

The Asunción Alkaline Province (Eastern Paraguay): Geologic Setting and Petrogenetic Aspects

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With 2 figures and 3 tables in the text

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Abstract: At the western border of the Paraná basin, in the region around Asunción, Eastern Paraguay, alkalibasaltic and phonolitic rocks of Paleogene age pierce red bed sediments. According to their major and trace element concentrations (e. g. Cr: 317-505 ppm; Nb: 96-117 ppm), high M values (62-68) and low Zr/Nb ratios (1.8-2.2) the basaltic rocks are considered to be geochemically primitive derivatives from low-grade melting (3 to 6 %) of a garnet-bearing upper mantle protolith, which may as well have had phlogopite or amphibole. The compositional heterogeneity of the phonolitic occurrence can be explained by in situ fractionation of sphene, alkalimafites, alkali-feldspar, foids, and apatite in a shallow magma reservoir.

Zusammenfassung: Am Westrand des Paranábeckens, in der Umgebung von Asunción, Ostparaguay, durchschlagen Alkalibasalte und Phonolithe paleozänen Alters ältere Rotsedimente. Gemäß ihren Haupt- und Spurenelementgehalten (e. g. Cr: 317-505 ppm; Nb: 96-117 ppm), M-Werten (62-68) und niedrigen Zr/Nb-Verhältnissen (1.8-2.2) werden die Basalte als geochemisch primitive Abkömmlinge eines granatführenden Oberen Erdmantel-Protolithes angesehen, welcher eventuell Phlogopit- oder Amphibol-führend war. Ihre kompositionelle Heterogenität verdanken die Phonolithe der In-situ-Fraktionierung von Titanit, Alkalimafiten, Alkalifeldspat, Foid und etwas Apatit in einem oberflächennahen Magmenreservoir.

Resumen: Basaltos alcalinos y fonolitas del Paleogeno atraviesan una secuencia de capas rojas en el borde occidental de la cuenca del Paraná, en las cercanías de Asunción/Paraguay Oriental. Las concentraciones en elementos mayores y traza (e. g. Cr: 317-505 ppm; Nb: 96-117 ppm), los contenidos altos de Mg en comparación con Fe (M#: 62-68), y los valores del cociente Zr/Nb (1.8-2.2) sugieren que los basaltos alcalinos son magmas relativamente primitivos, formados por una modesta fusión

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parcial (3 a 6 %) de rocas del manto superior que contenían granate, y tal vez también flogopita o anfíbol. La cristalización fraccionada de esfena, minerales ferromagnesianos alcalinos, feldespato alcalino, feldespatoide, y apatita en cámaras magmáticas someras es un proceso adecuado para explicar la variación composicional de las fonolitas.

1. Introduction

This pilot study contributes to the understanding of the geologic setting and petrogenetic evolution of non-orogenic volcanic rocks of Paleogene age in Eastern Paraguay. Results from geologic fieldwork, petrographic and geochemical investigations are presented. The scope of the petrologic part is to report on the compositional range of different small-volume, subvolcanic to volcanic, nephelinitic to basanitic rocks, which are genetically related to each other. As the compositional variation within single occurrences is very small and often within analytical error, special emphasis was laid on sampling of very fresh and representative rock specimen from the different locations and not to report on the compositional homogeneity of single occurrences.

1. 1 Regional geology

The occurrences with Paleogene (60 to 38 Ma; BITSCHENE 1987), alkalibasaltic and phonolitic, volcanic rocks lie within an approximately 30 km wide, NW striking zone with Mesozoic to Tertiary red bed sediments (Fig. 1). This graben-like zone is bordered to the NE by old crystalline basement and unconformably overlying Paleozoic clastic sediments, and to the SW by Paleozoic clastic sediments (HARRINGTON 1972). The NE and SW borders are marked by normal and antithetic faults with vertical offsets of about 900 and 1100 m respectively (DEGRAFF et al. 1981), whereas the NW extension of this tectonic block is obscured by young sediments of the Chaco basin, and the SE extension is not yet clear due to swampy terrain and changes in tectonic and magmatic style around the town of Paraguari.

All the occurrences of the alkaline volcanic rocks lie in central Eastern Paraguay, in the region around Asunción. They pierce red bed sediments of Triassic to Early Tertiary age, they are all Paleogene in age, and geochemically and isotopically significantly different from the Paraná basalts and their associated K-rich alkaline rocks. Therefore the alkalibasaltic and phonolitic occurrences can be grouped together and form an independent geologic magmatic province, the volcanic "Asunción Alkaline Province", hereinafter called AAP.

1. 2 Synopsis of previous work

Petrographic descriptions of "Ne basalts", "limburgites" and phonolites from Eastern Paraguay were reported by PÖHLMANN (1886), HIBSCH (1891) and MILCH (1895). MILCH (1895, 1905) was the first to describe petrography and geochemistry, and xenoliths from Tacumbú "limburgite".

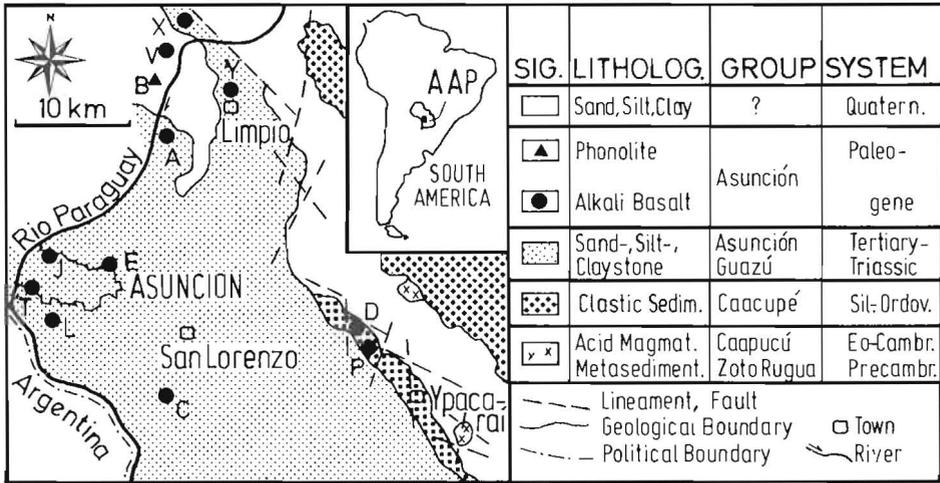


Fig. 1. Regional distribution and geologic setting of AAP volcanic rocks and position of the AAP within Paraguay and South America. Capital letters indicate outcrops of volcanic rocks; A = Puente Remanso, B = Cerro Confuso, C = Cerro Nemby, D = Cerro Coi, E = Jardín Botánico, J = San Jorge, L = Cerro Lambaré, P = Cerro Patiño, T = Cerro Tacumbú, V = Villa Hayes, X = Cerro Verde, Y = Limpio.

HARRINGTON (1950) listed several occurrences of "olivine basalt" near Asunción, which were repeated by ECKEL (1959), who furthermore mentioned basaltic sills from the Asunción area. PUTZER (1962) called the above mentioned rocks "Ne basalts" and described silicified country rock and amygdale fillings. Detailed outcrop descriptions were given by MIRAGLIA (1965), new occurrences of "olivine basalts" from the Asunción region are to be found in the "Cuadrícula 40, ITA" (M.O.P.C. 1966). COMTE & HASUI (1971) and STORMER et al. (1975) contributed first K-Ar measurements, microprobe data on phenocrysts and one Sr isotope ratio from these rocks. Only a few occurrences of alkali basalts, now wrongly attributed to the Mesozoic Paraná basalts, around Asunción can be found in the 1:500.000 geologic map provided by T. A. C. (1981, compiled by F. WIENS). DEGRAFF et al. (1981) and PALMIERI & VELAZQUEZ (1982) provide descriptions of volcanoclastic sediments with alkaline rocks from the AAP. COMIN-CHIARAMONTI et al. (1986), and DEMARCHI et al. (1989) studied the peridotitic xenoliths of the AAP, compared them to Brazilian occurrences and concluded that the upper mantle, where both Paraguayan and Brazilian occurrences come from, is heterogeneous on a regional scale. DEGRAFF (1985) and BITSCHENE et al. (1985) point out the interrelationship between reactivated continental rifting and Tertiary alkaline magmatism in Eastern Paraguay. K-Ar ages, geochemical and Sr isotope data, and the introduction of the term AAP were given by BITSCHENE et al. (1985) and BITSCHENE (1987).

2. Field observations

Some of the volcanic edifices with alkaline rocks emerge as conical hills up to 60 m above terrain (Cerro Nemby, Cerro Confuso, Cerro Lambaré, historically Tacumbú). Other indicators for not yet found occurrences of AAP rocks are columnar sandstones such as Cerro Coi near Aregua (Fig. 1). Nemby and Tacumbú are volcanic necks. Near Puente Remanso, a tephritic dike strikes NW and shows parallelepipedic jointing and abundant zeolites within cm wide fissures. Sills are reported from old drill holes within Asunción. Volcanism within the AAP was accompanied by major explosive phases. However, true volcanoclastic sediments are mostly eroded and can only be observed near Lambaré, where the stratigraphic sequence from bottom to top encompasses a basal volcanogenic mass flow unit with alkalibasaltic blocks up to m³ size. The upper 15 m of the Cerro Lambaré stratigraphic sequence comprise several layers of well stratified lapilli and ash layers with appreciable detrital quartz-sand admixture.

3. Petrography

Since two different suites of volcanogenic rocks have been observed in the field and each suite has its own macroscopic and microscopic characteristics, this chapter reports separately on the alkali basalts and the phonolites.

3. 1 Alkalibasalts

Macroscopically the basaltic rocks are black and aphanitic. Scoriaceous and vesicular basalt is restricted to the volcanic blocks in the basal volcanoclastic mass flow near Lambaré and to Cerro Nemby lava sheets. At Nemby, Lambaré and Tacumbú abundant green peridotitic xenoliths of up to 35 cm diameter can be observed. Studies on these xenoliths are reported in STORMER et al. (1975), COMIN CHIARAMONTI et al. (1986) and DEMARCHI et al. (1989). Other xenoliths found comprise sandstones and clayey siltstones in all sizes and states of decomposition and assimilation. Clearly, these rocks have been entrained from the sedimentary country rock of Mesozoic or possibly Silurian age.

Microscopically the alkali basalts have hypocrySTALLINE porphyritic to seriate porphyritic textures. Fo-rich olivine, clinopyroxene with sometimes green cores, and Cr spinel with corrosion features and overgrowth by opaque, Cr-poor spinel are upper mantle xenocrysts and high-p (?) phenocrysts. Microphenocrysts and supposed true crystallization phases are Fo-rich olivine, clinopyroxenes such as Ti augite, diopsidic augite and finally aegirin augite, opaque Fe-Ti ores, a few biotite flitters, amphibole (?), apatite, and a leucocratic matrix composed of nepheline, scarce plagioclase, alkalifeldspar, glass, and zeolite (natrolite, analcite ?). Secondary minerals comprise serpentine, smectite, Fe oxides and hydroxides, iddingsite, carbonate, zeolite. The latter paragenesis can also be found in amygdule fillings and veins up to 30 cm thick.

Clinopyroxene is the most abundant mafic mineral with 46 to 53 volume-%, next are olivine (9 to 16 %) and the opaques (4 to 9 %). The

resulting color index is between 65 and 79. The light colored groundmass totals volumetrically between 21 and 35 % and the accessory minerals (sheet silicates, amphibole, carbonate, apatite) amount to between 0,1 and 4,4 %. However, as the latter number comprises alteration minerals, it is mentioned only for completion and has the lowest reliability. Notably, the tephrite from Pte. Remanso has the highest light mineral content and the lowest color index, whereas the basanite from Cerro Patiño is conspicuous because of its high color index and low content in light colored minerals. Tab. 1 shows the modal compositions of some alkalibasalts from the AAP.

Tab. 1. Modal compositions of alkalibasalts in vol.-%. ol = Olivine, cpx = clinopyroxene, lg = light colored groundmass, op = opaque ores, ac = accessory minerals, CI = color index, S = sum, TS = thin section number, RN = rock name (First capital letter of thin section number refers to occurrences as marked in Fig. 1).

Occurrence	TS	ol	cpx	lg	op	ac	CI	S	RN
Nemby	C2b	15.3	51.3	27.3	6.1	0.1	73	100.1	ol-neph.
Nemby	C2a	12.4	56.7	25.5	4.7	0.7	76	100.0	ol-neph.
Pte. Remanso	Al	9.5	46.4	34.7	8.2	1.2	65	100.0	tephrite
Tacumbú	Tac1	12.9	52.6	25.9	8.3	0.4	74	100.1	ol-neph.
Cerro Lambaré	L1	15.7	52.9	24.0	7.0	0.5	76	100.1	ol-neph.
Cerro Patiño	P1a	12.6	52.9	21.2	8.9	4.4	79	100.0	ne-bas.
Cerro Patiño	P1b	13.4	51.7	23.6	8.3	3.0	76	100.0	ne-bas.

3. 2 Phonolite

The outcrop near the Confuso river (Cerro Confuso) displays two distinct types of phonolitic rocks. Sample B2b is dark green, the lighter variety B1 has appreciable white specks with zeolite, carbonate and glass. Microscopically the phonolites are hypocrySTALLINE porphyritic and display a marked fluidal texture. Some mm-wide, round aggregates consist of strongly resorbed former phlogopite (?), now replaced by fine-grained aegirine, biotite and opaque ore needles, and a glassy matrix. Microphenocrysts are aegirin augite and pure acmite, sanidine/anorthoclase and nepheline, accessory minerals are significant sphene, and some bluish pleochroic amphibole (arfvedsonite ?). A few opaque ore flitters, reddish Fe hydroxides and abundant brownish glass comprise the matrix, sometimes zeolite develops towards veins and cavities. Zeolites, green sheet silicates, carbonate, and very few fluorite are secondary minerals and are especially abundant in veins and bubbles. Zircon and quartz grains rimmed by brown glass are considered to be xenocrysts. Tuffitic material found at Cerro Confuso is cemented by carbonate and occasionally contains lapilli of alkalibasaltic composition and crystal fragments of green core pyroxenes with Ti-augitic rims, and brown amphiboles. Detrital

quartz grains have a dirty rim and are homoaxially overgrown by clear, authigenic quartz. The basaltic lapilli are important hints that at depth alkalibasaltic rocks existed or still exist, and that there is a very close relationship between primitive basalts and evolved phonolites.

4. Geochemistry

As this is a pilot study, only one representative sample was taken from each of six occurrences. Sampling was done on fresh rocks, xenolithic inclusions were carefully avoided on a macroscopical scale. Two previous analyses, though not highly reliable, of AAP rocks by STORMER et al. (1975) and MILCH (1905) have been included for completion of the data. Major and trace elements have been analyzed on fused glass disks (major elements) and powder pellets (trace elements) by XRF-analyses against well known international standards. All standards were reproduced within analytical error, which confirms the reliability of the data presented. Yb was determined by ICP-AES methods. Analytical procedures and operational set-up, detection limits and standard deviations for all elements analyzed, and reproducibility and reliability of data of the measured international standards are reported, for instance, in BITSCHENE (1987). Analytical conditions followed strictly the procedures in the geochemistry department at the "Institut für Geowissenschaften und Lithosphärenforschung, Universität Gießen".

4. 1 Major elements

The SiO_2 concentrations of the alkalibasalts range from 41 to 43 %, MgO from 9.4 to 12.7, Na_2O from 3.6 to 4.2. K_2O (1.17 to 1.95) and Al_2O_3 (11.9 to 14.1) concentrations have a wide range, which is matched by P_2O_5 (0.72 to 1.03 %) and TiO_2 (2.2 to 2.6 %). Rather constant concentrations are observed for CaO (11.1 to 11.8 %), Fe_2O_3 (3.9 to 4.6) and FeO (6.2 to 7.2) respectively, indicating equilibrium of crystallized Ti augite and perhaps magnetite with the residual melt. The $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio is always > 1 (2.1 to 3.5) and the M values (after HUGHES & HUSSEY 1976) lie between 62 and 68 (Tab. 2). Thus the alkalibasalts are typically SiO_2 -undersaturated, Na-rich alkaline rocks of the Atlantic family (after NIGGLI 1923) with a primitive geochemical character typical of not significantly differentiated rocks from the upper mantle.

Two analyses from the phonolitic rocks have been made. Remarkable are the high Al_2O_3 (20.1 and 20.6 %), Na_2O (9.8 and 10.0 %), K_2O (5.1 and 5.6 %), and low MgO (0.31 and 0.10 %), CaO (2.12 and 0.91 %) and P_2O_5 (0.15 and 0.07 %) concentrations. This is due to the removal of mafic mineral phases, apatite, and the crystallization of Na-rich minerals (aegirine, nepheline, anorthoclase, zeolite) from the residual peralkaline melt.

In Fig. 2 the major element concentrations are plotted against SiO_2 , whereas the trace element concentrations are plotted against MgO as differentiation index. It must be noted that true differentiation trends cannot be deduced as the occurrences are different in age, location and composition. Nevertheless the Harker diagrams are good indicators for

Tab. 2. Concentration of major elements, CO₂ and H₂O in AAP volcanic rocks (Sample numbers according to Fig. 1 and Tab. 1) including data from MILCH (1905; Mi 1) and STORMER et al. (1975; Sto) and M values (after HUGHES & HUSSEY 1976).

	A1	C1	L1	P1	Tac1	Sto	Mi1	B1	B2b
SiO ₂	42.69	42.72	41.13	41.83	42.03	41.52	40.95	53.25	51.75
TiO ₂	2.24	2.19	2.60	2.54	2.56	1.95	0.25	0.28	0.57
Al ₂ O ₃	14.05	12.22	11.93	13.41	13.58	18.48	15.37	20.62	20.21
Fe ₂ O ₃	4.36	3.89	4.55	4.19	4.48	6.03	6.36	2.80	2.94
FeO	6.28	7.19	6.80	6.18	6.28	6.62	4.38	0.89	1.43
MnO	0.18	0.20	0.19	0.17	0.18	0.36	traces	0.19	0.19
MgO	9.39	11.37	12.72	10.99	11.25	11.52	10.46	0.10	0.37
CaO	11.60	11.36	11.12	11.80	11.56	5.30	11.67	0.91	2.12
Na ₂ O	4.11	4.05	3.63	4.05	4.19	4.63	3.97	10.01	9.79
K ₂ O	1.46	1.95	1.40	1.17	1.86	2.70	1.26	5.62	5.14
P ₂ O ₅	0.80	1.03	0.97	0.72	0.76	0.09	0.09	0.07	0.15
H ₂ O	1.97	1.01	2.11	1.58	1.23	0.40	3.93	1.66	2.84
CO ₂	0.20	0.07	0.11	0.09	0.08	n.d.	n.d.	0.31	1.20
Sum	99.33	99.25	99.26	98.72	100.04	99.60	98.98	96.71	98.70
M-value	62	65	67	66	64	62	65	5	13

the compositional variety of the AAP rocks. Major element concentrations are furthermore very useful for the classification of aphanitic rocks. According to their position in the ne-normative space within the cpx - ne - ol - q tetrahedron (YODER & TILLEY 1962), the basaltic rocks are alkalibasalts. Samples fitted into a TAS diagram (ZANETTIN 1984) plot into the basaltic field 3b and into the phonolitic field 3e.

4. 2 Trace elements

The trace element budget of the alkalibasalts is marked by high concentrations in both compatible elements Cr (505 to 317 ppm) and Ni (293 to 134 ppm) and incompatible elements Zr (268 to 177 ppm), Nb (117 to 96 ppm) and Sr (1197 to 994 ppm). Cr and Ni are positively correlated with MgO (Fig. 2). Olivine bears most of the Mg available and has high Kd's for Ni (between 10 and 58 after IRVING 1978 and DOSTAL et al. 1983). Addition or subtraction of a few percent of olivine explains the observed trend and differences. The same holds true for Cr diopside and Cr spinel, which are the Cr-bearing minerals. Sr seems to be the only element which increases with decreasing MgO and might be due to suppressed plagioclase crystallization at depth (compare e. g. WEDEPOHL 1985) and thus enrichment in Sr (and Al₂O₃ and SiO₂), if small scale differentiation processes are assumed. As incompatible elements show no obvious trend, and highest concentrations in incompatible elements are matched by highest concentrations in compatible elements, different degrees in partial melting or regional/local inhomogeneities of an inferred peridotitic source rock are favoured as petrogenetic model rather than simple fractional crystallization of a common

parent magma. Of particular interest are the low Zr/Nb ratios (2.2 to 1.8) which indicate a relative enrichment in Nb (FLOYD & WINCHESTER 1975). Relative high Nb concentrations could result from biotite or amphibole or accessory mineral (garnet, rutile ?) partial melting which have highest Kd's for Nb compared to other peridotitic source minerals. The Zr/Nb ratio on the other hand is particularly insensitive to the degree of partial melting, the differences, even small so, can therefore be attributed to small-scale, local inhomogeneities of the source rock (PEARCE & NORRY 1979). This would favour derivation of the alkali-basaltic rocks from a locally heterogeneous mantle source. Yb (1.5 to 2.2 ppm) and Y (24-30 ppm) concentrations are low and rather heterogeneous suggesting garnet as a residual phase, where the HREE are stored (HASKIN 1984, FREY 1984), and imply regional, even local differences in REE and thus incompatible element enrichment. Differentiation of the alkali-basaltic rocks from an inferred common parent magma source or significantly different degrees of partial melting of a uniform protolith would require coupled incompatible element enrichment - compatible element depletion and no change in Zr/Nb ratios. As this is not the case, similar low-grade partial melting of a heterogeneously enriched mantle source is the most likely process to produce the observed decoupled trace element concentrations and ratios.

Tab. 3. Trace element concentrations (ppm) of some AAP volcanic rocks (Sample numbers according to Fig. 1 and Tab. 2).

	A1	C1	L1	P1	Tac1	B1	B2b
Cr	317	413	505	387	376	14	7
Co	48	49	58	46	53	2	3
Ni	134	214	293	173	203	8	8
Cu	50	47	43	58	49	5	7
Zn	91	98	104	78	80	152	131
Ga	18	17	17	16	15	31	26
Rb	65	50	62	36	62	224	166
Sr	1197	1180	994	1080	1088	445	916
Yb	1.9	2.2	1.9	1.5	1.6	2.2	2.8
Y	26	30	28	24	24	27	31

The slightly higher Zr/Nb ratios of the phonolites (3.3 for the more evolved sample B1 and 2.9 for the less evolved sample B2b), however, are attributed to the relative enrichment of Zr due to its higher incompatibility during advanced stages of magmatic differentiation. The more mafic phonolitic sample B2b has lower Zr (748 vs. 1085 ppm), Nb (256 vs. 332 ppm), Rb (166 vs. 224 ppm) and Zn (131 vs. 152 ppm) concentrations than the more evolved sample B1. Sr, which in the case of the alkali basalts behaved incompatibly, in the case of the phonolites seems to behave compatibly. As clinopyroxenes, sphene and apatite from phonolitic magmas commonly have low partition coefficients for Sr, but alkali-feldspars or even foides have appropriate Kd's for Sr (WOERNER et al. 1983), fractionation of alkali-feldspar, and foids (and apatite ?) can explain the Sr decrease. Sr, TiO₂, P₂O₅ and CaO are significantly higher in sample B2b, thus sphene, alkalimafites, alkali-feldspar, foids, and

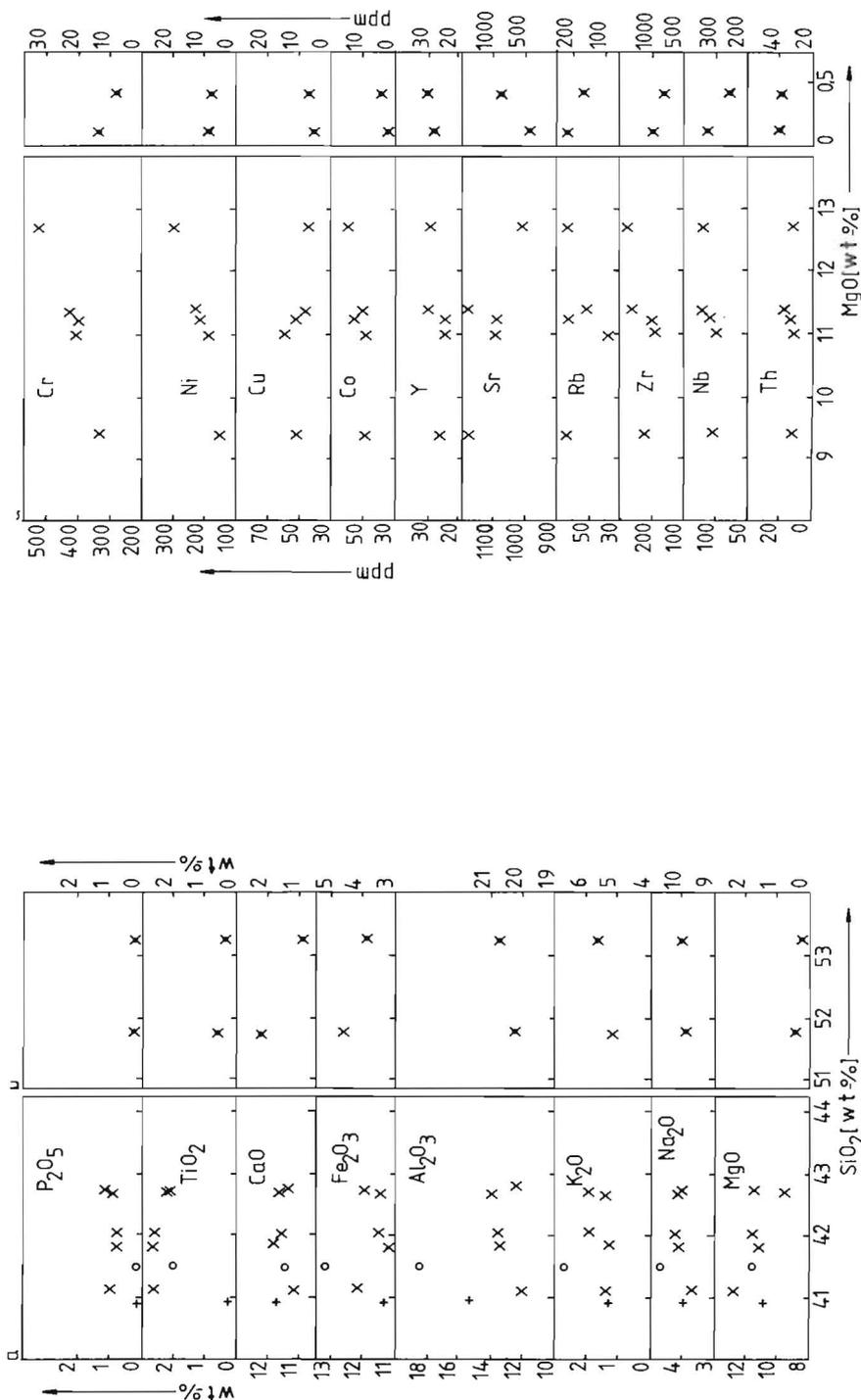


Fig. 2. Variation diagrams with major elements against SiO₂ and trace elements against MgO as differentiation index. In column a all available data on the alkalibasalts are plotted, in column b the data from the two phonolites. Own data are marked by "x", data from MILCH (1905) are marked with "+" and from STORMER et al. (1975) with "o".

apatite, though only a very subordinate phase, govern the differentiation processes within the shallow phonolitic magma chamber. Compositional heterogeneity of the Confuso phonolite is therefore related to fractionation of Ti, Ca, P, and Sr (Y and REE ?) bearing phases.

5. Geologic and petrogenetic model

The outcrops studied reveal Paleogene alkalibasaltic and phonolitic, volcanic activity at the western fringe of the Paraná basin. The volcanic rocks pierce Triassic to Tertiary red bed sediments and form an own volcanic province of intracontinental, Na-rich alkaline magmatism, the "Asunción Alkaline Province, AAP" related to reactivated rifting processes within the South American continent during Early Tertiary times.

The volcanic rocks are modally Ol nephelinites, Ne basanites, tephrites and phonolites. Major and trace element data indicate that the alkalibasalts are geochemically primitive, low-grade melting products from a heterogeneous mantle source. Trace element data indicate that the source rock is garnet-bearing and might have had additional phlogopite/amphibole phases. Compared with data from GAST (1968), GREEN (1970), FREY et al. (1978), and SUN & HANSON (1975) the AAP alkalibasaltic rocks can be generated by low-grade partial melting (3 to 6 %) of an incompatible element enriched upper mantle source, in this case a garnet lherzolite with \pm additional phlogopite/amphibole. However, to model quantitatively multistage evolution of the AAP rocks additional REE and isotope studies are required.

The phonolitic rocks may have derived from the alkalibasalts by fractional crystallization processes in shallow magma chambers. The Cerro Confuso occurrence is interpreted as an in situ crystallized, compositionally heterogeneous, phonolitic magma chamber, where prior to magma solidification, maybe during formation of a zoned magma chamber, sphene, alkalimafites, alkali-feldspar/foiid and minor apatite fractionation were responsible for the observed magma heterogeneity.

Future work should extend the knowledge on REE and isotopic characteristics, on volcanology, especially eruptive processes, within the AAP, on the ages and their geographic distribution, and on the relationship of the AAP rocks to the older but nearby Paraná basalts and associated K-rich alkaline rocks in Eastern Paraguay.

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