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Volcanic stratigraphy of intermediate to acidic rocks in southern Paraná Magmatic Province, Brazil

Vulcano-estratigrafia das rochas intermediárias a ácidas ao sul da Província Magmática Paraná, Brasil

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Abstract

This article presents the first map in detail scale for an area covered by Palmas type volcanic rocks in the south border of the eocretaceous Paraná Magmatic Province, south Brazil. The study of the structural features coupled with petrography and geochemistry made it possible to separate these rocks into three main volcanic sequences and recognize their stratigraphy. The older Caxias do Sul sequence rests directly over the first low-Ti basalt flows (Gramado type), and corresponds to the stacking of lobated lava flows, laminar flows and lava domes, mostly emitted as continuous eruptions; only the latest eruptions are intercalated with thin sandstone deposits. These rocks have dacitic composition (~ 68 wt% SiO_2) with microphenocrysts of plagioclase and subordinate pyroxenes and Ti-magnetite immersed in glassy or devitrified matrix. A second volcanic sequence, named Barros Cassal, is composed of several lava flows of basaltic andesite, andesitic and dacitic composition (~ 54; ~ 57 and ~ 63 wt% SiO_2, respectively), with microphenocrysts of plagioclase, pyroxenes and Ti-magnetite. The frequent intercalation of sandstone between the flows attests to the intermittent behaviour of this event. The upper sequence, Santa Maria, is made up of more silica-rich (~ 70 wt% SiO_2) rocks occurring as laminar flows, lobated flows and lava-domes. These rocks have rhyolitic composition with microphenocrysts of plagioclase and Ti-magnetite set in a glassy or devitrified matrix with microlites. The structures and textures of all three silicic sequences favor the interpretation that they had a predominantly effusive character, which is thought to be a reflection of the remarkably high temperatures of the lavas (~ 1,000 ºC).

Keywords: Volcanic stratigraphy; Silicic lavas; Paraná Magmatic Province; Palmas type.

Resumo

Este artigo apresenta o primeiro mapa em escala de detalhe de uma área coberta pelas rochas vulcânicas tipo Palmas, na borda sul da Província Magmática Paraná, de idade eocretácica. O estudo das características estruturais, juntamente com a petrografia e geoquímica, permitiu separar as rochas em três sequências vulcânicas principais, reconhecendo a sua estratigrafia. As rochas da primeira sequência, denominada Caxias do Sul, recobrem fluxos basálticos de baixo Ti (tipo Gramado), e correspondem a um empilhamento de derrames lobados, fluxos laminares e lava domos, emitidos por erupções contínuas. O final da atividade vulcânica é marcado por erupções mais intermitentes, permitindo assim a intercalação de delgados depósitos de arenitos. Estas rochas têm composição dacítica (~ 68 %, em peso, SiO_2) com microfenocristais de plagioclásio, piroxênios e Ti- magnetita imersos em matriz vítrea ou desvitrificada. A segunda sequência, denominada Barros Cassal, é composta por diversos fluxos de lavas de andesito basáltico, andesito e dacito (~ 54; ~ 57 e ~ 63%, em peso, SiO_2, respectivamente), com microfenocristais de plagioclásio, piroxênios e Ti-magnetita. A frequente intercalação de arenitos entre os fluxos atesta o comportamento intermitente deste evento. A sequência superior, Santa Maria, é composta pelas rochas mais ricas em sílica (~ 70%, em peso, SiO_2) que ocorrem como fluxos laminares, fluxos lobados e lava-domos. Estas rochas são de composição riolítica, com microfenocristais de plagioclásio e Ti-magnetita imersos em uma matriz vítrea ou desvitrificada com micrólitos. As estruturas e texturas apresentadas pelas rochas das três sequências ácidas indicam que elas foram geradas por erupções de caráter predominantemente efusivo, refletindo as altas temperaturas do magma (~ 1.000 ºC).

Palavras-chave: Vulcano-estratigrafia; Lavas ácidas; Província Magmática Paraná; tipo Palmas.

INTRODUCTION

The silicic volcanism, although volumetrically subordinate (~ 2.5% of the total volume of magmas), has a remarkable expression in the eocretacic (~135-131 Ma) Paraná Magmatic Province (PMP) if compared to other continental flood basalts (CFB). Importantly, several events of intermediate to acidic volcanism have been identified in the province, and may constitute important tectonic and stratigraphic markers.

The mode of effusion of these rocks has been attracting much interest, since their physical characteristics appear to be distinct from more typical silicic volcanic manifestations, resulting in a unique behavior, with little known analogues (e.g. Branney et al., 2008). It is still poorly understood, requiring detailed field studies and more precise estimates of their physical parameters, since most of their peculiarities may be related to the remarkably high temperatures of effusion, estimated at ~ 1,000°C (e.g. Bellieni et al., 1986; Garland et al., 1995; Janasi et al., 2007a; Lima et al., 2012).

As part of an effort to characterize and understand the mode of emplacement of the silicic volcanism in the PMP, we selected for study an area of ~ 100 km² located within the region where the most expressive manifestations of silicic magmatism occur, in the southern portion of the province, south of the town of Soledade, in the State of Rio Grande do Sul, Brazil. This area was mapped at the 1:50,000 scale, and the results revealed key stratigraphic relationships between different units of intermediate to acidic volcanic rocks, as well as important contemporary sedimentation, thus far poorly known. This article presents these results and discusses their implications for the stratigraphy of the PMP. The field work revealed the presence of various structures that are diagnostic of the mode of emplacement, and the main aspects of these features are presented here as part of the description of the various units. Detailed studies of some of these structures will be presented in a separate article, together with estimates of physical characteristics of the magmas, to support more comprehensive discussions on the volcanology of these occurrences.

SILICIC MAGMATISM IN THE CONTEXT OF THE PARANÁ MAGMATIC PROVINCE

General aspects

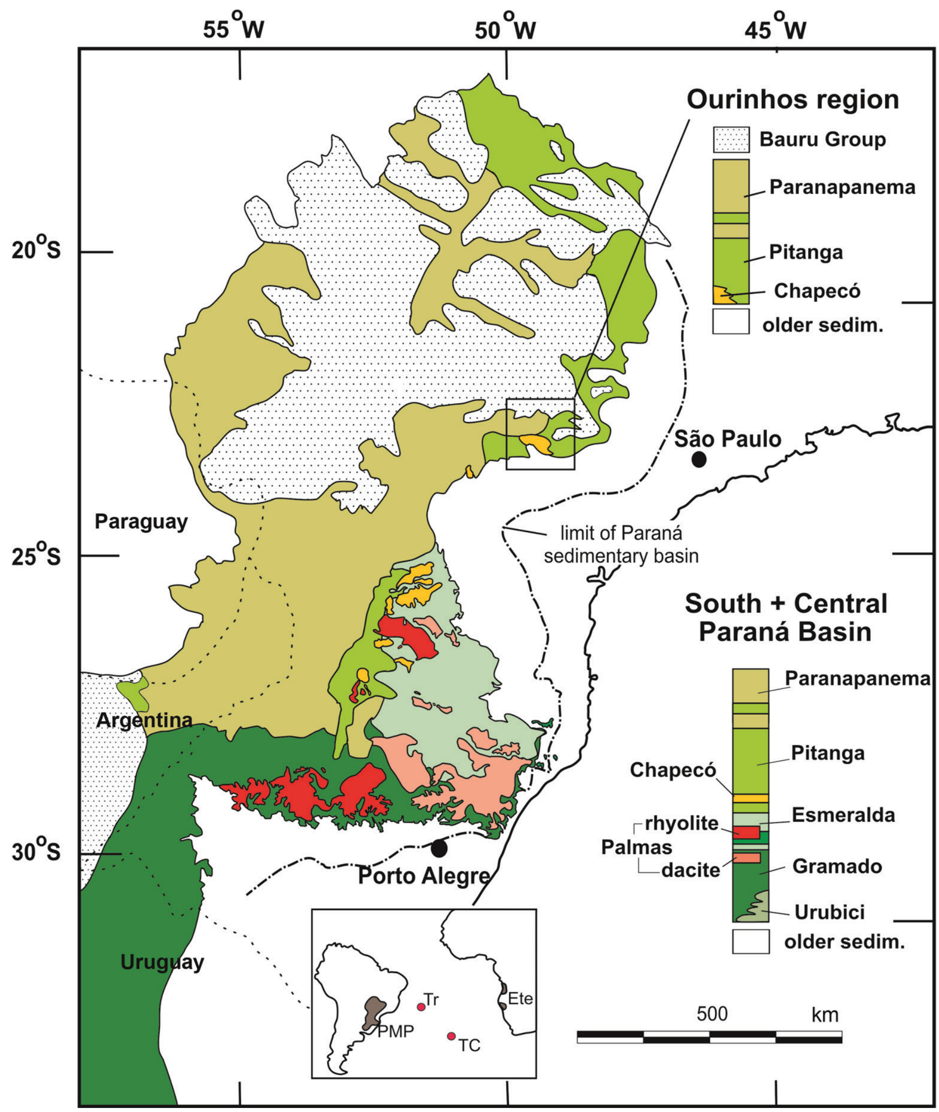
The Paraná Magmatic Province (Figure 1) extends over an area of approximately 900,000 km² in Southern and West-Central Brazil, where the lavas are grouped into the Serra Geral Formation, as well as in neighboring areas in southeastern Paraguay (Alto Paraná Formation), eastern Uruguay (Arapey Formation) and northern Argentina (Curuzú Cuatiá Formation, Posadas Member). The average thickness of the lava pile is estimated around 660 m, with a maximum of 1,700 m along the central axis of the Phanerozoic Paraná Sedimentary Basin; the estimated volume of preserved volcanic rocks in the province is 600,000 km³, of which ~ 450,000 km ³ are extrusive and ~ 112,000 km³ correspond to intrusive bodies such as sills and dikes (Frank et al., 2009). A small remnant of this magmatism is found in Africa (Etendeka; NW Namibia), which was formerly attached to the PMP in Gondwana, and separated by the opening of the Atlantic Ocean in the Eocretaceous; together, the whole province is referred to as the Paraná-Etendeka Magmatic Province (e.g. Peate, 1997).

Stratigraphy

The stratigraphic sequence of the PMP volcanism, as currently understood, is to a large extent based on concepts of chemical stratigraphy, successfully applied in other similar provinces (Cox and Hawkesworth, 1985; Beane et al., 1986; Mangan et al., 1986). This concept was employed by Peate et al. (1990; 1992) in continuous stratigraphic sections surveyed in the field or obtained from sampling of boreholes, and resulted in the distinction of six basalt magma types: three high TiO_2 (Pitanga, Paranapanema and Urubici) and three low TiO_2 (Gramado, Esmeralda and Ribeira). The silicic volcanic rocks were divided into two main types, called Palmas (outcropping in the southern portion of the province and with chemical affinities to low TiO_2 basalts) and Chapecó (outcropping in the north-central portion of the province, and related to high TiO_2 basalts), both further divided into several subtypes (e.g. Peate, 1997; Nardy et al., 2008).

The Gramado type low-Ti basalts correspond to the early PMP volcanic manifestations, and overlay eolian sandstones of the Paraná Basin in the southern portion of the province (Waichel et al., 2006, 2012). They were followed by the Esmeralda type basalts, which exhibit, towards the top, intercalations with silicic volcanic rocks of the low-Ti Palmas type (dacites and rhyolites; Bellieni et al., 1986; Garland et al., 1995; Nardy, 1995; Nardy et al., 2008; Waichel et al., 2012).

The manifestation of the high-Ti magmatism began with the effusion of a lesser volume of silicicic lavas (Chapecó type) that directly overlie the Botucatu Formation eolian sandstones in the northern portion of the province (Piccirillo et al., 1987; Janasi et al., 2007b; Luchetti, 2010), or cover the low-Ti Palmas and Esmeralda types volcanic rocks of the central portion of the PMP (Nardy, 1995; Nardy et al., 2008). The high-Ti basalts (Pitanga and Paranapanema types) are the latest volcanic manifestations of the PMP, covering the northern and western regions of the Paraná Basin (Peate et al., 1992; Peate, 1997).



Source: Modified from Janasi et al. (2011).

Figure 1. Map of the Paraná Etendeka Magmatic Province showing the distribution of the low and high-Ti basalt types and associated silicic volcanic rocks.

The Palmas type silicic volcanism: geochemistry and stratigraphy

Palmas type is the general name given to the low-Ti silicic volcanic rocks which were further divided into five magma types (defined by Peate, 1997, Garland et al., 1995; Nardy et al., 2008). These correspond to two main compositional groups:

a) Rhyolites: with 69-71 wt% SiO_2 and < 0.87 wt% TiO_2, divided into Santa Maria (P_2O_5 < 0.21 wt%) and Clevelândia (0.21 < P_2O_5 < 0.23 wt%);
b) Dacites: with 63-70 wt% SiO_2 and > 0.90 wt% TiO_2, divided into Caxias do Sul, Anita Garibaldi and Jacuí, each presenting a particular geochemical signature with variations in the contents of SiO_2, Ti, Cu, P and Zr (Nardy et al., 2008).

In a more recent study, Waichel et al. (2012) presented stratigraphic cross-sections along the Torres syncline (southern border of the PMP), identifying two main silicic volcanic manifestations (without correlating them to low-Ti magma types defined in the literature), and proposed that the first (AVE-I) resulted in a coalescent lava-dome field, whilst the second (AVE-II) would correspond to tabular flows. Basaltic floods (their BE-III) occur interbedded with these deposits. According to Waichel et al. (2012) and Nardy et al. (2008), the absence of paleosoils attests to short time intervals between the different volcanic events of the low-Ti magmatism.

GEOLOGY OF THE SOLEDADE AREA

The geological map in Figure 2 corresponds to an area of ~ 100 km² located in the southern border of the PMP, south of the town of Soledade, in the State of Rio Grande do Sul, Brazil. Low-Ti Palmas type silicic volcanic rocks are largely predominant; these were deposited over the initial basalt sequence (Gramado type; BE-1 episode of Waichel et al., 2012), exposed to the south of the map area, and are covered, to the north, by younger basalts (Figure 1). Three different sequences of silicic volcanic rocks were distinguished.

The lower silicic sequence is formed by the overlapping of several lava flows and lava domes of dacitic composition and corresponds to the first silicic volcanic manifestation in the region, covering the lower Gramado type basalt flows. The main exposures are in the southern portion of the area, along the Palmeira river valley, where it reaches maximums thicknesses of up to 140 m (Figure 3). These rocks also appear along the valleys of the Fãozinho and Pardo rivers, in the northern and western portions of Figure 2, respectively.

A more mafic and compositionally varied sequence of dacite to basaltic andesite flows overlies this lower sequence wherever the top of the latter occurs below the 420 m topographic elevation (Figure 3). In the central region of the map, this second sequence is up to 100 m thick and is composed of lower basalts, followed by an intercalation of andesitic and dacitic flows towards the top. In places where the top of the lower sequence occurs between topographic levels 380 and 420 m, this sequence is represented by a maximum of two dacitic flows.

The upper silicic sequence has rhyolitic composition, and outcrops throughout most of the mapped area, reaching total thicknesses of up to 400 m (Figure 3).

Sandstone deposits with variable thicknesses and lateral discontinuities occur interbedded with the upper lavas from the lower sequence, interlayered with and above the entire second sequence, and interacting with the base of the upper sequence (Figures 2 and 3).

The chemical composition of samples from all mapped units was used to compare them with magma types previously defined in the literature (Figure 4). Representative analyses are presented in Table 1; petrogenetic inferences based on these results are beyond the scope of the present study, and will be presented in a separate article.

The dacites from the lower unit are compositionally equivalent to the Caxias do Sul subtype whereas the rhyolites from the upper sequence match the composition of the Santa Maria subtype (Figure 4); in order to avoid proliferation of names, we decided to keep these designations.

Correlations of the intermediate unit, itself compositionally diverse (basalt to dacite), are less obvious. Although the basaltic andesites and dacites from this unit show some similarities with the Gramado and Anita Garibaldi subtype, respectively, there are some important differences, such as the more differentiated compositions of the basaltic andesites and the higher TiO_2 contents of the dacites, which are the highest among the Palmas silicic volcanics (Figure 4). Continuous compositional variations and isotope similarity (our unpublished data) indicate that all rock types from this sequence, for which we use a local name (Barros Cassal), are comagmatic.

Caxias do Sul dacites

The Caxias do Sul dacites predominate in the southern portion of the area, along the Palmeira river valley, west of the town of Gramado Xavier (Figure 2). Their thickness may reach over 140 m (the base does not outcrop in the mapped area), and they are composed of simple or compound lava flow lobes and lava domes. The rocks are hipohyaline to hipocrystaline with up to 12% microphenocrysts (0.8 to 1.2 mm) of plagioclase (An_{55-67}; our unpublished electron microprobe analyses), and lesser hypersthene, pigeonite, augite and Ti-magnetite. These crystals are set in a glassy matrix with varying degrees of devitrification hosting microlites (< 0.10 mm) of the same minerals (except hypersthene); these can represent 10 to 30% of the rock. One typical petrographic feature of these lavas is the presence of clusters of microphenocrysts dominated by plagioclase (Figures 5A and 5B).

The rocks have different colors, varying from black to gray to brownish, are massive to strongly vesiculated and/or amigdaloidal, and more rarely brecciated. A wide variety of volcanic structures indicative of their effusive origin was recognized in the field, and is described below:

Lava flow lobes

This flood (constituted by stacking of two or more lava flows) occurs as simple or compound lobes that are recognized by their concentric irregular shapes up to 5 m high (Figure 6), limited laterally or overlain by other lobes of similar dimensions.

Flow structures, such as banding and folding, appear in the center of some lobes. At the base and walls of the flows, the vesicles tend to be intensely stretched and flattened or occur in the form of inverted and twisted drops, which may indicate the direction of the lava flow and attempts of volatiles to escape from the sides, respectively. Vertical cooling joints may be prominent in some exposures.

Laminar flows

Laminar flows or sheet lobes are structurally massive, with joints parallel to the flow; thicknesses are up to 5 m, thinning

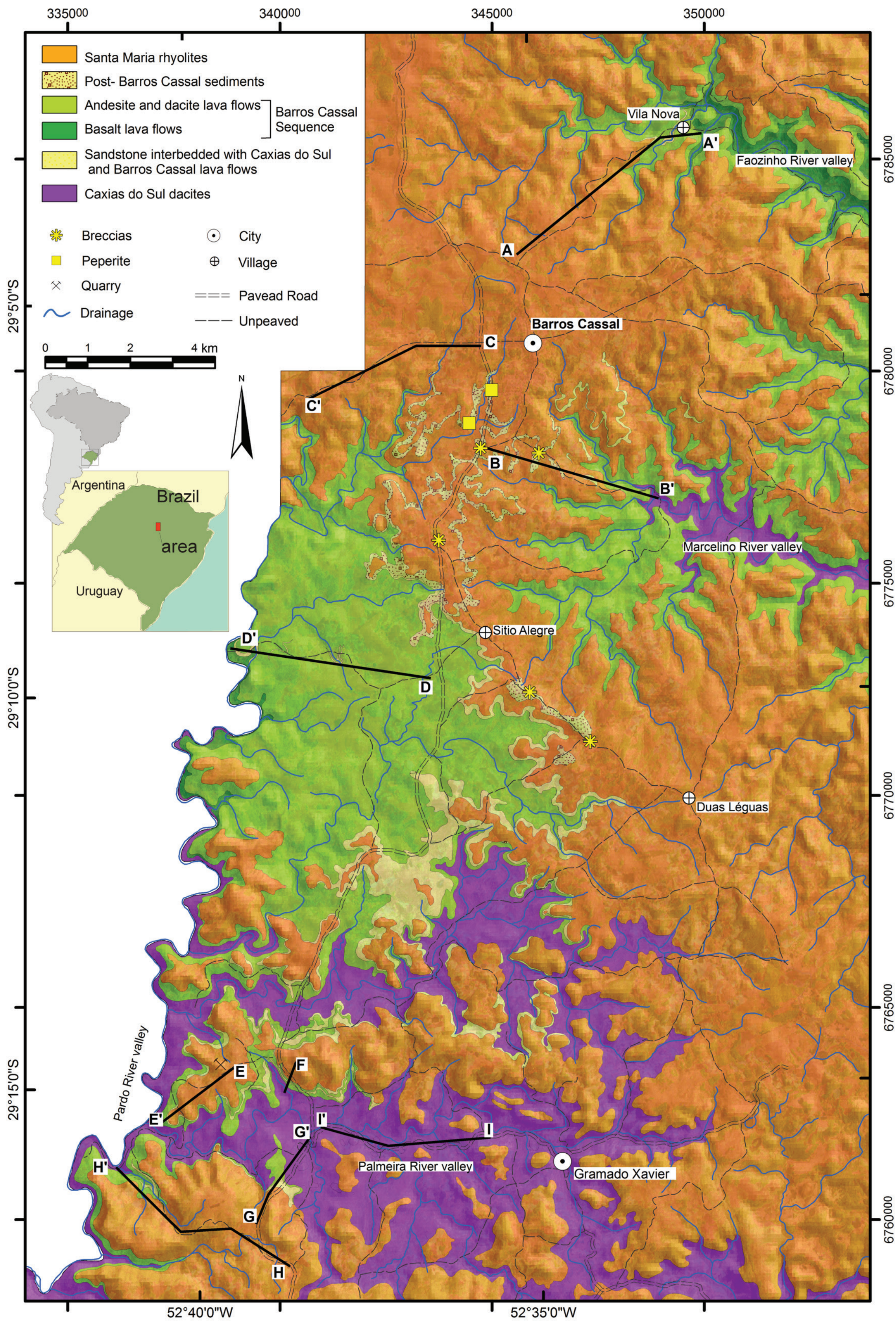
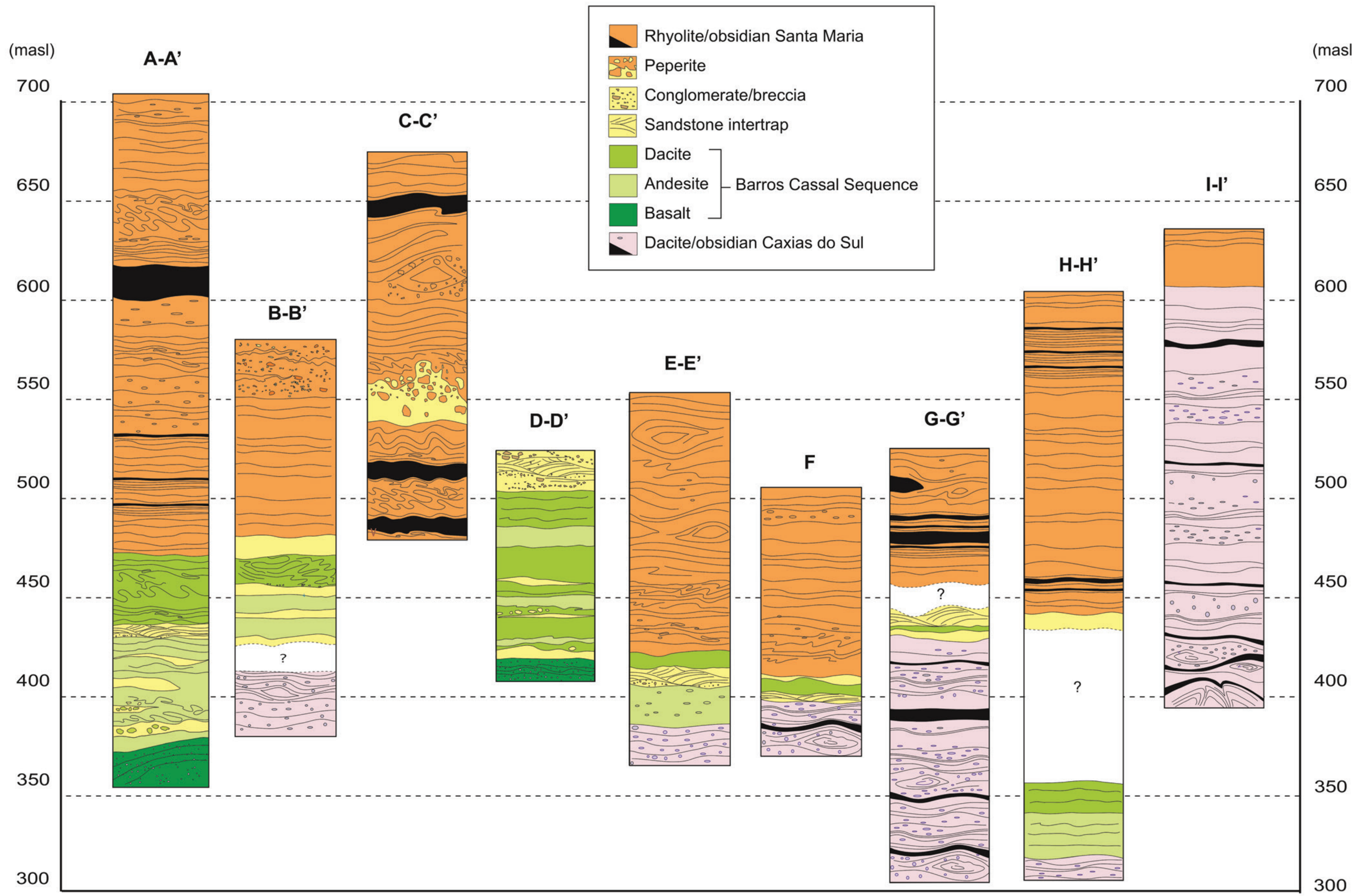


Figure 2. Geological map of the studied area, south of Soledade, Rio Grande do Sul, Brazil.



A-A': northern Barros Cassal to Fãozinho River valley; B-B': Barros Cassal to Marcelino River valley; C-C': Barros Cassal to Pardo River valley; D-D': Sítio Alegre to Pardo River valley; E-E': Quarry to Pardo River valley; F: Outcrop RS-73; G-G': Outcrop RS-74 to Pardo River; H-H': Pardo River to outcrop RS-97; I-I': Highway to Gramado Xavier.

Figure 3. Stratigraphic profiles showing key geological relations in the mapped area.

towards the edge in a gentle dip. These laminar flows can cover lava domes or other flows (simple and compound) and are the most intensely vesiculated lavas. Glassy rock, vesiculated or not, can occur on the top or at the base of the laminar flows, or even forming a single sheet flow (where the thickness of the flow does not exceed 0.5 m). In most cases it is not possible to estimate accurately the number of lava flows (sheeted or lobated) and their total extent, due to discontinuity of the outcrops.

Lava domes

The lava domes are recognized mainly by circular structures (observed in two-dimensional rock cuts) with typical dimensions from 5 to 8 m in height and up to 30 m in length at the base (Figure 7A). They occur individually or are coalescent with other domes, and are covered by lavas. In the most complete outcrops, circular joints can be identified from the center to the edges of the dome, in addition to structures such as "cauliflower-like" (Figure 7B) cooling vertical joints, massive carapace and auto-breccias. Vertical joints at the center of the dome converge to the circular joints, resembling an "onion cut in half".

The terms "dome" and "lobe" may refer to structures of similar shape; in this work we use "dome" for structures of larger size, where features like cauliflower type disjunction for instance may develop.

Lava-sediment interaction

The end of the Caxias do Sul magmatism is coeval with the deposition of sand. This sand filled the fractures of the latest Caxias do Sul lavas and also accumulated in depressions between domes and lava flows, forming small deposits 0.2 to 3 m thick. The fine to medium-grained red sandstone is constituted of round grains of quartz and feldspar, as well as devitrified obsidian and chalcedony.

Barros Cassal volcanic sequence

Basaltic andesite

Basaltic andesite flows outcrop in the Fão and Pardo river valleys, near the town of Barros Cassal (Figures 2 and 3), and are covered by sandstones and andesite lava flows. They ccur as glassy rocks, vesiculated and/or amygdaloidal,

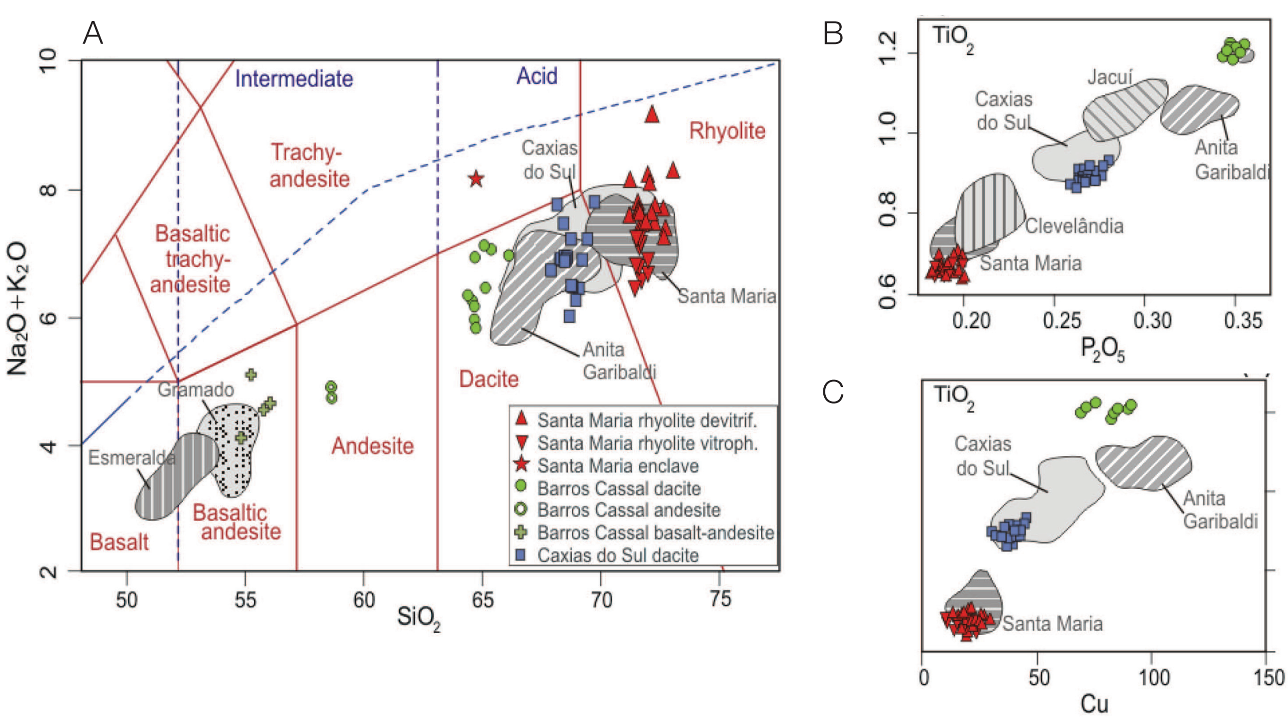
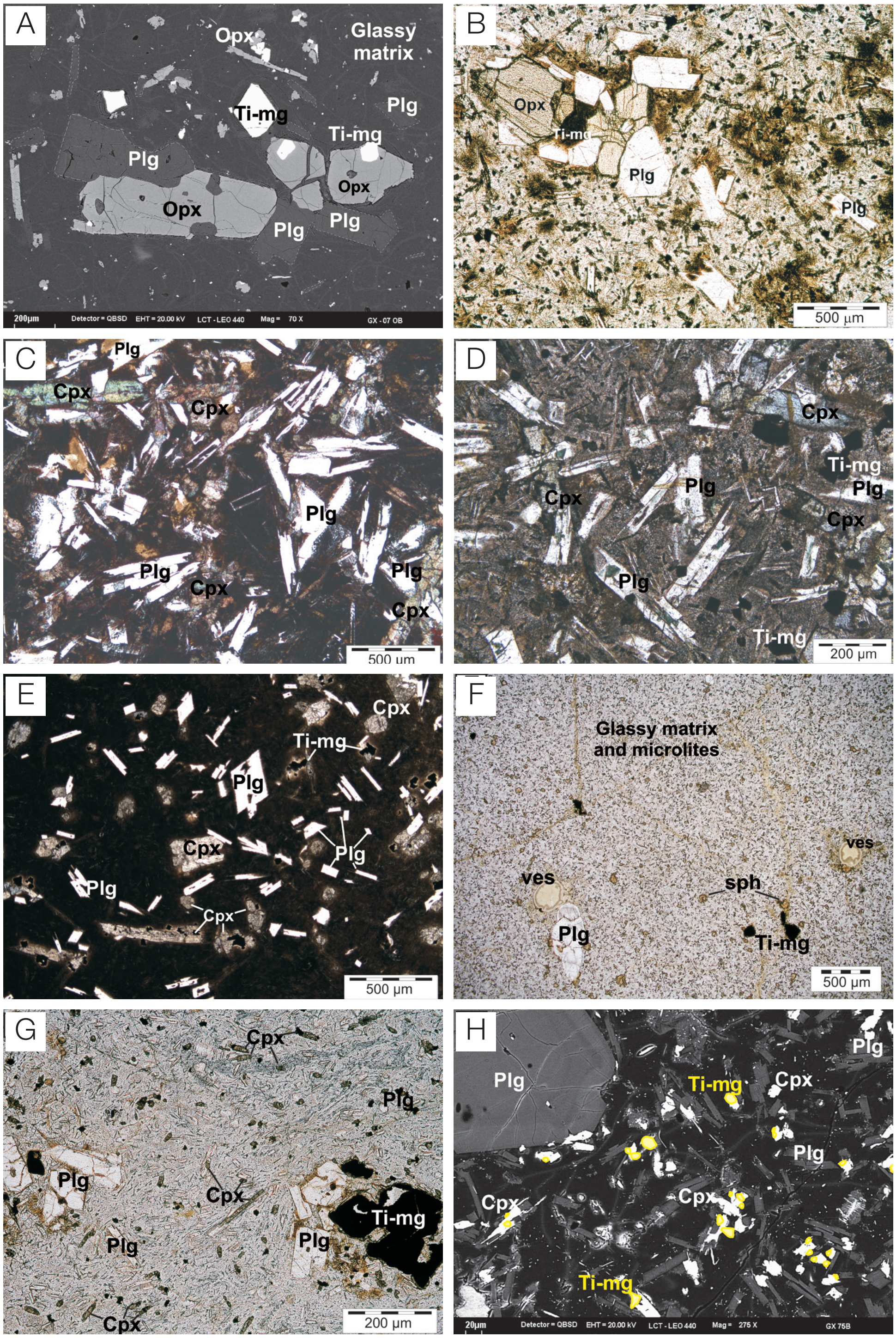


Figure 4. Geochemical discrimination diagrams for silicic volcanic rocks from Soledade region. Fields correspond to the compositions of several subtypes of Palmas intermediate and acid volcanics defined by Garland et al. (1995) and Nardy et al. (2008). (A) TAS diagram, with compositional fields from Middlemost (1994). (B) TiO_2 *versus* P_2O_5 diagram (fields from Nardy et al., 2008). (C) TiO_2 *versus* Cu diagram (fields from Garland et al., 1995).

Table 1. Representative results of chemical analyses of volcanic rocks from the Soledade region. All data from X-Ray Fluorescence (oxides in wt. % and trace elements in ppm).

	Caxias do Sul		Barros Cassal						Santa Maria			
Subtype	(Dacite)		(Basaltic andesite)		(Andesite)		(Dacite andesite)		(Obsidian)		(Rhyolite)	
Sample	RS85	GX7ob	GX09	GX10	GX94	GX113	RS73A	GX95	RS73B	GX35	GX21B	RS73C
SiO_2	67.64	66.01	55.10	54.53	56.96	56.96	62.99	62.82	69.32	69.36	71.97	71.78
TiO_2	0.91	0.87	1.71	1.72	1.49	1.49	1.19	1.20	0.66	0.65	0.64	0.66
Al_2O_3	13.03	12.53	12.83	12.76	12.57	12.62	12.49	12.32	12.18	12.15	11.85	12.21
Fe_2O_3	5.85	5.55	13.76	14.20	12.21	12.10	8.88	8.87	4.93	4.99	4.83	4.71
MnO	0.09	0.10	0.18	0.22	0.17	0.17	0.15	0.16	0.09	0.08	0.07	0.06
MgO	1.38	1.23	3.14	3.31	2.81	2.77	1.55	1.47	0.59	0.61	0.15	0.49
CaO	3.17	3.09	6.96	6.97	6.42	6.36	4.24	4.16	2.01	1.93	1.08	1.45
Na_2O	2.93	3.37	2.69	2.56	2.77	2.82	3.62	3.18	3.02	2.44	2.43	2.66
K_2O	3.92	2.80	1.88	2.48	1.78	1.93	2.21	2.84	3.97	4.63	5.72	4.93
P_2O_5	0.27	0.26	0.30	0.29	0.29	0.29	0.34	0.35	0.19	0.19	0.20	0.18
LOI	1.16	3.74	0.68	0.24	1.22	1.22	2.02	1.56	3.35	3.00	0.84	1.30
Total	100.36	99.55	99.23	99.28	98.69	98.73	99.68	98.93	100.30	100.03	99.78	100.43
Trace elements (ppm)												
Ba	624	584	328	354	400	596	848	619	698	725	813	680
Cu	41	39	166	161	152	157	81	91	20	19	20	19
Nb	22	20	14	13	15	15	18	18	27	26	25	26
Pb	23	15	14	16	18	31	20	18	29	18	19	27
Rb	169	177	75	89	111	98	171	205	238	257	232	220
Sc	17	15	39	39	29	29	20	21	13	13	16	14
Sr	154	153	167	161	173	174	167	163	104	101	80	99
Th	17	12	11	12	12	10	15	14	22	23	22	22
U	9	7	9	9	6	5	4	5	9	11	9	8
V	58	54	399	381	307	281	98	99	24	18	27	39
Y	43	43	38	40	41	45	59	58	55	68	54	58
Zn	76	77	116	114	107	107	105	107	80	83	75	83
Zr	242	237	175	175	203	207	294	291	304	310	300	300



Plg: plagioclase; Cpx: clinopyroxene; Opx: orthopyroxene; Ti-mg: Ti-magnetite; sph: spherulite; ves: vesicule.

Figure 5. Textural and mineralogical features of volcanic rocks from the Soledade region. (A) Clusters of plagioclase phenocrysts with pyroxene and Ti-magnetite immerse in glassy matrix, a typical feature of the Caxias do Sul dacite. (B) Caxias do Sul dacite, with clusters of phenocrysts and partially devitrified brownish (oxidized) glassy matrix. (C-E), respectively, textural aspects of basalt (intersertal texture), andesite (with swallow-tail plagioclase) and dacite (hialophitic texture) from the Barros Cassal sequence. (F-H), textural aspects of Santa Maria rhyolites, showing, respectively, typical aphyric aspect; flow structure and phenocryst aggregates; and the presence of microlites and a zoned plagioclase phenocryst. All images are from optical microscopy with parallel polarizers, except (A) and (H) which are from back-scattered electron microscopy (magnifications 70 x and 275 x, respectively).

Figure 6. Simple lava flow lobe of the Caxias do Sul subtype; note concentric shape in the center of structure.

hipohyaline to hipocrystalline, aphanitic to fine-grained, with seriate or subophitic textures. The matrix can be partially devitrified or altered. Plagioclase, augite and Ti-magnetite occur as crystals of 0.05 to 1 mm, with sub-euhedral, anhedral or skeletal shapes (Figure 5C) and together may represent 30 to 60% of the rock.

The basaltic andesite flows (< 3 m thick) are structurally massive, occurring as sheet lava, except in the Pardo river valley, where lobated structures were recognized, with vesiculated cores and carapaces of the coherent volcanic rock, resembling compound pahoehoe lava. At the top of the package, the last flow is covered by a thin layer of fine red feldspathic sandstone that filled the fractures of cooling lava.

Andesite

The andesite flows outcrop as thin and discontinuous sheet lava up to 3 m thick, intercalated with sandstone deposits, overlying the basalt flows or in direct contact with the Caxias do Sul dacites.

The andesite is a black-gray glassy rock, greenish when altered, and is composed of skeletal to euhedral crystals (0.1 to 1 mm) of plagioclase, augite and Ti-magnetite (Figure 5D), with hipohyaline to hipocrystalline and subophitic textures. Some crystals have features resulting from rapid cooling (e.g. swallow-tail terminations; void crystals). Plagioclase phenocrysts may be zoned and present thin resorbed rims. The glassy matrix may be devitrified or altered.

In a single flow, clastic dykes may be either formed from the base (fed from thin layers of sandstones intercalated to lava flows) or fill the fractures from the top, while features of lava-sediment interaction are visible only at the bottom, with "baked" angular sandstone fragments included in volcanic rock or vice-versa.

The sandstone is red and feldspathic; the deposits are typically thin and may display primary sedimentation structures, like cross-bedding and plane-parallel bedding.

Dacite

The dacite lava flows occur at the top of the sequence or intercalated with andesitic flows. Individual flows have thicknesses up to 5 m, and can be separated by sandstone deposits. In some profiles the Barros Cassal sequence is represented by a single dacite lava flow (Figure 3), sandwiched between the Caxias do Sul and Santa Maria sequences.

The Barros Cassal dacites occur as obsidians of intense black color, with a characteristic frosted luster, and a thin surface layer resulting from oxidation. They are aphyiric hipohyaline rocks with euhedral to subhedral crystals of plagioclase (An_{49-52}), augite, pigeonite and Ti-magnetite dispersed in a glassy matrix (Figure 5E). The crystals (< 30% in volume), ranging from 0.1 to 0.8 mm, may be oriented, and most have features resulting from rapid cooling.

In thick lava flows, irregular folds up to 5 m high occur, and exhibit related features, such as parasitic folds, at different scales.

Structures related to lava-sediment interactions (possible peperites) are common at the base of the flows that cover sandstone deposits. Also common are clastic dykes being formed from the base of the lava or filling fractures at the top with fine sand (Figure 8A).

Sandstones and conglomerates

The sandstones occur as thick (< 10 m) and extensive deposits, with some continuous exposures spreading for over 1.5 km, covering the lavas of the Barros Cassal sequence and underlying a Santa Maria flow (Figure 8B).

They are red colored, immature (feldspar-rich) and poorly selected, medium to coarse grained, with local conglomerate facies, and show some primary structures, such as plane-parallel layering and small to medium-scale cross-stratification. These structures and the presence of coarse facies and clasts (5 to 10 cm) dispersed in sandy matrix are suggestive of lacustrine-alluvial environments. Locally, these sandstones interacted with the rhyolite lavas of the Santa Maria forming peperite structures (see section 3.4.3 – Figure 8C).

Santa Maria rhyolites

The Santa Maria rhyolites constitute the most extensive and thick sequence of silicic volcanic rocks of the region, reaching thicknesses up to 400 m.

The rocks may have crystalline or vitreous aspect. The crystalline varieties are massive or banded (Figure 9), with colors varying from gray to yellow and pink, as a result of different degrees of oxidation or devitrification (spherulitic or, predominantly, granophyric textures). Such bandings are

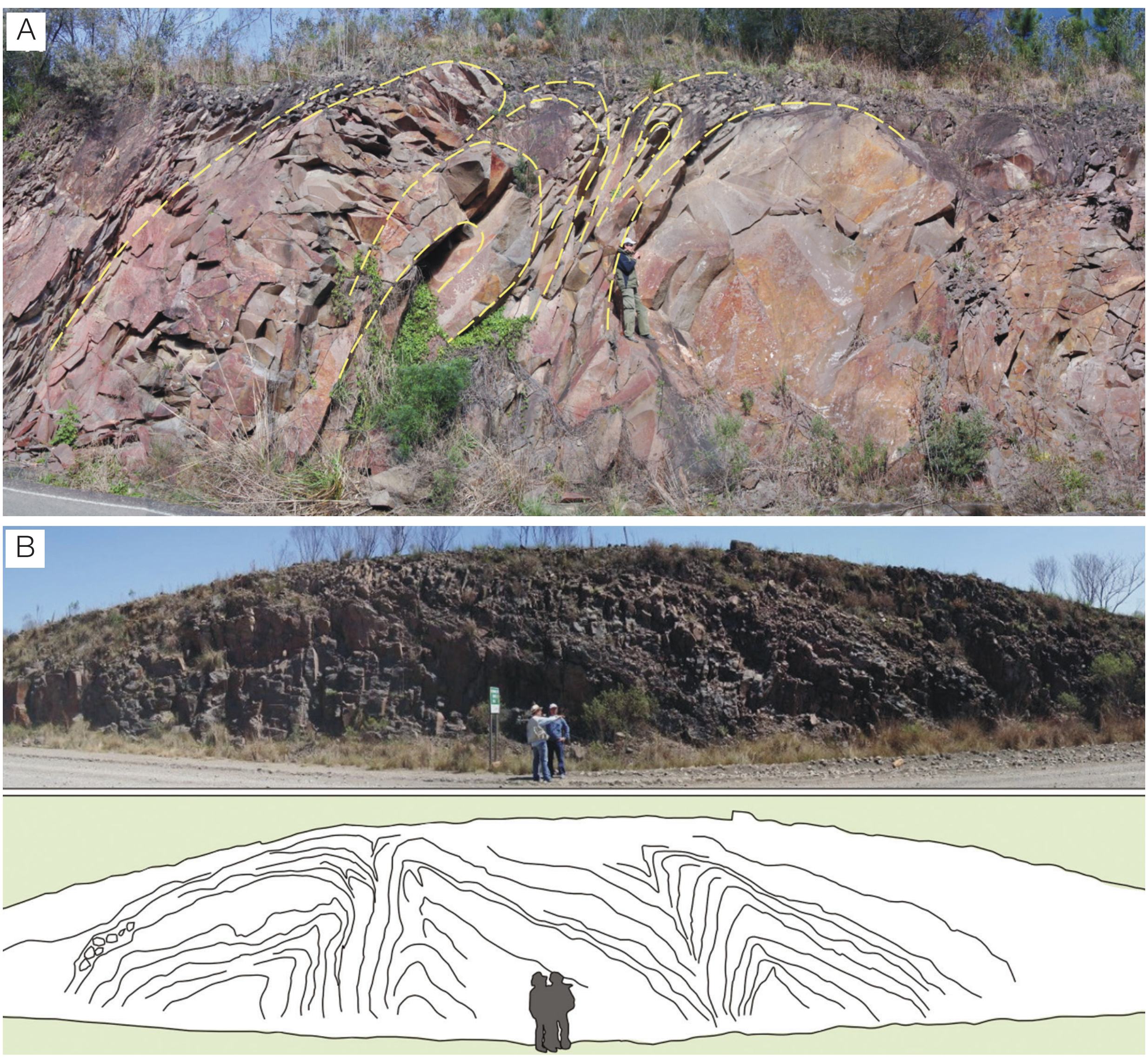


Figure 7. (A) Dacitic lava dome of the Caxias do Sul sequence that outcrop along the Palmeira River valley. (B) Outcrop of top of lava dome, with cauliflower-like structure.

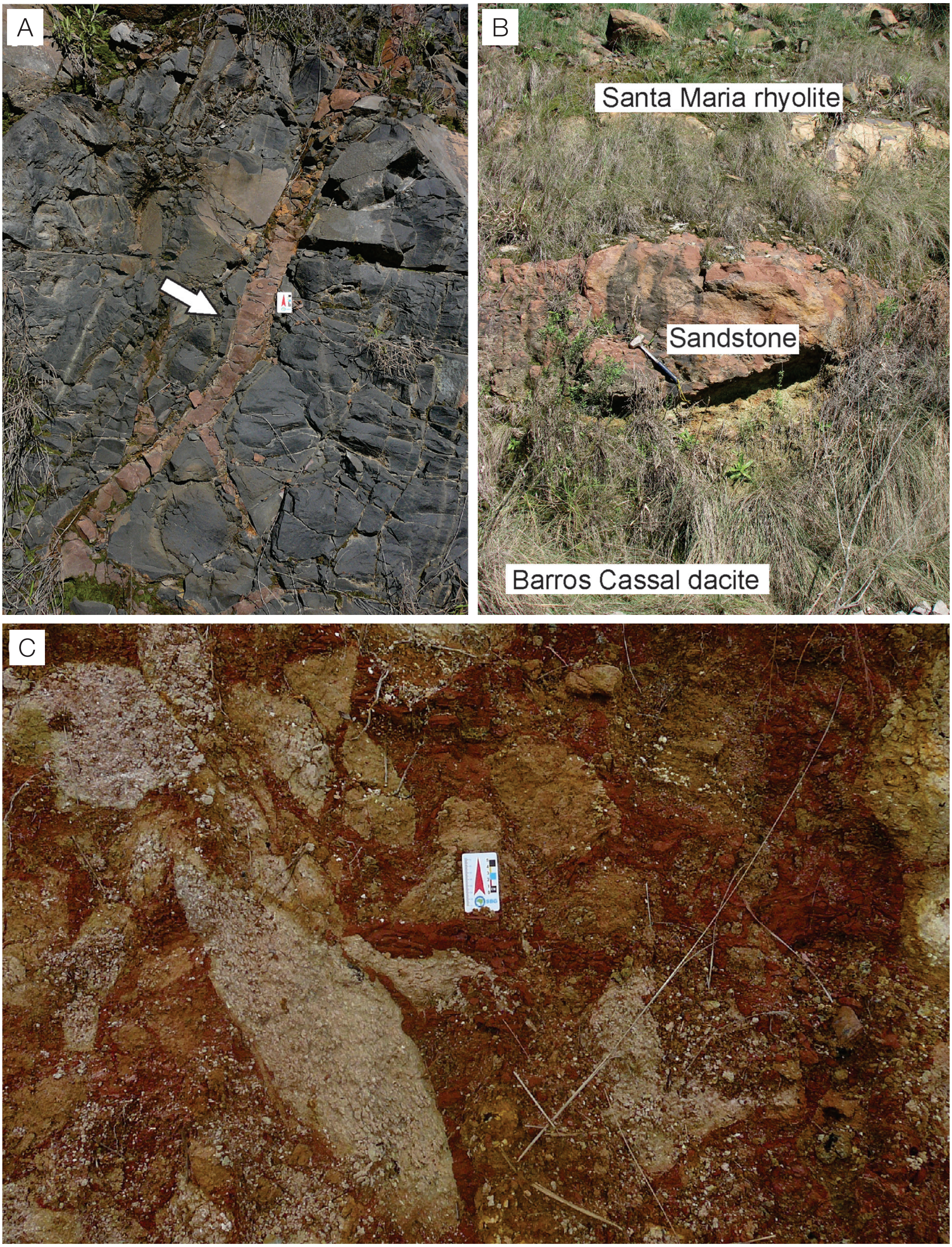


Figure 8. Field aspects of sedimentary deposits associated with the silicic volcanic rocks. (A) Cooling fractures in the lavas filled by sand. (B) Sandstone layer (indicated by arrow) deposited between a Barros Cassal and a Santa Maria flow. (C) Peperite constituted of angular fragments of quench-rhyolite (light) dispersed within "baked" vesiculated sandstone (darker).

Figure 9. Banded structure typical of rhyolites from the Santa Maria sequence.

fairly common in rhyolites, and can result from variations in the original water concentration in the alternating layers (Seaman et al., 2009).

The vitreous varieties are obsidians with high brightness and conchoidal fracture, hipohyaline texture (Figure 5F) and occasional fluidal structures (Figure 5G). Both varieties have scattered microphenocrysts (0.7 to 1.2 mm, rarely achieve 2 mm) of plagioclase (An_{40-60}) and Ti-magnetite, which together account for < 8% of the rock. Microlites (< 0.08 mm) of plagioclase and pigeonite, and more rarely augite, occur in several samples and may represent 5 to 20% of the total constituents (Figure 5H).

Regionally, the Santa Maria rhyolites are the most controversial sequence in terms of mode of emplacement, and are thought by some authors to correspond to rheoignimbrites (e.g. Bellieni et al., 1986; Milner et al., 1992; Bryan et al., 2010). However, the features identified in the studied area, such as laminar flow structure and simple or compound lava flow lobes, are consistent with effusive eruptions, as described below.

Laminar flows

These flows are composed of obsidian, devitrified or not, with massive or banded features which can also present remarkable flow structures with intense folding at their base. At the microscopic scale, features such as fluidal textures marked by the orientation of microlites are observed (Figure 5G).

Flow lobes

The flow lobes may be simple or compound, with diameters up to 4 m (Figure 10). These structures have a carapace of the coherent rock (hard; mostly unweathered) and a glassy core (often strongly weathered and altered to clay material) with fluidal structures and stretched vesicles indicating the direction of flow. Some lobes are covered by a laminar lava flow which caused a deformation of the lobe due to overload.

Autobreccia structures were observed in some outcrops (Figure 11), constituting the base, margins and front of lava lobes and lava domes. Their main features are:

(i) concentric shapes of the flow with obsidian cores, 3 to 4 m in diameter, exhibiting several flow features, such as folds and spirals;
(ii) angular lava clasts, up to 50 cm large, with varying textures: banded, massive, vesicular, devitrified and glassy;
(iii) discontinuous lenses of breccias in the margins of the flow with or without glassy matrix;
(iv) banded and deformed obsidian lenses at the base and lateral margins of the lobe;
(v) presence of sandstone fragments resulting from interaction with sedimentary deposits.

Peperite

Peperites, which are interpreted as results of "in situ" disintegration of hot lava that interacted with unconsolidated or poorly consolidated wet sediment (White et al., 2000), are present in some outcrops west of the locality of Barros Cassal (Figures 2 and 3).

The deposits are constituted by fragments of quench-rhyolite dispersed within a "baked" and vesiculated sandstone; the perfect arrangement between volcanic fragments (as jigsaw puzzle) reveals that the lava was fragmented in situ and did not undergo reworking (Figure 8C). The volcanic rock presents thermal contraction cracks filled with sand.

Lava-domes

These lavas correspond to thick flows (up to 200 m), with lobated and auto-brecciated margins or fronts, and may be divided in three sections:
(i) the lower section is constituted by black vitrophyre interlayered with banded rhyolite of varied thickness and pink, red, yellow or gray colors; abundant flow folds (< 2 m wavelength), stretched or flattened vesicles and horizontal jointing may occur;
(ii) the middle section is constituted of devitrified rhyolites, which can be massive or banded, and always show vertical cooling fractures; in larger vertical exposures, this portion may show larger folds and concentric fractures similar to internal structures observed in smaller lava lobes;
(iii) the upper section is composed of massive and devitrified rhyolite with strong horizontal jointing and open folds. This structure is similar to those described in the SR type (Snake River) lavas defined by Branney et al. (2008).

DISCUSSION

Mode of emplacement

The distinction between large-volume silicic lava flows and rheomorphic ignimbrite deposits is still a very controversial topic. The features of both are very similar and few evidences can aid in their differentiation (e.g. Wolff and Wright, 1981; Henry and Wolff, 1992; Manley, 1995; Umann et al., 2001; Sumner and Branney, 2002). Furthermore, the events generating rheoignimbrites are unusual; these deposits rarely are well exposed; the top of the flows, which may bring important evidence, can be easily eroded; and the location of vents is often unknown.

In the PMPE, the silicic volcanic rocks have been cited as an example of rheoignimbrite deposits generated by explosive eruptions of large magnitude (e.g. Milner et al., 1992, 1995; Bryan et al., 2010). It is remarkable, however, the

Figure 10. Lobe of a compound lava flow of Santa Maria rhyolites, showing the carapace of coherent rock and the strongly weathered glassy core.

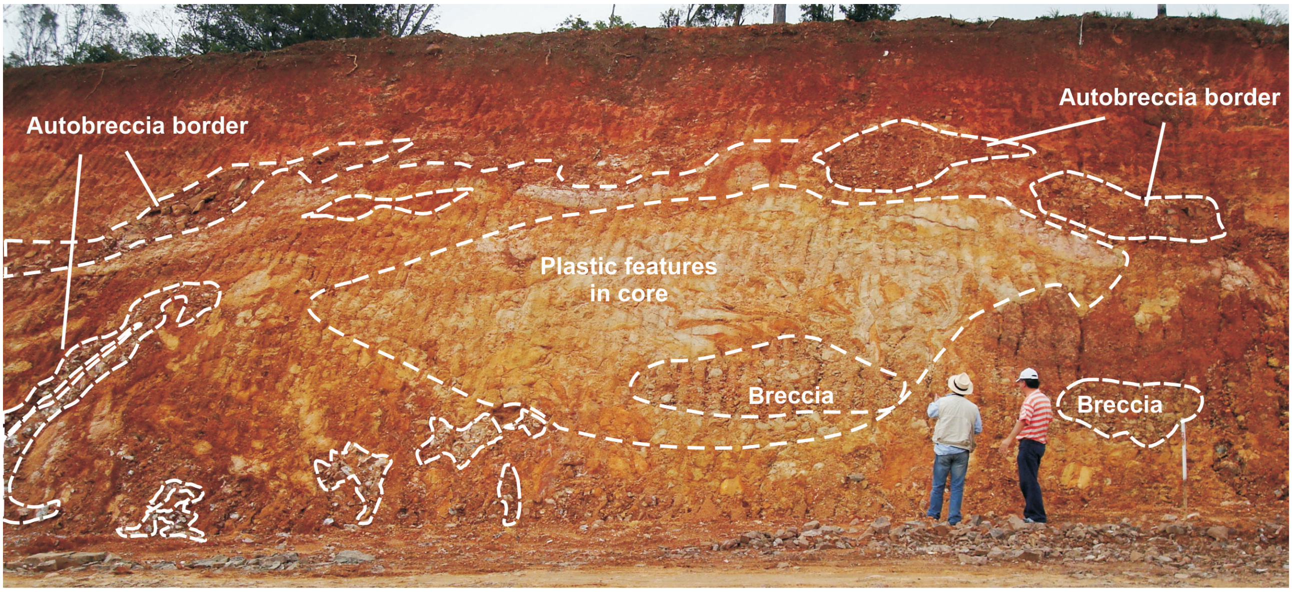


Figure 11. Large concentric auto-breccia structure in a compound Santa Maria lava lobe. These lavas exhibit internal structures such as folds and spirals in the obsidian, discontinuous lenses of the breccias without matrix, and angular fragments of the coherent volcanic rock disperse in a glassy matrix.

absence, or rarity, of pyroclastic features, and also the lack of the vertical or lateral welded zoning typical of deposits of this size and nature. Another aspect of particular interest are the high temperatures estimated for these magmas (~ 1,000ºC), which may result in singular volcanic behaviour, with few known analogues.

Our results, and in particular the structures identified and described above, such as laminar lava flows, simple and compound lava lobes, lava domes, auto-breccia and peperites, as well as the textures of the main rock types (non fragmented crystals and absence of shards and/or fiammes), led us to conclude that all three silicicic volcanic sequences from the Soledade region are largely dominated by effusive deposits, with very subordinate products of explosive processes. The wide distribution of these deposits was probably facilitated by low viscosities, resulting from anomalously high (~ 1,000ºC), near-liquidus eruptive temperatures combined with high rates of extrusion.

Evolution of the silicic magmatism in the Soledade region

The Palmas type volcanic eruptions started with the effusion of lava flows and lava domes of dacitic composition identified as the Caxias do Sul subtype. These eruptions took place continuously, i.e. without large time intervals between emissions, producing a thick stack of lava. The textural differences among the different flows (i.e. amount of microlites and/or vesicles, rate of devitrification and/or oxidation), as well as shape, thickness and length of each flow deposit were controlled by several interdependent variables, such as temperature, rate of discharge, distance from the vent, viscosity of the lava, etc; a more in depth discussion of these parameters will be presented in a separate article.

The latest eruptions of the Caxias do Sul magmatism occurred intermittently, allowing the intercalation of small sandstone deposits, which show some interaction with the lavas. The feeder conduits of these lavas were not mapped in the region; however, Lima et al. (2012) found in the São Marcos region (~ 80 km to the east of the study area) dike-like structures associated with their AVE-I silicic volcanic sequence, which we correlate with the Caxias do Sul sequence, supporting the idea that their extrusion occurred through fissures.

The paleo-relief formed at the end of the Caxias do Sul volcanism permitted the accumulation of small and discontinuous sand bodies that were deposited contemporaneously with the basaltic, andesitic and dacite lava flows of the Barros Cassal sequence. Paleo-relief played an important role in the distribution of the Barros Cassal sequence, which attained greater thicknesses where the upper Caxias do Sul lavas outcrop below the topographic elevation of 320 m (cf. profile D-D', Figure 3). In areas where the top of the Caxias do Sul sequence outcrops between 380 and 400 m, no more than two dacite lava flows of Barros Cassal are present (with thicknesses < 1 m), whereas in areas where the Caxias do Sul flows outcrop at higher elevations (along the Palmeira river valey, elevations between 400 and 500 m) the Barros Cassal sequence is absent. Sand deposits are similarly controlled by the topography left by the Caxias do Sul episode, and thus the greater thicknesses are observed where the latter occur in the lowest elevations.

The feeder conduits of the Barros Cassal lava flows were also not identified in the region. The frequent intercalation of sandstone between the individual flows attests to the intermittent behaviour of this volcanic event.

After the initial output of Santa Maria rhyolite lava sequence, which generated the first thin and laminar obsidian deposits, the discharge rate of the lavas increased, resulting in the formation of lava domes. These structures reached thicknesses up to 200 m, with lobated terminations and formation of autobreccia. Feeding through fissures, similar to the mechanism advocated for the outpouring of the PMP basalts, and proximity between feed channels, may have favoured the coalescence of these lava domes, resulting in the extensive plateaus that are typical of the area of exposure of this sequence.

Regional correlations and implications

The stratigraphic succession identified by our mapping survey reveals that the Palmas type silicic volcanism in the Soledade region consists of three main eruptive episodes.

The lowermost stratigraphic position of the Caxias do Sul dacites is in agreement with previous regional observations, as indicated in the works of Peate et al. (1992) and Nardy et al. (2008).

The subsequent Barros Cassal sequence, consisting of several basaltic, andesitic and dacitic lava flows interlayered with sandstone deposits, has no exact chemical equivalents among the Palmas subtypes of silicic volcanic rocks. Some previous studies report the presence of lavas of basic and/or intermediate composition above the first silicic volcanic sequence (Peate et al., 1992; Waichel et al., 2012). The more primitive Palmas subtypes, which show most similarities with the Barros Cassal mafic dacites, are apparently found in a similar stratigraphic position (Anita Garibaldi and Jacuí, as described by Peate, 1997 and Nardy et al., 2008, respectively).

The uppermost position of the Santa Maria unit is consistent with stratigraphic information from previous references (e.g. Peate et al., 1992, Garland et al., 1995; Nardy et al., 2008) which point out that the younger Palmas type volcanism has more differentiated composition (rhyolite) throughout the PMP. They must be correlated to the second silicic sequence (AVE II) described by Waichel et al. (2012).

CONCLUSIONS

The Palmas type volcanism from the southern PMP in the Soledade region consists of three main eruptive episodes characterized by silicic magmas of distinct geochemical signatures. The structures characteristic of the lava flows observed in the volcanic sequences and the rock textures favour the interpretation that all these silicic eruptions had a predominantly effusive character.

The intercalation of sedimentary deposits beginning in the last episodes of the first (Caxias do Sul) sequence and continuing throughout the whole time span of the magmatism reflects the generation of paleo-relief associated with the emplacement of the silicic magmas, and constitutes important markers of the intermittent character of the effusive episodes.

We evaluate that the results presented in this work encourage the combined use of field and geochemical tools to solve stratigraphic and volcanological problems in the study of the silicic magmatism in the PMP. More detailed petrological, geochemical and volcanological studies focusing on the individual units will be the focus of other articles, currently under preparation.

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