GAMMA-RAY SPECTROMETRY SIGNATURE OF PARANÁ VOLCANIC ROCKS: PRELIMINARY RESULTS

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RESUMO - As rochas vulcânicas da Província Magmática do Paraná (Formação Serra Geral) são caracterizadas por quatro tipos de rochas principais. Os basaltos são os mais comuns e exibem textura intergranular, de coloração cinza escura a preta, em afloramentos predominantemente maciços. Dois tipos de rochas ácidas são observados. O primeiro, denominado Palmas (ATP), é afírico, com coloração cinza clara e textura sal-e-pimenta. O segundo, Chapecó (ATC) é fortemente porfirítico, com coloração cinza clara a amarronzada. Andesitos são rochas de coloração cinza clara a preta e natureza afírica e difíceis de reconhecer macroscopicamente utilizando apenas critérios petrográficos. Porém, do ponto de vista geoquímico essas rochas são diferentes entre si, inclusive pela concentração de elementos radioativos (K, U e Th), sugerindo poderem ser reconhecidas por sua assinatura gama-espectrométrica. Trabalho de campo usando um espectrômetro gama portátil obteve valores de gama-total de 4,7 ± 0,8 μRh^{-1} para os basaltos, 7,2 ±1,2 μRh^{-1} para os andesitos, 11,3 ± 1,2 μRh^{-1} para as rochas ATC e 15,4 ± 2,4 μRh^{-1} para as rochas ATP, confirmando que o método é uma boa ferramenta para auxiliar a identificação macroscópica dos diferentes tipos de rochas vulcânicas da Formação Serra Geral.
Palavras-chave: Formação Serra Geral, Rochas Vulcânicas, Espectrometria de raios gama

ABSTRACT - The Paraná volcanic rocks (Serra Geral Formation) are characterized by four different types of rocks. The basalts are the most common, and display an integranular texture and dark gray to black color, in massive outcrops. The acid volcanics are represented by aphyric, salt-and-pepper texture, light gray color, named Palmas type (ATP), and by strongly porphyritic, green to brownish gray color, named Chapecó (ATC). The intermediate rocks are represented by light gray, aphyric andesites. Sometimes, it is very difficult to distinguish andesites from ATP rocks or even from basalts, using only petrographic criteria. However, from the geochemical point of view, these rocks are quite different, including the radioactive elements (K, U and Th). In this way the portable gamma-ray spectrometer argued being a useful tool to recognize different rock types with different total gamma-ray signature, such as basalts (4.7 ± 0.8 μRh^{-1}); andesites (7.2 ±1.2 μRh^{-1}), ATC (11.3 ± 1.2 μRh^{-1}) and for ATP (15.4 ± 2.4 μRh^{-1}).
Keywords: Paraná Magmatic Province, Serra Geral Formation, volcanic rocks, gamma-ray spectrometry.

INTRODUCTION

The Paraná Magmatic Province (PMP) is one of the most important Mesozoic continental large igneous province observed on the Earth surface. It is characterized by lava flows of Serra Geral Formation, covering the southern of Brazil, the eastern region of Paraguay, the western of Uruguay (Arapey Formation) and the northern of Argentina (Pousadas Member of Curuzú-Cuatiá Formation), or 75% of the Paraná Basin surface. Associated to the lava flows there was an intense activity of magma intrusions, as sills and dykes. Sills are common mainly emplaced within the Paleozoic sedimentary rocks at different stratigraphic levels, especially in Irati Formation and Itararé Group. The most significant dyke swarm of PMP is the NW-SE Ponta Grossa Arch. They are basic in composition and are found in the pre-Devonian crystalline basement in the northern-eastern regions of the Paraná Basin, where 1 to 4 dykes per square kilometer are observed. Another important dyke swarm is the

Santos-Rio de Janeiro observed parallel to the Brazilian coastal line.

The high precision $^{40}Ar:^{39}Ar$ dating has showed a age interval from 133.6 to 131.5 Ma in the northern region and from 134.6 to 134.1 Ma in the southern region (Renne et al., 1992, 1996a,b; Turner et al., 1994). In this way the duration of the volcanism was around of 3 Ma (Ernesto et al., 1999, 2002; Mincato et al., 2003; Thiede &Vasconcelos, 2010; Pinto et al, 2010 and Janasi et al., 2011). This time interval is in agreement with the paleomagnetical data which conclude that lavas was piled up in sequences up to 1km thick (Marques & Ernesto, 2004).

The volcanic rocks of Serra Geral Formation are characterized by tholeiitic basalts, andesites and two felsic acid rock types, named Palmas (aphyric) and Chapecó (porphyritic), and their distributions are showed in geological map of Figure 1 (Nardy et al., 2002; 2008).

Nevertheless, to recognize the different types of volcanic rocks are not always easy, using only the flows architecture and their macroscopic petrography, because the textures are very fine or glassy, and the structures observed in outcrops of one type of rock may be observed in another type too. Therefore the petrographyc microscopy and geochemical analysis are the most reliable methods to recognize the different volcanic rock types.

With the purpose to establish the lava flows stratigraphy of the western region of Rio Grande do Sul state, Martins et al. (2011) have used a gamma-ray scintilometry logging of a set of boreholes drilled by CPRM in 1980s, observing that basalts and andesites could be recognized each other.

Thereby the goal of this paper is to recognize gamma-ray signatures of the main volcanic rocks of Paraná Basin, using a portable gamma-spectrometer, getting data in different outcrops of Serra Geral Formation, Figure 1, which preliminary results are now presented.

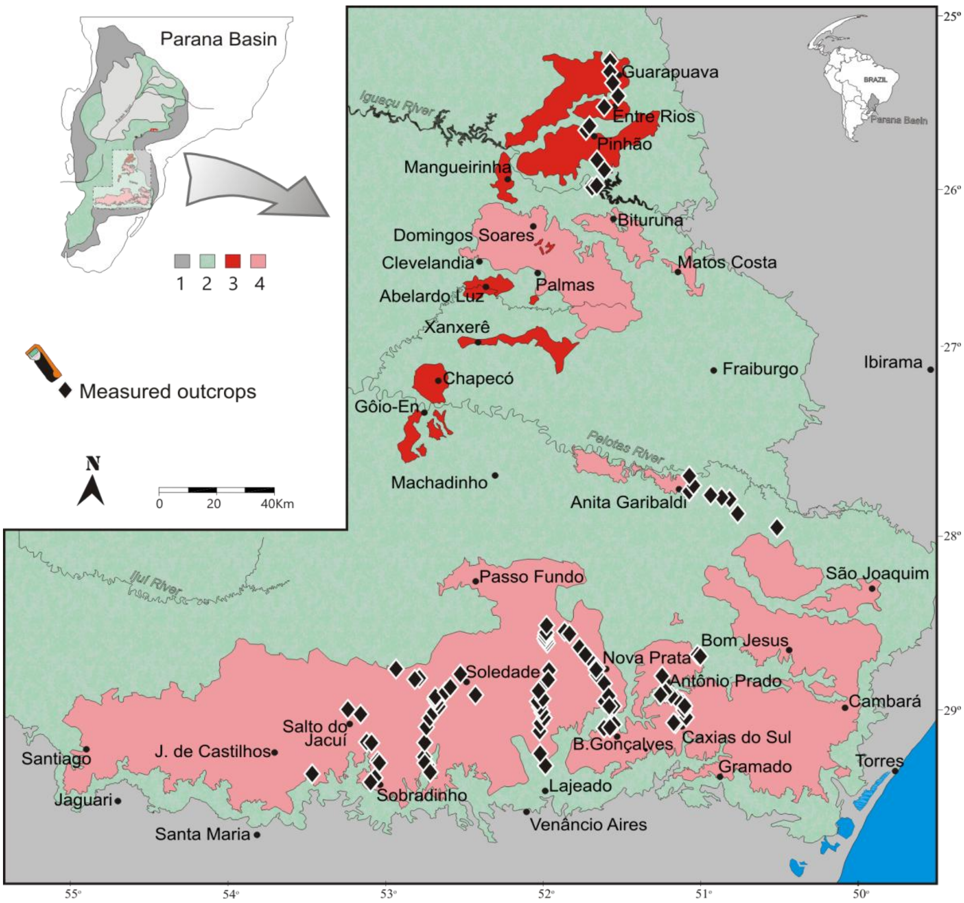

Figure 1. Sketched geological map of volcanic rocks of Serra Geral Formation, includding gamma-spectrometry measurement location. *Legend*: 1- pre-volcanic rocks, 2- basalts and andesites, 3- Palmas acid volcanics and 4- Chapecó acid volcanics.

GEOLOGICAL AND PETROGRAPHIC ASPECTS

Basalts and andesites are the most common volcanic rocks of the PMP. They are light -gray to black and the mineralogy is composed of 30 to 50% vol. of plagioclase (andesine-labradorite), 20 to 35% vol. of pyroxene (augite and pigeonite) and 5 to 15% vol. of opaque minerals (magnetite and ilmenite). Olivine, quartz and apatite are primary minerals found in less than 5% vol. of these rocks. The basalts/andesites are hypocrystalline (3 to 15% vol. of glass), but holocrystilline (less than 3% vol.of glass) to hypohyaline (more than 60% vol. of glass) rocks might be found. The main texture observed is the intergranular (the angular interstices between unoriented plagioclase laths are occupied by grains of pyroxenes and magnetite).

The ATP rocks are light-gray to brownish red, aphyric and hypohialyne to holohyaline with salt-and-pepper aspect, Figure 2, spreading out in extensive plateaus, with a few kilometers long, without vegetation cover. The mineralogy is composed of dominant *microphenocrysts* (grain size smaller than 0.5 mm) of 16% vol. of plagioclase (labradorite), 11% vol. of augite, 3% vol. of pigeonite, 5% vol. of magnetite, and less than 1% vol. of apatite. These crystals often exhibit quench texture (rapid cooling), developing skeletal, lath, sickle and hollow shapes, or swallowtail terminations. A dark-brown slightly birefringent glass matrix (up to 63% vol.) is observed with a granophyric texture of abundant alkali feldspar and quartz intergrowth, which surrounds all the crystal phases, Figure 3. Black holohyaline rocks (pichstones) are observed displaying conchoidal fractures and glassy luster, Figure 4. However, due to its amorphous nature, the glass alters easily and thus in most outcrops the rock is completely weathered, presenting a brownish color and (often resembling sedimentary deposits) with abundant vesicles up to 10 mm in length filled by quartz or zeolites.

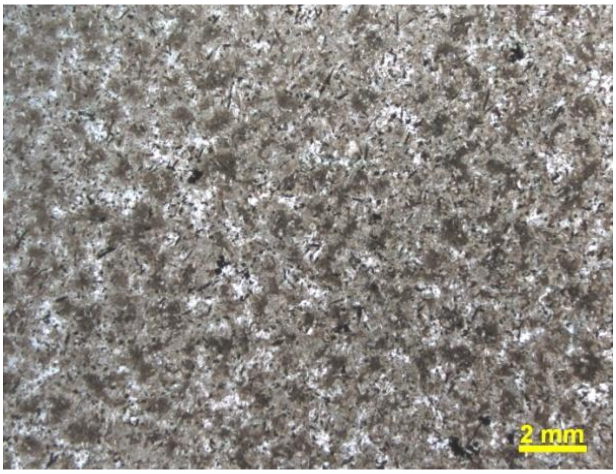

Figure 2. Photomicrography of ATP rock showing aphyric and salt-and-pepper texture.

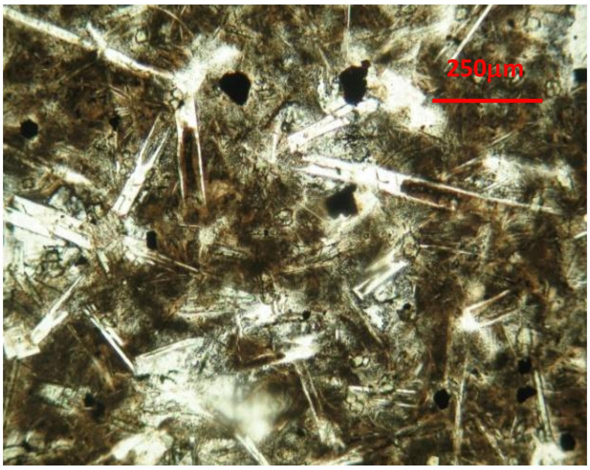

Figure 3. Photomicrography of ATP rock showing quench textures: hollow and swallowtail in microlites of plagioclase.

Subhorizontal joints are the main structure observed in ATP outcrops generating sheet-like structures formed by 5-20cm thick irregularly broken plates, Figure 5. These sheeting joints may show different dipping angles (up to vertical) suggesting a hot viscous magma (≈ 1000^oC), Nardy et al. (2011), flowing on an irregular surface, or paleotopography.

Figure 4. Pitchstone outcrop near Caxias do Sul (RS).

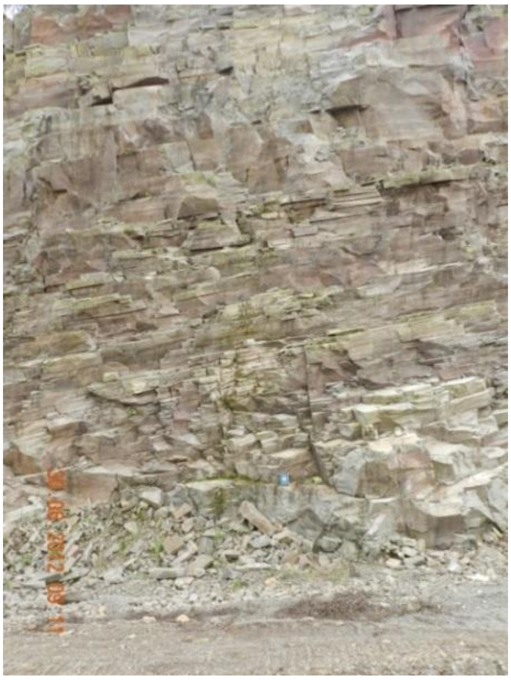

Figure 5. ATP outcrop in Soledade (RS) showing marked subborizontal sheeting joints.

These rocks may also exhibit centimetric subhorizontal flow banding defined by glassy dark lenses alternate with microcrystalline light gray layers, Figure 6.

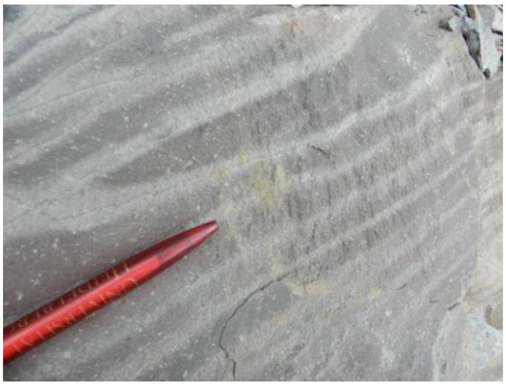

Figure 6. Flow banding in ATP rock outcrop in Nova Petrópolis (RS)

ATC volcanics cover large plateaus, where the soil thickness is more expressive comparing to ATP rocks. They are porphyritic with an average of 24% vol. of plagioclase macro-phenocrysts up to 2 cm long, in a light gray (fresh) to brown (weathered) aphanitic groundmass. The mineralogy consisits of euhedral andesine phenocrysts in a matrix of augite (4.5% wt.), pigeonite (2.2% wt.), magnetite (3.7% wt.) and apatite (1.7% wt) surrounded by a mesh of quartz and alkali feldspar in felsitic, locally granophyric arrangement (vitrophyric texture), Figures 7 and 8. Sheeting joints, Figure 9, and flow banding (where glassy dark lenses are within light gray microcrystalline material), Figure 10, are also common in these rocks.

Figure 7. Hand sample of ATC rock from Domingos Soraes (PR) showing euhedral plagioclase phenocrysts in a porphyritic texture.

Figure 8. Photomicrography under crossed polarizers of ATC acid rock, from Pinhão (PR) with vitrophyric texture, where euhedral plagioclase phenocrysts are rounded by glassy groundmass.

Figure 9. Outcrop of ATC rock near Domingos Soares (PR) showing marked sheeting joints.

Figure 10. Outcrop of ATC rock along BR466, near Gurapuava (PR) showing no continuous flow banding.

Palmas Member is characterized by acid volcanic bodies (ATP type) associated with a few basaltic lava flows, cropping out from the central region of the basin to southwards, where it may reaches 270 m thick. Chapecó Member, exclusively composed of acid volcanic rocks (ATC type), occurs in the northern and central regions of the Paraná Basin; reaching 250 m thick in the central region. It overlaps the basalts, but in the northern portion of the basin (Paranapanema River region - SP) may also be found directly on the sandstones of the Botucatu Formation.

In the center of the basin the two silicic members overlap showing that the Palmas Member is older than Chapecó, although ATC type rocks may be founded interlayered in the Palmas Member.

The last pulses of Paraná volcanism emplaced basalt flows that cover both the ATP and ATC rocks and become thicker northward of the basin.

GEOCHEMICAL ASPECTS

The geochemical data used in this paper have been compiled of Marques (1988) and Marques et al. (1989), since they are homogeneous in terms of analytical methods and K, U and Th concentrations are available too. Based on major elements two main tholeiitic suites may be distinguished as showed in Figure 11. The first group, named *tholeiitic-transitional*, is characterized by higher total alkalis concentrations (Na_2O+K_2O) for similar SiO_2 content than those *thoeliitc group*, being represented by high-Ti-basalts, andesi-basalts and ATC acid volcanics (trachytes and dacites) whereas the tholeiitic group is represented by low-Ti-basalts, andesi-basalts, andesites and ATP rocks (dacites and rhyodacites). As it t is possible to observe in the Figure 1, acidic rocks of tholeiitic group (ATP) are displaced to southern region while the tholeiitc transitional (ATC) to northern. It is important to observe that both associations are of tholeiitc nature, as it is shown in Figure 12.

Chemical comparison between tholeiitic and tholeiitic-transitional groups is illustrated by using average compositions and SiO_2 as variation parameter, Table 1. Using these data in Harker diagrams, Figure 13, the tholeiitic-transitional rocks are TiO_2 and K_2O enriched compared with tholeiitic rocks, which are enriched in U and Th. It is important to observe the positive correlation between U and Th with the SiO_2 concentration, and the ATP rocks are higher in both elements than ATC rocks.

The behavior of these elements in the volcanic rocks of Serra Geral Formation was very important to define the gamma-ray spectrometry to support the identification of the different rocks during the field works.

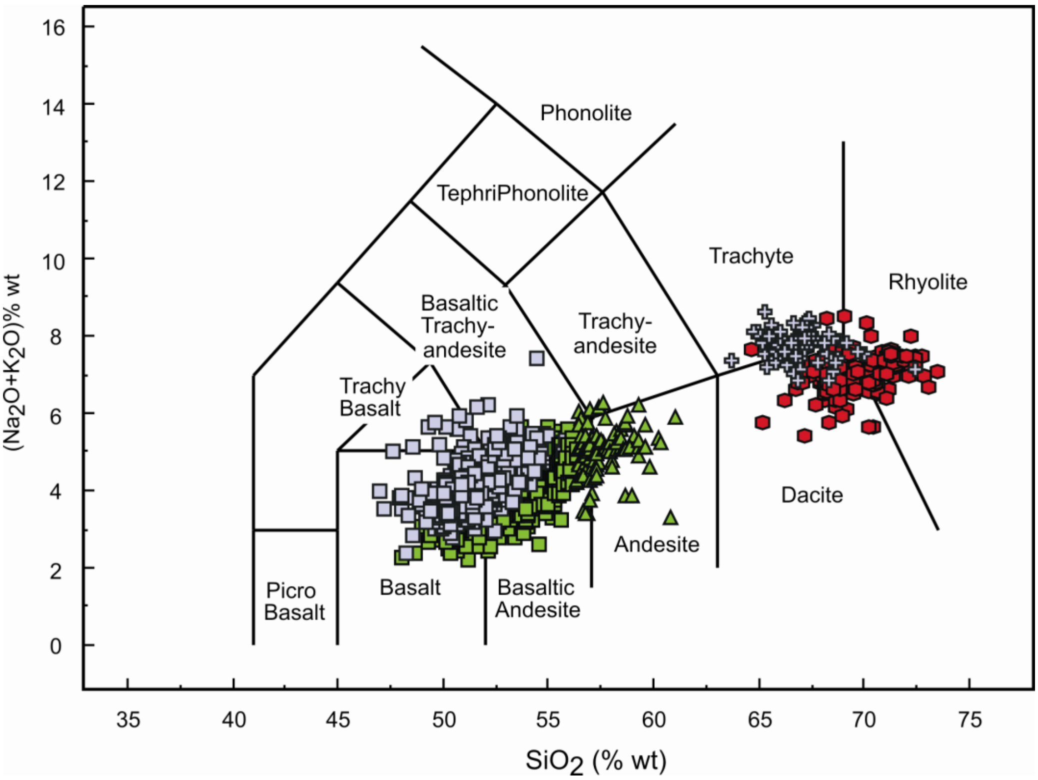

Figure 11. Alkalis vs Silica diagram, with nomenclature of Le Bas et al, (1896). *Legend of symbols*: green squares= tholeiitic basalts (TH); green triangles= tholeiitic andesites; red circles= ATP rocks; light-blue crosses= tholeiitic-transitional basalts.

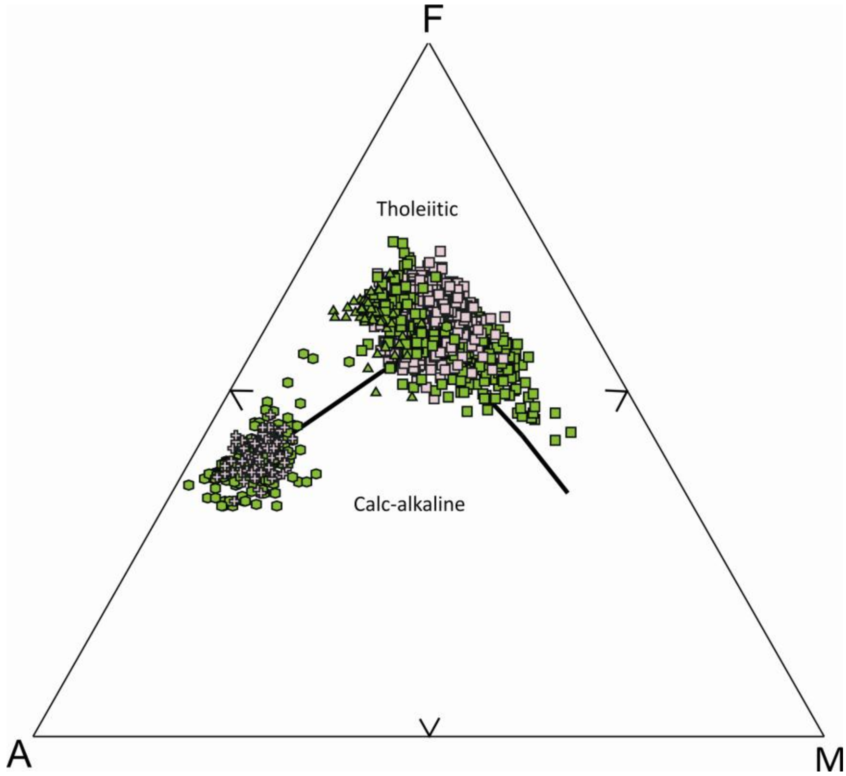

Figure 12. A (Na_2O+K_2O) – F (FeO_t) – M (MgO) diagram of volcanic rocks for tholeiitic and tholeiitic-transitional rocks. Legend= as Figure 11.

Table 1. Average (wt%) and trace (ppm) element contents of volcanic rocks of tholeiitic association (TH= basalts, AND= andesites, ATP= acid rocks) and tholeiitic-transitional association (THT= basalts, ATC= acid rocks). *n*= number of samples, *sd*= standard deviation. Based on data of Marques (1988) and Marques et al. (1989).

	TH-1		TH-2		TH-3		AND-4		ATP-5		ATP-6		ATP-7		THT-8		THT-9		ATC-10		ATC-11	
	n=20	*sd*	*n=26*	*sd*	*n=15*	*sd*	*n=12*	*sd*	*n=5*	*sd*		*sd*	*n=11*	*sd*	*n=11*	*sd*	*n=8*	*sd*	*n=8*	*sd*	*n=6*	*sd*
SiO_2	48.95	*0.57*	51.60	*0.72*	53.85	*0.49*	56.49	*0.74*	66.36	*0.60*	67.97	*0.56*	70.24	*0.85*	49.39	*0.54*	49.42	*0.89*	64.26	*0.41*	65.56	*0.53*
TiO_2	1.53	*0.21*	1.47	*0.28*	1.54	*0.25*	1.60	*0.20*	0.98	*0.05*	0.92	*0.07*	0.69	*0.13*	2.44	*0.38*	3.38	*0.21*	1.39	*0.16*	1.24	*0.14*
Al_2O_3	14.94	*0.44*	14.79	*0.80*	13.84	*0.71*	13.40	*0.59*	12.92	*0.33*	12.54	*0.40*	12.27	*0.40*	14.20	*0.35*	13.36	*0.46*	13.33	*0.48*	13.09	*0.48*
Fe_2O_3	4.88	*0.82*	4.66	*1.11*	5.21	*1.49*	6.06	*1.34*	4.29	*0.59*	4.18	*0.53*	3.81	*0.58*	4.05	*1.46*	5.50	*1.68*	4.40	*0.44*	4.46	*0.50*
FeO	7.54	*1.11*	7.43	*0.99*	6.99	*1.08*	5.73	*1.25*	1.90	*0.55*	1.64	*0.53*	1.11	*0.42*	9.22	*1.24*	8.21	*1.03*	2.49	*0.36*	1.93	*0.34*
MnO	0.20	*0.03*	0.19	*0.03*	0.19	*0.03*	0.16	*0.02*	0.10	*0.01*	0.10	*0.01*	0.09	*0.01*	0.19	*0.01*	0.19	*0.01*	0.15	*0.02*	0.12	*0.03*
MgO	5.97	*0.77*	4.60	*0.72*	3.62	*1.10*	2.58	*0.73*	1.44	*0.50*	1.29	*0.37*	0.89	*0.27*	4.71	*0.34*	4.40	*0.34*	1.36	*0.21*	1.15	*0.15*
CaO	10.47	*0.73*	8.90	*0.72*	7.69	*0.74*	6.21	*0.61*	2.82	*0.65*	2.74	*0.31*	2.03	*0.25*	9.40	*0.25*	8.64	*0.59*	3.02	*0.17*	2.80	*0.28*
Na_2O	2.47	*0.31*	2.58	*0.28*	2.72	*0.31*	2.71	*0.35*	3.12	*0.25*	2.90	*0.29*	2.61	*0.13*	2.58	*0.14*	2.68	*0.22*	3.55	*0.18*	3.47	*0.08*
K_2O	0.62	*0.41*	1.26	*0.26*	1.75	*0.26*	2.46	*0.26*	4.09	*0.53*	3.97	*0.40*	4.45	*0.21*	1.02	*0.12*	1.31	*0.43*	4.08	*0.22*	4.01	*0.25*
P_2O_5	0.22	*0.08*	0.24	*0.05*	0.25	*0.06*	0.31	*0.17*	0.26	*0.01*	0.25	*0.02*	0.20	*0.02*	0.39	*0.09*	0.47	*0.07*	0.45	*0.02*	0.41	*0.03*
LOI	1.38	*0.33*	1.43	*0.29*	1.58	*0.22*	1.65	*0.28*	1.50	*0.24*	1.32	*0.28*	1.49	*0.41*	1.38	*0.23*	1.53	*0.18*	1.24	*0.29*	1.44	*0.26*
Sum	99.16	*0.12*	99.16	*0.22*	99.22	*0.12*	99.36	*0.13*	99.79	*0.06*	99.82	*0.06*	99.88	*0.05*	98.98	*0.14*	99.10	*0.11*	99.72	*0.06*	99.69	*0.06*
Cr	172	*116*	61	*30*	55	*77*	24	*11*	9	*3*	9	*3*	5	*5*	103	*17*	63	*19*	10	*4*	7	*4*
Ni	91	*27*	55	*18*	46	*34*	20	*8*	7	*3*	6	*2*	6	*2*	65	*9*	53	*12*	5	*2*	5	*3*
Ba	292	*204*	379	*75*	409	*42*	600	*165*	585	*155*	636	*68*	688	*60*	470	*92*	621	*102*	1076	*96*	1077	*26*
Rb	15	*7*	42	*18*	68	*14*	98	*10*	177	*12*	174	*14*	198	*10*	23	*4*	27	*7*	106	*13*	120	*18*
Sr	236	*72*	237	*51*	201	*9*	210	*64*	129	*35*	131	*11*	100	*9*	374	*64*	506	*98*	347	*29*	341	*16*
La	14	*8*	24	*6*	28	*4*	41	*14*	50	*5*	50	*5*	58	*6*	27	*6*	37	*11*	90	*5*	88	*5*
Ce	41	*17*	54	*9*	57	*8*	84	*26*	95	*6*	96	*9*	118	*8*	61	*10*	85	*16*	177	*7*	177	*5*
Zr	117	*52*	150	*21*	168	*23*	248	*108*	288	*44*	295	*30*	312	*19*	192	*50*	253	*43*	668	*37*	629	*49*
Y	29	*8*	32	*6*	34	*5*	40	*9*	46	*7*	53	*11*	65	*14*	30	*3*	31	*3*	73	*26*	65	*5*
Th	1.77	*0.57*	3.89	*1.11*	6	*1*	7.62	*0.93*	13.92	*0.18*	13.70	*0.94*	16.40	*1.35*	2.54	*0.21*	3.10	*0.70*	10.06	*1.42*	11.10	*1.90*
U	0.32	*0.10*	0.96	*0.62*	2	*0.3*	1.75	*0.39*	4.40	*0.65*	4.74	*0.42*	5.07	*0.90*	0.57	*0.08*	0.72	*0.17*	2.54	*0.84*	2.36	*0.58*

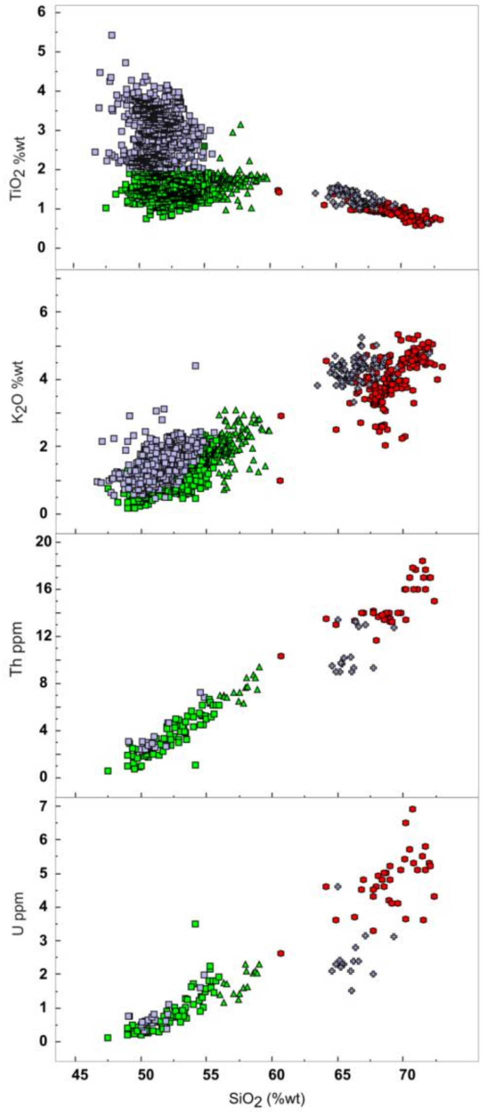

Figure 13. Harker diagrams from tholeiitic and tholeiitc-transicional associations. *Legend*: as Figure 12. Data of Marques (1988) and Marques et al. (1989).

GAMMA-RAY SPECTROMETRY

Methodology

The gamma-ray spectrometry is a geophysical method based on the measurement of gamma-ray emitted by radioactive elements of minerals, rocks, water, soil, etc. This portable equipment is a powerful method to detect a mineral occurrence and to recognize different types of rocks, considering the deep penetration of gamma-rays emitted by natural elements as U, Th and K.

In this study was used the RS-230 portable gamma-ray spectrometer, manufactured by Radiations Solutions Inc., calibrated for K (in %wt), U and Th (in ppm), and total gamma-ray emitted by the sample (in μRh^{-1}) measurements. The spectrometer calibration for Th, U and K was made at the factory, using international certified reference materials (CRM) of Canada Geologic Survey (CCRM) and the International Agency of Atomic Energy (IAAE).

In this work, the measurements were performed in outcrops along the highways, Figure 1, on flat and smooth surfaces so that the sensor was completely in contact with the rock. From each outcrop, one sample for chemical analysis was picked up (analysis are in progress) and three or more gamma-ray measurements were performed. In this paper 103 samples were picked up and 337 measurements of gamma-ray spectrometry were performed.

Petrographic analysis and flows architecture were used to identify the different types of rocks. The ATC rocks are recognized by their porphyritic texture and the flow banding structure, whereas ATP rocks by their aphyric, salt-and-pepper texture and the horizontal sheeting joints. Basalts are hypocristalline massive outcrops with vertical joints. Andesite is more difficult to be recognized using only macroscopic aspects, because the main observed structures in outcrops is of flow type, which depends of the silica contents. The andesite silica contents ranges from 56 to 62% wt, and the rocks must develop basalt-like structures, if silica content is around 56% wt or ATP-like structures, if silica content is around 62% wt. In this preliminary study a pre-described and sampled profiles were chosed, and the location of the intermediate rocks was known.

Results

The total gamma-ray results obtained in the field work are showed in the histograms of Figure 14, where the different types of rock may be recognized, and are: basalts= 4.7 ± 0.8 μRh^{-1}; andesites= 7.2 ±1.2 μRh^{-1}; ATC= 11.3 ±1.2 μRh^{-1} and for ATP= 15.4 ±2.4 μRh^{-1} *ie* different rocks have different ranges of gamma-rays values, pointing out the possibility to recognize the volcanic rocks of Serra Geral Formation using gamma-ray spectrometry. In Table 2, the gamma-ray spectrometry data is organized and summarized using all channels of the spectrometer.

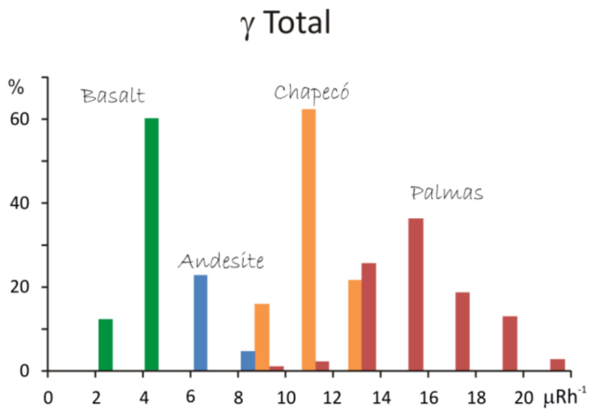

Figure 14. Total gamma-ray frequency (μRh^{-1}) histograms for the different volcanic rock types of Serra Geral Formation.

Table 2. Results of gamma-ray spectrometry for basalts (BAS), andesites (AND) and acid rocks of Palmas type (ATP) and Chapecó (ATC). *Legend*: *n*= number of measurements, *sd*= standard deviation, *max*= maximum observed value, *min*= minimum observed value.

		BAS	AND	ATP	ATC
	n	*74*	*38*	*176*	*49*
γ tot (μRh^{-1})	*mean*	4.7	7.2	15.4	11.3
	sd	0.8	1.2	2.4	1.2
	max	6.0	9.8	23.4	13.7
	min	2.7	5.7	9.1	8.3
K (% wt)	*mean*	1.3	1.9	3.9	3.9
	sd	0.4	0.5	0.9	0.7
	max	2.3	2.9	6.8	6.8
	min	0.2	1.2	1.0	2.2
U (ppm)	*mean*	1.5	2.3	5.7	2.9
	sd	0.6	0.6	1.6	0.9
	max	3.8	3.5	13.6	6.2
	min	0.5	1.0	1.4	1.2
Th (ppm)	*mean*	6.1	9.4	19.0	12.3
	sd	1.7	1.8	4.2	1.9
	max	10.3	13.6	31.1	18.0
	min	2.3	4.8	1.9	9.1

Variation diagrams for the different volcanic rocks were reproduced using total gamma-ray counts as discrimination index, Figure 15, and a good positive correlations is observed for K, U and Th, Figure 15, which are similar to those Harker diagrams using geochemical data, Figure 13. In the same way, the K, U and Th concentrations obtained by gamma-ray spectrometry are able to distinguish the different types of volcanic rocks, as can be seen in Table 2 and Figure 15.

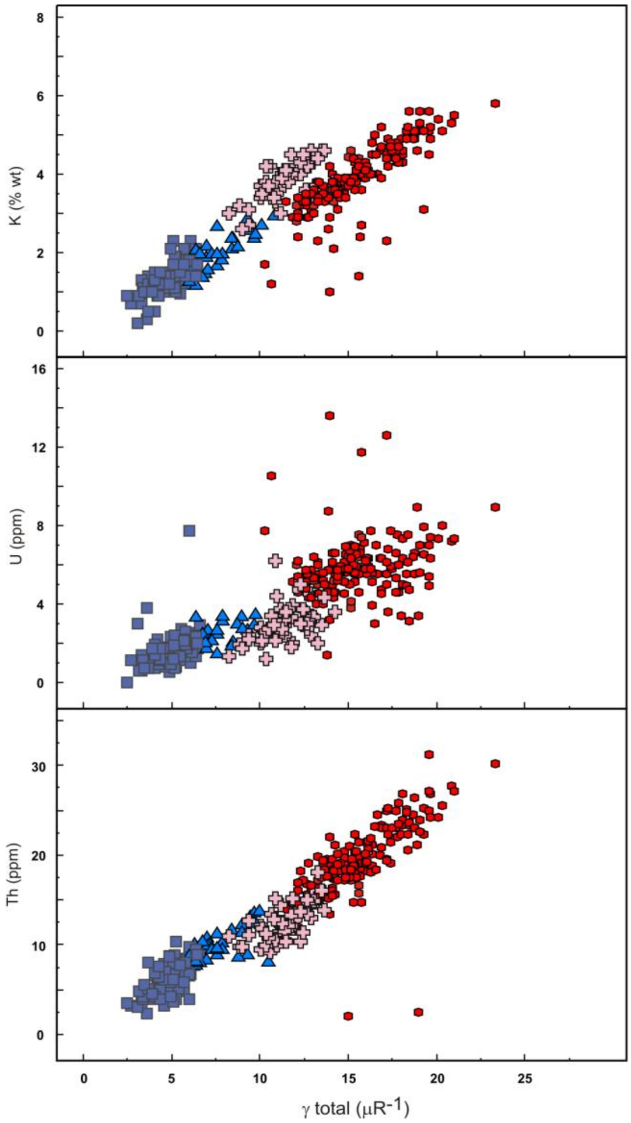

Figure 15. Total gamma-ray (γ total) vs K (%wt), U(ppm) and Th (ppm) obtained by gamma gamma-ray spectrometry during the field work. Legend: square= basalts, triangle= andesites, circle= ATP rocks, cross= ATC rocks.

FINAL REMARKS

The gamma-ray spectrometry is a valuable technique to be used in the field works as an auxiliary tool to recognize different types of volcanic rocks; in a minute is possible to get the total gamma counts and the K (% wt.), U (ppm) and Th (ppm) concentrations.

The preliminary results presented here have showed different gamma-ray signature with: basalts= 4.7 ± 0.8 μRh^{-1}; andesites= 7.2 ± 1.2 μRh^{-1}; ATC= 11.3 ± 1.2 μRh^{-1} and for ATP= 15.4 ± 2.4 μRh^{-1}, Figure 14, Table 2; which are in agreement with U and Th contents in these rocks as showed in Figure 15, Table 1. The obtained gamma ray values and the macroscopic textures of the rocks, allow us their identification. However, the K, U, and Th values obtained by gamma-ray spectrometry are higher than those grouped in Marques (1988) and Marques et al. (1989) obtained by geochemical methods, Tables 1, 2, Figure 16, and the applied method was not able to establish the gamma-ray signature of different types of basalts (high and low Ti). On the other hand the study is in progress and more data are being to try an improvement of the method.

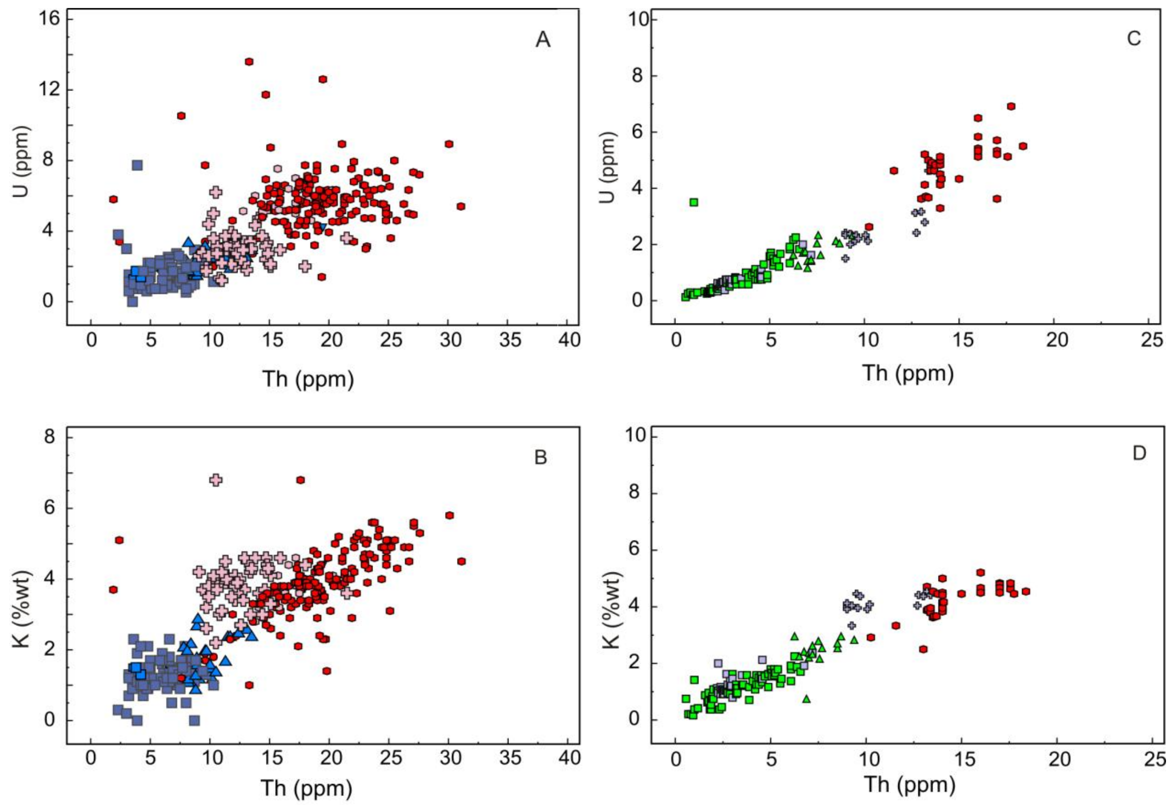

Figure 16. Th (ppm) vs. K (% wt), and U (ppm) obtained by gamma-ray spectrometry in this study (A and B) and geochemical data (C and D) from of Marques (1988) and Marques et al. (1989). Legend: as Figure 15 (for A and B) and Figure 13 (for C and D).

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