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ARTICLE

Morphology and stratigraphy of Serra Geral silicic lava flows in the northern segment of the Torres Trough, Paraná Igneous Province

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ABSTRACT: *The impetus for this research was the enigma regarding the origin of the extensive silicic volcanic units in the Paraná-Etendeka Igneous Province. Are they rheoignimbrites, lava flows, or a combination of both? The São Joaquim silicic eruptive sequence is comprised of Palmas-Type aphyric dacites and is located in the northern segment of Torres Trough, a dissected mountainous region in southern Brazil. These dacite outcrops form plateaus and remnant hills that are scattered above a basaltic andesitic landscape. The original morphology of the silicic volcanic flows was constrained based on the internal architecture, geometry, and cyclicity of the lithofacies, in conjunction with petrographic and geochemical information. The data suggests the presence of ancient large tabular and lobate silicic lava flows (~100 m thick and ~10–40 km extents). No pyroclastic features were found. Eight interdigitating units were mapped. These large aspect ratios are similar to ones for basaltic flows and those of Snake River-type rhyolites, and they suggest high effusion rates and high temperatures as well as the presence of well-insulated cooled crusts. Lavas would have overflowed from long fissure vents that had created an extensive volcanic silicic surface body composed of conjugated and interdigitated flows above the north segment of the Torres Trough region.*

KEYWORDS: *Extensive silicic lavas; Paraná-Etendeka Large Igneous Province; Serra Geral volcanism; stratigraphy of Torres Trough; São Joaquim Plateau.*

INTRODUCTION

Extensive silicic units are commonly associated with welded to rheomorfic high temperature (~1,100ºC) ignimbrites (White *et al.* 2009, Bryan *et al.* 2002, 2010, Ernest 2014, Wolff & Wright 1981). However, silicic lava flows can also form voluminous units, including those in some Large Igneous Provinces (LIPs) such as the North Atlantic, Madagascar, Snake River-Yellowstone, Chon Aike and Paraná-Etendeka LIPs (Mahoney & Coffin 1997, Ellis *et al.* 2013, Bonnichsen & Kauffman 1987, Pankhurst *et al.* 1998). The silicic volcanic units of the Cretaceous Paraná-Etendeka LIP were previously understood to be rheoignimbrites, in which pyroclastic textures would have been masked during emplacement. Therefore, extensive tabular silicic plateaus, high emplacement temperatures, and the presence of circular structures (e.g., Messum Crater in Namibia) led several pioneering authors to infer a pyroclastic origin for these rocks (Whittingham 1989, Garland *et al.* 1995, Roisenberg 1989, Milner *et al.* 1992, 1995). Since then, much important research on geochemistry and correlation has been conducted within the province, but there is still a lack of detailed cartographic and stratigraphic work, which could help in clarifying the origins of and relationships among the silicic rocks. Therefore, the emphasis of this study is on the physical aspects of the rocks, such as the internal architecture and geometry of bodies and their spatial distribution. The goal of this work is to begin to characterize the geologic framework of the wild and mountainous areas of the northern segment of the Torres Trough in the Santa Catarina Highlands by determining the origins of the extensive silicic rocks.

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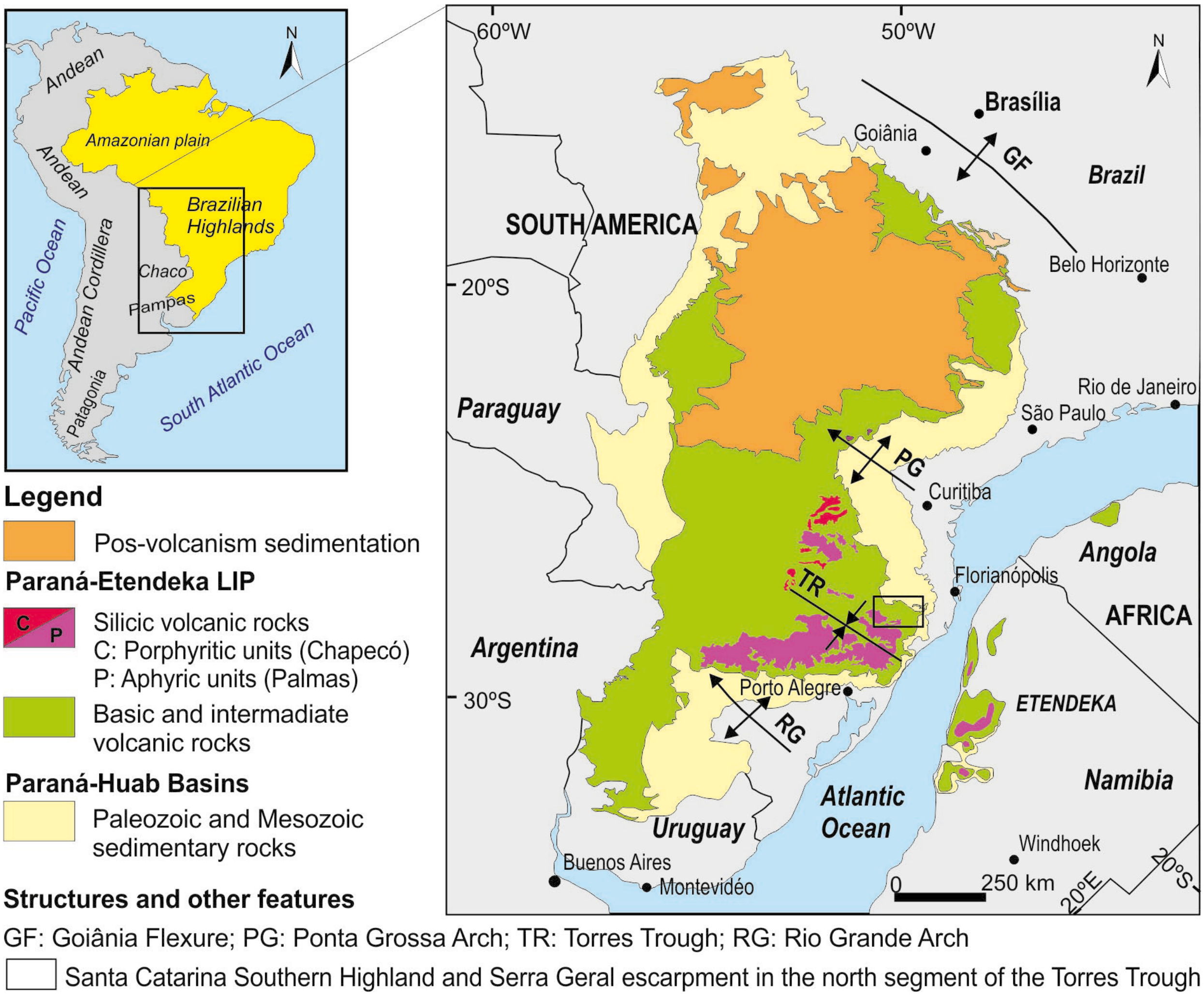
GEOLOGICAL SETTING

The Paraná-Etendeka Igneous Province (PEIP) provides a record of one of the largest eruptive episodes in the Phanerozoic preceding the breakup of southern Gondwana and the opening of the South Atlantic Ocean. The province overlies and intrudes sedimentary rocks of the Paraná Basin in South America, and it has a preserved emerged area estimated at 1.2 × 10^6 km^2, of which silicic volcanic rocks cover 64,000 km^2 and compose 3% of the total volume of the Paraná LIP (Melfi *et al.* 1988, Bellieni *et al.* 1986, Nardy *et al.* 2008). Its African counterpart outcrops mainly in northwestern Namibia as the Etendeka Group and covers almost 78,000 km² (Erlank *et al.* 1984). About one half of it is formed by silicic rocks recognized as quartz-latite rheoignimbrite sheets (Milner *et al.* 1992, 1995) (Fig. 1). Indeed, locally eutaxitic textures are preserved as described in the Bergsig Formation in Etendeka and in some places of southern Brazil (Miller 2008, Luchetti 2015, Luchetti *et al.* 2017). Volcaniclastic/epiclastic sediments are identified in Rio Grande do Sul as deposits formed of reworked pyroclastic material that was deposited during silicic magmatic activity (Riccomini *et al.* 2016). On the other hand, extensive silicic lava flows and local lava domes and their conduits are also recognized in the South American counterpart of the PEIP (Comin-Chiaramonti *et al.* 1988, Petrini *et al.* 1989, Bellieni *et al.* 1986, Umann *et al.* 2001, Lima *et al.* 2012, Waichel *et al.* 2012, Chmyz 2013, Polo & Janasi 2014, Simões *et al.* 2014, Cañón-Tapia & Raposo 2017, Rossetti *et al.* 2017, Simões *et al.* 2017, Lima *et al.* 2018).

Both the Paraná and Etendeka provinces can be divided based on geochemistry into two domains: a high TiO_2 domain that generally comprises northern basaltic units with porphyritic rhyodacites (Chapecó-Type in Brazil) and a low TiO_2 domain that comprises southern units, including Palmas-Type aphyric dacites and rhyolites in Brazil (Bellieni



Source: Modified from Licht (2016).

Figure 1. Paraná-Etendeka Igneous Province volcanic remnants. The area inside the rectangle is detailed in Figure 2.

et al. 1986, Piccirillo *et al.* 1987, Piccirillo & Melfi 1988, Peate *et al.* 1992, Nardy *et al.* 2008, Licht 2016).

The Palmas rocks are classified into subtypes according to their TiO_2 and P_2O_5 content, which is related to the surface and stratigraphic distribution of the units, as is also observed in Etendeka (Nardy *et al.* 2008, Milner *et al.* 1995, Marsh *et al.* 2001, Miller 2008). The Santa Maria subtype is defined by $TiO_2 \leq 0.87\%$ and $P_2O_5 \leq 0.21\%$; Clevelândia subtype, $TiO_2 \leq 0.87\%$ and $0.21\% < P_2O_5 \leq 0.23\%$; Jacuí subtype, $1.05\% < TiO_2 < 1.16\%$ and $0.28\% < P_2O_5 < 0.31\%$; Caxias do Sul subtype, $0.91\% < TiO_2 < 1.03\%$ and $0.25\% < P_2O_5 < 0.28\%$; and Anita Garibaldi subtype, $1.06\% < TiO_2 < 1.25\%$ and $0.32\% < P_2O_5 < 0.36\%$. Anita Garibaldi rocks most often overlie Caxias do Sul rocks. In Namibia, the Beacon Formation (correlated to the Anita Garibaldi Formation) overlies the Grootberg and Wêreldsend formations, both of which are correlated to the Caxias do Sul subtype (Nardy *et al.* 2008, Miller 2008).

The silicic PEIP rocks suggest high crystallization temperatures, between 995ºC to ~1,070ºC (Milner *et al.* 1992, Bellieni *et al.* 1984). The temperatures of the lavas of the southern segment of the Torres Trough were calculated at 1,067ºC ± 25ºC (Simões *et al.* 2014).

Torres Trough eruptive succession

In Brazil, the PEIP volcanic pile was formerly described as Serra Geral (SG) volcanics (White 1908), and was subsequently designated the SG Formation of the São Bento Group (Gordon Jr. 1947). There is a need for a new terminology that includes both the Paraná and Etendeka provinces. The Serra Geral Group has been mentioned in this context (Pinto & Hartmann 2011, Licht 2016, Rossetti *et al.* 2017). Serra Geral is a designation derived from the easternmost escarpment of the eruptive sequence, whose edges rise ~1,000 to ~1,850 m above sea level, demarcating the limits of the plateaus of the southern Brazilian Highlands through a set of canyons and steep cliffs off the lowlands and the coast between the states of Santa Catarina and Rio Grande do Sul. This region coincides with the Torres Trough threshold, a large trough structure whose main orientation is NW-SE. This structure was a paleo depression formerly connected to the Huab Basin (Namibia) in the Early Cretaceous (Waichel & Jerram 2015).

The first PEIP volcanic activity overlapped a palaeoerg that composes the aeolian sandstones of the Botucatu and Twyfelfontein Formations in the Paraná and Huab Basins, respectively (Jerram *et al.* 1999, 2000). The Torres Trough stratigraphy was previously divided into five volcanic episodes and later into four formations in an attempt to construct a formal stratigraphic framework (Waichel *et al.* 2012, Rossetti *et al.* 2014, 2017). According to Rossetti *et al.* (2017), the Torres Formation (TF) overlies the sandstones and reaches a thickness of almost 300 m. It is formed by thin (0.2–18 m) and chemically more primitive basaltic flows (MgO > 5 wt %) of compound braided facies with a typical pahoehoe structure. The Vale do Sol Formation (VSF) overlies the TF and represents the most voluminous mafic lava flows, reaching a thickness of 500 m. It is characterized by thick (20–60 m) basaltic andesitic flows (SiO_2 > 51 wt %; MgO < 5 wt %) of sheetlike facies of rubbly pahoehoe lavas with simple tabular geometry. The Palmas Formation (PF) contains dacitic and rhyolitic tabular lava flows and domes. These acidic units overlap with VSF flows in the central and eastern portions of the Torres Trough and rest directly upon TF basalts in the west. The total thickness can reach 400 m in the eastern portion, thinning toward the west and north. The Esmeralda Formation (EF) is the upper stratigraphic unit of the low-TiO_2 eruptive succession, and it has a thickness of 25 to 150 m in the Torres Trough. It includes the Esmeralda magma-type basalts (Peate *et al.* 1992) and is formed by very thin (0.2–3 m) lava flows and lobes showing compound braided facies with a typical pahoehoe structure (Rossetti *et al.* 2017).

The basaltic lavas of the São Joaquim region successively covered sediments of the Botucatu Formation toward the northeast, showing that there was a pre-eruptive relief of 400 m between the areas of the Serra do Rio do Rastro and Serra do Corvo Branco (Peate *et al.* 1999). These authors defined 18 Urubici magma-type basaltic flows (high Ti/Y) there, the farthest south ocorrences of these magmas in the Paraná LIP, interbedded with flows of the Gramado magma-type (low Ti/Y and Ti/Zr < 70 ppm). In addition, a flow of the Esmeralda magma-type (Ti/Zr > 60 ppm) occurs at the top of Morro da Igreja (1,822 m) (Fig. 2).

The São Joaquim Plateau (SJP) occupies 270 km^2 of predominantly flat relief compared to the surrounding deeply dissected basaltic region. The plateau is punctuated by hills and wetlands. It has steep-sided edges and a slight dip: elevations vary from 1,000 m in the west to 1,445 m in the northeast (Besser *et al.* 2015). It is divided into two crests that reach toward the west as interflows. Extending from this larger area, silicic rocks form dozens of inselbergs dispersed throughout the Santa Catarina Highland in the direction of the Serra Geral cliffs, where the occurrence of silicic rocks expands locally again, forming the Santa Bárbara Plateau (SBP). This plateau has an elevation of over 1,700 m, the highest in the PEIP (Figs. 2 and 3).

METHODS

The following six methods were used during the study of the SJP. First, detailed mapping was performed using topographic charts and aerial images to identify regional structures and relief break features. Second, a field lithofacies table was created to characterize lithotype, textural, and structural features (e.g., the presence, amount and shape of vesicles and amygdales; the presence of horizontal or top-deflected platy joints). Third, lithofacies were grouped into geological associations. Fourth, morphologies were described, and the lateral and/or vertical reappearance of lithofacies was used to identify individual volcanic units described as volcanic flows. Fifth, microscopic petrography of 56 thin sections was conducted to provide detailed data to confirm the presence of flow banding, crystal orientation, phenocrysts, or pyroclastic textures. Sixth, the major and trace element compositions of 47 samples were obtained by X-ray fluorescence at UNESP-Rio Claro and UFPR-LAMIR (Laboratório de Análise de Minerais e Rochas). The major oxides analyzed were: SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, and P_2O_5. Trace elements (present in units of µg/g) analyzed were: Cr, Ni, Ba, Rb, Sr, La, Ce, Zr, Y, Nb, Cu, Zn, Co, V, and Ga. The loss on ignition (LOI) values range from 0.59% to 3.07%. The chemical data were recalculated on an anhydrous basis. The geochemical correlation among the eroded volcanic flows were based mainly on analyses of the TiO_2, P_2O_5, Zr, and Cu content of the rocks, since they are less mobile components (Milner *et al.* 1992).

RESULTS

Weathering processes create widespread regolith, and rock exposures are intermittent due to the wet, mild climate of the Santa Catarina Highlands. In addition, a continuity of outcrops is difficult to establish because erosion has shaped the ancient volcanic flows into isolated plateaus or small inselbergs. In some instances, a

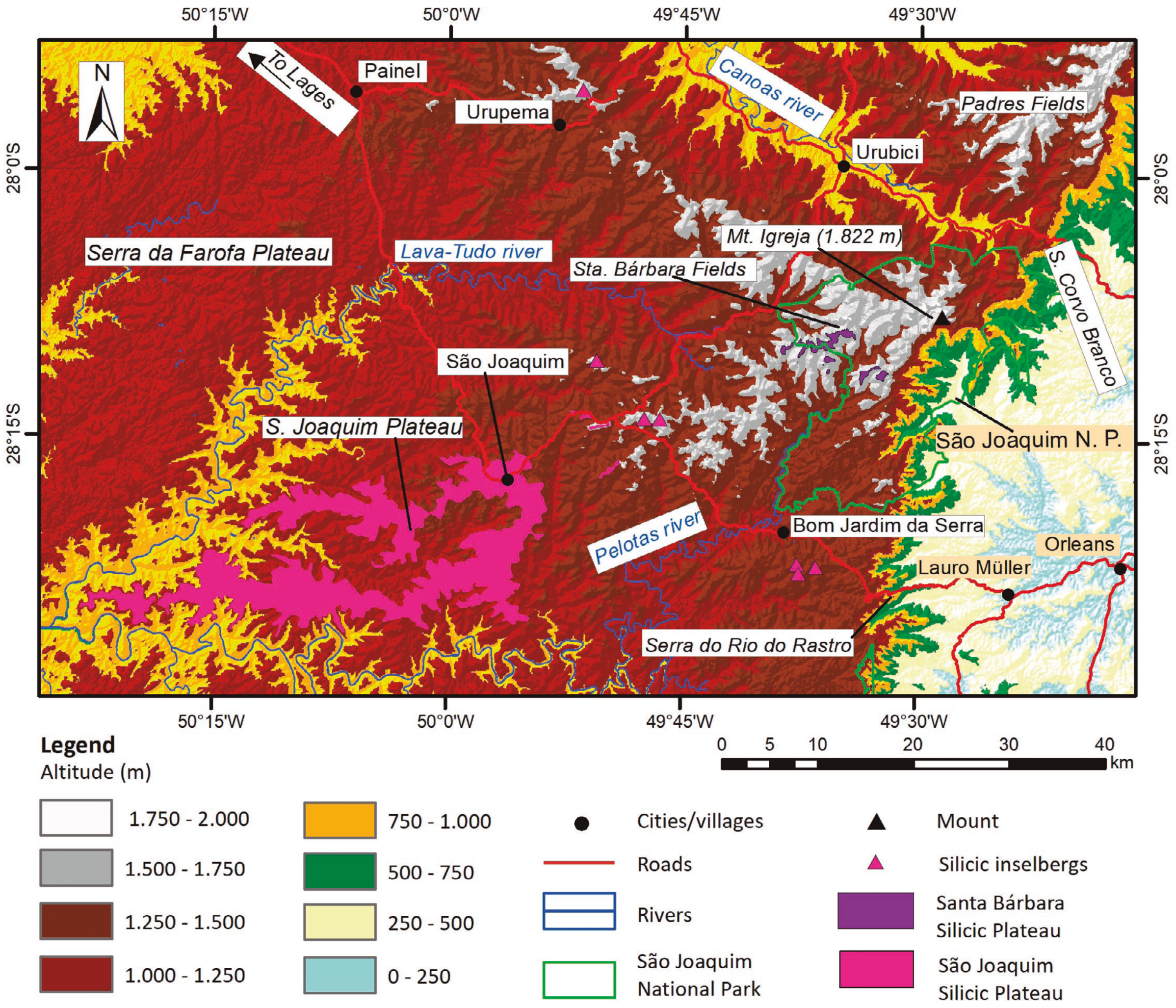


Figure 2. Regional map of the Santa Catarina Southern Highlands shows outcrops of silicic rocks.

tabular silicic volcanic flow eroded into little hills above the underlying silicic flows, giving the false appearance of lava domes (Fig. 3).

The lithofacies provide important evidence regarding the architecture of the volcanic units, from which it is possible to interpret the ancient characteristics of the volcanic flows. Four lithotypes are easily identified in field descriptions: basalt (B), microgabbro (E), silicic rock (D), and pitchstone (P). Lithogeochemistry was used to classify these rocks as dacites, basaltic-andesites, and microgabbros of basaltic composition (Besser 2017). The 21 lithofacies are grouped into three stratigraphic units that are linked to distinct volcanic episodes: a basic volcanic episode, a silicic volcanic episode, and a basic intrusive episode (Tab. 1).

Morphology of silicic lava flows

The dacitic flows are normally extensive (>> 5 km) and thick (~50–100 m), having a tabular geometry with lobate margins. Both small (decameter-scale) and extremely large (kilometer-scale) lobes occur. They are wrapped by meter-scale pitchstone layers (Fig. 4).

Weathered reddish brown pitchstone with oblate amygdales (aP) makes up the basal zone of the silicic flows, and is a few meters to decimeters thick. The geometry of the amygdales indicates flattening by overload (Fig. 5A). The pitchstones are overlaying highly amygdaloidal pitchstone (aaP) facie*s* at the top of the underlying flow along a wavy or completely linear contact. Above this level, horizontal platy jointed dacites (pjD-h) or flow banding dacites (bD) compose a thick layer that extends towards the core of the flow. Hypohyaline to holocrystalline narrow platy jointed dacites (pjD) are observed both in the interior and at the edges of the flows, and they can occupy one third of the total thickness (Fig. 5B). In the central flow, these structures are horizontal or subhorizontal and extend homogeneously for kilometers.

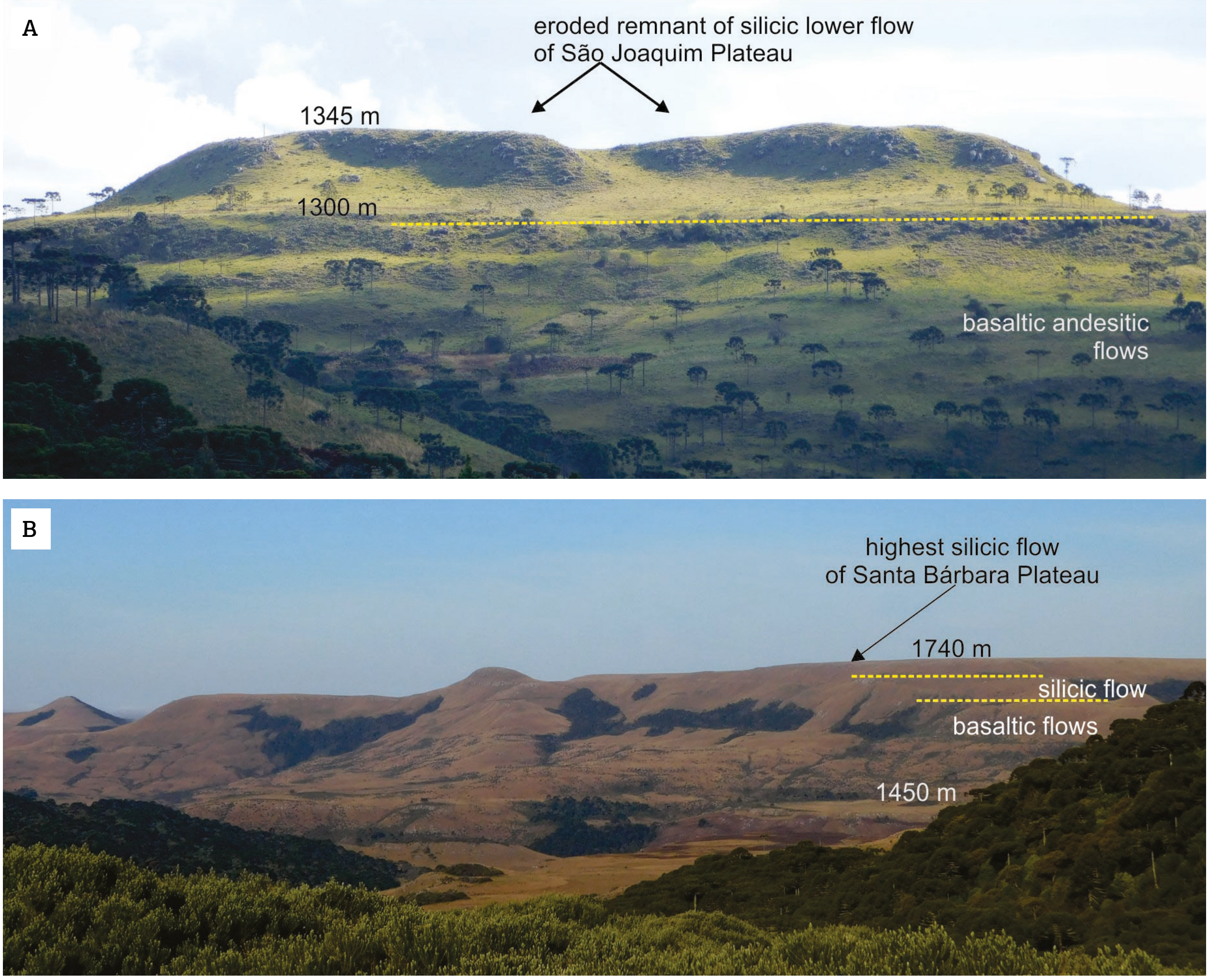


Figure 3. The silicic eruptive sequence forms the plateaus of (A) São Joaquim and (B) Santa Bárbara, where the erosion of tabular lava flows has created a landscape of flat-topped hills, similar to the Etendeka Plateau in Namibia.

Dacites with flow structures and/or banding (bD) facies are in the same architectural position as platy jointed dacites (pjD) and sometimes can be confused with them. In most cases, volcanic banding facies (bD) are not accompanied by any observable flow feature in the thin section (Tab. 2). However, flow structures are locally present, as shown by the orientation of plagioclase or pyroxene crystallites and, rarely, phenocrysts (Fig. 5C). Local meter-scale folds and centimeter-scale contortions are present (Fig. 5D).

Massive and very homogeneous dacites (mD) occupy the flow core, whose maximum thickness can reach 60 m. Crystallinity and devitrification are greater in the flow core (Fig. 6). Toward the top, some aligned zeolite amygdales and small geodes of amethyst are present, indicating ascending palaeoflow (aD).

Table 1. Lithofacies codes, descriptions and interpretations for the rocks of the São Joaquim eruptive sequence in the north segment of the Torres Trough.

Lithofacies	Description	Interpretation
	Facies of mafic intrusive rocks	Shallow intrusions (dykes and sills) with basaltic composition
hjB	Aphanitic to fine phaneritic massive basalt with horizontal polygonal joints	Dyke
vjE	Fine to medium phaneritic massive micrograbbro with vertical joints	Sill
	Facies of silicic volcanic rocks	Tabular and lobate lava flows forming volcanic facies with dacitic composition
aaP	Highly amygdaloidal weathered pitchstone; local breccias and flow banding	Carapace of volcanic foam (vesicular pumiceous zone); posteriorly filled by clay minerals; local autobrecciation; flow margins (mainly top and front)
aP	Weathered pitchstone with oblate amygdales	Basal zone of the flows (inland position)
bP	Banding and/or folded pitchstone	Flow sealant (obsidian layer/lens wrapping the flow core)
mP	Massive pitchstone	Flow sealant (obsidian layer/lens wrapping the flow core)
vjP	Vertical jointed pitchstone	Feeder dyke (?)
gD	Hyaline or lithoidal dacite with large amygdales, vesicles or geodes	Upper flow zone
aD	Lithoidal dacite with sparse amygdales	Top of flow core
mD	Massive lithoidal dacite with salt-and-pepper texture	Flow core
bD	Flow banding dacite	Basal flow zone
fbD	Folded banded dacite	Basal flow zone where flow moved over wavy substrate
pjD-h	Narrow horizontal platy jointed dacite	Basal flow zone
pjD-t	Narrow top-deflected platy jointed dacite	Front flow margin
vjD	Vertical jointed dacite	Flow margin or feeder dyke (?)
	Facies of mafic extrusive rocks	Flows with rubbly pahoehoe, sheet pahoehoe or lobate pahoehoe morphologies; basaltic andesite composition
aaBr	Amygdaloidal basaltic breccia	Upper flow brecciated zone (broken crust)
aaB	Amygdaloidal basalt	Upper flow zone (crust)
mB	Massive basalt	Flow core
aB	Basalt with amygdales	Basal flow zone
fB	Magmatic flow basalt	Basal flow zone
gB	Basalt with giant geodes (> 30 cm)	Upper flow zone

Near the upper zone, hyaline dacites with large vesicles and geodes (gD) are present (Figs. 7A and 7B). Highly amygdaloidal and vesicular pitchstones and breccia facies (aaP) make up the top and front of the silicic flows, which contain ancient volcanic scoriaceous foam and rubbish (Figs. 7C and 7D). Millimeter- to centimeter-scale cavities

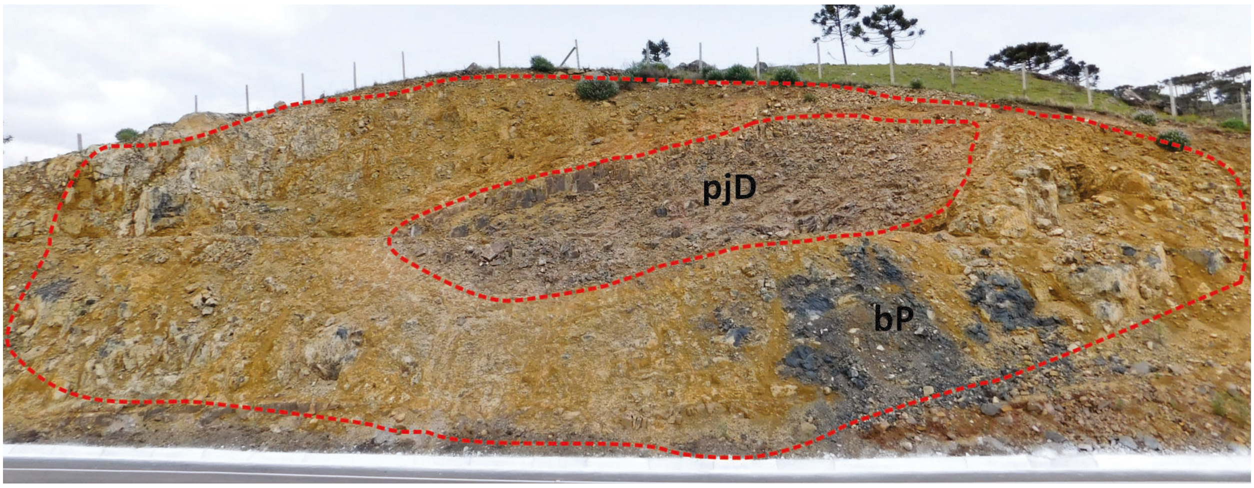


Figure 4. Small lava lobe wrapped by banded pitchstones (bP), with platy jointed dacite (pjD) occupying the lobe core.

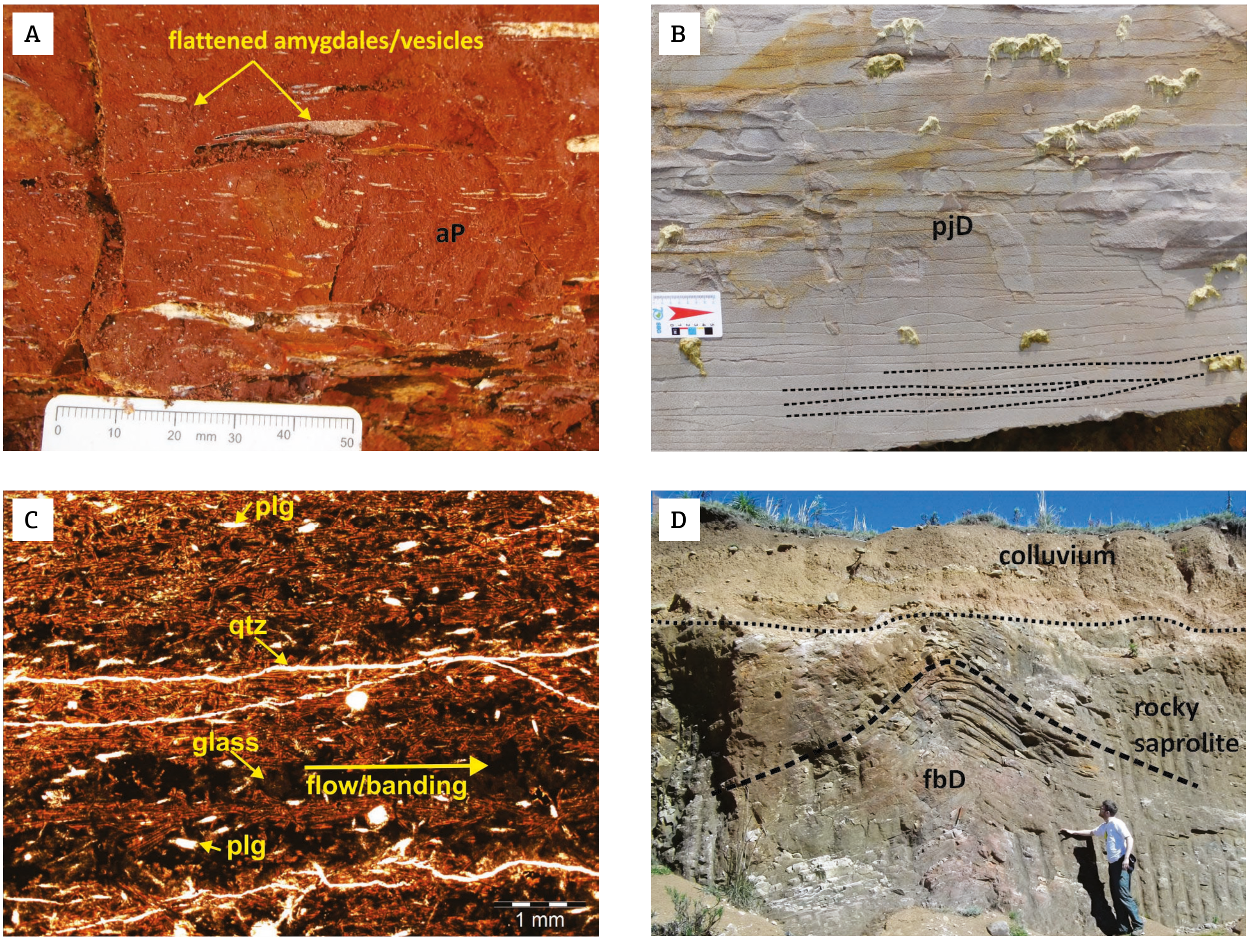


Figure 5. Lithofacies of basal and front zones of the silicic lava flows in the SJP; (A) weathered pitchstone with oblate amygdales (aP); (B) platy jointed dacite (pjD); (C) orthoscopic photomicrography of banded hyaline dacite (bD) with flow banding marked by oriented crystallites and quartz bands; qtz: quartz, plg: plagioclase; (D) folded and banded dacite (fbD).

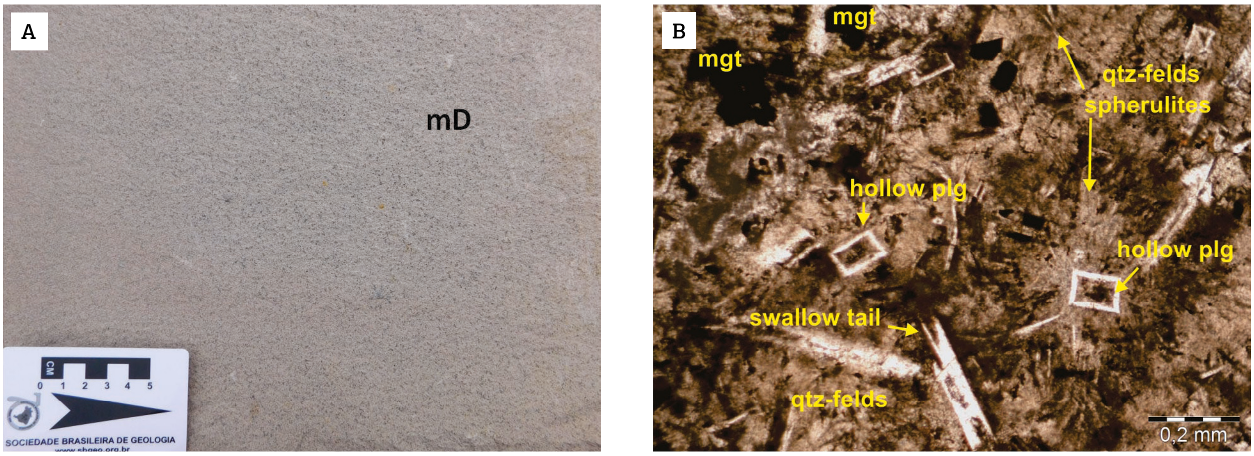
with irregular shapes compose up to 90% of the samples and sometimes are aligned, showing orientation. They are filled by clay minerals, zeolites, and often, quartz. Near the margin of the flow the platy joints deflect to the top of the flow (Fig. 8A). Note that the margin of the current plateau (the shape of the topographic relief), is not the same as the margin of the ancient lava flow.

Unweathered massive pitchstone lenses or fragments can be found within the amygdaloidal facies. In addition, irregularly shaped volcanic fragments are locally observed, which may deflect the flow structure (Fig. 8B). Massive or banded pitchstones (mP/bP) layers are 0.5 to 10 m thick, and they occur in the basal, front and, upper zones of thick flows and also as envelopes surrounding small lava lobes (Figs. 8C and 8D; Fig. 4). When massive, the pitchstones resist to weathering and, therefore, they outcrop as positive expressions of relief, locally marking the margins of the volcanic flows. Massive pitchstone layers are preserved as a black grease glass. However, it is common to find an orange to yellowish vesiculate pitchstone saprolite as a result of weathering. The morphology of the silicic volcanic flows and current plateaus in the São Joaquim region are summarized, and examples are shown, in Figure 9.

Table 2. Petrographic features of the silicic lithofacies of the SJP.

Facies	Gran. (mm)	Glass (%)	Plg (%)	Cpx (%)	Qtz-fds (%)	Mgt (%)	Phenocryst.	Orientation/ banding	Devitrif.	Quenching/ Low diffusion*
aaP	0.05–01	60–80	10–15	0–5	0–5	1–5	local plg	magmatic flow	locally	common
bP	~0.2	~70	~20	~4	0	~4	absent	no	rare	common
mP	0.05–01	60–70	20–30	3–5	0	5	absent	no	locally	locally
gD	< 0.05–0.2	~50	~40	~8	0	~2	plag	no	locally	pervasive
aD	0.1–0.5	25–50	20–40	5–10	9–40	5–7	local cpx	no	locally	pervasive
bD/ fbD	0.1–1	25–50 (70)	15–35	2–10	0–40	3–10	local (< 1 mm) plg/cpx	magmatic flow/ comp. band.**	common	common
pjD	0.05–05	30–50	25–30	8–10	8–30	5–7	local plg (0.5 mm)	no	common	rare
mD	0.1–0.5	15–40	15–40	5–10	10–40	5–10	rare (1 mm) plg/cpx	no	pervasive	common

Gran.: granulometry; plg: plagioclase; cpx: clinopyroxene; qtz-fds: quartz-feldspar aggregates; mgt: magnetite; phenocryst.: phenocrystals; devitrify.: devitrification features such as spherulites; *hollow crystals, swallowtail terminations: quenching/low diffusion rates; **only part of the rocks described in the field as *banded* dacite indeed shows true banding in the thin section: magmatic flow/compositional banding.



qtz: quartz; plg: plagioclase; mgt: magnetite; natural light.

Figure 6. Flow core; (A) massive lithoidal dacite (mD) and (B) photomicrographiy showing hollow and swallow tail plagioclase crystals, quartz-feldspar devitrification aggregates within spherulites.

Lithogeochemistry and stratigraphy

The samples from mafic lava flows are classified as basaltic andesites in the TAS diagram (Le Maitre *et al.* 1989) whereas those from shallow intrusions show a basaltic composition (Fig. 10A). The silicic rocks are classified as low-TiO_2 dacites, mainly of the Caxias do Sul subtype of the Palmas Type (Nardy *et al.* 2008). A variation diagram for TiO_2 × Cu shows an increase in copper as the locations from which samples were taken move up in the stratigraphy. Three chemical groups are linked to the (1) lower, (2) upper, and (3) uppermost levels of the silicic succession in the São Joaquim and Santa Bárbara Plateaus (Figs. 10B and 11).

A voluminous and thick basaltic-andesite lava pile composed mainly of rubbly pahoehoe flows composes the framework of the SJP (Fig. 11). These rocks predominately have a low TiO_2 content (~1.34–1.55%) and Sr/Y ratios > 7.5 μg/g (Tab. 3). The last upper flows that are in contact with the eastern part of the SJP and other silicic inselbergs toward the east are thinner and have typical pahoehoe structures. These lava flows have low TiO_2 (~1.75%) and low Sr/Y ratios (< 6.5 μg/g), distinguishing them from the western and lower mafic flows (Fig. 11).

The lower level of the silicic sequence is apparently composed of a single large (> 37 km) and thick (~125 m) flow that makes up the base of the SJP (Fig. 11). It has highly amygdaloidal upper zones, frequently contains large vesicles and geodes (20–30 cm), and has pitchstone layers. In its thick basal zone, oriented clinopyroxene phenocrysts and evidence of magmatic flow are present. Well-developed platy joints and indications of magmatic flow suggest a westward lava paleoflow. The main geological section of this flow was obtained in a quarry located next to road SC-114 (Fig. 12). This lower flow differs from the upper flows by having a high SiO_2 (69–70%), low TiO_2 (0.86–0.89%), low P_2O_5 (0.26–0.28%) and low Cu (< 50 μg/g) content (Tab. 3).

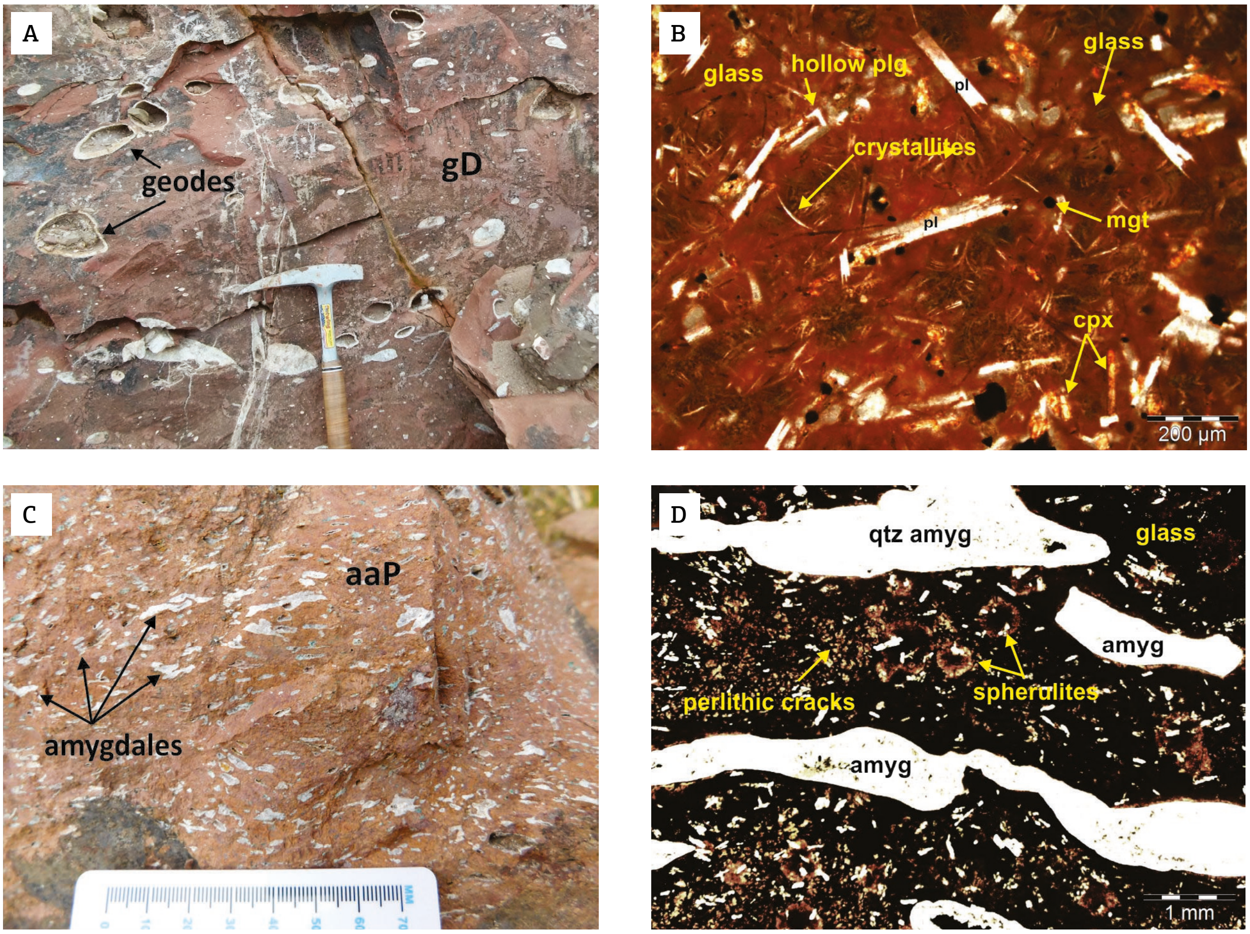


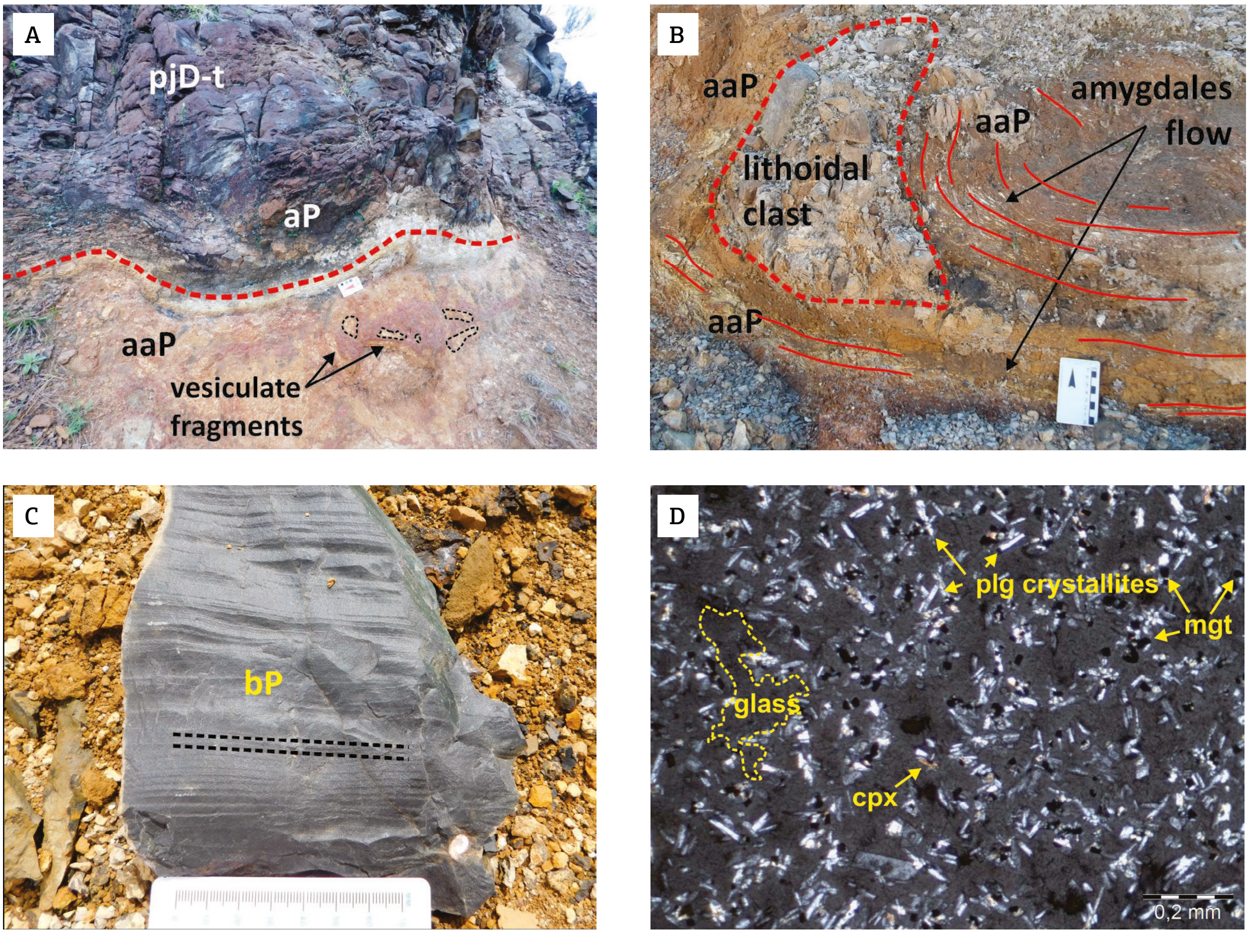
Figure 7. Upper flow zone; (A) hyaline dacite with large vesicles and geodes (gD); (B) orthoscopic photomicrography of hyaline dacite (gD) where hollow and swallowtail plagioclase can be distinguished among a glassy matrix; plg: plagioclase, cpx: clinopyroxene, mgt: magnetite; (C) upper flow zone with weathered amygdaloidal pitchstone (aaP); (D) natural light photomicrography of highly amygdaloidal pitchstone (aaP) where it is possible to distinguish perlithic cracks and spherulites in the altered glass; amyg: quartz amygdales.

The upper silicic stratigraphy is comprised of at least six smaller flows in the SJP and surrounding areas (Fig. 11). The flows are characterized by an increase in vesiculation at the top, with extremely amygdaloidal upper zones and flow banding. The core is devitrified, and the basal zones show laminar flow, flow banding, and, rarely, autobreccias. Narrow platy joints are widespread. Pitchstones layers or lenses wrap the units. These upper flows differ from the lower flow by having a lower SiO_2 (66–70%) and higher TiO_2 (0.92–1.01%), P_2O_5 (0.28–0.31%), and Cu (62–78 µg/g) content (Tab. 3).

Variations in lateral thickness of silicic flows are not significant. Nevertheless, lobate margins are narrower and more branched than the inner zones. Both are enveloped by glassy layers. The total maximum thickness observed is about 140 m, and an average thickness of 100 m is assumed. Therefore, the total remaining silicic volume of the SJP is about 27 km^3.

The upper volcanic flow of the Santa Bárbara Plateau in the north of São Joaquim National Park composes the uppermost silicic unit in stratigraphy of the southern Santa Catarina highlands (28°10’53”S;49°32’42”W; 1,720 m). It is a tabular 250-m-long and 30-m-thick remnant of a low TiO_2 (1.05%) and high P_2O_5 (0.33%) and Cu (97 µg/g) dacitic flow of the Anita Garibaldi subtype of the Palmas Type (Tab. 3). It overlaps other dacitic flows of the Caxias do Sul subtype.

Small sills and dykes of basaltic composition intrude the silicic sequence or between silicic and mafic flows. They have a high TiO_2 (3.6–3.9%) content and Ba/Y ratios > 14 µg/g. Some low TiO_2 (1.39–2.05%), high Ti/Zr (82–97 µg/g) and low Zr/Y (2.6–3 µg/g) dikes with meter-scale thickness and a N-S orientation have been mapped and cross the silicic sequence in both the SJP and SBP (Tab. 3).



plg: plagioclase; cpx: clinopyroxene; mgt: magnetite.

Figure 8. Flow margins: (A) in front of the flow zone with highly amygdaloidal weathered pitchstone and autobreccia (aaP) overlaid by aP lithofacies (which is overlaid by dacites with top-deflected platy joints (pjD-t)); (B) dacitic lithoidal clasts deflecting amygdale flow (aaP); (C) banded pitchstone flow sealant (bP); (D) orthoscopic photomicrography of massive pitchstone where crystallites can be observed in a glassy matrix.

DISCUSSION AND CONCLUSIONS

The silicic eruptive sequence of the northern segment of the Torres Trough in the southern Paraná LIP is comprised of extensive units emplaced by voluminous lava flows. The SJP is a remnant relief feature formed by eroded dacitic flows, some of them overlaid and others with lateral contacts. The residual volume of the entire plateau is about 27 km^3.

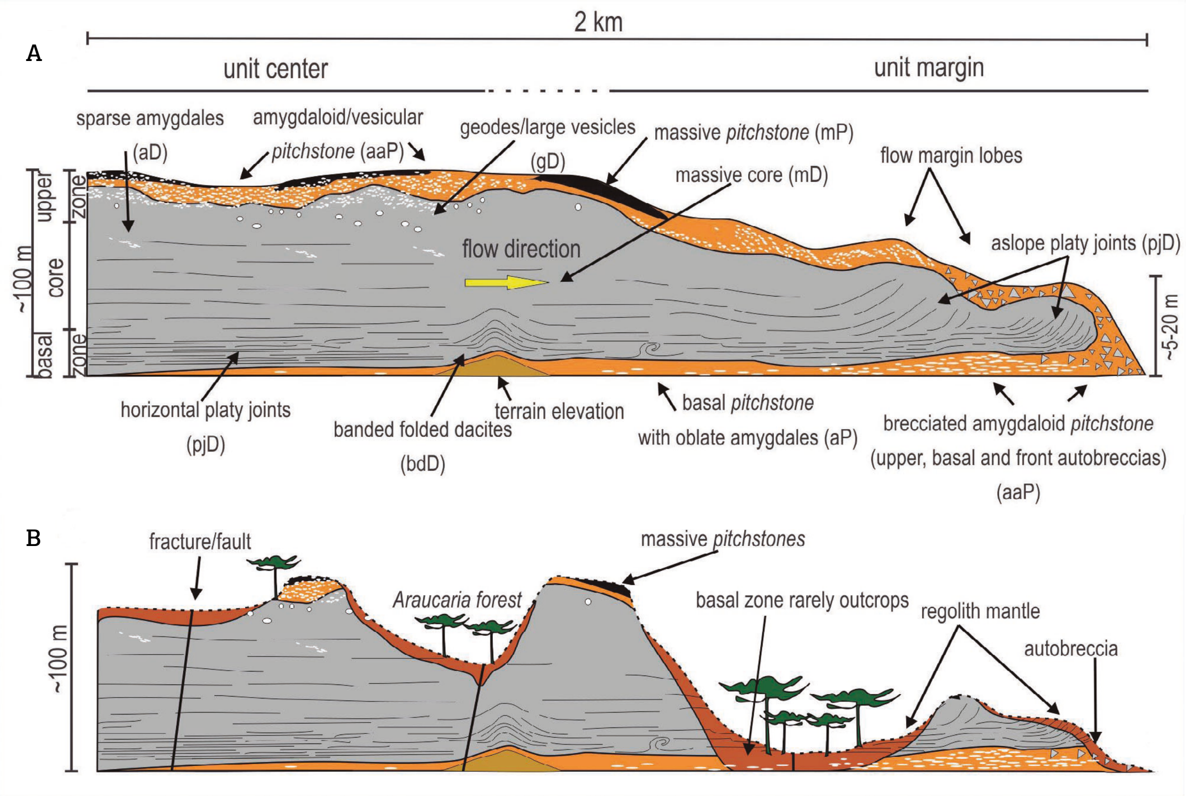


Figure 9. 2D model of profiles of silicic volcanic flows; (A) rebuilt morphology of dacitic flows and (B) current configuration of volcanic flow remnants in the São Joaquim Plateau.

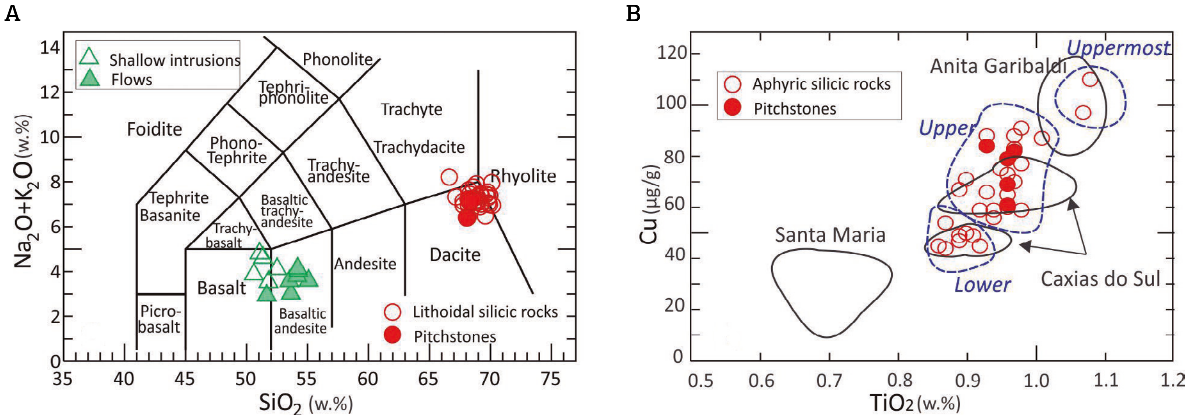


Figure 10. (A) Classification of São Joaquim eruptive sequence rocky samples according to the TAS (total alkalis x silica) diagram of Le Maitre et al. (1989) for volcanic rocks (N = 55); (B) variation diagram showing the distribution of silicic rocks in the São Joaquim region (lower, upper, and uppermost stratigraphic levels) according to Cu and TiO_2 content (black line circles based on Marsh et al. 2001 and Garland et al. 1995 for low-TiO_2 silicic rocks of the PEIP).

In comparison, the dacitic Chao Flow in northern Chile has a volume of 26 km^3. However, it is a single well-preserved porphyritic lava coulée that extends for 14 km and has a flow front ~400 m high (Silva *et al*. 1994). The dacitic lavas of the SJP flowed uncommonly long distances (> 10 km) despite their acidic composition (66–70% SiO_2).

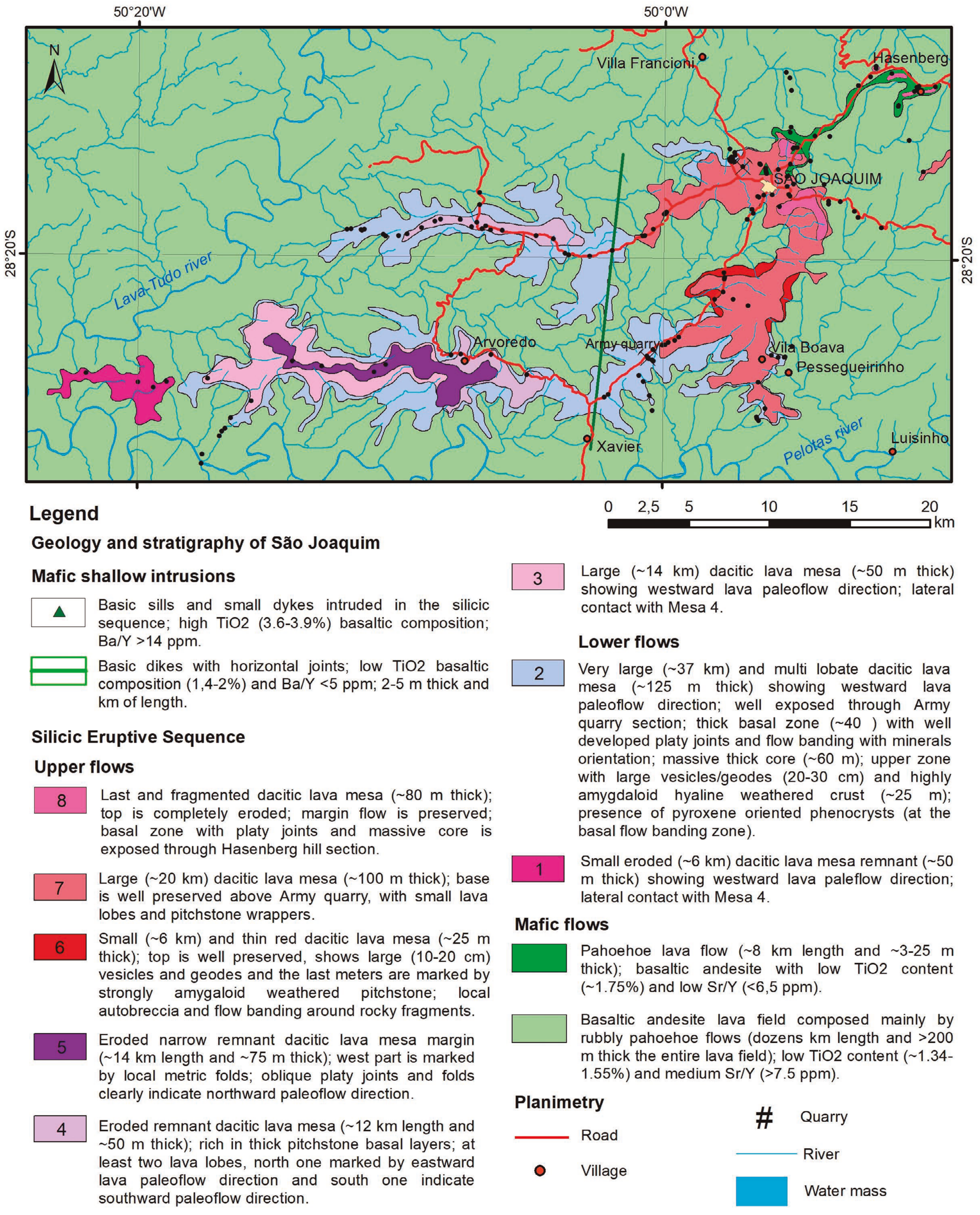


Figure 11. Geological map of the São Joaquim eruptive sequence, showing silicic volcanic flows and some basic volcanic features, such as dikes and sills.

They are an exception in this type of volcanism, with an aspect ratio even larger than that of the Chao Flow (Walker *et al.* 1973). The unusual Snake River-type lithofacies association also includes rhyolitic lavas with large aspect ratios (1:100) that reach 40 km in length and are ~100–400 m thick (Branney *et al.* 2008). The Bracks Rhyolite of the Trans-Pecos in Texas covers 1,000 km^2 as a single tabular body that is 35 km long and ~100 m high (Henry *et al.* 1990). The Keweenawan Plateau (USA) and Gawler Range (Australia) are also examples of volcanic fields that are composed of extensive silicic lava flows (Green & Fitz III 1993, McPhie *et al.* 2008).

The internal architecture and geometry of the SJP silicic lava flows follow a pattern (Fig. 13). Basal zones are formed by pitchstones with oblate amygdales. These pitchstones are a record of the basal glassy volcanic layer formed by the rapid cooling of lava at the surface. They would have served as a "mat" that provided a foundation for the drainage of the rest of the lava and insulated the lava above it. Platy jointed or flow banded dacites are also found in basal zones of the flows. Platy joints are interpreted as weakness surfaces of the rock that are coincident with the cooling isotherms of the volcanic flow. It is possible that some movement of the lava occurred as the solidification process began. During flow emplacement, the core of the lava body would have a subtly greater velocity than its lower edge. This difference in lava velocity would have generated shear surfaces that formed platy joints (Fig. 13). The expansion direction of the lavas is inferred from the attitudes of the joints, which deflect toward the top of the flows next to the margin of the volcanic body, as is observed in the Badlands Rhyolite (USA), which is also a silicic lobate unit and which covers 11,000 km^2 (Manley 1992, 1996). The meter-scale folds of the SJP are interpreted as the response of the lava flow to terrain protuberances, or in some places as a roughness surface of the lava body, as is observed in Chao (Guest & Sánchez 1969, Silva *et al.* 1994).

Dacitic vesiculated fragments found at the front of the flows are interpreted as resulting from the autobrecciation of

Table 3. Lithogeochemistry of the São Joaquim eruptive sequence (UTM Zone 22J).

Sample code	Mafic extrusive sequence			Lower silicic sequence				Upper silicic sequence					Upper-most silicic	Mafic intrusive	
	SJ-45	SJ-77	SJ-107	SJ-05	SJ-58	SJ-82	SJ-241	SJ-15-B	SJ-32	SJ-54	SJ-108	SJ-120	SJ-240	SJ-18	SJ-121
Geometry	rubbly Flow	rubbly Flow	pahoehoe Flow	Flow 2	Flow 2	Flow 2	Flow 2	Flow 7	Flow 6	Flow 4	Flow 8	Flow of SBP Base	Flow of SBP	Sill SJP	Dyke SBP
UTM(E)	569330	586588	613795	602149	605540	578603	597107	602955	601777	587302	613795	637354	642911	604384	637350
UTM(N)	6853221	6869490	6876034	6871485	6859252	6867235	6859174	6871101	6864509	6859430	6875839	6883847	6881874	6870993	6883840
Altitude m	821	1069	1534	1347	1231	1106	1199	1382	1271	1180	1560	1657	1704	1404	1655
SiO_2	53.58	53.89	53.13	69.18	68.96	68.44	68.27	67.79	66.70	66.37	67.44	67.84	67.81	50.38	51.46
TiO_2	1.53	1.40	1.71	0.85	0.87	0.89	0.88	0.96	0.92	0.95	0.96	0.96	1.05	3.57	1.38
Al_2O_3	13.86	13.49	12.52	12.16	12.67	12.85	12.65	13.02	12.87	12.80	13.12	12.48	13.09	13.28	13.41
Fe_2O_3	12.84	12.94	15.34	4.89	5.66	5.69	5.68	6.29	5.79	5.09	5.73	5.57	5.60	14	13.47
MnO	0.19	0.20	0.18	0.11	0.11	0.10	0.11	0.11	0.10	0.11	0.10	0.11	0.08	0.17	0.19
MgO	4.52	4.70	3.39	1.34	1.18	1.14	1.26	1.35	1.16	1.30	0.98	1.17	0.89	4.14	5.77
CaO	8.42	8.46	7.64	2.88	2.97	1.82	2.93	3.32	3.82	3.49	2.16	2.41	2.61	7.79	9.96
Na_2O	2.90	2.91	2.96	3.02	2.95	2.37	2.94	3.05	2.91	3.68	3.07	3.51	3.10	2.93	2.74
K_2O	0.87	1.20	1.04	4.30	4.04	4.55	4.07	3.91	3.38	3.37	4.12	3.81	3.93	1.82	0.77
P_2O_5	0.22	0.21	0.27	0.27	0.26	0.26	0.26	0.29	0.29	0.28	0.27	0.28	0.33	0.56	0.17
LOI	1.12	0.62	1.82	1.00	0.52	2.12	0.87	0.49	2.08	2.57	2.04	1.85	1.40	1.35	0.67
Total	100.06	100.01	99.99	99.99	100.19	100.23	99.91	100.56	100	100	99.99	100	99.90	99.99	100
Cu	144	146	171	45	44	49	49	60	59	82	59	77	97	99	98
Ni	26	30	19	9	5	7	4	9	7	8	7	6	8	40	51
Ba	347	356	366	624	609	819	568	583	528	544	637	644	633	607	143
Rb	53	40	30	140	170	188	163	156	76	134	144	140	162	36	17
Sr	219	229	202	148	122	90	118	129	191	166	118	137	116	448	172
Zr	148	128	143	230	252	274	256	258	244	234	235	232	289	218	86
Y	29	28	33	35	33	45	31	33	37	36	72	47	41	32	28
Nb	17	10	11	18	24	25	24	22	23	20	13	15	26	24	5
Ti/Zr	63	66	73	-	-	-	-	-	-	-	-	-	-	99	97
Ba/Y	12	13	11	-	-	-	-	-	-	-	-	-	-	19	5
Sr/Y	7.6	8.1	6.2	-	-	-	-	-	-	-	-	-	-	14.1	6.1

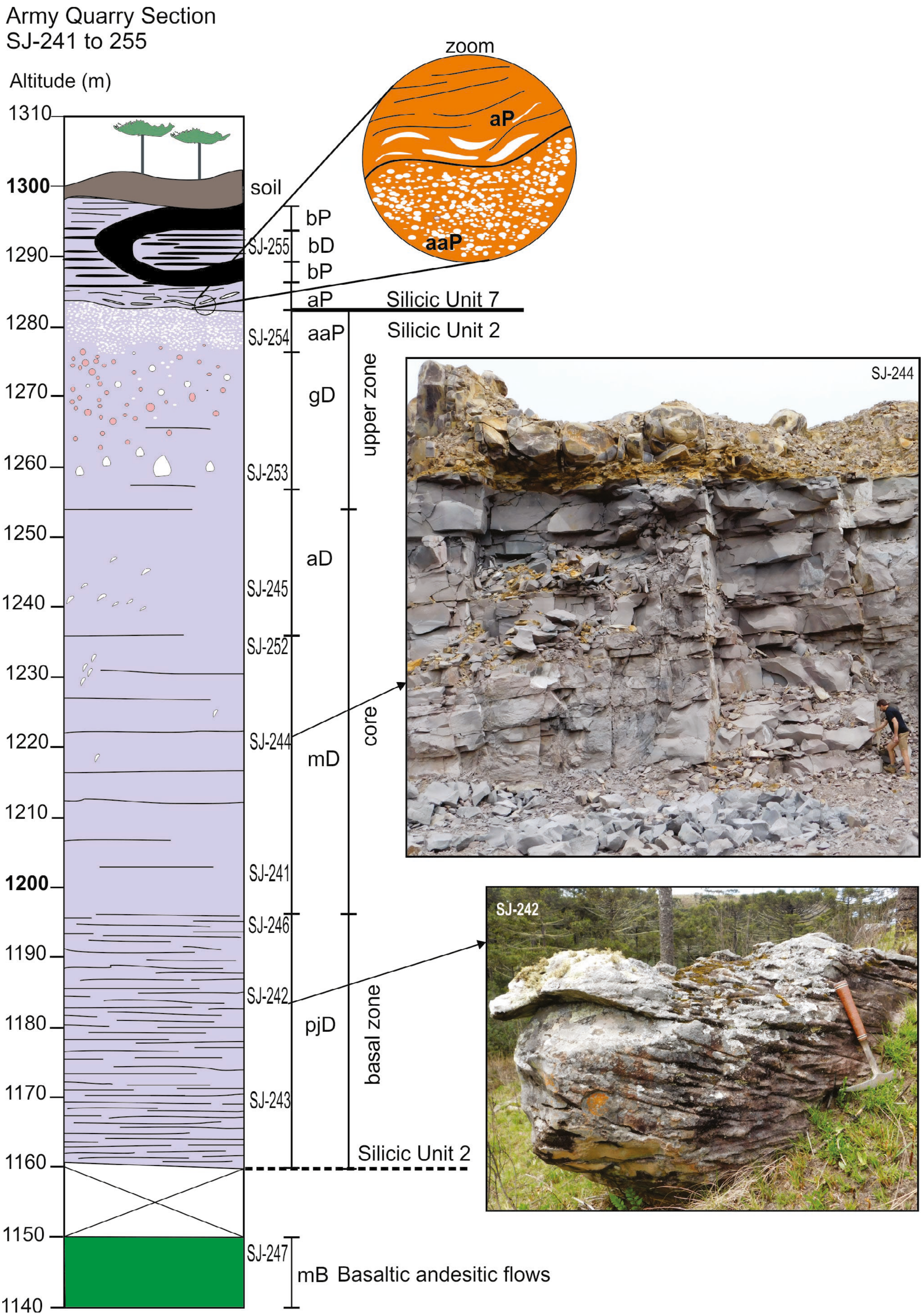


Figure 12. Geological profile of the lower eruptive sequence; lithofacies codes as in Table 1.

the lava. These represent the aprons of the silicic flows. A set of clasts was generated from the fragmentation of the outer part of the solidified lava stacked at the edges of the moving volcanic body, as has also been observed in the Bracks (Henry *et al.* 1990) and Badlands (Manley 1992). In the SJP, autobreccias are rare, perhaps because of the extent and long-term thermal history of the flows, which led to the autodigestion of the breccias (Manley 1992). The core of the flows is massive, hypocrystalline and devitrified. Wide (1–2 m) sub-horizontal joints common in the massive core are interpreted as relief joints caused by erosion decompression, as described by Faust (1978) in the Watchung Basalts of New Jersey. Toward the top of the unit, sparse amygdales begin to appear, indicating the flow and escape of gases, which is when large vesicles and geodes become abundant. The upper zone and margins of the lava body would have been sealed by highly amygdaloidal obsidian layers. Massive obsidian envelopes the small and narrow lobate edges of the volcanic flows (Fig. 13). Both Nardy *et al.* (2008) in the Paraná LIP and Milner *et al.* (1992) in the Etendeka Group have identified orange to yellowish saprolites resulting from the weathering of volcanic glasses.

The effusive origin of the rocks of the SJP is suggested by the following 13 characteristics. First, the geometry of the flows indicates thick (100–140 m), extensive (~2 to 40 km) and tabular lobate flows that are also associated with smaller lava lobes enveloped by layers of volcanic glass. Second, large aspect ratios (1:200 to 1:400) are compatible with high temperature dacitic lavas, similar to those in other volcanic fields such as the Snake River Plain (Branney *et al.* 2008). Third, an irregular basal contact was formed by a layer of volcanic glass containing oblate amygdales, and which is devoid of pyroclastic features. Fourth, horizontal platy joints are present at the base of flows and are deflected toward the top near the margins. Fifth, magmatic flow structures have oriented phenocrysts. Sixth, large geodes are present. Seventh, the upper zones are highly amygdaloidal. Eighth, the restricted occurrence of autobreccias can be explained by the autodigestion of the breccias during advance of the lavas (Manley 1992). Ninth, amygdale flow is associated with brecciated fragments. Tenth, the presence of unoriented crystallites, minerals with skeletal habits, and hollow crystals reflect rapid crystallization (at the margins) or low diffusion rates (in the flow core), which did not allow complete crystallization of most minerals (Crawford 1973, Waters *et al.* 2015, Zhang 1999). These features reflect crystallization from a liquid and therefore are only found in lavas (Henry & Wolff 1992). Eleventh, highly vesiculated brecciated fragments that are locally present were probably produced in a distal scenario where the lavas were already more viscous. Twelfth, internal chemistry is homogeneous in each flow. Thirteenth, strongly or weakly welded ignimbrites, tuff layers, or any pyroclastic features are absent.

The origin of the extensive SJP flows is attributed to the emplacement of hot lavas with a low content of pre-eruptive volatiles. The presence of pyroxene crystals attests to the anhydrous and hot nature of these lavas, which had lower viscosities than those of classic silicic lavas. The low pre-eruptive volatile content would both prevent explosive eruptions and limit cooling by loss of volatiles (Manley 1996). However, probably the most important characteristic leading to the extent of the lava flows was the large and continuous volume of erupted magma. In addition, moderate to rapid effusive rates and the high heat insulation capacity of these lavas also contributed to the growth of the lava body. Henry & Wolff (1992) consider the extravasation rate to be the most important factor in determining the total length

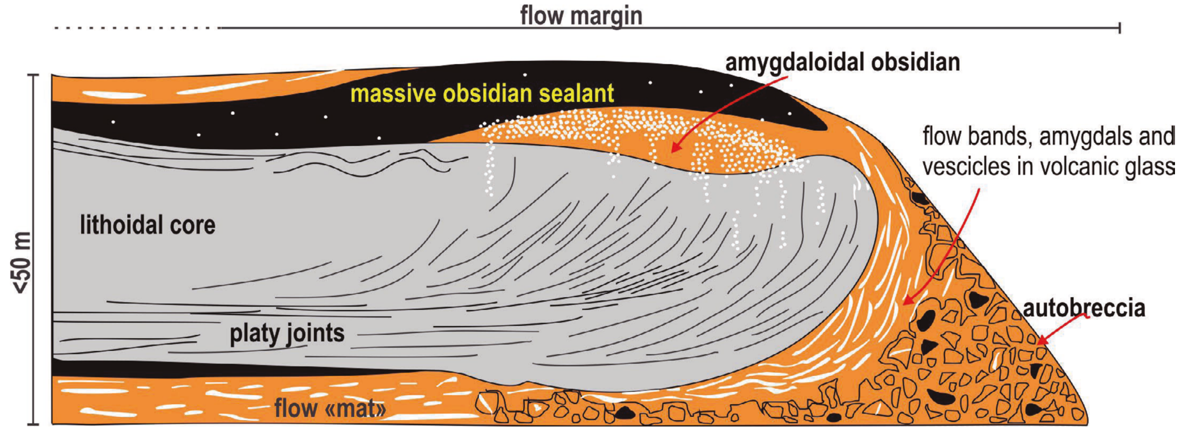


Figure 13. Front of the flow zone showing platy joints deflected toward the top.

Table 4. Stratigraphy of the Torres Trough.

Stratigraphy of the northern segment of the Torres Trough		Physical features	Lithogeochemistry (magma types) Peate *et al.* 1992[a], Nardy *et al.* 2008[b] and Licht 2016[c], this study[d]	Correlation Rossetti *et al.* 2017
Mafic intrusive	*Shallow intrusions*	(1) Sills and dykes (2) Dykes (metric thickness)	(1) TiO_2 3.6–3.9%, Ba/Y > 14 µg/g Urubici[a], Type 4[c] (2) TiO_2 1.39–2.05%, Ti/Zr 82–97 µg/g, Zr/Y 2.6–3 µg/g Esmeralda[a], Type 1(S)[c]	-
Silicic extrusive	*Uppermost* Top of SB Plateau	Tabular lava flow	TiO_2 1.05%, P_2O_5 0.33%, Cu 97 µg/g Anita Garibaldi[b]	Palmas Fm.
	Upper SJ Plateau	Many extensive tabular and lobate lava flows (~25 – ~100 m thick)	SiO_2 66–70%, TiO_2 0.92–1.01%, P_2O_5 0.28–0.31%, Cu 62–78 µg/g Upper Caxias do Sul[d]	
	Lower Base of SJ Plateau	Thick extensive tabular lava flow (~125 m)	SiO_2 69–70%, TiO_2 0.86–0.89%, P_2O_5 0.26–0.28%, Cu < 50 µg/g Lower Caxias do Sul[d]	
Mafic extrusive	*Upper*	Thin pahoehoe flows	TiO_2 ~1.34–1.55%, Sr/Y > 7.5 µg/g Esmeralda[a], Type 1(S)[c]	Esmeralda Fm.
	Lower	Thick rubbly pahoehoe flows	TiO_2 ~1.75%, Sr/Y < 6.5 µg/g Gramado[a], Type 1(S)[c]	Vale do Sol Fm.
Mafic extrusive	*Lowermost* Probably outcrops in Serra do Rio do Rastro cliffs at elevations of 700 to 1,000 m.		-	Torres Fm.

of a lava flow. Large-scale rhyolites may indeed have been emplaced in the same manner as intermediate blocky lavas (Manley 1992). In the Badlands, the cooling of flows 100–300 m thick was slow and was further slowed down by a vesicular carapace and the evolution of latent heat, which suggests that large and thick lava flows could remain active for several decades (Manley 1992, 1996). In the SJP, the glassy layers at the base and top of the flows acted as insulators while the lava continued to flow through the center, thus prolonging the flow time and distance traveled by lava.

The SJP lavas were probably emplaced from extensive fissures, possibly tens of kilometers long and organized in bundles that could extend hundreds of kilometers to the Etendeka plateau. Eruptions took the form of lava fountains or the continuous effusion of lavas from fissure vents. These eruptions created overlying and interdigitated flows. The rarity of volcanic conduits feeding this silicic fissure volcanism can be explained by the resumption of basic volcanism, which would have taken advantage of the feeder structures in order to load new lava flows on the surface, above the silicic succession. These have now been eroded. The stratigraphic position of the mafic intrusions shows they could have fed high- and low-TiO_2 lava fields on the surface above the São Joaquim and Santa Bárbara Plateaus.

The correlation of the isolated silicic plateaus present throughout the highlands allows the reassemblage of a volcanic field covering at least 8,000 km² and with a possible volume of 1,200 km³ of Palmas-Type silicic rocks. This silicic level and its basaltic andesitic framework can be correlated to the Vale do Sol, Esmeralda and Palmas formations of the southern and main valley segments of the Torres Trough (Table 4, Rossetti *et al.* 2017) and to the Etaka Subgroup of the upper southern Etendeka Group (Miller 2008). The set of structures, textures, and features found in the São Joaquim Plateau and surroundings areas corroborates the hypothesis of a genesis from high temperature lava flows. Large volcanic flows produced by voluminous and continuous eruptions formed the volcanic foundation of the São Joaquim region and possibly of the entire upper stratigraphic level of the Torres Trough in the southern tablelands of Santa Catarina during the Cretaceous volcanism of the Paraná-Etendeka Igneous Province.

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