PETROGRAPHY AND GEOCHEMISTRY OF THE VOLCANIC ROCKS OF THE RODEIO VELHO MEMBER, ORDOVICIAN OF THE CAMAQUÃ BASIN (RS-BRAZIL): PRELIMINARY RESULTS.

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ABSTRACT A geochemical study based in REE, minor elements and petrographic analyses from the volcanic rocks pertaining to the Rodeio Velho Member, comprising lava flows and epizonal intrusive bodies, both corresponding to andesites, subalkaline and alkaline basalts and trachyandesites; and stratified pyroclastic deposits, showed that fractional crystallization of deep source magma is the fundamental mechanism controlling the relationships among these rocks. This igneous event occurred in an alkaline intraplate environment, associated to a widespread extension tectonics, probably corresponding to a final stage of the Pan African - Brasiliano Orogeny during the Middle Ordovician.

INTRODUCTION Outcrop description, petrographic and geochemical analyses of volcanic rocks of the Rodeio Velho Member collected in three different areas located south of the city of Caçapava do Sul, Rio Grande do Sul State, southern Brazil (Fig. 1), allowed to a significative increase in knowledge of this Ordovician magmatic event of the Camaquã Basin.

GEOLOGIC SETTING The Camaquã Basin (*sensu* Paim *et al.* 1995) located at the southernmost region of Brazil, has been connected to a system of late to post-tectonic basins of the Brasiliano Orogeny. During the late stages of this orogenic phase (700 - 500 My.), depressions were formed in which sediments resulting from erosion of mountain areas which are still undergoing active uplifting were deposited (Almeida 1969).

Rodeio Velho Member (*sensu* Ribeiro *et al.* 1966) was described as an event of a minimum of three flows of vesicular andesites, with estimated thickness of 100m, without evidences of explosive activity and they display undulatory surfaces. These rocks constitute the Guaritas Allogroup of Paim *et al.* (1995), together with sedimentary alloformations Pedra Pintada (lower) and Varzinha (upper), representing the final stages in the evolution of the Camaquã Basin. The Rodeio Velho magmatism is associated with the lower unit as lava flows, pyroclastic deposits and shallow intrusions, as well as dykes hosted in earlier rocks of the basin.

There are sparse petrographic and geochemical papers about the Rodeio Velho Member. Almeida *et al.* (1993) suggested a fissural event possibly related to a local hot spot in an extensional intraplate environment. Hartmann *et al.* (1998) determined a U/Pb age of 470 My. for this event. Silva Filho (1996) showed the intrusive character of this magmatism, despite former ideas of an exclusively volcanic event. Lopes *et al.* (1999) reported a 119.5-m thick manifestation (CQP-1-RS drillhole north of Camaquã Copper Mines), and suggested that this magmatic event is "related to a new sedimentation cycle, precursor of the Paraná Basin".

Fragoso Cesar *et al.* (1999) denominated these rocks the Rodeio Velho Intrusive Suite, represented by tabular intrusions in the subhorizontal continental deposits of the Guaritas Group. Almeida *et al.* (1999) mentioned that this event is a basalt andesitic type of alkaline trend, outcropping as lava flows, pyroclastic deposits and intrusive rocks.

FIELD RELATIONSHIPS In outcrop, lava flows show *pahoehoe* structures and intrusive bodies are predominantly linear dykes, although some of them occur as sills. Pyroclastic deposits are ash tuffs and/or stratified lapillites. These rocks are amygdaloidal and vesicular.

Region 1 NORTHERN SECTOR at this zone, the Rodeio Velho Member outcrops as four volcanic cones, aligned NNE-SSW, parallel to the regional faults, a clear evidence of a structural-tectonic control in the its emplacement. These cones were preserved due to a later

Figure 1 – Geological and localization map.

deposition of sedimentary rocks corresponding to the upper Ordovician sedimentation of the Varzinha Alloformation. Immediately to the west, there are some dykes hosted in the Santa Bárbara Formation. Those dykes are subvertical, preferentially aligned to 26°, with vesicular and vitreous margins and massive central portions. Ejected blocks of vesicular andesitic/basaltic rocks can be found elsewhere in the area, in addition to localized concentrations of jasper, chalcedony and geodes, possibly related to a Strombolian-type event (Hansen *et al.* 1997).

SOUTHERN SECTOR Two km south of the cones, at the Arroio Carajá region, the Rodeio Velho Member outcrops as lava flows and intrusive rocks. Flows show *aa* and *pahoehoe* structures (Fig. 2) with

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Figure 2 - Detail of rod-like lava flow in the Arroio Carajá region.

centimetric to decimetric hollow tubes, as well as amygdaloids and/or vesicles up to 5 mm long, both at the base and top of each flow. Lima *et al.* (1995) interprets these rocks as typical Hawaiian tholeiitic lava flows, *pahoehoe* type. These lavas are in normal fault contact with the intrusive facies, which is hosted in rhythmites of the Pedra Pintada Alloformation.

Intrusive contacts with the sedimentary rocks are abrupt or with a reaction border, with assimilation textures. The intrusive body is amygdaloidal, vesicular in places (quartz, celadonite/chlorite, and carbonate). Xenoliths are common along the contact, as slabs of fine sandstone or has "sand dykes", preserving sedimentary structures and ichnofossils. Based on field analyses, emission centers may be situated northwards, possibly related to the cones.

Figure 3 - Detail showing sandstone enclave in amygdaloidal lava in the Passo do Moinho region

Figure 4 - Intrusive character of the Membro Rodeio Velho in the Pedra da Arara region.

Region 2 At the Rincão da Tigra region, the Rodeio Velho Member exhibits a more complete rock column, from intrusive-facies through flows and pyroclastics on the top. The intrusive bodies are hosted in metamorphic rocks of the basement and in sedimentary rocks of the Pedra Pintada Alloformation. Pyroclastic deposits occur as stratified and banded ash and lapilli tuffs, with oxidized shards and *fiammes*. At the bottom, rock clasts characterize this deposit as a breccia. Intrusive facies and lava flows are amygdaloidal and vesicular, massive in places.

Region 3 Intrusive rocks and lava flows occur at the regions of Rodeio Velho, Cerro do Diogo, Pedra da Arara and Arroio dos Neves. Similar to the Region 1, elongated xenoliths of stratified sandstones can be found (Fig. 3), with preservation of the sedimentary structures.

In the regions of Cerro do Diogo/Pedra da Arara (Fig. 4) to Arroio dos Neves, the Rodeio Velho Member is characterized by its intrusive contact with rhythmites (Pedra Pintada Alloformation), which preserved its sedimentary structures (climbing ripples, load casts and dish and pillar). The intrusion occurs as an amygdaloidal/vesicular dyke filled with carbonate, quartz and celadonite. Vesicles are oriented parallel to the intrusion direction.

PETROGRAPHY Flows and Intrusives (dykes) These rocks have similar textures and mineral compositions. Euhedral to subhedral plagioclase phenocrysts may be partially substituted by carbonate and/or clay minerals. Fractures are filled with oxides. Phenocrysts may or may not be associated to opaque minerals, as isolated grains or in a glomeroporphyritic texture. Accessory minerals are apatite and zircon, together with the opaque minerals. Rock matrix is pilotaxitic, vitrophiric or ophitic, constituted by plagioclase microcrystals and relicts of pyroxenes or olivines, normally associated to minor opaque minerals. Glass is interstitial, recrystallized and forms spherulites or is altered to clay minerals. Amygdaloids are filled with quartz, carbonate, clay and chlorites. Amygdaloids/vesicles are present in both intrusive and extrusive facies, showing that magma was rich in a

volatile phase. Observations on the field showed that intrusive facies and lava flows are very similar, perhaps due to a very shallow intrusion.

Petrographically, lava flows correspond to andesites (3 samples), subalkaline basalts (2 samples), trachyandesites and alkaline basalts (1 sample each). Intrusive subvolcanic bodies are trachyandesites (2 samples) and alkaline basalts (1 sample).

Tuffs Tuffs are bedded ash tuffs and lapilli tuffs, with a poor selection, composed of shards and *fiammes*, and brecciated in places, mainly at the base. Clasts composition varies from aphanitic volcanic rock to volcanic rock with plagioclase and euhedral quartz crystals. A dark brown glassy mixture of glass and opaque minerals constitutes the breccia matrix. Microcrystalline quartz occurs in veins or as matrix substitution. The ash tuff is a trachyandesite.

GEOCHEMISTRY The geochemical analyses of major elements, trace elements and rare earth elements (REE) were performed at the Activation Laboratories Ltd., at Ancaster, Canada. Results shown in Table 1 correspond to tuff (1 sample), lava flows (8 samples, 3 from the volcanic cones) and intrusive rocks (3 samples). All rocks show a marked hydrothermal alteration that influences the mobility of the major elements. Thus, the analysis of geochemical data was based mainly on the trace elements and REE, since these more easily controlled by the analyst.

Figure 5 – Bivariate-ratio diagram of Zr/TiO_2 versus Nb/Y (Winchester & Floy, 1977).

Table 1 – Geochemical analysis of major, trace and REE elements. (1) tuff at Rincão da Tigra; (2,3,4) lava flows (cones) at southeast of Passo do Correio; (5,9) lava flows; (10,12) intrusives. The three types of magmatism products in the Rodeio Velho are chemically very similar.

sample	JKF11	PH-3	PH-4	PH5	PM49	PM54	RLP1	RLP10	RLP12	RLP14	RLP15	PLR17
	1	2	3	4	5	6	7	8	9	10	11	12
SiO ₂	69.71	50.14	65.53	48.55	51.47	52.93	51.89	57.12	52.33	51.69	54.63	46.84
TiO ₂	0.916	2.15	1.82	1.71	2.71	2.13	1.66	2.24	1.83	1.856	1.807	2.099
Al ₂ O ₃	11.12	14.64	12.7	14.14	15.69	16.2	15.75	14.58	15.77	15.79	15.34	15.77
Fe ₂ O ₃	7.19	11.63	6.28	9.77	13.6	13.89	8.92	10.26	8.42	10.61	11.17	12.14
MnO	0.05	0.16	0.1	0.17	0.16	0.1	0.26	0.13	0.09	0.07	0.08	0.09
MgO	1.09	4.35	0.85	0.34	1.1	1.87	1.66	1.53	4.11	2.96	0	3.68
CaO	0.41	7.4	1.99	7.64	2.45	1.04	6.57	3.3	4.97	5.18	2.68	8.26
Na ₂ O	0.81	3.45	6.01	3.34	6.36	7.57	4.59	7.6	3.89	3.78	3.9	3.7
K ₂ O	5.61	1.24	1.06	6.27	1.95	0.88	2.75	0.26	2.24	2.2	5.56	1.43
P ₂ O ₅	0.27	1.18	1.2	0.91	1.41	0.36	1.05	1.4	1.08	1.1	1.08	0.85
LOI	2.81	3.22	1.42	5.95	2.14	2.35	4.57	1.73	3.89	3.59	2.05	4.51
total	99.98	99.56	98.94	98.78	99.05	99.32	99.68	100.15	98.62	98.83	98.83	99.37
K	46569	10293	8799	52047	16187	7305	22828	2158	18594	18262	46154	11870
Ba	607	1780	2695	2204	2093	344	1124	673	1150	1142	1560	1140
Rb	110	15.6	13.9	94.1	28	17	40	4.5	29	28	91	26
Sr	57	1186	276	222	824	328	558	454	775	808	387	805
Tl	0.6	0.2	0.2	1	0.3	0.2	0.2	-0.1	-0.1	-0.1	0.6	0.1
Ta	0.8	1.36	1.18	1.18	2.1	0.94	1.03	1.67	1.2	1.3	1.2	1.2
Nb	12	30.2	25.5	27.9	36	19	19	25	27	27	25	20
Hf	5.7	7.4	2.5	3.4	8.5	3.3	8	7.8	8.3	7.9	7.5	3.8
Zr	237	461	399	360	380	185	383	369	395	384	367	164
Ti	5491	12889	10911	10251	16246	12769	9952	13429	10971	11127	10833	12584
Y	16	54	48	36	84	27	51	41	42	41	36	28
Th	6.8	3.47	2.61	3.41	3.7	1.4	2.9	3	3.2	3.2	3.1	1.6
Cr	94	119	110	87	63	140	84	92	81	83	74	112
La	43.9	102.7	86.9	84.5	104	40	136	104	76.6	77.1	80.6	42.8
Ce	77	204.7	164	168	186	76	217	201	148	145	151	91.3
Pr	9.37	20.13	16.53	16.65	23.8	11	26.6	23.8	19.5	19.6	19	11.8
Nd	30.6	91.7	75.2	72.7	95	45	108	97	70.4	70	66.8	45.1
Sm	5	16.2	13.7	12.2	17	8.5	17	16	12	11.7	10.6	8
Eu	1.4	4.81	4.02	3.52	4.81	2.52	4.45	4.46	3.58	3.43	3	2.88
Gd	4	14.5	12.8	11.2	15	6.8	12	11	10.1	9.7	8.7	6.8
Tb	0.6	2	1.8	1.4	2.2	1	1.7	1.6	1.5	1.4	1.3	1
Dy	3.3	10	8.9	6.8	12	5.5	8.9	7.6	8.1	7.7	6.8	5.8
Ho	0.6	1.9	1.8	1.3	2.4	1	1.6	1.4	1.5	1.5	1.3	1.1
Er	1.8	5.4	5.2	3.7	7.1	2.9	4.6	3.7	4.3	4	3.6	3
Tm	0.27	0.65	0.59	0.45	0.94	0.39	0.61	0.49	0.57	0.56	0.51	0.41
Yb	1.8	4.5	3.8	3	5.5	2.4	3.5	2.9	3.5	3.4	3.1	2.5
Lu	0.27	0.73	0.6	0.47	0.85	0.34	0.57	0.45	0.52	0.49	0.46	0.36

Figure 6 – Chondrite normalized REE diagram (Nakamura 1977).

Figure 7- Multi-element spider diagram. Normalizing values are those of Sun & McDonough (1989) Legend same as in Figure 5.

Figure 8a and 8b –Bivariate diagram of Zr versus Y and Nb. Legend same as in Figure 5

Figure 9 a and b —Bivariate diagram of Ce versus Sm and La. Legend same as in Figure 5.

Figure 10 – Wood's diagram of tectonic discrimination, 1980. A- N-type MORB; B – E-type MORB and tholeiitic WPB and differentiates; C – Alkaline WPB and differentiates; D – destructive plate-margin basalts and differentiates.

Figure 11 – Multi-element spider diagram normalizing the values of Sun & McDonough (1989).

From the chemical standpoint, the sequence rocks are represented in diagram Nb/Y versus Zr/TiO₂ (Winchester & Floyd 1977 – Fig. 5), with the flows in the field of subalkaline basalt (2 samples), andesite (4 sample), trachyandesite (2 samples) and alkalibasalt (1 sample) and andesite basalts, the pyroclastic in the trachyandesite field and the intrusive in the trachyandesite and alkalibasalt field (1 sample).

The three types of magmatism found in the Rodeio Velho are chemically very similar. Chondrite-normalized REE pattern (Nakamura, 1977) show alkaline basalts with no expressive fractionation. The ratio La/Yb_N is 16.26 for the tuff, between 11.11 and 25.90 in the flows, and from 11.41 to 17.33 in the intrusives. There is an enrichment of light REE in relation to heavy REE, with a negative Eu anomaly in two samples (flows) and a positive Eu anomaly in one (intrusive) (Fig. 6). Most samples present a negative Ce anomaly, excepting the cones, which shown no anomaly. There is a clear parallel among the spectrum of all analyzed samples, the LREE:HREE ratio being almost constant.

The LREE:HREE ratio is 4.8 for the tuff, between 3.4 and 5.7 in the flows, and an average of 4.1 in the intrusives, confirming the shared magmatic affiliation of the studied rocks. There is a progressive increase in the REE content from tuff to intrusives and flows.

When normalized to N-MORB (Sun and McDonough 1989, Fig. 7), the REE pattern display a clear enrichment of Nb, Ce, Nd, Sm and Zr related with Ti, Tb, Y, Yb and Lu, suggesting an abundance of these elements in the original magma.

Trace elements analyses showed a positive correlation of Zr with many elements like Y and Nb (Fig. 8 a,b), as well as Al₂O₃ and REE, despite a gap in the Zr values of 238 ppm to 359 ppm. Other positive correlations exist between Ce and both Sm and La (Fig. 9a,b). A positive correlation between Ta and Th characterizes the enrichment of the residual liquid and suggests a fractional crystallization process as mechanism responsible for the evolution of the studied rocks. The negative correlation of Zr against Cr and Ti is understood to be due to the crystallization of mafic minerals and magnetite in the beginning of the process.

GEODYNAMIC ENVIRONMENT The amygdaloidal/vesicular character and hydrothermal alteration of the studied rocks invalidates the use of Irvine and Baragar (1971) classic variation diagrams of Na₂O+K₂O versus MgO versus FeO₁ and of Na₂O+K₂O versus SiO₂. Other trace-elements variations suggest a predominance of intraplate,

alkaline or E-MORB basalts, in terms of Hf/3 versus Th versus Nb/16, (Fig. 10) (after Wood 1980). This behavior is confirmed in the Zr/Y - versus - Zr diagram (Pearce and Cann 1973).

Trace elements were normalized to N-MORB (Sun and McDonough 1989, Fig. 11), in order to more precisely infer the geodynamic environment. A diagram with LFS (Sr, K, Rb, Ba, Th) and HFS elements compare basalts in different environments, in which the studied rocks are very similar to intraplate continental basalts (Pearce 1983), with Sr depletion and slight enrichment in K, Rb and Ba. A depletion of Yb, Y and Ti is also visualized.

DISCUSSION The Rodeio Velho Member represents a volcanic/intrusive sequence affected by an intense weathering or metasomatism, thus, only incompatible trace elements and REE diagrams are considered herein. The AFM diagram shows tholeiitic rocks, although an alkaline character is present in the Na₂O+K₂O - versus - SiO₂ diagram. The REE pattern is similar to that of alkaline basalts (Fig. 6). The alkaline character is confirmed in the REE behavior, with values corresponding to rocks evolved (Culler and Graf 1984) from fractionation and a clear parallelism among all rocks.

Fractional crystallization is the fundamental mechanism controlling the mutual relationships among these rocks. This is confirmed in the identified correlation between incompatible elements, for instance Ce and Zr. The gap observed may be explained because the studied outcrops are spatially and tectonically distant, in addition to display intense metasomatism/hydrothermal alteration. Thus, this gap may have no geologic meaning and is perhaps overdimensioned by the element mobility.

Based on the REE distribution, an increase of the LREE may occur with low rates of partial fusion and particularly through a garnet-depleted source, which indicates upper-mantle depths for rock generation. Low Sr values may be linked to a primitive magma, at the onset of fractionation. Alternatively, these Sr data may have no primary magmatic significance due to rock alteration.

The Rodeio Velho Member corresponds to the thermal generator of hydrothermal solutions that generated mineralizations of Cu (Ag, Au), Pb and Zn (Cu, Ag) of Minas do Camaquã, Jazida Santa Maria and others (Lima 1998).

The origin of Ce anomalies in volcanic rocks had been widely discussed, but it remains enigmatic. The negative Ce anomaly shown on this study can be explained by magma contamination by sediments or Ce-depleted rocks.

There is a general agreement that volcanism in the early stages of extension are tholeiitic, for instance during rift generation. So, it is most probable that the studied rocks correspond to a late Pan African - Brasiliano orogenic event. The tectonic process responsible for the Ordovician (470 Ma, Hartmann 1998) volcanism seems to be the reactivation of a localized hot spot, magma ascending through deep-seated faults during distensive tectonism.

CONCLUSION The Rodeio Velho Member corresponds to a late stage of the Pan African - Brasiliano Orogeny, showing intrusive, extrusive and pyroclastic rocks. The intrusive rocks outcrop in fault contact with lava flows and tuffs. The volcanic event manifested in the middle Ordovician, in a continental margin affected by intraplate distensive tectonism. The volcanism corresponds to the *locus* of thermal generation for the hydrothermal solutions, which in turn are responsible for ore mineralizations in the area.

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