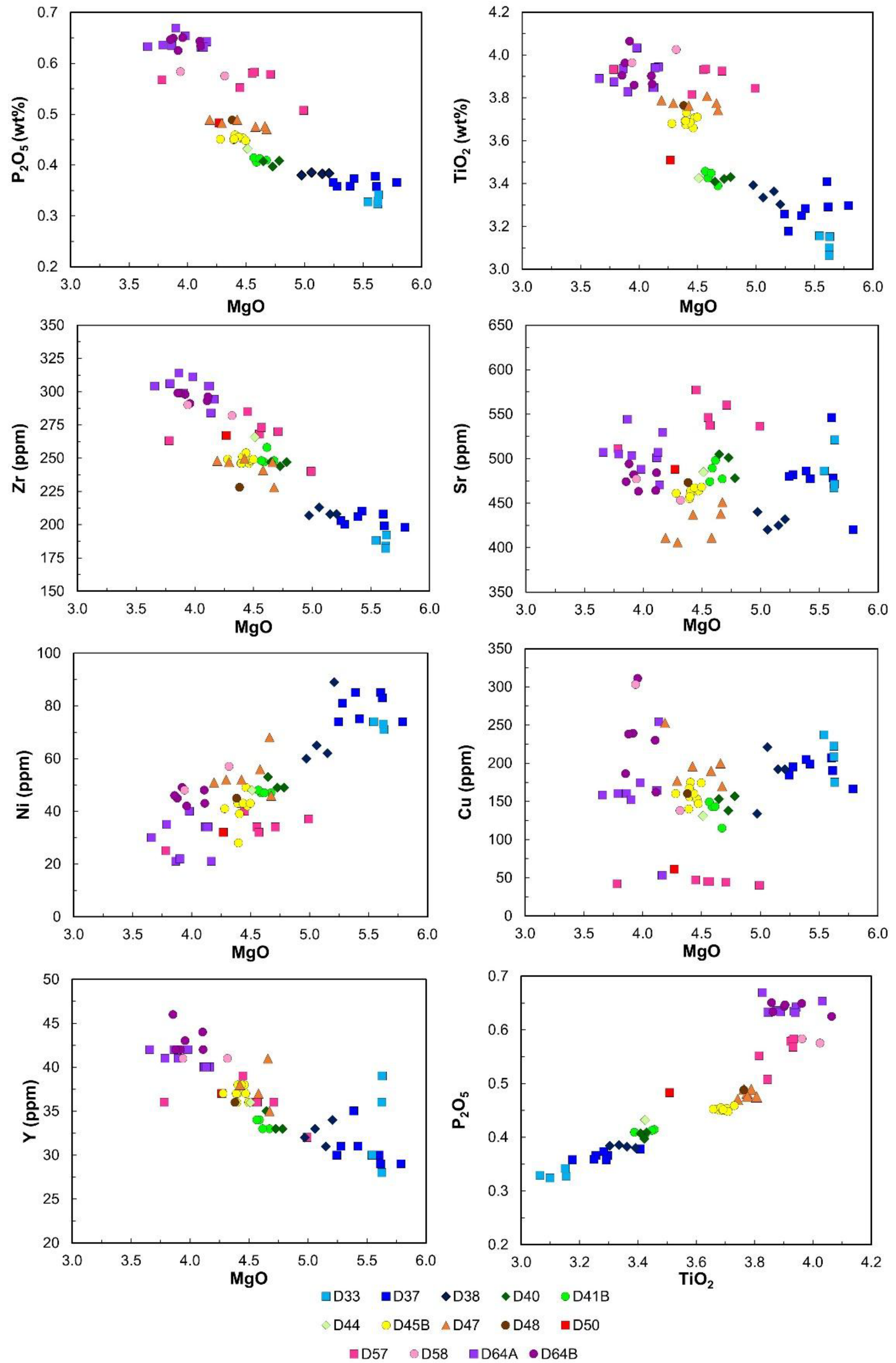

Figure 5. Chemical variation diagrams of minor and trace elements analyzed by XRF using MgO as a differentiation index for basaltic rocks from the Jaú region (note that the last diagram is a binary $TiO_2 \times P_2O_5$ plot). Values were normalized to 100% on an anhydrous basis. Different symbols refer to stratigraphic position: squares, lower sequence; circles, intermediate sequence; diamonds, upper sequence; triangle, flow D47.

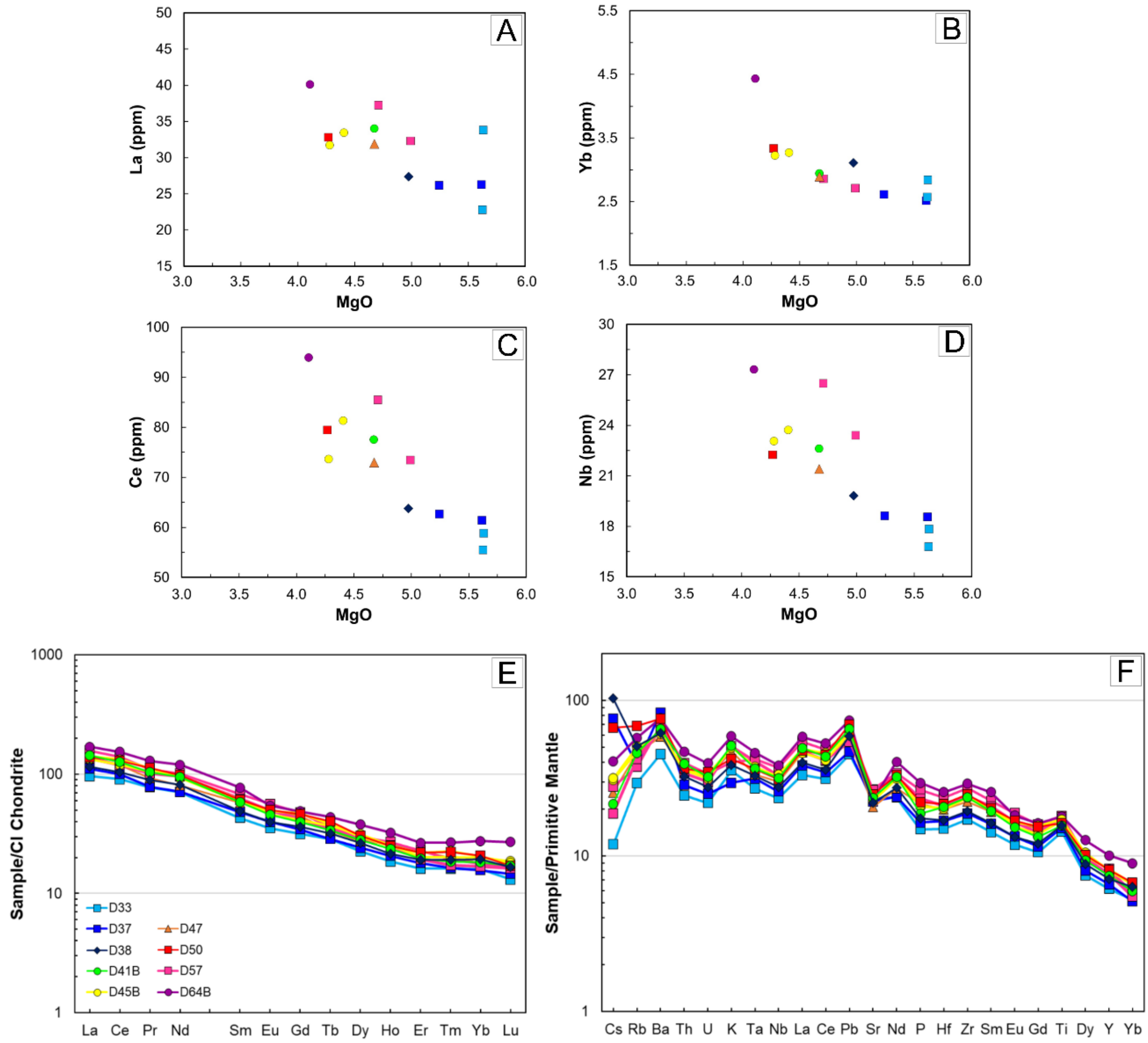

Figure 6. (A–D) Variation diagrams of trace elements analyzed by ICP-MS using MgO as a differentiation index, (E)CI chondrite (McDonough and Sun 1995) normalized rare-earth element patterns, and (F) primitive-mantle (Sun and McDonough 1989) normalized incompatible element patterns of selected basalt samples from the Jaú region. Different shapes of symbols refer to stratigraphic position: squares, lower sequence; circles, intermediate sequence; diamonds, upper sequence; triangle, flow D47.

Borehole V3	1-BRT	2-BRT	3-BB	4-BB	5-JAÚ	6-JAÚ	center	Integrated column	Sequence
							D47	D47	4?
D31								D31	3
D38							D38	D38	
D40							D40	D40	
D44								D44	
D53								D53	
D64B		D64B	D64B	D64B				D64B	2
abs.			D58					D58	
D48								D48	
D41B						D41B		D41B	
D45B		D45B	D45B	D45B		D45B		D45B	
abs.			D33	D33	D33			D33	1
D37					D37			D37	
D64A	D64A	D64A						D64A	
abs.	D57	D57						D57	
abs.		D50						D50	
Botucatu Fm.	Botucatu Fm.	Botucatu Fm.		Botucatu Fm.				Botucatu Fm.	

Figure 7. Stratigraphic correlations of the six main sections in the Jaú region and proposed integrated column.

(Fernandes *et al.* 2010) as they share key chemical features such as the unusually low Cu contents, also a feature of D57, which immediately overlaps D50.

D45B is used as a guide horizon to correlate the Barra Bonita sections with the V-3 borehole. The expressive D64 flow located above it is therefore equivalent to D64B from V-3. D41B and D48 found in V-3 are absent in sections 3-BB and 4-BB, and a D58 flow is present at this level in 3-BB. However, its stratigraphic relationship with D41B and D48 is unknown. The expressive D33 flow located at the base of 4-BB and at the level of Tietê River in 3-BB has no equivalent in V-3.

The D37 flow that outcrops in the 5-JAÚ section is correlated to D37 at the lower part of V-3, and D33 correlates to the lower flows in the BB sections. Thus, the stratigraphic relation in 5-JAÚ places D33 (absent in V-3) over D37. The upper flows identified in the Jaú region (D45B and D41B) correspond to the succession observed in V-3 as expected, as V-3 is located nearby in the urban area of Jaú. This close correlation suggests that isolated sites located west of 5-JAÚ (sites AQ-26, with 0.48 wt% P_2O_5 and AQ-27, with 0.62 wt% P_2O_5, Fig. 1) may correspond to the next two flows that complete the intermediate succession of V-3 (D48 and D64B).

The V-3 borehole section shows a thin (ca. 2 m) sandstone layer above D64B. This sedimentary layer high in the volcanic pile may mark a break in the volcanic activity, potentially defining the top of the second volcanic sequence (Sequence 2). Unlike the first sequence that ends with a thick least differentiated flow (D33), the second volcanic sequence would be marked by progressively more differentiated flows. The flows above D64B in V-3 (Sequence 3) invert the differentiation trend again, progressing from D53 to D31, the more primitive flow of the whole region. The two flows from the middle part of this third (upper) volcanic sequence (D40 and D38) are found in outcrops in the region of flat relief east of Jaú ("center area" in Fig. 7), where field relationships show the same stratigraphic order identified in V-3. Flow D47, identified at the top of the columns in 3-BB and in the area to the east of Jaú, might represent a younger (fourth) volcanic sequence, resting discordantly over different flows and sequences.

A summary of the main characteristics of each flow identified in the Jaú region, including estimated thickness, type of upper contact, and samples used in this study, is presented as Suppl. File 3.

Regional geological sections and tectonism

Three regional sections, along directions N-S (RS1), NW (RS2), and ENE (RS3), extending ca. 37, 32, and 42 km, respectively, were elaborated. RS1 integrates local sections 3-BB and 5-JAÚ, RS2 combines section 5-JAÚ with point 13, and RS3 integrates local sections 2-BRT and 3-BB (Fig. 8).

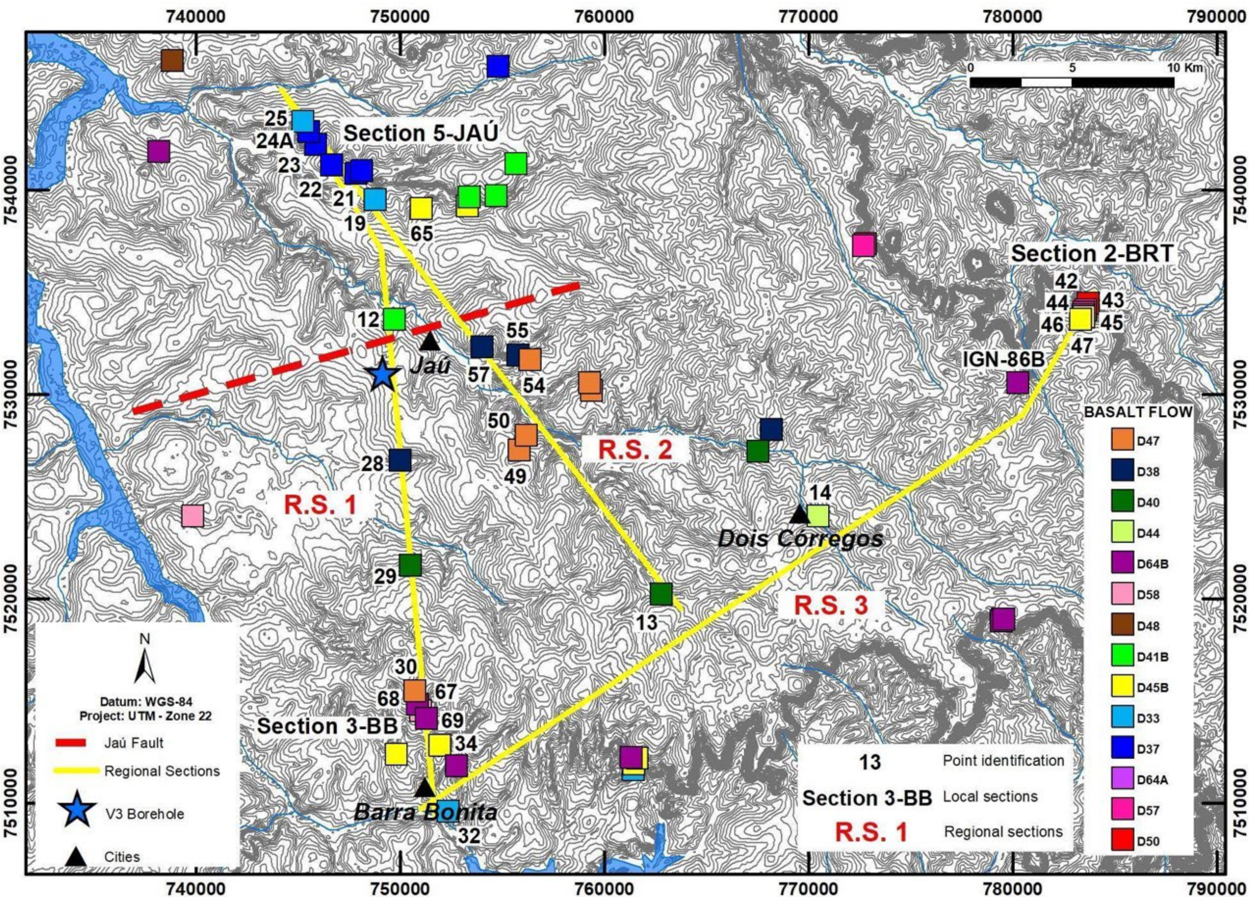

Figure 8. Topographic map with the location of the regional sections and the Jaú Fault. In the legend, the different flows are presented in the stratigraphic order defined in this study.

Sections RS1 and RS2 show a remarkable fault, here named Jaú Fault, with a dip around 75° and an apparent vertical offset, estimated from the total thickness of the displaced flows, of 150–185 m (Fig. 9). This is suggestive that it corresponds to a normal fault generated by an extensional tectonic event. It is noteworthy that the contacts of the flows are approximately horizontal to the north of the Jaú fault and dip around 2.5°–3° to the south of it, a contrast that may have resulted from tilting. In the RS3 regional section, where there is no evidence of faulting, the dip toward ESE is smaller and consistent with the regional pattern of the Paraná Basin geological units. The ~N75E direction of the Jaú fault was characterized because the points where it crosses sections RS1 and RS2 are known.

In addition to the identification of the Jaú fault, the regional sections made it possible to estimate the individual thickness of the flows present. In sections RS1, RS2, and RS3, the number of flows is, respectively, 13, 7, and 10. The estimated individual thicknesses range from 15 to 55 m, except for D47 whose thickness in RS3 is around 62 m. Only D33, D58, and D47 are not present in the V-3 borehole, whereas D33 and D58 are laterally discontinuous in RS1 and RS3; D33 is also discontinuous in RS2 and D40 and D44 in RS3. The three basalt sequences described in

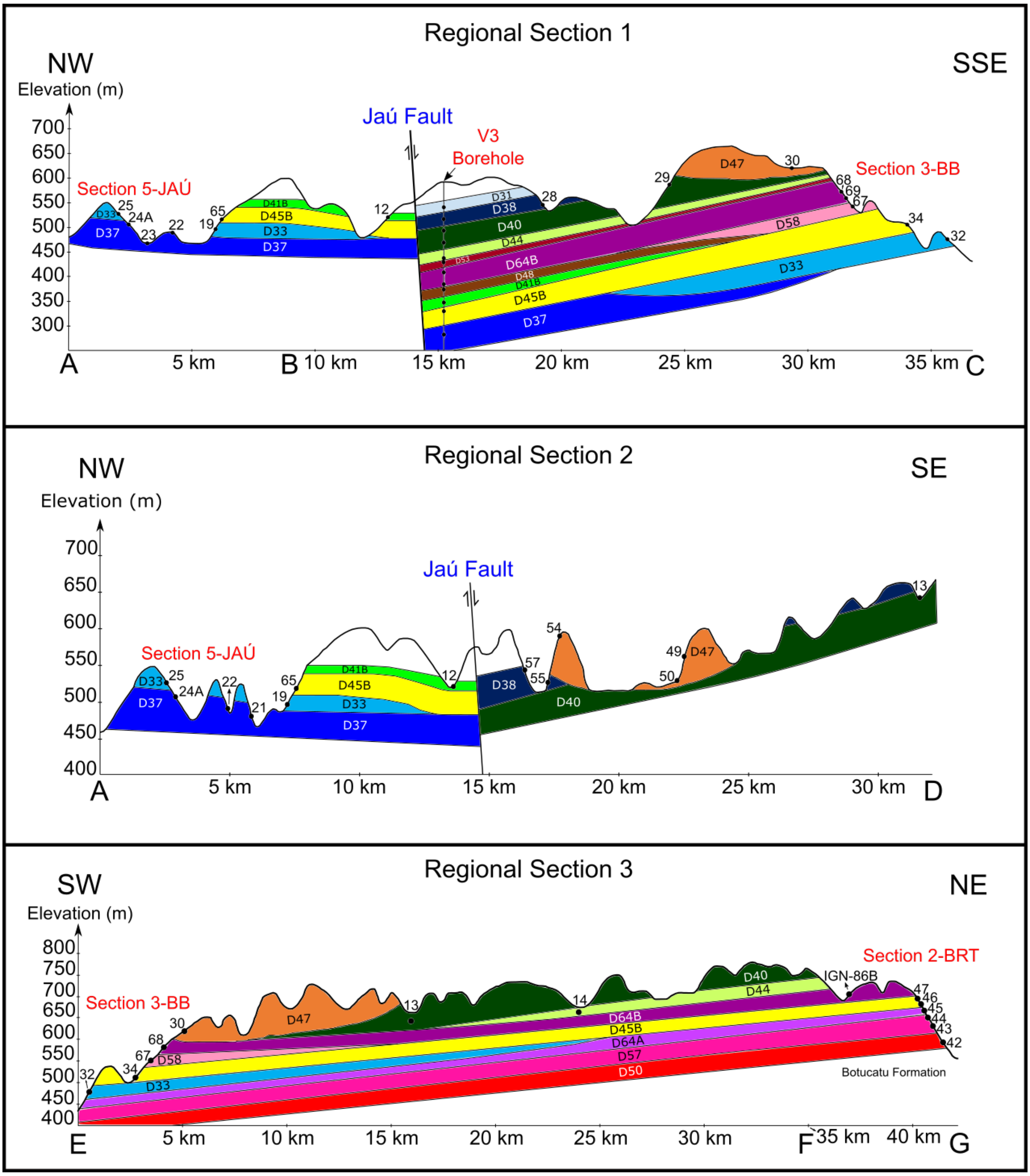

Figure 9. Interpretative geological sections showing the Jaú Fault, inferred from the correlation of the basalt flows.

Section 6.1 are present in all geological sections. The uppermost D47 flow directly overlies D40 in RS1, RS2, and RS3, and also overlays D64B in RS3. Interestingly, the dip of its lower contact is not consistent with that of the other flows, which can be explained in two ways: either D47 is an intrusive body placed discordantly of the other flows, or it was placed after the Jaú fault activity, which would then be contemporary with the volcanism. At the moment, our data are not conclusive in this regard.

The existence of faults and the characterization of their offsets and directions were only possible due to the knowledge of the stacking of the different basalt flows, which was characterized in the local sections and, above all, in well V-3. Therefore, this is another important consequence of the characterization of the basalt stratigraphy. Fernandes *et al.* (2012, 2016) emphasized that only faults of this magnitude should cut through the entire basalt stack and reach the Botucatu sandstones. In this way, faults would cross the vesicular layers of basalts, which constitute regional barriers to the vertical flow of groundwater and would enable both the recharge and the discharge of the Guarani Aquifer System, as pointed out by Fernandes *et al.* (2012, 2016), Therefore, such structures have strong implications for the potential and vulnerability of the aquifer.

Regional correlations

An attempt to correlate the general stratigraphic column defined in this study with recent works on the basalt stratigraphy of the northern PMP is shown in Fig. 10. The column proposed by Fernandes *et al.* (2018) is based on field profiles crossing the first basalt flows in a wide region from Araraquara to Avaré (170 km apart), which encompasses the Jaú region. A direct correlation is observed with the lower sequence identified in Jaú (Sequence 1), as expected, because that work focused on the first basalt flows and their relationship with the underlying Guarani Aquifer (Botucatu sandstone). This confirms that most flows might indeed have spread over larger distances from their (as yet unknown) vents, a feature considered common in CFB provinces (e.g., Self *et al.* 2008, Thordarson and Self 1998).

The second comparison is made with the sequence of six flows reported by Machado *et al.* (2018) which form the ~200-m-thick volcanic sequence in borehole PAI from Araraquara (~65 km NE from Jaú). The three lower flows at PAI correlate with the column by Fernandes *et al.* (2018) (and therefore with our lower sequence), while the upper three flows match perfectly the first three flows from our Sequence 2. The upper flow at PAI (D48) is covered by Upper Cretaceous sedimentary rocks of the Bauru Group, implying that the flows from the upper part of Sequence 2 up to D47 in our column were either not deposited or eroded prior to the deposition of the Bauru Group in the region of Araraquara.

Fernandes et al. 2018	Machado et al. 2018 (PAI borehole)	Jaú column	Regional column	Sequence
		D47	D47	4?
		D31	D31	
		D38	D38	
		D40	D40	3
		D44	D44	
		D53	D53	
		D64B	D64B	
		D58	D58	
	D48	D48	D48	2
	D41B	D41B	D41B	
	D45B	D45B	D45B	
D33	abs.	D33	D33	
D37	D37	D37	D37	
D64A	D64A	D64A	D64A	
D57	abs.	D57	D57	1
D45A	D45A	abs.	D45A	
D41A			D41A	
D50		D50	D50	
Botucatu Fm.		Botucatu Fm.	Botucatu Fm.	

Abs.: absent.
Source: Machado *et al.* (2018).
Figure 10. Correlation between the basalt stratigraphy determined in this work with the regional stratigraphy by Fernandes *et al.* (2018) and the flow succession observed in the PAI borehole located to the NE of the study area.

CONCLUSIONS

A combination of detailed field work and geochemical analyses of basalt samples from both surface exposures and rock chips from a ~300-m pile of basalt from a groundwater borehole allowed the establishment of a stratigraphic column with 16 flows, tentatively divided into three sequences in the Jaú region, the central part of the state of São Paulo, Brazil. Regional correlations show that the stratigraphy of the Pitanga-type basalt flows identified in recent works corresponds to the lower part of our column, whereas the upper eight flows of the Jaú column (upper part of Sequence 2 and above) were probably eroded in the region now corresponding to the edge of the Serra Geral Group exposures. Thus, their continuity should be tracked to the west, where the basalt pile reaches much greater thickness. In fact, these upper flows occur in this region at the top of the plateau near Torrinha, where the thickness of basalt reaches up to 300 m, and their preservation may be the result of significant (up to 170 m) displacements along the ENE-directed Jaú fault, here identified from stratigraphic relations in the basalt pile.

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JPG: Investigation, Writing – review & editing, Writing – original draft, Methodology. VAJ: Conceptualization, Investigation, Methodology, Writing – original draft, Funding acquisition, Resources, Supervision, Writing – review & edition. FAJ: Investigation, Writing – review & editing. AJF: Investigation, Writing – review & editing. JTMG: Investigation, Writing – review & editing, Methodology.

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