

## PETROGENESIS OF ALKALINE-CARBONATITIC COMPLEXES OF CATALÃO AND IPANEMA, IN SOUTHERN BRAZIL

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### INTRODUCTION

Mesozoic to Cenozoic alkaline magmatism is widespread throughout southern Brazil. The main areas of alkaline magmatism are: Alto Paranaíba Igneous Province (or APIP) and Ponta Grossa Arch.

The APIP (Fig. 1) is located between the São Francisco Craton and the NE border of the Paraná Basin, and cover an area of ~ 3,000 km<sup>2</sup> with an estimated volume of > 15,000 km<sup>3</sup> of strongly alkaline and carbonatitic rocks (mostly kamafugites, kimberlites, lamprophyres and carbonatites) found as lava flows, pyroclastic successions and hypabyssal intrusions (Gibson *et al.*, 1995; Brod *et al.*, 2000; Araújo *et al.*, 2001; Melluso *et al.*, 2008).

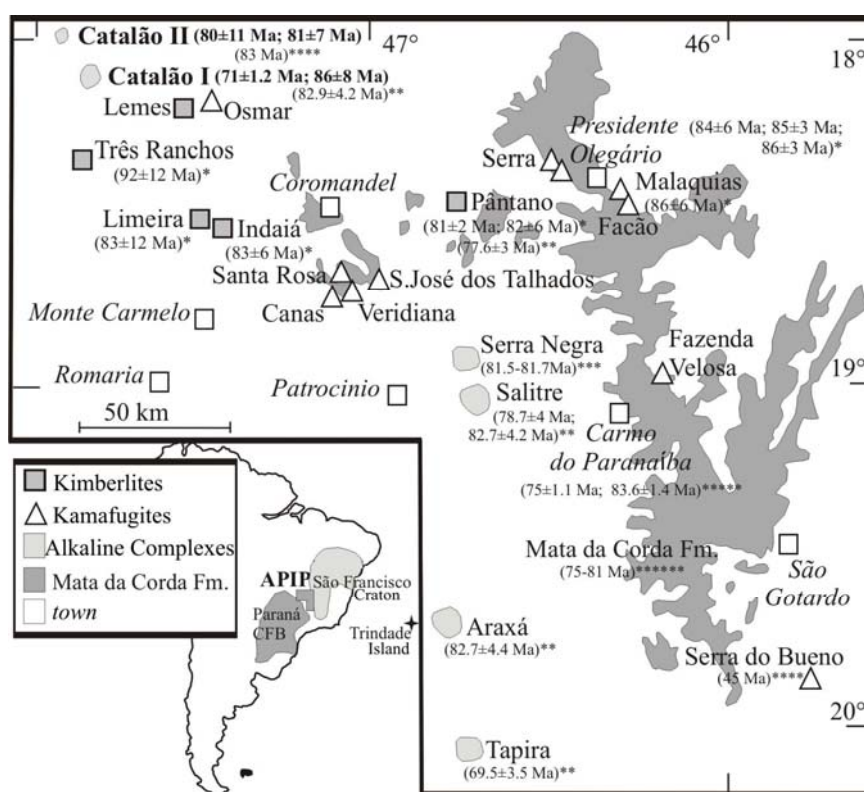


Fig. 1 - Localization of APIP and its main complexes including Catalão I and Catalão II complexes (in bold), southern Brazil (modified after Melluso *et al.*, 2008). Dating are from: (\*) Hasui & Cordani (1968); (\*\*) Ulbrich & Gomes (1981); (\*\*\*) Machado (1991); (\*\*\*\*) Gibson *et al.* (1995); (\*\*\*\*\*) Sgarbi *et al.* (2004).

The Ponta Grossa Arch (Fig. 2) is a large ( $\sim 134,000 \text{ km}^2$ ) tectonic feature on the eastern border of the Palaeozoic-Mesozoic Paraná Basin. This region is characterized by abundant NW-trending tholeiitic dykes. The petrographic associations of alkaline bodies are also quite variable in composition, with the alkaline-carbonatite complexes showing saturated-to-undersaturated syenitic suites related to mafic-ultramafic rocks, nepheline syenites or phonolites.

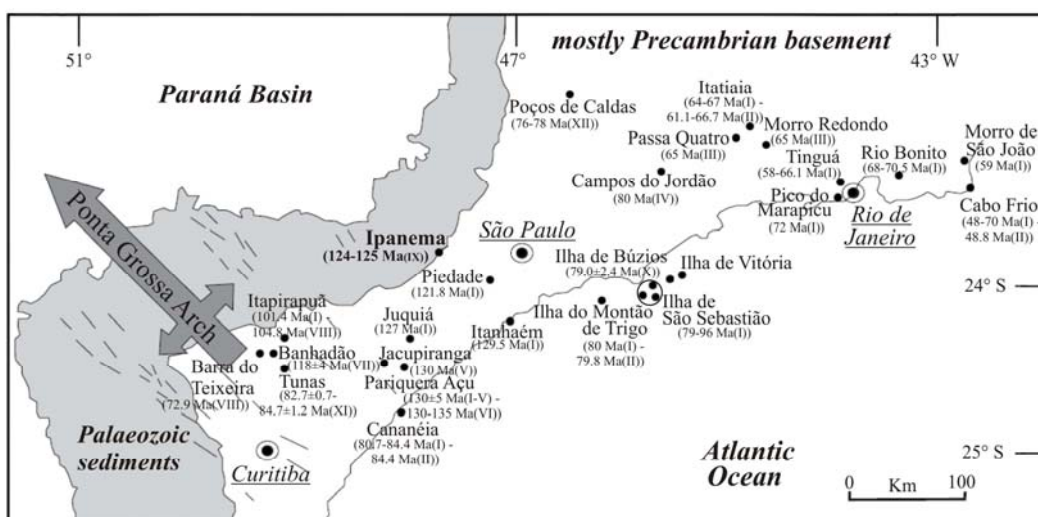


Fig. 2 - Localization of Ponta Grossa Arch and its main complexes including Ipanema complex (in bold). Dating are from: I: Amaral *et al.* (1967); II: Bushee (1974); III: Asmus (1978); IV: Ulbrich & Gomes (1981); V: Amaral (1978); VI: Gomes *et al.* (1990); VII: Hama *et al.* (1977); VIII: Cordani & Hasui (1968); IX: Sonoki & Garda (1988); X: Alves (1997); XI: Siga *et al.* (2007); XII: Shea (1992).

The igneous districts investigated in this paper are: Catalão I and Catalão II (Fig. 1), and Ipanema (Fig. 2), which represent typical alkaline-carbonatite complexes. The aim of this work is to propose a new data set of mineralogical, petrographical and geochemical data. This dataset is used to assess the petrogenetic processes that originated these complexes.

New U-Pb *in-situ* ages are estimated on perovskite, pyrochlore and baddeleyite from Catalão I and Catalão II complexes. The age determinations obtained (from 85 to 71 Ma) are coherent with the previous radiometric investigations (Fig. 1).

Ipanema complex has an age of  $\sim 125 \text{ Ma}$  (Morbidelli *et al.*, 1995).

## CLASSIFICATION

Catalão I and Catalão II complexes are composed of ultramafic lamprophyres, carbonatites, phoscorites, fenites, alkaline pyroxenites or clinopyroxenites, apatite-, magnetite- and phlogopite-bearing rocks.

Ipanema complex consists of lamprophyres, carbonatites, shonkinites, feldspar-rich rocks, apatite-, magnetite- and phlogopite-bearing rocks. The carbonatites are classified as magnesiocarbonatites and calciocarbonatites in Catalão complexes and calciocarbonatites in Ipanema complex, following the chemical classification proposed by Woolley & Kempe (1989). The ultramafic lamprophyres of Catalão

are classified as phlogopite-picrites in according to Gibson *et al.* (1995) and Brod *et al.* (2000), whereas the lamprophyre of Ipanema complex is chemically a tephrite following the chemical classification proposed by Le Bas *et al.* (1986). The rocks called here phoscorites, have been classified on the basis of modal mineral contents, as proposed by Hanekom *et al.* (1965).

The rocks identified as magnetite-, apatite- and phlogopite-bearing rocks are named, respectively, like magnetitites, apatitites and glimmerites, names used in the literature.

All lithologies observed for these complexes present a holocrystalline granular texture, with cumulitic aspect, except for Catalão phlogopite-picrites with a pseudofluidal porphyritic texture and Ipanema lamprophyre with a strongly porphyritic texture.

## MINERAL CHEMISTRY

The mineralogical phases, analysed in Catalão I and Catalão II complexes, are:

- carbonate that shows a wide variety in composition, especially in magnesiocarbonatites (dolomite associated with calcite, norsethite, magnesite, stronzianite, alstonite, witherite, burbankite) and in calciocarbonatites (calcite associated with stronzianite, nyerereite, gregoryite, ancyllite-Ce, burbankite, siderite, ankerite);

- magnetite is the predominant spinel in Catalão rocks, but it is totally absent in fenites and clinopyroxenites. Ilmenite is present in magnetitites, apatitites and in calciocarbonatites. Cromites are analysed in phlogopite-picrites, while small crystals of rutile in calciocarbonatites;

- clinopyroxene is present as aegirine-augite in fenites ( $\text{Na}_{23-20}\text{Mg}_{62}\text{Fe}^{2+}_{18-15}$ ), in clinopyroxenites ( $\text{Na}_{46-17}\text{Mg}_{59-40}\text{Fe}^{2+}_{24-14}$ ) and in calciocarbonatites ( $\text{Na}_{77-24}\text{Mg}_{48-11}\text{Fe}^{2+}_{28-13}$ );

- amphibole, as richterite, is an accessory phase in fenites, clinopyroxenites and rarely in calciocarbonatites;

- olivine is present exclusively in phoscorites ( $\text{Fo}_{97}\text{-Fo}_{98}$ ) and in phlogopite-picrites ( $\text{Fo}_{88}\text{-Fo}_{89}$ );

- alkali-feldspar is present only in fenites as orthoclase ( $\text{Or}_{99-97}\text{Ab}_{0-2}\text{An}_{0-1}$ );

- garnet is found in phlogopite-picrites (andradite 4-48% and morimotoite 29-68%; Locock, 2008);

- apatite is analysed in any type of rocks, while monazite are present only in magnesiocarbonatites;

- perovskite, pyrochlore and baddeleyite. Perovskite is present only in phlogopite-picrites, shows high  $\text{CaTiO}_3$  (88-97 mol.%) contents and variable values in loparite ( $\text{Ce}_{0.5}\text{Na}_{0.5}\text{TiO}_3$ , 2.2-9.1 mol.%) end-members. Pyrochlore is analysed in phoscorites, magnetitites, apatitites and rarely in magnesiocarbonatites. Baddeleyite is present in small crystals in apatitites and magnetitites. Perovskite and pyrochlore are enriched in light lanthanides ( $\text{La}_n/\text{Yb}_n$ , 768.1-872.1 in phlogopite-picrites, and 629.1-842.7 in magnetitites and 1411.7 in apatitites, respectively), whereas the baddeleyite is relatively depleted in light lanthanides (26.4-33.3 in magnetitites and 12.5 in apatitites);

- phlogopites belong to phlogopite-tetra-ferriphlogopites series. Chemical and structural analyses display the presence of  $\text{Fe}^{3+}$  in tetrahedral ( $^{\text{IV}}\text{Fe}^{3+}$ ) and octahedral ( $^{\text{VI}}\text{Fe}^{3+}$ ) site. The  $^{\text{VI}}\text{Fe}^{3+}$  defines the reaction  $\text{Fe}^{3+}\text{-oxy}$ , where excess charge in octahedral site, is compensated in anion site with the addition of OH.

The mineralogical phases, analysed in Ipanema complex, are:

- clinopyroxene is diopside in lamprophyre ( $\text{Mg}_{50-76}\text{Na}_{9-20}\text{Fe}^{2+}_{15-30}$ ) and aegirine-augite in feldspathic rocks ( $\text{Mg}_{17-60}\text{Na}_{21-39}\text{Fe}^{2+}_{19-44}$ ), in shonkinites ( $\text{Mg}_{12-44}\text{Na}_{32-64}\text{Fe}^{2+}_{24}$ ) and in glimmerites ( $\text{Mg}_{7-56}\text{Na}_{28-69}\text{Fe}^{2+}_{16-24}$ );

- amphibole shows a wide compositional variation in feldspathic rocks (edenite, arfvedsonite and richterite) and in shonkinites (arfvedsonite and richterite), while in glimmerites and in apatitites amphiboles are only richterites;
- phlogopite is always present in Ipanema rock. Its compositions indicate that belong to phlogopite-annite series; and in some of these micas take place the  $Fe^{3+}$  substitution in place of  $Al^{3+}$ ;
- feldspars are principally alkali-feldspar ( $An_{0.2}Ab_{5.9}Or_{89.95}$ ) in shonkinites, and alkali-feldspar ( $An_0Ab_{9.14}Or_{86.91}$ ) and plagioclase ( $An_{0.45}Ab_{54.94}Or_{1.6}$ ) in feldspathic rocks;
- apatites, present in all rocks, show a low TSI contents that indicate an environment of crystallization in equilibrium;
- magnetite is the predominant spinel in these rocks, but it is totally absent in lamprophyre, shonkinites and apatitites. Ilmenite is present only in feldspathic rocks;
- carbonate, exclusively as calcite, is present in calciocarbonatites, shonkinites and in some glimmerites.

ISOTOPE GEOCHEMISTRY

Sr and Nd isotopes were estimated on rocks and minerals for Catalão complexes, and only on rocks for Ipanema complex. The Sr and Nd isotopic ratio were age corrected to 82 Ma for Catalão complexes and 125 Ma for Ipanema complex.

In  $\epsilon Nd_i$  vs.  $\epsilon Sr_i$  diagram (Fig. 3), data for the igneous rocks of Catalão fall in the same field of APIP rocks (kimberlites and kamafugites), suggesting comparable magmatic sources. In contrast, Ipanema rocks are markedly different in having lower  $\epsilon Nd_i$  and higher  $\epsilon Sr_i$ . Ipanema rocks show an isotopic composition similar to the Paraguay potassic rocks.

These isotopic differences indicate that the mantle beneath the South American platform is heterogeneous on large scale.

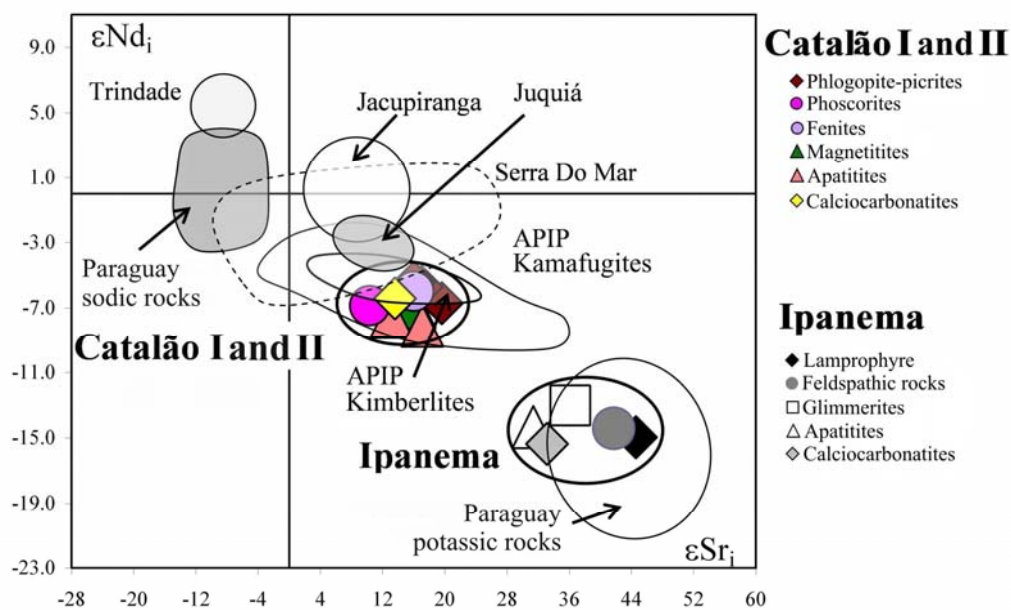


Fig. 3 -  $\epsilon Nd_i$  vs.  $\epsilon Sr_i$  diagram for Catalão and Ipanema rocks.

The O and C isotopic data were obtained on carbonate crystals separated from the Catalão and Ipanema carbonatites. In the  $\delta^{13}\text{C}$  (PDB) vs.  $\delta^{18}\text{O}$  (SMOW) diagram (Fig. 4), data for the Catalão magnesio- and calciocarbonatites fall within the field of “primary igneous carbonatites”, whereas Ipanema calciocarbonatite fall in “hydrothermal field”.

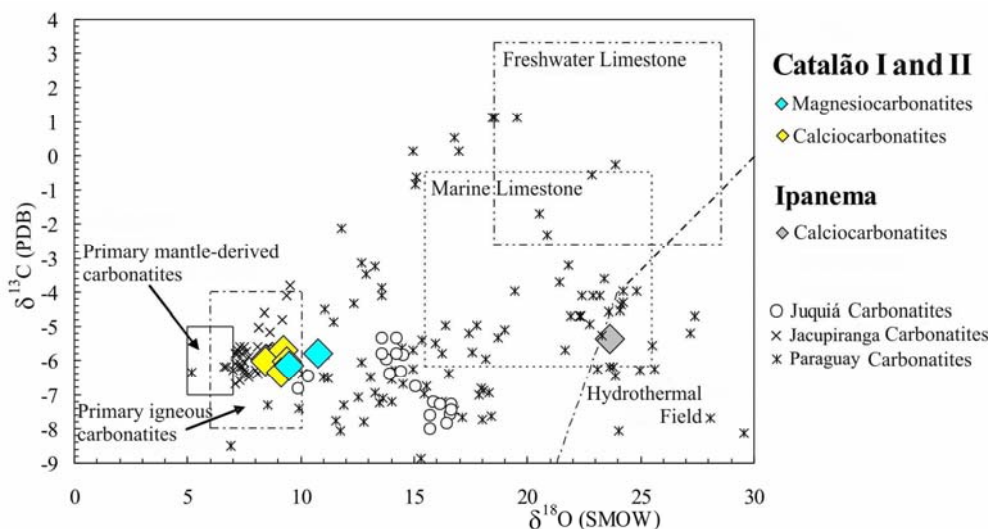


Fig. 4 -  $\delta^{13}\text{C}$  (PDB) vs.  $\delta^{18}\text{O}$  (SMOW) diagram for Catalão and Ipanema carbonatites. Data are taken from Comin-Chiaromonte *et al.* (2005) and Castorina *et al.* (1997).

## PETROGENESIS OF CATALÃO I AND CATALÃO II COMPLEXES

### Source characteristic

Catalão I and Catalão II alkaline-carbonatitic complexes are characterized by phoscorites, magnetites, apatites, glimmerites, clinopyroxenites, magnesio-, calciocarbonatites and phlogopite-picrites, associated with fenites, which is likely the product of fenitization process following the emplacement of the complexes.

Petrographic, mineralogical and geochemical data show the genetic relationship between the rocks, while the O and C isotopes confirm the magmatic origin of carbonatites.

Phlogopite-picrites could derived by a partial melting of a lherzolitic mantle source enriched in volatiles ( $\text{H}_2\text{O}$  and  $\text{CO}_2$ ) crossed by glimmeritic veins (Foley, 1992a, 1992b).

The  $\text{SiO}_2$  undersaturation and the CaO and  $\text{CO}_2$  enrichment highlights the lack of orthopyroxene in the source of these magmas, thereby producing a carbonatic metasomatism that converts a lherzolite in a carbonated wehrlite enriched in phlogopite.

### Magmatic evolution

Regarding cumulitic rocks are characterised by high  $\text{K}_2\text{O}$ , CaO,  $\text{Fe}_2\text{O}_3$ ,  $\text{P}_2\text{O}_5$ ,  $\text{H}_2\text{O}$  and  $\text{CO}_2$  contents and low  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  contents that reflect the peculiar characteristic both of their parental magma and of their different mineralogy.

In the CaO - ( $\text{MgO}+\text{FeO}^*$ ) - ( $\text{Na}_2\text{O}+\text{K}_2\text{O}$ ) - ( $\text{SiO}_2+\text{Al}_2\text{O}_3+\text{TiO}_2$ ) pseudoquaternary system in presence of  $\text{CO}_2$  at 1.0 GPa (Lee & Wyllie, 1998; Fig. 5), data for Catalão rocks fall within the

immiscibility fields of carbonatic and silicatic melts, confirming a process of liquid immiscibility for these cumulitic rocks.

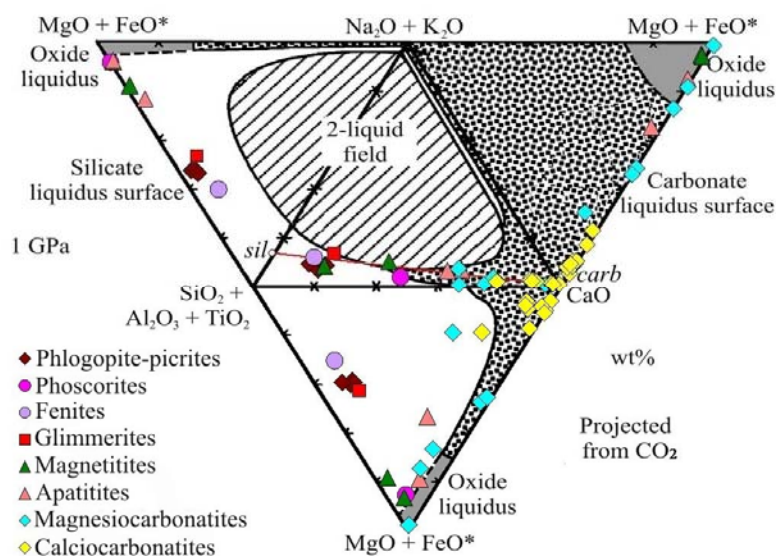


Fig. 5 - Pseudoquaternary system CaO - (MgO + FeO\*) - (Na<sub>2</sub>O + K<sub>2</sub>O) - (SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub> + TiO<sub>2</sub>) with CO<sub>2</sub>, (Lee & Wyllie, 1998) for Catalão rocks.

#### PETROGENESIS OF IPANEMA COMPLEX

To determine the characteristics source for Ipanema complex is difficult, because lamprophyre, feldspathic rocks and shonkinites are not a parental liquid.

The magmatic evolution of Ipanema rocks can be modelled via fractional crystallization process starting by a parental basanitic magma to produce the cumulitic rocks. The gap in SiO<sub>2</sub> and CaO, around 20-30%, can be a prove of a subsequent immiscibility liquid process that have originated a carbonatitic melts, without significant changes in their geochemical and isotopical features.

In the (SiO<sub>2</sub>+Al<sub>2</sub>O<sub>3</sub>+TiO<sub>2</sub>) - (CaO+MgO+FeO\*) - (Na<sub>2</sub>O+K<sub>2</sub>O) system (Lee & Wyllie, 1997; Fig. 6) are reported the AA' and BB' line that represent the comparison of immiscibility fields of carbonate and silicate melts. Ipanema rocks belong to BB' line and albite/calcite (Ab/Cc) cotectic line (Lee & Wyllie, 1998), and both line confirm an evolution trend with initial formation of lamprophyre, feldspathic rocks, shonkinites and glimmerites, and after immiscibility process, are formed apatitites, magnetitites and calciocarbonatites.

#### CONCLUSIONS

The main problem of the Catalão I, Catalão II and Ipanema complexes is explain the origin and the close relationship between the alkaline rocks, cumulitic rocks and carbonatites.

Mineralogical, petrographic and geochemical knowledge for Catalão I and Catalão II complexes indicate that the source is a carbonated wehrlite enriched in phlogopite. Carbonatites derived by a liquid immiscibility process. Moreover, the reaction <sup>VI</sup>Fe<sup>3+</sup>-oxy of phlogopites implies a change in the chemical and physical properties within the magmatic chamber.

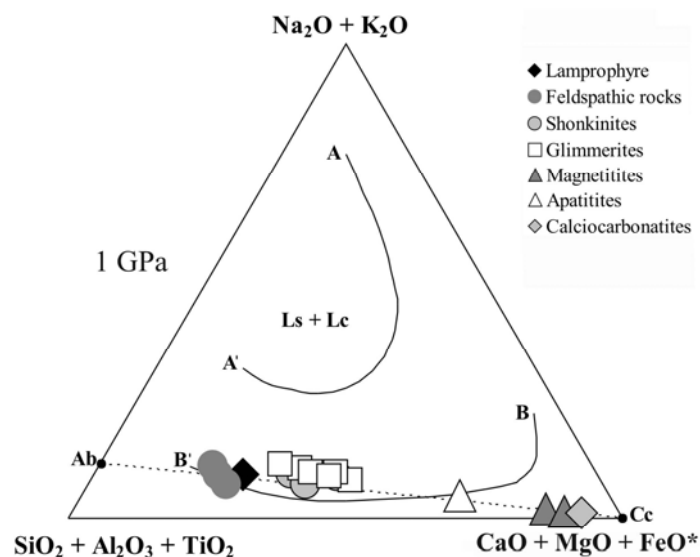


Fig. 6 -  $(\text{CaO} + \text{MgO} + \text{FeO}^*) - (\text{Na}_2\text{O} + \text{K}_2\text{O}) - (\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{TiO}_2)$  with  $\text{CO}_2$  system at 1 GPa (Lee & Wyllie, 1997) for Ipanema rocks.

The isotopic evidence shows the close relationship between the Catalão rocks and APIP kimberlites and kamafugites.

The Ipanema rocks derived by fractional crystallization and subsequent liquid immiscibility process, that have originated the calciocarbonatites.

The isotopic compositions show that the Ipanema rocks are much closer to the Paraguay potassic rocks rather than the rocks in the same area, the Ponta Grossa Arch.

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