Morphological and petrographic patterns of the pahoehoe and ´a´a flows of the Serra Geral Formation in the Torres Syncline (Rio Grande do Sul state, Brazil)

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Morphological and petrographic patterns of the pahoehoe and ´a´ā flows of the Serra Geral Formation in the Torres Syncline (Rio Grande do Sul state, Brazil)

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Abstract The Serra Geral Formation volcanic sequence in Torres Syncline (Rio Grande do Sul state, Brazil) may be divided into main valley, intermediate zone, and southern hinge. The first volcanic episode along the syncline is characterized by low eruption rates (< 5 m^3/s) forming compound *pahoehoe* flows near the dunes and ponded ones in interdune areas. The second episode is constituted by simple flows that rarely exceed 3 m in thickness, erupted with similar eruption rates. The third is defined by *´a´ā* flows that are thought to be developed when effusion rates are higher (> 5 – 10 m^3/s). The formation of *´a´ā* flows occurred on a plain relief. *Pahoehoe* and *´a´ā* flows have similar chemistry, and the difference in the flow type is related to an increase in eruption rates. The *´a´ā* lavas are plagioclase and clinopyroxene phyric, or glomeroporphyritic. All present an intergranular or intersertal microcrystalline groundmass of plagioclase, clinopyroxene, and opaque minerals (<< 0.1 mm in diameter). The *pahoehoe* lavas differ from the *´a´ā* ones in that they have a coarser-grained microcrystalline groundmass. The *pahoehoe* flows are microcrystalline with glomeroporphyritic and diktytaxitic textures and a plagioclase-poor matrix when compared to *´a´ā* lava flows. The higher content of microlites in the *´a´ā* flows is attributed to undercooling, higher rate of eruption, and degassing before and during emplacement. When it comes to regional stratigraphic correlation between the Serra Geral Formation flows, the morphological type of the lavas should be taken into account since *´a´ā* flows, unlike *pahoehoe*, do not reach longer distances from the source.

Keywords: ´a´ā lava flows; Torres Syncline; Paraná-Etendeka Province; *pahoehoe*.

Resumo *Morfologia e padrões petrográficos dos derrames pahoehoe e´a´ā da Formação Serra Geral na Sinclinal de Torres (Rio Grande do Sul).* A Formação Serra Geral na Sinclinal Torres, no Rio Grande do Sul, pode ser dividida em uma calha principal, uma zona intermediária e uma ombreira ao Sul. As primeiras manifestações vulcânicas nesta sinclinal marcam condições de taxas de efusão baixas (< 5 m^3/s), com as lavas do tipo *pahoehoe* espessas (*ponded*) ocupando espaços interdunas da Formação Botucatu. O segundo episódio vulcânico é constituído por derrames tabulares que atingem 3 m de espessura em casos excepcionais, com taxas de fusão semelhantes às primeiras manifestações. O terceiro gerou morfologia do tipo *´a´ā*, que pode ser atribuído a um aumento nas taxas de efusão, dadas as semelhanças químicas desses com as morfologias *pahoehoe*. As lavas *´a´ā* são constituídas por plagioclásio e piroxênio, sendo geralmente afaníticas ou afíricas, sendo comum também texturas intersetal e glomeroporfirítica, acompanhadas de grande densidade populacional de micrólitos de plagioclásio na matriz (<< 0,1 mm em diâmetro). Os lobos e derrames *pahoehoe* possuem texturas glomeroporfirítica e diktitaxítica, indicativas de um alto conteúdo de voláteis nos magmas, sendo comparativamente mais granulares. A densidade populacional de micrólitos de plagioclásio na matriz é menor do que as das lavas *´a´ā.* O maior conteúdo de micrólitos nestas últimas é atribuído ao subresfriamento, à desvolatização e à taxa de erupção. Correlações estratigráficas regionais entre derrames da Formação Serra Geral devem considerar o tipo morfológico dos das lavas, pois o tipo *´a´ā*, ao contrário das *pahoehoe*, não atinge grandes distâncias da fonte.

Palavras-chave: lavas *´a´ā*; Sinclinal de Torres; Província Panará-Etendeka; lavas *pahoehoe*.

INTRODUCTION Large igneous provinces (LIPs) represent anomalous events in the Earth's history. In a relatively short time span, immense volumes of lavas and intrusions are generated and accumulated (Coffin & Eldholm 1994, Storey *et al.* 2007, Bryan & Ernst 2008). Part of the LIPs are continental basalt provinces (CBPs), which, according to $^{40}Ar/^{39}Ar$ geochronological studies (Siberian Plateau, Karoo/Ferrar, Deccan, Columbia River, Paraná-Etendeka) were built from volumes of the $10^5 – 10^7$ km^3 order in short time intervals (~$10^5 – 10^6$ years).

The study about morphological characteristics and structures of CBP flows is indispensable to the interpretation of lava flows dynamics and volume in the identification of the types of deposits that are generated and in the determination of the related environmental consequences. In Brazil, this kind of study has received little attention, since priority has been

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given to a geochemical and geochronological approach in the study of the Paraná-Etendeka Magmatic Province. This approach itself does not properly contribute for stratigraphic correlations and for understanding the evolution of these volcanic big events.

Pioneer studies about lava flows morphology were carried out by Emerson (1926) and MacDonald (1953), who established definitions for flow types and their characteristics. The inclusion of these concepts and preparation of models involving morphology and physical characteristics of basic lavas (Self *et al*. 1998) have promoted a better understanding of the nature and dynamics of these eruptions in CBPs. These studies supplied the basis for the stratigraphic organization and identification of the facies architecture in these provinces (Bondre *et al*. 2004, Jerram 2002, Jerram & Widdowson 2005, Waichel *et al*. 2012). Several studies have indicated that the spreading of these immense volumes of continental basalts was similar to that of the Hawaiian pahoehoe-type flows (Hon *et al*. 1994, Kent *et al*. 1998, Bondre *et al*. 2004, Sheth 2006, Waichel *et al*. 2006).

It has been recognized that several factors are involved in the generation of *pahoehoe* and *´a´ā* flows (Peterson & Tilling 1980, Kilburn 1981, Rowland & Walker 1990, Self *et al*. 1998), especially effusion or eruption rate, cooling, apparent viscosity, topography type, deformation rate during flow, and degassing. Degassing takes place before eruption and during emplacement it raises the *liquidus* equilibrium temperature, promotes crystallization (Dragoni & Tallarico 1994, Lipman *et al.* 1985), and interferes in the apparent viscosity and textural patterns observed in the matrix of the *´a´ā* and *pahoehoe* lavas.

Researches involving the investigation of petrographic patterns and types or morphology of basic lavas are scarce. Kilburn (1987) suggests that the volume and fabric type of plagioclase microlites in the matrix of *´a´ā* flows indicate rise of the apparent viscosity during flow, as also stressed out by Lentz & Taylor (2002): "[...] The differences in the petrographic textures between pahoehoe and ´a´ā are clearly linked to their emplacement histories."

Morphology of the basic flow types of the Serra Geral Formation and the textural patterns of its *pahoehoe* and *´a´ā* lavas are characterized in this study. We have also discussed the factors that determined the textural contrasts identified in the volcanites of Torres Syncline, which is a major structure of the Eastern portion of Paraná-Etendeka Magmatic Province (Fig. 1). Papers focusing on the stratigraphy and architecture of volcanic pile facies have been recently published by Waichel *et al*. (2012).

Seven whole-rock chemical analyses were carried out at the ACME analytical laboratories Ltd., Vancouver, Canada, with the application of the analytical routines 4A and 4B. The former yielded the total contents of the main oxides and several trace elements by means of inductively coupled plasma atomic emission spectroscopy (ICP-AES). Routine 4B yielded the concentrations of rare-earth and refractory elements by means of ICP- mass spectrometry (MS). In both routines, 0.2 g of powdered sample were used.

CHARACTERIZATION OF SUBAERIAL BASIC FLOWS The terms used to describe the types of (subaerial) basaltic flows and related structures were taken from investigations on active lava flows in the Hawaiian archipelago, where these terms were established.

Based on surface features and structures, MacDonald (1953) defined the *pahoehoe*, *´a´ā* and block lava flow types. The surfaces of the *pahoehoe* type are smooth, billowy or ropy and the lava bodies are internally structured with an upper zone, a core, and a lower zone (MacDonald 1953, Aubele *et al*. 1988). The dynamics of the *pahoehoe* flow starts with the advance of thin lobes and rapid formation of the upper zone by the contact of the lava with the medium, thus isolating the system internally. This crust is inflated by the internal pressure of volatiles, which promotes lava spreading, thickening, and transport for long distances. Therefore, the *pahoehoe* flows are generated in close systems, which maintain a very slow heat loss (by conduction), around 0.5 ºC/km (Rowland & Walker 1990). To preserve these flows, a horizontal paleotopography (< 5^o declivity) and a low volumetric flow rate or discharge (< 5 m^3/s) are required. These factors favor the spreading of such flows for distances of tens of kilometers.

Differently, the *´a´ā* flows are characterized by scoriaceous top and base, presence of elongated/stretched vesicles on the top, and access through hollows of the upper portion of massive blocks as the lava flows (MacDonald 1953, Kilburn 1990). When compared to *pahoehoe*, *´a´ā* lava flows are associated with higher eruption rates (> 5 – 10 m^3/s) and/or with a higher declivity of the terrain. Such lavas are transported in open channels, being the flow sufficiently vigorous to

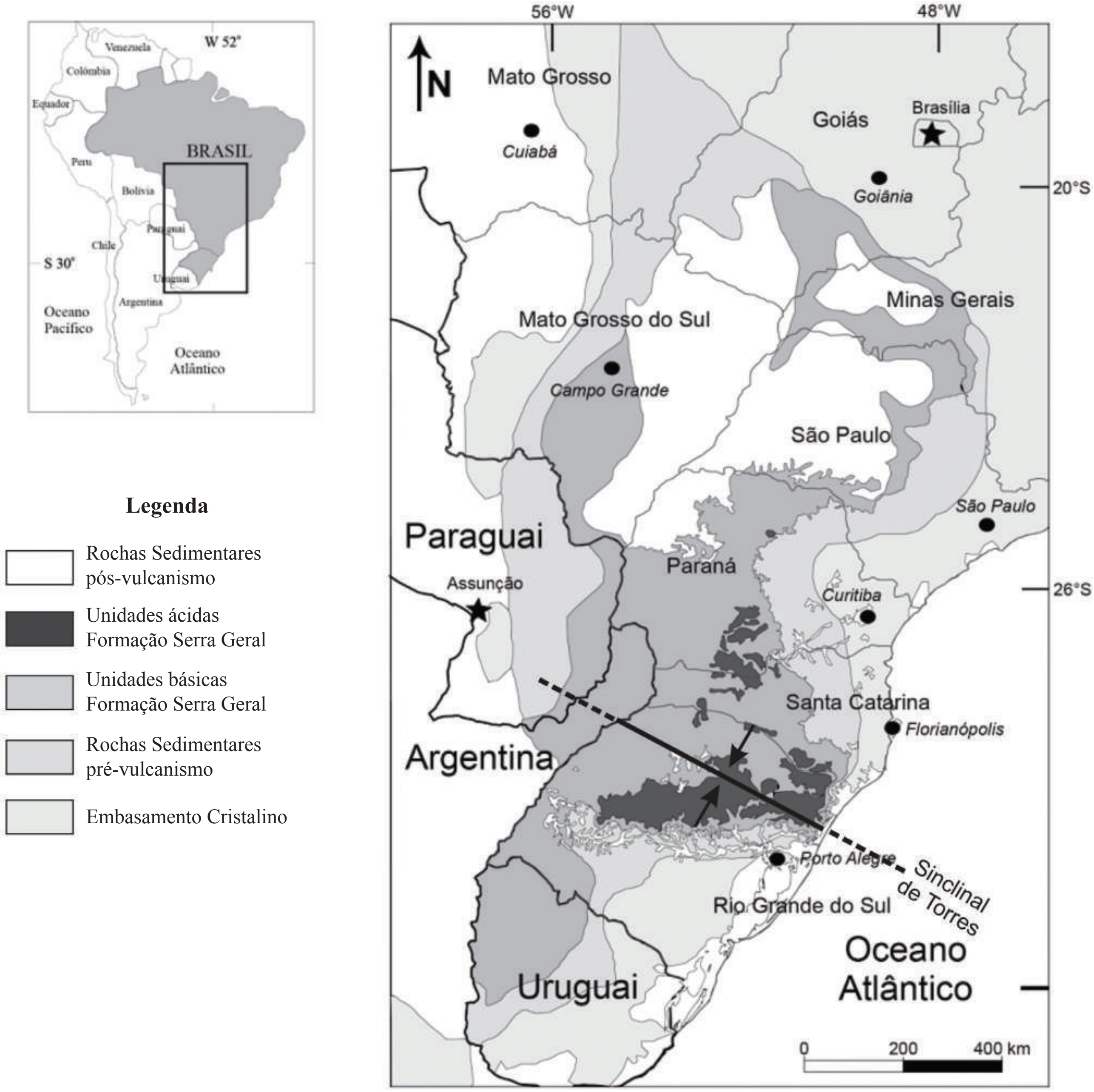

Figure 1 – Geologic map of the Paraná Basin, focusing on the Torres Syncline (Renner 2010).

prevent the generation of an external crust. Heat loss of the order of 3 – 5ºC/km increases the viscosity and deformation rate during the flow, preventing the lava from reaching longer distances from the source. The blocky/scoriaceous external shell is partially mixed with the more internal portions as the flow advances, therefore accelerating lava cooling. The area distribution in these flows may be ampler in plateaus (*e.g.* Deccan, Brown *et al.* 2011). Basal breccias occurrence in *´a´ā* flows of Serra Geral Formation, as interpreted here, is restricted or absent, contrasting with the channeled *´a´ā* flows (*e.g.* Hawaii and Etna, Italy) that are in general associated with slopes and central conduits and where the basal breccias are characteristically abundant.

The transitional type between *pahoehoe* and *´a´ā* is the rubbly *pahoehoe*. This term is applied to lava flows, whose top is composed of fragments of *pahoehoe* lobes (Keszthelyi *et al*. 2000, Keszthelyi 2002). The clasts are different from those observed in the *´a´ā* lavas, because they have a vitreous shell on both sides, indicating that the lobe was broken by the action of external forces instead of internal flow pressures. This top grades to a coherent vesicular portion, then to a dense core, and finally to the vesicular lower crust. These flows frequently have a smooth base that is typical of *pahoehoe.*

The upper portion of the block lavas is formed by angular and polyhedral fragments that are regular in shape and have smooth surfaces. This portion is generally formed by more viscous magmas (Schmincke 2004), and it was not recognized in the Paraná-Etendeka Magmatic Province.

MORPHOLOGY OF SERRA GERAL FORMATION BASIC ROCKS AT TORRES SYNCLINAL Torres Syncline can be divided into three regions – a main valley, an intermediate zone and a southern hinge – each showing distinct total thickness and stratigraphy, and reflecting the structural evolution of the synclinal.

One of the facies of the synclinal main valley is constituted by thick (ponded) *pahoehoe* flows as illustrated in Fig. 2, which fill interdune spaces of the Botucatu Formation. The other facies is anastomosed (lobes and compound *pahoehoe*) where the reliefs were smoother. In this lower portion of the Torres Syncline, S- (spongy, according to Walker 1989) and P-types (pipe vesicle, according to Wilmoth & Walker 1993) lobes were also identified.

S-type lobes are characterized by homogeneous distribution of vesicles, whereas the P-type have vesicles in the shape of tubes (pipes) at the base and massive rims. The emplacement of P-type lobes (Figs. 3A and B) involves lower extrusion temperatures than those of the S-type. In the P-type the rims are vitreous and the central portions more crystalline, which indicate slower crystallization. Such crystallization time interval favors the exsolution of volatiles present in the magma (Wilmoth & Walker 1993, Oze & Winter 2005). Alternatively, Hon *et al*. (1994) suggest that the P-type lobes can be generated by pressurized lavas, in which the vitreous and dense zones would cause an increase in the lobe internal pressure, dissolving the volatiles present in the magma and inhibiting the formation of vesicles.

Very fine vesicular sheet flows occur associated with the lobes and were produced by a single and continuous effusion, generating thin horizontal flows (Fig. 4).

These facies are overlain by a succession of 3 m-thick, simple P-type *pahoehoe* flows (Fig. 4). To

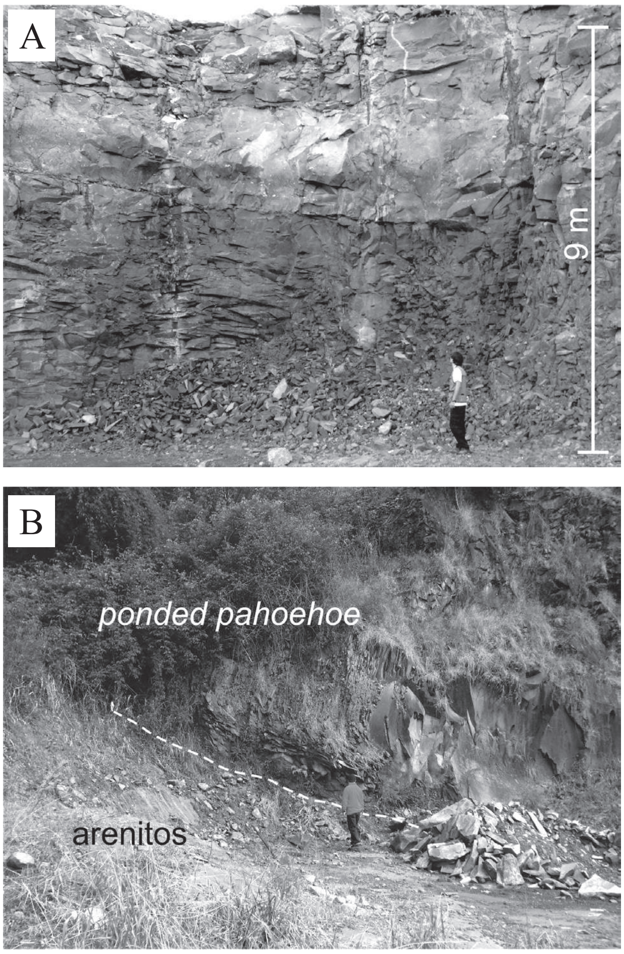

Figure 2 – Ponded pahoehoe outcrops: (A) massive internal organization and horizontal fracturing pattern; (B) filling of Botucatu Formation interdunes by ponded pahoehoe.

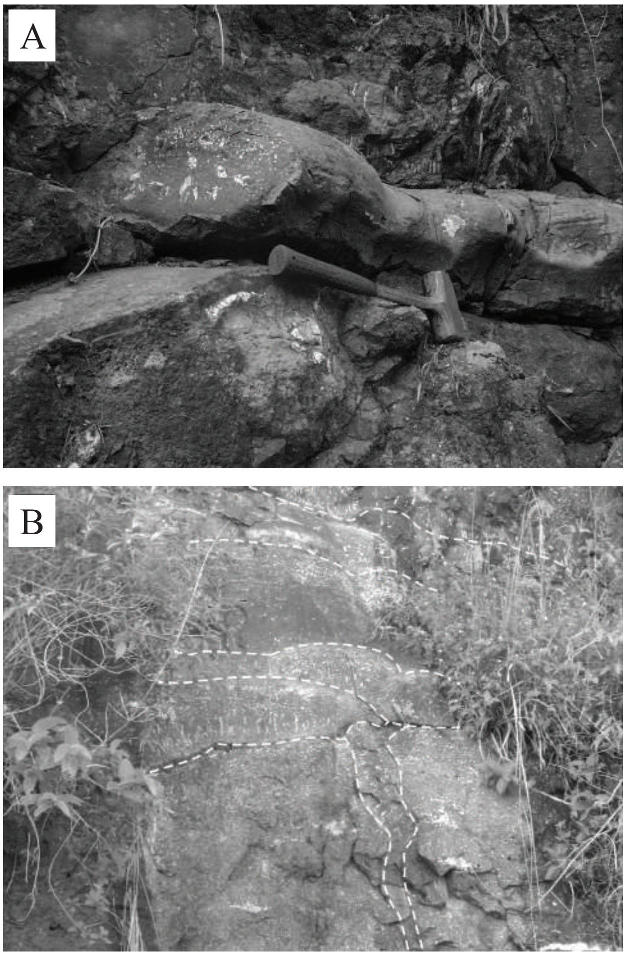

Figure 3 – (A) P-type lobe with pipe vesicles; (B) stratigraphic arrangement between P-type pahoehoe lobes.

the North, the succession of *pahoehoe* flows is exposed at altitudes up to 330 and 370 m in the synclinal main valley.

Following the *pahoehoe* flows, successive *´a´ā*-type flows (individual thickness of 15 – 20 m) with a scoriaceous lobular facies crop out at altitudes up to 630 m. The blocks on top and at the base of the *´a´ā* flows are sub-rounded, highly vesicular (Fig. 5) and internally deformed by the flow. These suggest that they were formed at the limit of the fragile-ductile conditions. The intense vesiculation of the fragments and the random distribution of the blocks indicate that break-up of the external portions and rotation occurred as the lava flowed. Some fragments reach an average of 10 to 30 cm in size and zeolitization is common in spaces between blocks. An important characteristic is that the fragments are oxidized, indicating the exposition of an original fragmented crust.

Figure 4 – Successive sheet flows. The arrows mark the limit of the flows; the upper dotted line indicates the contact between sheet flows and a simple pahoehoe flood.

The origin of these flows is attributed to an increase in magma effusion rate. The topographic factor is discarded because the relief constructed by the preceding *pahoehoe* flows is considered flat. The compositional factor is also ruled out as the chemical data presented in Table 1 indicate that the variations in SiO_2 contents and in $Fe_2O_3^t/MgO$ ratios are not enough to explain the formation of different morphological types.

In the upper portions of the Torres Syncline main valley, successive acid lava flows crop out with local intercalations of *´a´ā*-type basalts*,* reaching 400 m in thickness.

Petrography of the pahoehoe flows The petrographic studies aimed at mineralogical and textural identifications and classification of the basic rocks from the main valley, including the localities of Feliz, Caxias do Sul, Nova Pádua, São Marcos, and São Francisco da Paula. In these localities, *pahoehoe* flows were identified in the lower portions of the Torres Syncline and *´a´ā*-type flows in the intermediate and upper portions of the Serra Geral Formation.

The *pahoehoe* flows were separated in ponded, lobe (compound flows), sheet flow and simple *pahoehoe*. The primary mineral composition of these flows is constituted by plagioclase, augite, opaque minerals, and apatite.

Table 1 – Results of the chemical analyses of different types of Serra Geral Formation basic flows in the valley of the Torres Syncline

	LR-04-A *ponded*	LR-11-A *ponded*	LR-12-A *ponded*	LR-15-A *pahoehoe* Simples	LR-18-B *a´ā*	LR-23-A *a´ā*	LR-27-B *a´ā*
UTM	465957/ 6738398	465785/ 6743253	469516/ 6741931	464324/ 6752965	465352/ 6754868	466941/ 6757812	467971/ 6759967
SiO_2	55.65	50.91	50.56	48.69	56.84	53.07	51.11
TiO_2	1.33	1.17	1.07	1.06	1.46	1.17	1.52
Al_2O_3	14.29	14.42	14.09	15.02	13.10	14.81	13.44
Fe_2O_3	10.39	11.08	11.06	10.51	13.03	11.72	13.80
MnO	0.15	0.17	0.16	0.18	0.18	0.18	0.21
MgO	4.08	7.14	8.62	6.38	2.97	5.01	4.42
CaO	7.11	9.81	9.71	9.94	6.69	8.98	7.95
Na_2O	2.63	2.03	1.82	1.66	2.52	2.43	2.12
K_2O	2.34	1.06	0.92	1.14	2.55	1.73	1.40
P_2O_5	0.29	0.16	0.14	0.14	0.22	0.16	0.19
PF	1.5	1.7	1.5	5.0	0.2	0.5	3.5
SOMA	99.76	99.75	99.74	99.78	99.76	99.76	99.72
Fe_2O_3/MgO	2.29	1.40	1.15	1.48	3.95	2.11	2.81

Contents of major element oxides in weight percent. PF: loss on ignition

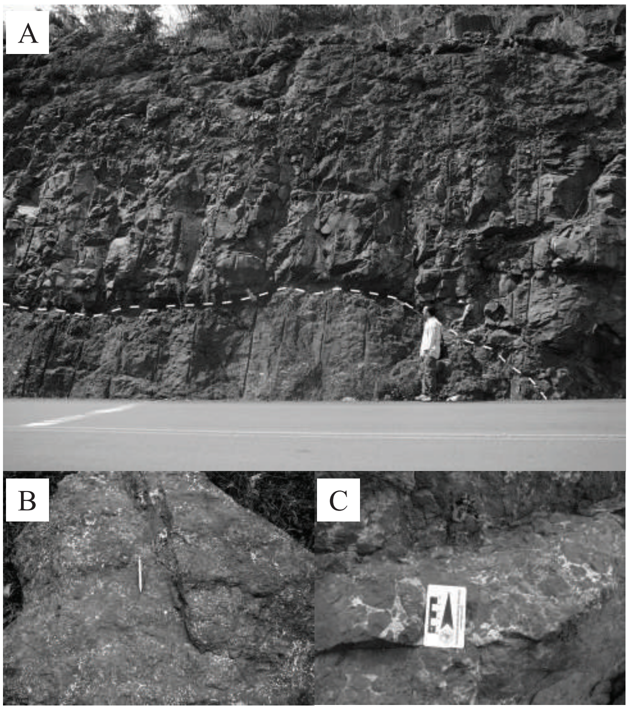

Figure 5 – (A) Contact between top and base of ´a´ā flows; (B) breccia on the surface of the lava flow, containing vesicular blocks; (C) breccia on top of ´a´ā lava, with spaces between the vesicular clasts filled with zeolite and quartz.

In the ponded-type *pahoehoe* the rock is generally holocrystalline (fine to medium-grained phaneritic), with a matrix in which augite is intergranular between plagioclase laths (Fig. 6). The porphyritic texture is common, with clinopyroxene and plagioclase phenocrysts, the latter partly arranged in a sieve texture. The glomeroporphyritic texture is frequent, with clustering of plagioclase and subordinately augite phenocrysts (Fig. 6C). The presence of segregation structures in the *pahoehoe* central portions plus the microvesiculation between plagioclase and pyroxene crystals, characterizing a diktytaxitic texture, indicate, according to Goff's (1996) criteria, a high volatile content in the magma that originated these lavas (Fig. 6D).

In the lobes, the cores are scarcely vesicular and sometimes include finer-grained strips or zones with aligned plagioclase. The upper crust is moderately to highly vesicular, and the vesicle size increases inwards (Figs. 6 E and F). The external portion of the upper crust is in general holohyaline and oxidized, and the basal one rarely contains plagioclase phenocrysts, which may have floated towards the top of the lobes.

The simple *pahoehoe* flows extruded after the peneplanation of the Botucatu Formation paleotopography. These flows are in average 3 m thick and differ from the compound *pahoehoe* for presenting a vesicular top, holocrystalline to hypocrystalline fine-grained phaneritic core, and a lower portion with pipe vesicles. The vesiculation pattern is marked by rounded to sub-rounded, rarely stretched vesicles. In the core, augite is intergranular and the diktytaxitic texture marks a microvesicular pattern, both suggesting a slower cooling than that of the *pahoehoe* lobes and *´a´ā* lavas. Although the porphyritic and glomeroporphyritic textures represented by isolated or clustered plagioclase phenocrysts are common, the abundance of phenocrysts in the simple *pahoehoe* type is lower than that of the ponded one.

Petrography of the ´a´ā flows The mineral composition of the Torres Syncline *´a´ā* lavas is the same of the *pahoehoe*: plagioclase, augite, opaque minerals, and apatite. The typical *´a´ā* flows are thick (15 to 20 m) and have a brecciated or clinkery shell (Fig. 7A) and a massive core (MacDonald 1972, Peterson & Tilling 1980, Rowland & Walker 1990). The latter is aphanitic and hypocrystalline, with abundant plagioclase microlites of the matrix surrounding plagioclase phenocrysts.

Below the scoriaceous blocks, the rock is hypocrystalline and aphanitic, sometimes partially brecciated, rich in plagioclase microlites, and with stretched vesicles. It grades to internal parts, in which the flow patterns can be autobrecciated generating fragments of fluidal aspect (Fig. 7B), and to central zones, where the very fine matrix surrounds plagioclase (Fig. 7C) and subordinately augite glomerocrysts. The matrix of the cores is characterized by intersertal and intergranular textural domains with clinopyroxene between plagioclase crystals. Characteristically, *´a´ā* lavas are more abundant in plagioclase microlites in the matrix (< 0.1 mm) when compared to the cores of the *pahoehoe* lavas (Fig. 7D). The microlites are elongated, skeletal and bifurcated, suggesting changes in the undercooling conditions.

DISCUSSION When comparing the basic flow types of Serra Geral Formation in the Torres Syncline, the marking petrographic aspect is the aphanitic and hypocrystalline texture and the large quantity of plagioclase microlites in the cores of the *´a´ā* lavas, which are different from the *pahoehoe* lobes and flows that are texturally thicker and have larger plagioclase phenocrysts. This textural contrast helps separating

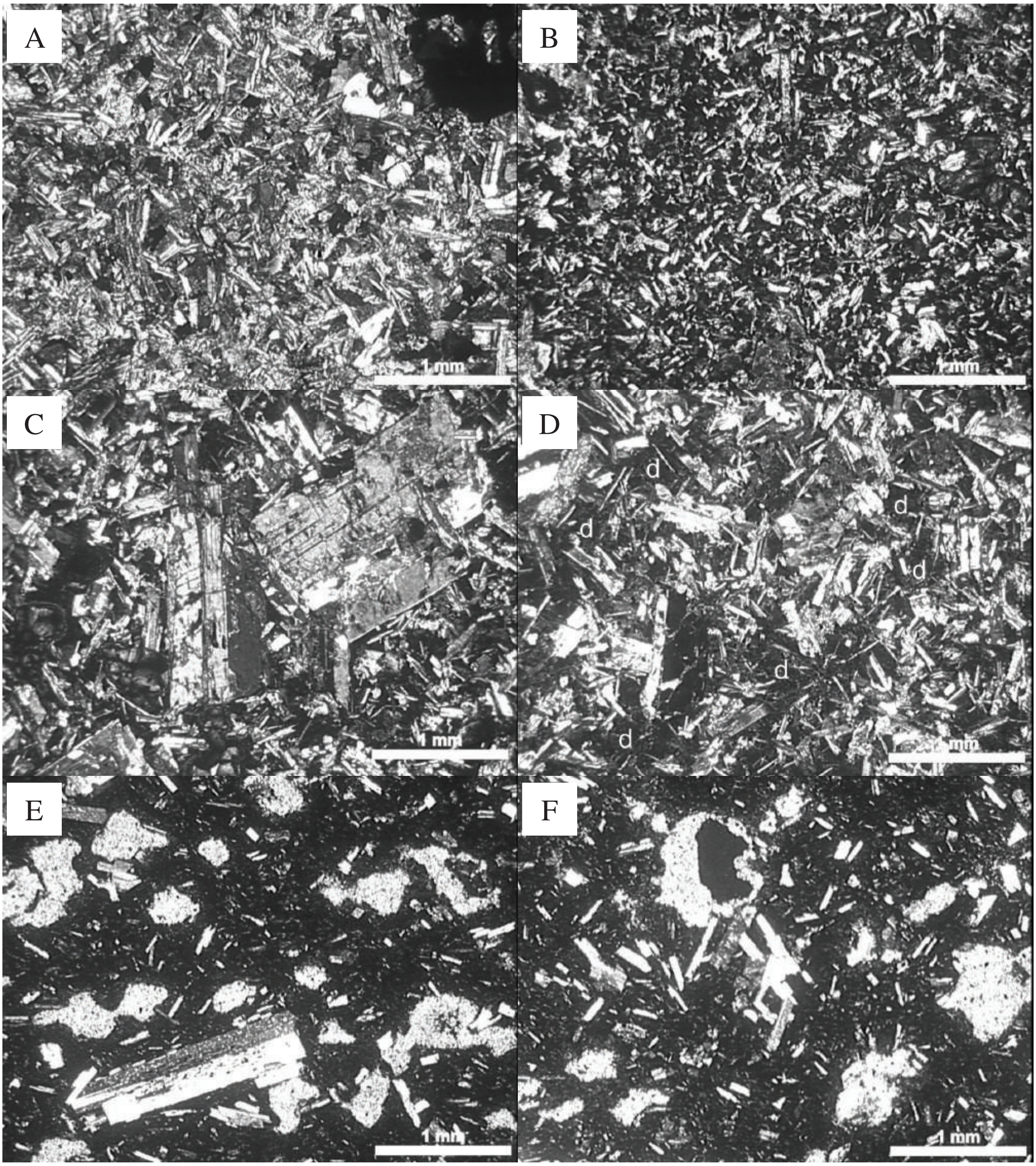

Figure 6 – Photomicrographs of pahoehoe flows, crossed nicols: (A–B) ponded pahoehoe showing fine-grained phaneritic and intergranular textures; (C) glomeroporphyritic texture with aggregates of plagioclase phenocrysts; (D) diktytaxitic texture with spaces between plagioclase crystals indicated in the image by the letter d; (E–F) upper crust of pahoehoe vesicular lobe filled with nontronite, and plagioclase phenocrysts surrounded by a microcrystalline matrix.

both subaerial flow types, and this criterion can be extended to geologically similar areas (*e.g.* Hawaii, Polacci *et al*. 1999, Lentz & Taylor 2002; Oregon Plateau, Bondre & Hart 2008; and Deccan, Brown *et al*. 2011). Textural differences of this type were highlighted by MacDonald (1953), who attributed the greater crystallinity (abundance of crystals) of the *´a´ā* cores to the more vigorous movement during emplacement.

Sato (1995), investigating the textural patterns of basic lava types, stressed out lower abundance of plagioclase in the matrix and the coarser texture

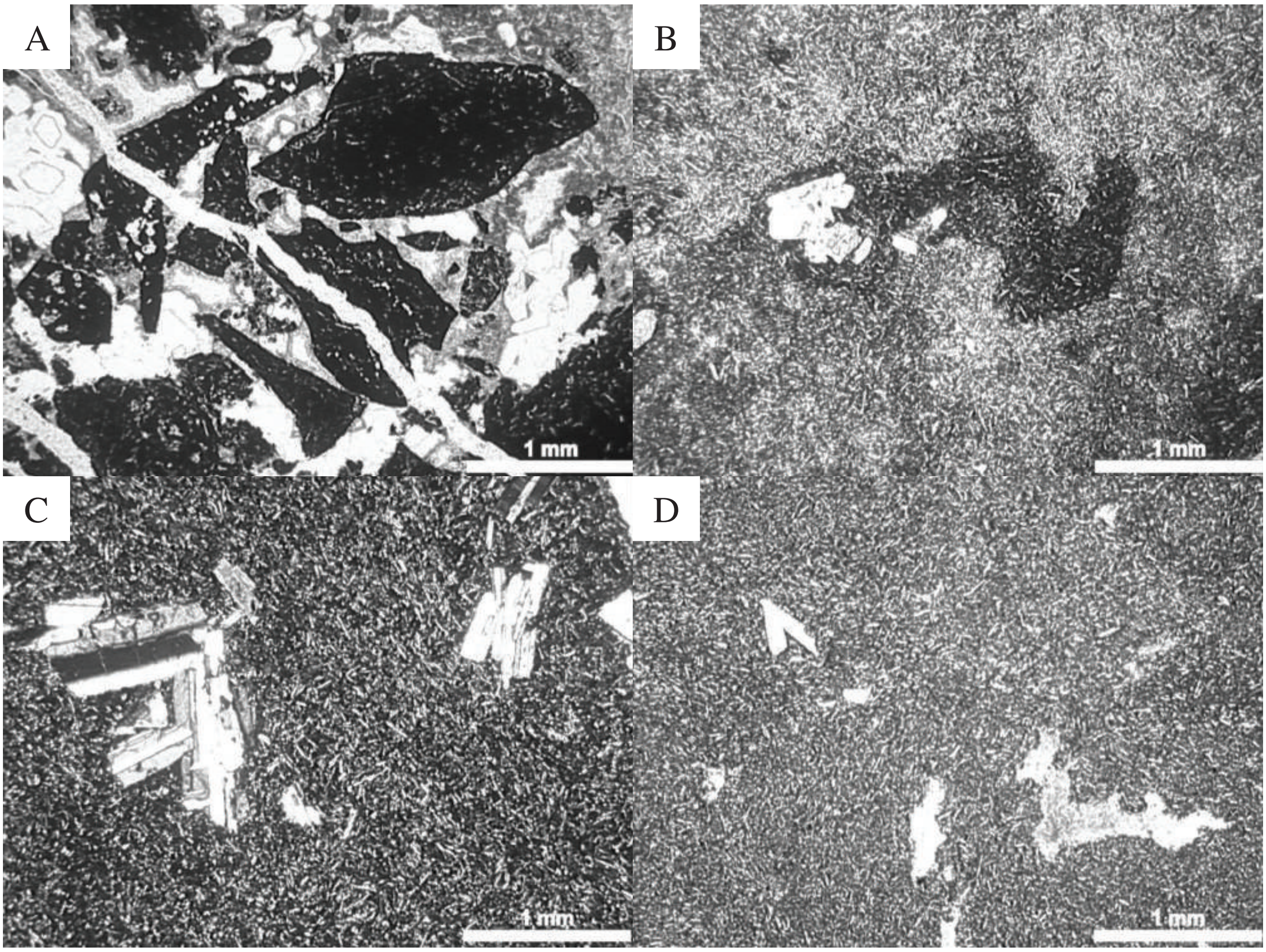

Figure 7 – Photomicrographs of ´a´ā lavas at the same scale of Fig. 5: (A) breccia composed of hypocrystalline basalt fragments cemented by quartz and zeolites, plane-polarized light; (B) fluidal fragment generated in autobrecciated flow, plane-polarized light; (C) core of a ´a´ā flow showing glomeroporphyritic texture in very fine-grained phaneritic matrix, contrasting with the grain-size in Fig. 5C, crossed nicols; (D) core of a ´a´ā flow with a very fine-grained phaneritic matrix, showing large abundance of plagioclase microlites (compare with Fig. 5), plane-polarized light.

surrounding plagioclase of the *pahoehoe* lavas when compared to *´a´ā* ones, despite the almost identical chemical composition of both types.

These differences are generically attributed to a more rapid cooling of the *´a´ā* lavas (open and channeled system) when compared to *pahoehoe* (closed and leveled system), although this fact does not explain the larger volume of plagioclase microlites in the matrix of the *´a´ā* lavas.

The higher abundance of plagioclase in the matrix of the *´a´ā* flows can be related to the combination of some factors, such as undercooling, devolatization, and eruption or flow rate.

The undercooling that marks the difference between the *liquidus* temperature and the effective one of the first crystallization has influence in the nucleation rate, growing, and crystal morphology. Moderate undercooling indicates a more rapid drop in the magma temperature and favors nucleation rather than crystal growing. This temperature interval is strongly modified by degassing. The increase in *liquidus* temperature caused by devolatization enhances undercooling, which in turn increases the nucleation rate. The decrease in *liquidus* temperature with pressure before devolatization followed by a rapid one may generate early partial reabsorption of the phases.

Kouchi *et al*. (1986) experimentally demonstrated that an increase in the internal movement of a basic magma increases plagioclase nucleation (shear effect), thus decreasing the incubation time of these crystals.

The textural pattern and the plagioclase abundance in the *´a´ā* lavas can be explained by the higher effusion rate (> 5 m^3/s) of these systems. The pre-eruptive condition of rapid magma ascension would promote the loss of volatiles in the upper portions, generating a convective pattern of the system with the nondevolatized portions (Kazahaya *et al*. 1994). This movement would also accelerate the degassing process and would increase the undercooling interval and shear effect in the system. Their combination could favor the rapid nucleation of plagioclase crystals with elongated and partially reabsorbed shapes.

CONCLUSIONS Serra Geral Formation in the Syncline Torres can be divided in three regions: a main valley, an intermediate zone, and a southern hinge.

Low effusion rates (< 5 m^3/s) mark the Serra Geral Formation initial volcanic manifestations, where the spaces between the Botucatu Formation dunes were filled with thick (ponded) *pahoehoe* flows. In the smoother portions, the anastomosed facies predominated with compound *pahoehoe*, S- and P-type lobes, and thin sheet flows.

With the peneplanation of the relief, flows succession acquired a simple P-type *pahoehoe* morphology (average thickness of 3 m), however maintaining the low effusion rates (< 5 m^3/s).

As rates increased, successive 15 to 20 m-thick *ʹaʹā*-type flows were formed. The occurrence of *ʹaʹā* flows might only be attributed to an increase in the magma effusion rates, discarding the paleorelief and chemical variations in the generation of these flows.

Petrographically, the cores of the *ʹaʹā*-type basic flows are characterized by an aphanitic and hypocrystalline texture and abundance of plagioclase microlites. The *pahoehoe* lobes and flows are texturally coarser and include larger plagioclase phenocrysts. These differences are generically attributed to rapid cooling of the *ʹaʹā* lavas (open and channeled system), when compared to *pahoehoe* (close and leveled system), although this fact does not explain the greater volume of plagioclase microlites in the matrix of the *ʹaʹā* lavas.

The greater abundance of plagioclase in the matrix of the *ʹaʹā* flows in comparison to *pahoehoe* is attributed to undercooling, devolatization, and higher eruption rate of the *ʹaʹā* lavas.

When it comes to regional stratigraphic correlations between flows of Serra Geral Formation, the fact that the *ʹaʹā*-type flows, differently from the *pahoehoe* type, do not reach long distances from the source, must be taken into account.

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References

Aubele J.C., Crumpler L.S., Elston W.E. 1988. Vesicle zonation and vertical structure of basalt flows. *Journal of Volcanology and Geothermal Research*, **35**:349-374.

Bondre N.R., Duraiswami R.A., Dole G. 2004. Morphology and emplacement of flows from the Deccan Volcanic Province, India; *Bulletin of Volcanology*, **66**:29-45.

Bondre N.R. & Hart W.K. 2008. Morphological and textural diversity of the Steens Basalt lava flows, southeastern Oregon, USA: implications for emplacement style and nature of eruptive episodes. *Bulletin of Volcanology*, **70**:999-1019.

Brown R.J., Blake S., Bondre N.R., Phadnis V.M., Self S. 2011. ʹAʹā lava flows in the Deccan Volcanic Province, India, and their significance for the nature of continental flood basalt eruptions. *Bulletin of Volcanology*, **73**:737-752.

Bryan S.E. & Ernst R.E. 2008. Revised definition of Large Igneous Provinces (LIPs). *Earth Science Reviews*, **86**:175-202.

Coffin M.F. & Eldholm O. 1994. Large Igneous Provinces: crustal structure, dimensions and external consequences. *Reviews of Geophysics*, **32**:1-36.

Dragoni M. & Tallarico A. 1994.The effect of crystallization on the rheology and dynamics of lava flows. *Journal of Volcanology and Geothermal Research*, **59**(3):241-252.

Emerson O.H. 1926. The formation of aa and pahohoe. *American Journal of Science*, Series 5, **12**:109-114.

Goff F. 1996. Vesicle cylinders in vapor-differentiated basalt flows. *Journal of Volcanology and Geothermal Research*, **71**:167-185.

Hon K., Kauahikaua J., Denlinger R., Mackay K. 1994. Emplacement and inflation of pahoehoe sheet flows: Observations and measurements of active lava flows on Kilauea, Hawaii. *Geological Society of America Bulletin*, **106**:351-370.

Jerram D. 2002. Volcanology and facies architecture of Flood basalts. *In*: Menzies M.A., Klemperer S.L., Ebinger C.J., Baker J., eds. Volcanic Rifted 360

Margins: Boulder, Colorado, *Geological Society of America Special Paper*, **362**:132-199.

Jerram D.A. & Widdowson M. 2005. The anatomy of Continental Flood Basalt Provinces: geological constraints on the processes and products of flood volcanism. *Lithos*, **79**:385-405.

Kazahaya K., Shinohara H., Saito G. 1994. Excessive degassing of Izu-Oshima volcano: magma convection in a conduit. *Bulletin of Volcanology*, **56**(3):207-216.

Kent R.W., Thomson B.A., Skelhorn R.R., Kerr A.C., Norry M.J., Walsh J.N. 1998. Emplacement of Hebridean Tertiary flood basalts: evidence from an inflated pahoehoe lava flow on Mull, Scotland. *Journal of Geological Society London*, **155**:599-607.

Keszthelyi L. 2002. Classification of the mafic lava flows from OPD Leg 183. *In*: Frey F.A., Coffin M.F., Wallace P.J., Quality P.G. (eds.) Proceedings of the Ocean Drilling Program. *Scientific Results*, **183**:1-28.

Keszthelyi L., McEwen A.S., Thordarson T. 2000. Terrestrial analogs and thermal models for Martian lava. *Journal of Geophysical Research*, **105**(E6):27-49.

Kilburn C.R.J. 1981. Pahoehoe and ´a´ā lavas: a discussion and continuation of the model by Peterson and Tilling. *Journal of Volcanology and Geothermal Research*, **11**:373-389.

Kilburn C.R.J. 1987. Rheological implications of the pahoehoe-aa transition in lavas. *Abstract International. Union of Geodesy and Geophysics, 19th General Assembly, Vancouver*, **2**:418.

Kilburn C.R.J. 1990. Surfaces of aa flows-fields on Mount Etna, Sicily: Morphology, rheology, crystallization and scaling phenomena. *In*: Fink J.H. (ed.) *Lava Flows and Domes*, Berlin, Springer-Verlag, p. 129-156.

Kouchi A., Tsuchiyama A., Sunagawa I. 1986. Effect of stirring on crystallization kinetics of basalt: texture and element partitioning. *Contributions to Mineralogy and Petrology*, **93**:426-438.

Lentz R.C.F. & Taylor G.J. 2002. Petrographic textures and insights into basaltic lava flow emplacement on Earth, the Moon, and Vesta. In: Lunar and Planetary Science Conference XXXIII, *Abstract 1332*.

Lipman P.W., Banks N.G., Rhodes J.M. 1985. Degassing induced crystallization of basalt magma and its effects on lava rheology. *Nature*, **317**:604-607.

MacDonald G.A. 1953. Pahoehoe, aa and block lava. *American Journal of Science*, **251**(3):169-191.

MacDonald G.A. 1972. *Volcanoes*. Prentice-Hall Inc., Englewood Cliffs. 510 p.

Oze C. & Winter J.D. 2005. The occurrence, vesiculation and solidification of dense blue glassy pahoehoe. *Journal of Volcanology and Geothermal Research*, **142**:285-301.

Peterson D.W. & Tilling R.I. 1980. Transition of basaltic lava from pahoehoe to aa, Kilauea Volcano, Hawaii: field observations and key factors. *Journal of Volcanology and Geothermal Research*, **7**:271-293.

Polacci M., Cashman K.V., Kauahikaua J.P. 1999. Textural characterization of the pāhoehoe -´a´ā transition in Hawaiian basalt. *Bulletin of Volcanology*, **60**:595-609.

Renner L. 2010. *Metalogenia de Ni e EGP nos basaltos da Formação Serra Geral, porção sul da província.* Tese de Doutorado, Instituto de Geociências, Universidade Federal do Rio Grande do Sul, Porto Alegre, 256 p.

Rowland S.K. & Walker G.P.L. 1990. Pahoehoe and aa in Hawaii: volumetric flow rate controls the lava structure. *Bulletin of Volcanology*, **52**:631-664.

Sato H. 1995. Textural difference between pahoehoe and aa lavas of Izu-Oshima Volcano, Japan, and experimental study on population density of plagioclase. *Journal of Volcanology and Geothermal Research*, **66**:101-113.

Schmincke H.U. *Volcanism*. Berlin, Springer-Verlag, 2004.

Self S., Keszthelyi L., Thordarson T. 1998. The importance of pahoehoe. *Annual Reviews of Earth and Planetary Science*, **26**:81-110.

Sheth H.C. 2006. The emplacement of pahoehoe lavas on Kilauea and in the Deccan Traps. *Journal of Earth System Sciences*, **115**:615-629.

Storey M., Duncan R.A., Swisher III C.C. 2007. Paleocene-Eocene Thermal Maximum and the Opening of the Northeast Atlantic. *Science*, **316**:587-589.

Waichel B.L., Lima E.F., Lubachesky R., Sommer C.A. 2006. *Pahoehoe* flows from the central Paraná Continental Flood Basalts. *Bulletin of Volcanology*, **68**:599-610.

Waichel B.L, Lima E.F., Viana A.R., Scherer C.M., Bueno G.V., Dutra G. 2012. Stratigraphy and volcanic facies architecture of the Torres Syncline, Southern Brazil, and its role in understanding the Paraná-Etendeka Continental Flood Basalt Province. *Journal of Volcanology and Geothermal Research*, **216**:74-82.

Walker G.P.L. 1989. Spongy pahoehoe in Hawaii: a study of vesicle-distribution patterns in basalt and their significance. *Bulletin of Volcanology*, **51**:199-209.

Wilmoth R.A. & Walker G.P.L. 1993. P-type and S-type pahoehoe: a study of vesicle distribution patterns in Hawaiian lava flows. *Journal of Volcanology and Geothermal Research*, **55**(1-2):129-142.

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