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 years 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 the occurrence~~s~~ 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; Figure 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). 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 & 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 & 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 Palmas type acidic volcanic rocks (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*~~ phenocrysts (grain size ~~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 Chapecó type acidic volcanic rocks (ATC) are porphyritic, with an average of 24% of plagioclase phenocryst~~als~~ 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<2wt%). Major and trace elements were carried out at Unesp laboratories, using X-ray fluorescence spectrometry. Major elements were analysed using fusion beads (1:10 lithium tetraborate) while trace elements were obtained using pressed (30 ton/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~~ is 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.

Silicic volcanic rocks chemical compositions of the Paraná Magmatic Province shows two main groups which may be observed in a R1xR2 diagram (De La Roche et al., 1980). The first one, Low-Ti suite, belongs to tholeiitic field (tholeiitic basalts, andesi-basalts and andesites) associated to Palmas type silicic volcanic rocks, the latter plot~~ed~~ 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 (Figure 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, (Figure 1).

ATC major and trace elements signatures are quite different compared to the Palmas type. The ATC have lower SiO_2 contents (63.37% to 68.37%) than Palmas type (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~~ plot~~ed~~ in the rhyodacite and rhyolite fields in the TAS diagram (Le Bas et al., 1986 – Figure 3). Harker diagrams (Figure 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.

The spidergram of incompatible trace element ratios of silicic rocks normalized to primordial mantle (Sun & McDonough, 1989 – Figure 5), shows a similar pattern of distribution of trace elements, although the ATP rocks are higher ~~more~~ Rb/Ba, U/Nb and Ce/Sr ratios ~~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 ~~major,~~ trace ~~and~~ incompatible element~~s~~ concentrations are notable, since they ~~it the~~ ~~ATP rocks~~ cannot be generated by partial melting from the same parental source (it would be a very low degree of fusion, e.g.< 5%) or fractional crystallization ~~from ATC rocks~~, ~~or from the same parental source.~~(it would be a very high degree of crystallization, changing the composition and probably the observed mineralogy of the rocks)-

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 (HTiB) and ATP from tholeiitic basalts (LTiB), more or less contaminated by continental crust, as suggested by the spidergram of Figure 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 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 & Ernesto, 2004; Thiede & Vasconcellos, 2011) indicates that magmatism of the PMP occurred quickly, during a time interval that didn't exceed 3 Ma, and in a rather continuous way. This hypothesis ~~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 hot magma (intrusive bodies, lava or piroclastic flows) ~~volcanic rocks~~ and coeval wet sediments. ~~The magma 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 & 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 & Stollhofen). Peperite is classified into two basic types according to the shape of its elements (Busby-Spera & 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 intermediate or more complex shapes that 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 Figure 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 (Figure 7). It comprises clastic dikes a few centimeters to just over 1m thick (Figure 7a) and breccias composed of matrix-supported angular to rounded volcanic blocks of variable size (Figure 7b). The sandstone is poorly sorted with angular to rounded quartz grains (Figure 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 (Figure 8a and b), while in the underlying ATP unit, the sediment filled cooling joints without any peperitic interaction (figure 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 (Figure 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 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 juvenile clast shapes of several sizes, separated by an orange colored sedimentary material (Figure 10). The sediment exhibits a high degree of baking (thermal metamorphism) and the juvenile 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 (Figure 11). The volcanic unit presents well developed horizontal jointed base and the contact with the sandstone is sharp, apparently lacking peperitic interaction (Figure 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 juvenile 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 (Figure 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 (Figure 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 (Figure 14). The green and vesicular volcanic clasts are surrounded by a reddish brown siltstone, which also fills vesicles and fractures in volcanic clasts (Figure 14d). It is slightly coarser and more poorly sorted than the previous two sediments (Figure 15), and many clasts of the stratigraphically lower peperite display perlitic fractures (Figure 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 years) 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, 2000; Jerram & Stollhofen, 2002) 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 the Paraná Basin associated with silicic and basaltic units of the Palmas and Chapecó Members.

Some works on the PMP report peperites derived from the basalt flows-sediment interaction (Petry *et al*., 2007; Waichel *et al*., 2007, 2008), the most common types found in worldwide volcanic sequences. Nevertheless, structures observed in this present study reveal this interaction also occurred between silicic extrusive bodies and wet sediment. These "silicic peperites" are mostly blocky, highlighting a more viscous magma (Dadd & Wagoner, 2002). However, they also may display locally fluidal features, wich indicate less viscous melts, likely due to the higher temperatures (> 1000ºC, Piccirillo & Melfi, 1988).

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. Evidences for a wet and unconsolidated or poorly consolidated sediment are the variety of morphologies found, injections of sediment into fractures, vesicles in the juvenile clast filled by sediment and vesiculated sediment (Skilling *et al*., 2002).

Paleoenvironment climatic conditions at the time of the PMP volcanism were quite dry, since the Serra Geral Formation overlies the Botucatu Formation, discribed as a dry eolian system (Sherer, 2000). Sandstone lenses up to 20 m thick interlayered in the first basalt lava flows (Jerram et al., 1999, 2000; Jerram & Stollhofen, 2002; Petry *et al*., 2007; Waichel *et al*., 2008) reveal wich this system remained active during the magmatic event. However, these new evidences of wet and locally silty sediment between main basalt pile and silicic units and interlayered in the silicic units (end of the volcanic sequence) presented here reflect a paleoenvironmental change, from a dry climate in the beginning of the PMP volcanic activity to a more humid environment (fluvial-lacustrine) during the latest phases of the magmatism, as also evidenced by Waichel et al. (2007) in peperites found in some basalt units of the PMP in contact with lacustrine sediments. From São Jerônimo da Serra region, northward of the basin, the change must have started before the volcanism. Furthermore, this seems to be common in this type of setting in wich humid and dry eolian systems may alternate over time due to climate changes (Assine et al., 2004).

The deposition of sediments must have taken place in depressed portions of the paleo-relief (small valleys or depressions of the original volcanic morphology), and also suggests a decrease in eruptive frequency towards the end of the volcanic activity, allowing time for the material cumulation between individual volcanic events.

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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References

Assine, M. L., Piranha, J. M., Carneiro, C. D. R.: Os paleodesertos Pirambóia e Botucatu. In: Mantesso-Neto, V., Bartorelli, A., Carneiro, C. D. R., Brito-Neves, B. B. (Eds), Geologia do Continente Sul-Americano: evolução da obra de Fernando Flávio Marques de Almeida. SP, Brasil: Beca Prod Cult Ltda, p. 77-92, 2004.

Bellieni, G., Brotzu, P., Comin-Chiaramonti, P., Ernesto, M., Ernesto, M., Melfi, A. J., Pacca, I. G., Piccirillo, E. M.: Flood basalt to rhyolites suites in the southern Paraná plateau (Brazil): paleomagnetism, petrogenis and geodynamic implications. J. Petrol., 25, 579-618, 1984.

Bellieni, G., Comin-Chiaramonti, P., Marques, L. S., Melfi, A. J., Nardy, A. J. R., Papatrechas, C., Piccirillo, E. M., Roisenberg, A.: Petrogenetic aspects of acid and basaltic lavas from the Paraná plateau (Brazil): geological, mineralogical and petrochemical relationships. J. Petrol., 27, 915-944, 1986.

Bryan, S. E., Ukstins-Peate, I., Peate, D. W., Self, S., Jerram, D. A., Mawby, M. R., Marsh, J. S., Miller, J. A.: The largest volcanic eruptions on Earth. Earth-Sci. Rev., 102, 207-229, 2010.

Busby-Spera, C. J. And White, J. D. L.: Variation in peperite textures associated with differing host sediment properties. B. Volcanol., 49, 765-775, 1987.

Dadd, K. A., Van Wagoner, N. A.: Magma composition and viscosity as controls on peperite texture: an example from Passamaquoddy Bay, southeastern Canada. In: Skilling, I.P., White, J.D.L., McPhie, J. (Eds.), Peperite: Processes and Products of Magma-Sediment Mingling. J. Volcanol. Geoth. Res. 114, 63-80, 2002.

De La Roche H., Leterrier P., Grandclaude P., Marshal M. 1980. A classification of volcanic and plutonic rocks using R1xR2 diagram and major element analysis. Its relationships with current nomenclature. Chem. Geol., 28: 183-210.

Ernesto, M., Raposo, M. I. B., Marques, L. S., Renne, P. R., Diogo, L. A., De Min, A.: Paleomagnetism, geochemistry and 40ar/39ar dating of the north-eastern Paraná Magmatic Province. Tectonic implications. J. Geodyn., 28, 321-340, 1999.

Fisher, R. V.: Classification of volcanic breccias. Geol. Soc. Am. Bull., 71, 973-982, 1960.

Frank, H. T., Gomes, M. E. B., Formoso, M. L. L.: Review of the areal extent and the volume of the Serra Geral Formation, Paraná Basin, South America. Pesquisas em Geociências, 36 (1), 49-57, 2009.

Garland, F., Hawkesworth, C. J., Mantovani, M. S. M.: Description and Petrogenesis of the Paraná Rhyolites, Southern Brazil. J. Petrol., 36 (5), 1193-1227, 1995.

Janasi, V. A., Montanheiro, T. J., Freitas, V. A., Reis, P. M., Negri, F. A., Dantas, F. A.: Geology, petrography and geochemistry of the acid volcanism of the Paraná Magmatic Province in the Piraju–Ourinhos region, SE Brazilian Journal of Geosciences, 37, 745–759, 2007.

Janasi, V. A., Freitas, V. A., Heaman, L. H.: The onset of flood basalt volcanism, Northern Paraná Basin, Brazil: A precise U–Pb baddeleyite/zircon age for a Chapecó-type dacite. Earth. Planet. Sc. Lett., 302, 147–153, 2011.

Jerram, D. A., Mountney, N., Stollhofen, H.: Facies architecture of the Etjo Sandstone Formation and its interaction with the Basal Etendeka food basalts of NW Namibia: Implications for offshore analogues. in: Cameron, N., Bate, R. & Clure , V. (eds) The Oil and Gas Habitats of the South Atlantic. Geological Society, London, Special Publications, 153, 367–380, 1999.

Jerram, D.A., Mountney, N., Howell, J., Long, D., Stollhofen, H.: Death of a Sand Sea: an active erg systematically buried by the Etendeka flood basalts of NW Namibia. J. Geol. Soc. London, 157, 513–516, 2000.

Jerram, D. A. and Stollhofen, H.: Lava-sediment interaction in desert settings; are all peperite like textures the result of magma-water interaction? J. Volcanol. Geoth. Res., 114: 231- 49, 2002.

Le Bas, M. J., Le Maitre, T. W., Streckeisen, A., Zanettin, B.: A chemical classification of volcanic rocks based on the total alkali-silica diagram. Journal of Petrology, 27:745-750, 1986.

Luchetti, A. C. F.: Aspectos vulcanológicos dos traquidacitos da região de Piraju–Ourinhos (SP) [Master Dissertation]. São Paulo, SP, Brazil, Universidade de São Paulo, 92 pp, 2010.

Malagutti, M. I. A., Bahia F, Moreno, M. M. T., Nardy, A. J. R.: Determinação de elementos terras raras e ítrio em rochas silicáticas por ICP-OES com separação em resina trocadora de íons. Geochem. Bras., 12, 2, 75-80, 1998.

Marques, L. S. And Ernesto, M.: O magmatismo toleítico da Bacia do Paraná. In: Geologia do Continente Sul-Americano, Mantesso-Neto, V.; Bartorelli, A.; Carneiro, C.D.R.; Brito-Neves, B.B. Beca Produções Culturais Ltda, 2004.

McPhie, J., Doyle, M., Allen, R.: Volcanic textures: a guide to the interpretation of textures in volcanic rocks. University of Tasmania, 197 p, 1993.

Milner, S. C., Duncan, A. R., Ewart, A.: Quartz latite rheoignimbrite flows of the Etendeka Formation, north western Namibia. B. Volcanol., 54, 200- 219, 1992.

Mincato, R. L., Enzweiler, J., Schrank, A.: Novas idades 39Ar/40Ar e implicações na metalogênese dos depósitos de sulfetos magmáticos de Ni-Cu-EPG na Província Ígnea Continental do Paraná. in: 9th Brazilian Congress of Geochemistry, Belém (Pará), Brazil, 2 – 9 November 2003, 67-92, 2003.

Nardy, A. J. R., Enzweiler, J., Bahia F, O., Oliveira, M. A. F., Peneiro, M. A. V.: Determinação de Elementos Maiores e Menores em Rochas Silicáticas por Espectometria de Fluorescência de Raios-X: Resultados Preliminares. in: 6th Brazilian Congress of Geochemistry, Salvador (Bahia), Brazil, 346-348, 1997.

Nardy, A. J. R., Oliveira, M. A. F., Betancourt, R. H. S., Verdugo, D. R. H., Machado, F. B.: Geologia e estrtigrafia da Formaçõ Serra Geral. Revista Geociências, 21, 15-32, 2002.

Nardy, A. J. R., Machado, F. B., Oliveira, M. A. F.: As rochas vulcânicas mesozóicas ácidas da Bacia do Paraná: litoestratigrafia e considerações geoquímico-estratigráficas. Brazilian Journal of Geosciences, 38 (1), 178-195, 2008.

Peate, D., Hawkesworth, C. J., Mantovani, M. S. M.: Chemical Stratigraphy of the Paraná Lavas (South America): Classification of Magma Types and their Spatial Distribution. B. Volcanol., 55, 119-139, 1992.

Petry, K., Jerram, D. A., De Almeida, D. P. M., Zerfass, H.: Volcanic-sedimentary features in the Serra Geral Fm., Paraná Basin, southern Brazil: Examples of dynamic lava-sediment interactions in an arid setting. J. Volcanol. Geoth. Res., 159, 313-325, 2007.

Piccirillo, E. M. & Melfi, A. J. (eds.): The Mesozoic Flood Volcanism of the Paraná Basin: Petrogenetic and Geophysical Aspects. Instituto Geofísico, Astronômico e Ciências Atmosféricas, Universidade de São Paulo, São Paulo, Brazil, 1988.

Renne, P. R., Ernesto, M., Pacca, I. G., Coe, R. S., Glen, J. M., Prévot, M., Perrin, M.: The age of Parana flood volcanism, rifting of Gondwanaland, and the Jurassic–Cretaceous boundary. Science 258, 975–979, 1992.

Renne, P. R., Deckart, K., Ernesto, M., Féraud, G., Piccirillo, E. M.: Age of the Ponta Grossa dyke swarm (Brazil), and implications to Paraná flood volcanism. Earth. Planet. Sc. Lett. 144, 199–211, 1996a.

Renne, P. R., Glen, J. M., Milner, S. C., Duncan, A. R.: Age of Etendeka flood volcanism and associated intrusions in southwestern Africa. Geology 24, 659–662, 1996b.
Santos, R. N., Marques, L. S., Brenha-Ribeiro, F., Nicola, S. H. A.: Determination of uranium concentrations and activity ratios in silicate rocks by alpha spectrometry: application to volcanic rocks from Trindade and Martin Vaz Islands. Appl. Radiation and Isotopes, 56, 5, 741-750, 2002.
Santos, R. N., Marques, L. S., Brenha-Ribeiro, F., Nicola, S. H. A.: Determination of thorium concentrations and activity ratios in silicate rocks by alpha spectrometry. Appl. Radiation and Isotopes, 56, 5, 741-750, 2004.
Scherer, C.: Aeolian dunes of the Botucatu Formation (Cretaceous) in southernmost Brazil: morphology and origin. Sed. Geol., 137: 63-84, 2000.
Skilling, I. P., White, J. D. L., Mcphie, J.: Peperite: a review of magma-sediment mingling. J. Volcanol. Geoth. Res., 114, 1-17, 2002.
Sun, S. And Mcdonough, W. F.: Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. in: Saunders A.D. and Norry M.J. (eds.) Magmatism in the Ocean Basins. Geol. Soc. London, 1, London, 313-345, 1989.
Thiede, D.S., Vasconcelos, P.M.: Paraná flood basalts: rapid extrusion hypothesis confirmed by new 40Ar/39Ar results. Geology, 38 (8), 747-750, 2010.
Turner, S., Regelous, M., Kelley, S., Hawksworth, C., Mantovani, M. M. S.: Magmatism and continental break-up in the South Atlantic: high precision 40 Ar / 39Ar geochronology. Earth Plan. Sci. Lett., 121, 333-348, 1994.
Waichel, B. L., Lima, E. F., Sommer, C. A., Lubachesky, R.: Peperite formed by lava flows over sediments: An example from the central Paraná Continental Flood Basalts, Brazil. J. Volcanol. Geoth. Res., 159, 343–354, 2007.
Waichel, B. L., Scherer, C. M. S., Frank, H. T.: Basaltic lava flows covering active aeolian dunes in the Paraná Basin in southern Brazil: Features and emplacement aspects. J. Volcanol. Geoth. Res., 171, 59–72, 2008.
Waichel, B. L., Lima, E. F. de, Viana, A. R., Scherer, C. M., Bueno, G. V., Dutra, G.: Stratigraphy and volcanic facies architecture of the Torres Syncline, Southern Brazil, and its role in understanding the Paraná–Etendeka Continental Flood Basalt Province. J. Volcanol. Geoth. Res., 215-216, 74–82, 2012.
Williams, H., McBirney, A. R.: Volcanoes: San Francisco, Freeman, Cooper and Company, 397 p., 1979.
White, J. D. L., Mcphie, J., Skilling, I. P.: Peperite: a useful genetic term. B. Volcanol., 62, 65-66, 2000.

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

Legend: major elements- in oxide *wt%;* trace elements- in *ppm*.

	Palmas					Chapecó		
Sample	KC	KSE	KSE	KS	KSU	KC	PU	KNO
#	505	406	419	319	237	482	1011	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

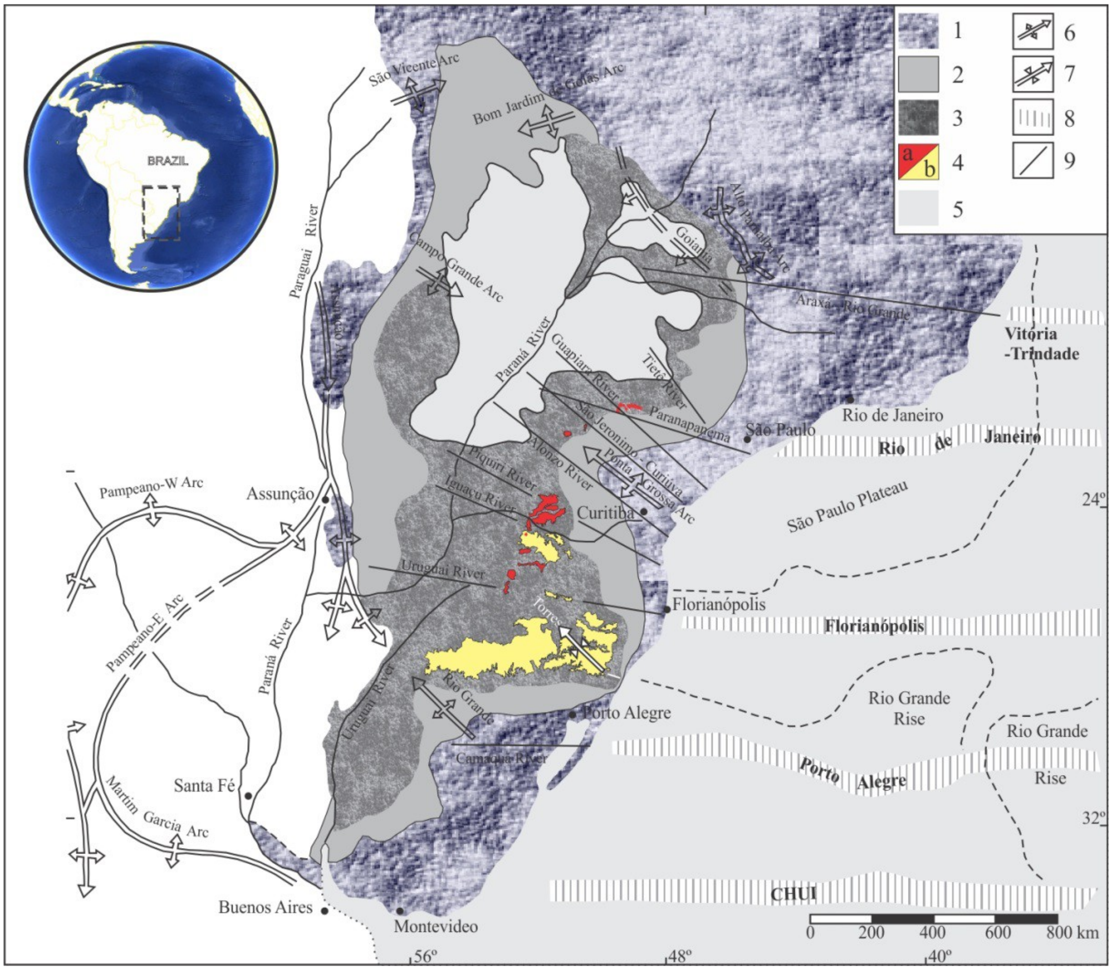

Figure 01 **–**Map of the Paraná Basin with the location of the acidic members of the Serra Geral Formation according to Nardy *et al*. (2008). Legend: 1- Areas surrounding Paraná Basin; 2- Pre-volcanic sedimentary rocks; 3- Basalts (Serra Geral Formation); 4– acidic (a) Chapecó and (b) Palmas Members (Serra Geral Formation); 5- Sedimentary post-volcanic sequences (Bauru Basin); 6- Anticline structures; 7- Syncline structures; 8- Oceanic lineaments; 9 - Continental lineaments.

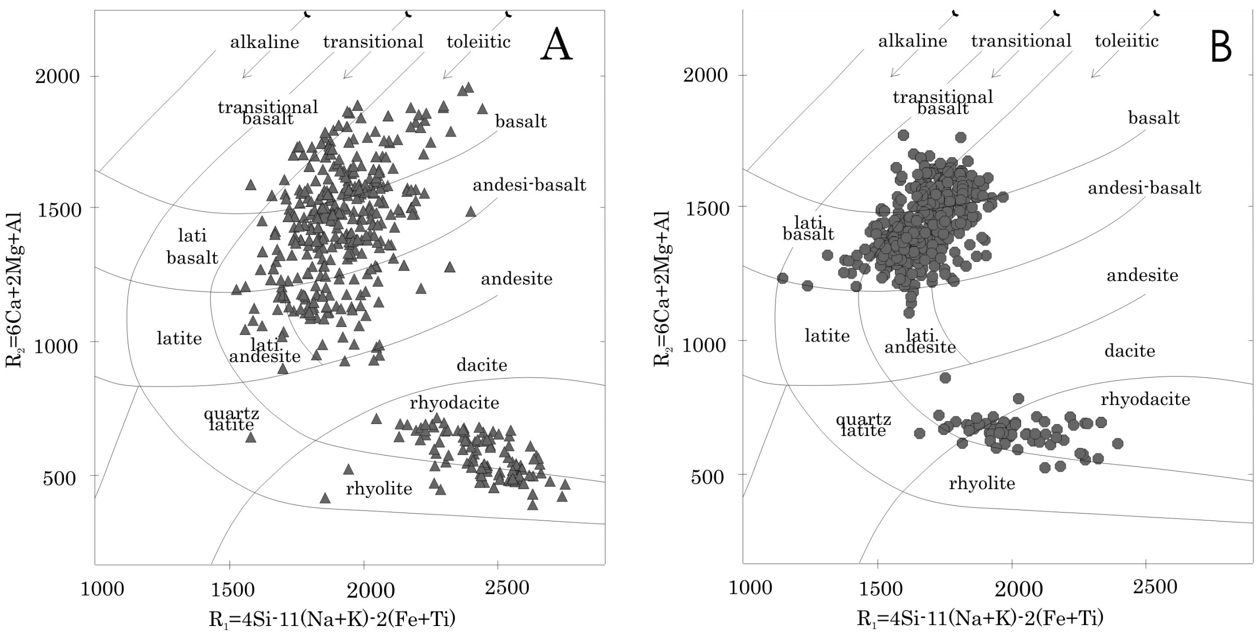

Figure 2- R1xR2 diagram (De La Roche et al., 1980). A- tholeiitic suite (Low-Ti basalts and ATP), B- Tholeiitic-transitional suite (High-Ti basalts and ATC).

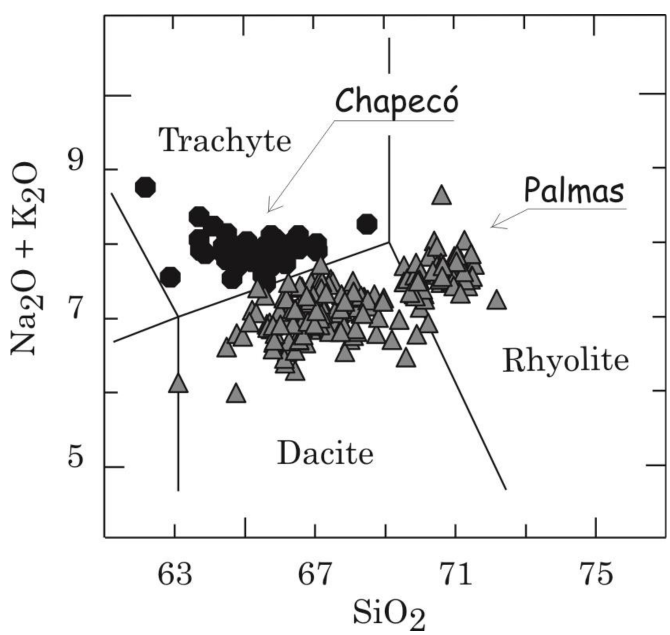

Figure 3 - Total alkalis x silica diagram (Le Bas et al., 1986) for ATC (circles) and ATP samples (triangles).

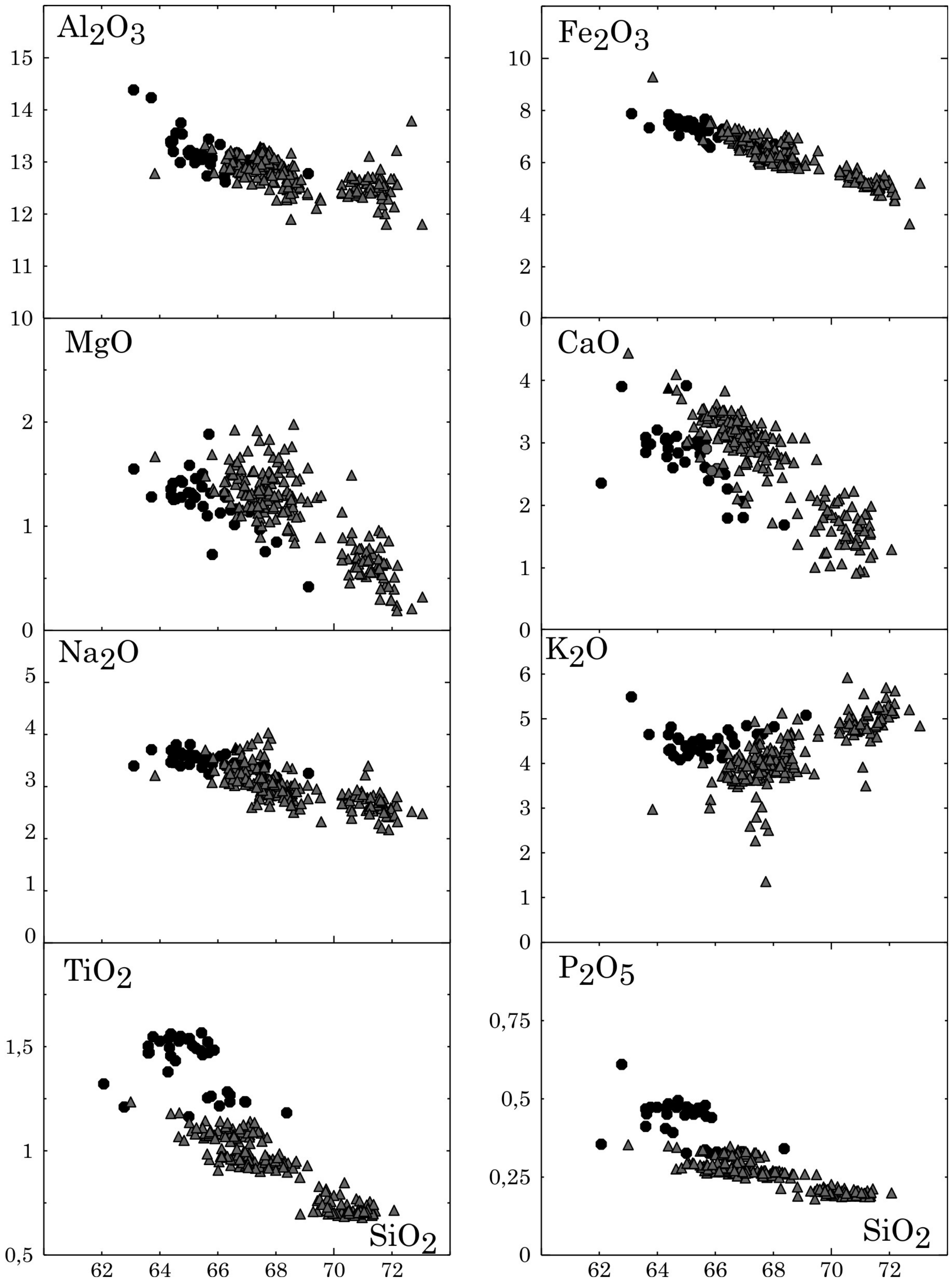

Figure 4- Harker diagrams of ATP (triangles) and ATC (circles).

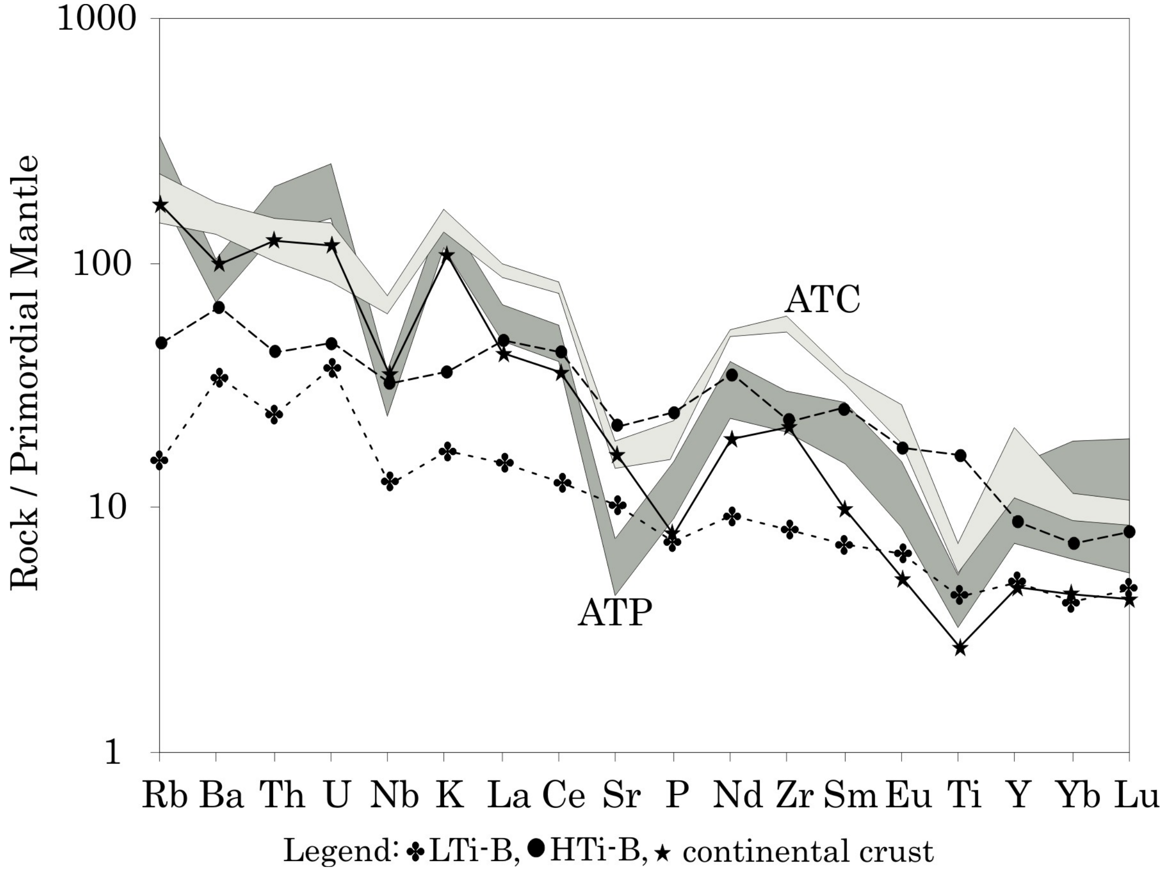

Figure 5 - Spiderdiagram of incompatible elements of the Palmas and Chapecó types normalized to primordial mantle (Sun & McDonough, 1989).

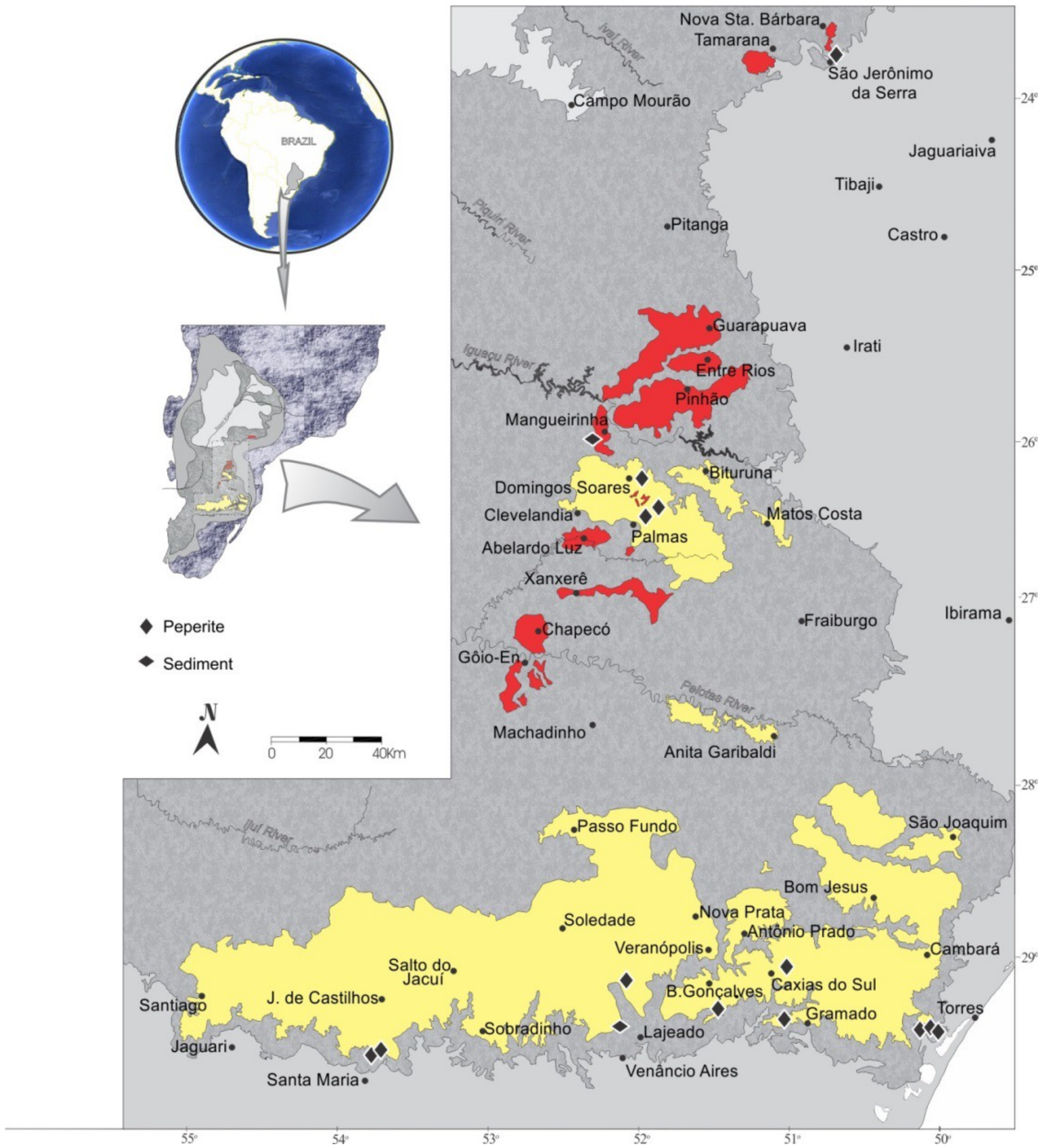

Figure 6 - Map with the location of sediment and peperite outcrops within the Palmas and Chapecó Members; Yellow – Palmas units, red – Chapecó units.

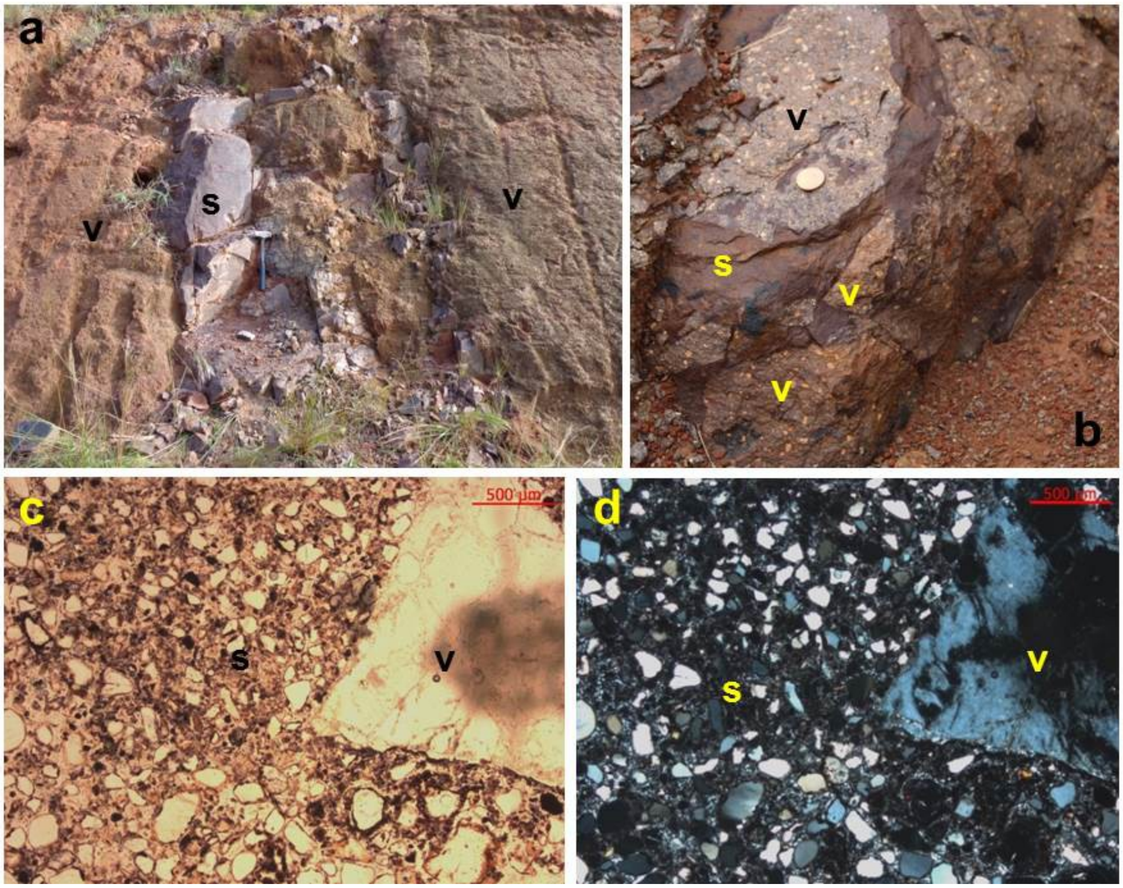

Figure 7 – Peperite from São Jerônimo da Serra: (a, b) photomicrographs of the immature and poorly sorted sediment (c = // polarizers; d = X polarizers); (c) clastic dike more than 1 m thick; (d) angular to sub-angular shaped clasts set in a sandstone matrix. S –sandstone; V - volcanic rock.

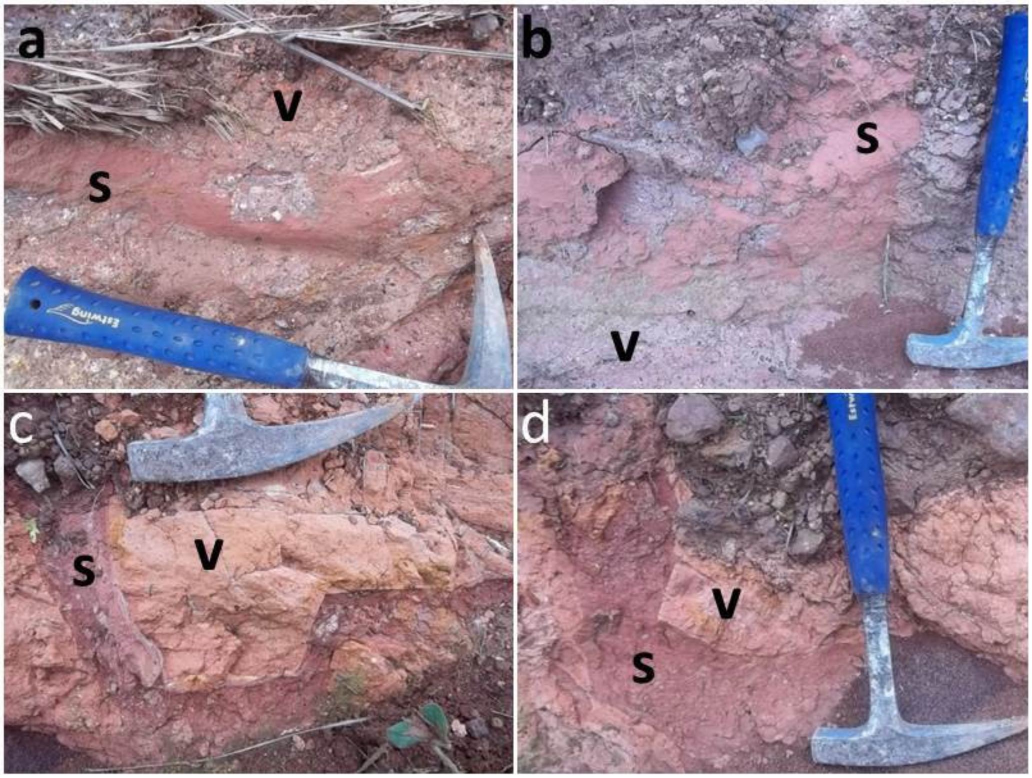

Figure 8 – Silicic ATC and ATP type rocks (V) in contact with red clayey-siltstone (s): (a, b) peperites in the base of ATC type rocks; (c and d) fractures in the top of ATP type rock filled with sediment, in the central region of the Paraná Basin.

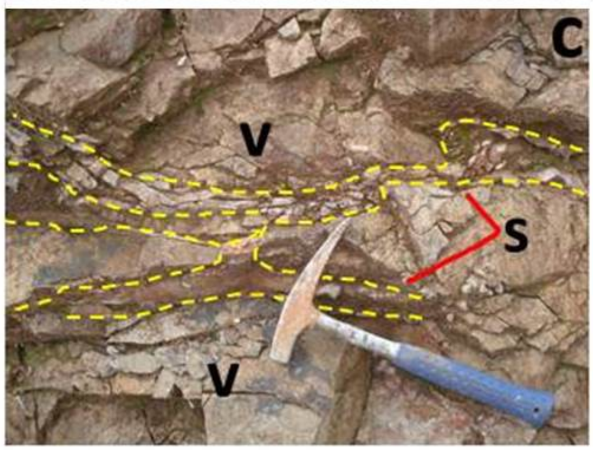

Figure 9 - Blocky jointed peperite in the base of an ATP type unit (Domingos Soares city - Paraná State, central region of the Paraná Basin); V- ATP rock, S – sediment.

Figure 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.

Figure 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).

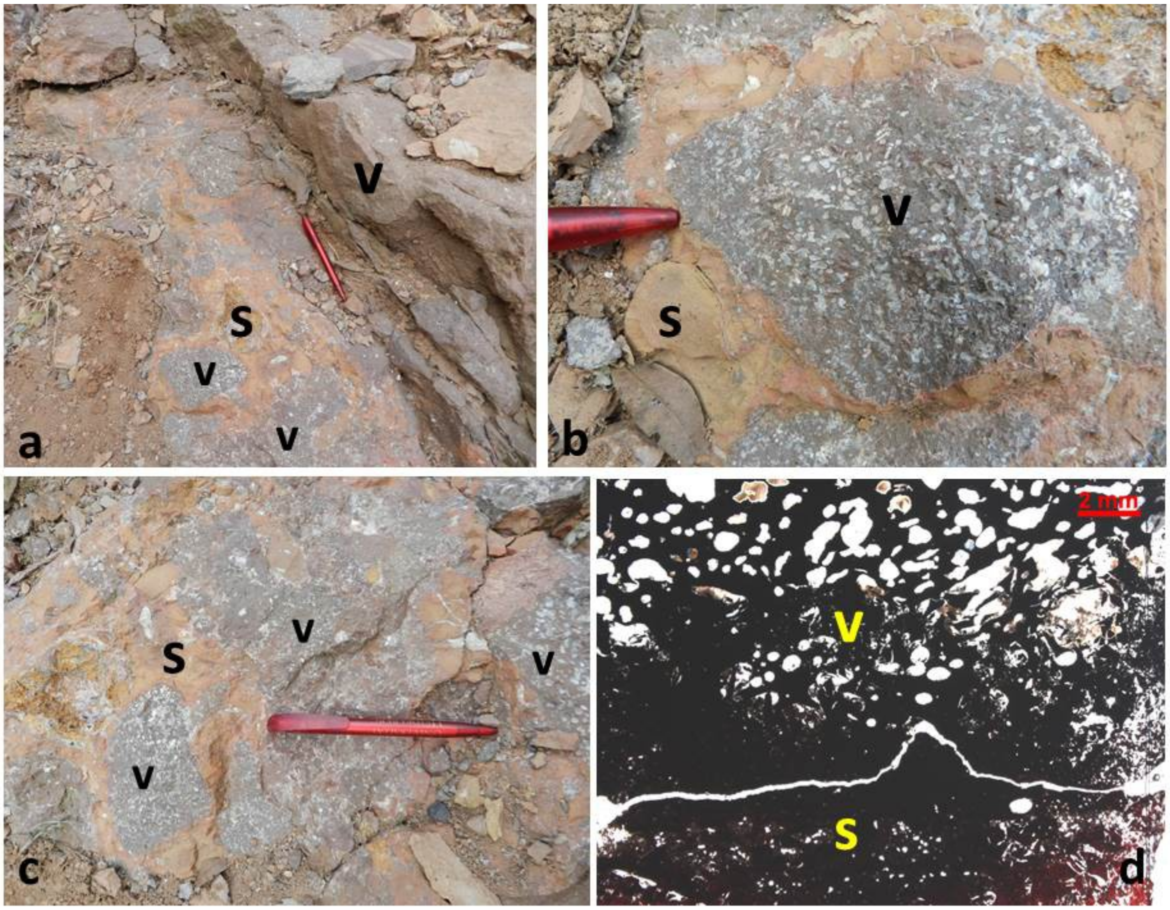

Figure 12 – Aspects of a peperite produced by interaction of a thin basalt flow (within the silicic Palmas Member) and fine grained sediment near Nova Petrópolis (Rio Grande do Sul State), south part of the basin: (a-c) irregular blocky volcanic clasts (V) in a reddish sandstone matrix (S); (d) photomicrograph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

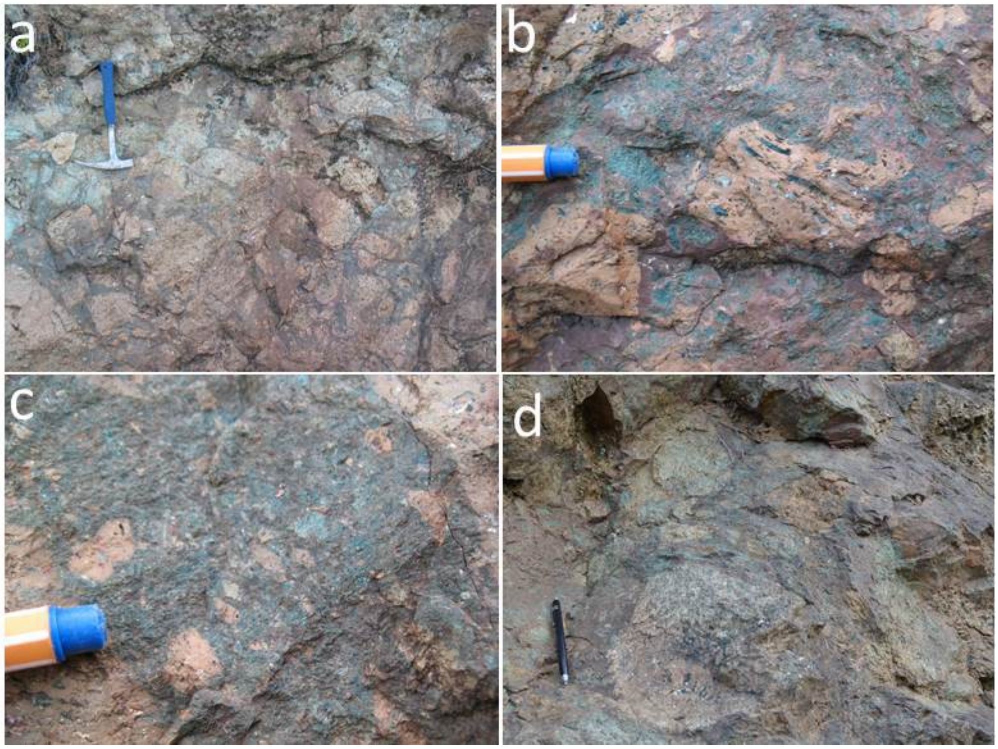

Figure 13 - Aspects of the two lowermost peperites in the Palmas volcanic sequence, along the Rota do Sol highway (Rio Grande do Sul State): (a, b, and c) images of the lowermost peperite; and (d) photo of the middle peperite. The volcanic clasts are pale and light or dark green, while the siltstone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

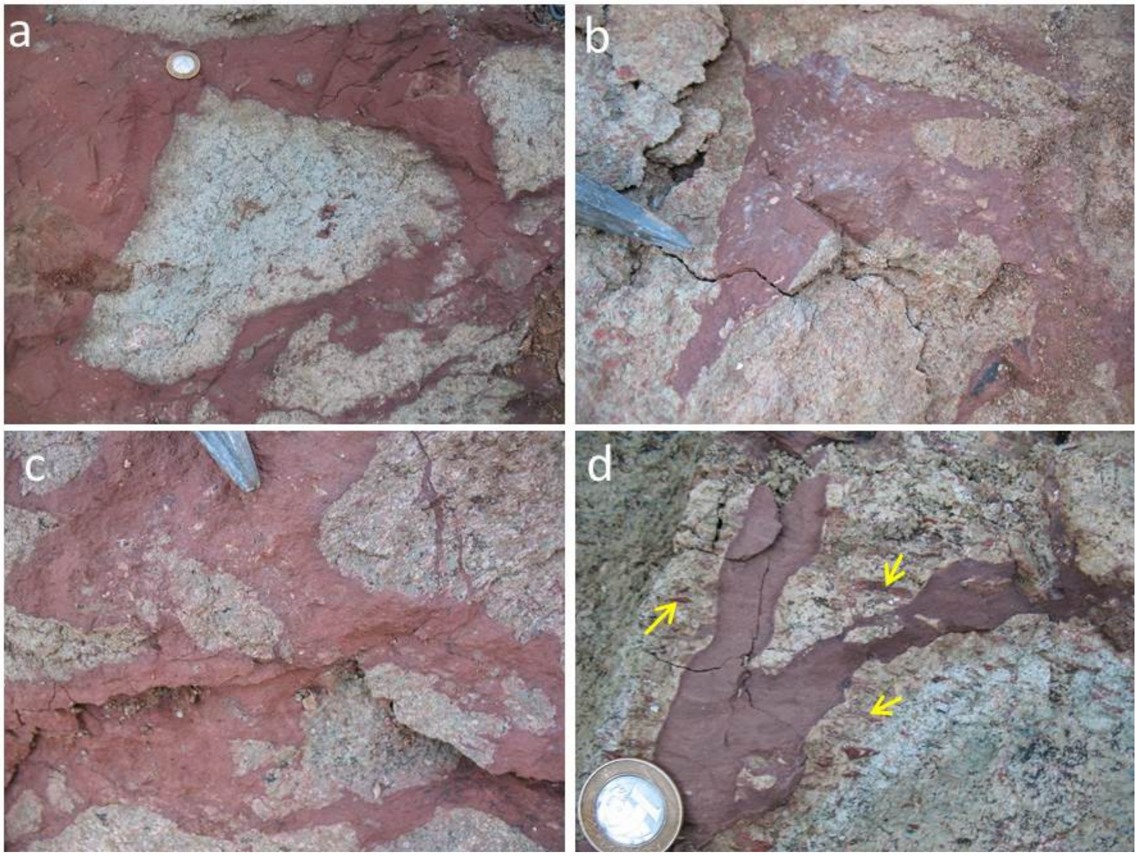

Figure 14 - Peperite from the stratigraphically higher level on the section exposed in the Rota do Sol highway: green to pale volcanic clasts, displaying sub-angular to irregular morphologies, set in a reddish brown siltstone matrix, which also fills vesicles in volcanic clasts (yellow arrows in d).

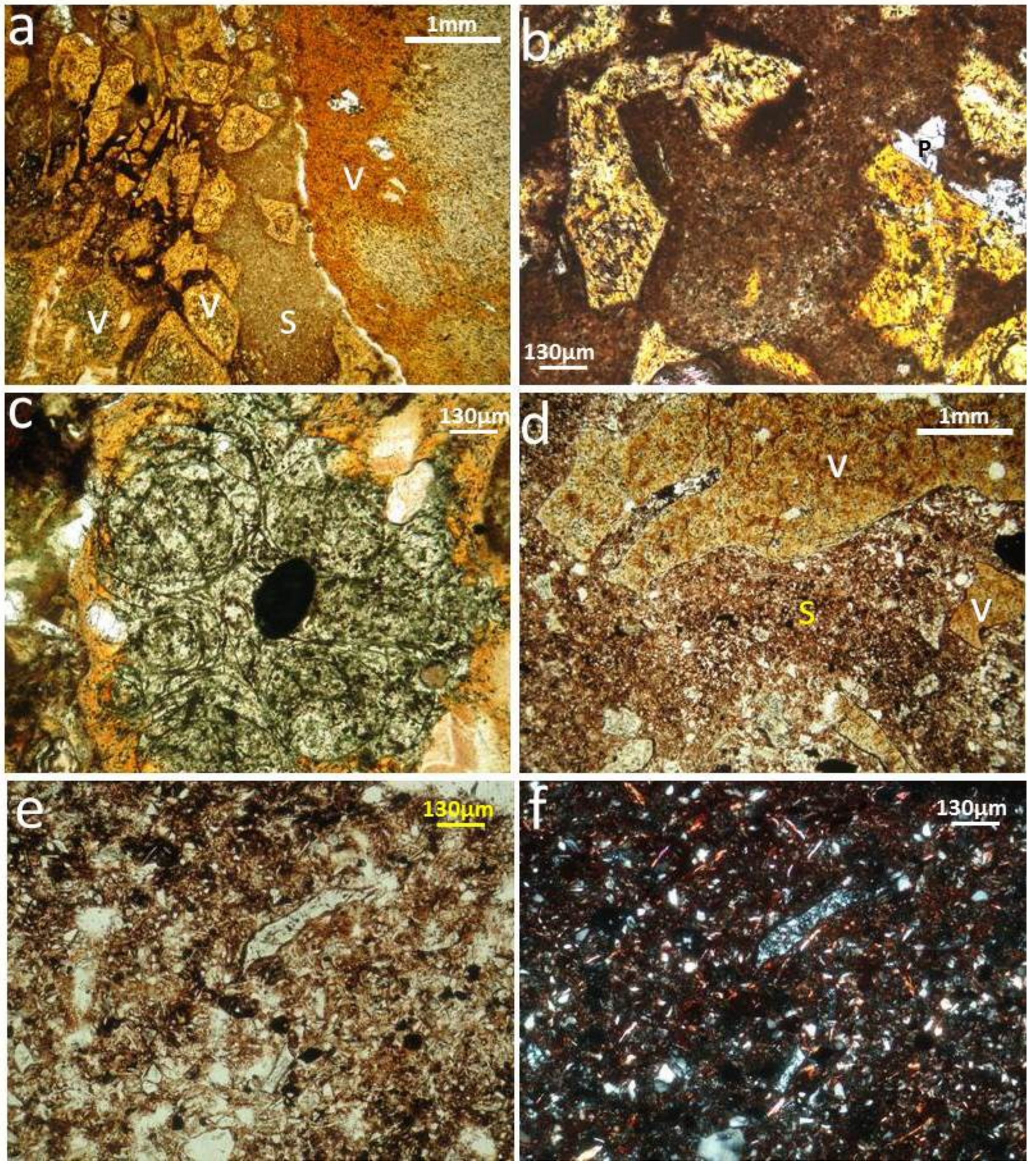

Figure 15 - Photomicrographs of peperites from the Palmas volcanic sequence, along Rota do Sol highway: (a, b and d) volcanic glassy clasts (V) set in a brown siltstone matrix (S); (c) volcanic clast displaying concentric fractures - perlitic texture - common in the two lowermost peperites; (e and f)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