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ARTICLE

Local geological sections and regional stratigraphy based on physical geology and chemical stratigraphy of the Serra Geral Group from Araraquara to Avaré, SP

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ABSTRACT: *From Araraquara to Avaré, in the Serra Geral Group outcropping area, 22 detailed geological sections were elaborated. The stratigraphic relationships and the chemical analysis allowed the identification of seven [P_2O_5] basalt classes, all of them pertaining to the Pitanga type, showing a consistent stacking order across the studied region. Thus, each class is considered to correspond to a specific lava flow, allowing a general stratigraphic column to be proposed. Besides the stacking order, the validation of P_2O_5 as a tool for lava correlation at great distances was also based on the values obtained from samples collected at different positions in a single flow, and on the remarkable [P_2O_5] contrast between adjacent flows. Minimum lateral extensions range from 75 to 185 km, and thickness from 20 to 80 m. Vertical tectonic displacements, which took place in different periods, were inferred from the altitude of specific flows, and also from the Botucatu and Piramboia formations. They are noticeable in a region bounded by EW drainage lineaments, which contains a large area where Piramboia and Botucatu formations crop out, probably due to the tectonic activity causing this region to be a generalized structural high.*

KEYWORDS: *basalt; chemical stratigraphy; Serra Geral Group; São Paulo.*

INTRODUCTION

The Geological Institute (IG-SMASP) has carried out a research aiming to evaluate the recharge of the Guarani Aquifer System, through the overlying Serra Geral Group, as recently defined by Rossetti et al. (2017). A first detailed study, FRATASG I, was completed in Ribeirão Preto area (Wahnfried 2010, Fernandes *et al*. 2010, 2011, 2016). A following project, namely FRATASG II, was carried out in a much larger area, from Avaré to Araraquara (Fernandes *et al.* 2012), and the objective of this article is to present part of the results of the second project, concerning the stratigraphy of basalt flows in 22 local and detailed geological sections.

A general stratigraphic column, based on the correlation of flows, from one section to the other, was proposed and is consistent with the basalt flow stratigraphy identified by Fernandes *et al.* (2010) in Ribeirão Preto. The P_2O_5 content of the basalts was of central importance for the lava correlation.

Correlating flows from different sections is a major challenge, even for distances of only a few kilometers, as even gently dipping contacts already preclude extrapolations based just on topographic elevation. The use of basalt geochemistry, in order to recognize and correlate individual flows, is based on the concept that primary differentiation is limited during the emplacement of lavas due to rapid emplacement and solidification, and was largely used in classical continental basalt provinces (e.g., Beane *et al.* 1986). It has been demonstrated, in several regions of the Paraná Magmatic Province, that some immobile minor elements, such as Ti and especially P, may be useful "fingerprints" of single basalt flows and effective for correlations

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even when affected by later faulting (Pinto & Hartmann 2011, Rosenstengel & Hartmann 2012). Our previous work in the region of Ribeirão Preto was based on detailed studies of physical geology and stratigraphic relations, and confirmed that the geochemistry could be successfully used for flow correlation in the high Ti/Y basalt flows of the state of São Paulo (Fernandes *et al.* 2010). The validity of using the content of P_2O_5, always associated with detailed stratigraphic control, for large distance lava correlation, is discussed in the present paper.

METHODS

Field work, resulting in the description of 164 outcrops, was carried out in the Serra Geral Group outcropping area, from Avaré to Araraquara. The described outcrops were plotted on 1:10,000 topographic maps (elaborated by IGC in the period 1978-2006, found in IGC, 2003). The 1:10,000 maps and outcrop location, respectively in the Córrego Alegre and SAD69 projections, were redesigned for the 1984 WGS datum in order to be compatible with the digital map projection in the ArcGis platform. The distribution of the outcrops allowed the elaboration of 22 local and detailed stratigraphic sections. Of these, 18 were constructed based on at least two neighboring outcrops, the distance between them varying from 100 to 1200 m. The other three were based on single continuous exposures in quarries, where flow contacts were very well characterized. When necessary, sections were subdivided so that the direction of each part was as transverse as possible to the topographic contour lines. Vertical and horizontal scales of geological sections are 1:5,000 and 1:10,000, respectively. Figure 1 shows the location of the outcrops and local sections.

Samples for chemical analysis and petrographic description were collected whenever the basalts were nonweathered. In large and continuous rock exposures, several samples of the same lava flow were collected in variable positions (base, intermediate, and top portions). This was done with the objective of identifying possible petrographic and chemical composition variations in the same flow.

Whole-rock chemical analysis (oxides and trace elements) were performed by X-ray fluorescence, for a total of 98 samples, at IGc-USP Geoanalitica Facilities. Representative rock samples were crushed with a hydraulic press to granule size and then quartered; about 100 g fraction was then powdered to <200 mesh in a planetary type agate mill. Major elements were obtained in fused discs and trace elements in pressed pellets, following the methods described by Mori *et al.* (1999).

Sampling of several portions of the same flow, in continuous rock exposures, was especially useful for evaluating the representativeness of the P_2O_5 content of a sample in a specific flow. This aimed the validation of the use of this parameter as a flow correlation criterion from one section to another. All the values of P_2O_5 content, obtained in sample analyses, were plotted in cumulative frequency graphs, where natural breaks were identified. It was concluded that each sample set, separated by two consecutive breaks, is representative of one specific flow. This is discussed in results.

GEOLOGICAL CONTEXT

The lava sequence of the Serra Geral Group (Upper Cretaceous) reaches up to 2000 m in its depocenter, located in the Pontal do Paranapanema region (Milani 2004). This formation belongs to the Paraná Magmatic Province, which spreads across approximately 917,000 km^2 (± 15,000 Km^2), with a volume of more than 600,000 km^3 (450,000 km^3 extrusive, and 112,000 km^3 intrusive sill-type bodies; Frank *et al.* 2009) in central to south Brazil and neighboring areas in Argentina, Paraguay, and Uruguay, constituting one of the largest provinces of continental basalts in the world (Jerram & Widdowson 2005). The basalt volcanism preceded the opening of the South Atlantic, and recent precise Ar-Ar dating indicates that the main phase of volcanic activity occurred between 134 and 131 Ma (e.g., Thiede & Vasconcelos 2010, Janasi *et al.* 2011). Tholeiitic basalts are largely predominant in the province, and a major two-fold division based on the TiO_2 content or Ti/Y ratio is recognized, with the low Ti/Y sequence restricted to the southernmost portion (e.g., Bellieni *et al.* 1984, Peate 1997).

"High Ti/Y" (Ti/Y>310) basalt types, that constitute the northern area and are found in exposures throughout the state of São Paulo, are usually divided into two main "magma types", named Pitanga and Paranapanema (Peate 1997). Equivalent intrusive volcanic rocks occur as abundant dykes and sills intruding the older sedimentary and crystalline sequences, and constitute the plumbing system of the basalt volcanism. A general stratigraphic sequence for the lava pile is recognized from field and borehole evidence. The less differentiated (Mg-richer; lower Ti/Y, lower P_2O_5) Paranapanema magma type typically appears in the upper part of the lava pile (e.g., Peate 1997, Nardy *et al.* 2002, Machado *et al.* 2007, Torres *et al.* 2008, Machado *et al.* submitted), while Pitanga rests directly over the older eolian sedimentary rocks of the Botucatu Formation or, locally, over "high-Ti" silicic rocks of trachydacitic composition (Chapecó-type) (e.g., Janasi *et al.* 2007). A more primitive magma type (Ribeira) is recognized in neighboring areas of the states of Mato Grosso (Machado *et al.* 2009) and Paraná (younger low-Ti sequence of Licht 2016), where it overlies the Paranapanema-type lavas.

The basalts cover the Botucatu Formation (Jurassic-Cretaceous), which in turn is younger than the Piramboia Formation (Permo-Triassic). The Piramboia Formation consists of medium to fine

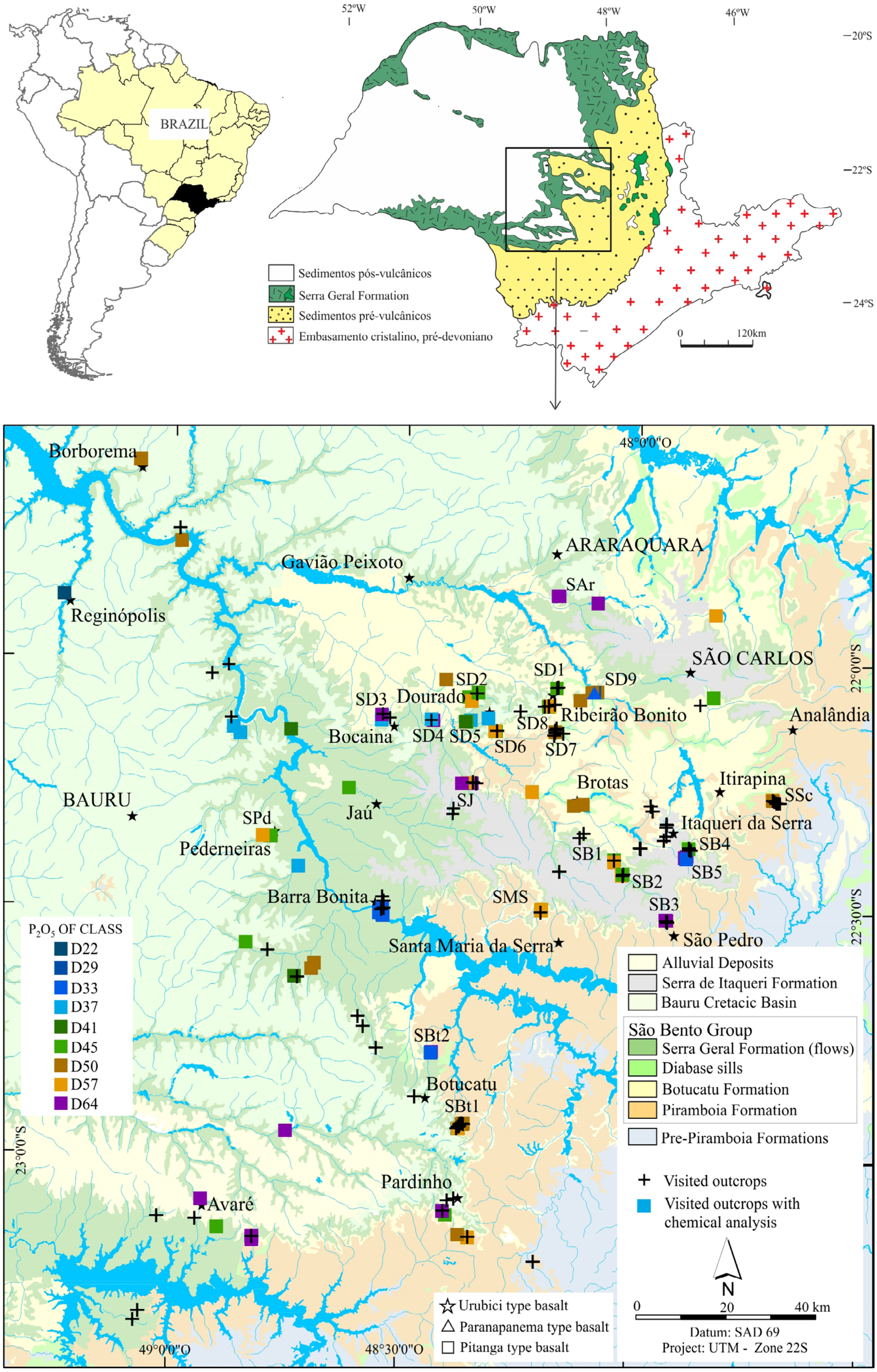


Figure 1. Localization of the study area, the visited outcrops, the outcrops with chemical analyses (colored squares), and the geological sections (SB1, SD1 and so on).

sandstones, locally thick and conglomeratic, deposited in a fluvio-lacustrine and aeolian environment (Soares 1975, Wu & Caetano-Chang 1992, Milani 2004). These sandstones have medium-sized cross stratification (channeled or planar) and plane-parallel stratification, with variable clay and silt content in the matrix or as laminae. It was followed, in the Jurassic-Cretaceous period, by eolian deposition of the medium to fine-grained sandstones of Botucatu Formation, composed of well-sorted and spheric quartz grains, also showing large cross-stratification (Soares 1975, Assine *et al.* 2004, among others).

The Serra Geral Group, in the study area of the FRATASG II project, is directly covered by the following units: Vale do Rio do Peixe and Marília Formations (Neocretaceous), belonging to the Bauru Group; Itaqueri Formation (Neocretaceous-Paleogene), in the region of Brotas; and alluvial and colluvio-eluvial deposits, more expressive in Itirapina area (Perrotta *et al.* 2005). The Vale do Rio do Peixe Formation consists of fine to very fine-grained sandstones, interspersed with siltstones or sandy mudstones. The Marília Formation, in the study area, consists of fine to medium-grained sandstones, with interlayering mudstones, muddy sandstones, conglomerates and conglomeratic sandstones, all with carbonate cementation, nodules and crusts (Fernandes & Coimbra 2000).

The Itaqueri Formation is composed of silicified sands and conglomerates (synthesis by Riccomini 1995). Alluvial and colluvio-eluvial deposits have a basal level of accumulation of clasts of quartz, quartzite, and limonite concretions, and contain dispersed fragments of charcoal and large amounts of magnetite (Sinelli 1971, Melo 1995).

RESULTS

General geochemical features

An extensive geochemical program throughout the study region was done (Fig. 1), resulting in 98 whole-rock analyses, whose results are presented in Supplementary Table A1. According to the geochemical criteria of Peate (1997), nearly all samples fit into the Pitanga magma-type; just 3 samples, with low P_2O_5 (0.22%-0.29%) and TiO_2 (<2.5%) are classified as Paranapanema and another 4 samples with low Fe_2O_3 (ca. 12.5%), high TiO_2 (ca. 3.5%) and Sr (650-690 ppm) are classified as Urubici (Fig. 2). The MgO of the whole set of basalts spreads from 6 to ~3.5%; as usual in tholeiitic

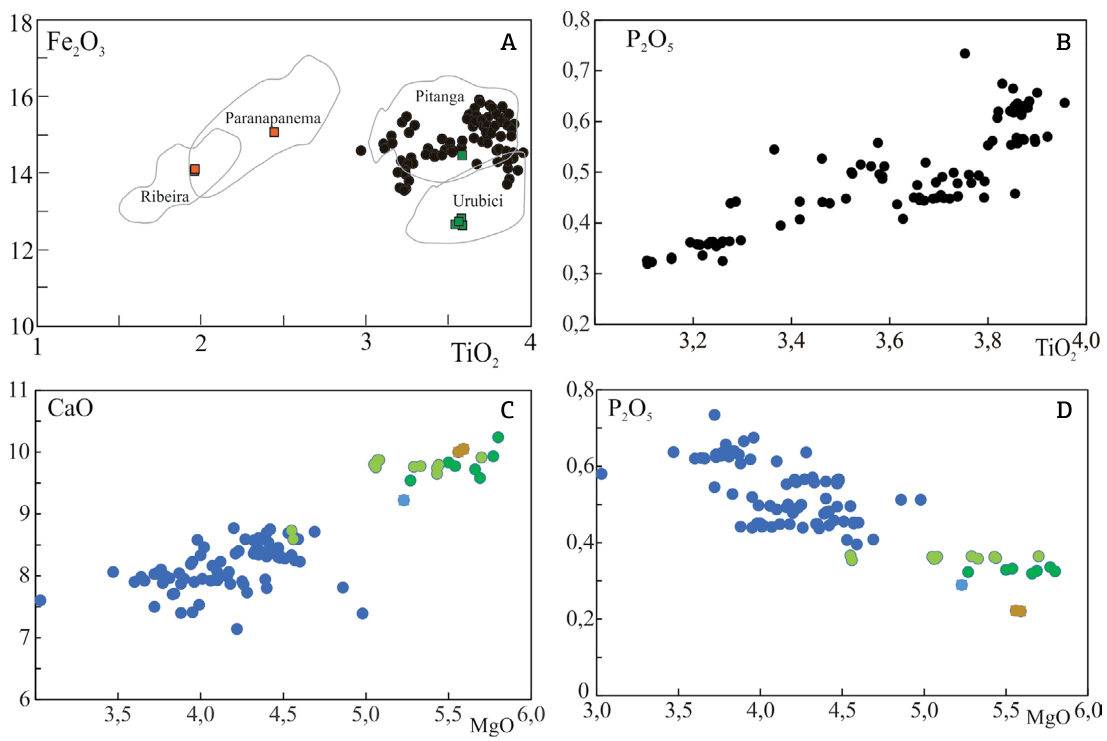


Figure 2. (A) TiO_2 x Fe_2O_3 diagram for the whole set of basalts from the study region with fields of high-Ti magma types from Peate (1997). The three samples (two overlapping) plotting in the Paranapanema field have P_2O_5 < 0.30%; the four samples clearly within the Urubici field have Sr>600 ppm; (B) TiO_2 x P_2O_5; (C) MgO x CaO; (D) MgO x P_2O_5. In (C) and (D), classes with lower P_2O_5 are distinguished: D33: green circle; D36: light green circle; D22: brown circle; D29: light blue circle.

basalts, MgO has positive correlation with CaO and negative correlation with P, which behaves as an incompatible element over the entire compositional range (Fig. 2). There is a small but evident gap in CaO between samples with MgO contents higher and lower than 5%; the latter correspond to more primitive samples with P_2O_5 < 0.37%. A broadly positive correlation between P and Ti is evident, but incorporation of Fe-Ti oxides in the fractionating mineral assemblage of basalts, within this MgO range (usually at about 4.5% MgO), results in lower degree of increase or even decrease of Ti with differentiation. The MgO/TiO_2 is therefore used as fractionation marker (see below).

P_2O_5 content as a guide for lava correlation

The 22 sections elaborated are denominated with acronyms based on the names of their localities: SB, region of Brotas and surroundings; SD, Dourado region; SJ, Jaú region; SSM, Santa Maria da Serra cuestas; SAr, Araraquara region; SBt, Botucatu cuestas; SSC, São Carlos cuestas; SBB, Barra Bonita region; SPd, Pederneiras region. In the southern portion of the study area, namely Avaré and Pardinho, sections were not constructed due to the larger distances between the outcrops.

In the study region, P_2O_5 concentration was proven efficient for distinguishing and correlating basalt flows from one section to another, regardless of the distance among them. Natural breaks of $[P_2O_5]$ were clearly observed in cumulative frequency graphs (Fig. 3). The same breaks are reinforced by the P_2O_5 versus P_2O_5/ (TiO_2/MgO) graph. TiO_2/MgO is used as a normalizer, as it tends to be constant and equivalent to the slope of line that characterizes chemical differentiation within a given flow. The natural breaks indicate the existence of 9 $[P_2O_5]$ classes (Fig. 3).

A specific order of stacking in these classes is consistent throughout the local geological sections (Fig. 4), and this indicates that each class must correspond to a specific event of lava emplacement (that means, a specific flow), allowing a general stratigraphic column to be proposed for the study region (Fig. 5). Besides the consistency of the stacking order of $[P_2O_5]$ classes throughout the study region, two other aspects indicate that a single sample collected from one outcrop is representative of the entire flow. The first aspect is that the P_2O_5 content of samples collected in different positions (top, base, and intermediate portions laterally distributed) of the same flow, as

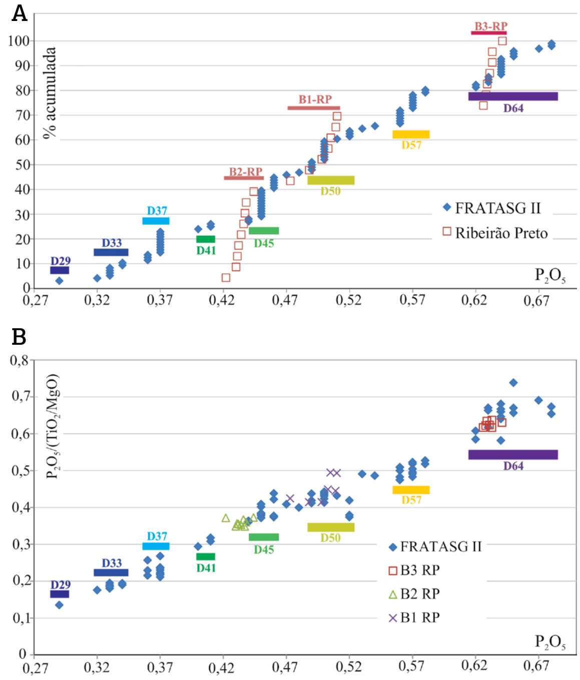
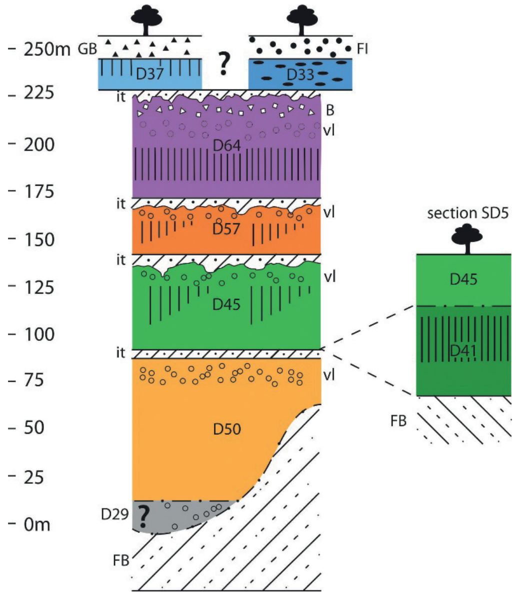


Figure 3. (A) Cumulative frequency of [P2O5], (B) [P2O5] versus [TiO2]/[MgO]. The position of [P2O5] classes are shown as colored bars (D29, D33 etc.), class D22 (one sample) is not represented in this graph. The width of the bar shows the [P2O5] range and the same class colors are used throughout all the figures (map and sections). Samples from Ribeirão Preto (B1-RP, B2-RP, B3-RP; Fernandes *et al.* 2010) were plotted in the graph, where B1 directly overlies the Botucatu Formation, and B2 and B3, in this order, overlay B1.

	Seccion																					Ribeirão Preto
Lava flow	SAr	SSC	SD1	SD2	SD3	SD4	SD5	SD6	SD7	SD8	SD9	SJ	SB1	SB2	SB3	SB4	SB5	SSM	SPd	SBB	SBt1	SBt2	
D37/D33	D37				D37	D37	D37									NCA	D33			D33	D37	D33	NCA
D64																NCA					absent		
D57															NCA	NCA							absent
D45		Sill													NCA		NCA				NCA		
D41									0.54	absent		absent											absent
D50			absent	absent			absent	absent	sill?				absent	absent				absent			Urubici		
D29										NCA													
Botucatu																							
Piramboia																							

Figure 4. Comparison of the 22 local sections. The flows are named after their $[P_2O_5]$ content (see text for explanation). Flows in grey do not have chemical analysis data (NCA=No Chemical Analysis). The word "absent" means that one or more flows are not present at the section. Ribeirão Preto stratigraphic column (Fernandes *et al.* 2010), is represented in the last column.



FB, Botucatu Formation; GB, Bauru Group; FI, Itaqueri Formation; it, intertrap sandstone; vl, vesicular layer; B, breccia.

Figure 5. General stratigraphic column.
The relationship between D37 and D33 is not known, and because of that they are laterally represented. The irregular contacts between "it" and the underlying basalt represent the presence of peperite-like breccia. The closely spaced vertical lines denote the presence of entablature, which is frequent in D64, relatively frequent in D37, and occasional in D45, D57 and D37.

attested by continuous exposures, are practically constant and clearly belong to one of the P_2O_5 classes identified by natural breaks (Fig. 2). This behavior was identified in several places:

- Close to Araraquara, section SAr (outcrop 152), the P_2O_5 content, of the lower flow, is 0.63% for both colonnade and entablature portions (Fig. 6). The same happens for the samples collected for the columnar and entablature portions of the upper flow, whose $[P_2O_5]$ values are 0.36% and 0.37%, respectively.
- In a quarry close to Borborema (outcrop 66), the P_2O_5 content of samples A and C, positioned at the base and top of the same flow, is 0.49% for both (Suppl. Tab. A1).
- Close to Jaú, section SJ (outcrop 111), the $[P_2O_5]$ of the entablature and of the colonnade portions of the upper flow are 0.63% (111A) and 0.64% (111B), respectively (Suppl. Tab. A1).
- Close to Pederneiras, section SPd (outcrop 154), samples of the columnar portions at two different depths yielded the same value (0.46%), very similar to the one of the entablature portion in the same flow (0.45%). On the other hand, for the upper flow observed in the same outcrop continuous exposure, the very distinct value of 0.56% was obtained (see further ahead the description of section SPd).
- Three samples of the entablature of the uppermost flow of the section SB3, which crosses São Pedro Cuestas, were collected in two close outcrops, yielded $[P_2O_5]$ values of the same class (0.64%, 0.67%, and 0.68%) (see further ahead the description of section SB3).

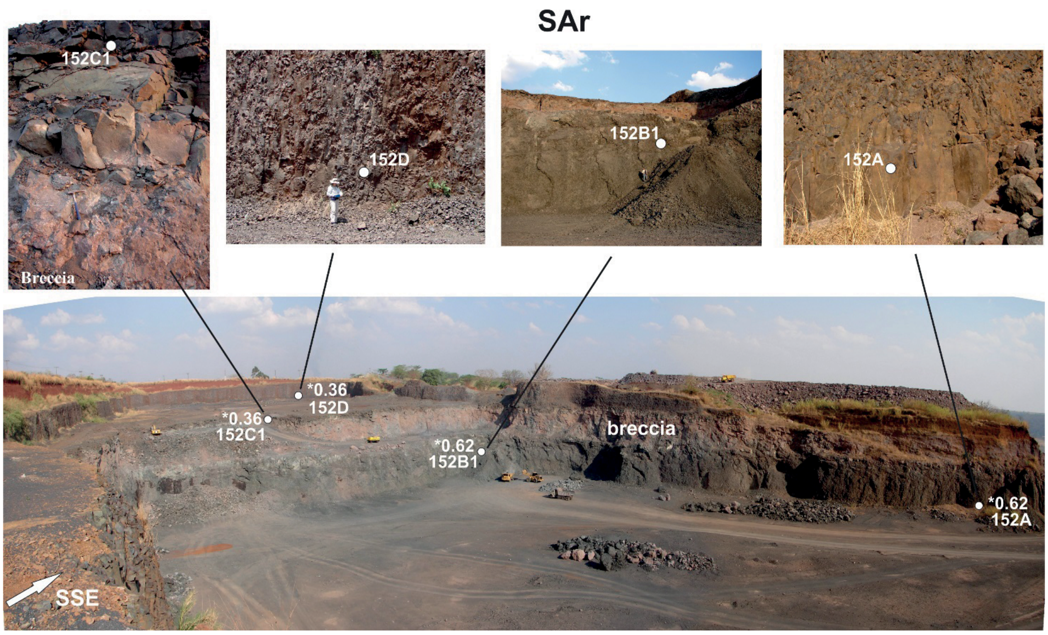


Figure 6. Example of sample collection (section SAr, flow D64 overlaid by flow D37), showing that the P2O5, for different positions in one single flow, is constant. See additional examples in the text. This validates the use of [P2O5] for lava flow correlation.

- In Barra Bonita, section SBB, 5 samples, each collected at a distinct outcrop (whose distances vary from 200 to 1200 m), yielded practically constant values of [P_2O_5] (0.33%-0.34%), and were interpreted as belonging to the same flow (see further ahead the description of section SBB).

The second aspect that strengthens the use of P_2O_5, as a parameter for lava correlation, is the direct overlapping of flows with distinctly contrasting values of [P_2O_5] (ie, D57 overlapping D45, D37 overlapping D64 etc), which indicates that the breaks, identified in the graphs of Figure 3, are real limits between distinct flows.

As described above, 4 samples are classified as Urubici, and all of them occur south of the city of Botucatu. Two were sampled in the cuestas located close to the city of Pardinho and yielded [P_2O_5] equal to 0.56% (outcrop 2) and 0.52% (outcrop 4); the other two belong to the lowermost basalt of section SBt1, both yielding [P_2O_5] of 0.52%. These cannot be correlated to the other sections, which contain only Pitanga flows. However, two basalts of the upper part of the section SBt1 are Pitanga, and the correlation with the others of the same type is discussed in the next section, where the physical characteristics and relationships between flows are presented.

Local sections and macroscopic characteristics of the flows

As the P_2O_5 content was proven useful for lava correlation, each flow was individually designated after the most frequent value of their class (Fig. 4). For example, the flow whose [P_2O_5] ranges from 0.48% to 0.53%, with a most frequent value of 0.50%, was named D50 (Fig. 3). Figure 1 depicts the study area, the P_2O_5 class for each sample analyzed, and the location of the sections. The sections were elaborated in a very detailed scale (1:10,000), and the geological map used as a reference in this figure is in 1:250,000 scale (DAEE/UNESP 2013). As a consequence, the geological unit of the map may not coincide with the ones depicted in the sections. It is recommended that the data collected in this work be used for correcting regional maps in the future.

Intertrap quartz sandstones and breccias, both present at the contacts between the flows and vesicular layers, which are thicker at the basalt tops, evidence the extrusive nature of the mafic rocks. The peperite-like breccias found are always the result of a mixture of fragments of a basalt upper vesicular layer with the overlying intertrap sandstone, and true peperites (Jerram & Stollhofen 2002) were never observed. Auto-breccias, on the other hand, may occur at the base and/or on top of a specific flow.

Horizontal to low angle dipping laminations and jointing in basalts exhibit variable attitudes. They may dip in opposite directions, in the same or nearby outcrops, suggesting that the contacts accompany the paleo-relief of dunes. In large outcrops, it is common to observe waving contacts without noticeable preferential dipping. For this reason, the attitudes of the contacts between flows, although presumably subparallel to the lamination and jointing, were usually represented as horizontal at the local sections, in order to avoid the propagation of errors.

The Botucatu Formation, present in 9 sections (Fig. 4), was either observed directly in outcrops or inferred from the terrain morphology (negative relief break at the base of basalt cliffs, observed in the field and on 1: 10,000 maps), as well as from geological maps. In 13 sections, the relationship of the most basal flow with the Botucatu Formation is unknown.

Each flow, from the oldest to the youngest, is described below. The stratigraphic position of flow D22, a Paranapanema type (Peate 1977), is not known, as it occurs in an isolated outcrop, and it is described at the end of this sub-section.

Flow D29

Flow D29, along with D22, is classified as Paranapanema type, because of its low P_2O_5content (only 0.29%). According to the general stratigraphic sequence described in the literature, Pitanga type flows are generally older than the Paranapanema ones (e.g., Peate 1997, Nardy *et al.* 2002, Machado *et al.* 2007, Torres *et al.* 2008, Machado *et al.*). However, in section SD9 (Fig. 7), it occurs beneath D50, a Pitanga type, and the presence of sparse or concentrated vesicles and amygdales suggests an extrusive nature. Furthermore, the mafic rock underlying D50 (Fig. 7), in section SD8, could be correlated to D29. This rock is aphanitic and contains very small amygdales, being separated from D50 by an intertrap sandstone. The features observed in the exposures are not conclusive regarding the nature (extrusive or intrusive) of the mafic rock that underlies D50 in sections SD8 and SD9, and more data are necessary.

Flow D50

Flow D50 occurs in three sections, all of them in Ribeirão Bonito area, and its estimated thickness is 25 m in SD9, 75 m in SD8, and uncertain in SD7 (Fig. 7), as discussed below. The thickness of the correlated flow in Ribeirão Preto, well characterized from outcrop and borehole data (Fernandes et al. 2010), is the most variable, and probably related to the fact that it overlies the irregular topography of the paleo-relief. Basalt D50 is predominantly fine-grained, with occasional lamination and horizontal jointing (closely spaced horizontal fractures); it contains glass in drops or in irregular portions that may accompany the lamination (Tab. 1). The vesicular top contains small white amygdales, and no breccias were observed at the contact with the overlaid intertrap sandstone, which is fine-grained, well sorted, and few-meters thick (SD8).

In the southwestern segment of section SD7 (Fig. 7), a massive (non-vesicular) mafic rock occurs at the lower portion (outcrops 90 and 93), and a vesicular basalt layer (with amygdales and abundant glass drops – round and small portions of glass) occurs at the top (outcrops 91 and 92), and no contact between them was observed. The [P_2O_5] at outcrop 90 is 0.50%, typical of D50, however at 91 it is 0.54%, an ambiguous value, positioned between classes

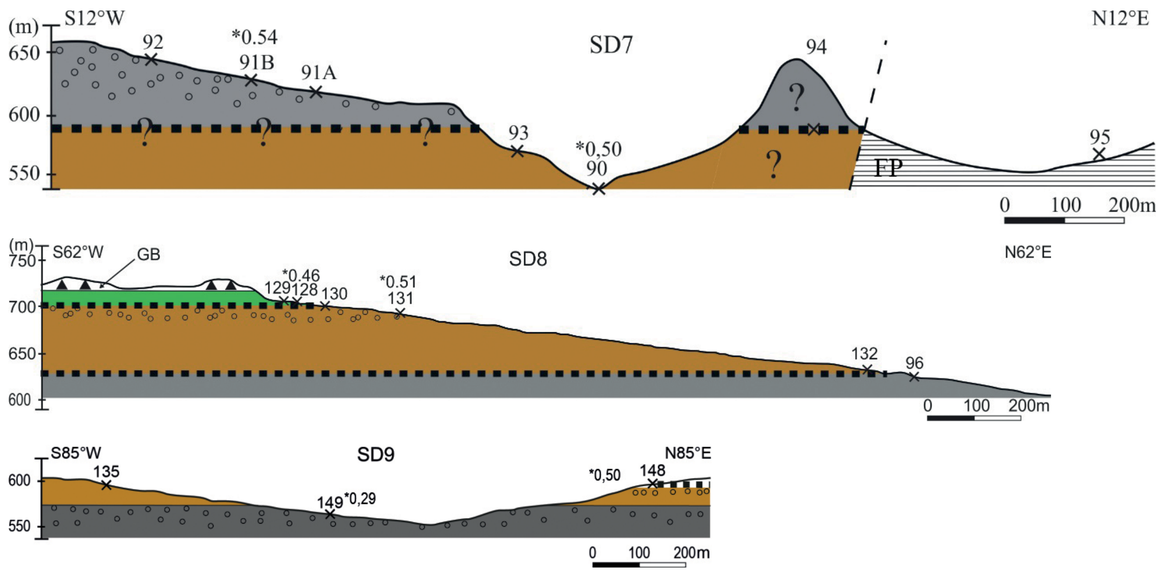


Figure 7. Class D29 was observed only in SD9. It might be a sill correlated to the mafic rock at outcrop 96 of section SD8 (see text for explanation), as both underlie D50. In section SD7, Piramboia Formation (FP) is almost levelled with an intertrap sandstone, implying a vertical offset; the dashed line represents the tectonic structure presumably responsible for the offset (see the text for other details). GB, Bauru Group. Common features: intertrap sandstones (thick dashed line), entablature layers (vertical lines). Vesicular layers (open circles) are commonly observed at the upper portion of basalts. Numbers represent outcrops and each number that follows the * represent P_2O_5 concentration at that outcrop.

Table 1. Macroscopic characteristics of the flows. The phenocrysts are usually small (1-2 mm) and ocasional. The numbers in the table refer to the amount of outcrops in which the feature was observed in that specific flow.

Flow	D26	D50	D41	D45	D57	D54	D37	D33	D22
Number of expositions	1	12	3	16	15	17	10	6	1
Texture	F	F,A	F	F,A	F,A	A,F	F=A	F=A	F,A
Phenocrysts	0	A,P	0	A=P	A=P	P,A	P,A,O	A=P	A
Glass droops	0	7	1	4	10	13	5	1	1
Lamination	0	2	0	3	3	3	3	3	0
Horizontal jointing	0	3	1	1	5	2	2	2	0
Basal auto-breccia	NO	**1	1	NO	1	1	1	NO	NO
Top breccia	NO	0	NO	3	2	3	NO	NO	NO
Entablature	0	*1	1	3	3	10	4	0	1
Thicknesses (m)	NO	25,75	~50	35,40,60,80	15,20,55	40, >65	15	NO	NO

Number of expositions: total amount of expositions in which the flow was observed and where there are chemical analyses.
Texture (in order of abundance): A=aphanitic, F=fine
Top breccia: autobreccia or peperite-like breccia
Phenocrists (in order of abundance): A=augite, P=plagioclase, O=olivine
*1: entablature in flow D50 was observed only in an isolated point
**1: the basal breccia was observed in an isolated point close to Borborema
NO: non observed
Glass drops: round and small (milimetric) portions of glass

D50 and D57. In the northeastern segment of section SD7, only sedimentary rocks were observed. A poorly sorted fine-grained sandstone (containing a 50 cm layer with deformed stratification), intercalated with centimetric mudstone and rhythmite (clayey and sandy laminae) layers, crops out at outcrop 95, and is likely correlated with the finer sedimentary rocks of the Piramboia Formation, regionally described by Soares (1975). The sandstone, at outcrop 94, is different from the ones of the Botucatu Formation, since its texture is bimodal and the grains are sub-rounded. As such it could be interpreted either as an intertrap or as belonging to Piramboia Formation. Either way, the altitude of the Piramboia Formation, with regard to the flow of outcrops 91-92, and the absence of the Botucatu Formation suggest that vertical tectonic displacements took place at this site. A strong tectonic pattern formed by EW-WNW and NS-NNW subvertical tectonic fractures measured in outcrop 91 and nearby outcrops, along with conspicuous parallel lineaments, some of them crossing the section SD7, also suggests tectonic deformation, probably related to trans-extensional stress fields described by Fernandes *et al.* (2012). Further evidence of vertical offsets is presented in the section "Evidence of vertical tectonic displacements". This issue is to be addressed by Fernandes *et al.* (in preparation). Regarding the mafic rocks of the section (outcrops 90-93), although no contacts were observed, one plausible hypothesis is that outcrops 90 and 93 could be a sill of class D50, and 91-92 a flow of a dubious class, as it lies between D50 and D57. An alternative interpretation, is that there is just one thick flow; in this case, more significant vertical offsets are required to place the Piramboia Formation at the same altitude of D50.

The mafic rocks of class D50, which occur in isolated outcrops, south of Barra Bonita and close to Borborema (Fig. 1), are clearly extrusive. South of Barra Bonita (61A=0.50%, 29=0.50%, data in the Suppl. Tab. A1), the rock is fine-grained, with sparse vesicles and amygdales parallel to the lamination, and contains an upper vesicular layer with glass drops, small amygdales and geodes, both filled with silica and quartz. South of Borborema, the basalt presents a basal auto-breccia, an evidence of its rubbly nature (outcrop 66 with two samples with P_2O_5=0.49%), overlying a peperite-like breccia, probably related to the underlaid basalt. Colonnade and entablature layers were observed in one outcrop (outcrop 156, two samples with P_2O_5=0.49%). Close to Brotas, the mafic rock at outcrop 38 (P_2O_5=0.51%, Suppl. Tab. A1) has horizontal jointing, is fine-grained and contains amygdales, that may reach 5 cm horizontally, with quartz. At outcrop 30 (Suppl. Tab. A1), the P_2O_5 value of 0.47% is ambiguous (intermediate position between D45 and D50 classes) and the rock, which is fine to medium-grained, may be a sill, once no typical flow feature was observed along its extensive exposure.

Flow D41

The D41 flow occurs only in section SD5, where it is about 50 m thick (Fig. 8), and in two isolated outcrops (27 and 153, Suppl. Tab. A1). The contact with the Botucatu Formation, in the section, was deduced from the negative morphological break at the base of D41, from the sandy soil that occurs thereafter, and from the geological maps. D41 presents small diameter columns (77a), typical of entablature columns, that are a little larger at outcrop 119. Along with peperite-like rocks, this is probably related to the underlaid basalt, at its base (outcrop 153), and a basal auto-breccia (fragments of vesicular basalt embedded in an aphanitic basalt), in a close and correlated outcrop (28), indicates extrusive nature. D41 is fine-grained or aphanitic and contains glass drops. Although it was sampled in few outcrops, it was considered a different flow with regard to D45, as the break between them is very clear in both graphs of Figure 3.

Flow D45

From the 10 sections where flow D45 occurs, it directly overlies the Botucatu Formation in 5 of them (Figs. 4 and 8), indicating that the occurrence of the previous flows is discontinuous. It was observed in Ribeirão Bonito and Dourado areas, was well as close to São Carlos, Itirapina, São Pedro and Barra Bonita. A flow from the same P_2O_5 class occurs in the vicinity of the more distant city of Avaré, where stratigraphic relationships were not observed. In Ribeirão Preto, D45 directly overlies D50, and was very well characterized from outcrop and borehole data (Fernandes *et al.* 2010).

In the mentioned sections, D45 thickness ranges from 35 to 80 m (Tab. 1); it is predominantly fine-grained and contains glass drops. The basal contact, as well as the lamination or horizontal jointing, is parallel to the stratification of the underlying sandstones (intertrap or Botucatu, SD8 and SSM). Breccia was not observed at the base of D45. A thick vesicular layer is usually present at the top of the flow, and an overlying peperite-like breccia occurs occasionally, followed by intertrap sandstones. These have variable thickness (less than 1 m to more than 10 m) and were frequently observed. Entablature is present in three out of 16 expositions. In the section SPd, both the upper part of the colonnade and the overlying entablature contain amygdales, but lacks a typical vesicular layer, with great number of vesicles, amygdales, and geodes (Fig. 9). The top of the entablature is overlaid by a peperite-like breccia, less than two meters thick, whose contact with D57 is sharp and planar.

In section SD1 (Fig. 8), D45 occurs on top of a hill in an unexpected elevation, when compared to neighboring sections. This elevation cannot be explained by dunne palaeo-relief, as the Botucatu sandstone at this site is only 40-50 meters thick. This suggests that vertical tectonic displacements took place, an aspect to be discussed further on.

Flow D57

Flow D57 was identified in 9 sections, directly superimposed on the Botucatu Formation in one of them (Figs. 4 and 10). It overlays D45 in 6 sections located in the areas of Dourado (SD2, SD6), Brotas - São Pedro (SB1, SB2), Serra de Santa Maria (SSM) and Pederneiras (SPd) (Figs. 8 and 9). Section SPd was constructed on the excellent and continuous exposure of a quarry (outcrop 154). Where the contact between D45 and D57 was directly observed, usually thin and discontinuous intertrap sandstones are present (Figs. 8 and 9). In section SJ, an auto-breccia, containing irregular portions of sandstone may overlay the vesicular layers on top of D57; the sandstone may also occur as sand dikes on top of the flow. Basal auto-breccia mixed with sandstone portions may also occur in section SB5 (Fig. 10). No basal breccia is seen where it lies on top of the Botucatu Formation (SJ). The top vesicular layer is characterized by abundant

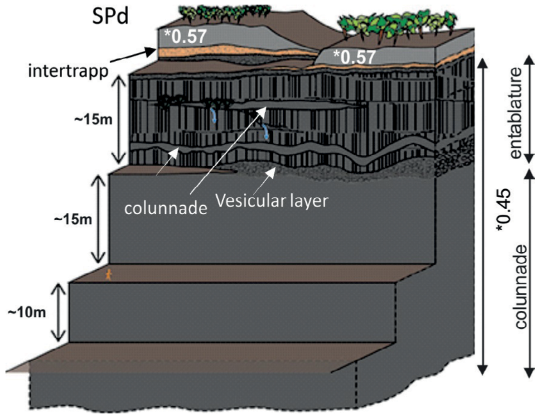


Figure 9. Section SPd (outcrop 154 in the Suppl. Tab. A1). The lower flow is D45, and the upper, D59. In the flow D45, 3 samples were collected, whose location is schematically shown in the drawing: lower and upper part of the colonnade, $[P_2O_5]$=0.46%; entablature with $[P_2O_5]$=0.45%. One sample was collected in D57, yielding $[P_2O_5]$=0.57%.

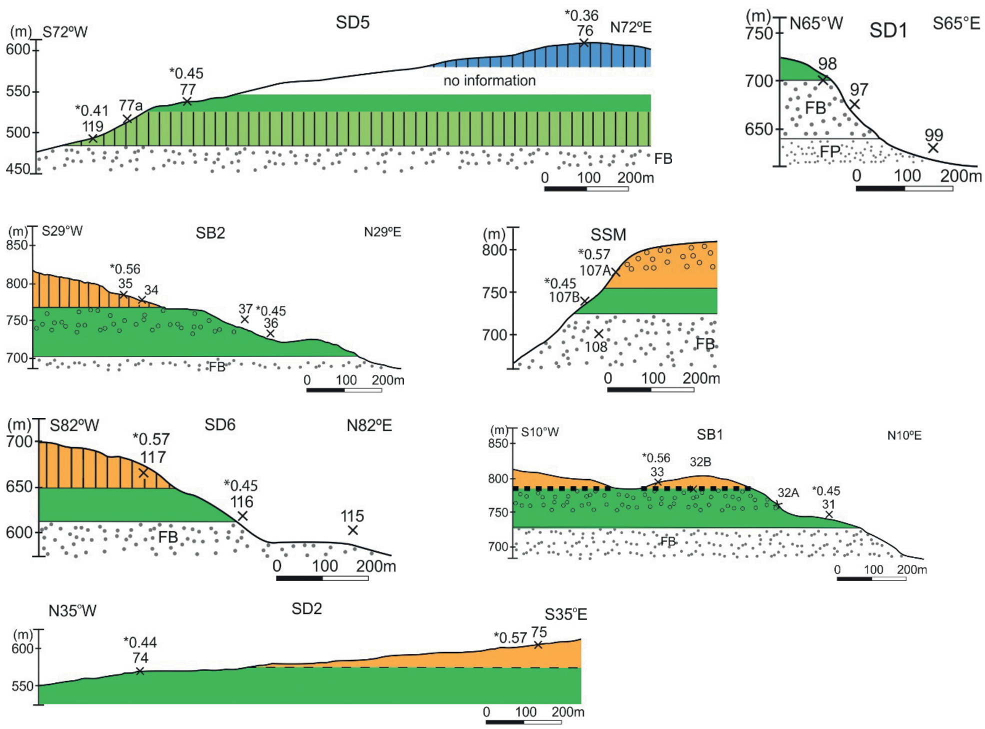


Figure 8. Section SD5 is the only section where D41 was chemically analyzed. In sections SD1, SB1, SB2, SSM, and SD6, D45 directly overlays the Botucatu Formation (FB) and is overlaid by D57. Common features: intertrap sandstones (thick dashed line), entablature layers (vertical lines). Vesicular layers (open circles) are commonly observed at the upper portion of basalts. Numbers represent outcrops and each number that follows the * represent P2O5 concentration at that outcrop. Basalt colors are the same as in the general stratigraphic column (see Fig. 5).

and small vesicles and amygdales, and also by geodes, the infillings being silica, quartz, and calcite. The central and massive portion of the flow is characterized by fine-grained, aphanitic or, very occasionally, medium-grained texture. It contains glass as drops or irregular portions, and basal horizontal jointing. Entablature was observed in SB2, SB5 and SD6. Where the bottom and top of the flow was observed, thicknesses ranges from 15 to 20 m.

In Ribeirão Preto, D57 is absent and the D64 flow directly overlies D45 (Fernandes *et al.* 2010).

Flow D64

The flow D64 was identified in 7 sections (Fig. 2) and in some isolated outcrops, amounting to 17 outcrops. It directly overlies D57 in two sections, located close to Jaú (SJ) and Itaqueri da Serra (SB5) (Fig. 10), and it is directly overlaid by D33, in sections SB5 and SBt2, and by D37, in sections SAr, SD3 and SD4, one of which (SAr) being the continuous exposure of the quarry at outcrop 152 (Fig. 11). In section SB3, stratigraphy of neighboring sections suggests that the two flows occurring below D64 are probably D45 and

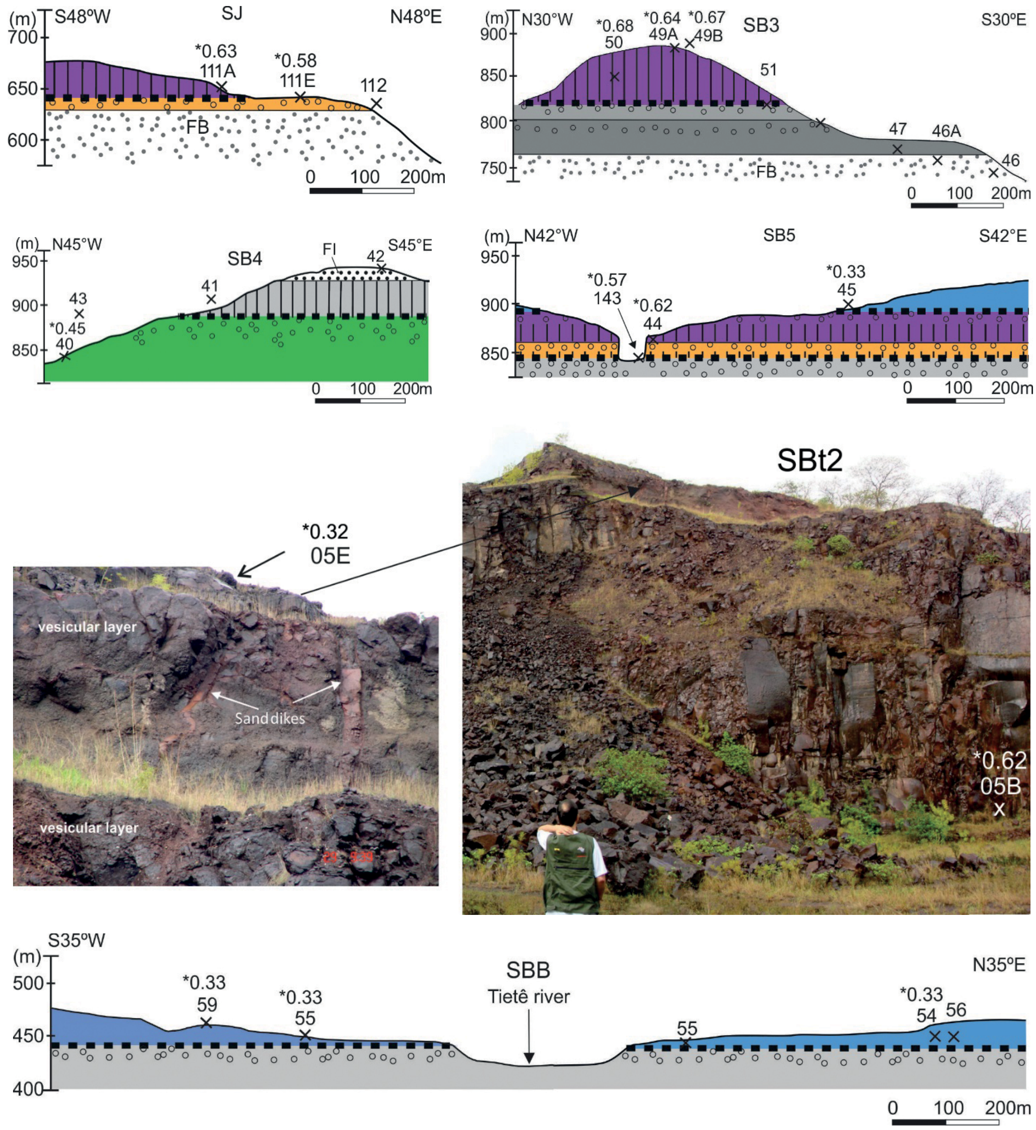


Figure 10. D64 overlies D57 in SJ (Jaú region) and SB5. SB4 is 1.5 km apart from section SB5 and the lowermost basalt of both sections are correlated. Both are nearby Cachoeira do Saltão. The two basalts that underlie D64, in SB3, are likely D45 and D57, from the base to the top, as a few nearby sections (SB1, SB2, SB4/SB5) show this stratigraphy. In sections SB5 and SBt2 (outcrop 5, north of Botucatu) D64 is overlaid by D33, and peperite-like breccias occur at the contact, and the top vesicular layer of D64 may be cut by sandstone dikes. The several D33 samples collected at section SBB yielded the same [P2O5] value (0.33%).

D57 (Fig. 10). The thicknesses of D64, deduced from the sections, ranges from 40 to more than 70 m.

Some tens of centimeters thick and discontinuous intertrap sandstones were observed at the base of D64 in two sections (SB3 and SJ), and at the top of 4 sections (SB5, SAr, SD3 and SBt2) (Figs. 10 and 11); in SBt2, sandstone dikes cut the upper vesicular layer. The basal vesicular layer, 20-to-30 cm thick, may contain small and abundant vesicles and amygdales. The central portion of D64 is aphanitic or fine-grained, and presents lamination and horizontal jointing. It is usually rich in glass drops, mainly when colonnade and entablature are present, which occurs in 10 out of 17 outcrops (Tab. 1). The upper vesicular layer contains dark-coated amygdales infilled with silica and quartz, as well as geodes with agate and quartz. In section SAr, where D64 is superimposed by D37, this layer is overlaid by a breccia, 2-3 meters thick, with cavities that were infilled with zeolite, silica, calcite, and quartz. The fragments of this breccia consist of vesicular basalt and

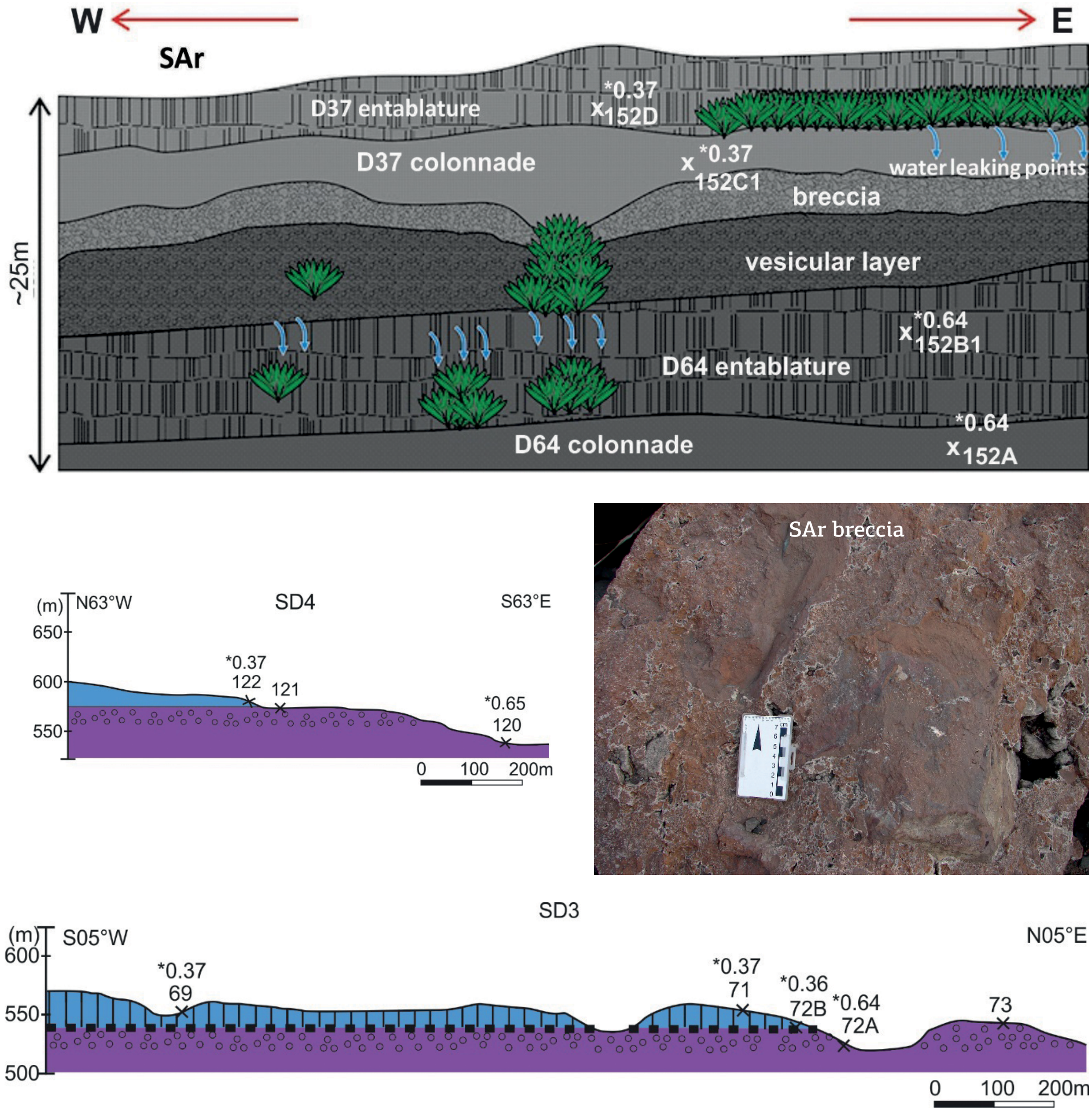


Figure 11. In sections SAr, SD3 and SD4, the flow D64 is overlaid by flow D37. At SAr (outcrop 152 of the Suppl. Tab. A1), samples (152A, B1, C1 and D) collected in the colonnade and entablature portions of the same flow, yielded the same [P_2O_5] value, which validates the use of this parameter for correlating flows. Figure 6 shows the actual position of the samples, for section SAr. The picture shows a detail of SAr breccia

auto-breccia (fragments of vesicular basalt welded by basalt with less vesicles). This breccia layer, located close to the base of D37, occasionally contains small and very irregular portions of an intertrap sandstone, and this suggests that the basal portion of the breccia is related to D64 lava emplacement, and the upper part, to the emplacement of D37 (Fig. 6). Fernandes *et al.* (2016) describes very similar breccia contained in flow D64, in the region of Ribeirão Preto. In the isolated outcrops close to Avaré, D64 overlies intertrap sandstones; it presents a basal auto-breccia and, above it, flattened vesicles, lamination and horizontal jointing. The massive basalt is aphanitic, contains frequent glass drops and presents entablature. The top is characterized by vesicular portions.

Flow D37

Flow D37 was observed in sections SAr, SD3 and SD4, where it lies over D64 (Fig. 11), and in sections SD5, SBt1 (Figs. 8 and 12), as well as in three isolated outcrops, close to Tietê River (Fig. 1). In its central part, the rock is usually very fine-grained and contains glass drops; entablature is present in three sections. The basal vesicular layer may contain abundant, small and white (silica) amygdales. Horizontal jointing may be present in the colonnade layer, and lamination, at the base of the flow, is parallel to irregular elongated glass rich laminae. Basal auto-breccia with small and irregular portions of intertrap sandstone was observed in SAr, where it overlays D64. The upper vesicular layer was observed only in section SBt1, the only place where total thickness (about 15 m) could be estimated. The vesicular layer is about half this thickness.

Flow D33

Flow D33 is present in three sections (SB5, SBB and SBt2), directly overlying D64 in two of them; section SBt2 is a continuous exposure of a quarry (Fig. 10). Underlying D33, intertrap sandstones and peperite-like breccia, containing vesicular fragments of the previous flow, are present in the three sections. These sandstones are usually fine-grained, well sorted, thin and discontinuous, however in SB5 they contain a muddy matrix.

In section SBB (Fig. 10), 5 samples were collected in different outcrops, all of them yielding the same content of P_2O_5 (0.33% to 0.34%). It was not possible to analyze the underlying flow, that was weathered. The basal vesicular layer, in contact with the intertrap sandstone, is 20 cm thick, the amygdale being white and, in general, horizontally flattened. On top of this vesicular layer, a horizontal and dense jointing, in a 20-cm thick layer, is remarkable; upwards this jointing becomes tens of centimeters apart. The central portion of D33 is aphanitic to fine-grained and, in section SBB, it always contains flattened vesicles and amygdales, which are parallel to a lamination, defined by parallel to irregular and elongated portions of glass. In section SB5, D33 also exhibits lamination. The upper part of D33, in section SBB, presents frequent geodes infilled with agate and quartz.

Flow D22

Flow D22 was identified only in the northwestern part of the studied region, close to the city of Reginópolis, and distant from the outer limits of the main exposure of Serra Geral Group. The very low P_2O_5 (0.22%) content characterizes it as a Paranapanema type (Fig. 1). Its stratigraphic position is unknown; however, taking into account the regional data form the literature (e.g., Torres *et al.* 2008, Machado *et al.* submitted), and inferring that the lava pile is thicker at this site, it might be considered to lay above the flows of Pitanga type.

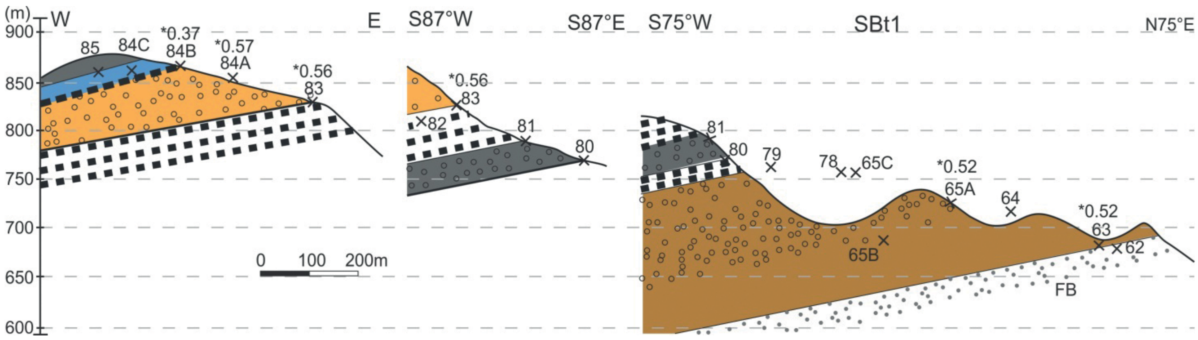


Figure 12. In section SBt1 (close to the city of Botucatu), the lowermost flow, whose [P2O5] is 0.52 at both outcrops 63 and 65A, is of Urubici type. It is overlaid by an intertrap sandstone and, then by a flow with no chemical analyses. The two flows that overlie the thick intertrap sandstone (outcrops 81-83) are Pitanga types and their stratigraphy (D33 over D57) is consistent with the general stratigraphic column. The uppermost flow (outcrop 85) has no chemical analysis.

This basalt is aphanitic to fine-grained, and has glass drops, which may be more concentrated in some portions. At the only outcrop observed, it consists of a lower colonnade layer, and an upper entablature layer. The colonnade contains portions where the columns are regular, well formed, and vertical, inclined or curved. In the entablature, the thin columns are inclined. No upper vesicular layer was observed, and the entablature layer is directly overlaid by conglomerates and poorly sorted sandstones of the Bauru Group, as observed in the same outcrop. From this outcrop, at least 20-m thickness was estimated for D22.

Sills

The occurrence of Pitanga type diabase sills in the study region stretches across the area that encompasses the surroundings of Brotas, Ribeirão Bonito, and São Carlos cuestas, as depicted in the regional geological maps (Perrota *et al.* 2005, DAEE/UNESP 2013).

In the section SSC, which crosses São Carlos cuestas, the Piramboia Formation is overlaid by a mafic rock approximately 80-m thick, mapped as a sill by Perrota *et al.* (2005) and DAEE/UNESP (2013), which is positioned between the Piramboia and Botucatu formations. Its intrusive nature is consistent with the fact that vesicular layers were not observed, despite its extensive exposure. The [P_2O_5] values of 0.50% (samples 89C and 90) and 0.58% (sample 89A) were collected in the same continuously exposed rock, and are suggestive of *in situ* differentiation. However, the nature of the mafic rocks close to Brotas and Ribeirão Bonito, all of them belonging to the class D50, is not as evident. In section SD7, the relationship of the vesicular layer, outcrops 91-92, with the massive rock of outcrops 90 and 93 is unknown. Should these outcrops belong to one single flow, it would be more than 100-m thick, which is quite unusual. So, a plausible hypothesis is that the massive rock is a sill of class D50. For the other nearby sections SD8 and SD9, on the other hand, field evidence, namely vesicular layers and intertrap sandstones, is indicative that the rocks of class D50 are flows, and the geological maps, that represent them as sills, should be modified. By the same token, the maps should also be corrected in the area that contains outcrop 114 (between Brotas and section SJ), where the mafic rock, which is class D57, contains an expressive vesicular layer at the top.

Between Brotas and Itaqueri da Serra, at outcrop 137, the top of a mafic body directly beneath the Botucatu Formation (Figs. 13A) is devoid of vesicular layers, being interpreted as a sill. South of Brotas, both mafic rocks, likely belonging to class D50 (P_2O_5 is 0.47% and 0.51% at outcrops 30 and 38, respectively), are either massive (outcrop 30) or present sparse vesicles and amygdales (outcrop 38), and may also be part of a sill.

Finally, the 4 samples classified as Urubici, as described above, occur at the cuestas located close to Pardinho and south of Botucatu, in section SBt1 (Fig.1). In this section, the rock is a flow, with an expressive upper vesicular layer cut by sandstone dikes, originated from the superimposed intertrap sandstone. Both samples reached 0.52% of P_2O_5. However, the rocks sampled close to Pardinho are probably part of a sill, as they do not show vesicle layers along their extensive expositions. The variation of P_2O_5 content, 0.56% and 0.52%, for outcrops 2 and 4, respectively, may reflect differentiation. In view of the uniqueness of the Urubici-like chemistry, this sill and the lowermost flow of section SBt1 may be genetically related.

General stratigraphic column and flow lateral extents

The great majority of the flows in the study region are of Pitanga type and, based on the local sections and on the use of P_2O_5 for correlating the lava flows, whose validation was discussed above, a general stratigraphic column is proposed in this work. The consistency of the order of stacking of the P_2O_5 classes, not only throughout the study region, but extending to the Ribeirão Preto area (Fernandes *et al.* 2010), is one essential element of the validation. In this sub-section, a broad description of the general column, the most outstanding characteristics of the flows, and their inter-relationships are presented.

Except for D41, which occurs only in section SD5, the stratigraphic relationships of the Pitanga flows were well characterized and are synthesized in Figure 4. From base to top of the column here proposed, [P_2O_5] firstly declines, as indicated by D45 lying over D50. Afterwards, it successively increases, with the emplacement of the sequence D45, D57 and D64. This is followed by a strong reduction, with D37 and D33 overlying D64. This correlation indicates that the minimum lateral extension of the flow D50, that extends from Ribeirão Preto up to Ribeirão Bonito (sections SD7, SD8 and SD9), is 100 km. However, if one considers that it reaches the isolated outcrops south of Barra Bonita, the minimum extension would be 175 km. By the same token, the minimum lateral extension of flow D45 is 160 km (from Ribeirão Preto up to section SPd) or 240 km (up to the isolated outcrop nearby Avaré), and for flow D64, 185 km (up to section SBt2) or 240 km (up to the isolated outcrop nearby Avaré). D57 flow is absent in Ribeirão Preto, but samples of this class were collected from the outskirts of São Carlos to section SBt1 (Fig. 1), an extension of 150 km. Furthermore, flow D37 extends 87 or 121 km, from Araraquara to outcrop 162 or to section SBt1, and flow D33 extends 74 km, from section SD5 to section SBt1. Those lateral extents require voluminous lava flows, besides an emplacement mechanism that minimizes heat loss, typical of sheet-like lobes of flood basalt

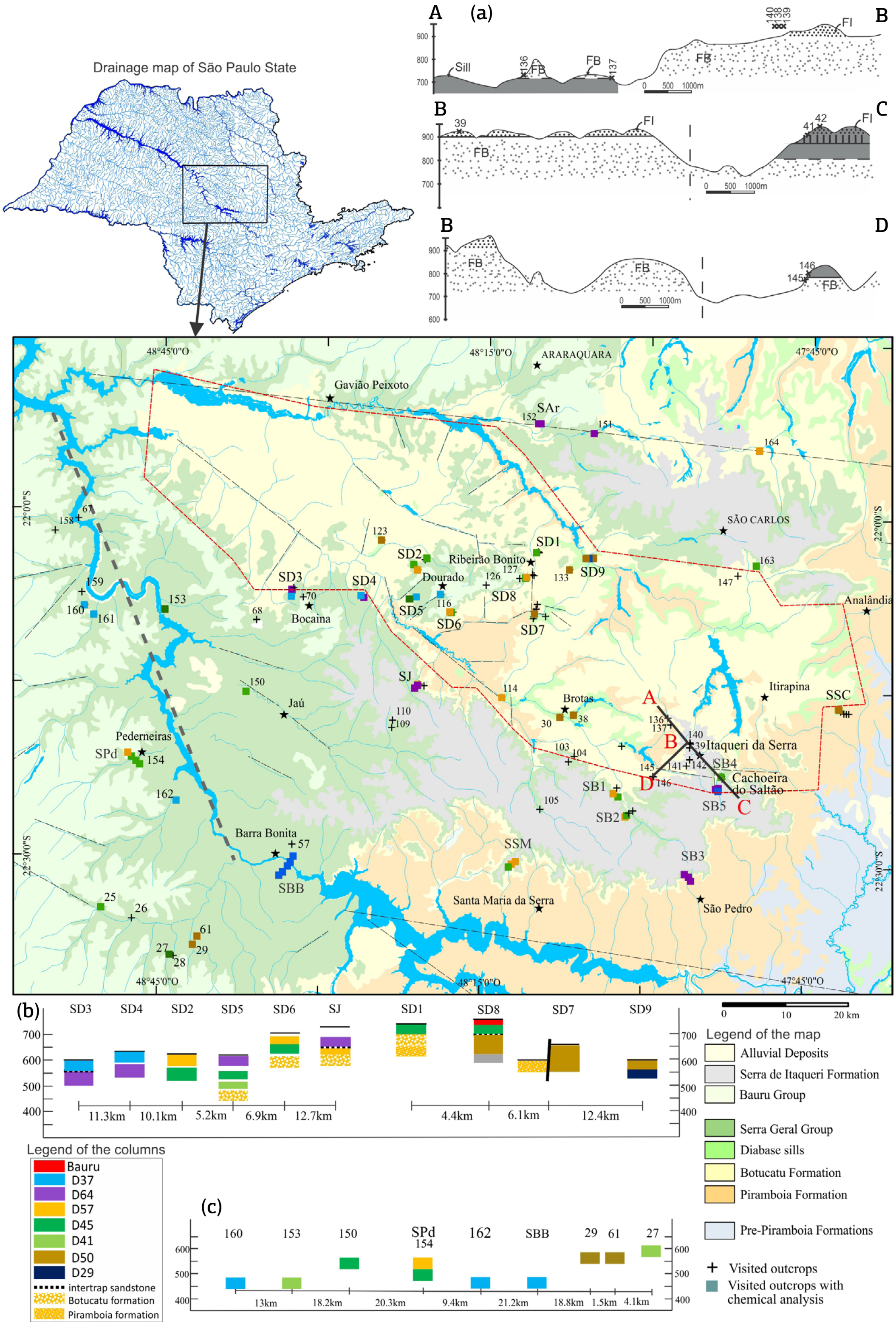


Figure 13. The sections close to Itaqueri da Serra (A) and the stratigraphic columns, close to Ribeirão Bonito (B) and Barra Bonita (C), show evidence of tectonic displacements. These are in a region bounded by extensive EW lineaments (fine dashed lines) parallel to the Piracicaba and Jacaré-Guaçu rivers. These lineaments also limit the stretch where the Tietê river direction is N20W (thick dashed line). The area bounded by the red dashed line, where Piramboia and Botucatu Formation crop out outside of the Peripheral Depression, is probably a structural high (see text for explanation). In (a): FI=Itaqueri Formation, FB=Botucatu Formation.

provinces, as proposed by Self *et al*. (1998), Self (2008) and Self *et al*. (2008).

Intertrap sandstones are a common feature and were frequently observed at the contacts between the flows (Tab. 1). They are usually fine-grained and relatively well sorted, and unlike the Botucatu Formation sandstones, typically present a bimodal texture with less-rounded grains. Muddy or clayey sandstones appear only in three of the outcrops, underneath D64 north of Avaré, between D64 and D33 in section SB5, and above D50 in section SD9. They are usually thin (tens of centimeters to few meters) and may be very discontinuous and lenticular.

Upper vesicular layers, at least several meters thick, are a common feature for all flows (Fig. 5) and indicate that the emplacement was predominantly of pahoehoe type and thermally efficient, which is consistent with the great lateral extents indicated by the chemical stratigraphy. Those vesicular layers are occasionally followed by peperite-like top breccias, indicating local rubbly pahoehoe emplacement. This type of emplacement is typical of the Vale do Sol Formation, as described by Rossetti *et al*. (2017). The breccias observed in flows D41, D45, D57, D64 and D37 (Tab. 1) are around one-meter thick, that may disappear in short distances for the same flow. D64 upper vesicular layer is overlaid by a continuous upper auto-breccia layer (see Fig. 6), with irregular portions of sandstone at its top, at section SAr, but is absent in sections SD3, SD4 and SBt2. Both D64 and D37, in section SAr, present auto-breccias and conspicuous entablature. Lower vesicular layers are also a common feature for all basalts, and basal auto-breccia was observed for flows D41, D57, D64 and D37 each in only one outcrop (Tab. 1).

Thickness was estimated for some flows, ranging from 20 up to 80 m (Tab. 1). The values obtained are more reliable for D45 and D57, which occur at intermediate positions of the general stratigraphic column. D37 and D41 had thickness estimated only for sections SBt1 and SD5, respectively.

Entablature layers in basalt, characterized by thin and irregular columns (the diameter is centimetric) or by closely spaced, very irregular and random fractures (rubble), are relatively frequent (Tab. 1). This structure implies fast cooling, which can only occur due to water convection currents that took place at the spaces between the cooling fractures (Long & Wood 1986). Entablature was observed in almost all flows, but is much more frequent in D64 (10 out of 17 outcrops), indicating wetter climate conditions during its emplacement. Glass drops and aphanitic texture are also more frequent in D64, and are consistent with the faster cooling. The thick auto-breccia layer, where the cavities are typically infilled by zeolite and other ordinary minerals (agate, quartz and calcite), occurs only in section SAr, between D64 and D37, where both basalts present entablature. In Ribeirão Preto, this type of breccia was observed in D64, the only basalt in the region with entablature, therefore suggesting it is also related to the fast cooling.

D64 is also the flow with one of the largest lateral extensions, and this characteristic, along with fast cooling, indicates that the emplacement must have been very fast. Similar conditions are described for Columbia River basalts (Bronde *et al*. 2004).

The macroscopic characteristics of flows, including entablature, cannot be used to correlate a specific flow from one section to another, as practically all the textures and structures occur in every flow (Tab. 1).

Section SBt1, that crosses the Botucatu cuesta, is the only one that contains an Urubici flow, with an estimated thickness of about 75 m (Fig. 12). It occupies the lowermost position in the section, and is the only basalt where veins (with a coarse-grained texture) were observed. Close to the top, two Pitanga flows of the classes D57 and D37 are seen, and, although D64 is missing, it may be correlated to flows D57 and D37, as they keep the same stacking order of the general column (Fig. 5). An outstanding feature of section SBt1 is the thick intertrap sandstone that underlies D57, which suggests a large period before the D57 emplacement. This longer period may be related to a change in magma type from Urubici to Pitanga.

Evidence of vertical tectonic displacements

The identification of a stratigraphic column, applicable to the entire studied region, allowed to find irregularities in the altitude of the basaltic column and the contact with the Botucatu Formation. These were identified in three areas:

- Itaqueri da Serra - Cachoeira do Saltão. In the area of Itaqueri da Serra (sections AB and BC, Fig. 13), high plateaus are supported by silicified sandstones of the Itaqueri Formation, directly superimposed on the Botucatu Formation. In this region, the latter is exposed from the top to the base of the plateaus cliffs (Fig. 13). However, further south, in the area of the Cachoeira do Saltão, the Itaqueri Formation, constituted here of limonitized conglomerates, rests on a column of basalts with more than 100 m thick (where sections SB4 and SB5 are located), indicating that there are tectonic structures responsible for important vertical tectonic displacements between Itaqueri da Serra and Cachoeira do Saltão. Such structures are previous to the deposition of the Itaqueri Formation, but younger than the basalts. To the west (section BD, Fig. 13), a similar situation occurs: at the northern part, the hills are constituted only of the Botucatu Formation, and to the south, basalts occur at their tops.
- Ribeirão Bonito - Bocaina. This area encompasses section SD7, where rocks assigned to the Piramboia Formation are almost at the same altitude of intertrap sandstones, as previously described, indicating the existence of a structure which uplifted the northern portion of the section

In section SD1, basalt D45 overlaps the Botucatu Formation, whose top is at an altitude of 700 m; the top of the Piramboia Formation, in the same section, is at 650 m. In the nearby section, SD8, D45 is superimposed on D50 and D29, and the Botucatu Formation top is lower than 580m (Fig. 7). The Botucatu Formation, at SD1, is only 50-m thick, and thus the difference in altitude, between sections SD1 and SD8, cannot be explained by the local occurrence of a high dune. This suggests that vertical tectonic displacements occurred prior to the emplacement of D45 and after D50 (present at SD8) emplacement. On the other hand, in section SD5, the altitude of the Botucatu Formation is 580 m, 100 m lower than in the nearest section, SD6 (Fig. 8). Briefly, sections SD1 and SD6 are likely to be located in tectonically higher areas, and sections SD8 and SD9 in downthrown areas.

- Barra Bonita - Arealva. In the vicinity of the Tietê river, basalts of the top of the general column (D33 and D37) occur at lower altitudes than basalts of intermediate (D41, D45, D57) or lower (D50) positions (Fig. 13). The evidence for tectonic displacements causing such unevenness is most striking in Pederneiras, due to the proximity of the outcrops: basalt D37 is exposed around an altitude of 450 m (outcrop 162), while the contact between D45 and D57 is at about 530 m (outcrop 154). Pederneiras is located just east of the Bauru's structural high, where the Bauru Group directly covers the basalts, as well as the Botucatu and Piramboia formations, which are side by side (Paula-Silva 1988). This indicates post-basalt and pre-Bauru tectonics.

It is noteworthy that all the three areas just described occur within a region bounded by extensive EW lineaments, whose traces follow the Piracicaba river, to the north, and Jacaré-Guaçu river, to the south. These lineaments also limit the stretch where the Tietê river direction is N20W, different from its otherwise constant direction, which is around N50-60W. This region is also marked by the confluence of several large alignments already described in the literature: Mogi-Guaçu, trending N20W (Coimbra *et al.* 1981); Tietê and São Carlos - Leme, respectively trending N60W and N70W; and Ibitinga - Botucatu, trending N20W (Riccomini 1995, 1997a - Bauru). All these elements evidence that this region was affected by relevant tectonic activity.

It is proposed that the large region that encompasses Itirapina, Brotas, and Ribeirão Bonito up to Gavião Peixoto, where the Botucatu and Piramboia formations crop out, constitutes a main structural high. Such a structural high would have been responsible for the appearance of these formations outside their typical area of exposure, i.e. the Peripheral Depression. It is suggested that the tectonic activity that occurred there in different periods (syn- or post-basalt, as well as pre-Bauru and pre-Itaqueri) is probably related to trans-extensional tectonic events (therefore involving normal vertical displacements) which affect the basalts, as described by Fernandes *et al.* (2012). Given the importance of EW-WNW lineaments, such as the ones parallel to the Piracicaba and Jacaré-Guaçu rivers, and NNW-NS lineaments, it can be suggested that the event with a main principal stress of NW direction, named eNW by Fernandes *et al.* (2012), was one of the most active ones. This subject will be further elaborated in an article addressing the influence of structural geology on the hydrogeology of basalts and the Guarani Aquifer System.

CONCLUSIONS

Eight P_2O_5 concentration classes of basalts, separated by natural breaks in cumulative frequency graph, were identified in the region where Serra Geral Group crops out, between Araraquara and Avaré. Of these classes, seven exhibit a consistent stacking order verified in detailed geological sections elaborated for the region. Thus, each class is considered to correspond to a specific lava flow, allowing a general stratigraphic column to be proposed, where each flow is designated after the most frequent P_2O_5 content of its respective class. The most basal flow is D50, followed by the successive emplacement of D41, D45, D57 and D64, characterizing first a depletion (D50 to D41) and then a successive enrichment in P_2O_5. After these, a strong reduction in $[P_2O_5]$, represented by the lava flows D37 and D33, took place.

The validation of P_2O_5 as a tool for lava correlation was confirmed by the values obtained for samples collected at different positions in the same flow (which yielded constant values of $[P_2O_5]$), and on the remarkable $[P_2O_5]$ contrast between adjacent flows, such as D57 overlying D45, and D37 overlying D64. This shows that the natural breaks observed in the cumulative frequency graph actually constitute real limits between different lava flows.

Flows D50, D45 and D64, from base to top, are present in Ribeirão Preto, and the correlation with the study area indicates minimum lateral extensions of 100, 160, 185 km, respectively. The D57 flow, absent in Ribeirão Preto, was observed from São Carlos to Pardinho over an extension of 150 km. Flows D37 and D33 minimum extensions are 87 and 74 km, respectively.

The Botucatu Formation is present in 9 sections, and D45 constitutes the most basal flow in 5 of them, indicating that D41 and D50, each directly lying on top of the Botucatu Formation in just one section, are less continuous. D45 being overlapped by D57 is the best characterized stratigraphic relationship, since it was observed in six sections throughout the study region. D64 overlaps D57 in two sections, and is overlapped by D37 in three sections and by D33, in two sections. Flows at intermediate positions of the general stratigraphic column were observed in a larger number of sections and isolated outcrops. Thickness estimated for some flows ranged from 20 to 80 m.

The macroscopic textures and structures are inappropriate to establish correlations from one section to the other. Entablature indicates wetter climatic conditions contemporary to D64 basalt, in which this feature is much more frequent, however, it occurs in practically all classes of basalts. Therefore, as the other macroscopic characteristics, it cannot be used as a correlation guide between lava flows.

Evidence of vertical tectonic displacements based on the altitude of specific flows and the Botucatu and Piramboia formations was found in areas bounded by extensive EW lineaments. These lineaments also limit the stretch where the Tietê river direction is N20W, different from its otherwise typical direction around N50-60W. The tectonic displacements took place in different periods: contemporaneous to the basalt emplacement, on one side, and post-volcanism but previous to the deposition of the Bauru Group and the Itaqueri Formation, on the other side.

It is proposed that the large region that encompasses Itirapina, Brotas, and Ribeirão Bonito until Gavião Peixoto, where Botucatu and Piramboia formations crop out, constitutes a structural high of regional expression. Such high would have been responsible for the appearance of these formations outside their typical area of exposure, i.e. the Peripheral Depression. This tectonics is probably related to the trans-extensional tectonic events (therefore, involving normal vertical displacements), which affect the basalts in the form of striking tectonic fracture patterns, previously described in the literature. This subject will be further addressed by an article on the influence of structural geology on the hydrogeology of basalts and the Guarani Aquifer System.

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SUPPLEMENTARY DATA

Supplementary data associated with this article can be found in the online version: Suplementary Table A1

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