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ARTICLE

The Mato Perso Conduit System: evidence of silicic magma transport in the southern portion of the Paraná-Etendeka LIP, Brazil

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ABSTRACT: *The Mato Perso Conduit System is described from a ~ 120 km² area in south Brazil exposing silicic volcanics of the Paraná-Etendeka LIP. A volcanic succession is defined by basaltic flows covered by flat-lying oxidized vitrophyres, banded vitrophyres cutting the lower lavas and grey flat-lying vitrophyres covering all the units. Flow morphologies determined by the recognition of structures, textures, and vesicle distribution were observed. Oxidized vitrophyres display massive flat-lying banded cores and flow tops from vesicular to frothy. Grey flat-lying vitrophyres have sharp contacts in the top of both basalt flows and oxidized vitrophyres, locally exhibit basal breccia and have a flat-lying foliation. Conduits are represented by banded vitrophyres and breccias, which outcrop in a 6 km wide, NW-SE oriented segment downthrown by normal faults towards the Antas River. The interpretation of the units on the geological map scale indicates intrusive contact relations. Recognition of dike-like structures in banded vitrophyres and dykes of oxidized vitrophyre are evidence of felsic magma transport. Based on field observations, we propose the emplacement of subaerial oxidized and grey vitrophyres fed by a fault-related conduit system. Sustained high temperature magmatic systems ensure the silicic lavas have a low viscosity and travel great distances.*

KEYWORDS: *Large Igneous Province; magma transport; conduit system; Paraná-Etendeka LIP; Paraná Basin.*

INTRODUCTION

The Paraná-Etendeka Large Igneous Province (LIP) is exposed primarily in South America (~90 outcrop area%), with a minor portion in the African continent (~10 outcrop area%). It erupted at ~134–131 Ma (Ernesto *et al*. 1999, Thiede & Vasconcelos 2010, Janasi *et al*. 2011, Florisbal *et al*. 2014) in an intraplate setting, after a long period of marine and continental sedimentation in the Paraná Basin (for the South American counterpart). This basin is considered a large intracratonic syneclise developed in western Gondwana (Allen & Armitage 2012). In the Cretaceous, the Andean chain uplifting started in the west of this supercontinent, while continental extension accompanied by voluminous volcanism were dominant within the continent (Milani & Ramos 1998). Those episodes were followed by rifting and seafloor spreading, leading to the opening of the South Atlantic Ocean. In South America, this LIP occupies approximately, 917,000±15,000 km² (Frank *et al*. 2009) of a 1,700 m-thick tholeiitic rock association (Melfi *et al*. 1988) with basic to intermediate volcanics dominating (97.5% in volume) over silicic volcanics (2.5% in volume).

The plumbing system which transported magma and fed the volcanic pile on the surface is represented by Ponta Grossa (NW-SE), Santos-Rio de Janeiro (ENE-SSW) and Florianópolis (NNE-SSW) dyke swarms. These intrusive systems are the main exposures of diabase dykes and sills throughout the Paraná Basin (Melfi *et al*. 1988, Raposo & Ernesto 1995, Peate 1997, Raposo *et al*. 1998, Florisbal *et al*. 2014) and are located north of Torres Valley (Fig. 1). In the southern part of the basin, the mafic dykes cutting the sedimentary rocks have NE-SW preferred orientation.

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These dykes trend NNW-SSE when cutting the volcanic pile (Sarmento *et al.* 2017).

Silicic dykes are less common among the intrusive units. An example is the Florianópolis dyke swarm, where they are described as ~70–80 m thick porphyritic vitrophyre dykes trending NNE-SSW and NNW-SSE (Marteleto *et al.* 2016). Composite dykes with basaltic andesite mingled with rhyodacite also occur (Tomazzoli & Lima 2006). The intrusive felsic magmatism in the south of this basin is represented by one ~1 m thick occurrence of rhyodacite dyke in the Praia Grande — Cambará do Sul profile (Piccirillo *et al.* 1988). Assuming an average thickness of 120 m for felsic units in southern Brazil (maximum of 400 m, e.g. Rossetti *et al.* 2017) and an estimated volume of 12,000 km^3, one should expect a larger volume of silicic intrusive in the LIP.

The purpose of this work was to present a mapped area of the northeast of the state of Rio Grande do Sul, which exposes different silicic vitrophyre units previously recognized only as fragments within the conduits (e.g. Lima *et al.* 2012, 2018, Simões *et al.* 2017). Field relationships, internal

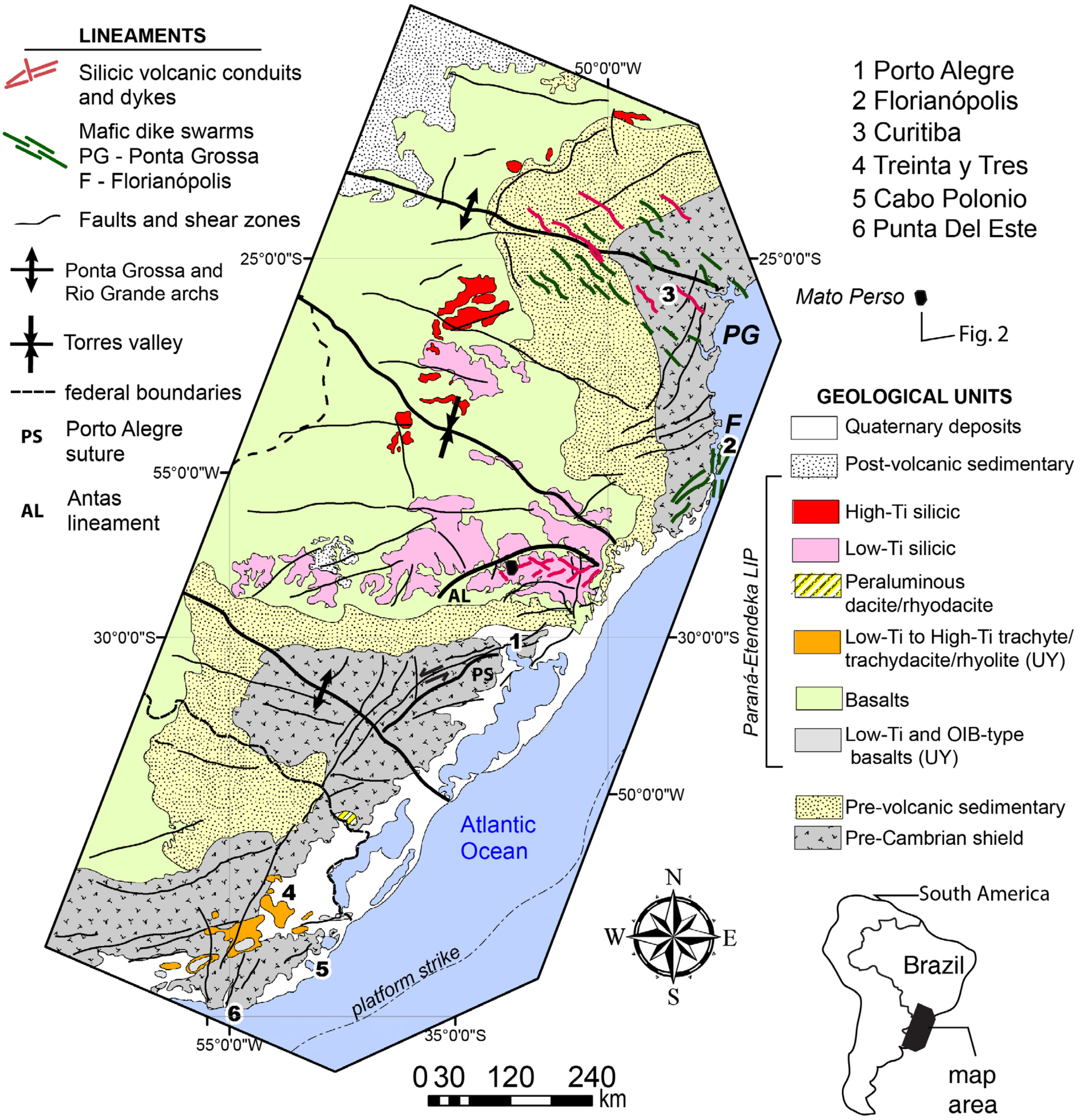

Figure 1. Distribution of Paraná-Etendeka volcanic units in eastern Brazil (UY corresponds to volcanics in Uruguay). The compilation of units and the main structures are from Fernandes *et al.* (1995), Kirstein *et al.* (2000), Nardy *et al.* (2008) and Florisbal *et al.* (2014).

morphologies of the lava flows, structural patterns and vitrophyre texture are shown in order to discuss the magma transport and emplacement, considering their implications for effusive volcanic episodes in the south of the Paraná Basin.

GEOLOGICAL BACKGROUND

In southern Brazil, the volcanic units of Paraná-Etendeka LIP are represented by the Serra Geral Group (Rossetti *et al.* 2017). This association is chemically more primitive and is dominated by simple pahoehoe basaltic flows in the base, assigned to the Torres Formation. The Vertically stacked, sheet-like, rubbly pahoehoe basaltic flows of the Vale do Sol Formation cover the compound flows and represent the more voluminous basaltic lava unit. The silicic volcanics overlying these basalt flows are assigned to the Palmas Formation. The last volcanic manifestations in the area are the compound and simple oxidized mafic flows of Esmeralda Formation.

The chemical classification of the volcanics is based primarily on the TiO_2 content of basic and silicic terms (e.g., Bellieni *et al.* 1984; Peate *et al.* 1992). High-Ti (TiO_2 > 2 wt.%) volcanics are called Chapecó-type magmas (Peate *et al.* 1992). They are exposed in the northern portion of the basin and scarce in the south of Torres Valley (Fig. 1), a NW-SE oriented depositional locus between the Ponta Grossa and Rio Grande arches. In the southern portion of the basin, both mafic and felsic magmas have low-Ti (TiO_2 < 2 wt.%) content. Palmas-type volcanics are dacites and rhyolites presenting no more than ~10 vol.% of phenocrysts. Chapecó-type volcanics are porphyritic, chemically classified as trachytes, with phenocryst content up to ~25 vol.%. Trachytes have higher Ba, Nb, La, Ce, Zr, P, Nd, Y, Yb, Lu and K, being depleted in Rb, Th and U in relation to low-Ti volcanics of the Palmas-type (Peate *et al.* 1992, Peate 1997, Nardy *et al.* 2008).

Further south in the LIP, a small area (3.2 km^3) of peraluminous dacitic lavas with cordierite, orthopyroxene, plagioclase and ilmenite as liquidus phases (Vieira Jr. 1985, Vieira Jr. & Roisemberg 1985) is present in the Jaguarão region, and is related to major shear zones from the Neoproterozoic age that may have been reactivated during the Early Cretaceous (Comin-Chiaramonti *et al.* 2010). In Uruguay, the volcanics are NE-trending oriented and the rocks are also bimodal. The basaltic Santa Lucía magma type has Oceanic Island Basalt (OIB) geochemical signatures with high Nb/La and Treinta Y Trés is broadly similar to the low-Ti Gramado lavas (Kirstein *et al.* 2000). Silicic rocks are dacites to rhyolites from Lavalleja Series (high Ti/Zr, low Nb/Y, higher Sr and Nd isotope ratios) and Aigua Series (high Rb/Sr, high Rb/Ba, high Th).

Figure 1 shows the spatial distribution of different silicic volcanic chemical types in the Paraná-Etendeka LIP. Precambrian structures are highlighted and differentiated from younger faults also cross-cutting the basin. The Ponta Grossa and Santa Catarina dyke swarms as well as postulated conduit systems in Rio Grande do Sul are represented by traces with directions compiled from the literature (Raposo 1997, Florisbal *et al.* 2014, Simões *et al.* 2017; this study).

EMPLACEMENT OF SILICIC UNITS IN PARANÁ-ETENDEKA LIP

The silicic volcanics of the Serra Geral Group generally outcrop with a laterally wide sheet-like form. Bellieni *et al.* (1986) observed this geometry and suggested an explosive origin for the deposits. It was admitted that Palmas-type flows could be traced over 60 km, but typical ignimbrite textures were not usually found. These silicic volcanics were first described as volatile-poor and high-temperature rheomorphic ignimbrites. Arguments used include their laterally persistent sheet-like nature and the absence of typical ignimbrite textures even near the top and base of each unit, which was attributed to obliteration by intense welding (Bellieni *et al.* 1986, Melfi *et al.* 1988, Petrini *et al.* 1989, Roisenberg 1989, Garland *et al.* 1995, Milner *et al.* 1995, Bryan *et al.* 2010). Milner *et al.* (1995) proposed the correlation of some subgroups of Palmas magma-type with the Namibian quartz latites. The intrusive, circular Messum Complex was identified as a potential emission center (Milner & Duncan 1987, Milner *et al.* 1992, Ewart *et al.* 1998, 2002), even though the thickness of the silicic volcanic sequence is inferior in the African counterpart. In these models, the silicic deposits in South America would need to have traveled > 300 km from their source and been deposited as extensive pyroclastic density currents (e.g., Milner *et al.* 1995, Bryan *et al.* 2010).

The paucity of pyroclastic lithofacies, with recognition of only local pyroclastic textures in extensive petrographic studies (Comin-Chiaramonti *et al.* 1988), together with the regional description of coherent and autoclastic lithofacies in a variety of lava bodies (lobes, domes and flows) led other authors to suggest that the silicic deposits are predominantly effusive (Henry & Wolff 1992, Umann *et al.* 2001, Lima *et al.* 2012, Polo & Janasi 2014, Simões *et al.* 2014, Guimarães *et al.* 2015; Polo *et al.* 2017). Silicic lava feeder conduits were described showing compound magmatic foliation revealed by bands of contrasting crystallinity and oxidation (Lima *et al.* 2012, 2018).

Typical pyroclastic deposits are found in the Mesozoic (132–124 Ma) Arequita Formation (AF), Uruguay, and described by Muzio *et al.* (2009). The AF contains high SiO_2 (> 72 wt.%) lava flows with quartz, K-feldspar and sodic plagioclase phenocrysts. The deposits are confined to the east of the India Muerta Lineament and are consisted of pyroclastic breccias, lapilli tuffs and monomictic breccias. The composition of the pyroclastic rocks is very similar to the lava flows and both are chemically more evolved than the counterpart Brazilian silicic units (with SiO_2 contents of 63–73%, Garland *et al.* 1995).

Conduit feeder systems were first proposed and described in quarries at the city of São Marcos, Rio Grande do Sul (e.g., Lima *et al.* 2012, De Campos *et al.* 2016, Lima *et al.* 2018). This region is characterized by the exposure of vitrophyres with a compound magmatic foliation with alternating layers of different crystallinity and oxidation (Lima *et al.* 2012). Fragmentation episodes involving rheomorphic and re-melting events were described by De Campos *et al.* (2016) and the authors suggested parallel oscillations in a very efficient magma ascent system together with high heat flux for conduit evolution.

The ubiquitous NE-SW or NW-SE orientations of dominantly sub-vertical banding in banded vitrophyres in northeastern Rio Grande do Sul is consistent with the orientation of the main pre-existing Precambrian structures. Some felsic vitrophyre and obsidian flows are aligned according to the regional faulting structural patterns (Simões *et al.* 2015, 2017). The observation of other expositions sharing very similar structural and stratigraphic arrangement at Caxias do Sul, São Marcos, Jaquirana and Cambará do Sul cities indicate that it is widespread along the Antas River adjacencies (Simões *et al.* 2015). The recognition of these systems is an important key to understanding how magma ascended through the crust to the surface as hot voluminous pyroclastic density currents or as structurally-controlled effusive lava flows.

MATO PERSO CONDUIT SYSTEM (MPCS)

The Mato Perso Conduit System (MPCS) is located at the south hinge of Torres Valley, in a district of the city of Farroupilha.. It outcrops in the highest elevations of Farroupilha and Caxias do Sul cities, being covered by dominantly flat-lying grey vitrophyres.

One characteristic feature of MPCS vitrophyres is their microporphyritic texture, with 2–11 vol.% of plagioclase, pyroxene and Ti-magnetite microphenocrysts. This characteristic is found in oxidized, banded and upper grey vitrophyres. Oxidized red vesicular vitrophyres occur as fragments inside red and black poorly-vesicular vitrophyres. Black vitrophyres cross-cut red vitrophyres, but also have very localized oxidized bands. The mixing patterns between these units generate banded lithofacies with dominant sub-vertical (> 60º) to subordinate flat-lying (< 30º) banding. Both banded and coherent vitrophyres have plagioclase (6/10) + clinopyroxene (3/10) + Fe-Ti oxides (1/10) as microphenocrysts. The same mineral assemblage is present in the groundmass as microlites (pl. 4/10, Fe-Ti ox. 4/10, cpx. 2/10) together with apatite (early magmatic) ± quartz (late-magmatic).

Mapping and identification of volcanic units

The geological mapping of the investigated area was made on a scale of 1:50,000, allowing the recognition of different vitrophyre units formerly recognized as fragments in the conduits (Lima *et al.* 2012, Simões *et al.* 2015, De Campos *et al.* 2016). The geological map (Fig. 2) and the interpreted cross-sections (Fig. 3) demonstrate that banded vitrophyres are distributed in a NW-SE trending region and the relationship with the subaerial silicic volcanics is detailed in section 2.2.5. Other details and features of mapped units are discussed in the following sections.

LITHOLOGICAL UNITS

Basaltic rubbly pahoehoe flows (Vale do Sol Formation)

Mafic volcanics are at the base of the volcanic succession in Mato Perso and outcrop in elevations of 290 m (Fig. 3), where they are under grey flat-lying vitrophyre flows on road RS-448 (Fig. 4A). The tops of the basalt flows tend to be covered by vegetation, but in the exposures below them, a vesicular carapace with cm-scale spherical and stretched vesicles filled with calcite crystals (Fig. 4B) can be found. In faulted regions, the basalt flows outcrop at elevations of 470 to 495 m. The tops of the flows also contain rubble (Fig. 4C) and the basaltic units were strongly affected by normal faults, registered in fault slickensides with vertical steps and crystallization of fibrous minerals (Fig. 4D). Regional correlation and the presence of rubble in the top of the flows of the area suggest that the mafic unit belongs to the Vale do Sol Formation, composed of rubbly pahoehoe basaltic and basaltic-andesite flows.

Oxidized vitrophyres (Ov)

The oxidized vitrophyres (Ov) are the lowest silicic unit in the succession. They occur as flat-lying units occupying the valleys in elevations between 350 and 600 m (Figs. 2 and 3). Ov are aphanitic to microporphyritic, showing sparse plagioclase and pyroxene microphenocrysts in a vitreous matrix. A large spectrum of vesiculation degree in Ov varies throughout the parts of the flows. Thus, the vitrophyres can be divided into poorly and highly vesiculated.

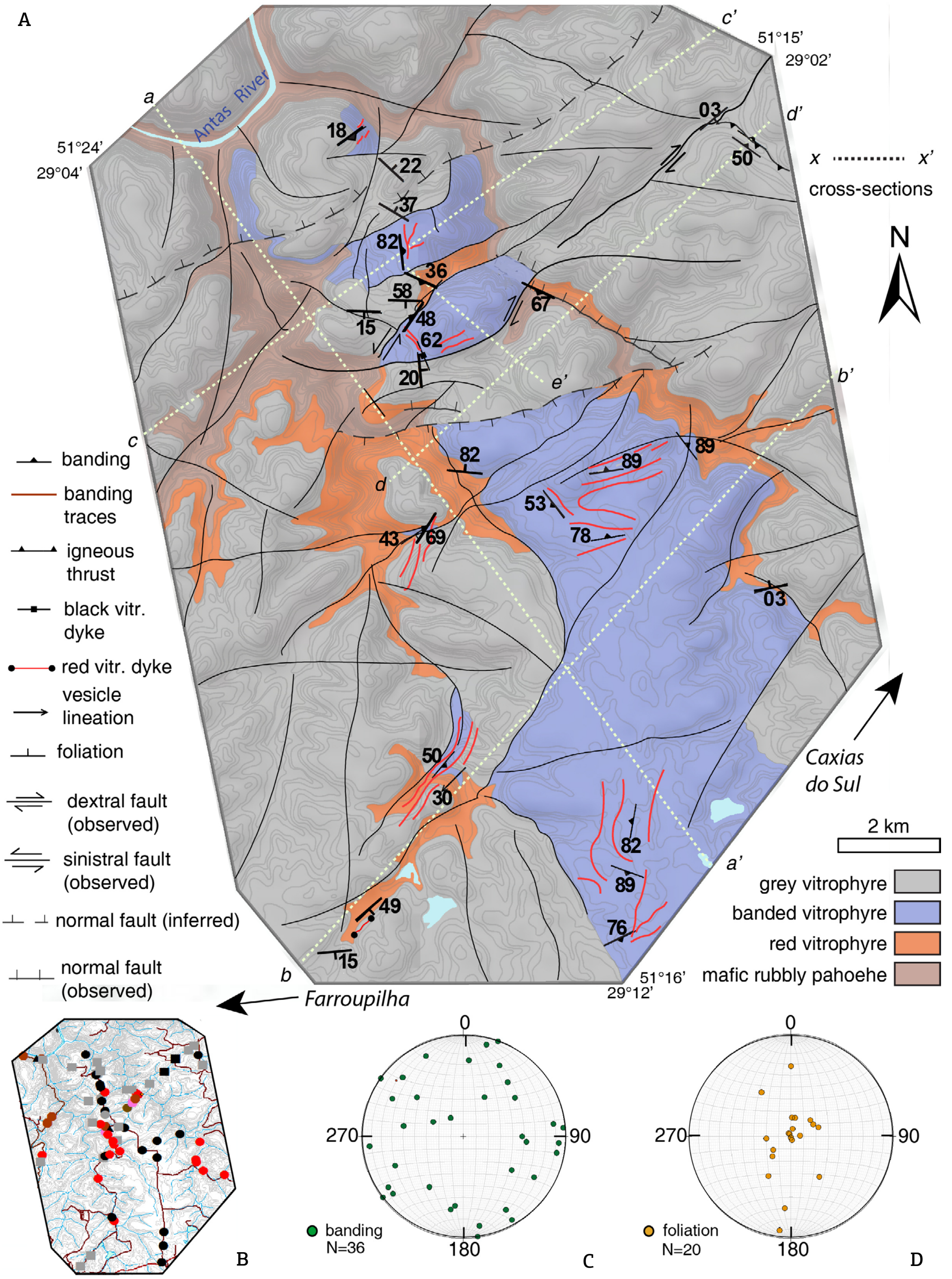

Figure 2. (A) Geological map of Mato Perso area, between cities of Caxias do Sul and Farroupilha indicating the cross-sections of Figure 3 and with (B) geological station map showing the distribution of mapped units (dots: red-oxidized vitrophyre, black-banded vitrophyre, grey- grey flat-lying vitrophyre, brown-basalt rubbly pahoehoe) and roads (brown lines); (C) stereonet showing the variable dipping distribution of poles of banding planes in banded vitrophyres (N = 36); (D) poles of magmatic foliation planes in grey vitrophyres with dominant flat-lying planes (N = 20).

Poorly vesiculated vitrophyre lithofacies are 2–3 m thick units (Fig. 5A) with flat-lying banding marked by cm-spaced continuous planes of more or less oxidized rock (Fig. 5B). The banding is reinforced by regular foliation spaced at approximately 7 cm. The presence of only sparse mm-size spheroid vesicles gives the vitrophyre a vesicle-absent appearance (Fig. 5B).

Vesiculated lithofacies are characterized by globular or stretched vesicles and quartz/calcite-filled amygdales ranging from few millimeters to 5–8 cm (Fig. 5C). Some of the cavities are cm-sized pockets filled with quartz-cemented autobreccias. The breccias are composed of very angular vitrophyre fragments with several mm- to cm-scale sizes (Fig. 5D). The upper parts of the Ov display a frothy (highly vesiculated) aspect with vesicles of up to 1 cm. In this part of the flow, vesicles have a less dispersed size range (Fig. 5E). The vesicles acquire stretched patterns and develop another type of autobreccia with cm-size angular vitrophyre fragments embedded in diaphanous quartz cement (Fig. 5F).

Banded vitrophyres (Bv)

Banded vitrophyres (Bv) occupy an approximately 15-km long NW-SE oriented area from the high elevations of Caxias do Sul city (~760 m) to the valleys at 550 m and 405 m elevations in Mato Perso where their occurrence is more restricted. This unit is characterized by a conspicuous colored banding marked by alternating bands of red to black vitrophyre.

In the valleys, Bv's occur in isolated outcrops where the banding is dominantly sub-vertical (dipping 82 to SW — Fig. 6A). Other exposures display tabular shapes resembling a dike-like structure (Fig. 6B). In this case, the banding parallel to the structure dips 69º–58º to NE and NW. The complex magmatic flow generated a broad range of fold geometries which modify the direction and dip of the bands. Stretched or open types are generally common (Fig. 6C). The presence of boudinated vitrophyre layers parallel to the banding with quartz venules filling the void spaces is another common feature (Fig. 6D).

In the highlands, at elevations of approximately 750 m, the Bv.s are well exposed and exhibit a wide range of magmatic structures which passes from ductile to fragile fields. A common feature of Bv, in the center of the conduits, is the divergent opening geometry formed by the sub-vertical bands with stretched to isoclinal parasitic folds (Fig. 7A). To the boards, Bv gets more oxidized and engulfs cm-sized black vitrophyre angular fragments (Figs. 7B and 7C); the occurrence of boxwork-like fracturing filled with quartz and the intense mixing of oxidized to less-oxidized layers is frequent. Banded vitrophyres register several folding

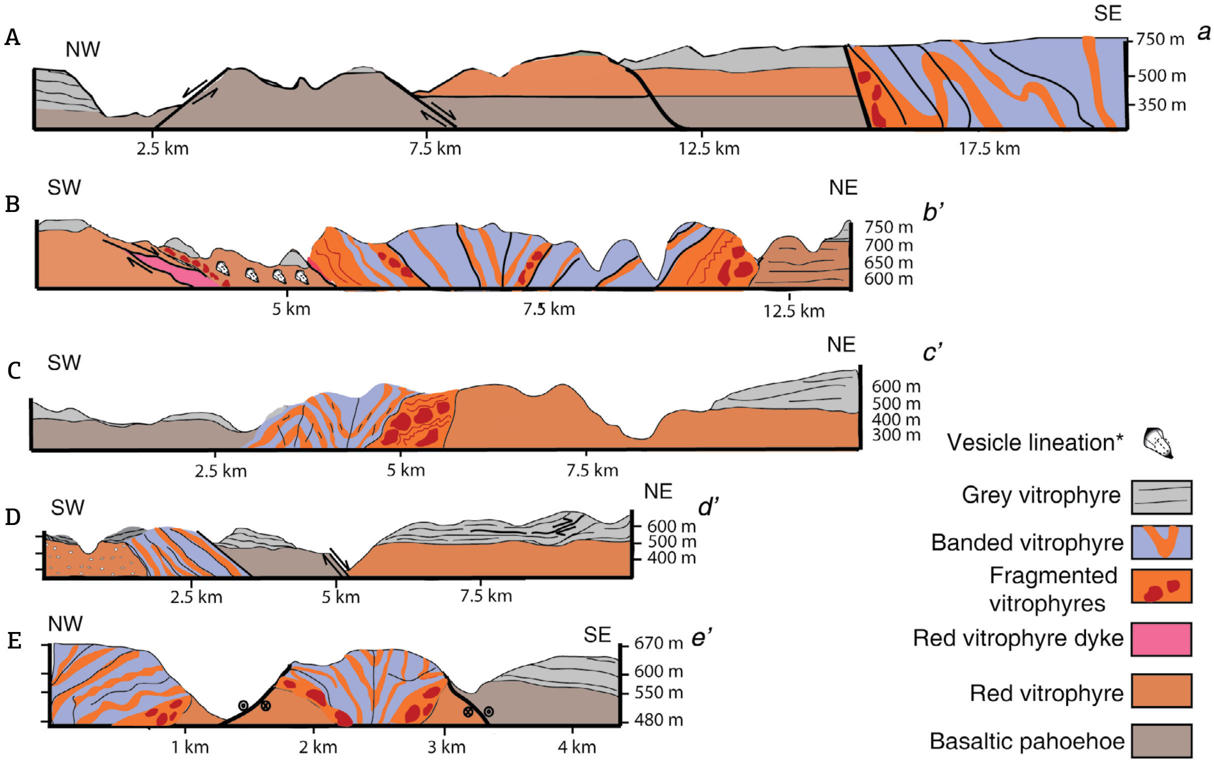

Figure 3. Geological cross-sections showing the field relations between the vitrophyre units. The position of the sections is present in Figure 2. Vesicle lineation* symbol cuts the plane of the paper, plunging to SE.

phases with quartz-filled fractures parallel to the axial surface of F4-phase folds (Fig. 7D). Localized outcrops show the banding of Bv thrusting over a more competent vitrophyre layer (Fig. 7E). Structures reveal that fractions of the magma banding are stretched by backflow movement (Fig. 7F).

A banded vitrophyre exposure laterally associated with breccia outcrops is present in the central part of cross-section 'e' in Figure 3. If we look at this outcrop in detail (Fig. 8A), banded vitrophyres carry and contour large oxidized fragments (Fig. 8B) besides presenting F3-phase folds with flat-lying limbs (Fig. 8C). To board of the system, cm-sized oxidized vitrophyre fragments with high vesicle content are embedded in the banded vitrophyre (Fig. 8D).

Grey flat-lying vitrophyres (Gv)

Grey flat-lying vitrophyres (Gv) are widespread in the area and outcrop in the highest elevations near the city of Caxias do Sul (~803 m) down to 610 m in the São Vitor region, toward northwest. This unit is generally composed of overlying red oxidized vitrophyres and has microporphyritic texture. In the proximities of the Antas River, the Gv occur covering basaltic rubbly pahoehoe flows at an elevation of ~300 m (see section 4). The main feature of Gv is its flat shape, highlighted in the relief by the absence of intense vegetation. This shape is sustained by a penetrative foliation which is flat-lying (< 20°) in most outcrops but can dip to ~40° to 80° (Fig. 9A).

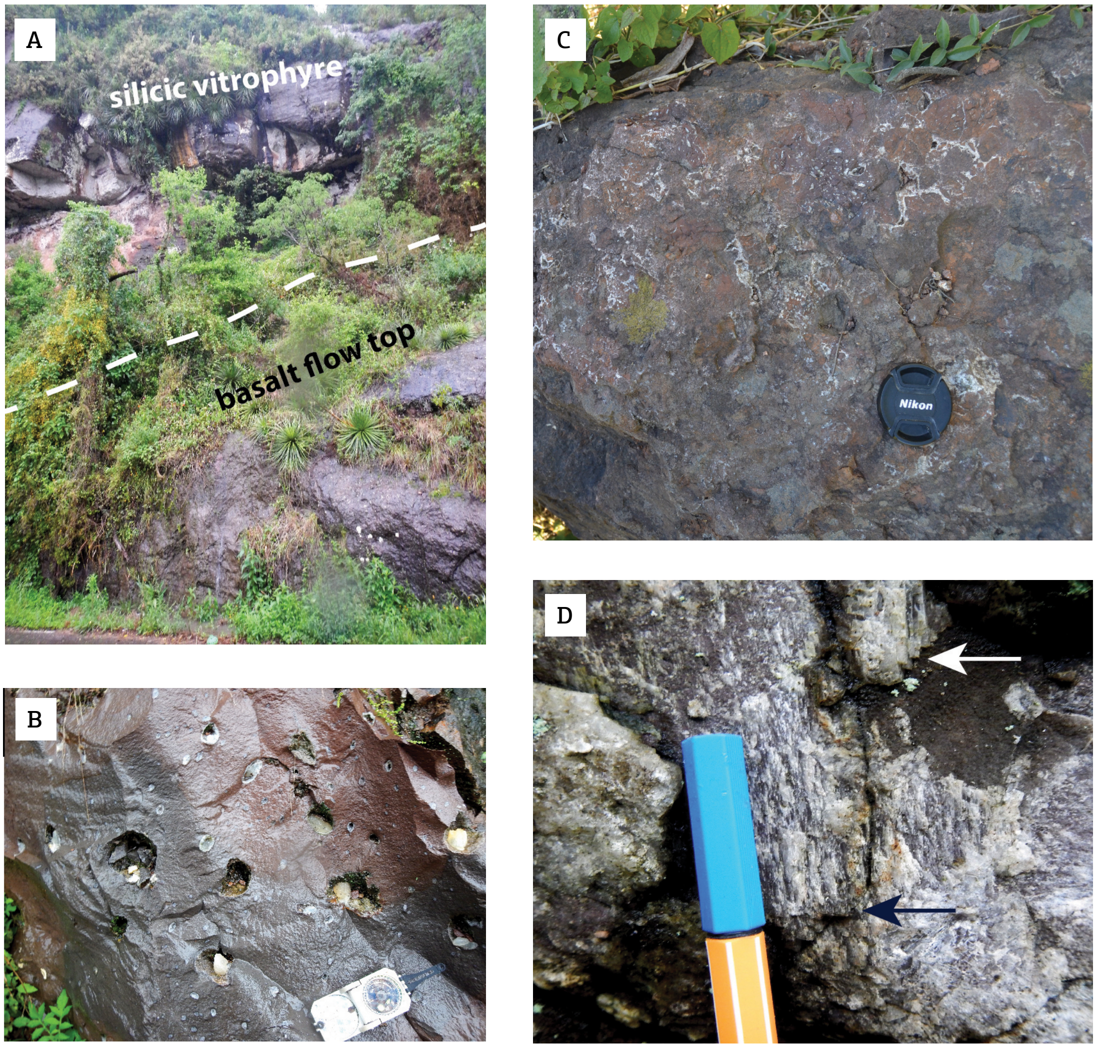

Figure 4. Field features of basaltic flows in the base of the volcanic succession (Vale do Sol Formation). (A) Top of a rubbly pahoehoe flow covered by vegetation in the contact with silicic grey vitrophyres; (B) vesicular crust near the rubbly top of the flow (detail of Fig. 4A); (C) rubbles of mafic vesiculated volcanic in an exposition of the basalt flows near faulted regions; (D) slickenside with vertical steps indicating gravitational movement (following the criteria of Petit 1987).

At the base of these flows are cm-spaced oxidized bands concordant with the main foliation (Fig. 9B). Where the lower oxidized vitrophyres have irregular tops, with more than 1 m of level difference, the Gv develop a poorly sorted autobreccia (Fig. 9C) with angular cm-sized fragments embedded in a mm-sized fragment matrix (Fig. 9D). Another feature of the base of these flows is the arrangement of stretched vesicles with vertical disposition (pipe-like vesicles) having no more than 2 cm in length (Fig. 9E).

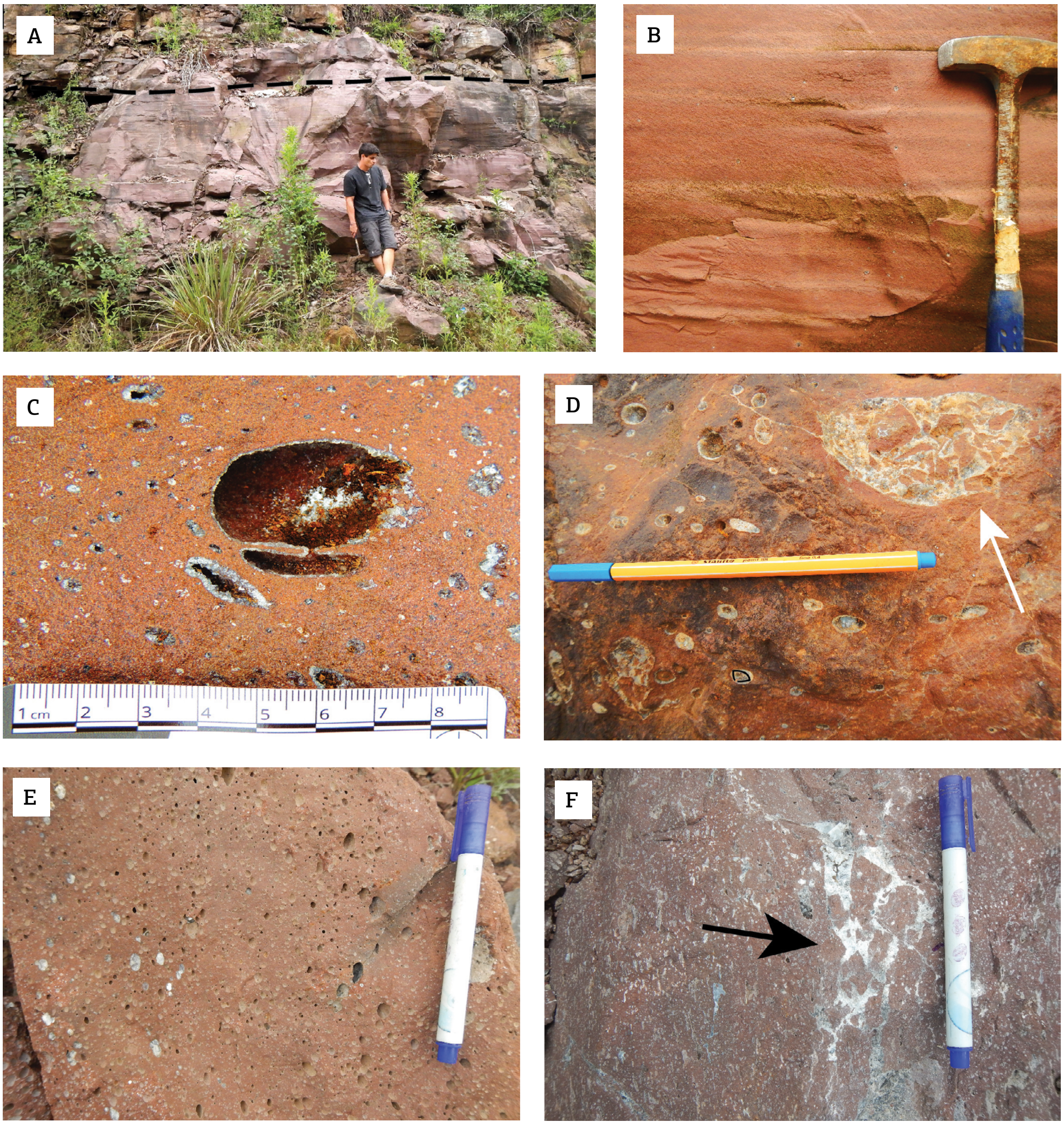

Figure 5. Oxidized vitrophyres in the Mato Perso region. (A) Flat-lying magmatic banding in red poorly vesiculated vitrophyre (elevation 600 m); (B) fresh poorly-vesiculated aphanitic vitrophyre with sparse mm-scale vesicles and horizontal magmatic foliation; (C) highly-vesiculated oxidized vitrophyre with mm- to cm-scale amygdales filled with quartz and calcite; (D) red vesicular vitrophyre with stretched vesicles and amygdales. The arrow points to a pocket with angular fragments cemented by quartz; (E) frothy top of an oxidized vitrophyre flow. The vesicles and amygdales show a narrower distribution of sizes; (F) sheared vesicles and autobreccia with cm-size vitrophyre fragments, near the flow top.

The sheet-like form (Fig. 10A) related to the flat-lying foliation of Gv dips 1° to 23° in general and is highlighted when alteration surfaces are well developed (Fig. 10B). Toward the core of the flows the amount and size of vesicles are in a broader range and present elongated and spherical shapes (Fig. 10C). Rarely, fresh outcrops reveal that Gv are grey colored and the foliation is generated by alteration halos through quartz-filled microfractures (Figs. 10D and 10E).

Geological contacts

As described in section 2.2.1, in RS-448 (290 m of elevation) grey vitrophyres are in direct contact with the top of basaltic rubbly pahoehoe flows at a minimum thickness of 20 m (Fig. 11A). Grey flat-lying vitrophyres cover the vesiculated flow-topping oxidized units with sharp contacts (Fig. 11B). The contacts can be direct (Fig. 11B) or indirect, with cm-size (~30 cm) well-sorted sandstone layers between the two volcanic units (Fig. 11C). Some contacts between the silicic rocks are more complex. For example, in Figure 12A the older unit is composed of large, angular to sub-rounded fragments of a highly vesiculated vitrophyre. The fragments are cm- to meter sized, contain large amygdales (~2–10 cm) filled by quartz and have borders with different degrees of oxidation. The groundmass between the fragments is a vesiculated altered oxidized vitrophyre (Fig. 12B). This vitrophyre has minor vesicles (mm- to cm-size) and is cross-cut by a poorly-vesiculated vitrophyre dyke. The dyke is 1 m thick and is associated with quartz venules associated, indicating normal displacement with a southeast top with slightly oblique components (Fig. 12C). The oxidized vitrophyres are covered by a porphyritic grey vitrophyre with foliation also dipping southeast (Fig. 12D).

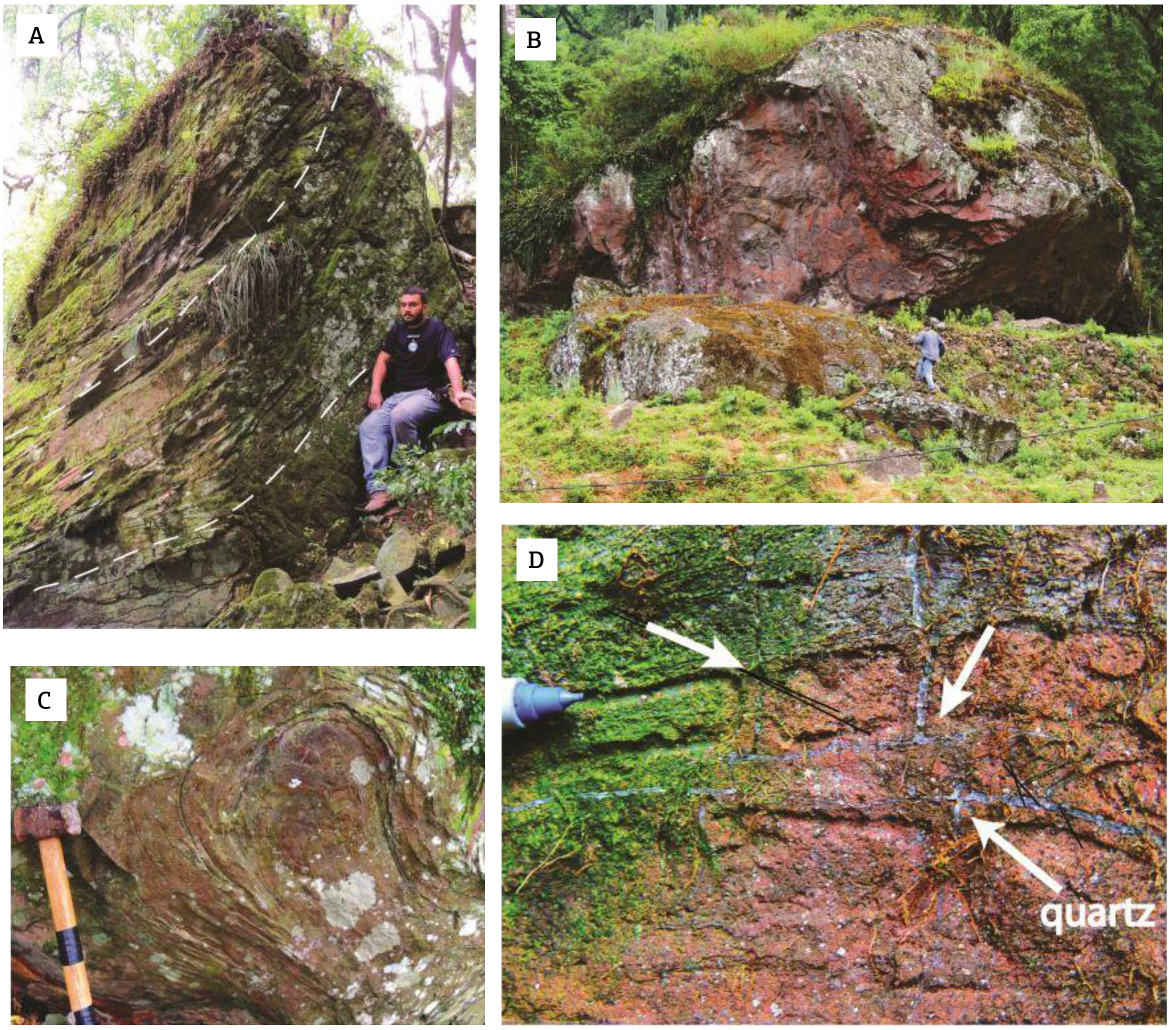

Figure 6. Banded vitrophyres mapped in lower elevations of the area. (A) Magmatic banding dipping 50° to 82° to NW and NE (29°10′44.28″S/51°19′22.28W, altitude of 590 m). (B) Tabular “dike-like” structure (29°8′13.12″S/51°19′38.39″W, elevation of 537 m); (C) fan fold in banded vitrophyre, contorting the magmatic banding; (D) banded vitrophyre showing exsolved diaphanous quartz between boudinated vitrophyre layers.

DISCUSSION

Stratigraphy

The local stratigraphy we propose here is based on the recognition that thick rubbly pahoehoe basaltic flows of Vale do Sol Formation are older volcanics. The relationship between basaltic flows and oxidized vitrophyres remains unclear if we consider that no outcrop of silicic dyke cutting the underlain mafic units was found. In the northwest portion of the area, near the Antas River, the basalts are directly

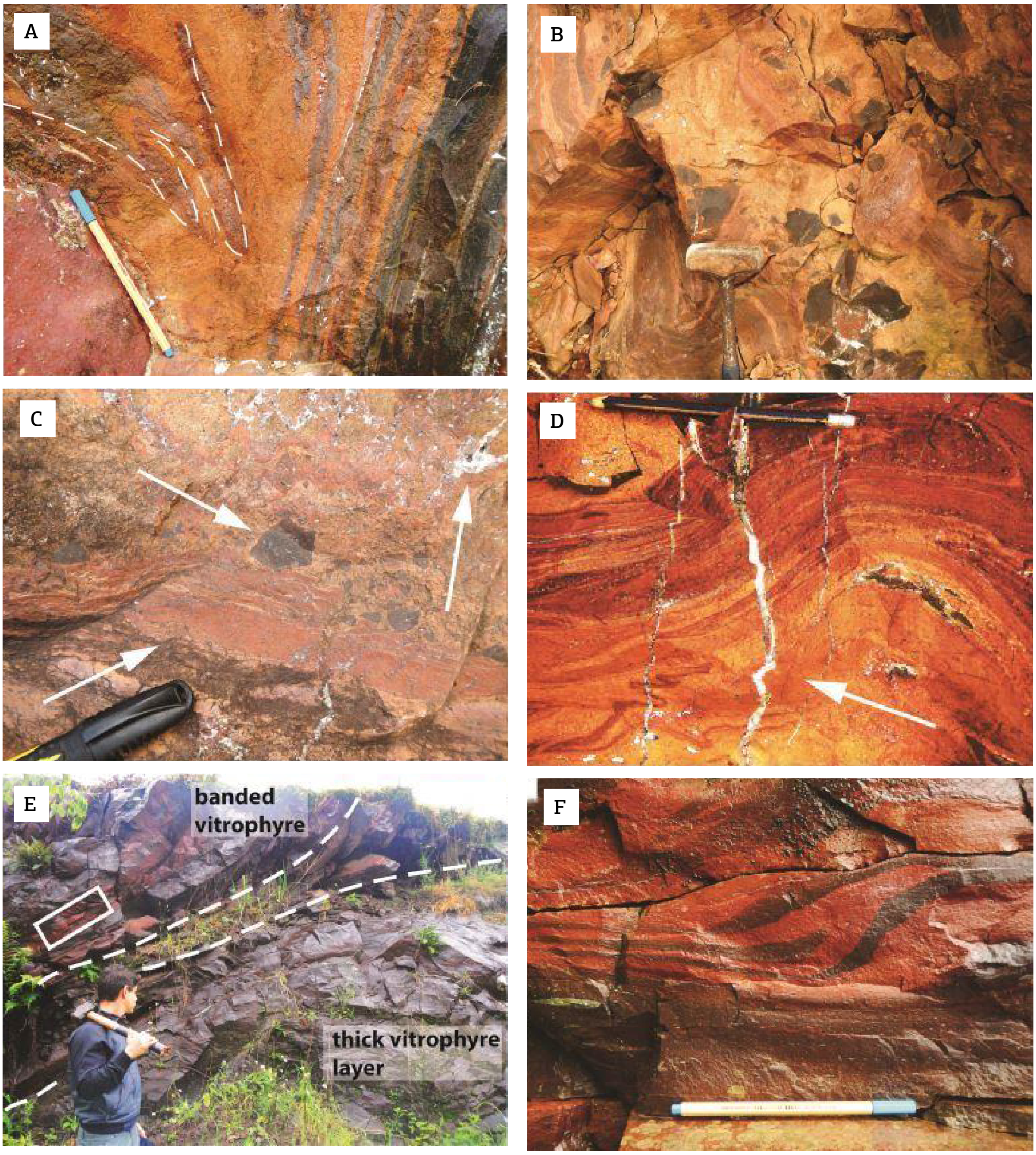

Figure 7. Banded vitrophyres mapped in higher elevations of the area. (A) Vertical banding between black and oxidized vitrophyres (29º11’20.91”S/51º17’8.02”W, elevation of 746 m); (B) boarder of the conduit with black angular vitrophyre fragments within a banded oxidized matrix; (C) boarder of the conduit system with oxidized bands, variable sized black vitrophyre fragments and boxwork-like disposal of fractures filled by quartz; (D) quartz-filled fractures with mm-scale spacing cutting the axial surfaces of F4-related folds; (E) banded vitrophyre layers thrusting a thicker more competent black vitrophyre layer (29º4’4.52”S/51º15’38.31”W, elevation of 680 m); (F) detail of Figure 7D showing the normal relative movement of the magma backflow.

covered by silicic grey vitrophyres. This sharp contact between upper basalt-andesite flows with the grey flat-lying flows of Palmas Formation is very frequently recognized throughout the southern Paraná Basin in elevations between ~350-880 m (Umann *et al.* 2001, Lima *et al.* 2012, Waichel *et al.* 2012, Rossetti *et al.* 2014, Barreto *et al.* 2014, Polo & Janasi 2014, Rossetti *et al.* 2017, Simões *et al.*, 2017).

Even though no contact between oxidized vitrophyres over basaltic flows were observed, the field relations illustrated in Figures 2 and 3 are our support to assume that the former unit is younger than the second. Thus, oxidized vitrophyres are the basal silicic unit, lying over the mafic units and are covered by grey flat-lying silicic vitrophyres.

Banded vitrophyres are regionally exposed along an ~6 km width, NW-trending structure (Fig. 2). According to the distribution of structures in contours, they occur either below or above oxidized vitrophyres and always have a grey vitrophyre unit above them, the contact between the units, however, is frequently absent. Outcrops showing these vitrophyres as dike-like structures, along with the presence of oxidized vitrophyres and breccias toward the borders of the expositions and the association of the inferred intrusive units with regional tectonic structures are arguments for interpreting them as conduits.

Flow morphologies

Flow morphologies and physical characteristics of the subaerial silicic vitrophyres are divided between oxidized and grey units. Both share incomplete characterization because the total area calculation of the flows is difficult due to fault occurrence and cannot be estimated by using conventional remote sensing tools. However, it is inferred from field observations and outcrop elevation correlation that grey flat-lying vitrophyres (Gv) must reach an extent area greater than 30 km^2.

In the oxidized vitrophyres (Fig. 13A), typical base structures such as autobreccias, pipe vesicles and vesicular crusts were not found. By outcrop correlation and comparison with other types of subaerial flows, the poorly-vesiculated vitrophyre with flat-lying foliation (Figs. 5A and 5B) represents the core of the flow unit. Toward the top of the flow, the vesiculation degree rises, the size of the vesicles variate more (Figs. 5C and 5D) and in the upper crust, which is observed in contact with upper grey flows, the vesicles have uniform and smaller sizes (Figs. 5E and 5F).

Oxidized flows (Ov) are estimated to be at least 10 to 30 m thick, and the core-related flat-lying foliations (Fig. 13) are interpreted as flat movement of magma in the flow core. The top of the core with larger vesicles and

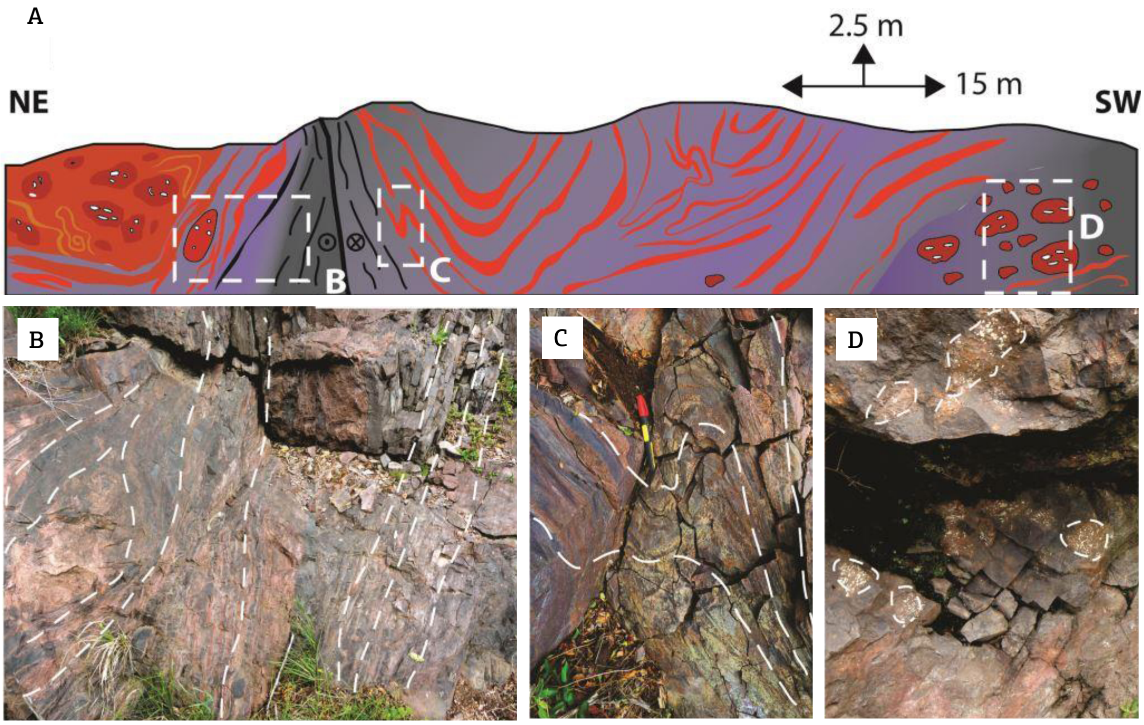

Figure 8. Geological cross section an outcrop of conduit system in highlands (29º6'22.68"S/51º19'38.31"W, elevation 654 m). (A) Schematic sketch showing the field relations between oxidized, brecciated and banded vitrophyres; (B) sub-vertical banding (dipping 72º to NW) in banded vitrophyre; (C) F3-phase fold of banded vitrophyre with sub-horizontal plunge (10º to SE); (D) vesiculated oxidized vitrophyre fragments embedded in banded vitrophyre.

the crust in the top of the flow with abundant smaller vesicles seem like closed-system patterns observed in pahoehoe basaltic flows (e.g., Aubele 1988, Thordarson & Self 1998, Harris *et al.* 2017).

The base of grey vitrophyre flows is characterized by the presence of autobreccias, but only where the paleorelief had dip slopes. The breccias are absent and the contact is sharp where the paleorelief slope is steep. The bases of

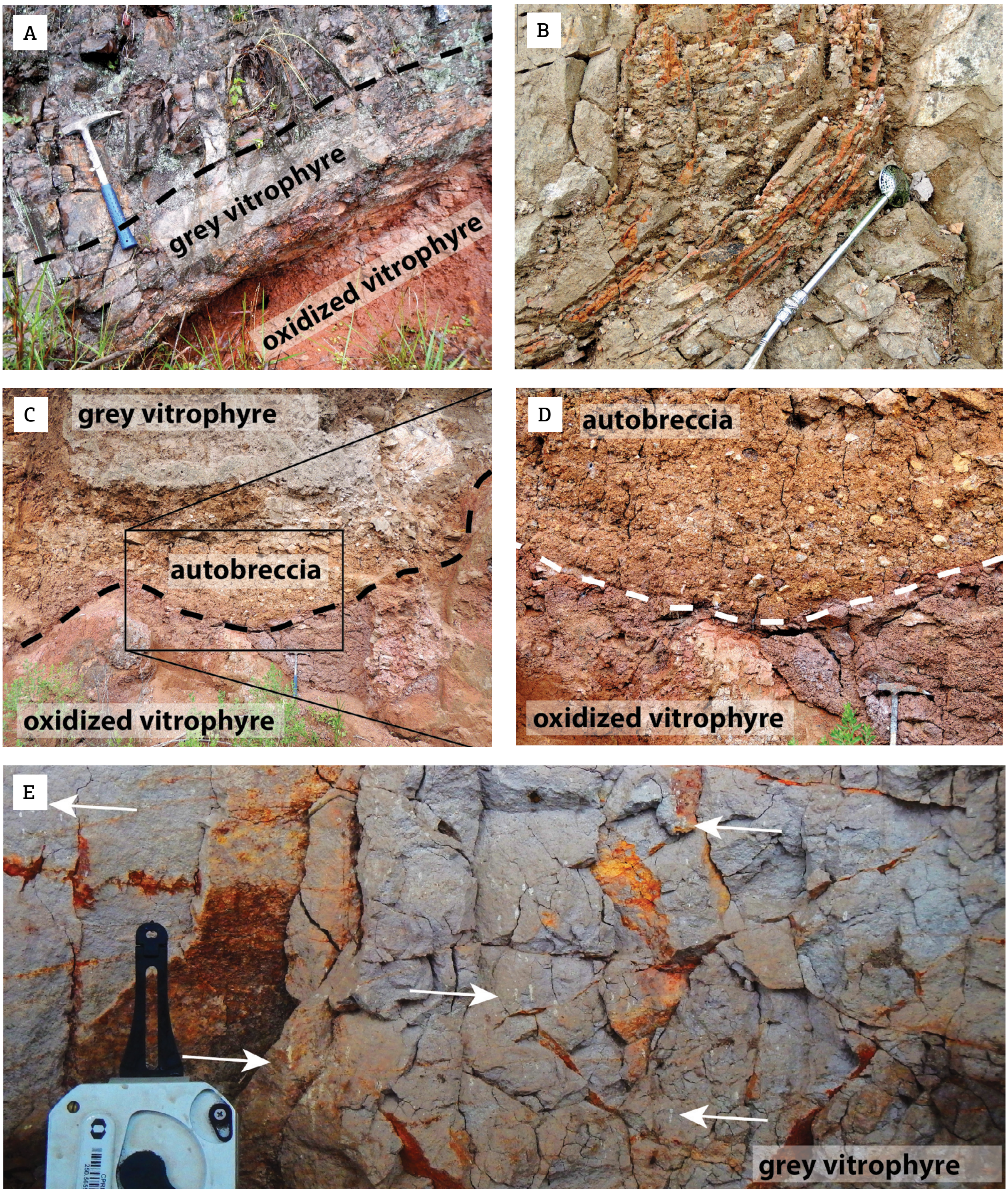

Figure 9. Grey flat-lying lithofacies. (A) Intermediate-angle contact between grey vitrophyre base and an oxidized vitrophyre altered top; (B) oxidized bands in the base of a grey vitrophyre flow; (C) autobreccia in the contact between Ov and Gv. Note the inclination of the paleorelief; (D) detail in the fragment in the altered autobreccia on the top of the oxidized vitrophyre; (E) altered grey vitrophyre with flat foliation and mm-sized pipe vesicles.

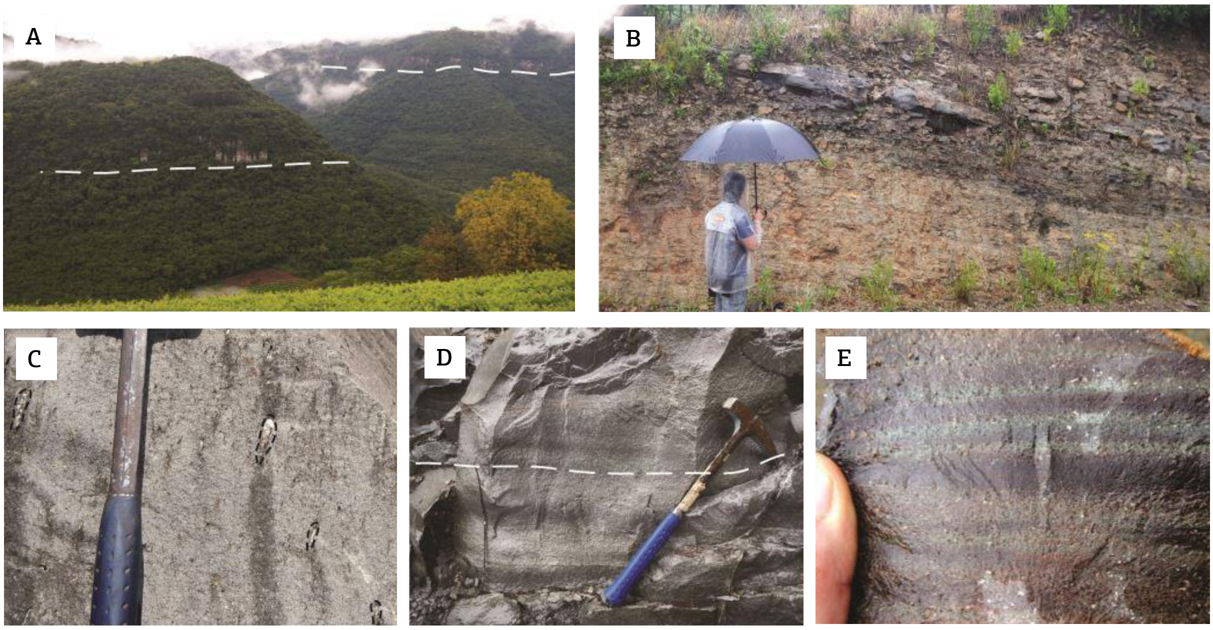

Figure 10. Grey flat-lying vitrophyres field features. (A) Sheet-like form of the expositions, generally absent of vegetation; (B) inclined foliation highlighted by alteration surfaces in grey vitrophyre; (C) grey vitrophyre with mm-size round to stretched vesicles; (D, E) fresh expositions of grey vitrophyre with flat alteration halos.

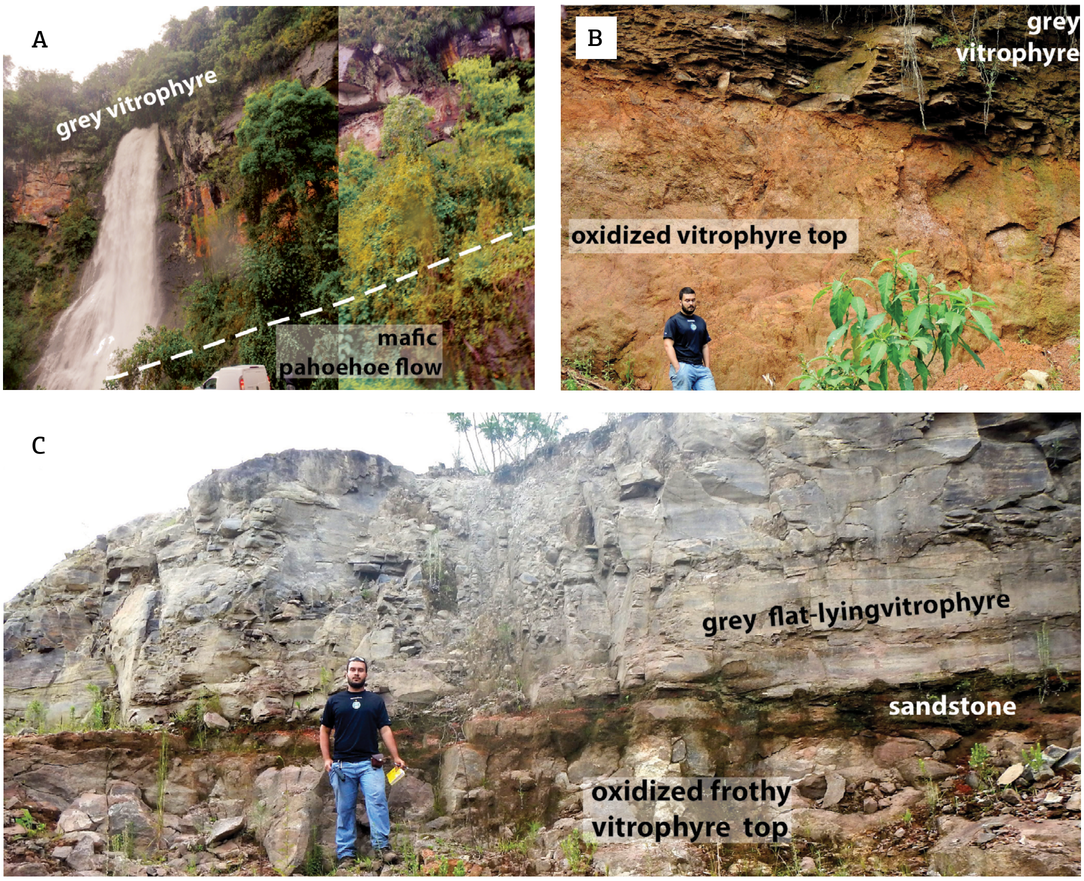

Figure 11. Contacts between volcanic units in the area. (A) Grey flat-lying felsic vitrophyre covering a basaltic rubbly pahoehoe flow; (B) vesiculated top of a red oxidized flow covered by grey silicic vitrophyre; (C) contact between vesiculated top of oxidized vitrophyre and grey vitrophyre with a ~30 cm sandstone layer in the middle (29°2’3.15”S/51°11’47.48”W, elevation of 790 m).

the flows also have smaller pipe vesicles that grow in size toward the core of the flow, which also displays spherical vesicles. The top of grey vitrophyres was probably eroded, once it is the uppermost geological unit in the area (Fig. 13B). In other expositions through the south of the Paraná Basin, the top of these grey flows were characterized by upper vesicular crust or autobreccia (Waichel *et al.* 2012, Rossetti *et al.* 2017).

Gv flows tend to remain uniform and at least 20 m thick in the area covering the oxidized unit and following the irregular paleorelief. No margins of the flow were observed, but field evidence of lateral autobreccias in similar silicic flows in adjacent areas (e.g., Waichel *et al.* 2012, Polo & Janasi 2014, Simões *et al.* 2014) show hat flow margins of conventional silicic types in Palmas Formation remain thick for long areas, are massive and can be laterally brecciated.

EMPLACEMENT OF THE VOLCANIC UNITS

Rheology

Both oxidized and grey vitrophyres have distinguishing features more compatible with extensive lava flows (e.g., Henry & Wolff 1992). Other similar silicic units in the south of the province have also been recognized as lavas (Umann *et al.* 2001, Polo & Janasi 2014, Simões *et al.* 2014, Guimarães *et al.* 2015). The extension and uniformity of these types of flow are observed in dacite flows with well insulated crusts, allowing even high viscosity magma to attain great distances (Harris & Rowland 2009). A system sustained at high effusion rates is also important to form long simple lava flows (Walker 1971; Walker 1973).

A significant rheological property of the Paraná-Etendeka LIP silicic volcanics is the very high pre- and syn-eruptive temperatures, obtained by apatite saturation and pyroxene-liquid geothermometry data, in the order of 1,000–1,100°C as well as low relative viscosities for rhyodacite-rhyolite magmas (Milner *et al.* 1992, Bellieni *et al.* 1984, 1986, Garland *et al.* 1995, Janasi *et al.* 2007, Simões *et al.* 2014). Low viscosity is a favorable property for efficient magma flow, emplaced at long distances.

The viscosity of the magma is related to gas loss during eruption; the magma ascent rate is also sensitive to this loss. As the volume proportion of gas affects magma density, compressibility and rheology, it results in both horizontal and vertical pressure gradients in the magma column to allow gas to escape (Sparks 2003).

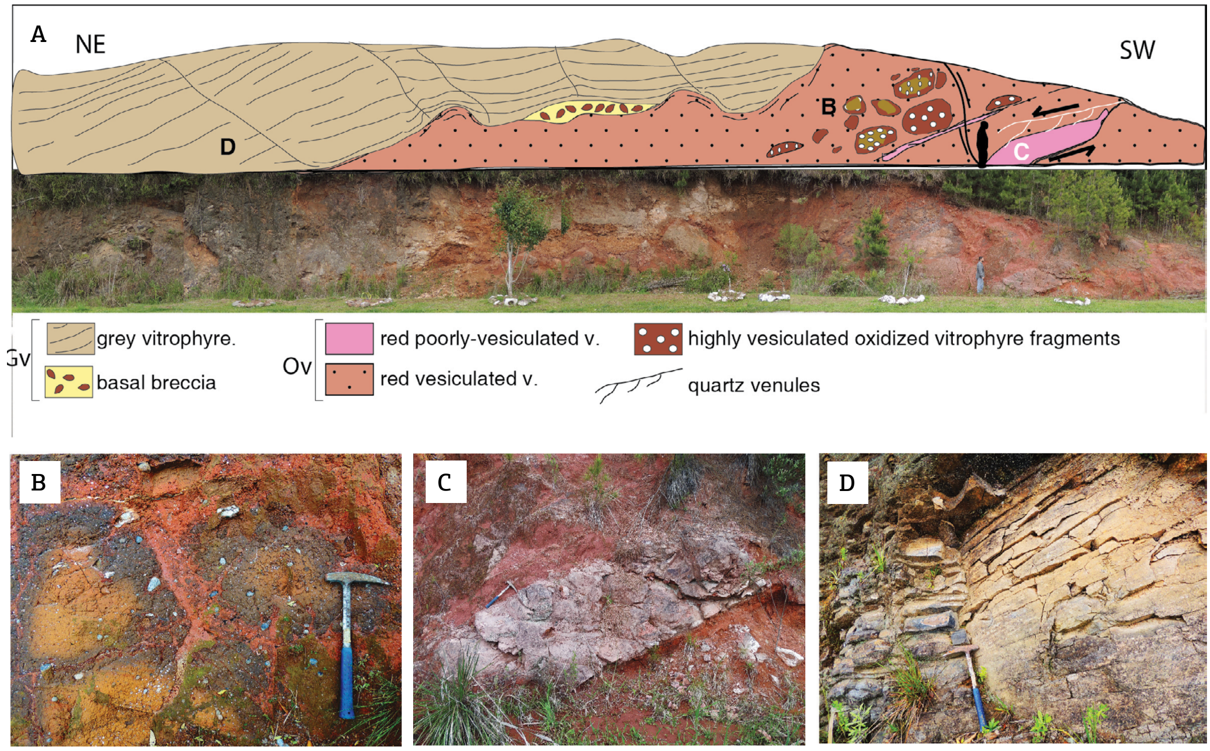

Figure 12. Contacts between volcanic units in the area. (A) Geologic cross-section of approximately 30 m showing field relations (29°12’17.92”S/51°20’16.83”W, elevation of 675 m); (B) large oxidized vitrophyre fragments with cm-sized amygdales; (C) oxidized poorly-vesiculated vitrophyre dyke cutting the sequence with NE-SW direction and dipping 52° to SE; (D) upper grey vitrophyre with variable foliation dips. The main foliation dips 49° to SE.

According to the Massol & Jaupart model (1999), if bubbles are interconnected gases can escape to the conduit walls. In rhyolite lavas, high porosity bands are often developed. Therefore, they potentially act as pathways for gas movement to the lava surface (Sparks 2003, Houghton *et al.* 2010, Furukawa & Uno 2015). A volatile-rich magma is less dense than a degassed magma, both because of reduced dissolved volatiles within the melt (Richet *et al.* 2000) and (at low pressure) because of the presence of an exsolved fluid phase (Witham 2011). When we analyze the mapped units as a whole, the banding, shearing and fragmentation of magma described in variable parts of the conduit outcrops, more commonly in their borders can be interpreted as favorable paths to degassing. Sustained high temperatures and consequently low viscosity could be held by a competent heat flux.

Conditioning structures for the conduit system

A plausible explanation of why the conduit-related rocks were not observed cutting the lower basaltic units is because their outcrops are controlled by tectonic structures. The conduits are regionally exposed, mostly in the south, near the Antas river bed (Fig. 1). This river forms a curved NE-SW structure comprising a set of normal and transcurrent faults (Fig. 2). In the south of the river, the NW-trending structures contain the conduit expositions. It resembles the São Marcos (Lima *et al.* 2012, 2018, Simões *et al.* 2017) and

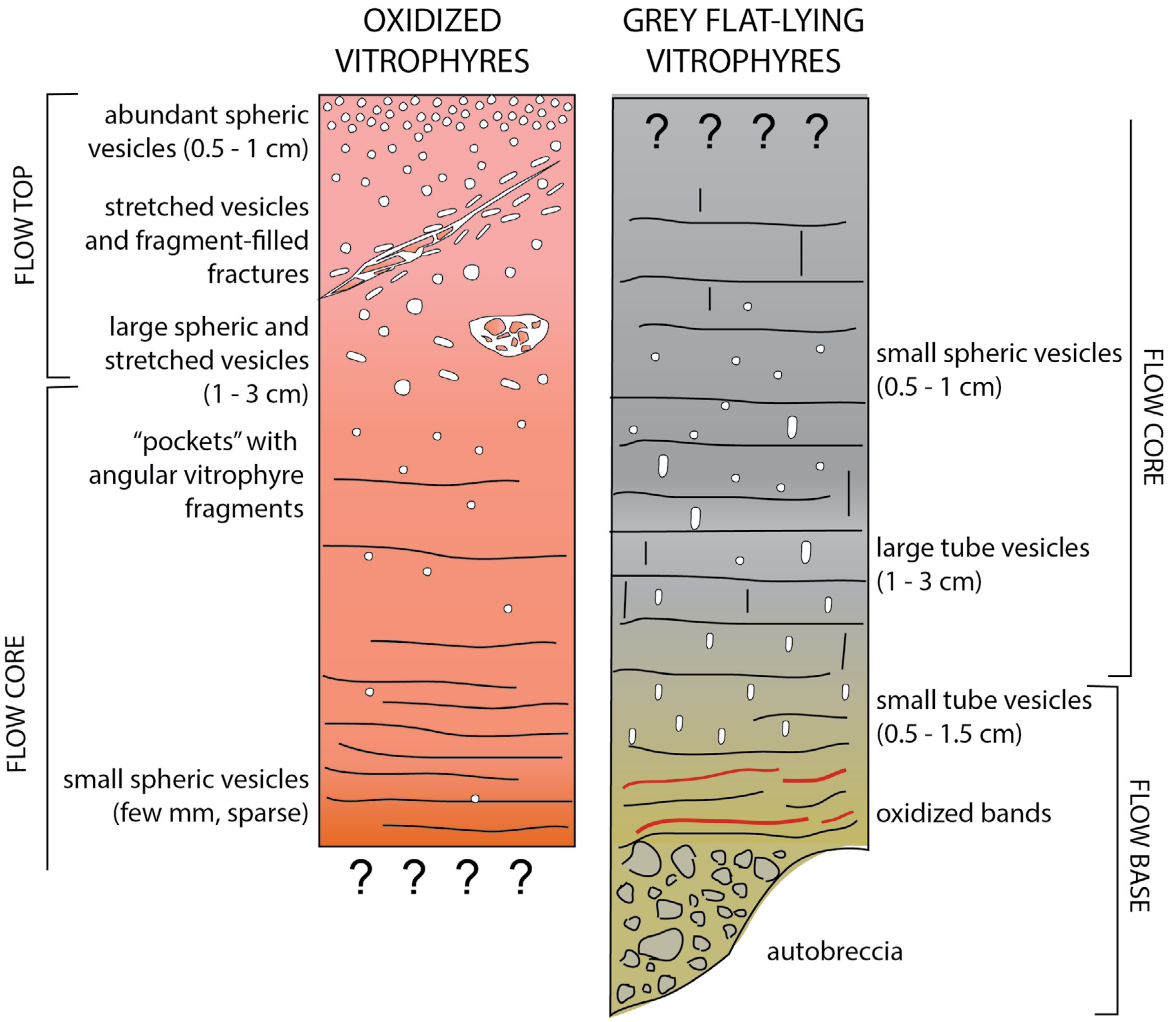

Figure 13. Flow morphologies for oxidized and grey flat-lying vitrophyres. (A) Oxidized vitrophyres have flat-lying banding and sparse spherical vesicles in the flow core. Discrete breccias, elongated and larger vesicles are on the top of the core and abundant spherical vesicles make up the frothy vesicular upper crust; (B) grey vitrophyres display, in the base, autobreccias, where the paleorelief slope is high (> 45°) and sharp contacts at flat paleorelief. Small tube vesicles grow to the core of the flow, where spherical vesicles are also common.

Jaquirana-Cambará do Sul areas (Simões *et al.* 2015, 2017), both also south of this NE-SW structure. The observed banding is folded several times (Figs. 6C, 7A, 7B, 7D, 8). F1- and F2-phase folds are generally present in the center of the conduits, with sub-vertical disposal of the axial surfaces. Toward the margins, a variety of fold phases is generated (at least four) mainly by mixing between more and less oxidized bands (Fig. 7D). Thus, a complex arrangement of flow directions within the conduits is recognized.

One regional scale, the geometrical and kinematical interpretation of transcurrent faults made by Nummer *et al.* (2011), shows that the NW-SE faults with sinistral strike-slip movement are older (Eocretaceous) than NE-SW faults with dextral and NW-SE faults with sinistral relative movements in the northeast of Rio Grande do Sul. The fault reactivation in NE-SW direction coincides with Precambrian structures like the Porto Alegre suture and Dorsal de Canguçu shear zone (Fernandes *et al.* 1995). Additionally, the NE-trending Antas Lineament can be correlated to the NE-SW orientation of Huab, Ugab and several other rivers in Namibia. We interpret that the role of major NE-SW structural reactivation is fundamental to open spaces at NW-SE faults, the dominant trend of conduit area outcrops in this study.

Considering the tectonic setting for the Paraná Basin, the thermomechanical study of Quintas *et al.* (1999) concludes that the major extension of the basin occurred in the Permo-Carboniferous. In the Juro-Cretaceous, during volcanism, the subsidence was associated to reactivation of older structures allied with a thermal component. The thermal component, considered to be plume-related (Hawkesworth *et al.* 1992, Peate 1997, Gibson *et al.* 2006), was connected to the surface through a feeder system that is proposed to reach the mantle at ~35 km, at least in the northern portion of the basin (Molina *et al.* 1988). This indicates that emplacement of the conduits in the shallow crust must be a reflection of a deeper feeder system.

The injection of magma through dykes during gravitational displacement of blocks is evidenced in Figure 12A and may have played an important role in magma transport. In the places where the dykes intruded on more friable rocks, at the valleys of the mapped area, the main intrusive structure remain preserved (see Figs. 6A and 6B). The evolution from the syneclise phase to pre-rift in the Paraná Basin, increasing the regional extension, is an appropriate scenario fostering the propagation of normal fault sets and the reactivation of older structures.

Crustal extension is generally followed by basin cooling (McKenzie 1978, Latin & White 1993), but this does not appear to be the case for the Paraná Basin, where the thermal component remained active. We believe that in the Paraná-Etendeka LIP the movements in regional faults triggered the silicic magma ascent through regional-scale conduit systems.

Geological model for Mato Perso Conduit System

The vitrophyre relative chronology observed in the field favors the hypothesis that oxidized vitrophyres are cut by the conduits. These contain oxidized vitrophyre fragments with variable vesiculation patterns. Transition from breccias,most oftenly, and more oxidized vitrophyre in the borders to grey/black vitrophyre intruding them on the center of the conduits, presence of oxidized bands only in the base of the grey vitrophyres and mixing features between vitrophyres lead us to infer that the described conduits fed at least the upper grey vitrophyre units (Fig. 14).

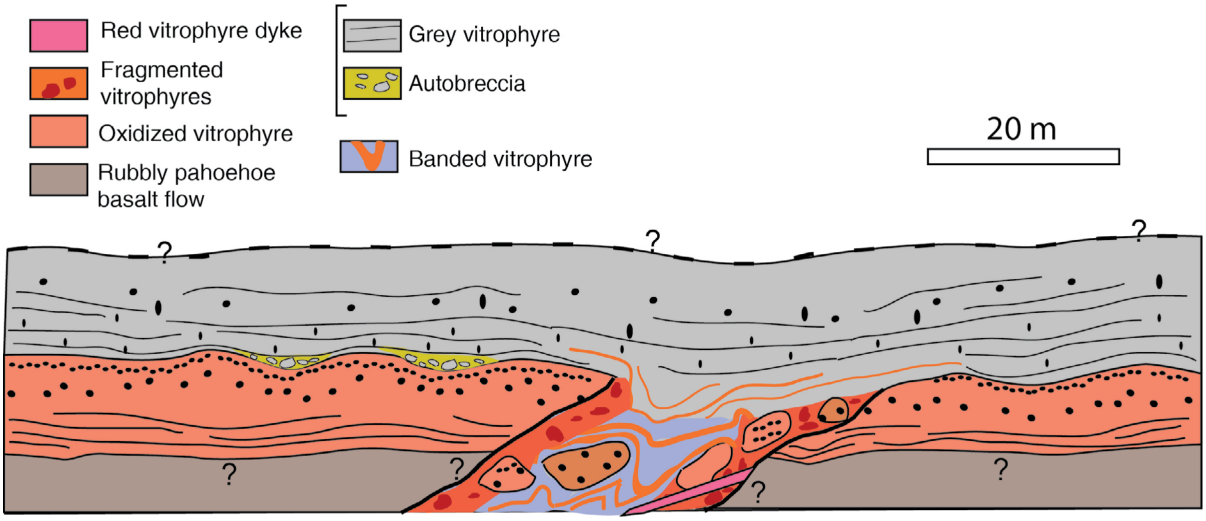

Figure 14. Simplified model for the emplacement of volcanic units in the Mato Perso Conduit System.

CONCLUSIONS

In conclusion, in the Mato Perso area, the silicic volcanic succession overlying the basaltic units of the Vale do Sol Formation, Serra Geral Group, comprises oxidized vitrophyres at the base which are cut and locally incorporated by banded vitrophyres. The conduit system fed the upper grey flat-lying vitrophyres. Subaerial flows are similar to extensive lava flows described in literature, suggesting large emplacement areas. The conduit paths in the crust were conditioned by the normal and oblique faults developed during extensional stages combined with a thermal component in the Paraná Basin. A system sustained at high temperatures ensured that the silicic magma remained in low viscosity during ascent and the emplacement of the upper grey vitrophyre units was driven by effusion rates sufficient for enabling the lava to run at long distances.

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