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BIMODAL FISSURAL VOLCANIC SUITES FROM THE PARANÁ BASIN (BRAZIL): K-Ar AGE, Sr-ISOTOPES AND GEOCHEMISTRY

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ABSTRACT

The stratoid acid volcanics of Ourinhos and Piraju (SP; northern Paraná basin) are relatively rich in incompatible elements (Chapecó type), and are closely associated with high-Ti (TiO_2 > 2 wt %) tholeiitic basalts rich in incompatible elements.

K-Ar ages on feldspar concentrates indicate that the acid volcanics and the overlying basalts were erupted around 135 m.y. ago.

The acid volcanics are characterized by relatively high initial $^{87}Sr/^{86}Sr$ ratios (Ro = 0.7076-0.7080), while the associated high-Ti basic rock-types have Ro ranging from 0.7059 to 0.7078. The highest Ro values appear consistent with relatively low (5-9%) degrees of contamination by crustal radiogenic (Ro ≅ 0.730) material(s)).

High-Ti (TiO_2 = 2.1-3.4 wt %) basalts have variable chemical compositions which reflect different primary melts, probably related to heterogeneous mantle material(s).

In general, the generation of the Chapecó acid melts appears to be in part consistent with assimilation-fractional crystallization processes, starting from the associated high-Ti basic rocks. An alternative model for the production of the Chapecó acid melts should be the melting of mafic granulites with appropriate composition(s), or of basalts trapped at the crust-mantle discontinuity, and corresponding in composition to the high-Ti basalts that flooded the northern regions of the Paraná basin.

RESUMO

As vulcânicas ácidas estratificadas de Ourinhos e Piraju (SP; parte setentrional da bacia do Paraná) são relativamente ricas em elementos incompatíveis (tipo Chapecó) e estão claramente associadas com basaltos toleíticos de alto-Ti (TiO_2 > 2% em peso), ricos em elementos incompatíveis.

Idades K-Ar em concentrados de feldspato indicam que as vulcânicas ácidas e os basaltos sobrejacentes foram extrudidas a cerca de 135 m.a.

As vulcânicas ácidas são caracterizadas por razões iniciais $^{87}Sr/^{86}Sr$ relativamente elevadas (Ro = 0,7076-0,7080), enquanto que as rochas básicas de alto-Ti associadas têm Ro de ≅ 0,7059 a 0,7078. Os valores de Ro mais elevados parecem consistentes com graus relativamente pequenos (5-9%) de contaminação por materiais radiogênicos crustais (Ro ≅ 0,730).

Basaltos de alto-Ti (TiO_2 = 2,1 - 3,4% em peso) apresentam composições químicas variáveis, que refletem fusões primárias diferentes, provavelmente relacionadas com materiais mantélicos heterogêneos.

Em geral, a geração das fusões ácidas tipo Chapecó parece ser, em parte, consistente com processos de cristalização fracionada-assimilação, a partir das rochas básicas de alto-Ti associadas. Um modelo alternativo para a produção das fusões ácidas Chapecó seria a fusão de granulitos máficos de composição apropriada, ou de basaltos aprisionados na discontinuidade crosta-manto e correspondendo em composição aos basaltos de alto-Ti que extrudiram nas regiões setentrionais da bacia do Paraná.

INTRODUCTION

Continental flood (plateau) volcanism from the Paraná basin has played an important role in the history of S. America-Africa continental break-up. The dominant volcanics are two-pyroxene tholeiitic basalts but significant quantity of closely associated acid rocks (rhyodacites and rhyolites), covering about 150,000 km², are also found preferentially in the eastern part of the Paraná basin, towards the continental margin (Fig. 1).

It is apparent that the genetic relationship between basalts and closely associated acid volcanics are of fundamental importance, mainly if we consider that in Paraná, as in Ethiopia and Karoo (S. Africa), the majority of the stratoid acid volcanism occurred just before the beginning of the major rifting processes (Bellieni *et al.*, 1986b; Piccirillo *et al.*, 1986).

Geochemical evidence (Bellieni *et al.*, 1984a, 1984b; Mantovani *et al.*, 1985a; Petrini *et al.*, 1986) has already shown the existence of at least two main distinctive mantle sources (high and low in TiO_2 and incompatible element contents) for the Paraná tholeiitic basalts, and also that the associated intermediate to acid volcanics can be modelled through assimilation-fractional crystallization processes at low pressure (<10 kb). It is also apparent that the acid volcanics can be clearly divided into two types: (1) high-Ti type: rich in incompatible elements (Chapecó type) and (2) low-Ti type: poor in incompatible elements (Palmas type).

In the present paper, focus will be given to some petrogenetic aspects of the high-Ti basalts, and their associated high-Ti Chapecó type acid volcanics.

Firstly, a small scale geochemical work on the samples from Ourinhos-Piraju area (southern São Paulo State, near the Paraná State boundary). This region was selected because it includes the northernmost known locality in which Chapecó type acid volcanics crop out, associated only with high-Ti basalts. Low-Ti basalts, and Palmas type acid volcanics were not identified in the selected area, a fact that simplifies the task of understand-

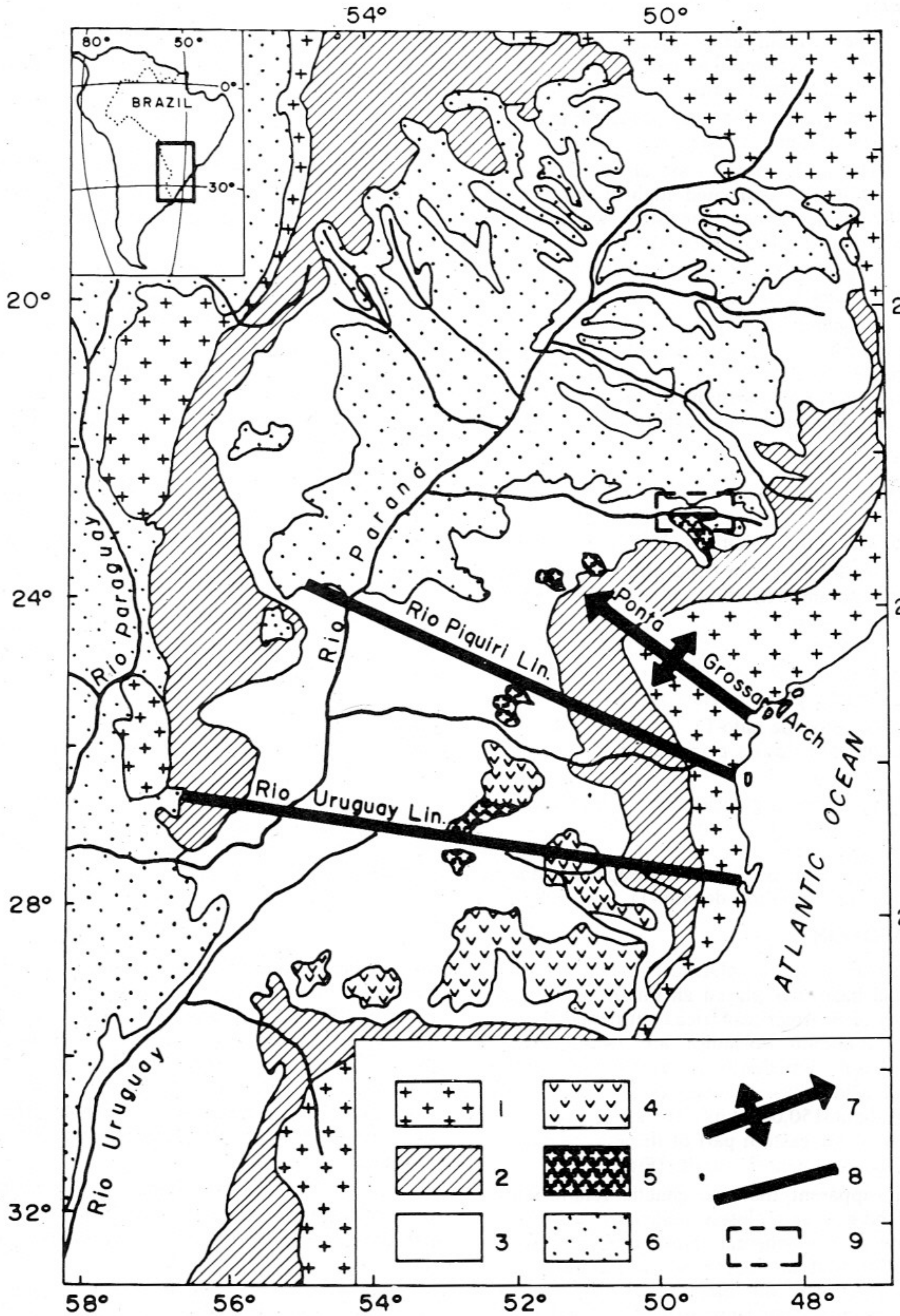

Figure 1 — Simplified geological sketch-map of Paraná basin (after Bellieni *et al.*, 1986b). 1 = pre-Devonian crystalline basement; 2 = pre-volcanic sediments (mainly Paleozoic); 3 = basic to intermediate flood volcanics (Serra Geral Formation: Lower Cretaceous); 4 = acid stratoid volcanics: 'Palmas type' (Serra Geral Formation); 5 = acid stratoid volcanics: 'Chapecó type' (Serra Geral Formation); 6 = post-volcanic sediments (mainly Upper Cretaceous); 7 = arch-type structure; 8 = tectonic and/or magnetic lineament and 9 = investigated region.

ing the relationships (geologic, stratigraphical, geochemical, isotopic and finally petrogenetic) between the basic and acid melts.

Secondly, in a larger scale, and by taking into account the results obtained for the Ourinhos-Piraju region, the comparative pattern of Sr isotopes will be examined for the high-Ti basalts and associated Chapecó type acid volcanics, as well as their correlation with major and trace element geochemistry. Such data will be evaluated by means of the processes involved in the generation of this bimodal basic-acid volcanic suite.

STRATIGRAPHY AND GEOCHEMICAL PROVINCIALITY OF THE PARANÁ VOLCANIC SUITES

The continental flood volcanics of the Paraná basin are of Lower Cretaceous age (140-120 m.y.; Amaral *et al.*, 1966; Cordani *et al.*, 1980; Creer *et al.*, 1965; Mantovani *et al.*, 1985b; Melfi, 1967; Sartori *et al.*, 1975), and cover an area of about 1.2×10^6 km^2. The volcanics flooded a Paleozoic basin elongated along NE-SW, essentially formed by sedimentary rocks of Devonian to Permian age.

The volcanics are given of dominant basalts (c. 90 vol. %) with subordinate intermediate (c. 7 vol. %) and acid (c. 3 vol. %) rock-types.

Geological and geochemical data (Piccirillo *et al.*, 1986) allow the Paraná basin to be divided into three main portions (Fig. 1): (a) *southern Paraná:* region south of the Rio Uruguay lineament; (b) *central Paraná:* region between Rio Uruguay and Rio Piquiri lineaments, and (c) *northern Paraná:* region north of the Rio Piquiri lineament.

In the *southern Paraná basin* the lower parts of the volcanic suites (Bellieni *et al.*, 1986b) are mainly composed of tholeiitic basalt types, while the upper portions are largely represented by rhyodacites and rhyolites (*Palmas type:* see later). The intermediate rock-types tend to be more concentrated between the lower (basic) and upper (acid) portions of the suite.

The *northern Paraná basin* is characterized by tholeiitic basalt types which, in the southeasternmost regions (present study) are overlain by scarce rhyodacites and rhyolites (Chapecó *type:* see later). Intermediate rock-types are virtually absent.

The *central Paraná basin* is composed of volcanic suites similar to those occurring in both the southern and northern Paraná. Lava suites including acid volcanics of Palmas and Chapecó types are found in relatively restricted areas (Bellieni *et al.*, 1986b). Intermediate rock-types are virtually absent. The central Paraná basin may therefore be considered a transitional zone between the northern and southern Paraná basin.

Recent studies (Comin-Chiaramonti *et al.*, 1983; Bellieni *et al.*, 1983, 1984a, 1984b, 1984c, 1986a, 1986b; Piccirillo *et al.*, 1986 and unpublished data) have demonstrated that the Paraná basalts are represented by two main rock-types showing important differences in chemical composition. They may be distinguished by their contrasting low (< 2 wt %) and high (> 2 wt %) TiO_2 and incompatible element (I.E.; e.g. P, Ba, Sr, La, Ce, Zr) contents.

In Table 1 the average compositions believed to be representative of the low- and high-Ti basalts are reported from southern, central and northern Paraná. In the same table are also included the average compositions of acid volcanics, namely Palmas (southern + central Paraná) and Chapecó (central + northern Paraná) types. The average compositions of Table 1 are derived from c. 650 selected analyses (Comin-Chiaramonti & Stolfa, unpublished data).

In general, the acid volcanics (Table 1) of Palmas type are relatively poor in TiO_2 and I.E., and are usually associated with basalts low in TiO_2 and I.E. (southern Paraná basin). Those of Chapecó type are comparatively rich in TiO_2 and incompatible elements, and are systematically associated with basalts high in TiO_2 and I.E. (northern Paraná basin) (Bellieni *et al.*, 1986b).

The laterally persistent sheet-like nature of acid volcanics suggests that they may be ignimbrites. Individual Palmas flows can be traced over 60 km, but textures typical of ignimbrites are not usually found. If the Paraná acid volcanics are ignimbrites, their high temperatures (over 1000°C; Bellieni *et al.*, 1986b), and relatively low volatile content may be responsible for very strong welding, leaving almost negligible pore-space.

GEOLOGICAL NOTES OF THE STUDIED AREA

The investigated area (northern Paraná basin) includes the border between São Paulo and Paraná States beween Ourinhos and Cerqueira Cesar to the north (latitude c. 23.00°), and between Carlópolis and Fartura to the south (latitude c. 23.30°) (Fig. 2).

The volcanics are mainly represented by stratoid basalts and Chapecó acid rock-types which overlain the Botucatu sandstones. The sequence of the volcanic suite is the following; from bottom to top: (1) "lower basalts" (thickness = 0-50 m); (2) slightly to strongly porphyritic rhyodacites (and rhyolites), (Chapecó type; thickness = 50-180 m), sometimes with thin basalt intercalations, and (3) "upper basalts" (thickness = 10-200 m). It is worth noting that sometimes the "lower basalts" are missing and therefore the Chapecó acid volcanics directly rest on the sedimentary basement. Many basic dykes trending NW-SE intrude the basement. Dyke age is believed to be of the same age of the associated volcanic rocks.

All the investigated region was affected by prevailing NW-SE faults which caused the acid

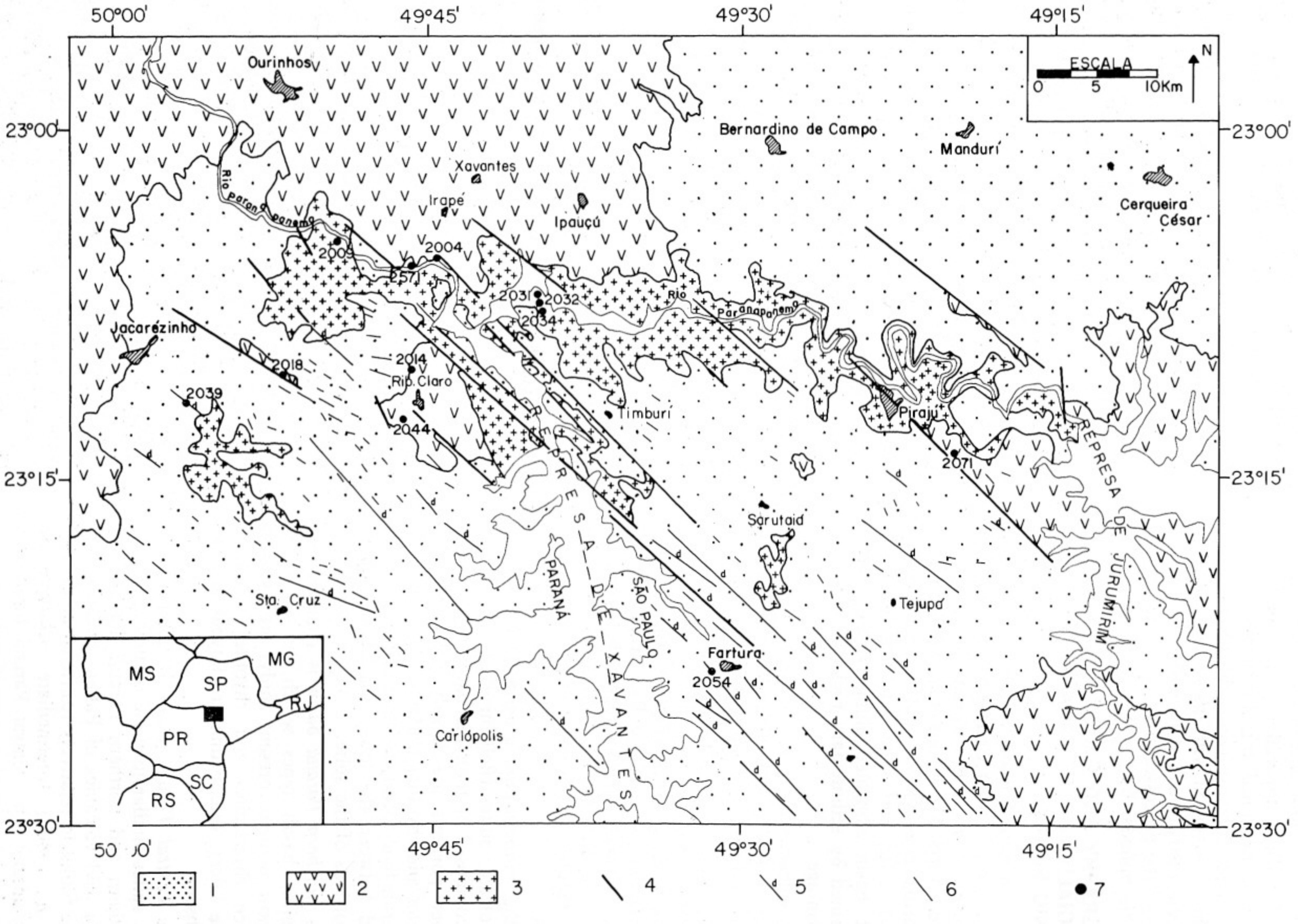

Figure 2 — Simplified geological sketch-map of the studied area (after Raposo, unpublished data). 1 = pre- and post volcanic sediments; 2 = stratoid basalts (Serra Geral Formation); 3 = stratoid Chapecó acid volcanics (Serra Geral Formation); 4 = fault; 5-6 = dykes (d) and associated structural lineament (6) and 7 = sample location.

Table 1 — Average major (wt %) and trace (ppm) element contents of low- (< 2 wt %) and high-Ti (> 2 wt %) basalts and acid volcanics (Palmas and Chapecó types) from the Paraná Basin. N = number of samples (loss on ignition lower than 2 wt %). Major element contents recalculated to 100% on volatile-free basis, and $Fe_2O_3/FeO = 0.15$.

	Southern Paraná (SPB)		Central Paraná (CPB)		Northern Paraná (NPB)		SPB+CPB	CPB+NPB
	LTiB (N = 62)	HTiB (N = 14)	LTiB (N = 104)	HTiB (N = 191)	LTiB (N = 15)	HTiB (N = 104)	Palmas (N = 104)	Chapecó (N = 51)
SiO_2	52.30	52.02	51.82	51.41	51.19	51.41	69.72	66.30
TiO_2	1.34	2.95	1.57	3.03	1.82	3.14	0.89	1.33
Al_2O_3	15.59	14.08	15.03	13.94	15.43	13.90	12.87	13.46
Fe_2O_3	1.46	1.61	1.64	1.75	1.60	1.80	0.72	0.83
FeO	9.74	10.77	10.97	11.74	10.66	12.01	4.72	5.56
MnO	0.18	0.17	0.21	0.21	0.20	0.21	0.10	0.13
MgO	5.61	4.88	5.07	4.33	5.16	4.07	1.13	1.31
CaO	10.05	8.89	9.79	8.89	10.18	8.76	2.56	2.95
Na_2O	2.51	2.63	2.72	2.76	2.56	2.78	2.95	3.49
K_2O	1.02	1.52	0.94	1.43	0.89	1.44	4.19	4.20
P_2O_5	0.20	0.48	0.24	0.51	0.31	0.48	0.25	0.44
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Cr	128	93	84	72	116	51	8	5
Ni	75	67	62	50	76	42	6	6
Ba	352	549	303	551	370	574	658	1117
Rb	29	30	27	31	17	28	182	113
Sr	231	497	222	434	303	420	120	356
La	20	38	18	37	19	34	54	91
Ce	47	80	45	82	50	81	108	180
Zr	133	233	129	241	139	240	286	643
Y	27	33	31	36	30	34	58	74

volcanics to occur at the same level of the underlying Botucatu sandstones.

SAMPLE SELECTION AND PETROGRAPHIC NOTES

The investigated samples are represented by high-Ti andesi-basalts (S. 2018, 2034, 2039, 2044 and 2071), latibasalt (S. 2054), tholeiitic andesite (S. 2014), rhyodacites (S. 2009, 2031 and 2032) and rhyolites (S. 2004 and 2571) (De La Roche *et al.*, 1980; Bellieni *et al.*, 1981). They were selected taking into account petrography (low phenocryst content and minimum degree of alteration), and chemistry (low values of loss on ignition and Fe_2O_3/FeO ratio). These samples are considered representative of the 'upper basalts' (S. 2014, 2018, 2044 and 2071), basalt intercalations (S. 2034) in Chapecó acid volcanics, mafic dykes (S. 2039 and 2054) and acid rock-types. Notably the tholeiitic andesite 2014 has a somewhat high (3.48 wt %) loss on ignition value but it was studied for Sr-isotopes since it is the only intermediate rock-type found in the entire northern Paraná basin.

The studied samples are characterized by phenocryst (0.5-2 mm) contents usually lower than 5-10% by volume (see Appendix).

The *basaltic* and *andesitic volcanics* contain

Table 2 — K-Ar ages of feldspar concentrates from Chapecó acid volcanics (S. 2031 and 2032) and high-Ti basalts (S. 2018 and 2034). See Fig. 2 for sample location.

	No. Lab.	% K	^{40}Ar rad. (10^{-6} cc/g)	^{40}Ar atm %	Age (m.y.)
2031	5706	2.487	13.45	13.15	134 ± 6
2032	5708	1.780	9.50	8.39	133 ± 6
2018	5709	0.385	1.88	36.20	122 ± 7
2034	5707	0.665	2.09	25.81	79 ± 3

phenocrysts and/or microphenocrysts (0.2-0.5 mm) of augite (Wo_{42-30}), plagioclase (An_{75-50}), scarce pigeonite (Wo_{12-6}), minor Ti-magnetite and ilmenite, and sporadic olivine, the latter completely altered. Plagioclase, augite, pigeonite, abundant Ti-magnetite and ilmenite usually make up the groundmass.

The *Chapecó acid volcanics* contain phenocrysts and/or microphenocrysts of plagioclase (An_{45-40}), augite (Wo_{34-32}), pigeonite (Wo_{10-8}), Ti-magnetite and apatite. Typically Chapecó rock-types have variable degree of crystallinity (obsidians are virtually absent), and with a groundmass composed of quartz, alkali fedspar (Or_{68-52}), plagioclase, pyroxenes, Ti-magnetite, ilmenite and glass (cf. Bellieni *et al.*, 1986b).

ANALYTICAL PROCEDURES

Major and trace element contents were determined by the X-ray fluorescence procedures described in Bellieni *et al.* (1983). Analyses are considered accurate to within 2.5% for major elements and better than 10% for trace elements.

The K-Ar analyses were obtained in the Geochronology Research Center (GRC) of the USP, and the methodology is described by Amaral *et al.* (1966), the only difference being the use of a calibrated pipette for the addition of the ^{38}Ar tracer. The overall analytical precision, at the time of the measurements, was of the order of 3%, in normal determinations.

Rb-Sr determinations, and Sr isotopic analyses, for the investigated rocks, were also carried out at the GRC of São Paulo University employing methodology described by Sato (1986). Rb and Sr determinations were made by X-ray fluorescence and individual precision of measurements is better than 2%. The results obtained at São Paulo (Table 3) compare with those obtained at Trieste University (Table 4) by the same methodology. A slight systematic difference concerns Sr contents and this is probably due to a different procedure of interference correction operated at Trieste University.

Sr-isotopic determinations were obtained on unspiked samples, in a Varian-MAT TH-5 mass spectrometer. Repeated measurements of $^{87}Sr/^{86}Sr$ ratios on standard samples yielded the following results:

Sr carbonate (NB5-987) = 0.71024 ± 0.00006 (2σ)
Sr carbonate (E and A) = 0.70800 ± 0.00006 (2σ)

^{40}K and ^{87}Rb decay constants, as well as the necessary isotopic ratios for K, Rb, Sr and Ar are from Steiger & Jaeger (1978).

K-Ar AGES

K-Ar ages (Table 2) were determined on plagioclase concentrates from basalts (S. 2018 and 2034), and on feldspar concentrates from rhyodacites (S. 2031 and 2032).

The four samples selected for K-Ar determinations were among the coarsest available in grain size, and an attempt to separate feldspar crystals was made in all cases. The microscope examination of the final concentrates indicated that a reasonable separation was obtained in the case of the feldspars from acid rock samples, and the basic rock-type 2018, but only a concentration of plagioclase fragments was possible for the basalt type 2034.

Table 3 — Rb-Sr data on bulk rock from high-Ti volcanic suite from northern Paraná basin. See Fig. 2 for sample location.

	No. Lab.	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$(^{87}Sr/^{86}Sr)^o$ (135 m.y.)
(1) 2018	7992	26.0	310.9	0.242	0.70718	0.7067 (± 1)
(2) 2071	7993	39.7	501.1	0.229	0.70640	0.7060 (± 1)
(3) 2044	7991	34.5	513.5	0.196	0.70637	0.7060 (± 3)
(4) 2034	7990	41.7	314.9	0.384	0.70661	0.7058 (± 2)
(5) 2039	7994	35.5	562.6	0.183	0.70811	0.7078 (± 1)
(6) 2054	7995	50.9	531.5	0.277	0.70640	0.7059 (± 1)
(7) 2014	7996	54.4	594.1	0.265	0.70642	0.7059 (± 2)
(8) 2031	7988	145.4	340.6	1.235	0.70998	0.7076 (± 1)
(9) 2032	7989	131.7	309.4	1.232	0.71018	0.7078 (± 2)
(10) 2009	7987	142.8	317.5	1.302	0.71046	0.7980 (± 1)
(11) 2004	7985	144.8	305.7	1.371	0.71037	0.7077 (± 1)
(12) 2571	7986	143.0	285.8	1.448	0.71029	0.7075 (± 3)

(1)-(4) = basaltic flows; (5)-(6) = basalt dykes; (7) = andesitic flow; (8)-(10) = rhyodacitic flows, and (11)-(12) = rhyolitic flows

The analytical data relative to K-Ar determinations are shown in Table 2. K and ^{40}Ar concentrations are within adequate range of detection, and the atmospheric correction is not critical, hence the apparent age results are of good analytical quality. Nevertheless, they are not entirely concordant, within experimental errors, and some comments on geological interpretation are necessary.

Preliminarly, as demonstrated by Amaral *et al.* (1966), K-Ar determinations on whole-rock basaltic rocks can be affected by argon loss in a way that cannot be adequately monitored by petrographic studies. The same effect was sometimes verified even when plagioclase concentrates were employed for the determination. In our case, argon loss seems to be the case for sample 2018, whose K-Ar apparent age (122 m.y.) is somewhat younger than the acid rock-types (133-134 m.y.), but certainly is the case for sample 2034, whose K-Ar age (79 m.y.) is dramatically lower than any other reported result for the Paraná basin basaltic rocks. Since all the volcanic rocks in the Ourinhos-Piraju region are believed to be essentially

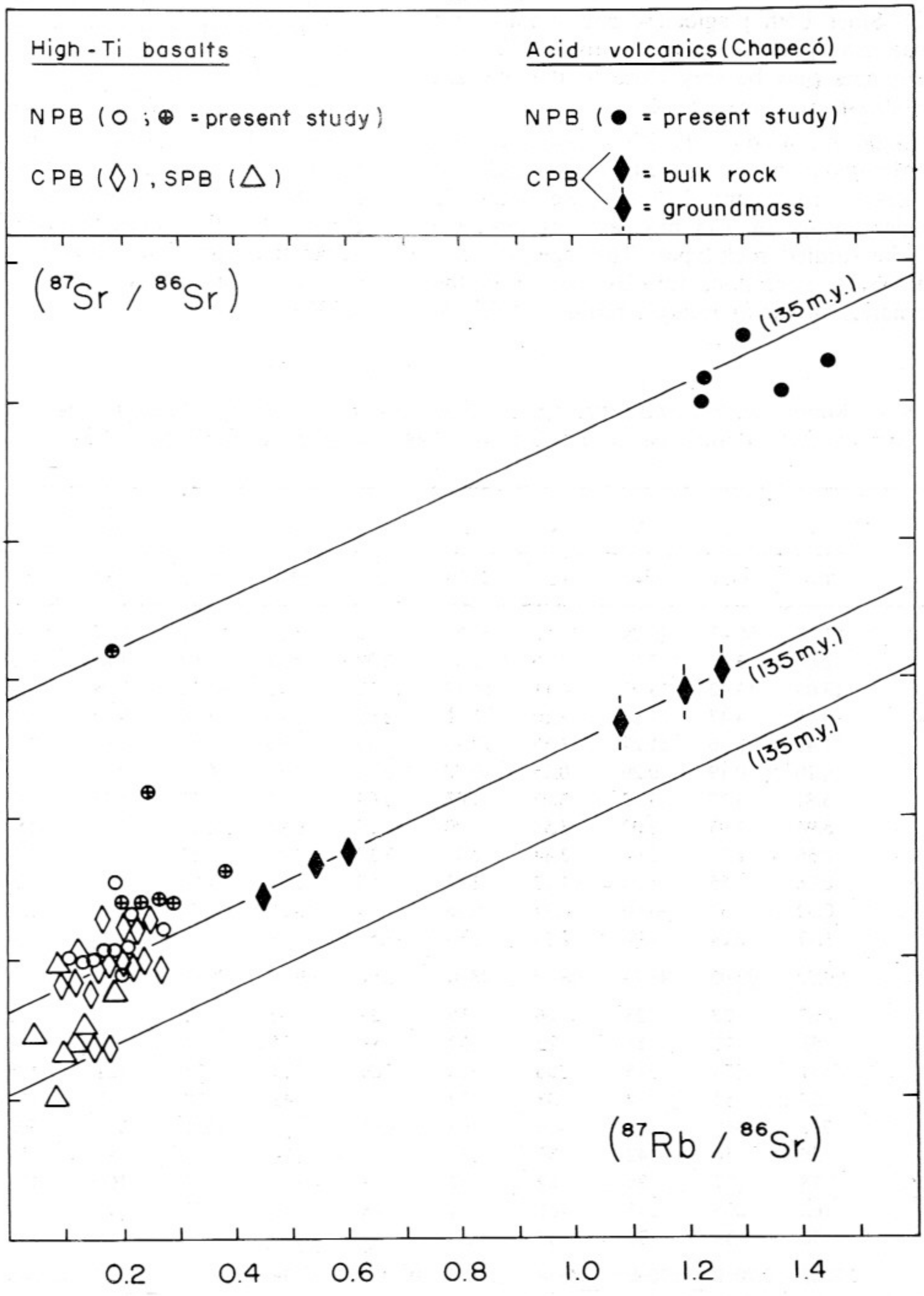

Figure 3 — $^{87}Rb/^{86}Sr$ vs $^{87}Sr/^{86}Sr$ for high-Ti basaltic rock-types and Chapecó rhyodacites and rhyolites. NPB = northern Paraná basin, CPB = central Paraná basin and SPB = southern Paraná basin. Source data: Mantovani *et al.* (1985a, 1985b); Civetta & Petrini (personal communication) and present study.

of same age (there is no geological evidence of any relevant hiatus in the volcanic sequence), the K-Ar result on sample 2034 shall not be considered in the geologic interpretation, also considering that it corresponds to a basaltic flow intercalated within the acid sequence (i.e. samples 2031 and 2032).

The two K-Ar results on feldspar from rhyodacites are concordant, and should be geologically significant. It must be pointed out that the analysed mineral concentrates are composed by substantial quantity of groundmass alkali feldspar (Or_{68-52}) and minor amount of plagioclase (An_{45-40}). Since both plagioclase and sanidine are adequate in respect to argon retentivity, the K-Ar apparent ages may be very close to the real age of crystallization of the acid melts.

Taking into account the Rb-Sr results obtained by Mantovani *et al.* (1985b) for Chapecó type acid volcanics from central Paraná, we assume in this paper an age of 135 m.y. as representative for all the studied rock-types. This age was employed in the corrections for Rb content in the determination of the Sr isotopic ratios of Table 3.

Sr-ISOTOPES

The investigated basic and intermediate rock-types have $^{87}Sr/^{86}Sr$ initial (135 m.y.) ratios (Ro) ranging from 0.7059 to 0.7078, while the acid volcanics have Ro in a narrow range, i.e. 0.7076-0.7080 (Table 3).

Three samples of Chapecó acid volcanics, belonging to the central Paraná basin, were investigated by Mantovani *et al.* (1985b). The Ro values of such Chapecó volcanics, calculated using Rb-Sr data relative to plagioclase, groundmass and whole rock, range from 0.7056 to 0.7057. These last Ro values are quite similar to those relative to high-Ti basalts, namely northern Paraná basin: Ro = 0.7055-0.7062 (Mantovani *et al.*, 1985a; Civetta & Petrini, personal communication), central Paraná basin: Ro = 0.7051-0.7060 (Mantovani *et al.*, 1985a; Civetta & Petrini, personal communication) and southern Paraná basin: Ro = 0.7048-0.7065 (Mantovani *et al.*, 1985a). In conclusion, the Ro values of high-Ti basalts, usually associated with Chapecó acid volcanics, exhibit a narrow range of variations, from 0.7051 to 0.7062.

Table 4 — Major (wt %) and trace (ppm) element contents of high-Ti basic and Chapecó acidic rock-types from northern Paraná basin. 5 and 6 = dykes. Ro = initial (135 m.y.) $^{87}Sr/^{86}Sr$ ratio.

	1	2	3	4	5	6	7	8	9	10	11	12
	2018	2071	2044	2034	2039	2054	2014	2031	2032	2009	2004	2571
SiO_2	51.19	50.43	49.99	49.98	49.62	53.40	54.66	64.18	66.17	66.81	65.43	68.50
TiO_2	2.09	3.31	3.38	2.46	2.57	2.99	2.82	1.04	1.01	1.15	1.07	1.09
Al_2O_3	15.05	13.42	13.95	14.11	14.17	13.72	14.17	14.16	13.04	13.16	13.24	11.76
Fe_2O_3	0.95	4.47	1.54	2.10	3.16	2.90	1.70	4.29	3.94	2.76	4.53	4.64
FeO	11.49	8.46	11.27	11.52	10.10	8.35	8.05	1.82	2.00	2.87	1.62	1.38
MnO	0.20	0.19	0.20	0.25	0.20	0.18	0.17	0.17	0.11	0.14	0.12	0.11
MgO	3.81	3.77	3.52	3.07	4.03	3.03	2.24	1.76	1.33	1.02	1.16	1.03
CaO	8.94	7.93	8.02	8.56	9.20	7.05	6.97	2.97	2.70	2.66	2.48	2.33
Na_2O	2.55	2.71	3.06	2.44	2.33	3.17	2.89	3.47	3.57	3.30	3.06	3.08
K_2O	0.96	1.55	1.25	1.12	1.26	2.08	1.28	4.33	4.29	4.37	4.91	4.26
P_2O_5	0.32	0.57	0.60	0.37	0.38	0.63	0.68	0.40	0.37	0.40	0.37	0.29
L.O.I.	1.47	2.24	1.96	2.74	1.85	1.56	3.48	1.21	1.26	1.04	1.83	1.39
Sum	99.02	99.05	98.74	98.72	98.87	99.06	99.11	99.80	99.79	99.68	99.82	99.86
Cr	82	22	23	66	66	29	22	2	1	2	3	4
Ni	57	31	31	29	52	31	24	7	6	7	5	5
Ba	391	553	545	500	498	709	715	1297	1101	1128	1140	1026
Rb	23	31	32	33	32	45	42	138	132	136	151	140
Sr	298	460	480	324	403	493	544	331	317	300	308	278
La	20	36	42	30	23	52	54	88	87	85	83	72
Ce	58	77	96	62	67	97	113	177	166	174	178	147
Zr	162	263	257	181	169	348	346	589	547	585	588	494
Y	30	39	35	38	31	44	38	81	61	63	60	58
Ro	0.7067	0.7060	0.7060	0.7058	0.7078	0.7059	0.7059	0.7076	0.7078	0.7080	0.7077	0.7075

1-4 = tholeiitic andesi-basalts (flows); 5 = tholeiitic andesi-basalt (dyke); 6 = latiandesite (dyke); 7 = tholeiitic andesite (flow); 8-10 = rhyodacites (flows); 11-12 = rhyolites (flows)

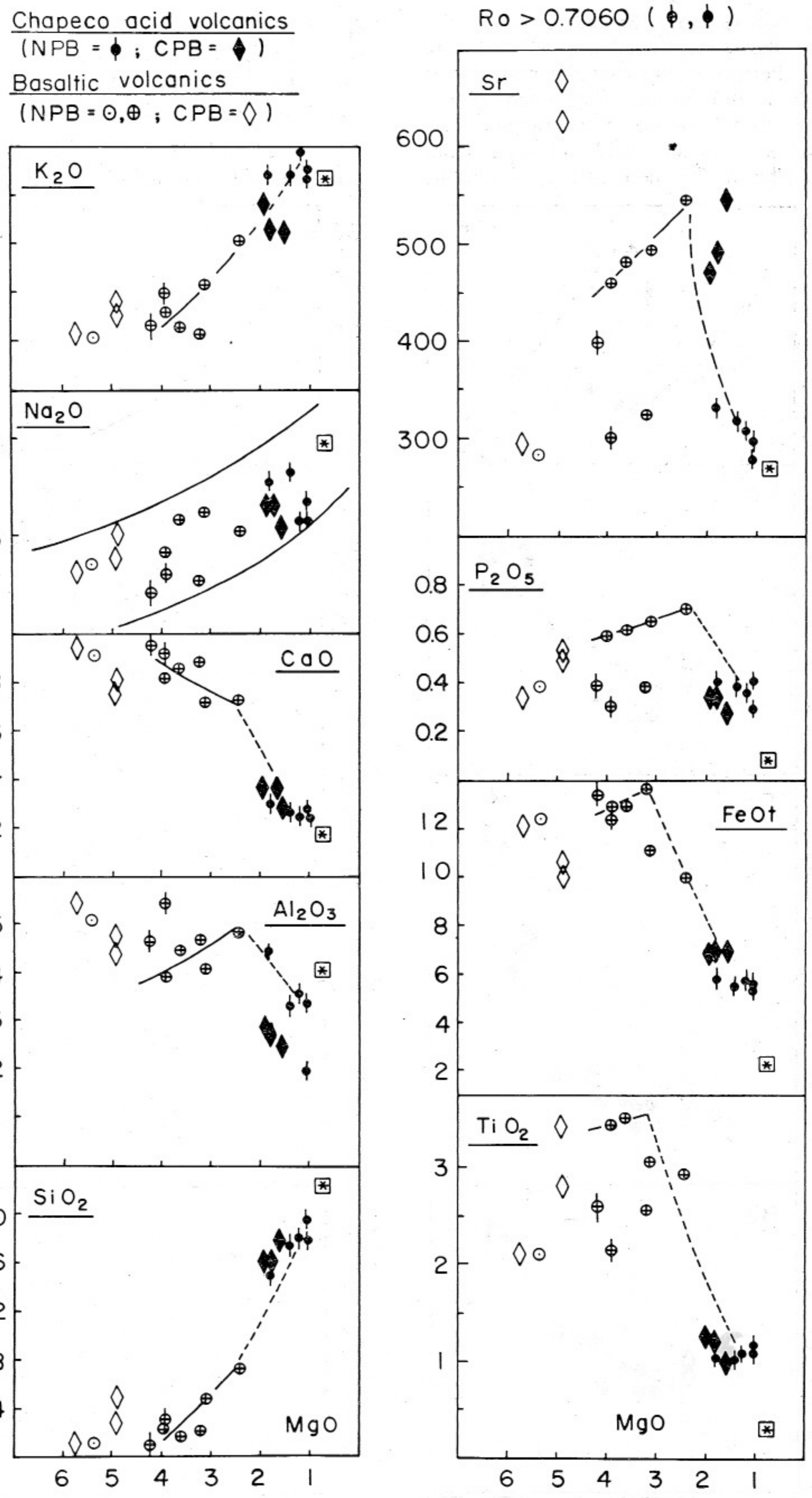

Figure 4 — MgO (wt %) vs SiO_2, Al_2O_3, CaO, Na_2O, K_2O, TiO_2, FeO_t, P_2O_5 (wt %) and Sr (ppm). Ro = initial (135 m.y.) $^{87}Sr/^{86}Sr$ ratio; NPB and CPB = northern and central Paraná basin, respectively. Asterisk = average composition of granitic rock-types from crystalline basement from central Paraná (unpublished data). Solid and dashed curves refer to basalt-rhyolite evolution discussed in the text. Source data: Mantovani *et al.* (1985a, 1985b) and present study. Major element contents normalized to 100% on a volatile-free basis.

A $^{87}Rb/^{86}Sr$ vs $^{87}Sr/^{86}Sr$ diagram (Fig. 3), including the above mentioned unpublished data by Civetta & Petrini, shows that the majority of high-Ti (> 2 wt %) basalts distributed in the entire Paraná basin have Ro in the range 0.705-0.706, as do the Chapecó acid volcanics from central Paraná basin. On the contrary, two basalt rock-types and all the Chapecó acid volcanics from northern Paraná, here investigated, have somewhat higher Ro values (0.707-0.708). These last Sr-isotope data suggest that the role of contamination has to be considered in the petrogenesis of the basic-acid magmatic suite.

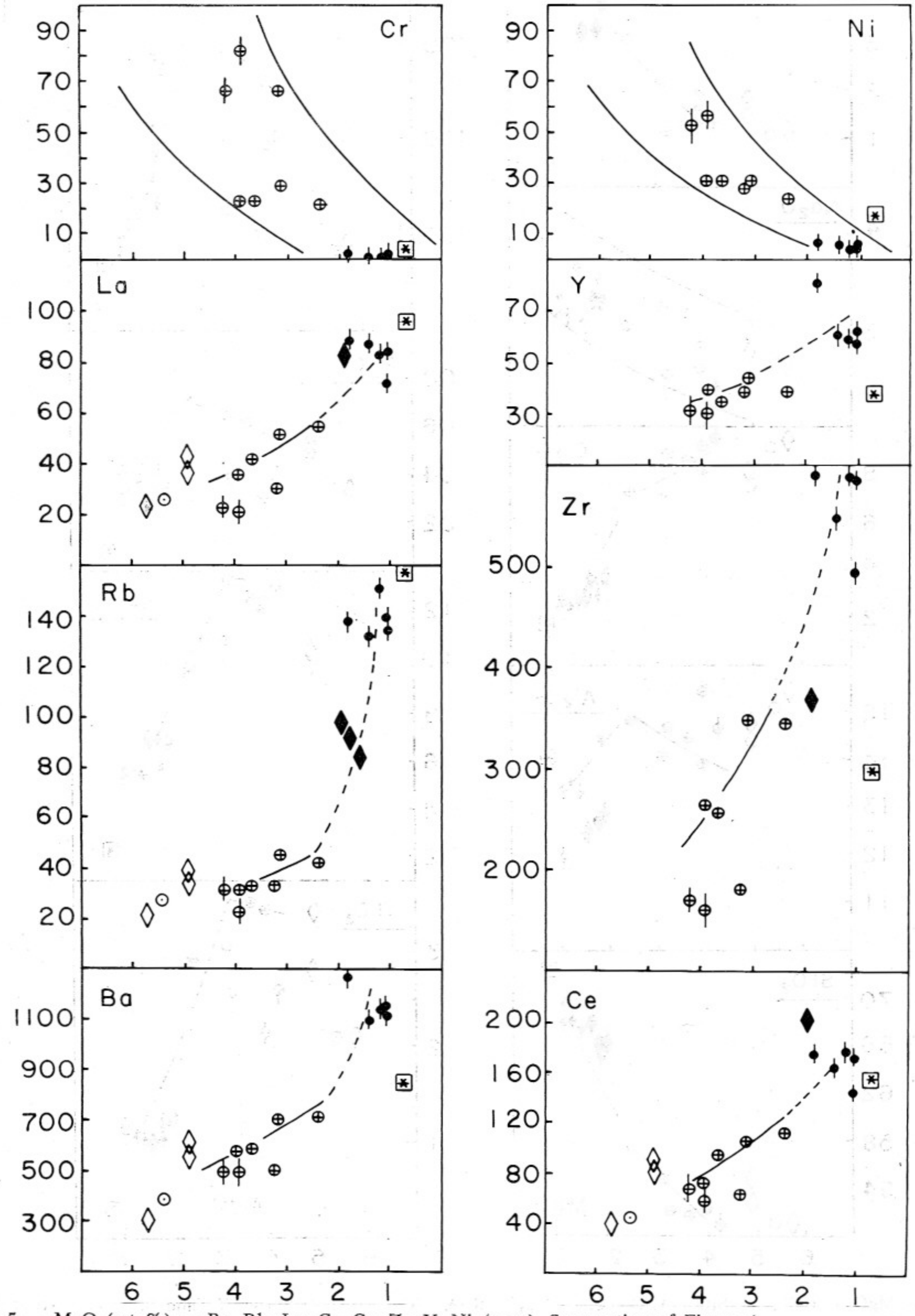

Figure 5 — MgO (wt %) vs Ba, Rb, La, Cr, Ce, Zr, Y, Ni (ppm). See caption of Figure 4.

PETROGENETIC ASPECTS

Basalt and intermediate rock-types

The investigated basic rock-types (Table 4), as the majority of the high-Ti basalts of the entire Paraná basin, are characterized by relatively low atomic $Mg/Mg + Fe^{2+}$ ratios ($mg \leqslant 0.50$), and therefore they are representative of evolved melts (Piccirillo *et al.,* 1986).

The studied high-Ti basalts and those from central Paraná (Mantovani *et al.,* 1985a) show chemical diversity which in some cases is accompanied by important variations of Ro (0.705-0.708), while in other cases Ro is virtually constant (c. 0.706).

High-Ti basalts with Ro lower than 0.7060 can be distinguished (Figs. 4 and 5) into two groups characterized for similar MgO content, by distinct different concentrations of TiO_2 and incompatible elements (I.E.) (e.g. P, Ba, La, Ce, Sr, Zr). In general the basalts with TiO_2 higher than 2.8 wt % have higher contents of I.E., relative to those of basalts with comparatively low TiO_2 content (2.0-2.6 wt %). It is apparent that such chemical differences (up to two times) cannot be simply explained by means of fractional crystallization (up to 50%), considering that both groups of high-Ti basalts have similar major-element chemistry. Moreover, the increase of Sr content for the basalts with the highest TiO_2 content is not compatible with the extraction of large amounts of plagioclase. Fractionation of other mineral assemblages such as eclogite seems unlikely, due to the lack of depletion in Y. Instead, fractional crystallization processes may account for the chemical variability within each basalt group.

The transition from high-Ti (> 3 wt %) basalts to tholeiitic andesites (similar to S. 2014; Ro = 0.7059) appears to be compatible for major and trace elements (Table 5) with the extraction of about 36% of solid composed by olivine (6.1%), plagioclase (46.0%), clinopyroxene (32.4%) and Ti-magnetite (15.5%) (cf. solid curves of Figs. 4 and 5).

All the data (cf. Piccirillo *et al.,* 1986) for the investigated high-Ti basalts point to the existence of primary chemical differences which may be related to different degrees of partial melting of an homogeneus spinel or garnet peridotite source, or for similar degrees of melting to heterogeneous mantle source.

High-Ti basalts with Ro higher than 0.7060 belong to the basalt group with relatively low content of incompatible elements. These two basic rock-types do not show distinct chemical behaviour relative to the basalt analogues with Ro < 0.7060. If we assume Ro = 0.730 for a granitic contaminant, and Ro = 0.7058 for an "un-

Table 5 — Fractionation model for basalt-andesite-rhyolite transitions relative to northern Paraná basin (Table 6). Res^2 = sum of squares of major element residuals; F = fraction of residual liquid; Ol = olivine; Cpx = Ca-rich pyroxene; Mt = Ti-magnetite; Ap = apatite.

	N1—N2 (1)	N2—N3 (2)	N3—N4 (3)	N1—N3 (4)
Ol	2.18			0.73
Cpx	11.65	13.75	0.38	21.85
Pl	16.58	25.69	9.39	31.92
Mt	5.58	6.07	1.17	9.62
Ap		0.51	0.06	0.88
Sum	35.99	46.02	11.00	65.00
Res^2	0.63	2.32	0.95	0.54
F	0.64	0.35	0.31	0.35
Calculated/observed element abundances				
Cr	0.17	1.47	0.57	0.21
Ni	0.43	1.58	0.95	0.69
Ba	1.06	0.92	1.16	0.97
Rb	1.14	0.53	1.13	0.59
Sr	0.91	1.65	0.96	1.09
La	1.07	1.03	1.19	1.04
Ce	1.12	1.04	1.17	1.09
Zr	1.05	0.96	1.16	0.99
Y	1.36	0.88	1.21	1.16
K	1.29	1.73	1.14	0.94
P	1.29	1.73	1.12	1.17

Olivine: Fo_{66} = (1), (4)
Plagioclase: An_{58} = (1), (4); An_{56} = (2); An_{42} = (3)
N1 - N2 = basalt → andesite; N2 - N3 = andesite → rhyodacite
N3 - N4 = rhyodacite → rhyolite; N1 - N3 = basalt → rhyodacite

contaminated" high-Ti basalt, about 5% of radiogenic crustal component is required for obtaining a contaminated basalt with Ro = 0.7070. Such relatively low degree of contamination, as well as small chemical differences in primary basalt melts may, at least in part, account for the virtual absence of chemical (major and trace elements) distinctive features for the contaminated high-Ti basalts.

We wish to emphasize that for the first time in northern Paraná basin high-Ti basalts with relatively high Sr-isotope ratios were detected, a fact which suggests contamination by crustal material(s).

Chapecó acid volcanics

Mass balance calculations (Tables 5 and 7) and the virtual absence of intermediate rock-types suggest that Chapecó acid melts may be obtained by fractional crystallization directly from high-Ti basalts. The calculated residual liquid fraction for the Chapecó acid melt parent (F = 0.35) is reasonable considering that the adopted basalt is somewhat evolved (mg = 0.37 for Fe_2O_3/FeO = 0.15).

The distinctly high initial Sr-isotope ratios (Ro = 0.7075-0.7080) of the Chapecó acid volcanics from northern Paraná, compared with those of the coexisting high-Ti basalts (Ro = 0.705-0.706; cf. Fig. 3), and those of Chapecó analogues from central Paraná (Ro = 0.705-0.706) clearly indicate the possibility of a crustal radiogenic component in the genesis of the acid melts from northern Paraná. Assuming a granitic contaminant with Ro = 0.730 and "uncontaminated" Chapecó acid melt with Ro = 0.7058, the genesis of contaminated (Ro = 0.7080) Chapecó acid melt requires about 9% of contaminant. It is apparent from variation diagrams (Figs. 4 and 5) that such low degree of contamination cannot be responsible for significant chemical changes.

In terms of assimilation-fractional crystallization model (AFC; De Paolo, 1981), we note (Fig. 6) that the evolution from high-Ti basalt (Ro

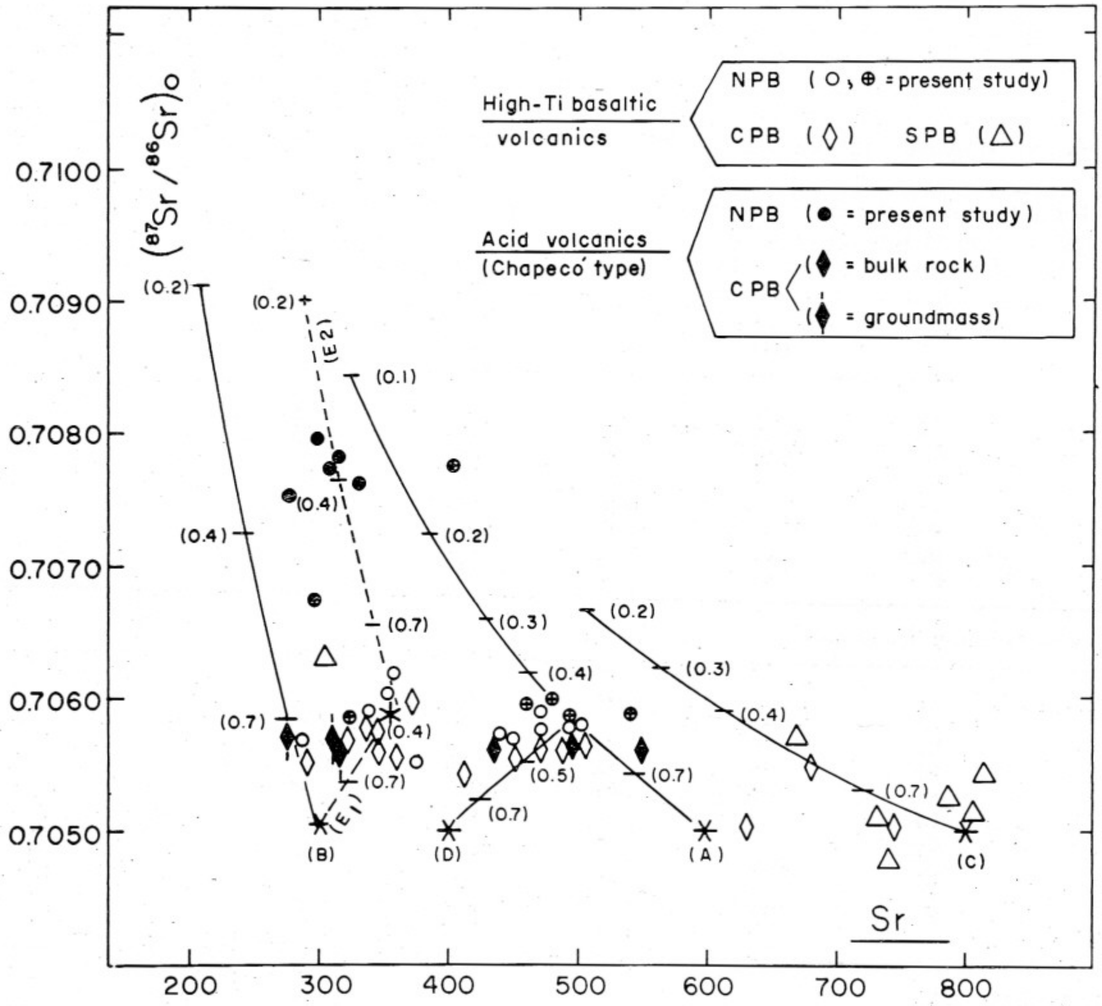

Figure 6 — Initial (135 m.y.) $^{87}Sr/^{86}Sr$ vs Sr (ppm) content. Asterisk = parent basalt; contaminant: Sr = 250 ppm, $^{87}Sr/^{86}Sr$ = 0.730. (A): bulk distribution coefficient for Sr ($\bar{D}_{Sr}$) = 1.2, assimilation/fractionation rate (AFR) = 0.10; (B): $\bar{D}_{Sr}$ = 1.2, AFR = 0.10; (C): $\bar{D}_{Sr}$ = 1,2, AFR = 0.10; (D) $\bar{D}_{Sr}$ = 0.8, AFR = 0.05; (E1): $\bar{D}_{Sr}$ = 0.8, AFR = 0.05 and (E2): $\bar{D}_{Sr}$ = 1.1, AFR = 0.10. In brackets the fraction of residual liquid.

Table 6 — Bulk-rock compositions used for mass balance calculations (Table 4).

	N1	N2	N3	N4
SiO_2	52.06	57.26	66.64	68.87
TiO_2	3.46	2.95	1.06	1.14
Al_2O_3	14.18	14.84	13.76	12.69
FeO_t	13.02	10.04	5.74	5.56
MnO	0.20	0.18	0.13	0.13
MgO	3.77	2.35	1.45	1.05
CaO	8.27	7.30	2.78	2.55
Na_2O	2.99	3.03	3.44	3.25
K_2O	1.45	1.34	4.61	4.40
P_2O_5	0.60	0.71	0.39	0.36
Sum	100.00	100.00	100.00	100.00
Cr	23	22	2	3
Ni	31	24	6	6
Ba	549	715	1179	1077
Rb	32	42	140	138
Sr	470	544	319	289
La	39	54	86	79
Ce	87	113	74	161
Zr	260	346	575	539
Y	37	38	67	61

N1 = andesi-basalt; N2 = andesite
N3 = rhyodacite; N4 = rhyolite

= 0.7050; cf. Mantovani *et al.*, 1985a) to Chapecó acid volcanics is consistent with a two-stages evolution. The first stage (basalt evolution) requires a bulk distribution coefficient for Sr ($\overline{D}_{Sr}$) of about 0.8 and the assimilation/crystallization rate (ACR) is 0.05, while the second stage (basalt-rhyodacite evolution) is characterized by $\overline{D}_{Sr}$ of 1.2 and ACR = 0.10 (cf. Bellieni *et al.*, 1986b; Petrini *et al.*, 1986).

The generation of acid volcanics (Chapecó and Palmas types) by fractional crystallization associated with crustal contamination conflicts wich the relative absence of intermediate rock-types ("silica gap": 54-56 to 63-65 wt %) and with the confinement of the acid volcanics towards the continental margin. This suggests as a plausible alternative that the Paraná acid volcanics derived by melting of lower crustal material of basic composition. Such material could be represented by mafic granulites of different compositions, or by basalts trapped at the crust-mantle discontinuity (Betton & Cox, 1979). In this case these basalts should correspond in composition to the contrasting low- and high-TiO_2 basalts from which derived Palmas (southern Paraná) and Chapecó (northern Paraná) acid volcanics, respectively. In addition, the primary Palmas and Chapecó acid melts underwent crustal contamination during their ascent to the surface.

Table 7 — Distribution coefficients used in this paper for olivine (Ol), Ca-rich pyroxene (Cpx), plagioclase (Pl), Ti-magnetite (Mt) and apatite (Ap).

	Ol/Liq	Cpx/Liq	Pl/Liq	Mt/Liq	Ap/Liq
Cr	2.8	5.3	0.08	20	0.04
Ni	10.0	3.0	0.04	12	0.04
Ba	0.01	0.02	0.50	0.29	0.08
Rb	0.02	0.03	0.07	0.18	0.04
Sr	0.01	0.1	1.8*	0.15	0.06
La	0.02	0.02	0.15	0.29	20.5
Ce	0.02	0.02	0.17	0.34	24.5
Zr	0.06	0.27	0.20	0.40	3.0
Y	0.06	0.27	0.20	0.40	8.0

* 2.5 value used for acid rock modelling

SUMMARY AND CONCLUSIONS

1. The acid volcanics of the northern Paraná basin (Chapecó type) are relatively rich in incompatible elements (e.g. Ba, La, Ce, Sr, Zr) and are closely associated with high-Ti (> 2 wt %) basalts relatively rich in incompatible elements. On the contrary, the acid volcanics of the southern Paraná basin (Palmas type) are relatively poor in incompatible elements and result closely associated with low-Ti (< 2 wt %) basalts relatively poor in incompatible elements. Both suites (high-Ti basalts-Chapecó acid volcanics, and low-Ti basalts-Palmas acid volcanics) are found in the transitional zone of central Paraná.

2. The significant radiometric (K-Ar) ages of the acid volcanics and associated basalts from northern Paraná range from 134 to 122 m.y.. An age of 135 m.y. for the Chapecó acid volcanics is believed to be more probable taking into account the Rb-Sr results obtained for the Chapecó acid analogues from the central Paraná basin (Mantovani *et al.,* 1985b).

3. The Chapecó acid rock-types and some associated basalts from the northern Paraná basin have initial $^{87}Sr/^{86}Sr$ values (Ro) relatively high (0.7076-0.7080 and 0.7067-0.7078, respectively), while the Chapecó analogues from central Paraná and the great majority of high-Ti basalts from the entire Paraná basin have relatively low Ro values (0.7049-0.7060). This suggests, especially for the Chapecó acid volcanics from northern Paraná, the intervention of a radiogenic crustal contaminant (9 and 5% for the acid and basic contaminated rock-types, respectively).

4. High-Ti (> 2 wt %) basalts from northern and central Paraná have variable compositions which reflect different primary melts, probably related to heterogeneus mantle sources.

5. The evolution from high-Ti basalts to Chapecó rhyodacites from northern Paraná basin appears consistent with assimilation-fractional crystallization (AFC) model, as found for low-Ti basalt - Palmas rhyolite suite from southern Paraná basin (Mantovani *et al.,* 1985a). An important difference is that in southern Paraná basin the evolution from basic to acid melts requires an assimilation/fractionation rate (AFR) of 0.4 (Mantovani *et al.,* 1985a), while in northern Paraná basin the transition from basic to acid melts requires AFR = 0.1. This indicates that the effects of crustal contamination were probably more important in southern Paraná, and arises the possibility that the high-Ti basalts may also be crustally contaminated (Ro = 0.7049-0.7060). High-Ti basalts have high (up to 900 ppm) Sr content which requires relatively large amounts of crustal strontium to produce a significant variation in their $^{87}Sr/^{86}Sr$ ratios (cf. Mantovani *et al.,* 1985a).

6. An alternative model for the generation of Chapecó (and Palmas) acid melts may be found in the melting of mafic granulites of appropriate composition(s), or of basalts trapped at the crust-mantle discontinuity and corresponding in composition to high-TiO_2 (and low-TiO_2) basalts that flooded the northern (and southern) Paraná basin (cf. Betton & Cox, 1979 for Karoo Province, S. Africa).

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APPENDIX

PETROGRAPHICAL NOTES AND MODAL ANALYSES

Abbreviations: 01 = olivine, cpx = augite, pig = pigeonite, op = Ti-magnetite and ilmenite, pl = plagioclase, qz = quartz, af = alkali feldspar, ap = apatite.

Others: macrophenocryst > 2 mm, phenocryst = 0.5 – 2.0 mm and microphenocryst = 0.2 – 0.5 mm.

Tholeiitic andesi-basalts

2018 — Phenocrysts (av. size = 0.8 mm): pl. (11.8%) and cpx (7.0%); microphenocrysts: pl (11.9%), cpx (6.5%), pig (0.3%), 11 (0.5%) and op (0.6%). Groundmass: pl, cpx, pig, op and glass.

2071 — Phenocrysts: (av. size = 0.6 mm): pl (4.7%), cpx (2.0%) and op (1.6%); microphenocrysts: pl (13.9%), cpx (7.8%), pig (0.4%), ol (0.7%) and op (2.4%). Groundmass: pl, cpx (pig) and op.

2044 — Phenocrysts (av. size = 0.6 mm): pl (0.9%); microphenocrysts: pl (10.8%), cpx (0.9%), pig (0.2%) and op (0.8%). Groundmass: pl, cpx, pig and op.

2034 — Phenocrysts (av. size = 0.8 mm): pl (14.8%) and cpx (7.5%); microphenocrysts: pl (9.6%), cpx (6.2%), pig (0.5%) and op (0.6%). Groundmass: pl, cpx, pig, op and glass.

Latiandesite

2039 (dyke) — Doleritic texture. Mineral assemblage: pl, cpx, pig and op.

Tholeiitic andesite

2014 — Phenocrysts (av. size = 0.8 mm): pl (11.7%), cpx (1.1%) and op (0.6%); microphenocrysts: pl (11,5%), cpx (6.4%), pig (0.4%) and op (2.0%) and op (0.2%). Groundmass: pl, cpx, pig, op and glass.

Rhyodacites

2031 — Phenocrysts (av. size = 0.7 mm): pl (1.3%), cpx (0.6%) and op (1.2%); microphenocrysts: pl (3.6%), cpx (0.8%), pig (0.3%), op (0.5%), and ap (2.0%). Groundmass: af + qz, cpx, pig, pig, and op.

2032 — Phenocrysts (av. size = 0.6 mm): pl (2.8%), cpx (0.9%) and op (0.3%); microphenocrysts: pl (6.1%), cpx (0.4%), pig (0.2%), op (0.7%) and ap (2.0%). Groundmass: af + qz, cpx, pig, pl and op.

2009 — Macrophenocrysts (av. size = 2.3 mm): pl (2.7%); phenocrysts (av. size = 0.7 mm): pl (2.0%), cpx (0.3%), op (0.2%) and ap (0.2%); microphenocrysts: pl (2.4%), cpx (0.7%), pig (0.3%) and op (1.0%). Groundmass: af + qz, cpx, pig, pl, op and glass.

Rhyolites

2004 — Macrophenocrysts (av. size = 2.4 mm). pl (1.2%); phenocrysts (av. size = 0.8 mm): pl (2.2%), cpx (0.6%) and op (0.3%); microphenocrysts: pl (6.7%), cpx (1.5%), pig (0.3%), op (1.3%) and ap (0.2%). Groundmass: af + qz, cpx, pig, pl and op.

2571 — Macrophenocrysts (av. size = 2.6 mm): pl (0.3%); phenocrysts (av. size = 0.8 mm): pl (3.1%), cpx (1.4%) and op (0.7%); microphenocrysts: pl (4.1%), cpx (2.0%), pig (0.2%), op (1.7%) and ap (0.2%). Groundmass; af + qz, cpx, pig, pl and op.