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New insights on the occurrence of peperites and sedimentary deposits within the silicic volcanic sequences of the Paraná Magmatic Province, Brazil

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Abstract

In the Paraná Basin (southern and southeastern Brazil), the stratigraphy of the Paraná Magmatic Province (PMP) is composed of a thick (up to 1600 m) volcanic sequence formed by a succession of petrographically and geochemically distinct units of basic and acidic composition. The whole package may have been emplaced in approximately 3 million yr of almost uninterrupted activity. A few aeolian sandstone layers, indicating arid environmental conditions (Botucatu Formation), are interlayered in the lower basalts. Above the basalts, the Palmas and Chapecó Members of the Early Cretaceous Serra Geral Formation, are composed of silicic volcanic rocks (trachydacites, dacites, rhyolites, and rhyodacites) and basalts. This paper presents new evidence of episodes of sedimentation separating silicic volcanic events, expressed by occurrences of sedimentary deposits. Interaction between the volcanic bodies and the coeval unconsolidated sediments formed peperites. The sediments were observed between basaltic lava flows and silicic rocks or interlayered in the Palmas type rocks, between Chapecó type rocks and underlying basaltic flows, between silicic bodies of Palmas and Chapecó types, and interlayered with Palmas type units. The observed structures indicate that the sediments were still wet and unconsolidated, or weakly consolidated, at the time of volcanism, which coupled with the sediment features reflect environmental conditions that are different from those characterizing the Botucatu arid conditions.

1 Introduction

The Early Cretaceous Serra Geral Formation is the result of a major volcanic phase that covered about 917 000 km^2, about 60 % of the surface of the Paraná Basin (Frank et al., 2009; Fig. 1). Three main petrographic types can be distinguished from macroscopic observation of these rocks. The most common corresponds to basalt presenting predominant intergranular texture and its variations (subofitic, intersertal, hialofitic, etc).

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The other two types, corresponding to rocks of acidic composition present massive and aphiric textures (Palmas type – ATP) and porphyritic textures (Chapecó type – ATC).

These macroscopic characteristics allowed an easy separation in the field of these two members of the Serra Geral Formation and their geological mapping (Bellieni et al., 1983; Piccirillo et al., 1988). The Palmas and Chapecó rock-types occur in association with basaltic flows that are more frequent near the top and bottom of these two lithostratigraphic units. Geological mapping also shown that Palmas and Chapecó Members cover 63 000 km^2, in the states of Paraná, Santa Catarina, and Rio Grande do Sul. The volume the two members amounts to approximately 14 500 km^3, which correspond to 2.5 % of the total volume of the Serra Geral Formation (Nardy et al., 2002, 2008). Geochronological dating by $^{40}Ar/^{39}Ar$ show that the age of volcanic rocks of the Serra Geral Formation range from 133.6 to 131.5 Ma in its northern sector, and from 134.6 to 134.1 Ma in the south (Renne et al., 1992, 1996a, b; Turner et al., 1994; Ernest et al., 1999, 2002; Mincato et al., 2003; Thiede and Vasconcelos, 2010; Pinto et al., 2010). More recently, Janasi et al. (2011), using U/Pb ratios from baddeleyite/zircon crystals determined by ID-TIMS from rocks of the Chapecó Member, obtained an age of 134.3 ± 0.8 Ma, compatible with the previous age determinations. However, ages obtained in the dominant basaltic flows indicates duration of the volcanism of around 3 Ma, which is consistent with paleomagnetic data presented by Ernesto and Marques (2004).

Up to now, the presence of sediments (sandstones of the Botucatu Formation) intercalated in the volcanic sequence was only reported in the lower basaltic pile. These consist of sand bodies presenting aeolian structures such as bypass surfaces, single-dunes, sand-filled cracks, multi-dune ergs, representing a desert environment that persisted during the voluminous initial phase of basaltic volcanism.

In this work, the occurrence of sedimentation and development of associated peperites in the final stages of the PMP volcanic event, is presented.

The sediments, dominantly pelitic, and unrelated to the Botucatu Formation, indicate a change in the environmental conditions in the Paraná Basin, and attest to the occurrence of significant periods of quiescence during the final stages of the magmatic activity.

2 Petrographic and geochemical aspects of silicic volcanic rocks

The acidic volcanic rocks of Palmas type (ATP) are characterized by light-gray to brownish red color, hipohialine-holohialine aphiric texture with a striking salt-and-pepper aspect. The mineralogy is composed of dominant micro phenocrystals (granularity smaller than 0.2 mm) of plagioclase (labradorite) constitutes up to 16 % of the total volume of the rock, 11 % of augite, 3 % of pigeonite, 5 % of magnetite, and less than 1 % of apatite. These crystals often exhibit rapid cooling structures, developing skeletal, acicular, and hollow shapes, or cusp-shaped terminations. The matrix reaches 63 % of the rock volume on average, and is composed of dark-brown slightly birefringent glass, characterized by a granophiric texture of abundant intergrowth microlites of alkali feldspar and quartz, which completely surrounds the crystal phases. When holohialine (pichstone) these rocks show black color and prominent concoidal fracture. However, due to its amorphous nature, the glass alters easily and thus in most outcrops the rock is completely weathered, presenting a brownish color and (often resembling sedimentary deposits) dotted with abundant vesicles and quartz-filled amygdales up to 10 mm in length.

The acidic volcanic rocks of the Chapecó type (ATC) are porphyritic, with an average of 24 % of plagioclase phenocrystals up to 2 cm long, in a light gray (when fresh) to brown (when weathered) aphanitic matrix. The mineralogy consists of euhedral andesine phenocrysts in a matrix composed of 4.5 % of augite, 2.2 % of pigeonite, 3.7 % of magnetite, and 1.7 % of apatite (average composition) surrounded by a mesh of quartz and alkali feldspar in a felsitic, locally granophiric, arrangement (vitrophiric texture).

The geochemical data presented in this study were obtained from a set of 250 samples of fresh acid rocks (LOI < 2 wt %). Major and trace elements were carried out at Unesp laboratories, using X-ray fluorescence spectrometry. Major elements were anal-

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ysed using fusion beads (1 : 10 lithium tetraborate) while trace elements were obtained using pressed (30 t cm^{-2}) powder discs (mixed with 25 wt% of micropowder wax). All methodology (including errors) was described in Nardy et al. (1997). REE were analysed by ICP-OES, using chromatographic concentration of elements, and the analytical approach are presented in Malagutti et al. (1998). U and Th were obtained by alpha spectrometry at IAG-USP laboratories, using the methodology presented by Santos et al. (2002) and Santos et al. (2004). The bulk-rock representative compositions for both Palmas and Chapecó types are listed in Table 1.

The chemical composition of volcanic rocks of the Paraná Magmatic Province shows two main groups which may be observed in a R1 × R2 diagram (De La Roche et al., 1980). The first one, Low-Ti suite, belongs to tholeiitic field (tholeiitic basalts, andesibasalts and andesites) associated to Palmas type silicic volcanic rocks, the latter ploted in the rhyodicite and rhyolite field. The second group, High-Ti suite is displaced towards the transitional field (transitional basalt, lati-basalt and latites). The Chapecó type silicic volcanic rocks belong to this group in the rhyodacite and quartz latite fields (Fig. 2).

According to Bellieni et al. (1984a) the chemistry of the volcanic rocks and their spacial distribution allow the Paraná basin to be schematically subdivided into three main regions: (1) southern, encompassing the tholeiitic suite in the southern Uruguay River alignment; (2) northern, where tholeiitic-transitinal rocks occur in the northern Piquiri River alignment; and (3) central, located between Piquiri and Uruguay Rivers alignments, where both rock types are present, (Fig. 1).

The major and trace elements signatures, of ATC type is quite different compared to the Palmas type. The ATC have lower SiO_2 contents (63.37 % to 68.37 %) than Palmas (63.00 to 72.07 %) although, for a same concentration of SiO_2, ATC is alkalis enriched (from 7.45 % to 8.34 %) compared to ATP (from 5.98 % to 8.64 %). ATC rocks belong to the thrachyte field, while ATP rocks are ploted in the rhyodacite and rhyolite fields in the TAS diagram (Le Bas et al., 1986 – Fig. 3). Harker diagrams (Fig. 4) shows that ATC is enriched in TiO_2, P_2O_5, Al_2O_3 and Fe_2O_3 compared to ATP, which are enriched in CaO and MgO compared to ATC.

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The spidergram of incompatible trace element ratios of silicic rocks normalized to primordial mantle (Sun and McDonough, 1989 – Fig. 5), shows a similar pattern of distribution of trace elements, although the ATP rocks are more Rb / Ba, U / Nb and Ce / Sr enriched than ATC. In this way, the ATC rocks are Nb, La, Ce, Zr, P. Nd, Y, Yb, and K enriched; and Rb, Th and U depleted, when compared to ATP.

The differences in chemical concentration of major, trace and incompatible elements are notable, since the ATP rocks cannot be generated by partial melting or fractional crystallization from ATC rocks, or from the same parental source.

The spatial distribution of the tholeiitic – ATP and transitional-tholeiitic-ATC suites suggest that acidic volcanic rocks may have derived from the associated basalts, or ATC melts are derived from tholeiitic-transitional basalts and ATP from tholeiitic basalts, more or less contaminated by continental crust, as suggested by the spidergram of Fig. 5.

3 Stratigraphy

The 1600 m thick Paraná Magmatic Province (PMP) volcanic sequence consists of up to 32 lava flows of predominant basic to intermediate composition (basalts, andesi-tholeiitic basalts, and andesites), as well as felsic volcanic rocks (dacites, rhyodacites, and rhyolites; Bellieni et al., 1984, 1986).

The base of the stratigraphic column is composed of a thick sequence of basic to intermediate flows that overlap the aeolian sandstones of the Botucatu Formation. The sandstones may also occur interlayered in the first hundred meters of the basaltic pile. The Palmas and Chapecó Members overly the basalt flows. The Palmas Member is characterized by silicic volcanic bodies (ATP type) associated with a few basaltic lava flows, crops out from the central region of the basin southwards, where it may reach a thickness of 270 m.The Chapecó Member, exclusively composed of silicic volcanic rocks (ATC type), occurs in the northern and central regions of the Paraná Basin; the largest thickness, reaching 250 m, is present in the central region. It overlaps the

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basalts, but in the northern portion of the basin (Paranapanema River region – SP) may also be found directly on the sandstones of the Botucatu Formation.

In the center of the basin the two silicic members overlap showing that the Palmas Member is older than Chapecó, although ATC type rocks may be found interlayered in the Palmas Member.

The last pulses of Paraná volcanism volcanic emplaced basalt flows that cover both the Palmas and Chapecó type rocks and become thicker towards the north of the basin.

4 Peperites and sedimentary deposit

The Literature (Marques and Ernesto, 2004; Thiede and Vasconcellos, 2010) indicates that magmatism of the PMP occurred quickly, during a time interval that did not exceed 3 Ma, and in a rather continuous way, which was supported by the scarce observations of sedimentary intercalations or paleosols within the volcanic sequence. However, recent field work revealed the presence of frequent sediment lenses and peperites in various stratigraphic levels of the silicic volcanic sequence.

Peperite is as genetic term used for rocks formed in situ by the interaction between volcanic rocks and coeval sediment. The volcanic bodies interacting with sediment can be intrusive, in the form of lava flows, or pyroclastic deposits, and the sediment can be unconsolidated to partially consolidated and typically wet (Fisher, 1960; Williams and McBirney, 1979; White et al., 2000; Skilling et al., 2002). Nonetheless, interaction with dry sediment has also been described by some authors (Jerram et al., 1999; Jerram and Stollhofen, 2002; Waichel et al., 2007, 2008). Peperite is classified into two basic types according to the shape of its elements (Busby-Spera and White, 1987): blocky, in which the volcanic clasts present angular shapes and show jigsaw-fit texture reflecting in situ quench fragmentation in a brittle state; and fluidal in which volcanic clasts present irregular, fluid (amoeboid), globular to undefined shapes, reflecting a ductile state during fragmentation, with the sediment often filling vesicles and fractures in the volcanic clasts. These types correspond to two extreme of a continuum and interme-

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diate or more complex shapes may also be found (McPhie et al., 1993; Skilling et al., 2002).

Sedimentary deposits and peperites found in the Chapecó and Palmas Members present a wide distribution in the Paraná Basin, as shown in Fig. 6, are described below.

In the São Jerônimo da Serra (Paraná State) region, in the northern sector of the Paraná Basin, silicic rocks of the ATC type overly a sandstone forming peperite with fluidal and blocky features (Fig. 7). It comprises clastic dikes a few centimeters to just over 1 m thick (Fig. 7a) and breccias composed of matrix-supported angular to rounded volcanic blocks of variable size (Fig. 7b). The sandstone is poorly sorted with angular to rounded quartz grains (Fig. 7c and d) and it was silicified by thermal metamorphism by the overlying volcanic material.

In the region of Mangueirinha and Palmas (Paraná State), in the center of the basin, both ATC and ATP type rocks crop out, either overlying basalts or overlapping each other. A sandstone layer was observed intercalated between a silicic body of the ATC type and the overlying basaltic lava flow. The base of the sediment is a breccia formed by vesicular clasts of ATC rock material set in a sandy matrix, implying some degree of erosion of the top of the lava body during sedimentation. In another location, a vesicular ATC type silicic unit overlies another silicic body of the ATP type, with a red clayey-silty sediment intercalated between the two units. The sediment was injected upwards into fractures in the overlying ATC unit forming a peperite with both fluidal and blocky features (Fig. 8a and b), while in the underlying ATP unit, the sediment filled cooling joints without any peperitic interaction (Fig. 8c and d). In a third exposure, a reddish brown silty sediment, intercalated between two volcanic units of the ATP type, formed a peperite with blocky jointing morphology (Skilling et al., 2002) characterized by the injection of sediment into centimeter to millimeter spaced joints in the base of the overlying volcanic unit (Fig. 9).

In the southern region of the Paraná Basin (Rio Grande do Sul State), sediments and peperites were observed between the basaltic lower unit and the silicic Palmas

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sequence. In Santa Maria region, blocky peperite was observed in the base of the lowermost silicic volcanic unit. The peperite displays a well-developed jigsaw-fit texture, and closely packed, blocky to cuneiform clast shapes of several sizes, separated by an orange colored sedimentary material (Fig. 10). The sediment exhibits a high degree of baking (thermal metamorphism) and the volcanic clasts show intense devitrification, indicating very high temperature of the volcanic material interacting with the sediment.

In the central part of the Paraná Basin, near the cities of Soledade and Venâncio Aires (Rio Grande do Sul State), a 10 m thick sedimentary layer underlies a silicic volcanic unit of the ATP type. The sediment is a redish colored sandstone composed of sub-angular to rounded quartz grains (Fig. 11). The volcanic unit presents well developed horizontal jointed base and the contact with the sandstone is sharp, apparently lacking peperitic interaction (Fig. 11).

A road-cut on the Soledade to Lajeado highway exposes a peperite in the base of a 25 m thick basaltic lava flow from the middle of the silicic volcanic sequence. Volcanic clasts in the peperite are vesicular and display a variety of morphologies, from blocky to fluidal. The sediment is a red poorly sorted sandstone, which partially fills vesicles in the volcanic clasts.

Eastward, in the area between Bento Gonçalves and Cambará do Sul (Rio Grande do Sul), all the observed peperites are interlayered in the silicic volcanic sequence and the sedimentary material becomes finer, dominantly silty. Another peperite was observed in a quarry floor in Nova Petrópolis, near Gramado city, resulting from the interaction with sediment of a thin (~ 1 m thick) amygdaloidal basalt interlayered in the silicic volcanic sequence. It displays blocky clasts with irregular shapes separated by orange to reddish, poorly-sorted fine-grained sandstone. The sediment presents vesicles that probably resulted from volatilization of sediment water by heating (Fig. 12).

On the Rota do Sol highway, connecting Caxias do Sul to the coast, three peperites were observed interlayered in a sequence of black glassy volcanic units of Palmas Member. The stratigraphically lower two are similar and characterized by vesicular, pale to greenish glassy volcanic clasts, presenting angular to rounded irregular shapes

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(Fig. 13). The sedimentary material is a brown moderate to poorly sorted siltstone that also fills vesicles in volcanic clasts. The uppermost peperite presents volcanic clasts with a wide variety of morphologies, being the fluidal shapes more frequent (Fig. 14). The green and vesicular volcanic clasts are surrounded by a reddish brown siltstone, which also fills vesicles and fractures in volcanic clasts (Fig. 14d). It is slightly coarser and more poorly sorted than the previous two sediments (Fig. 15), and many clasts of the stratigraphically lower peperite display perlitic fractures (Fig. 15c).

5 Discussion and concluding remarks

The PEMP (Paraná–Etendeka Magmatic Province) is considered one of the largest LIPs (Large Igneous Province) in continental crust in the world, with nearly 1 million km^3 (Bryan et al., 2010). 95 % of the total volume of the volcanic products is preserved in the South American continent, the Paraná Magmatic Province (PMP). All volcanic material was erupted in a short period of time (~ 3 million yr) without significant interruption, as deduced from the scarcity of sediments interlayered within the volcanic sequence. In fact, and up to now, the only references to the presence of sediments interbedded within the volcanics corresponded to layers or lenses of sandstones (intertraps), a few centimeters to several meters thick, from the Botucatu Formation. These occurred only in the base of the lava flow pile in both the African (Jerram et al., 1999) and South American continents (Petry et al., 2007; Waichel et al., 2008). Sandstone intertraps in trachydacites of the Piraju–Ourinhos region (São Paulo State; Janasi et al., 2007; Luchetti, 2010), where the thick basaltic sequence is missing, were also known. However, until now, there were no reports of features indicating significant time breaks in the upper part of the PMP stratigraphic sequence.

New observations of the occurrence of sedimentary lenses and peperites, resulting from volcano-sedimentary interaction, at the base and within the upper silicic sequences of the PMP are presented in this paper. These were observed throughout

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the Paraná Basin associated with silicic and basaltic units of the Palmas and Chapecó Members.

The sediments display immature features suggesting limited transport and, depending on the location, range from moderately to poorly-sorted sandstones to siltstones. Often, there was lava/sediment interaction producing peperites or sediment deformation by the weight of overlying volcanic units. The sediments display features, such as the variety of morphologies found and the injection of sediments into fractures and vesicles in the volcanic rocks, which indicate that they were still wet and unconsolidated or poorly consolidated at the time of volcanism (Skilling et al., 2002). This reflects a paleoenvironmental change, from a desertic climate in the beginning of the PMP volcanic activity to a more humid environment during the latest phases of the magmatism. It also suggests a decrease in eruptive frequency towards the end of the volcanic activity, allowing time for sediment deposition in slightly depressed regions between individual volcanic events. From São Jerônimo da Serra region, northward of the basin, the change seems to have started before the volcanism.

The deposition of sediments must have taken place in depressed portions of the paleo-relief (small valleys or depressions of the original volcanic morphology).

In conclusion, the PMP volcanism was not totally continuous, but presented significant pauses, mainly in the initial and terminal phases. On the other hand, the occurrence of sediments separating the top of the lower basaltic sequence and the beginning of the silicic extrusions may represent a pause in the volcanic activity that coincides with the compositional change in the magmatism of the Paraná Magmatic Province.

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Table 1. Representative analysis of Palmas and Chapecó silicic volcanics of the PMP.

Sample	Palmas KC 505	Palmas KSE 406	Palmas KSE 419	Palmas KS 319	Palmas KSU 237	Chapecó KC 482	Chapecó PU 1011	Chapecó KNO 442
SiO_2	65.48	66.44	67.58	68.70	70.46	64.38	65.44	66.93
TiO_2	1.11	0.96	0.95	0.95	0.71	1.46	1.57	1.24
Al_2O_3	12.96	12.74	12.35	12.12	12.38	12.83	13.03	13.03
Fe_2O_3	6.78	6.15	6.15	5.69	5.22	7.01	7.57	6.54
MnO	0.08	0.11	0.20	0.10	0.09	0.16	0.12	0.10
MgO	1.08	1.70	1.22	1.28	0.61	1.36	1.28	0.75
CaO	2.78	2.93	3.09	2.68	2.20	2.91	2.94	2.07
Na_2O	3.64	2.87	2.78	2.30	2.92	3.32	3.61	3.36
K_2O	4.01	3.89	4.17	4.69	4.74	4.45	4.33	4.61
P_2O_5	0.33	0.27	0.26	0.26	0.20	0.48	0.46	0.33
LOI	1.93	1.91	1.01	0.99	0.57	1.05	0.61	1.63
SUM	100.17	99.98	99.75	99.76	100.09	99.41	100.96	100.60
Cu	128	75	78	63	18	7	9	14
Ni	7	8	7	8	3	4	5	5
Ba	610	706	694	588	613	1076	1003	1199
Rb	169	160	165	175	206	100	101	136
Sr	135	143	127	137	102	360	337	318
Zr	279	258	252	266	319	633	670	592
Y	63	41	57	42	55	65	66	60
Nb	22	20	20	21	23	48	51	44
U	3.51	4.07	4.04	4.17	3.25	1.74	1.91	2.68
Th	11.53	11.30	11.64	12.09	12.25	8.76	8.62	12.69
La	42.0	35.0	36.1	36.0	43.2	60.4	63.7	67.8
Ce	88.0	76.0	78.0	73.0	95.5	144.6	147.0	145.0
Nd	46.0	36.0	34.8	34.0	42.7	68.4	71.7	70.9
Sm	9.40	7.00	7.47	7.10	8.78	15.78	15.10	14.50
Eu	2.02	1.66	1.53	1.53	1.60	3.60	3.52	3.11
Gd	9.80	7.30	7.28	8.10	8.78	14.04	13.10	11.90
Dy	8.30	6.90	7.43	7.40	8.32	10.83	11.50	10.20
Ho	1.70	1.40		1.60				
Er	4.70	4.00	4.54	4.60	5.25	5.97	6.21	5.42
Yb	4.50	3.40	3.92	3.70	4.61	4.79	5.03	4.39
Lu	0.60	0.50	0.61	0.60	0.71	0.65	0.76	0.65

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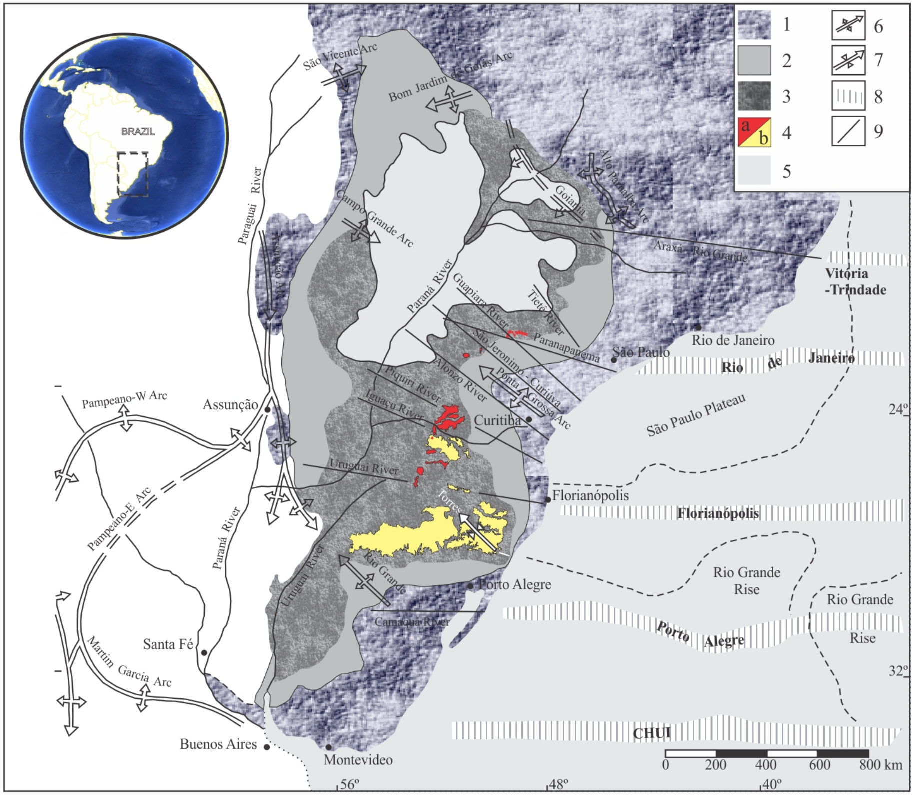

Fig. 1. Map of the Paraná Basin with the location of the acidic members of the Serra Geral Formation according to Nardy et al. (2008). Legend: 1 – areas surrounding Paraná Basin; 2 – pre-volcanic sedimentary rocks; 3 – basalts (Serra Geral Formation); 4 – acidic (a) Chapecó and (b) Palmas Members (Serra Geral Formation); 5 – sedimentary post-volcanic sequences (Bauru Basin); 6 – anticline structures; 7 – syncline structures; 8 – oceanic lineaments; 9 – continental lineaments.

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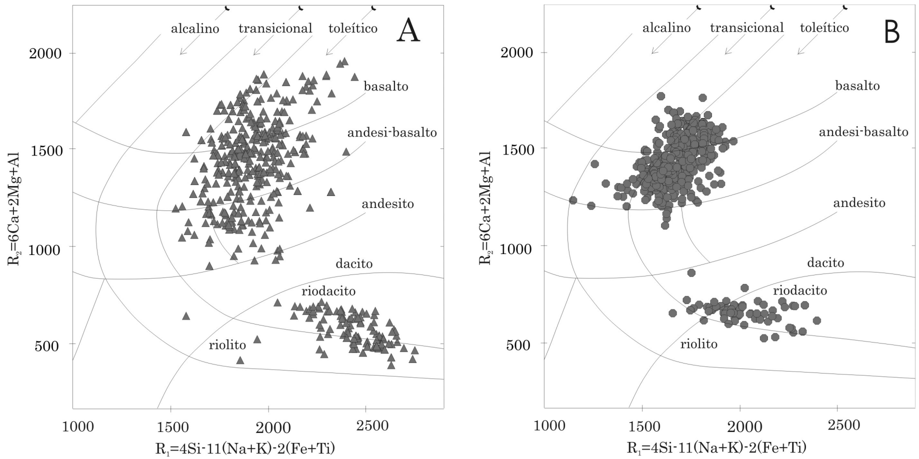

Fig. 2. R1 × R2 diagram (De La Roche et al., 1980). **(A)** tholeiitic suite (Low-Ti basalts and ATP), **(B)** tholeiitic-transitional suite (High-Ti basalts and ATC).

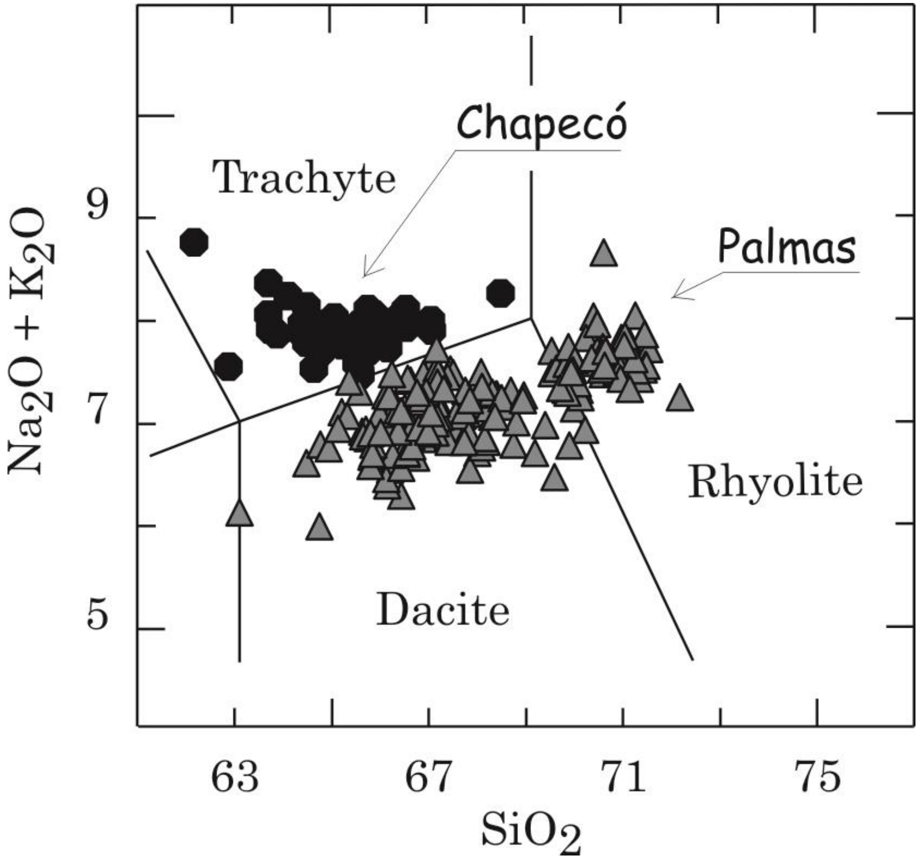

Fig. 3. Total alkalis × silica diagram (Le Bas et al., 1986) for ATC (circles) and ATP samples (triangles).

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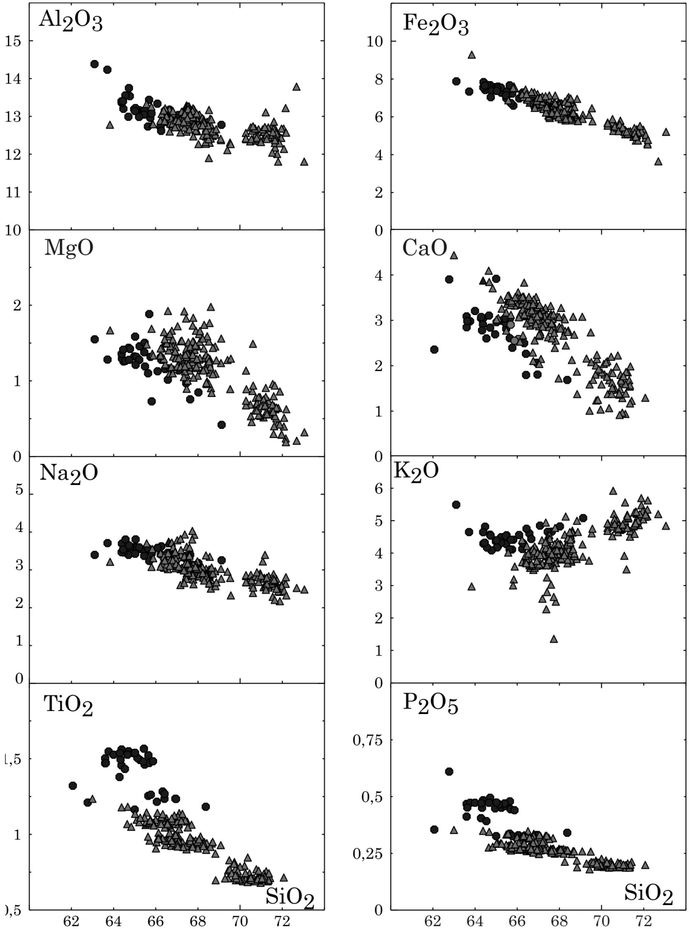

Fig. 4. Harker diagrams of ATP (triangles) and ATC (circles).

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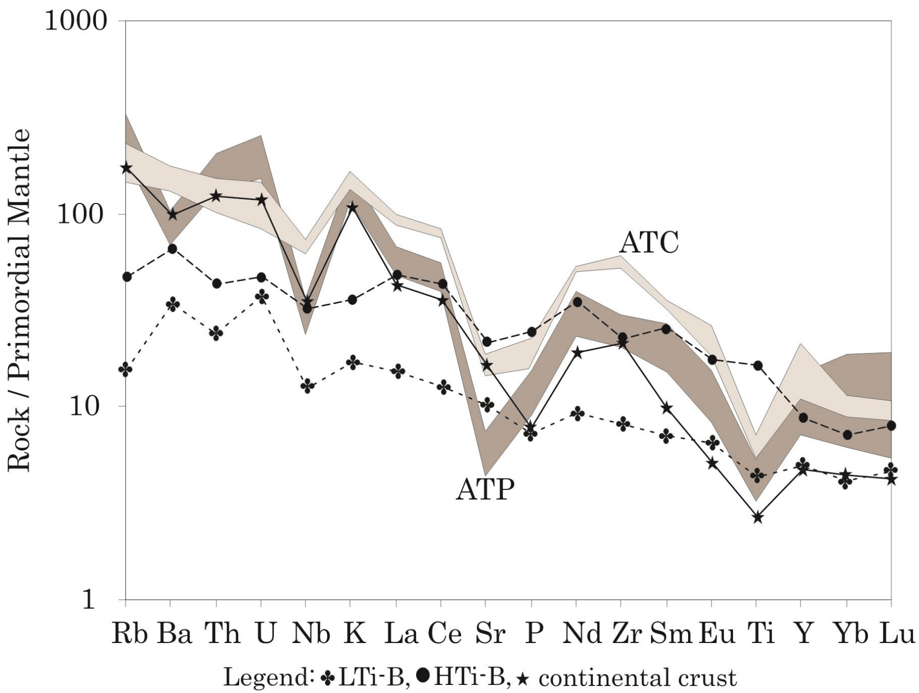

Fig. 5. Spiderdiagram of incompatible elements of the Palmas and Chapecó types normalized to primordial mantle (Sun and McDonough, 1989).

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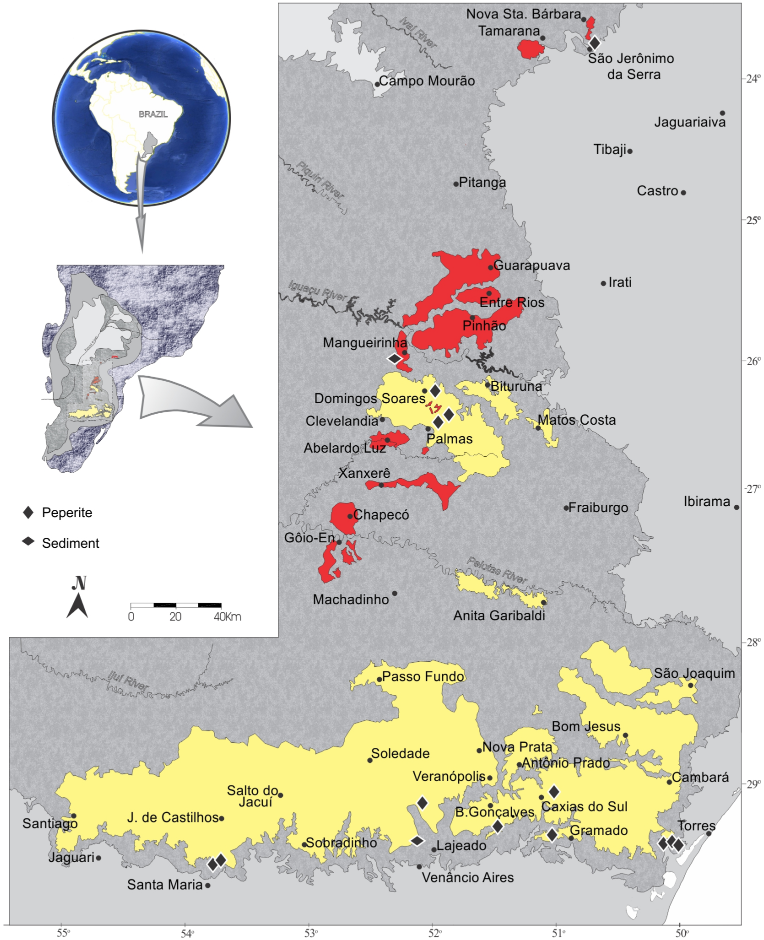

Fig. 6. Map with the location of sediment and peperite outcrops within the Palmas and Chapecó Members.

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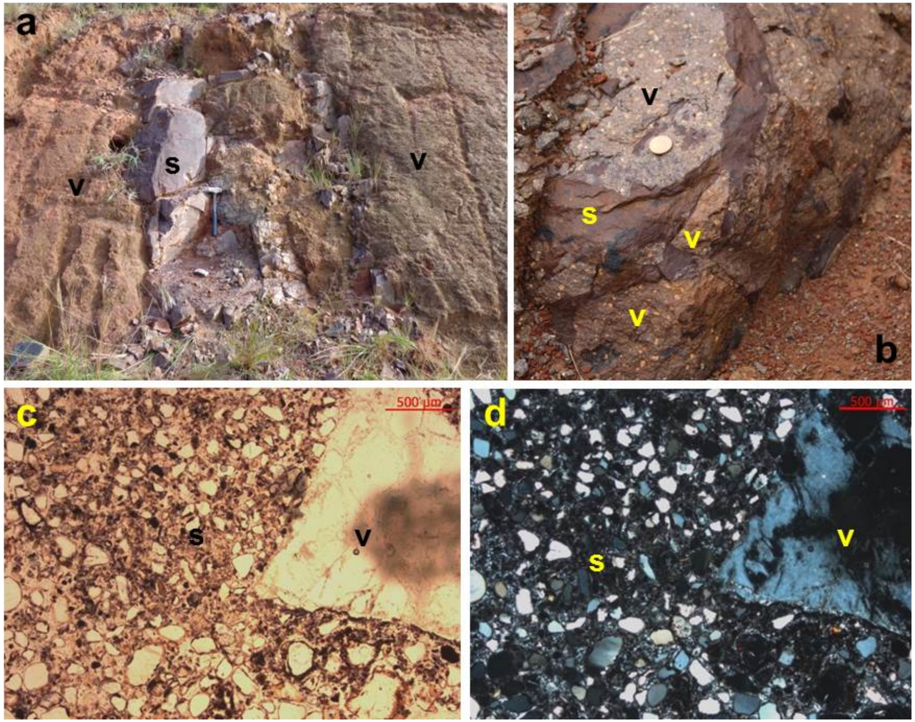

Fig. 7. Peperite from São Jerônimo da Serra: **(a, b)** photomicrographs of the immature and poorly sorted sediment (**c** = // polarizers; **d** = X polarizers); **(c)** clastic dike more than 1 m thick; **(d)** angular to sub-angular shaped clasts set in a sandstone matrix. S – sandstone; V – volcanic rock.

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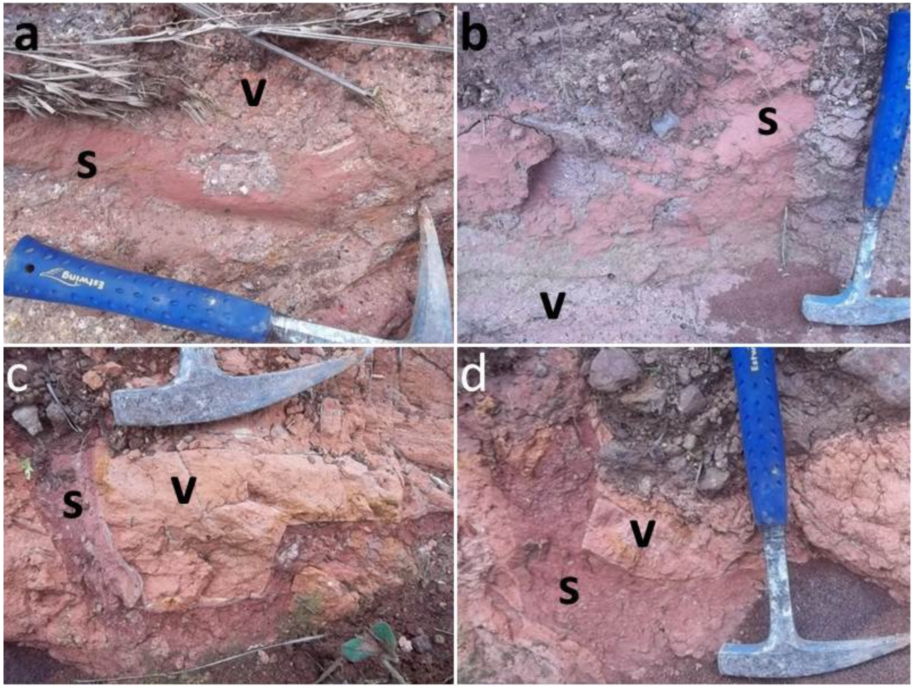

Fig. 8. Silicic ATC and ATP type rocks (V) in contact with red clayey-siltstone (s): **(a, b)** peperites in the base of ATC type rocks; (**c** and **d**) fractures in the top of ATP type rock filled with sediment, in the central region of the Paraná Basin.

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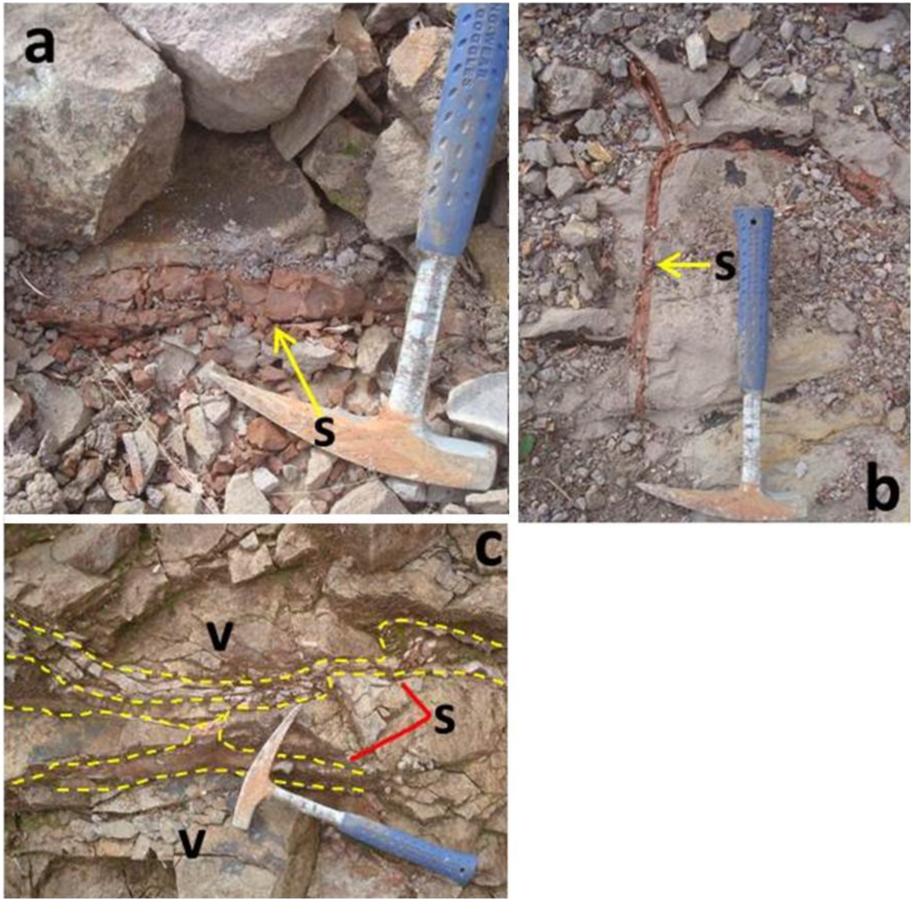

Fig. 9. Blocky jointed peperite in the base of an ATP type unit (Domingos Soares city – Paraná State, central region of the Paraná Basin); V – ATP rock, S – sediment.

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Fig. 10. Blocky peperite formed by interaction of an ATP type volcanic body with sediment in Santa Maria region (Rio Grande do Sul State): well-developed jigsaw-fit texture, closely packed, gray blocky to cuneiform clasts of variable sizes, separated by orange sedimentary material, displaying intense baking.

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Fig. 11. Outcrop in the Venâncio Aires area (Rio Grande do Sul State), where a silicic volcanic unit of the ATP type (V) rests on a reddish sedimentary layer (s) lacking peperitic interaction. On the right lower corner a photomicrograph of the sandstone (X polarizers).

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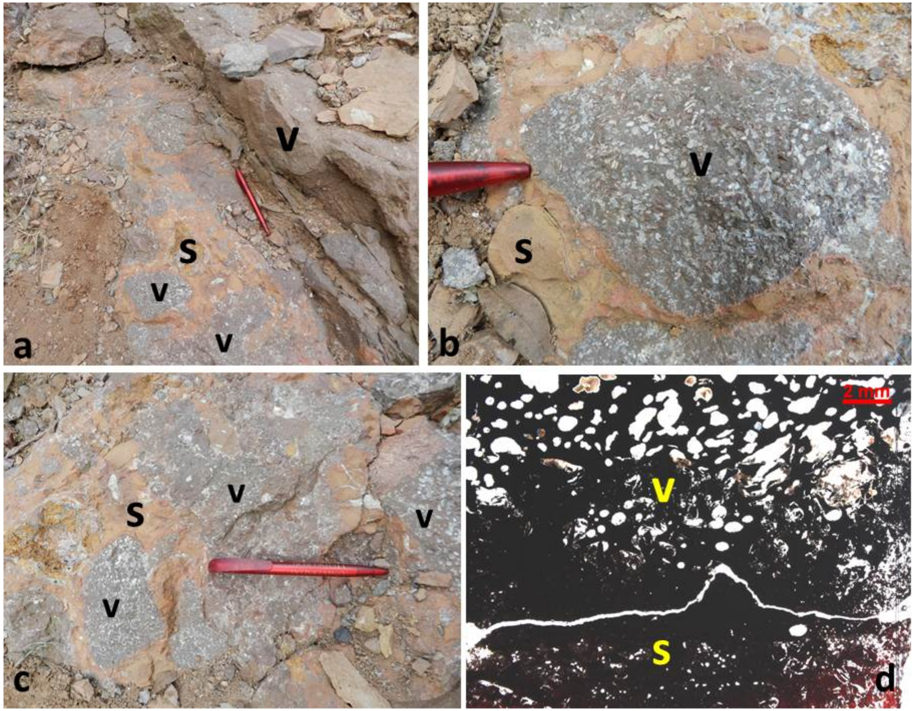

Fig. 12. Aspects of a peperite produced by interaction of a thin basalt flow (within the silicic Palmas Member) and fine grained sediment near Nova Petrópolis (Rio Grande do Sul State), south part of the basin: **(a–c)** irregular blocky volcanic clasts (V) in a reddish sandstone matrix (S); **(d)** photomicrograph showing the amygdaloidal basalt (V) in the upper part and a poorly sorted fine-grained sandstone in the bottom (S).

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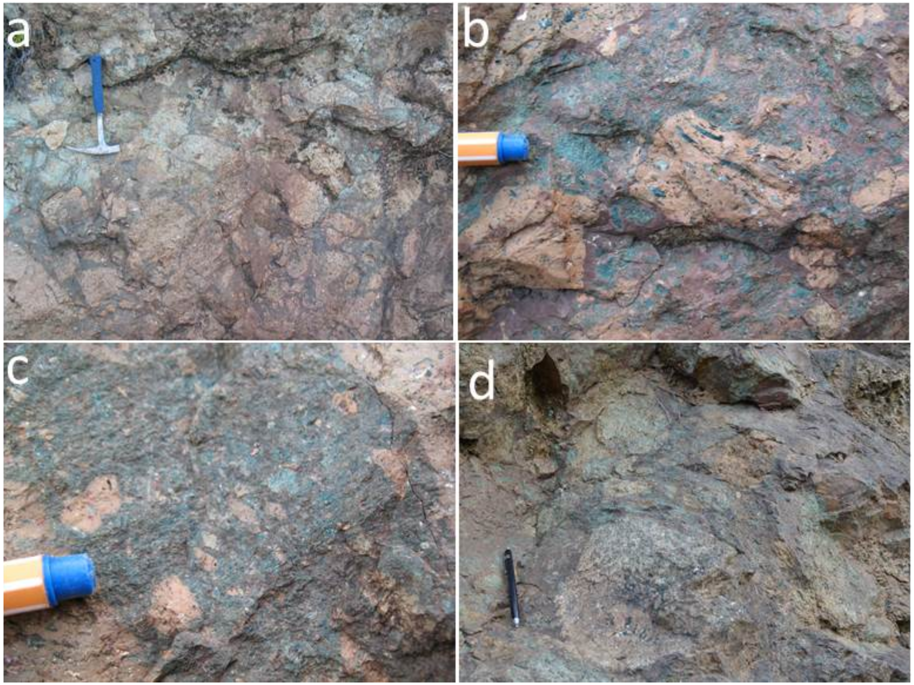

Fig. 13. Aspects of the two lowermost peperites in the Palmas volcanic sequence, along the Rota do Sol highway (Rio Grande do Sul State): (**a**, **b** and **c**) images of the lowermost peperite; and **(d)** photo of the middle peperite. The volcanic clasts are pale and light or dark green, while the siltstone is dark brown.

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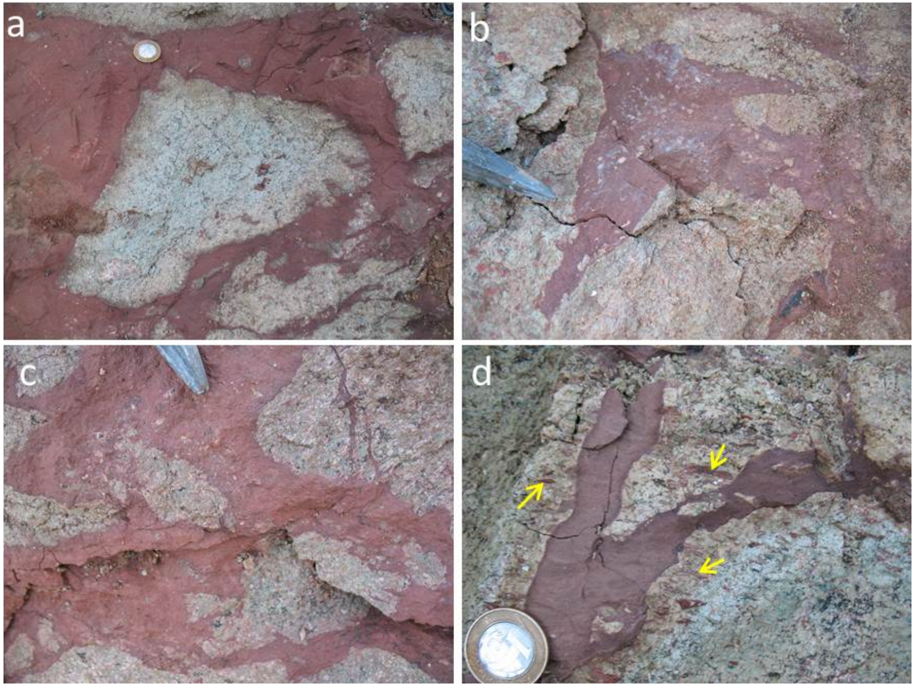

Fig. 14. Peperite from the stratigraphically higher level on the section exposed in the Rota do Sol highway: green to pale volcanic clasts, displaying sub-angular to irregular morphologies, set in a reddish brown siltstone matrix, which also fills vesicles in volcanic clasts (yellow arrows in **(d)**.

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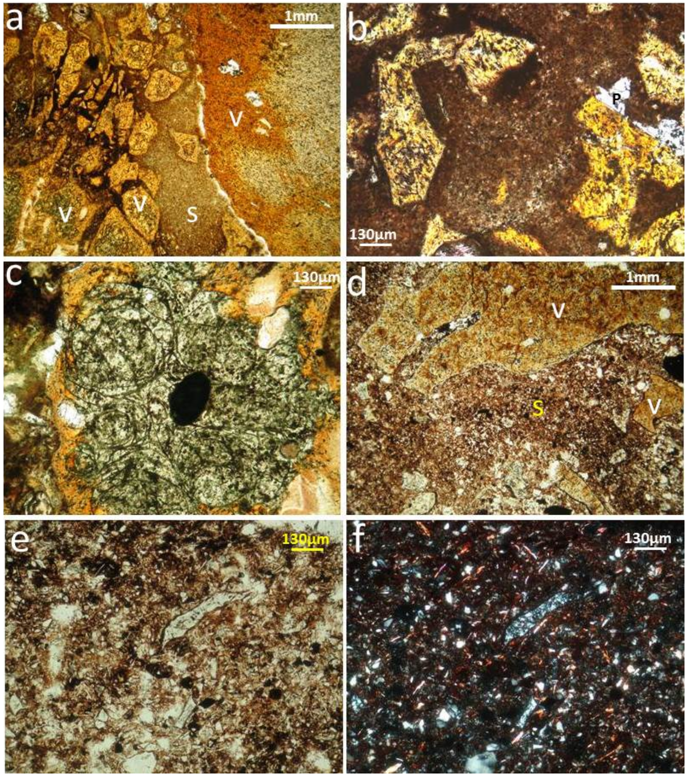

Fig. 15. Photomicrographs of peperites from the Palmas volcanic sequence, along Rota do Sol highway: (**a**, **b** and **d**) volcanic glassy clasts (V) set in a brown siltstone matrix (S); **(c)** volcanic clast displaying concentric fractures – perlitic texture – common in the two lowermost peperites; (**e** and **f**) detail of the poorly sorted, slightly coarser siltstone from **(d)** (**a**–**e** – // polarizers; **f** – X polarizers; P = plagioclase).