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Structural Constraints on Paraná Basalt Volcanism and their Implications on Agate Geode Mineralization (Salto do Jacuí, RS, Brazil)

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Abstract- The Paraná-Etendeka Continental Flood Basalt province hosts world-class agate and amethyst geode deposits in Rio Grande do Sul (Brazil; Serra Geral Fm.). Salto do Jacuí Mining District (Rio Grande do Sul, Brasil) has different types of agate geode hosted in vesicular basalt. A series of structural features has recently been investigated in the Salto do Jacuí Mining District, and indicates at least two volcanic episodes: i) normal tholeiitic basalt and dacite eruption, and ii) vesicular basalt and dacite intrusions as sills and dikes. These structural features include: basalt and aeolian sandstone xenoliths in vesicular basalts, vesicular basalt apophyses in massive basalts, sandstone and basalt breccias, sandstone dikes cutting across vesicular lavas and connected to mixed sandstone-agate geodes, sandstone assimilation by vesicular lava, and mixed sandstone and agate geodes. These features show that agate geodes were formed by melting of Botucatu sandstone xenoliths. High density contrast between vesicular basalt and Botucatu sandstone melts makes them immiscible during flow. Botucatu sandstone xenoliths melting is favored by degasing of intrusive volatile-rich basalts. The high-silica globs crystallize dynamically in a closed-system environment, giving rise to agate banding and fibrosity.

Keywords- flood basalt, flood dacites, volcanic structures, agate deposits, ore control, mineralization processes, volcanic processes.

INTRODUCTION

The Serra Geral Fm. in southern Brazil is made up mostly by volcanic rocks of the Paraná-Etendeka Continental Flood Basalt province (Wilson, 1989), and hosts world-class agate and amethyst geode deposits. Many investigations evaluated the amethyst mineralization (*e.g.* Gilg *et al.*, 2003). Agate mineralization in Serra Geral Fm. is usually considered similar to amethyst. However, agate-bearing geodes in Salto do Jacuí Mining District (Heemann, 1997; Rio Grande do Sul State, Southern Brazil) show very distinctive geological features when compared to amethyst-bearing geodes from Ametista do Sul Mining District (Rio Grande do Sul State, Southern Brazil) and Artigas Department (Northern Uruguay).

Agate occurs as geode infillings known as "geode in basalt" deposits (Bossi & Caggiano, 1974). In the Salto do Jacuí Mining District (Fig. 1), the geodes are filled by chalcedony (agate), quartz, onyx, opal, calcite, zeolite and amethyst. Agate origin in Serra Geral flood basalts was evaluated from a geochemical point of view (Fallick *et al*., 1987; Merino *et al*., 1992), while similar investigation was done in Karoo (Africa; Harris, 1989). Additional evaluations of agate origin in flood basalts were conducted by Merino et al. (1995, 2001) and Wang & Merino (1990, 1995).

The Serra Geral Formation (Lower Cretaceous) is characterized by a sequence of tholeiitic basalts and dacites. Aeolian sandstones (Botucatu Fm.) occur between some of the basaltic lava flow units. A number of regional geochemical investigations in the Serra Geral Formation basalts leds to the identification of two main geochemical units: i) low-Ti, and ii) high-Ti basalts (Peate *et al.*, 1992). However, no integration of volcanic, structural, and geochemical data of the basalts, were carried out in these investigations.

The integration of all these features is essential for the understanding of volcanism and mineralization processes in the Serra Geral Fm., and is the major objective of this work. Thus, in this paper, the volcanic structures and geochemical features of the volcanic sequence exposed in the Salto do Jacuí Mining District (Fig. 1) are described to demonstrate their relevance to agate geodes formation.

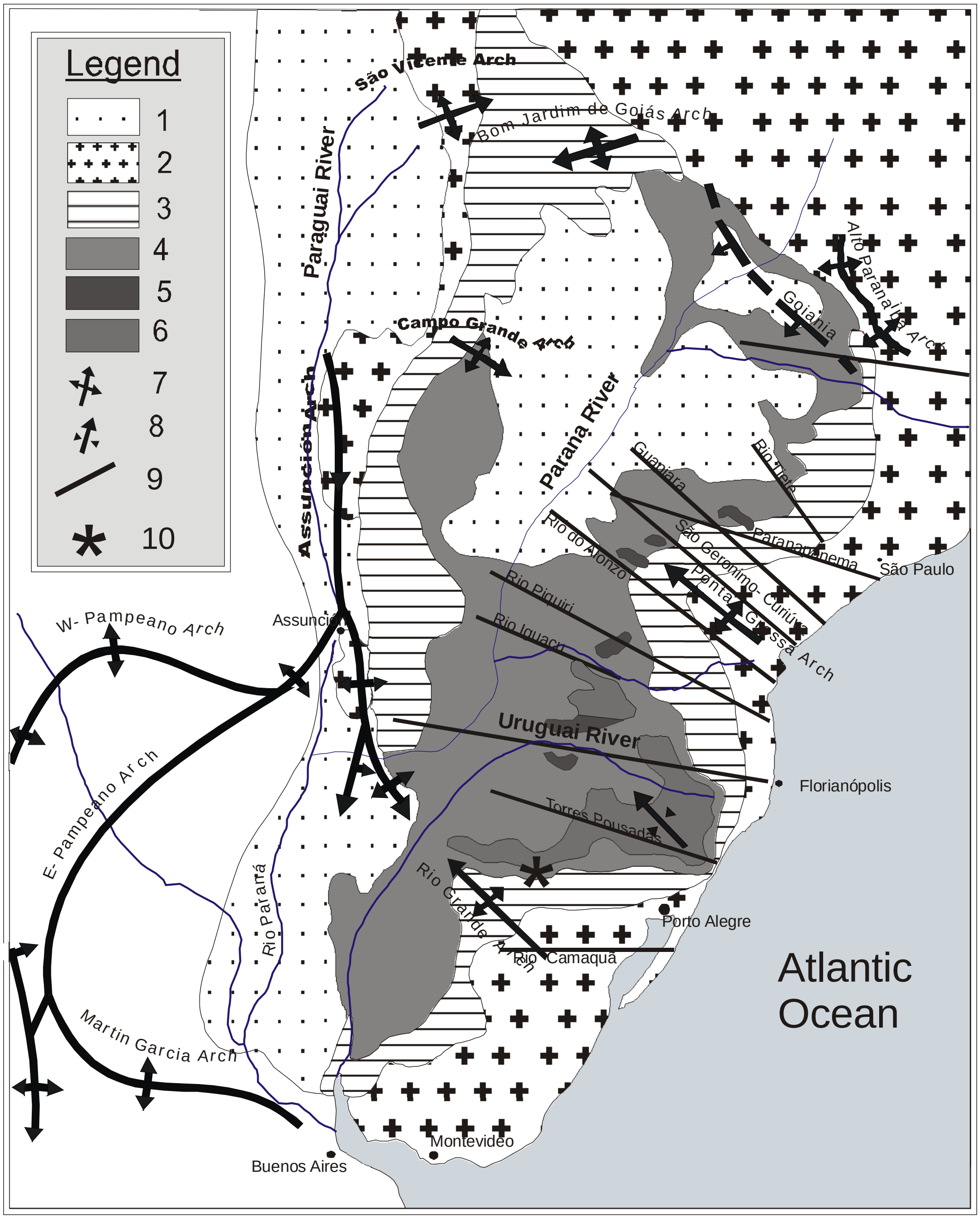

Figure 1 – Regional geological sketch of the Paraná Continental Flood Basalt Province, showing the Serra Geral Fm. Location of Salto do Jacuí Mining district shown by asterisc (*). 1) Post-volcanic sediments; 2) Pré-Devonian basement rocks; 3) Paraná Basin sedimentary rocks; 4) Basalts and andesites of the Serra Geral Fm; 5) Dacites of the Serra Geral Fm. (Chapecó type); 6) Dacites of the Serra Geral Fm. (Palmas type); 7) arch-type structure (anticlinal); 8) synclinal structure; 9) tectonic lineaments; 10) Salto do Jacuí Mining District. (Figure modified from Bellieni *et al*., 1986).

REGIONAL STRATIGRAPHIC UNITS IN THE SALTO DO JACUÍ MINING DISTRICT

The regional stratigraphic units in the Salto do Jacuí (Southern Brazil region) are characterized on the basis of petrographic and geochemical criteria (Tab 1). Three basaltic to dacitic groups (Fig. 2) are defined:

1) lower intergranular basaltic group (R1);
2) intermediate glomeroporphyritic basaltic to dacitic group (R2);
3) upper holocrystalline dacite (R3).

Lenses of aeolian sandstones of the Botucatu Formation occur at the contact between these groups (Fig. 2). The most continuous Botucatu Fm. intertrap beds crop out in two stratigraphic positions at altitudes of 200 m and 400 m. A discontinuous Botucatu Fm. intertrap bed is also present on altitude of 300 m, in the glomeroporphyritic basaltic to dacitic group (R2).

The R1 group occurs just above the top of the Botucatu Fm., at an altitude of 80 m. This unit has a thickness of 180 m, and is made up of basaltic flows. These flows show a fine-grained matrix with crystals of plagioclase, clinopyroxene and opaque minerals smaller than 0.15 mm in length. The well-developed intergranular texture is the most important petrographic feature to distinguish this lower basaltic unit from the other units above. The R1 group has a tholeiitic basalt geochemical signature (Fig. 3a).

The R2 group crops out between two Botucatu Fm. sandstone intertraps (200 m and 400 m altitude). The R2 group is comprised by two subgroups named the acid flows (R2A), and the basic flows (R2B), that are generally interlayered. Both basic and acid flows in the R2 group show lath-shaped phenocrysts of plagioclase, clinopyroxene and opaque minerals. These phenocrysts, mainly the plagioclase, are agglomerated to give rise to the glomeroporphyritic texture. Small crystals and microlites of plagioclase, clinopyroxene and opaque minerals are present in the glassy hypohyaline matrix. The geochemical signature of the R2B basalts is also tholeiitic (Fig. 3b).

The R3 group is exposed above the 400 m horizon of Botucatu Fm. sandstone intertrap. The upper contact of the R3 group was eroded. This group is comprised by holocrystalline dacite flows, composed mainly by plagioclase, clinopyroxene, quartz, and subordinately opaque minerals. The dacitic rocks of the R3 group and that of the R2A subgroup show similar geochemical signatures (Fig 3a).

The SiO2 x Zr/TiO2 diagrams of Figure 3 show the silica gap for the basaltic and dacitic flows of the Salto do Jacuí Mining District. This silica gap is present from 55 to 63 wt% range. According to

Table 1 – Average geochemical composition of basaltic to dacitic units in the Salto do Jacuí region (Southern Brazil).

Unidade	**R1**	**R2B**	**R2A**	**R3**
SiO_2	49-54	50-52	63-69	67-71
Al_2O_3	12.0-14.6	11.9-15.0	11.9-13.1	11.8-12.3
Fe_2O_3	9.5-14.5	10.0-12.5	5.3-7.2	5.0
MnO	0.14-0.19	0.11-0.17	0.06-0.16	0.04-0.10
MgO	3.0-5.8	3.8-5.7	0.7-1.6	0.19-0.86
CaO	7.0-9.6	8.3-9.4	1.0-3.6	0.65-2.40
Na_2O	1.7-3.2	1.4-2.3	2.8-3.1	2.5-2.9
K_2O	0.8-3.0	0.53-1.59	2.7-4.9	3.5-5.6
TiO_2	1.0-1.8	0.86-1.20	0.6-1.0	0.6
P_2O_5	0.15-0.20	0.12-0.19	0.29-0.31	0.20-0.22
Ba	300-400	200	550-600	650
Sr	200	200-300	130-150	100
Y	25	20	40-50	50
Sc	35	35	18	15
Zr	120-150	100	220-230	290
V	250-300	260-300	100	20
Cr	>40	20-50	20-30	20-40
Co	45	40-45	12.0-14.0	5.0-6.0
Cu	100	70	70	25-239
Zn	100-200	100-300	90	70-80
Rb	30-50	30-40	160	210
Nb	10.0-13.0	7.0-9.0	21.0	27.0
Sn	2.0		4.0-5.0	6.0
Cs	0.7-2	2.0	7.0	10.0-12.0
Hf	3.5-4	2.5-2.8	6.0-7.0	8.0
Ta	0.6-0.7	0.4-0.5	1.7	2.0
W	/	/	0.6-2.7	2.5
Tl	0.1-0.6	0.1-0.6	0.9	1.2-1.8
U	0.8-1.6	0.6	4.0	5.0
Th	4.0-5.0	3.5	12.0-13.0	17.0

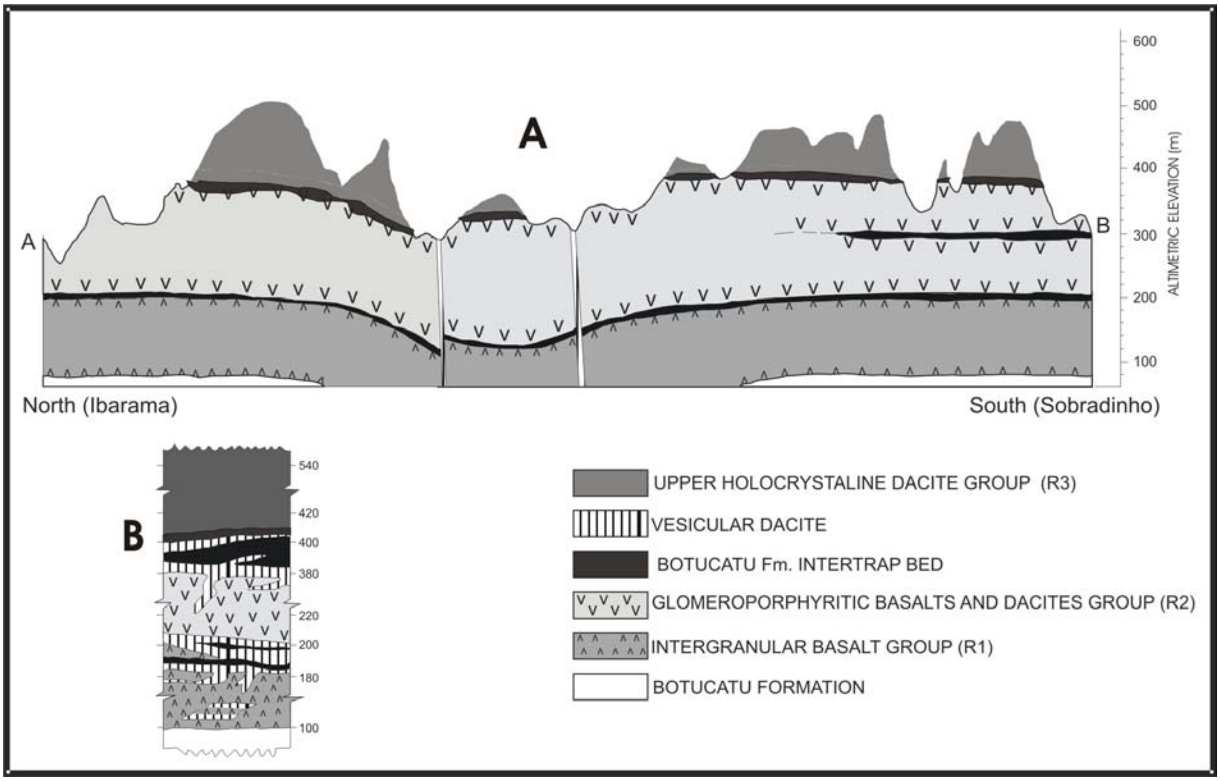

Figure 2 – N-S cross section in the Salto do Jacuí (RS, Brazil) region distinguishing basaltic to dacitic units. A) Regional cross section from near Sobradinho to Ibarama cities, showing fault displacement on stratigraphy. B) Schematic section showing geological contacts close to main Botucatu intertrap beds.

Heemann (1997), the main geochemical signature of the basaltic rocks (R1 and R2B) in the Salto do Jacuí region is similar to low-Ti Gramado type basalts defined by Peate *et al*. (1992).

PETROLOGICAL AND GEOCHEMICAL FEATURES OF VOLCANIC UNITS IN THE SALTO DO JACUÍ MINING DISTRICT

The agate deposits in the Salto do Jacuí Mining District crop out between the 200 m and 260 m altitude. The deposits show well-defined lithological, stratigraphic and structural controls. The lithological units that comprise the volcanic sequence in the Salto do Jacuí Mining District were defined by means of stratigraphic ordering, macroscopic structures, petrographic and geochemical features (Tab. 2).

Seven volcanic units were defined in the Salto do Jacuí Mining District (Figure 4) on the basis of petrologic and stratigraphic data:

1) lower dacite (LD);
2) lower basalt (LB);
3) lower semi-glassy vesicular-amygdaloidal dacite (LSGD);
4) mineralized vesicular basalt (mVB);
5) vesicular dacite (VD);
6) upper semi-glassy dacite (USGD);
7) upper dacite (UD).

The lowest unit that crops out in the Salto do Jacuí Mining District, the Lower Dacite, displays poor vesicular texture and has gray color. Few microphenocrysts of plagioclase, clinopyroxene and opaque minerals occur in this unit. The matrix is hypohyaline and formed by feldspar and pyroxene microlites. The lower basalt, on the other hand, is holocrystalline and shows intergranular to porphyritic texture. The phenocrysts in the Lower Basalt are plagioclase, clinopyroxene and opaque minerals. Both units belong to the R1 regional volcanic group.

The Lower Semi-glassy Dacite is dark colored, with resinous lustre, and strongly vesicular. The Lower Semi-glassy Dacite unit has a tabular morphology (1.0 – 1.5 m thick in most places) and an extensive lateral continuity in the Mining District. This feature is considered a useful guide horizon for the exploration and exploitation of agate geode. The Lower semi-glassy Dacite unit is also a host level for small and large diameter agate geodes.

The mineralized vesicular basalt, although deeply weathered in most places, is the host unit for

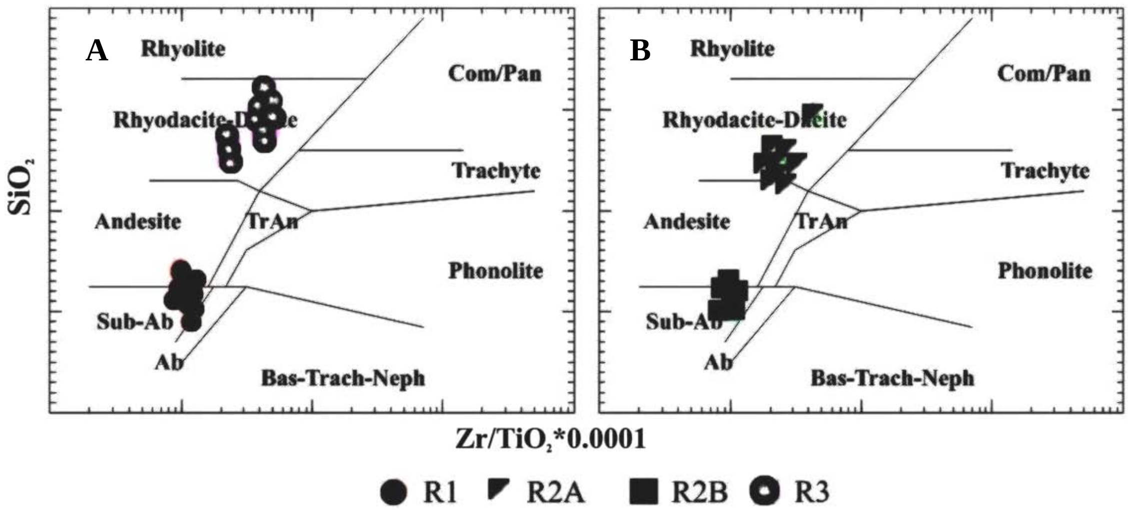

Figure 3 – Geochemical signature of regional basaltic and dacitic flows in the Salto do Jacuí Mining District (Heemann, 1987). A) SiO_2 x Zr/TiO_2 diagram for the intergranular basaltic flow (R1) and regional dacites (R3). B) SiO_2 x Zr/TiO_2 diagram for glomeroporphyric dacitic (R2A) and glomeroporphyric basaltic (R2B) flows.

Table 2 – Average geochemical composition of the volcanic units related to mineralized vesicular basalt in the Salto do Jacuí Mining District. Symbols are the same as used in the text.

Unidade	LD	LB	LSGD	mVB	VD	UD
SiO_2	65.0-66.0	54.0-55.0	64.0-65.0	48.0-56.0	64.0-67.0	63.0-68.0
Al_2O_3	12.0	12.0	12.0	13.0-15.0	12.0	12.0-13.0
Fe_2O_3	6.0-7.0	13.0	2.0-3.0	4.0-7.0	5.0-6.0	6.0-7.0
MnO	0.06-0.12	0.16-0.21	0.10-0.11	0.04-0.24	0.06-0.09	0.06-0.11
MgO	1.0-1.2	3.0	1.3-1.4	2.1-3.3	0.6-1.1	0.7-1.6
Cão	2.5-3.1	6.9-7.2	3.3-3.4	2.4-4.9	1.7-2.0	2.4-3.5
Na_2O	2.6-3.0	2.6-2.9	2.8-3.0	1.1-1.9	1.7-2.5	2.7-3.0
K_2O	3.9-4.9	2.0-2.5	3.3-3.6	0.3-3.6	3.0-4.9	4.0-4.8
TiO_2	0.86-1.00	1.60	0.88-0.93	0.95-1.10	0.91-0.96	0.91-1.00
P_2O_5	0.27-0.28	0.29-0.31	0.26-0.70	0.27-0.33	0.24-0.29	0.28-0.33
Ba	550	300-400	510	134-998	580	560
Sr	120	160	150	160-200	120-170	140
Y	36	38	36	35	37	40
Sc	16	36	17	20	17	18
Zr	190	160	220	260	220	230
V	100	380-400	85	100	70-125	100
Cr	26	30	20	/	20	20
Co	12	40	12	13	10	11.5-13
Cu	60	200	60	70	60	60
Zn	77	120-250	70	100		70-80
Rb	200	100	200	20-90	60-70	170
Nb	15.0	14.0	22.0	25.0	22.0	14.0-23.0
Sn	4.0	2.0	5.0	5.0-7.0	5.0	4.0-5.0
Cs	7.0-19.0	3.0	9.0	2.2-6.8	1.4-6.4	7.0-8.0
Hf	5.0	4.5	6.0	7.0-8.0	6.5	5.0-6.0
Ta	1.6	1.0	1.7	1.7-2.0	1.7-1.8	1.6-1.8
W	1.2	1.0	1.8-2.0	1.0	1.3-1.9	0.7-2.4
Tl	1.0	0.5	1.8-2.0	0.1-0.5	0.5-1.1	1.0
U	3.5-4.0	1.5-2.0	4.3	4.6	3.5	3.5-4.0
Th	13.0	6.6-7.0	13.0	15.0-16.0	14.0	12.0-14.0

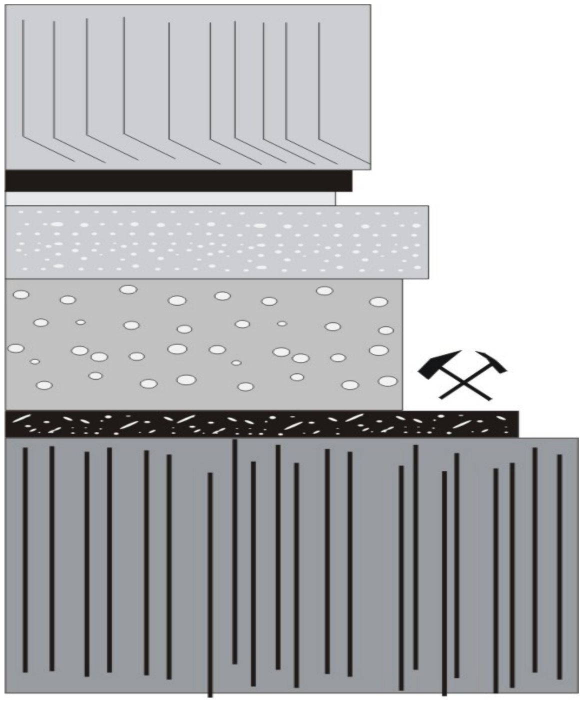

Figure 4 – Salto do Jacuí Mining District section showing the volcanic sequence of the most important mining sites.

agate geode mineralization. This unit is generally 4.0 to 6.0 m thick, but can reach 7.0-8.0 m in some places. It is brownish gray colored, and displays strong vesicular-amygdaloidal and aphanitic textures. The basalt has a fine-grained matrix with crystals of plagioclase, clinopyroxene and opaque minerals smaller than 0.2 mm in length. The agate geodes have variable size, but the larger ones can reach up to 0.8 m in diameter. The mineralized vesicular basalt and the lower semi-glassy Dacite show assimilation features at their contacts. Elliptical boulders of lower semi-glassy dacite are seen within the mineralized vesicular basalt and, in the same way, vesicular basalt fragments do occur within the lower semi-glassy dacites unit. This unit also shows thermally metamorphosed sandstone dikes and rounded sandstone boulders sometimes connected to each other. Lenses of volcanic breccia, composed by sandstone and basalt fragments, are also present in some places.

The vesicular dacite occurs just above the mineralized vesicular basalt and has also a strong vesicular texture. The vesicles are very elongated and their diameter is up to 0.5 cm. This unit is generally 3.0 to 4.0 m thick, but can reach up to 7.0 m in some places. The vesicular dacite has a weak glomeroporphyritic texture and consist of a purplish brown glassy matrix (90%). It is composed of microlites of plagioclase, clinopyroxene and opaque minerals; minor amounts of lath-shaped phenocrysts of plagioclase, clinopyroxene and opaque minerals occur.

The Upper Semi-glassy Dacite is dark colored, with resinous luster, and is devoid of vesicules. The upper semi-glassy dacite unit has a tabular morphology (0.5 to 1.5 m in thickness), but shows limited lateral continuity. Plagioclase, clinopyroxene and opaque minerals are the main rock-forming minerals, while the groundmass is, in some cases, devitrified. The upper dacite is gray colored and shows a massive structure. The glomeroporphyritic texture is well developed and the phenocrysts are plagioclase, clinopyroxene and quartz, with subordinate opaque minerals. The upper dacites has a thickness greater than 5 m in areas being mined, depending on the erosion level close to Jacuí River.

The geochemical signature of the lower basalt and the dacites in the Salto do Jacuí Mining District are similar to the regional R1, R2B, R2A and R3 volcanic groups (Fig. 5). The silica gap (55 to 63 wt%) is still evident for volcanic rocks at the mining sites. However, the mineralized vesicular basalts show an alkaline shift as seen by their higher Zr contents than other basaltic rocks in the region (Figure 5b). Most major elements of the mineralized vesicular basalt display similar geochemical signature to low-Ti Gramado type basalt defined by Peate *et al*. (1992). But, minor elements such as Sr and Ba, as well as Zr/Y, Sr/Y and Ba/Y ratios are compatible with high-Ti Ubirici-type basalts also defined by Peate *et al*. (1992).

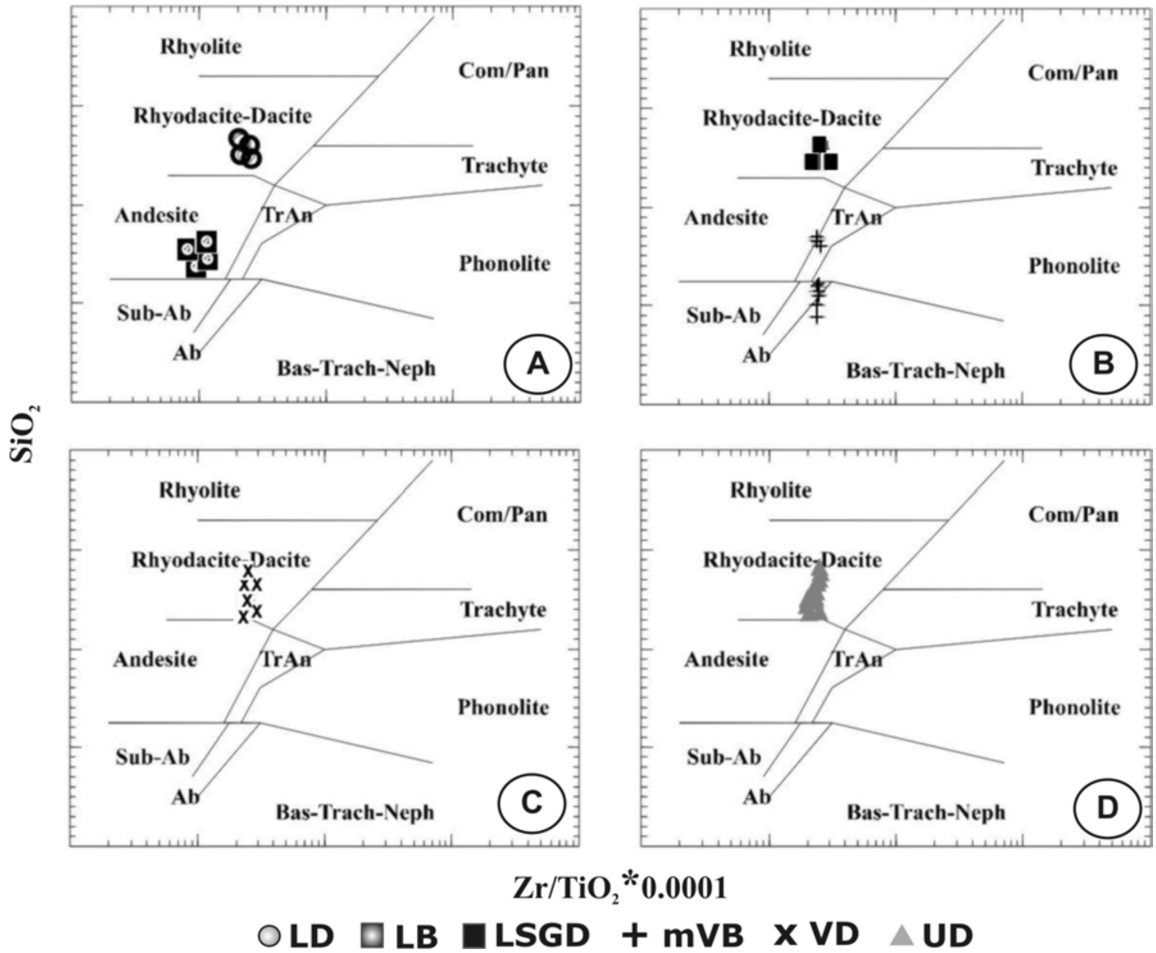

Figure 5 - Geochemical signature of the volcanic rocks of the Salto do Jacuí Mining District (Heemann, 1987). A) SiO2 x Zr/TiO2 diagram for the Lower Dacite and Lower Basalt units (R1 group); B) SiO2 x Zr/TiO2 diagram for the Lower Semi-glassy Dacite and mineralized Vesicular Basalt units; C) SiO2 x Zr/TiO2 diagram for the Vesicular Dacite unit; and D) SiO2 x Zr/TiO2 diagram for the Upper Dacite unit (R2A group).

MAIN STRUCTURAL FEATURES OF THE VOLCANIC UNITS

The agate-geode mineralized units in the Salto do Jacuí Mining District are placed in the contact between R1 and R2 regional units. The volcanic unit contacts, including the Botucatu sandstone intertraps, show particular structural features that must be evaluated in regard to volcanic succession and the mineralization process.

The most important structural feature is well exposed at RST-481 road, close to Jacuizinho River (Fig. 6a). This outcrop is in the R1-R2 regional units contact zone, the same contact zone as mineralized Salto do Jacuí Mining District units. This road cut exposure shows large basaltic and Botucatu boulders (>3m diametre) displayed in strongly vesicular basalt. Basalt boulders are poorly vesiculated at their margins, and show glomeroporphyritic texture (macroscopically identified by plagioclase laths agglomerations). Botucatu boulders show a rim of glassy basaltic rock; this basaltic rim and also Botucatu sandstone are poorly vesiculated close to the contact to vesicular basalt. Large boulders are also seen to detach from upper glomeroporphyritic dacites unit and still preserve their embayments in the exploitation area of the Salto do Jacuí Mining District (Fig. 6b). It can also be observed that vesicular basalt show embayments into the upper glomeroporphyritic flow (Fig. 6c), what can be defined as apophyses.

Botucatu Fm. intertrap beds (200 m, 300 m, and 400 m altitude) also show important structural features regarded as volcanic breccias. At Boa Esperança Village (Ibarama County, RS), vesicular basalt breccia (sandstone as matrix; Fig. 7a) grades down-ward to sandstone breccia (vesicular basalt as matrix; Fig. 7b); this structural feature is placed in the 400 m altitude intertrap (R2-R3 regional units contact). These features were interpreted as *AA*-type breccias at volcanic flow top (e.g. Corrêa *et al*., 1994). However, this breccia is not restricted to the base of a Botucatu intertrap, but can also be seen at the top of the Botucatu Fm. intertraps. These volcanic breccias usually enclose remnant lenses of Botucatu sandstone, and irregular elongated sandstone fragments can be seen displaced from Botucatu lenses (Fig. 7c). Botucatu sandstone lenses and sandstone breccia fragments show contact metamorphism (well-developed granoblastic texture).

The main local units in the Salto do Jacuí Mining District also show important structural featu-

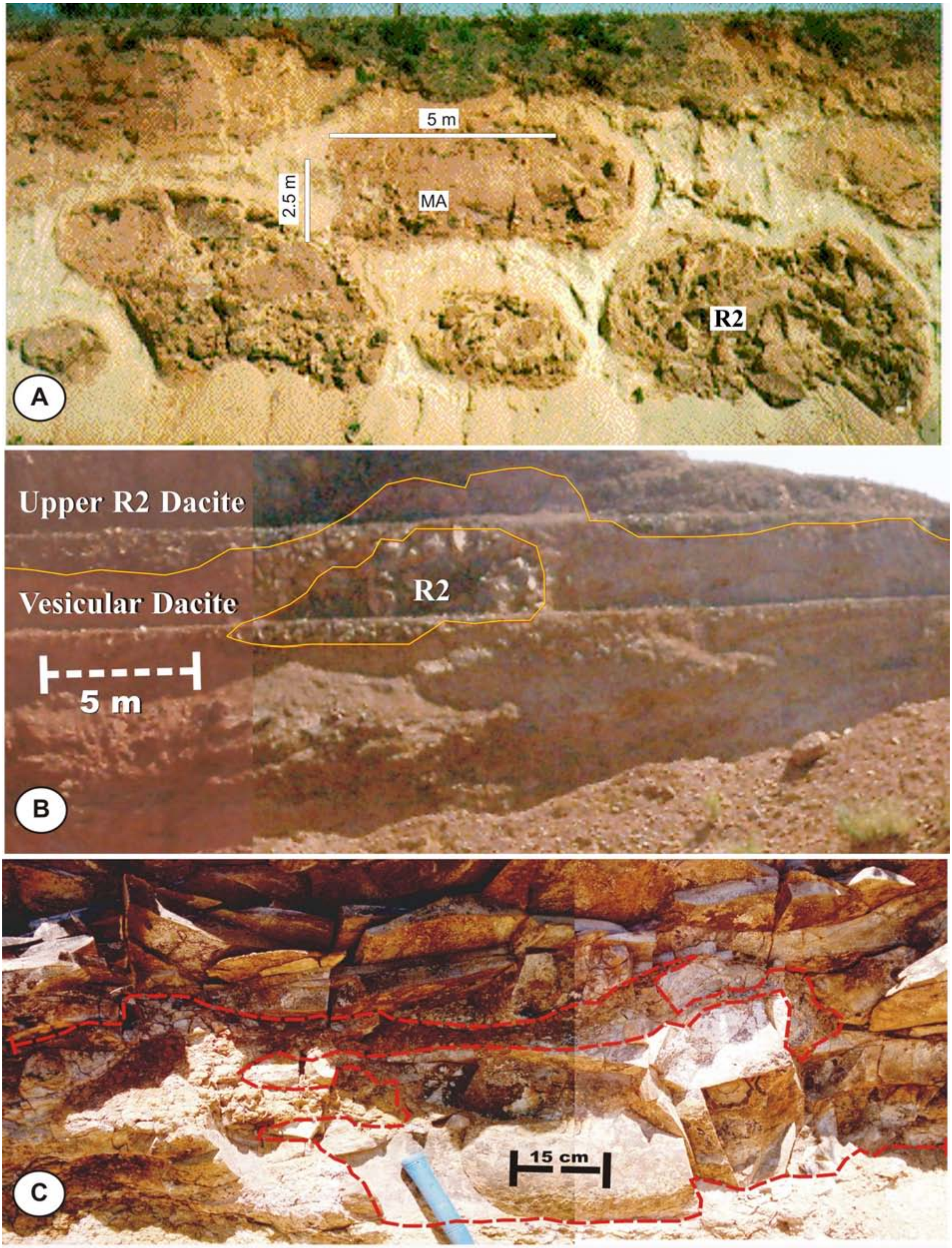

Figure 6 – Photographs of the structural features relating glomeroprophyric flows (R2) and lower vesicular basalts and dacites in the Salto do Jacuí Mining District. A) Basalt (R2) and Botucatu boulders (MA) in a strongly vesicular basalt matrix exposed in RST-481 road cut close to Jacuizinho River; B) Glomeroporphyric dacite (R2) boulder detached from Upper dacite unit in a open pit at Salto do Jacuí Mining District; C) Apophyses of Vesicular Basalt entering lower contact of the Glomeroporphyric Basalt unit at the same RST-481 road cut.

res related to agate mineralization. Sandstone dikes (5 to 50 cm thick) commonly cut across Lower Semi-glassy Dacite, mineralized Vesicular Basalt and Vesicular Dacite units. The dikes end at Lower Basalt – Lower Semi-glassy Dacite and Vesicular Dacite – Upper Semi-glassy Dacite unit contacts (Fig. 8a). Geode-like sandstone boulders are usually present in the mineralized vesicular basalt (Figure 8b). There exists a transition between geode-like sandstone boulders and massive agate-geodes, that is named mixed geodes (Fig. 9). The mixed geodes usually show sandstone at their base, interlayered sandstone-agate, and agate at their top (Fig. 9). In some places, thin (1-5 cm thick) sill-like apophyses connect sandstone dikes, sandstone boulders, and mixed geodes.

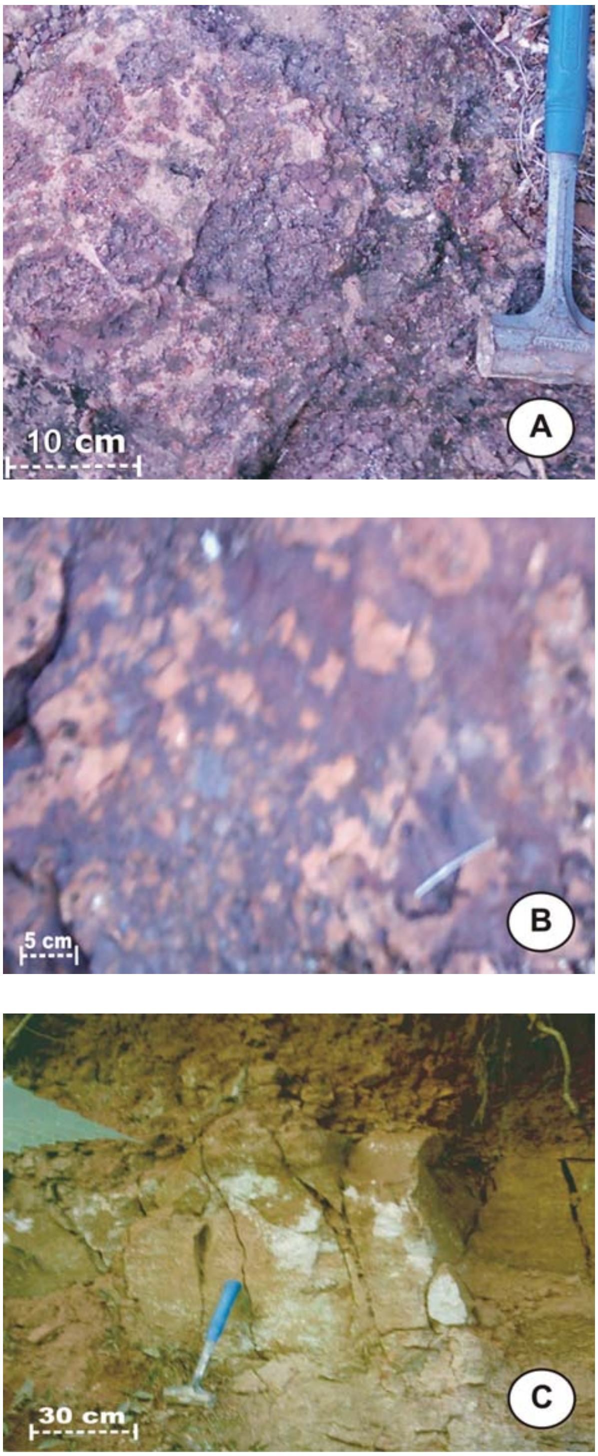

Figure 7 – Strutural features of breccias related to Botucatu Fm. sandstone intertraps. A) Vesicular basalts fragments in sandstone matrix; B) Sandstone fragments in vesicular basalt matrix; C) Irregular Botucatu sandstone lens enclosed in vesicular basalt breccia.

DISCUSSION ON BASALTIC VOLCANISM AND MINERALIZATION PROCESSES

The mineralization process in the Serra Geral Fm. has been discussed in a number of papers taking into account different aspects mainly for amethyst geodes. However, structural features reported above for agate-geode mineralization in the Salto do Jacuí Mining District are distinct from that reported for amethyst geodes in the Ametista do Sul Mining District (e.g. Meunier *et al*., 1988; Juchen *et al*., 1987, 1990; Corrêa, 1995). Then, the main propositions are briefly reviewed and discussed from the point of view of the structural features described above. In this way, the general aspects of a model for agate mineralization can be understood.

Magmatic differentiation of the lava flows

The lava flow structures were organized and discussed by Coleman (1946). On this basis, Leinz (1949) proposed a model of magmatic differentiation of basaltic lava during flow and cooling to explain structural features and vesicle formation in the Paraná Basin Flood Basalt Province (Fig. 10). This model was more recently supported by Meunier *et al.* (1988) and Juchen *et al.* (1987, 1990) to establish more detailed genetic constraints on amethyst mineralization. The model favours an *in situ* differentiation of the lava column during the cooling stage, leading to a layered lava flow structure (Fig. 10). Thus, the vesicle formation is seen as a result of lava degassing, while geodes may result from upward migration and coalescence of small volatile-rich bubbles. Amethyst concentration, on the other hand, would result from the crystallization of silica-rich volatiles.

The proposal states that, immediately after eruption, the upper glassy basalt layer trapped the magmatic fluids released from crystallization. The magmatic fluid entrapment produced, then, the intensely vesiculated basalt layer, where the geodes occur.

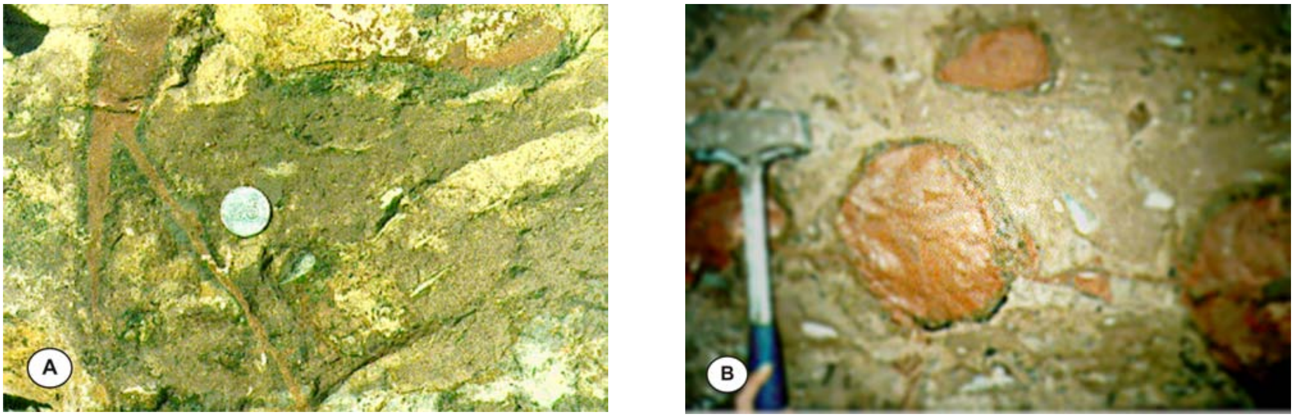

Figure 8 – Sandstone – volcanic rocks interaction structures in the Salto do Jacuí Mining District. A) Sandstone dyke cutting across Lower Semi-glassy Dacite; note, close to top right, a small lense of sandstone enclosed in the Lower Semi-glassy Dacite. B) Sandstone boulders (geodes) in the mineralized vesicular basalt (mVB); note thin sandstone sill like struture connecting sandstone geodes.

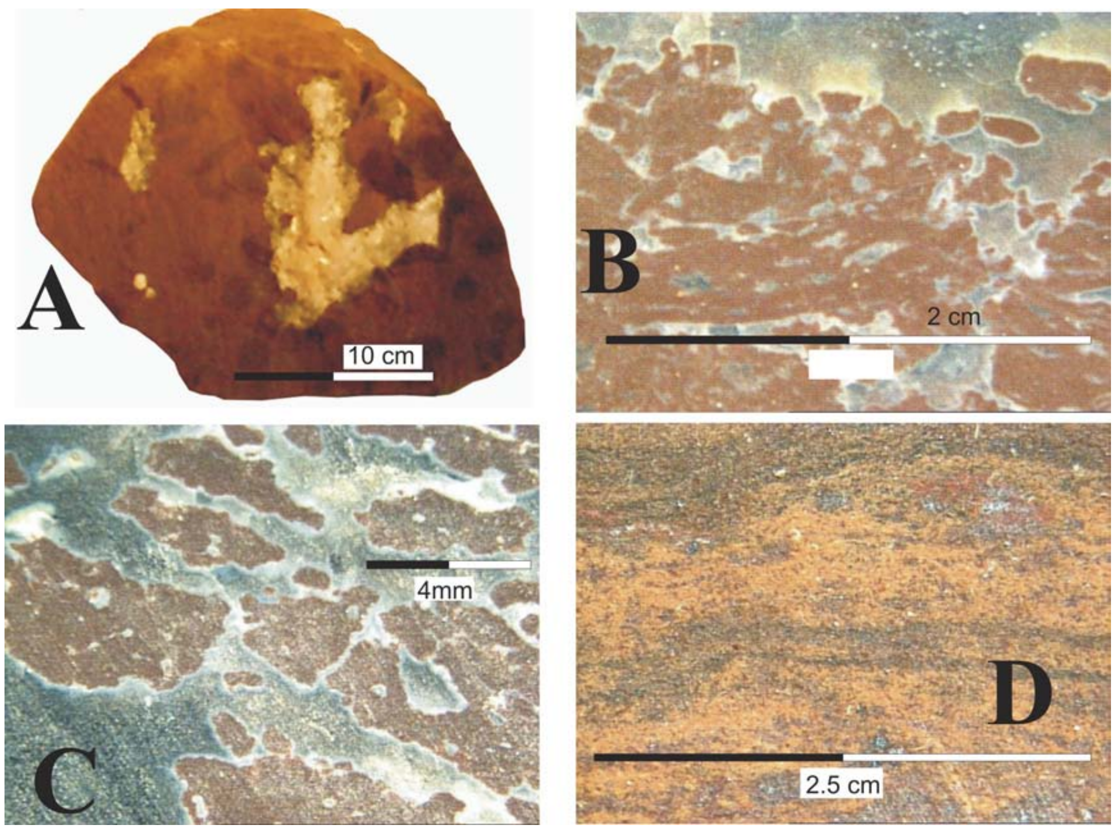

Figure 9 – Inner features of mixed (sandstone+agate) geodes. A) "massive" sandstone geode, with a small inner irregular quartz+calcite fill; B) breccia-type geode: sandstone fragments in an agate matrix; C) sandstone fragment with lobate contacts; D) banded sandstone-agate geode.

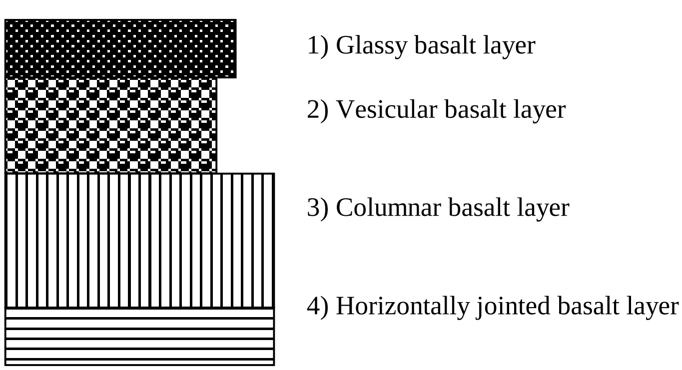

Figure 10 – Structural differentiation of a lava flow in the Paraná Basin Flood Basalt, as porposed by Leinz (1949).

The columnar basalt layer is the slowly cooling lava that gave rise to the magmatic fluids, while the lower horizontally jointed basalt layer is derived from cooling of flowing lava. This model, however, does not account for:

a) the source of high silica content present in the geodes;
b) the source of fluids (magmatic?), since continental tholeiitic basalt has less than 1% volatile content;
c) the sharp contact between massive basalt (without vesicles) and vesicular basalt, as well as the vesicle orientation (Heemann, 2005);
d) the absence of geochemical differentiation in the flow column (Heemann, 1997);
e) the interaction between lava and aeolian Botucatu Fm. sandstone.

Interaction between basalt lavas and aeolian sandstone

This model was first proposed by Bossi & Caggiano (1974). Montana & Bossi (1993) and Corrêa (1995) presented a detailed discussion about the structure developed during each lava flow (Fig. 11). Their hypothesis is related to the aeolian sandstone and lava interaction structure, which accounts for the silica source for the geodes. The interaction of aeolian sandstone with basaltic lava occurs at the top of lava flow; the flowing lava cooled and brecciated (***aa*** lava type) at the top and the blowing sand fills intersticial spaces between lava fragments. On the other hand, magmatic differentiation of the lava flow is still suggested as responsible for vesicle formation. This proposal also does not account for the source of fluids (magmatic?) and the absence of geochemical differentiation in the flow column.

Two-stage geode formation

This hypothesis was first proposed by Gilg *et al.* (2003), based on fluid inclusion and stable isotope data. Gilg *et al*. (2003) proposed that vesicles were formed during lava flow and cooling; the coalescence of vesicles during their upward migration was responsible for protogeode formation (protogeode stage). The protogeode infilling took place long time after Paraná Basin Flood Basalt formation (± 80 Ma; Vasconcelos *et al.* 1998) mainly by meteoric water circulation. The volatile content for the generation of the high amount of vesicle in the original tholeiitic basalt, however, is not clear. In the same way, the long-lasting meteoric water circulation (± 100 Ma, to Recent) is difficult to accept, taking into account intraplate tectonic changes in the period.

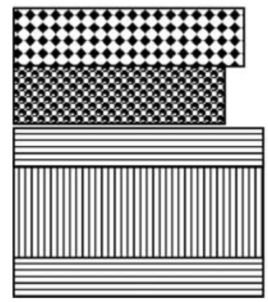

Figure 11 – Structure of a lava flow as porposed by Montana & Bossi (1993) and Corrêa (1995).

MODEL FOR AGATE-BEARING GEODE MINERALIZATION

A large number of questions remain to be explained by the models discussed above when applied for agate mineralization in the Paraná Basin Flood Basalts. The structural evidences reported in the Salto do Jacuí Mining District require a new interpretation for magmatic and mineralization histories in this mining district. Based on structural, petrographical and geochemical detailed studies, Heemann (1997, 2005) was able to distinguish between different types of lavas in the volcanic sequence in the Salto do Jacuí region: i) normal massive tholeiitic basalts and dacites (non-vesiculated), and ii) vesicular basalts and dacites. The presence of sandstone boulders and glomeroporphyric basalts and dacite boulders are the key structure to characterise the volatile rich lavas as a younger unit, intruded into the previously erupted Hawaiian-type lava flows (volatile-poor basalts, or normal tholeiitic basalt).

The sandstone and glomeroporphyric basalt boulders, the volcanic breccias, the Botucatu sandstone lenses and the contact relations, as described above, show that vesicular basalts were emplaced after Botucatu sandstone deposition; in the same way, vesicular basalt was also emplaced after upper glomeroporphyric basalt flow (R1-R2 regional units contact). Thus, sandstone and glomeroporphyric basalt boulders are interpreted as xenoliths.

The distinction between normal and vesiculated basalts and dacites, as performed in structural and petrological basis above, is also supported by geochemical data (Heemann, 1997). The geochemical signature of vesiculated lavas is different from that of non-vesiculated ones; this is mainly true for basalts, which show an alkaline shift in some petrochemical diagrams (Fig. 5). Detailed geochemical investigation, as done in the Salto do Jacuí Mining District, also shows difficulties in regarding vesiculated lavas to regional geochemical lava types as defined by Peate *et al.* (1992), since that classifycation do not take into account such recent investigations.

Intrusion of a volatile-rich basaltic and dacitic magma can explain their prominent sheet-like structure, since they are not viscous and can spread laterally. Sheet-like structure can be defined because vesicular basalt is mainly located at large magmatic changes (limits of regional units: R1, R2 and R3). Each regional magmatic unit represents a change in the magma chamber conditions. The time span between each volcanic episodes (end of R1 flows and the beginning of the R2 flows, e.g.) is sufficiently long to permit the aeolian sandstone deposition (Botucatu Fm. intertraps); this time span is usually known as volcanic quiescent period. Then, the quiescent volcanic periods introduced structural discontinuities in the lava flow sequence, which were used by volatile-rich basaltic and dacitic magmas to give to rise the sheet-like structure.

The intrusion of a volatile-rich basaltic and dacitic magmas at high crustal levels plays an important role in developing the observed structural features and also in the mineralization process. In such a context, volatile immiscibility is mainly controlled by a balance between volatile content in magma, magma pressure, and lithostatic pressure (Cas & Wright, 1987). The highly vesiculated basalts and dacites of the second magmatic event suggest that volatile immiscibility effectively took place. The irregular embayments and apophyses-like contact between normal tholeiitic and vesicular basalts, as well as between sandstone and basalt xenoliths, sandstone breccia (vesicular basalt as matrix), and vesicular basalt breccia (sandstone as matrix) point that volatile immiscibility occurred under confined conditions (volatile pressure ~ lithostatic pressure). In places where volatile pressure is much higher than lithostatic pressure, rounded breccia fragments can be formed, and it is possible to interpret such features as peperites. These features are different from lava-sediment interaction in desertic settings as described by Jerram & Stollhofen (2002) for Etendeka Flood Basalt Province in Huab Basin (NW Namibia).

The intrusion of volatile-rich lavas into the R1-R2 regional unit limit (at 200m altitude) provides a reasonable explanation for the presence of boulders (xenoliths) in the vesicular basalt. It can also explain some aspects related to agate geode mineralization process. This new model for agate-bearing geode formation accounts for the:

1) source of silica content in the geodes. The mineralized vesicular basalt cannot provide silica rich melt at the crystallization end since magmatic differentation of individual flows was poorly developed. In this way, different degrees of sandstone melting and assimilation by vesicular basalt can provide enough silica for massive agate geodes at Salto do Jacuí Mining District as described in figure 9;
2) source of fluids (magmatic?). The normal continental tholeitic basalt has less than 1% in volatile content and can not account for highly vesiculated units. However, a volatile-rich magma, displaying a more alkaline trend can account for vesicles and fluids in the mineralization process. The close connection between sandstone and agate in the geodes (Fig. 9), and the lack of widespread hydrothermal alteration in the Salto do Jacuí Mining District do not support the interpretation of an early "protogeode" formation and its later filling by an aqueous fluid as mineralization process for agate (Gilg *et al*., 2003).

The metamorphic effects upon Botucatu sandstones (Fig. 6) and also the sandstone-agate connection in mixed geodes (Fig. 9) are evidence of high-temperature reaction between mineralized basalt and sandstone. In this way, intrusion of vesicular basalt must have produced immiscible silica melts from sandstone assimilation to fill geodes and dikes. The evidences show that vesicular basalt melted Botucatu sandstone, but do not favor basaltic and silica-rich melts homogenization. The high density contrast between vesicular basalt and sandstone melts can keep them immiscible during flow and cooling, similar to metapelitic xenoliths that underwent bulk melting, but did not mix with Skaergaard magma (Markl, 2005). The high-silica globs can, then, be formed by melting during degassing of intrusive volatile-rich basalts, instead of hot basalt flow on ground traps water puddles (Merino *et al*., 2001). The high-silica globs, then, can crystallize in a high-temperature, closed-system environment, which give rise to agate banding and fibrosity, according to the dynamic crystallizaton model proposed by Wang & Merino (1990,1995) and Merino *et al*. (1995) for agate-bearing geodes.

The lack of widespread hydrothermal alteration, specially in the mineralized structure, shows that the circulation of an aqueous and/or carbonic fluid did not play an important role in the mineralization process in the Salto do Jacuí Mining District. In the same way, silica gel globs cannot form from surface water and flowing lava interaction, because the Paraná lavas flowed over desert sand dunes. The confined intrusion and volatile immiscibility (volatile pressure >~ lithostatic pressure), however, can produce enough fluid for chalcedony and quartz alternate banding as predicted by Wang & Merino (1995).

The fluid inclusions data (e.g. Juchen, 1999; Gilg *et al*., 2003) are from amethyst-bearing geodes of the Ametista do Sul Mining Disctrict. They show consistent results for meteoric water as the main fluid related to mineralization process. However, no fluid inclusion data are available for agate geodes in the Salto do Jacuí Mining Disctrict. Even for amethyst-bearing geodes, it is nowadays clear that structural characteristics of geodes have to be considered in sampling for geochemical investigation (Amorim *et al.*, 2005 a, b).

Finally, it is interesting to point out that elucidating contact relationship between vesicle free and vesicle rich basalts in the Serra Geral Fm. may lead to the understanding of a number of structural features related to agate and amethyst deposits. Additional field, petrographic and geochemical data are needed to improve the understanding of the magmatic and mineralization histories. Further investigations are being carried out and could show a complex relation between vesicular basalt fluid (magmatic) and meteoric fluid.

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