DOI: 10.5327/Z23174889201400040010

ARTICLE

The role of viscosity in the emplacement of high-temperature acidic flows of Serra Geral Formation in Torres Syncline (Rio Grande do Sul State, Brazil)

O papel da viscosidade na colocação de fluxos ácidos de alta temperatura da Formação Serra Geral na Sinclinal de Torres (Rio Grande do Sul, Brasil)

Matheus Silva Simões[1]*, Lucas de Magalhães May Rossetti[2], Evandro Fernandes de Lima[3], Bruno Pinto Ribeiro[2]

ABSTRACT: The acidic flows from Serra Geral Formation in Torres Syncline, Rio Grande do Sul, Brazil, are on the top of a volcanic sequence composed by a complex facies association of compound, simple and rubbly *pahoehoe* basic flows, acidic lava domes, and tabular acidic lava flows. The origin and emplacement conditions of the acidic volcanic rocks are discussed in this paper based on petrology, on calculated apatite saturation thermometry temperatures, and on estimated viscosity data. The liquidus temperatures for metaluminous rhyodacite to rhyolite samples are about 1,067.5 ± 25ºC in average. The viscosity (η) values vary from 10^5 to 10^6 Pas for anhydrous conditions, suggesting the emplacement of high-temperature – low-viscosity lava flows and domes. The occurrence of acidic lava domes above simple *pahoehoe* flows as flow-banded vitrophyres was under low effusion rates, in spite of their high temperature and low viscosities, which are reflected in their small height. The emplacement of lava domes has continued until the eruption of rubbly *pahoehoe* flows and the geometry of these deposits rugged the relief. Presence of tabular acidic lava flows covering the landscape indicates that it was under high effusion rates conditions and such flows had well-insulated cooled surface crusts. The capacity to attain greater distances and overpass relief obstacles is explained not only by high effusion rates, but also by very low viscosities at the time of emplacement.

KEYWORDS: Viscosity; Acidic Flows; Torres Syncline; Serra Geral Formation; Paraná-Etendeka Province.

RESUMO: *Os fluxos ácidos da Formação Serra Geral na Sinclinal de Torres, Rio Grande do Sul, Brasil, estão no topo de uma sequência vulcânica composta por uma associação de fácies complexa de fluxos básicos do tipo pahoehoe compostos, simples e rubbly, domos e fluxos tabulares de lava ácida. A origem e as condições de colocação das rochas vulcânicas ácidas são discutidas neste trabalho com base em petrologia, em temperaturas calculadas por termometria de saturação em apatita e em dados de viscosidade estimada. As temperaturas liquidus para as amostras de riodacitos a riolitos são de 1067,5 ± 25ºC em média. Os valores de viscosidade (η) variam de 10^5 to 10^6 Pas para condições anidras, sugerindo a colocação de fluxos e domos de lava de alta temperatura e baixa viscosidade. A ocorrência de domos de lava ácida sobrepostos a fluxos pahoehoe simples como vitrófiros com bandamento de fluxo foi sob baixas taxas de efusão, apesar das suas altas temperaturas e baixas viscosidades que são refletidas na sua baixa dimensão vertical. A colocação de domos de lava continuou até a erupção de fluxos do tipo rubbly pahoehoe e a geometria destes depósitos tornou o relevo acidentado. A presença de fluxos de lava tabulares cobrindo a topografia indica uma colocação sob altas taxas de efusão de fluxos com isolamento térmico causado pelas superfícies externas já resfriadas. A capacidade para atingir maiores distâncias e ultrapassar obstáculos do relevo é explicada não apenas por altas taxas de efusão, mas também por viscosidades muito baixas no momento da sua colocação.*

PALAVRAS-CHAVE: *Viscosidade; Fluxos Ácidos; Sinclinal de Torres; Formação Serra Geral; Província Paraná-Etendeka.*

[1]Curso de Pós-graduação em Geociências, Instituto de Geociências, Universidade Federal do Rio Grande do Sul - UFRGS; Serviço Geológico do Brasil - CPRM, Manaus (AM), Brasil. *E-mail: matheus.simoes@ufrgs.br*

[2]Curso de Pós-graduação em Geociências, Instituto de Geociências, Universidade Federal do Rio Grande do Sul - UFRGS, Porto Alegre (RS), Brasil. E-mail: *lucasross@hotmail.com; bmacario@gmail.com*

[3]Instituto de Geociências, Universidade Federal do Rio Grande do Sul - UFRGS, Porto Alegre (RS), Brasil. *E-mail: evandro.lima@ufrgs.br*

*Corresponding author

Manuscrito ID: 30094. **Recebido em:** 04/03/2014. **Aprovado em:** 13/10/2014.

INTRODUCTION

Large Igneous Provinces (LIPs) are a continuum of voluminous Fe and Mg rich rock emplacements, which include continental flood basalts (CFB) and associated intrusive rocks, volcanic passive margins, oceanic plateaus, submarine ridges, seamount groups, and ocean basin flood basalts (Coffin & Eldholm 1994). The CFBs are individual volcanic constructs that are laterally extensive (several hundred km^2) and thick (about 1 km average), representing the eruption of enormous volumes of mantle-derived magma in relatively short-time periods (few million years) generally of tholeiitic composition (Coffin & Eldholm 1992; Sheth 2007).

Paraná-Etendeka CFB occupies, approximately, an $1,3 \times 10^6\ km^2$ area, in which 90% are located in South America, above the aeolian sedimentary rocks of Botucatu Formation in the Paraná Basin. The stratigraphic reference to this part of the Paraná-Etendeka CFB is defined as Serra Geral Formation (SGF), which is a tholeiitic volcanic rock association, 1,700 m thick, with a great proportion of basic and less representative intermediate to acidic volcanic rocks (Melfi *et al*. 1988).

Waichel *et al*. (2012) described the facies architecture of SGF in the Torres Syncline region, identifying five distinct volcanic episodes: Basic Volcanic Episode I (BVE I) that covers Botucatu paleoerg with compound *pahoehoe* flows; BVE II representing the volcanic climax and composed of ~ 500 m tabular-classic simple *pahoehoe* flows; Acidic Volcanic Episode I (AVE I), which is composed of acidic lava dome-field facies association; BVE III that comprises *'a'a* flows with tabular/lobate escoriaceous facies association; and AVE II represented by acidic tabular facies. Recently, detailed studies of basic lavas from the BVE III identified a four-part structure with internal characteristics typical of rubbly *pahoehoe* lavas (Rossetti *et al*. 2014).

The acidic volcanism of Paraná-Etendeka CFB has been largely studied regarding petrographic and geochemical aspects. It is divided into two main groups: Palmas and Chapecó types (Bellieni *et al*. 1986; Peate 1997). Palmas type rocks are aphyric low-Ti dacites and rhyolites. The dacites are subdivided into Caxias do Sul (0.91 wt.%<TiO_2<1.03 wt.% and 0.25%<P_2O_5<0.28 wt.%), Anita Garibaldi (1.06 wt.%<-TiO_2<1.25 wt.% and 0.32 wt.%<P_2O_5<0.36 wt.%), and Jacuí (1.05 wt.%<TiO_2<1.16 wt.% and 0.28 wt.%<P_2O_5<0.31 wt.%) sub-types (Nardy *et al*. 2008).The rhyolites are subdivided into Santa Maria (P_2O_5≤0.21%) and Clevelândia (0.21 wt.%<P_2O_5≤0.23 wt.%) sub-types (Peate *et al*. 1992; Nardy *et al*. 2008). The Chapecó type are high-Ti porphyritic trachytes with higher Ba, Nb, La, Ce, Zr, P, Nd, Y, Yb, Lu and K and lower Rb, Th and U contents than Palmas type. This magma-type is also divided into Ourinhos, Guarapuava (Peate 1997), and Tamarana (Nardy *et al*. 2008) sub-types.

In the African counterpart of Paraná-Etendeka CFB, a series of acidic magma-types has been described, and the low-Ti quartz latites are represented by Goboboseb, Springbok, Wereldsend, Grootberg, Beacon, Hoas, and Fria types. The high-Ti magma-types are represented by Nil Despeandum, Nadas, Sechomib and Hoarusib latites and also by Sarusas, Ventura, Khoraseb, Naudé and Elliott quartz latites (Marsh *et al*. 2001). The geochemical equivalences of major and trace elements between the two counterparts of Paraná-Etendeka CFB were recognized as Santa Maria→Fria, Ourinhos→Khoraseb and Guarapuava→Sarusas (Marsh *et al*. 2001) or Guarapuava→Ventura and Tamarana→Sarusas (Bryan *et al*. 2010).

The mineral chemistry studies available present anorthite contents of An_{63-38} for the plagioclase phenocrysts and micro-phenocrysts of Palmas-type rhyodacites and An_{68-63} for resorbed plagioclase grains. Pyroxenes in the acidic units are generally pigeonite with Wo_{12-7} with initial Ca increase accompanied by Fe decrease in the late pyroxenes (Bellieni *et al*. 1984; 1986).

Identification of acidic rock strata with lateral extension >> thickness conducted many authors to think of a pyroclastic genesis hypothesis for the silicic volcanic rocks of Parana-Etendeka Province CFB, which could be explained by high-grade welding and formation of rheoignimbrites (Petrini *et al*. 1989; Whittingham 1989; Roisenberg 1989; Milner *et al*. 1992; 1995; Bryan *et al*. 2010). The effusive origin for the same rock association was assumed (Bellieni *et al*. 1986; Comin-Chiaramonti *et al*. 1988; Henry & Wolff 1992; Umann *et al*. 2001; Waichel *et al*. 2012; Polo & Janasi 2014) and the volcanic conduits of lava flows were described in the Northeastern portion of Rio Grande do Sul State (Lima *et al*. 2012).

Paraná-Etendeka CFB acidic rocks are characterized by high crystallization temperatures. In the Etendeka Group quartz-latites, the obtained temperatures range between 995 and 1,025ºC by apatite saturation method (Milner *et al*. 1992). In the Paraná Basin, temperatures obtained by the coexisting pyroxenes method are 1,030 ± 38ºC (Bellieni *et al*. 1984) and 1,117 ± 17ºC (Bellieni *et al*. 1986) for earlier crystals. In Piraju-Ourinhos region, central part of the Paraná Basin, the application of apatite saturation method yielded temperatures between 980 and 1,010ºC (Janasi *et al*. 2007). Viscosity studies are available for the Etendeka Group and yielded relatively low viscosity of 10^6 Pa s for quartz latites (Milner *et al*. 1992).

Viscosity is, consensually, one of the most important properties of the magma rheology. The Arrhenius relation and the conclusion derived from it (*e.g.* Shaw 1972) are insufficient to describe the viscosity of melts over the entire temperature interval, which are now accessible using new techniques (Vetere 2006). Hence, the evolution of viscometers for silicate liquids has been traced by changing from Arrhenian temperature dependence (*e.g.* Shaw 1972; Bottinga & Weill 1972) to non-Arrhenian models, considering magma composition and volatile effects (*e.g.* Baker 1996; Hess & Dingwell 1996; Russell *et al.* 2002; Giordano & Dingwell 2003; Russell & Giordano 2005; Giordano *et al.* 2006; Vetere *et al.* 2006; Hui & Zhang 2007; Giordano *et al.* 2008).

This work presents a specific study of geochemistry based on thermometry and viscosity estimations together with field features to evaluate the conditions of emplacement and arrangement of facies associations for the Southern portion of SGF in Torres Syncline.

GEOLOGICAL SETTING

The study areas are located in three different sites in the Northeastern part of Rio Grande do Sul State along Torres Syncline (Fig. 1): São Marcos-Antônio Prado Region, RS – 122 road, and RS – 486 road (Rota do Sol).

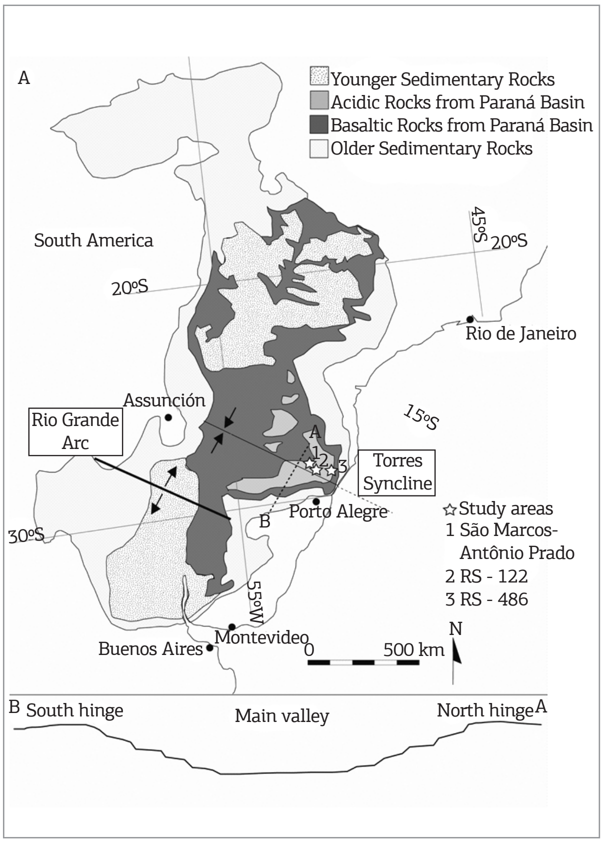

Figure 1. Simplified geologic map of Paraná Basin (after Renner 2010).

Lima *et al.* (2012) described the SGF volcanic succession in São Marcos-Antônio Prado region and identified, above the low-TiO_2 basic tholeiitic volcanic flows of BVE II and III, the root of acidic lava dome feeder conduits. These volcanic rocks are rhyodacites of Palmas magma-type and Caxias do Sul sub-type and are characterized by a vertical magmatic flow foliation in positive flower structure, which becomes a flat-lying foliation away from the conduits. In RS – 122 road, between Caxias do Sul and Feliz cities, the stratigraphic framework is composed by *pahoehoe* flow fields (Unit I) and simple rubbly flows (Unit II). Geochemically, both units are low-TiO_2 tholeiitic basalts and andesi-basalts of Gramado magma-type. Unit I is build up by *pahoehoe* lava flow fields that cover the sandstones of Botucatu Formation, and the first *pahoehoe* lavas are primitive olivine basalts with high contents of MgO. These flows occur as sheet and compound *pahoehoe*, and as ponded lavas in the interdune settings. Unit II is formed by thick simple rubbly lavas, characterized by a massive core and a rubbly top (Rossetti *et al.* 2014). The acidic rocks are lava domes and flows with tabular horizontal jointing classified as Palmas magma-type and Caxias do Sul sub-type and occur above the basaltic rocks in the area.

In the RS-486 road (Rota do Sol) outcrops, the acidic flows happen after BVE I and II compound and simple *pahoehoe* basic flows from the base to the top of the pile. This part of the volcanic succession is represented by 4 to 15 m thick lava domes with conspicuous spheroidal exfoliation, alternating with resinous aspect vitrophyres (pitchstones) that show several devitrification textures, such as spherulites. The BVE III rubbly *pahoehoe* basic flows occur superimposed with variable thickness (10 to 20 m). The last volcanic manifestation is represented by acidic tabular flows from AVE II with 15 m thickness, which is characterized by flat-lying jointing (5 to 15 cm spacing) and flow foliation structures associated with different degrees of devitrification (5 to 10 mm).

METHODS

The fieldwork was made in road outcrops and pits and 18 rock samples were selected for the confection of thin sections and geochemical analyses. The whole rock chemical analyses were made at Acme Analytical Laboratories Ltd., in Vancouver, Canada, using analysis routines 4A and 4B. In the first one, total abundance of main oxides and several minor elements was obtained from 0.2 g of the analyzed sample by inductively coupled plasma — emission spectrometry (ICP-ES) with the detection limit of 0.01% for SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O, MnO, TiO_2 and P_2O_5.

In the second one, the results of rare earth and refractory element were obtained from 0.2 g of analyzed sample by ICP – MS (mass spectrometry) with detection limit of 0.1 ppm for Rb and Zr.

The apatite saturation model of Harrison & Watson (1984) was used to estimate liquidus temperatures for the analyzed samples, since apatite is the main accessory phase as microphenocrysts. The model is based on experimental data of apatite solubility as function of magma temperature and composition. We assumed, by definition, the phosphorus partition coefficient as 42 (Watson & Green 1981; Prowatke & Klemme 2006) and used wt.% of P_2O_5 as apatite partition in the magma, considering phosphorus as an essential structural constituent (Sun & Hanson 1975).

The model used in this work to estimate viscosity (Giordano *et al.* 2008) is based on whole-rock chemical compositions and provides Newtonian non-Arrhenian temperature dependence of silicate melts. It was calibrated from more than 1,770 samples of an experimental analysis in a wide range of temperatures and magma compositions. The loss on ignition (LOI) values up to 2.9 wt.% do not substantially affect the final result of the estimated viscosities, and the effective H_2O content is an estimated value. Results of geochemical analysis, calculated temperatures and viscosities are presented in Tabs. 1 and 2.

RESULTS

Field and petrographic background

In a wide scale, the acidic flows in Torres Syncline are described as occurrences of lava dome fields and tabular flows representing two main events (AVE I and AVE II, Waichel *et al.* 2012). In a more detailed scale of work, there is a more complex arrangement of facies architecture, therefore lava domes and flows can be individually divided into massive pitchstones, flow-banded vitrophyres, tabular-foliated flows and auto-clastic breccia.

The acidic lava dome feeder conduits in São Marcos – Antônio Prado described by Lima *et al.* (2012) show a composed magmatic foliation revealed by alternation of different crystallization and oxidation grades, and presence of autoliths and xenoliths from the lower volcanic sequences. This area is characterized by the occurrence of tabular flows, massive pitchstones, lava domes, and feeder conduits.

The Caxias do Sul – Feliz profile is characterized by an association of tabular facies with sub-horizontal jointing (Fig. 2) and flow-banding with lava dome facies. Lava domes are characterized by an autobrecciated external portion and a coherent core with increase of crystallinity from external portions towards the core.

In RS-486 (Rota do Sol) profile, the first occurrence of acidic rocks is represented by flow-banded vitrophyres with millimetric to centimetric flat-lying flow-banding, which is symmetrically folded in some outcrops (Figs. 3A and 3B).

Table 1. Geochemical analyses compiled from Lima *et al.* (2012) with major elements, apatite temperatures, and viscosities results.

Sample	GA-03P	GA-04	GA-07	GA-10	GA-11	GA-12	GA-13	GA-16	GA-35B	Average	SD
SiO_2	68.88	66.91	68.96	66.51	66.88	67.07	67.01	67.24	67.66	67.46	0.83
Al_2O_3	12.13	13.1	11.95	12.87	12.74	13.05	12.76	12.74	12.92	12.70	0.37
FeO(T)	5.99	5.87	6	5.93	5.84	5.9	5.84	6.24	6.03	5.96	0.12
MnO	0.1	0.07	0.1	0.11	0.09	0.11	0.09	0.11	0.09	0.10	0.01
MgO	1.21	0.92	1.13	1.22	1.31	0.95	1.31	1.00	1.15	1.13	0.14
CaO	2.96	2.14	2.76	3.1	2.94	2.5	3.03	2.5	3.02	2.77	0.31
Na_2O	2.72	2.54	2.59	2.86	2.84	2.8	2.87	2.63	3.05	2.77	0.15
K_2O	3.99	4.19	4.46	4.3	4.02	4.09	4.14	4.54	3.68	4.16	0.24
TiO_2	0.87	0.9	0.85	0.89	0.91	0.92	0.9	0.92	0.96	0.90	0.03
P_2O_5	0.26	0.26	0.25	0.27	0.28	0.27	0.28	0.27	0.26	0.27	0.01
LOI	0.7	2.9	0.8	1.8	2	2.2	1.6	1.7	1	1.63	0.67
Total	99.81	99.8	99.85	99.86	99.85	99.86	99.83	99.89	99.82	99.84	0.03
Rb	178.5	187.9	181.9	177.5	165.6	172.3	177.6	185	157.2	175.94	9.09
Zr	224.2	248	218.6	233.5	233.6	242.9	240.9	238.4	225.1	233.91	9.16
D (apatite)	16238	16238	16888	15637	15078	15637	15078	15637	16238	15852.11	563.43
T °C	1112.9	1059.0	1109.5	1053.2	1068.4	1068.6	1072.0	1073.3	1079.5	1077.38	19.50
log (Pa s)	5.96	-	5.49	5.92	5.79	5.9	5.73	5.83	5.7	5.79	0.14
NBO/T*	0.101	0.054	0.107	0.098	0.091	0.068	0.095	0.089	0.085	0.09	0.02

SD: standard deviation; *NBO/T: $(2*(K_2O+Na_2O+CaO+FeO-Al_2O_3/SiO_2+2*Al_2O_3))$.

Table 2. Geochemical analyses from RS-486 road (BR samples) and Caxias do Sul – Feliz (LR samples) with major elements, apatite temperatures, and viscosities results.

Sample	BR029A	BR-29B	BR-41B	BR-41C	Average	SD	LR-28-A	LR-29-A	LR-32-A	LR-33-B	LR-35-A	Average	SD
SiO_2	66.38	67.79	67.72	66.71	67.15	0.55	66.24	66.05	65.83	65.49	68.41	66.40	1.03
Al_2O_3	12.84	12.43	12.61	12.82	12.68	0.15	12.78	13.23	13.05	12.78	12.47	12.86	0.26
FeO(T)	6.04	5.63	6.21	5.83	5.93	0.20	6.45	6.07	6.42	6.35	6.02	6.26	0.18
MnO	0.11	0.1	0.09	0.11	0.10	0.01	0.1	0.08	0.1	0.11	0.11	0.10	0.01
MgO	1.23	1.52	0.87	1.01	1.16	0.22	1.33	0.93	1.39	1.38	0.99	1.20	0.20
CaO	3.33	2.25	1.1	2.95	2.41	0.76	2.82	2.45	3.14	3.49	2.63	2.91	0.37
Na_2O	3.46	2.61	2.82	2.91	2.95	0.28	2.83	2.86	2.96	3.47	2.94	3.01	0.23
K_2O	2.78	4.28	6.01	3.58	4.16	1.07	4	4.02	4.19	2.8	4.25	3.85	0.53
TiO_2	0.9	0.87	0.85	0.86	0.87	0.02	0.93	0.96	0.97	0.95	0.86	0.93	0.04
P_2O_5	0.27	0.27	0.27	0.27	0.27	0.00	0.27	0.26	0.27	0.26	0.26	0.26	0.00
LOI	2.5	2.1	1.3	2.8	2.18	0.50	2.1	2.9	1.5	2.7	0.9	2.02	0.74
Total	99.84	99.85	99.85	99.85	99.85	0.00	99.85	99.81	99.82	99.78	99.84	99.82	0.02
Rb	218.6	180.9	211.8	180.5	197.95	15.58	165.5	168.1	163.9	186.9	166.7	170.22	8.45
Zr	255.3	245.6	251	261.2	253.28	5.12	215.5	224.2	255.2	244	245.7	236.92	14.71
D (apatite)	15637	15.637	15.637	15.637	15637.00	0.00	15637	16238	15637	16238	16238	15997.60	294.43
T ºC	1049.7	1088.4	1086.5	1058.7	1070.83	15.15	1045.8	1035.5	1034.6	1020.2	1100.1	1047.24	27.66
log (Pa s)	5.92	5.66	5.59	5.98	5.79	0.15	5.96	5.99	5.99	6.14	5.53	5.92	0.21
NBO/T*	0.086	0.083	0.094	0.074	0.08	0.01	0.101	0.067	0.109	0.103	0.093	0.09	0.01

SD: standard deviation; *NBO/T: $(2*(K_2O+Na_2O+CaO+FeO-Al_2O_3/SiO_2+2*Al_2O_3))$.

Figure 2. Lava flow with tabular jointing in Caxias do Sul – Feliz region. 29°13'40.28"S/51°19'53.13"W/ elevation: 733 m.

The petrographic features of these flows are represented by sparse plagioclase and pyroxene phenocrysts, some with swallow-tail textures, rotated by flow foliation and a microlith-rich groundmass with hyalopilitic texture (Fig. 4A). The lateral variations of the flow-banded vitrophyres are autobreccias with centimetric clasts of red glass with perlitic cracks and external irregular shape, cemented by zeolite (Fig. 3C).

Towards the top of the sequence, there are spherulite-bearing pitchstones (Fig. 3D) with porphyritic and glomeroporphyritic textures of plagioclase, pyroxene, and Fe-Ti oxides. Plagioclase commonly presents sieve texture and groundmass is composed of microliths in intersetal texture (Figs. 4C and 4D). The pitchstones are intercalated with 4 to 6 m lava domes with sparse plagioclase and pyroxenes within a glassy groundmass and rubbly *pahoehoe* basic lava flows. This sequence is superimposed by tabular acidic flows with sub-horizontal centimetric jointing.

Geochemistry, temperatures, and viscosities

The studied rocks are characterized by SiO_2 contents between 66.05 and 68.96 wt.%, with Na_2O+K_2O usually lower than 7.0 wt.%. In the R_1-R_2 (De La Roche *et al.* 1980) and A/NK *versus* A/CNK plots (Shand 1943), samples can be classified as metaluminous rhyodacites, with only one occurrence of rhyolite (Fig. 5). The TiO_2 contents between 0.85 and 0.97 wt.% are near the lower limit established for high-Ti acid rocks of SGF (Nardy *et al.* 2008).

To classify the samples regarding magma-types, the use of total alkali-silica (TAS) diagram, with SiO_2 against Na_2O+K_2O, shows that the studied samples occupy the Palmas-type field (except for BR-41B). In the Zr *versus* Rb diagram, the samples plot within or near the Caxias magma sub-type (Fig. 6).

The apatite saturation model of Harrison & Watson (1984) suggests that apatite dissolution in felsic magmas is limited by diffusion of phosphorous in the melt. In the studied samples, P_2O_5 contents range from 0.25 to 0.28 wt.% and the lnDapatite/melt varies between 9.6 and 9.7. These results within the SiO_2 contents provided a calculated temperature of 1,077.3 ± 19ºC in São Marcos-Antônio Prado profile; 1,047.2 ± 27ºC in Caxias do Sul – Feliz profile, and 1,070.8 ± 16ºC in RS-486 (Rota do Sol) profile. These results are in agreement with previous data for Parana-Etendeka CFB (Bellieni *et al.* 1984; 1986; Milner *et al.* 1992; Janasi *et al.* 2007).

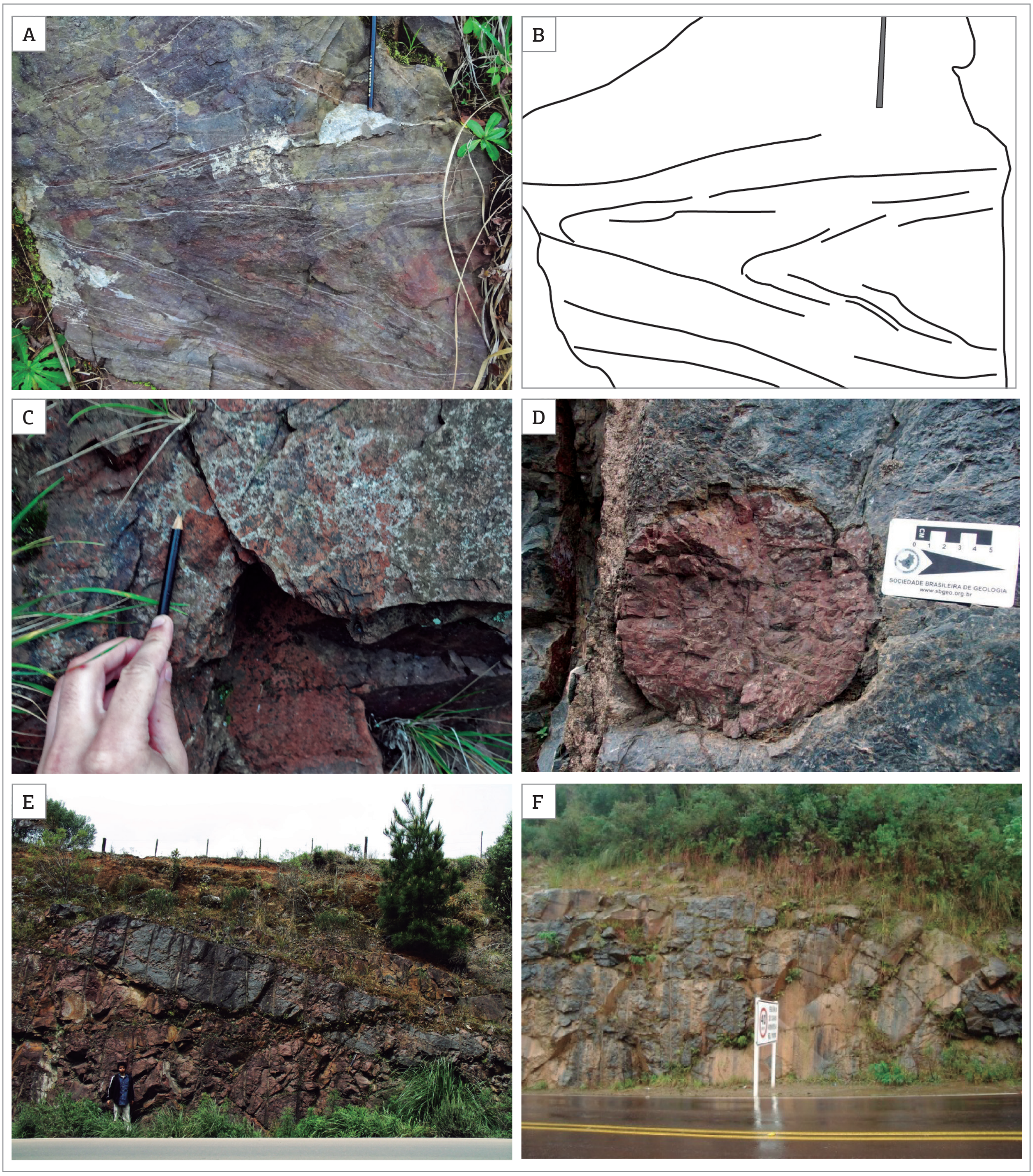

Figure 3. Field and textural characteristics of RS – 486 (Rota do Sol) road acidic flows. (A) Tight recumbent fold in flow-banded vitrophyre; (B) Schematic sketch of the fold in Fig. A; (C) Auto-clastic facies of the flow-banded vitrophyre with millimeter to centimeter size volcanic rock fragments cemented by zeolite; (D) Pitchstone with centimeter size spherulite presenting different colors of alteration; (E) Slightly dome-shaped vitrophyre with different color alteration; (F) Lava dome with spheroidal exfoliation.

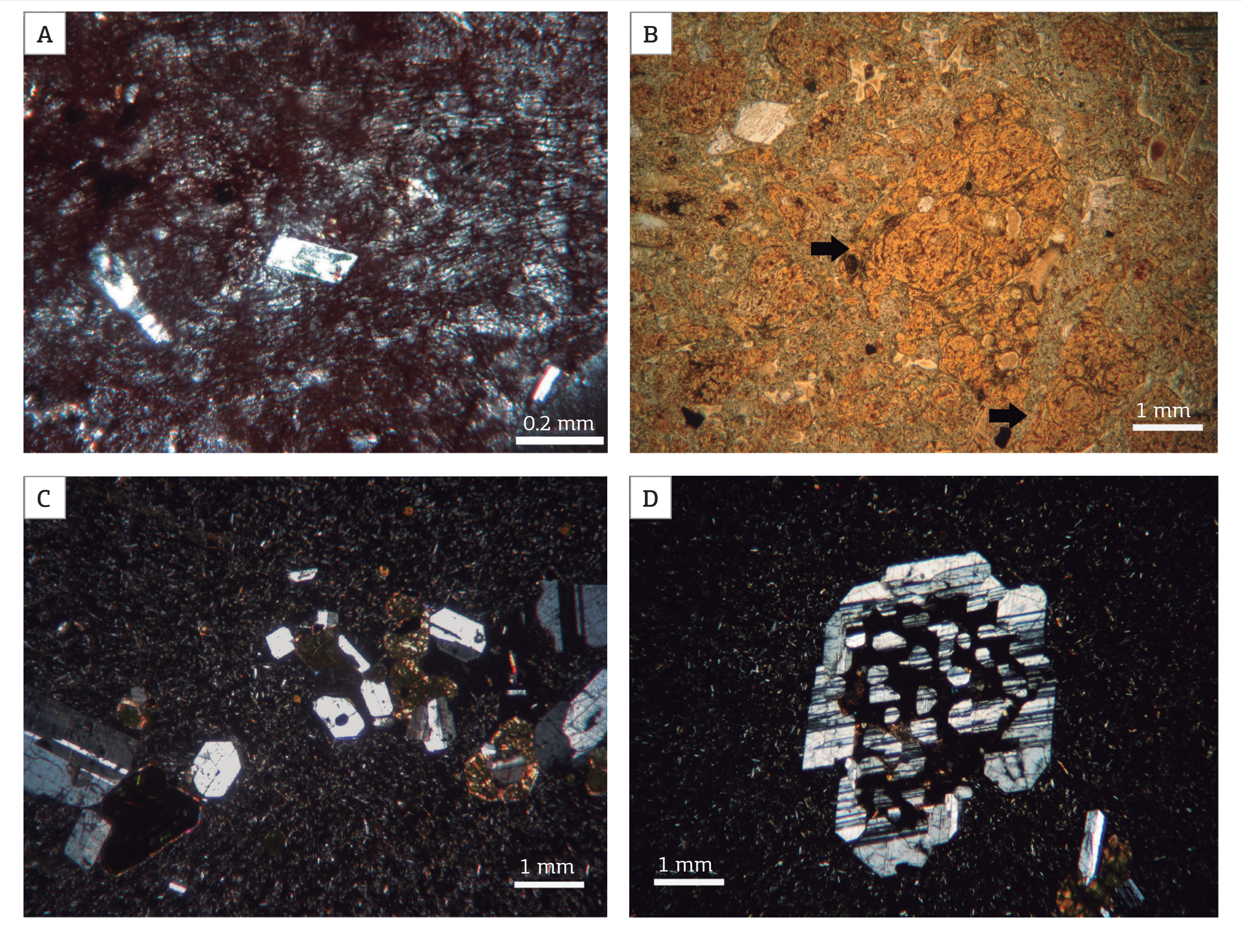

Figure 4. Petrographic features of Rota do Sol profile. (A) Plagioclase phenocryst in a groundmass with hyalopilitic texture (crossed polarizers); (B) Autobreccia with perlitic rock auto-clasts (indicated by arrows; uncrossed polarizers); (C) Plagioclase + Clinopyroxene in glomeroporphyritic texture set in an intersetal groundmass (crossed polarizers); (D) Sieve texture in plagioclase phenocryst set in an intersetal groundmass (crossed polarizers).

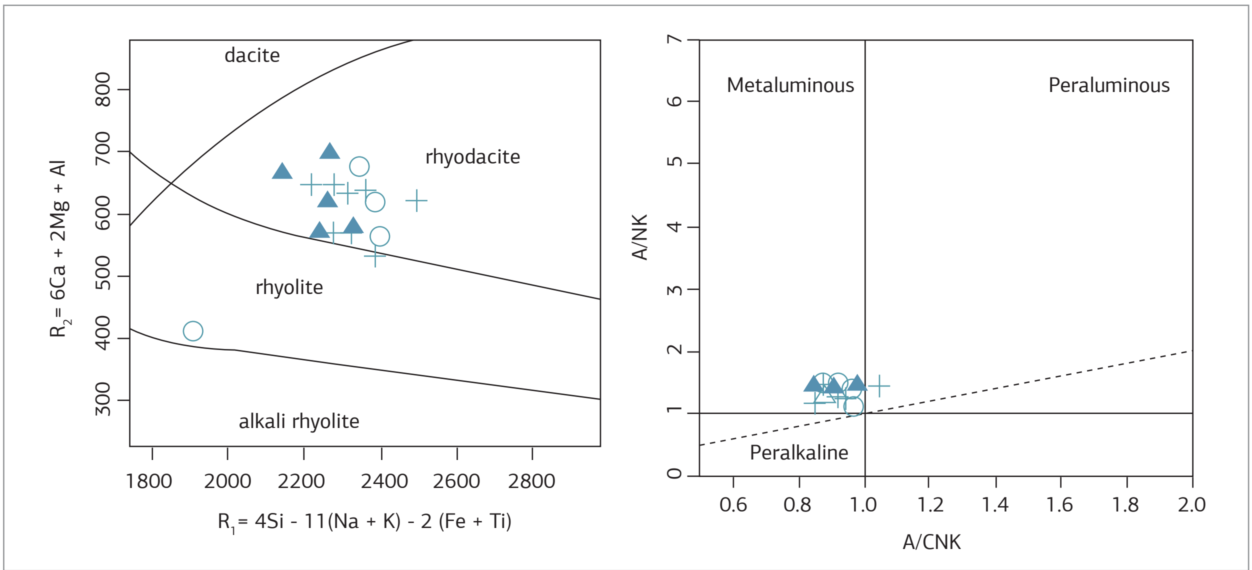

Figure 5. R_1 – R_2 diagram (De La Roche *et al.* 1980) and alumina saturation index (A/CNK-A/NK) diagram (Shand 1943) for selected samples. A/CNK=Al_2O_3/(CaO+Na_2O+K_2O) (mol.%) and A/NK=Al_2O_3/(Na_2O+K_2O) (mol.%). Empty circles are from RS-486 profile, filled triangles are from Caxias do Sul – Feliz profile, and crosses are samples compiled from Lima *et al.* (2012).

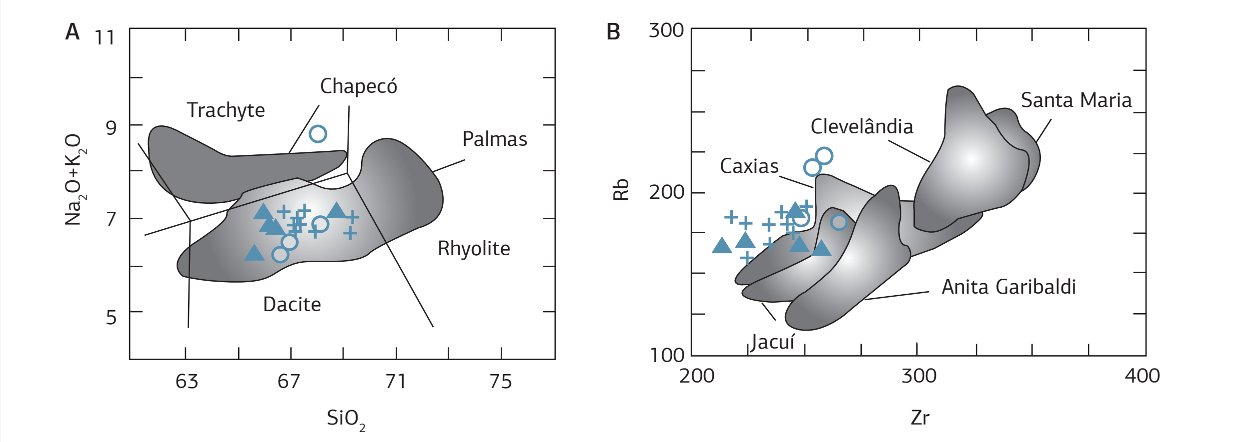

Figure 6. Geochemical discrimination for the studied samples. (A) Total Alkali-Silica (TAS) diagram (Le Bas *et al.* 1986) for lithological classification with magma-type fields; (B) Zr *versus* Rb diagram with magma sub-type fields, from Nardy *et al.* (2008). Same legend as in Fig. 4.

The viscosity (η) data obtained for the studied samples were firstly calculated for an anhydrous basis. In São Marcos – Antônio Prado profile, η values are about 5.79 ± 0.14 log Pas, whereas in Caxias do Sul – Feliz profile, they are about 5.92 ± 0.20 log Pas and in RS-486 (Rota do Sol), about 5.78 ± 0.16 log Pas. To compare these quantities with an aqueous basis, we selected one sample from each profile and estimated the η values for 0, 2, 4, and 6 wt.% of H_2O and for 1,000 and 1,100ºC. This information show a drastic decrease of viscosity from up to 6.7 to 2.6 – 2.8 log Pas for 1,000ºC and from 5.3 – 5.5 to 2.0 – 2.2 log Pas for 1,100ºC (Fig. 7) with water addition.

The number of non-bridging oxygen per tetrahedrally coordinated cations (NBO/T) is a way to quantify the polymerization degree of the melt. If NBO/T=0, the melt is fully polymerized (Mysen *et al.* 1985). For the analyzed samples, the values of NBO/T are between 0.05 and 0.1, which is common for rhyodacite compositions (Hellwig 2006).

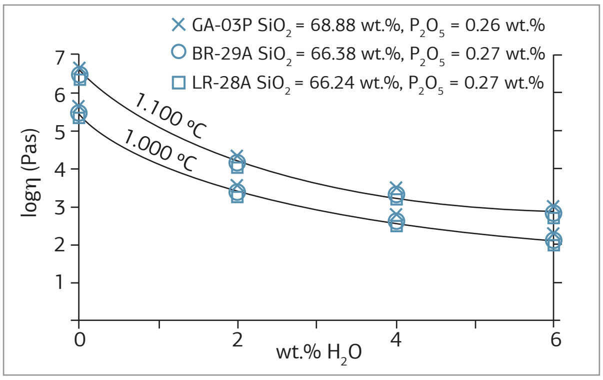

Figure 7. Diagram of estimated viscosity (η) values for 0, 2, 4, and 6 wt.% of H_2O over 1,000 and 1,100ºC. The viscosity was estimated for the samples GA-03P, BR-29A, LR-28A using the model of Giordano *et al.* (2008).

DISCUSSION AND CONCLUSIONS

The previous studies concerning facies architecture and geochemistry characterization of the volcanic rocks in the Southern portion of SGF have assumed an effusive nature for the acidic units (Umann *et al.* 2001; Waichel *et al.* 2006; 2012; Simões & Lima 2011; Rossetti 2011; Lima *et al.* 2012; Polo & Janasi 2014). In the present work, three profiles of volcanic rocks exposure were investigated. The field features, such as tabular and dome geometries associated with auto-clastic facies, presence of magmatic flow foliation and absence of pyroclastic textures, accidental fragments and fall, surge or pyroclastic flow deposits, agree with an effusive origin for the acidic rocks in Torres Syncline. The complex arrangement of the effusive acidic volcanism of SGF was also identified by Polo and Janasi (2014) in the South of Soledade city.

The concordance of very high temperatures for acidic rocks of Parana-Etendeka CFB (liquidus>1,100ºC and equilibration temperature>1,000ºC, Bellieni *et al.* 1986) is confirmed and has an important role due to the resemblance with super-liquidus temperatures (Green & Fitz III 1993; Lima *et al.* 2012).

Presence of apatite as phenocryst and microphenocryst is a characteristic of Palmas-type acidic rocks (Comin-Chiaramonti *et al.* 1988), and the very high temperatures between 1,000ºC and 1,100ºC obtained in this study reflect the amounts of P_2O_5 and SiO_2 in the studied samples. It is well explained because the level of dissolved P_2O_5 required for apatite saturation is positively dependent upon temperature, and negatively dependent upon SiO_2 content (Harrison & Watson 1984).

The composition of SGF acidic rocks in Torres Syncline, with SiO_2 contents between 66.05 and 68.96 wt.% and P_2O_5 contents between 0.25 and 0.28 wt.%, is different from other acidic volcanic rocks associations and has relative higher phosphorous content than rhyolites of shoshonitic associations (P_2O_5~0.11 – 0.20 wt.%; Lima & Nardi 1998); rhyolites associated with tholeiitic basalts in bimodal associations (P_2O_5~0.02 – 0.07 wt.%; Streck & Grunder 2008); A-type metaluminous to weakly peraluminous rhyolites (P_2O_5~0.14 wt.%; Pierosan *et al*. 2011; Simões *et al*. 2014); and peralkaline rhyolites (P_2O_5~0.01 – 0.04 wt.%; Sommer *et al*. 2013).

As a consequence of high-temperature values, viscosities calculated for anhydrous conditions are below the expected for rhyolites and rhyodacites (Giordano *et al*. 2008; Whittington *et al*. 2009; Pierosan *et al*. 2011; Sommer *et al*. 2013; Simões *et al*. 2014). Although low-viscosity lava flows have been described in other Large Igneous Provinces as Gawler Ranges, Australia (Pankhurst *et al*. 2011) and Snake River Plain (Branney *et al*. 2008). The decrease of viscosity with addition of water content (Fig. 6) is explained by the H_2O effect in the values B and C of the used model, a consequence of its role in the structure of silicate melts relative to other network-modifying cations (Dingwell 1991; Giordano *et al*. 2008). If the magma of the studied rocks were not anhydrous, the viscosities would have been significantly lower.

The emplacement of erupted lava is controlled mainly by viscosity and effusion rate. Secondarily, the vent geometry, characteristic of the shallow ground water and the shape of landscape drive the manner of emplacement. Lateral confinement of the lava flow will depend on the shape of the relief. According to Bardintzeff and McBirney (1998), there are six main types of domes based on their morphological aspects: cryptodomes, plug domes, Peléan domes, spines, lava domes, and couleés. The classification of lava domes based on viscosity measurements of Yokoyama (2005) explains that squeeze-type lava domes are the result of magma squeezes through conduits, as Bingham bodies pilling up to the vent with growth rates governed by Hagen-Pouiseuille Law (involving viscosity and eruption parameters). On the other hand, spyne-type lava domes are the result of displacements of solidified lava driven up by fluid magma beneath with growth rates smaller than squeeze types because of larger resistance between solidified spines and conduit walls.

Moreover, lava will emplace as lava dome or flow depending on heat loss per volume unit (Walker 1973). The distance traveled by the flow, after the initial cooling, will depend on the effect of thermal insulation of cooled surface crusts that allows the magma to flow in the core of the flow unit (Harris & Rowland 2009). These concepts explain why flows erupted at high effusion rates have more potential to attain greater distances than those at low ones.

In Torres Syncline, the first volcanic episode (BVE I) covered Botucatu paleoerg with simple *pahoehoe* flows, associated with low effusion rates, near the dunes and with ponded *pahoehoe* flows (~40 m thick) in interdune areas, flattening the rouged relief. The BVE II is composed of tabular-classic simple *pahoehoe* flows and covers the BVE I under high effusion rates conditions (Waichel *et al*. 2012).

The occurrence of acidic lava domes above the BVE II as flow-banded vitrophyres was probably controlled by squeezes of lava under low effusion rates, in spite of their high temperature and low viscosities, which are reflected in their small height. The emplacement of lava domes has continued until the BVE III, characterized by the eruption of rubbly *pahoehoe* flows, and the relief probably became rugged. Presence of tabular acidic lava flows covering the landscape indicates that it was under high effusion rates conditions and that these flows had well-insulated surface crusts. The capacity to attain greater distances and overpass relief obstacles is explained not only by high effusion rates, but also by very low viscosities at the time of the emplacement.

ACKNOWLEDGMENTS

We thank *Conselho Nacional de Desenvolvimento Científico e Tecnológico* (CNPq) for the financial support (Project 479784/2012-4), *Programa de Pós-graduação em Geociências of UFRGS* and the reviewers Doctors Zorano de Souza and Umberto Cordani for the contributions.

REFERENCES

Baker D.R. 1996. Granitic melt viscosities: Empirical and configurational entropy models for their calculation. *American Mineralogist*, **81**:126-134.

Bardintzeff J.M. & McBirney A. 1998. *Volcanology*. Jones Bartlett Pub., Sudbury, Mass., p. 268.

Bellieni G., Brotzu P., Comin-Chiaramonti P., Ernesto M., Melfi A.J., Pacca I.G., Piccirillo E.M., Stolfa D. 1984. Flood basalt to rhyolite suites in the southern Paraná plateau (Brazil): paleomagnetism, petrogenesis and geodynamic implications. *Journal of Petrology*, **25**:579-618.

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

Bottinga Y., Weill D. 1972. The viscosity of magmatic silicate liquids: a model for calculation. *American Journal of Science*, **272**:438-475.

Branney M.J., Bonnichsen B., Andrews G.D.M., Ellis B., Barry T.L., McCurry M. 2008. "Snake River (SR)-type" volcanism at the Yellowstone hotspot track: distinctive products from unusual, high-temperature silicic super-eruptions. *Bulletin of Volcanology*, **70**(3):293-314.

Bryan S.E., Peate I.U., Peate D.W., Self S., Jerram D.A., Mawby M.R., Marsh J.S., Miller J.A. 2010. The largest volcanic eruptions on Earth. *Earth-Science Reviews*, **102**(3-4):207-229.

Coffin M.F. & Eldholm O. 1992. Volcanism and continental break-up: a global compilation of large igneous provinces. *In*: Storey B.C., Alabaster T., Pankhurst R.J. (eds.) *Magmatism and the Causes of Continental Breakup*. London, Special Publication of the Geological Society of London, p. 17-30.

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

Comin-Chiaramonti P., Bellieni G., Piccirillo E.M., Melfi A.J. 1988. Classification and petrography of continental stratoid volcanic and related intrusive from the Paraná Basin (Brasil). *In*: Piccirillo E.M., Melfi A.J. (eds) *The Mesozoic flood volcanism of the Paraná Basin: petrogenetic and geophysical aspects*. São Paulo, Instituto Astronômico e Geofísico, 600 p.

De La Roche H., Leterrier J., Grandclaude P., Marchal M. 1980. A classification of volcanic and plutonic rocks using R1R2-diagram and major element analyses – its relationships with current nomenclature. *Chemical Geology*, **29**:183-210.

Dingwell D.B. 1991. Redox viscometry of some Fe-bearing silicate liquids. *American Mineralogist*, **76**:1560-1562.

Giordano D. & Dingwell D.B. 2003. Non-Arrhenian multicomponent melt viscosity: A model. *Earth and Planetary Science Letters*, **208**:337-349.

Giordano D., Mangicapra A., Potuzak M., Russell J.K., Romano C., Dingwell D.B., Di Muro A. 2006. An expanded non-Arrhenian model for silicate melt viscosity: A treatment for metaluminous, peraluminous and peralkaline melts. *Chemical Geology*, **229:**42-56.

Giordano D., Russell J.K., Dingwell D.B. 2008. Viscosity of magmatic liquids: A model. *Earth and Planetary Science Letters*, **271:**123-134.

Green J.C. & Fitz III T.J. 1993. Extensive felsic lavas and rheoignimbrites in the Keweenawan Midcontinent Rift plateau volcanics, Minnesota: petrographic and field recognition: *Journal of Volcanology and Geothermal Research*, **54**:177-196.

Harris A. & Rowland S. 2009. Effusion rate controls on lava flowlength and the role of heat loss: a review. *In:* Thordarson T., Self S., Larsen G., Rowland S.K., Hoskuldsson A. (eds.) *Studies in Volcanology:* The Legacy of George Walker. Special Publications of IAVCEI, p. 33-51.

Harrison T.M. & Watson E.B. 1984. The behaviour of apatite during crustal anatexis: equilibrium and kinetic considerations. *Geochimica et Cosmochimica Acta*, **48**(7):1467-1477.

Hellwig B.M. 2006 *The viscosity of dacitic liquids measured at conditions relevant to explosive arc volcanism: determining the influence of temperature, silicate composition, and dissolved volatile content*. MS dissertation, University of Missouri-Columbia, 158 p.

Henry C.D. & Wolff J.A. 1992. Distinguishing strongly rheomorphic tuffs from extensive silicic lavas. *Bulletin of Volcanology*, **54**:171-186.

Hess K.U. & Dingwell D.B. 1996. Viscosities of hydrous leucogranitic melts: A non-Arrhenian model. *American Mineralogist*, **81**:1297-1300.

Hui H. & Zhang Y. 2007. Toward a general viscosity equation for natural anhydrous and hydrous silicate melts. *Geochimca et Cosmochimica Acta*, **71**:403-416.

Janasi V.A., Montanheiro T.J., Freitas V.A., Reis P.M., Negri F.A., Dantas F.A. 2007. Geology, petrography and geochemistry of the acid volcanism of the Paraná Magmatic Province in the Piraju-Ourinhos region, SE Brazil. *Revista Brasileira de Geociências*, **37**:745-759.

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

Lima E.F., Philipp R.P., Rizzon G.C., Waichel B.L., Rossetti L.M.M. 2012. Sucessões Vulcânicas e Modelo de Alimentação e Geração de Domos de Lava Ácidos da Formação Serra Geral na Região de São Marcos-Antonio Prado (RS). *Geologia USP Série Científica*, **12**:49-64.

Lima E.F. & Nardi L.V.S. 1998. The Lavras do Sul Shoshonitic Association: implications for the origin and evolution of Neoproterozoic shoshonitic magmatism in the southernmost Brazil. *Journal of South American Earth Sciences*, **11**:67-77.

Marsh J.S., Ewart A., Milner S.C., Duncan A.R., Miller R. 2001. The Etendeka Igneous Province: magma types and their stratigraphic distribution with implications for the evolution of the Paraná-Etendeka flood basalt province. *Bulletin of Volcanology*, **62**:464-486.

Melfi A.J., Nardy A.J.R., Piccirillo E.M. 1988. Geological and magmatic aspects of the Paraná Basin: An introduction. *In:* Piccirillo E.M. & Melfi A.J. (eds.) *The Mesozoic flood volcanism of the Paraná Basin:* Petrogenetic and geophysical aspects. IAG-USP, p. 1-13.

Milner S.C., Duncan A.R., Whittingham A.M., Ewart A. 1995. Trans-Atlantic correlation of eruptive sequences and individual silic volcanic units within Paraná- Etendeka Igneous Province. *Journal of Volcanology and Geothermal Research*, **69**:137-157.

Milner S.C., Duncan A.R., Ewart A. 1992. Quartz latite rheoignimbrite flow of the Etendeka Formation, North-Western Namibia. *Bulletin of Volcanology*, **54**:200-219.

Mysen B.O., Virgo D., Seifert F.A. 1985. Relationship between properties and structure of aluminosilicate melts. *American Mineralogist*, **70**:88-105.

Nardy A.J.R., Machado F.B., Oliveira M.A.F. 2008. As rochas vulcânicas mesozoicas ácidas da Bacia do Paraná: litoestratigrafia e considerações geoquímicas-estratigráficas. *Revista Brasileira de Geociências*, **38**(1):178-195.

Pankhurst M.J., Schaefer B.F., Betts P.G., Phillips N., Hand M. 2011. A Mesoproterozoic continental flood rhyolite province, the Gawler Ranges, Australia: the end member example of the Large Igneous Province clan. *Solid Earth*, **2**:25-33.

Peate D.W. 1997. The Paraná-Etendeka Province. *In*: Mahoney J.J., Coffin M.F. (eds.) *Large igneous provinces:* continental, oceanic and planetary flood volcanism. Geophysics Monography Series, 100, p. 217-245.

Petrini R., Civetta L., Iacumin P., Longinelli A., Belliene G., Comin-Chiaramonti P., Ernesto N., Marques L.S., Melfi A., Pacca I., Piccirillo E.M. 1989. High temperature flood silicic lavas (?) from the Paraná Basin (Brasil). *New Mexico Bureau of Mines & Mineral Resources Bulletin*, **131**:213.

Pierosan R., Lima E.F., Nardi L.V.S., Bastos Neto A.C., Campos C.P., Jarvis K., Ferron J.M.T.M., Prado M. 2011. Geochemistry of Palaeoproterozoic volcanic rocks of the Iricoumé Group, Pitinga Mining District, Amazonian Craton, Brazil. *International Geology Review*, **53**:946-979.

Polo L.A. & Janasi V.A. 2014. Volcanic stratigraphy of intermediate to acidic rocks in Southern Paraná Magmatic Province, Brazil. *Geologia USP Série Científica*, **14**:83-100.

Prowatke S. & Klemme S. 2006. Trace element partitioning between apatite and silicate melts. *Geochimica et Cosmochimica Acta*, **70**:4513-4527.

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

Roisenberg A. 1989. *Petrologia e geoquímica do vulcanismo ácido mesozoico da Província Meridional da Bacia do Paraná*. PhD Thesis, Instituto de Geociências, Universidade Federal do Rio Grande do Sul, Porto Alegre, 285 p.

Rossetti L.M.M. 2011. *Arquitetura de fácies vulcânicas da Formação Serra Geral na região de Feliz – Caxias do Sul*. Graduation Conclusion, Curso de Graduação em Geologia, Instituto de Geociências, Universidade Federal do Rio Grande do Sul, Porto Alegre, 65 p.

Rossetti L.M.M., Lima E.F., Waichel B.L., Scherer C.M.S., Barreto C.J. 2014. Stratigraphical framework of basaltic lavas in Torres Syncline main valley, Southern Paraná-Etendeka Volcanic Province. *Journal of South American Earth Sciences*, **56**:409-421.

Russell J.K. & Giordano D. 2005. A model for silicate melt viscosity in the System $CaMgSi_2O_6$–$CaAl_2Si_2O_8$–$NaAlSi_3O_8$. *Geochimica et Cosmochimica Acta*, **69**:5333-5349.

Russell J.K., Giordano D., Dingwell D.B., Hess K.U. 2002. Modelling the non-Arrhenian rheology of silicate melts: Numerical considerations. *European Journal of Mineralogy*, **14**:417-427.

Shand S. J. 1943. *Eruptive Rocks. Their Genesis, Composition, Classification, and their Relation to Ore Deposits, with a chapter on Meteorites* (revised second edition): Hafner Publishing Co., New York, 444 p.

Shaw H.R. 1972. Viscosities of magmatic silicate liquids: An empirical method of prediction. *American Journal of Science*, **272**:870-893.

Sheth H. 2007. Large Igneous Provinces (LIPs): definition, recommended terminology, and a hierarchical classification. *Earth Science Reviews*, **85**:117-124.

Simões M.S., Almeida M.E., Souza A.G.H., Silva D.P.B., Rocha P.G. 2014. Characterization of the volcanic and hypabyssal rocks of the Paleoproterozoic Iricoumé Group in the Pitinga Region and Balbina Lake area, Amazonian Craton, Brazil: Petrographic distinguishing features and emplacement conditions. *Journal of Volcanology and Geothermal Research*, **286**:138-147.

Simões M.S., Lima E.F. 2011. Geoquímica, geotermometria e viscosidades dos fluxos ácidos da Formação Serra Geral nas regiões de São Marcos e da Rota do Sol. *In:* XIII Congresso Brasileiro de Geoquímica. RS. *Anais* do XIII Congresso Brasileiro de Geoquímica, Gramado.

Sommer C.A., Lima E.F., Machado A., Rossetti L.M.R., Pierosan R. 2013. Recognition and characterisation of high-grade ignimbrites from the neoproterozoic rhyolitic volcanism in southernmost Brazil. *Journal of South American Earth Sciences*, **47**:152-165.

Streck M.J. & Grunder A.L. 2008. Phenocryst-poor rhyolites of bimodal, tholeiitic provinces: the Rattlesnake Tuff and implications for mush extraction models. *Bulletin of Volcanology*, **70**:385-401.

Sun S.S. & Hanson G.N. 1975. Origin of Ross Island Basanitoids and limitations upon the heterogeneity of mantle sources for alkali basalts and nephelinites. *Contributions to Mineralogy and Petrology*, **52**:77-106.

Umann L.V., Lima E.F., Sommer C.A., De Liz J.D. 2001. Vulcanismo ácido da região de Cambará do Sul-RS: litoquímica e discussão sobre a origem dos depósitos. *Revista Brasileira de Geociências*, **31**(3):357-364.

Vetere F., Behrens H., Holtz F., Neuville D.R. 2006. Viscosity of andesitic melts – New experimental data and a revised calculation model. *Chemical Geology*, **228**:233-245.

Vetere F.P. 2006. *Viscous flows of magma from Unzen volcano, Japan – implication for magma mixing and ascent*. PhD thesis, Naturwissenschaftlichen Fakultät der Universität Hannover, 140 p.

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 M.S., Bueno G.V., Dutra G.T. 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*, **215**:74-82.

Walker G.P.L. 1973. Lengths of lava flows. *Philosophical Transactions of the Royal Society of London*, **274**:107-118.

Watson E.B. & Green T.H. 1981. Apatite/liquid partition coefficients for rare earth elements and strontium. *Earth and Planetary Science Letters*, **56**:405-421.

Whittingham A.M. 1989. Geological features and geochemistry of the acid units of the Serra Geral Formation, south Brazil. *In*: *Continental Magmatism*, Santa Fé IAVCEI Abstracts: Santa Fé, New Mexico, p. 293.

Whittington A.G., Hellwig B.M., Behrens H., Joachim B., Stechern A., Vetere F. 2009. The viscosity of hydrous dacitic liquids: Implications for the rheology of evolving silicic magmas, *Bulletin of Volcanology*, **71**:185-199.

Yokoyama I. 2005. Growth rates of lava domes with respect to viscosity of magmas. *Annals of Geophysics*, **48**:957-971.

Arquivo digital disponível on-line no site www.sbgeo.org.br