

Cretaceous carbonatites of the southeastern Brazilian Platform: a review

Celso de Barros Gomes^{1*}, Piero Comin-Chiaramonti², Rogério Guitarrari Azzone¹,
Excelso Ruberti¹, Gaston Eduardo Enrich Rojas¹

ABSTRACT: This paper reviews general aspects of alkaline-carbonatitic rocks of Brazilian, Paraguayan and Bolivian terrains. Although 30 such occurrences are known in literature, only the major ones have been thoroughly investigated. The carbonatites are of Cretaceous age, with two well-defined Lower Cretaceous and Upper Cretaceous generation episodes. A clear tectonic control by ancient structural features such as arches, lineaments and faults characterizes most cases. The rocks exhibit a large compositional variation, in decreasing orders of abundance from calcicarbonatites to magnesiocarbonatites to ferrocarnatites. In some complexes, they form multistage intrusions. C-O isotopes indicate that, in general, the carbonatites were affected by post-magmatic processes associated with the topographic level of emplacement and low-temperature H₂O-CO₂ rich fluids responsible for the increased amount of heavy carbon and oxygen. Sr-Nd isotopic compositions similar to those of coeval alkaline silicate rocks, ranging from depleted to enriched mantle sources, have been influenced by two distinct metasomatic events in Proterozoic at 2,0-1.4 Ga and 1.0-0.5 Ga. Sr-Nd-Pb-Os data seem related to an isotopically enriched source, their chemical heterogeneities reflecting a depleted mantle that was metasomatized by small-volume melts and by fluids rich in incompatible elements. Fractional crystallization and liquid immiscibility are believed to be the most effective processes in the formation of the Cretaceous carbonatites, with minor contribution of crustal contamination. Pb isotopic ratios yield evidence that HIMU and EM I mantle components played an important role in the genesis of the carbonatitic magma.

KEYWORDS: Carbonatites; Alkaline Rocks; Brazilian Platform.

INTRODUCTION

Only a few review papers dealing specifically with Cretaceous carbonatites of the southeastern Brazilian Platform are known in literature. Studies by Rodrigues and Lima (1984), Berbert (1984), and Gomes *et al.* (1990) are among the first ones. More recently, papers such as those by Castorina *et al.* (1996, 1997), Comin-Chiaramonti *et al.* (2005c, 2014) and a general review by Comin-Chiaramonti *et al.* (2007a), including some African occurrences in Angola and Namibia, became available. The associated silicate alkaline rocks, on the other hand, have more frequently been reviewed (Ulbrich & Gomes 1981, Woolley 1987, Morbidelli *et al.* 1995, Comin-Chiaramonti *et al.* 2005a, 2005d, 2007b, 2015, Brod *et al.* 2005, Gomes *et al.* 2011a, 2011b, 2013, Gomes & Comin-Chiaramonti 2017, etc.).

According to Gomes and Comin-Chiaramonti (2017), a total of 30 carbonatite occurrences have been described,

most of them in Brazilian terrains (23), but also in Paraguay (6) and Bolivia (1) (Table 1). Included are carbonate *ocelli* in a few occurrences of fine-grained and intrusive rocks. Carbonatites are predominantly represented by intrusive and hypabissal bodies, only two groups of volcanic occurrences having been described: the lava flows of Santo Antônio da Barra, in Goiás (Gaspar & Danni 1981, Moraes 1988), and those of Sapucaí, in Paraguay (Comin-Chiaramonti *et al.* 1992). Volcanic occurrences are scarcely present, probably due to intense erosion (Morbidelli *et al.* 1995, Comin-Chiaramonti *et al.* 2005c). Carbonatites concentrate in two well-delimited areas of the Brazilian territory: the Ribeira Valley in the southeast (Ruberti *et al.* 2005, Gomes *et al.* 2011a) and the Alto Paranaíba in the central-west (Araújo *et al.* 2001, Guarino *et al.* 2013). Over the last years, these rocks have also been described near the city of Bagé (Joca Tavares and Porteira bodies; Toniolo *et al.* 2013, Monteiro *et al.* 2016) and also in

¹Instituto de Geociências, Universidade de São Paulo – USP, São Paulo (SP), Brazil. E-mails: cgomes@usp.br, rgazzone@usp.br, exrubert@usp.br, gastonenrich@usp.br

²Dipartimento di Matematica e Geoscienze, Università degli Studi di Trieste, Trieste, Italia. E-mail: piero.cominchiamonti@gmail.com

*Corresponding author.

Manuscript ID: 20170213. Received on: 10/10/2017. Approved on: 01/30/2018.

Cretaceous carbonatites, SE Brazilian Platform

Table 1. General information on the carbonatite occurrences of different regions of Brazil, Paraguay and Bolivia.

| Locality | | Occurrence | Petrography | Mineralogy | Age | References |
|-----------------------------|--------------------------------------|---------------------------|---|---|------------------|---|
| BRAZIL | | | | | | |
| Ribeira Valley | | | | | | |
| 1 | Barra do Itapirapuã | Dike, vein, breccia | Mg-ca, Fe-ca, Si-ca, Ca-ca, Fe, S, L | Do, Ank, Cc, Phl, Pr, Qz, Ap, Bas, Pa, Syn, AB, Ga, Sph | Lower Cretaceous | 1-19 |
| 2 | Ipanema | Dike, vein | Ca-ca Gl, Sh, Di, S, Fe, Te | Cc, Phl, Op, Ap, Cpx, Amp, Ba, Sf | Lower Cretaceous | 2-6, 12, 13, 15, 18-26, 59 |
| 3 | Itanhaém (Ilha das Cabras or Givura) | Dike | Mg-ca | Do, Ap, Phl, Pv, Gr, altered mafics | Lower Cretaceous | 2, 4-6, 18, 19, 21, 23, 24, 27, 28, 59 |
| 4 | Itapirapuã | Dike, vein, breccia | Ca-ca NS, I-Mel, Ti | Cc, Ap, AF, Ne, Mt, Pt | Lower Cretaceous | 2, 4-6, 12, 13, 18-19, 21, 23, 24, 29-32, 59 |
| 5 | Jacupiranga | Plug, dike | Ca-ca, Mg-ca Du, Py (Ja), I-Mel, Tr, E, Mz, Fe, Sd, S, A, AB | Cc, Do, Phl, Ol, Mt, Ap, Pr, Il, Pv, Pyr, Ga, Cl, Ne, Amp | Lower Cretaceous | 2-6, 12-15, 18, 19, 21, 23, 24, 33-48, 59 |
| 6 | Juquiá (Serrote) | Plug, dike | Mg-ca, Ca-ca Py, AG, I-Mel, NS, S, Sd, AB, Te, Pho, Fe | Do, Ank, Cc, Phl, Mt, Ba, Ap, Mo, Anc, No | Lower Cretaceous | 2-6, 12-15, 18, 19, 21, 23, 24, 41, 49-52, 59 |
| 7 | Mato Preto | Plug, breccia | Ca-ca, Fe-ca NS, Ti, Pho, Ga, I, Mel, L, Ta | Cc, Ank, Mt, Ap, Pr, Ba, Fl, Qz, AF, Flca | Lower Cretaceous | 1, 2, 4-8, 12-19, 21, 24, 27, 53-57, 59 |
| 8 | Piedade | | | | Lower Cretaceous | 12, 21, 58, 59 |
| São Paulo Coast Line | | | | | | |
| 9 | Ilhas | Dike | Mg-ca, Si-ca | Cc, Do, Phl, Ap, phyllosilicates | n.d. | 60 |
| Cabo Frio Lineament | | | | | | |
| 10. | Poços de Caldas | Dike, breccia | Si-ca, <i>ocelli</i> in lamprophyre NS, Ti, Pho, L, La, Lp, | Cc, Pr, Phl | Upper Cretaceous | 2, 5, 21, 59, 61-63 |
| Santa Catarina | | | | | | |
| 11 | Anitápolis | Plug, dike, vein | Ca-ca, Mg-ca Py, Biot, I-Mel, NS, Phos, Fe, Apt, Ne, L, Pho | Cc, Do, Ap, Mt, Ol, Phl, Pr, Bd, Qz, Al, Anc, Bas, Sf | Lower Cretaceous | 2-6, 13-15, 18, 19, 21, 23, 24, 59, 64-69 |
| 12 | Lages | Plug, dike, vein, breccia | Fe-ca, Ca-ca NS, Pho, Ba, Ne, Meli, Te, Pht, Ki | Ank, Cc, Ap, Phl, Qz, AF, Pr, Pyr, Syn, Bas | Upper Cretaceous | 2-6, 13-15, 19, 21, 23, 24, 59, 70-74 |
| Rio Grande do Sul | | | | | | |
| 13 | Joca Tavares | Plug? | Ca | Do (Cc), Ap, Op (Hm, Il), Ch | n.d. | 75, 76 |
| 14 | Porteira | Dike | Ca | Do, Ap., Flo, Op (Hm, Il), Ch | n.d. | 75, 76 |
| Alto Paranaíba | | | | | | |
| 15 | Araxá (Barreiro) | Stock, dike | Mg-ca, Ca-ca, Fe-ca Gl, Py, Phos, Sil | Do, Cc, Ank, Str, Si, Mg, Bu, Mt Ap, Phl, AF, Anc, Pr, Mo, Sf | Upper Cretaceous | 2-6, 13-15, 19, 21, 23, 24, 59, 77, 78 |
| 16 | Catalão I | Dike | Mg-ca, Ca-ca, Si-ca Phl, Du, Be, Phos, NS, Nel, Sil | Do, Cc, Mg, Ap, Phl, Mt, Ba, Ti, Mo, Zr, Pr, Sf, Fl, No | Upper Cretaceous | 2-6, 13-15, 19, 21, 23, 24, 59, 79-81 |
| 17 | Catalão II | Stock | Ca-ca, Mg-ca Py, Gl, Phos, Apt, Mgt, Fe, S, L, Sil | Cc, Phl, Ver, AF, Mt, Pr, Ba, Pyr, REE minerals | Upper Cretaceous | 2-6, 13-15, 19, 21, 23, 24, 59, 81 |

Continue...

Table 1. Continuation.

| Locality | | Occurrence | Petrography | Mineralogy | Age | References |
|----------|------------------------------------|---------------------|--|---|---------------------|--|
| 18 | Salitre | Stock, dike, vein | Ca-ca, Mg-ca Be, Py, Du, Phos, NS, S, Ti, T | Cc, Do, Ap, Mt, Phl, Ol, Pr, Zr, Ba, Sf | Upper Cretaceous | 2-6, 13-15, 21, 23, 24, 59, 81-86 |
| 19 | Tapira | Stock, dike, vein | Ca-ca, Mg-ca Be, Du, Pe, Py, Phos, S, T, Melil, Ka | Cc, Do, Ap, Phl, Mt, Pr, Il, Pv, Ti, Pyr | Upper Cretaceous | 2-6, 13-15, 19, 21, 23, 24, 59, 81, 87-90 |
| 20 | Serra Negra | Plug | Ca-ca Du, Be, Sh, Py (Ja), Ti, T, Fe | Cc, Mt, Ap, Pr, Pv, Bd | Upper Cretaceous | 2-6, 13, 21, 23, 24, 59, 81, 91-93 |
| Goiás | | | | | | |
| 21 | Caiapó | Plug, breccia | Mg-ca, Ca-ca, Fe-ca I, L, Fe | Do, Cc, Ank, Si, Ap, Mt, Pr, AF, Qz, REE minerals | n.d. | 4-6, 13 |
| 22 | Morro do Engenho | Vein | Ca Py, Pe, AG, NS | Cc, Phl | n.d. | 2, 4-6, 13, 90, 94 |
| 23 | Santo Antônio da Barra (Rio Verde) | Lava, breccia, plug | Si-ca, Ca-ca Ana (?), Ka, Pho, T, Phou, Mo, Br | Cc aggregate in vitreous matrix | Upper Cretaceous | 4-6, 13, 21, 24, 59, 90, 95-99 |
| PARAGUAY | | | | | | |
| Rio Apa | | | | | | |
| 24 | Valle-mí | Dike | Ocelli in basanite | Cc | Lower Cretaceous | 13, 14, 19, 41, 100-106 |
| Amambay | | | | | | |
| 25 | Cerro Chiriguelo (Cerro Corá) | Dike | Ca-ca, Fe-ca Fe, NS, T | Cc, Ap, AB, Qz, Phl, AF, Mt, Cpx, Zr, Ura, Syn, Hm, Pyr, Go | Lower Cretaceous | 2, 5, 13, 14, 19, 21, 41, 59, 100, 102-111 |
| 26 | Cerro Sarambí | Dike | Ca-ca, Si-ca Py, NS, Fe, Pho, T, L | Cc, Qz, Fl, Ver, Op | Lower Cretaceous | 2, 5, 13, 14, 19, 41, 100, 102-106, 109, 111, 112 |
| Central | | | | | | |
| 27 | Cerro Cañada | Stock | Ocelli in ijolite AG, NS, I | Cpx, Ol, Bi, Cc | Lower Cretaceous | 103-106, |
| 28 | Cerro E Santa Elena | Stock | Ocelli in ijolite Ga, I, Te, Ba, AB, Tph | Cpx, Ol, Mt, Amp, Bi, Cc | Lower Cretaceous | 103-106-111, |
| 29 | Sapucai | Lava | Mg-ca | Do, AF, Mt, Bi, Ap | Lower Cretaceous | 41, 103-106- 111, 113 |
| BOLIVIA | | | | | | |
| Velasco | | | | | | |
| 30 | Cerro Manomó | Dike | Si-ca NS, S, Gr, Tph, T | Si, Ank, Cc, Go, Li, Qz, Ap, Bas, Syn | Lower Cretaceous | 2, 5, 114-116 |

Data sources: Barra do Itapirapuã: 1, Lapido-Loureiro & Tavares (1983); 2, Almeida (1983); 3, Berbert (1984); 4, Rodrigues & Lima (1984); 5, Woolley (1987); 6, Gomes et al. (1990); 7, Ruberti et al. (1997); 8, Speziale et al. (1997); 9, Andrade et al. (1999a); 10, Andrade et al. (1999b); 11, Ruberti et al. (2002); 12, Ruberti et al. (2005); 13, Comin-Chiaramonti et al. (2005a); 14, Comin-Chiaramonti et al. (2005d); 15, Biondi (2005); 16, Ruberti (1998); 17, Ruberti et al. (2008); 18, Gomes et al. (2011a); 19, Comin-Chiaramonti et al. (2007a); Ipanema: 20, Leinz (1940); 21, Sonoki & Garda (1988); 22, Davino (1975); 23, Ulbrich & Gomes (1981); 24, Morbidelli et al. (1995); 25, Guarino et al. (2012); 26, Ruginski et al. (2006); Itanhaém: 27, Coutinho & Ens (1992); 28, Mariano (1989); Itapirapuã: 29, Gomes & Cordani (1965); 30, Gomes & Dutra (1969); 31, Gomes (1970); 32, Gomes & Dutra (1970); Jacupiranga: 33, Melcher (1966); 34, Amaral (1978); 35, Gaspar (1989); 36, Ruberti et al. (1988); 37, Roden et al. (1985); 38, Germann et al. (1987); 39, Menezes & Martins (1984); 40, Morbidelli et al. (1986); 41, Castorina et al. (1996); 42, Santos & Clayton (1995); 43, Huang et al. (1995); 44, Ruberti et al. (1991); 45, Gomes et al. (1996a); 46, Azzone et al. (2012); 47, Beccaluva et al. (2017); 48, Chmyz et al. (2017); Juquiá: 49, Born (1971); 50, Beccaluva et al. (1992); 51, Walter et al. (1995); 52, Azzone et al. (2013);

Mato Preto: 53, Jenkis II (1987); 54, Santos (1988); 55, Santos *et al.* (1996); 56, Santos *et al.* (1990); 57, Comin-Chiaramonti *et al.* (2001); **Piedade:** 58, Knecht (1960); 59, Amaral *et al.* (1967); **Ilhas:** 60, Coutinho (2008); **Poços de Caldas:** 61, Ulbrich *et al.* (2002); 62, Vlach *et al.* (2003); 63, Ulbrich *et al.* (2005); **Anitápolis:** 64, Melcher & Coutinho (1966); 65, Rodrigues (1985); **65, Furtado** (1986); 67, Furtado (1989); 68, Comin-Chiaramonti *et al.* (2002); 69, Scheibe *et al.* (2005); **Lages:** 70, Scheibe & Formoso (1982); 71, Scheibe (1986); 72, Traversa *et al.* (1994); 73, Traversa *et al.* (1996); 74, Barabino *et al.* (2007); **Joca Tavares and Porteira:** 75, Toniolo *et al.* (2013); 76, Monteiro *et al.* (2016); **Araxá:** 77, Issa Filho *et al.* (1984); 78, Traversa *et al.* (2001); **Catalão I:** 79, Carvalho & Bressan (1981); 80, Cordeiro *et al.* (2010); 81, Gomes & Comin-Chiaramonti (2005); **Salitre:** 82, Morbidelli *et al.* (1997); 83, Barbosa (2009); 84, Barbosa *et al.* (2012a); 85, Barbosa *et al.* (2012b); 86, Haggerty & Mariano (1983); **Tapira:** 87, Guimarães *et al.* (1980); 88, Brod (1999); 89, Brod *et al.* (2000); 90, Brod *et al.* (2005); **Serra Negra:** 91, Mariano & Marchetto (1991); 92, Souza Filho (1974); 93, Grasso (2010); **Morro do Engenho:** 94, Pena (1974); **Santo Antônio da Barra:** 95, Gaspar & Danni (1981); 96, Moraes (1984); 97, Moraes (1988); 98, Sgarbi (1998); 99, Junqueira-Brod *et al.* (2002); **Valle-mí:** 100, Livieres e Quade (1987); 101, Gibson *et al.* (1995a); 102, Gomes *et al.* (1996b); 103, Castorina *et al.* (1997); 104, Comin-Chiaramonti *et al.* (2007b); 105, Gomes *et al.* (2013); 106, Comin-Chiaramonti *et al.* (2014); **Cerro Chiriguelo:** 107, Comte & Hasui (1971); 108, Censi *et al.* (1989); 109, Comin-Chiaramonti *et al.* (1999); 110, Gibson *et al.* (2006); 111, Comin-Chiaramonti *et al.* (2007c); **Cerro Sarambí:** 112, Gomes *et al.* (2011b); **Sapucai:** 113, Comin-Chiaramonti *et al.* (1992); **Cerro Manomó:** 114, Fletcher *et al.* (1981); 115, Comin-Chiaramonti *et al.* (2005b); 116, Comin-Chiaramonti *et al.* (2011). Other references consulted are listed in Gomes and Comin-Chiaramonti (2017).

Rock abbreviations: A, ankaratrite; AB, alkali basalt; AG, alkali gabbro; Ana, analcinite; Apt, apatite; Ba, basanite; Be, bebedourite; Biot, biotite; Ca, carbonatite; Ca-ca, calciocarbonatite; Di, diorite; Du, dunite; E, essexite; Fe, fenite; Fe-ca, ferrocronatite; Fou, fourchite; Ga, gabbro; Gl, glimmerite; Gr, granite; I, ijolite; Ja, jacupiranguite; Ka, kamafugite; Ki, kimberlite; L, lamprophyre; Lp, lamproite; Mel, melteigite; Meli, melilitite; Melil, melilitolite; Mgt, magnetite; MMzd, melamonzodiorite; Mo, monchiquite; Mz, monzonite; Ne, nephelinite; Nel, nelsonite; NS, nepheline syenite; Pc, picrite; Pe, peridotite; Phl, phlogopite; Pho, phonolite; Phos, phoscorite; Pht, phonotephrite; Py, pyroxenite; S, syenite; Sd, syenodiorite; Sh, shonkinite; Si-ca, silicocarbonatite; Sil, silxite; T, trachyte; Ta, trachyandesite; Te, tephrite; Tph, trachyphonolite; Ti, tinguaitite; Tr, theralite; Ur, urtite; We, wehrlite.

Mineral abbreviations: AF, alkali feldspar; Al, alstonite; Amp, amphibole; An, ancyllite; Ank, ankerite; Ap, apatite; Ba, barite; Bas, bastnaesite; Bd, baddeleyite; Bi, biotite; Bu, burbankite; Caz, calzirtite; Cc, calcite; Ch, chlorite; Cl, clinohumite; Cpx, clinopyroxene; Do, dolomite; F, feldspar; Fl, fluorite; Flca, fluorocarbonates; Ga, galena; Go, goethite; Gr, garnet; Hb, hornblende; Hm, hematite; Il, ilmenite; Mg, magnesite; Mt, magnetite; Mo, monazite; Ne, nepheline; No, norsethite; Ol, olivine; Op, opaques; Pa, parisite; Phl, phlogopite; Pyr, pyrite; Pr, pyrochlore; Pt, pyrrhotite; Pv, perovskite; Sph, sphalerite; Str, strontianite; Qz, quartz; Sf, sulfide; Si, siderite; Sy, synchysite; Ti, titanite; To, thorite; Ura, uranopyrochlore; Ver, vermiculite; Zir, zirconolite; Zr, zircon.

Caçapava do Sul (Passo Feio and Picada dos Tocos) and Lavra do Sul (Três Estradas) areas (Rocha *et al.* 2013, Toniolo *et al.* 2013, Maciel 2016, Cerva-Alves *et al.* 2017), all in the Rio Grande do Sul State. Because the last three intrusions are believed to be of Proterozoic age, with U-Pb zircon data indicating a ca. value of 603.2 ± 4.5 Ma for the Picada dos Tocos beforosite (Cerva-Alves *et al.* 2017), they are excluded of this study. Other important carbonatitic occurrences are the Amambay (Cerro Chiriguelo, Cerro Sarambí; Comin-Chiaramonti *et al.* 2014) and Velasco (Cerro Manomó; Comin-Chiaramonti *et al.* 2011) regions in Paraguay and Bolivia, respectively. Figure 1 shows the distribution of alkaline and alkaline-carbonatite occurrences in the three countries.

The present paper reviews general aspects of carbonatite bodies represented by not only well-defined structures and a variety of dikes and veins, but also small aggregates (*ocelli*) in coarse and fine-grained alkaline silicate rocks.

GEOLOGICAL SETTING

The most remarkable alkaline-carbonatite complexes of the southeastern Brazilian Platform usually show intrusive/subintrusive, subcircular or oval-shaped structures that are clearly discerned in aerial photographs and are indicative of high emplacement energy. In general, carbonatites are found chiefly as stocks, plugs, dikes, dike swarms, and veins, forming occasionally complex systems (stockworks) as in Barra do Itaipirapuá in the Ribeira Valley (Ruberti *et al.* 2002, 2008), where distinct events may be recognized from a network of multiple intrusions. Dikes and veins

constitute single bodies or complex systems that cut associated alkaline silicate rocks or penetrate country rocks. Occasionally, dikes conform to a radial or ring-like distribution. Sometimes, they correspond to more than one rock generation phase, like in Barra do Itaipirapuá (Ruberti *et al.* 2002, 2008), Juquiá (Walter *et al.* 1995) and Cerro Chiriguelo (Censi *et al.* 1989) districts, for example. Carbonatites and their associated alkaline rocks are commonly emplaced into Precambrian groups (e.g., Açungui, Araxá, Canastra, etc.) and have quartzites, schists, granites and gneisses as their main country rocks. However, some complexes also intrude sedimentary rocks of different types and ages, the regional rocks consisting, in a few cases (e.g., Lages and Santo Antônio da Barra), of tholeiitic basalts of the Paraná Basin.

In most cases, the emplacement of alkaline-carbonatite complexes is controlled by ancient tectonic features that were reactivated in Mesozoic times, related mainly to regional structures such as arches, lineaments and rifts. These tectonic alignments have been active since Lower Cretaceous, as suggested by the distribution of earthquakes in southern Brazil (Berrocal & Fernandes 1996). The most prominent tectonic lineaments are represented by deep, NW-trending parallel fractures clearly associated with arch structures (Almeida 1971) and, apparently, in some cases, by old NE-trending fault zones as in Itanhaém (Coutinho & Ens 1992) and Cerro Manomó (Comin-Chiaramonti *et al.* 2005d). In the Ribeira Valley, emplacement was tectonically related to the Ponta Grossa Arch (Algate 1972), a NW-trending uplift structure active since Paleozoic times that consists of four different lineaments (Guapiara, São Jerônimo-Curiúva, Rio Alonso and Piqueri; Almeida 1983). The

major Jacupiranga and Juquiá complexes are related to the Guapiara Lineament, whereas Barra do Itapirapuá, Itapirapuá and Mato Preto ones associate with the São Jerônimo-Curiúva Lineament. Other occurrences in the region (Ipanema, Itanhaém and Piedade) are linked to the Piedade Lineament, a parallel structural feature lying to the south (Riccomini *et al.* 2005). The Alto Paranaíba complexes in Minas Gerais (Araxá, Catalão I and II, Salitre, Serra Negra, and Tapira) follow a NW-trending linear structure that borders the São Francisco Craton, as indicated by aeromagnetic surveys, corresponding to a well-marked regional high, the Alto Paranaíba Uplift (Hasui *et al.* 1975). In the state of Goiás, occurrences (Caiapó, Morro do Engenho and Santo Antônio da Barra) are controlled by a pronounced NW-trending alignment that shows rift tectonics characteristics (Almeida 1983). Considering the distribution of alkaline bodies in both areas along NW-trending crustal discontinuities, that extend for considerable distances, and the nature of the magmatism, Riccomini *et al.* (2005) postulated that deep lithospheric faults played a major role in the tectonic control of these carbonatitic occurrences. According to these authors, the emplacement of carbonatites in the state of Santa Catarina is still a matter of debate: Lages appears to have been subject to NW-trending faults, whereas Anitápolis does not show a clear structural control. In the specific case of Anitápolis, Melcher and Coutinho (1966) pointed out the influence of N-S-trending faults. Comin-Chiaramonti *et al.* (2005c) proposed the Uruguay Lineament to have controlled the emplacement of both complexes. The recently described occurrences in Rio Grande do Sul (Jocas Tavares and Porteira) are structurally controlled by NE-trending faults related to the Ibaré Lineament (Costa *et al.* 1995). In Amambay, northeastern Paraguay, the Cerro Chiriguelo and Cerro Sarambí complexes are tectonically related to the NE-trending Ponta Porã Arch (Livieres & Quade 1987, Comin-Chiaramonti *et al.* 1999). There, more intense magnetic anomalies at the southwestern end of the arch seem to support such a hypothesis (Velázquez *et al.* 1998). Comin-Chiaramonti *et al.* (2005c) also recall that both these Paraguayan complexes and the Valle-mí dikes are mainly found along the Piquiri Lineament. Sapucaí in central-eastern Paraguay is located within the domains of the Asunción Rift and its associated faults.

Deep and extensive weathering processes are characteristics of alkaline-carbonatite occurrences, rocks being usually covered by laterite layers that can reach 300 m thick. Soils originate mainly from alteration of cumulate (ultramafic) rocks and from dissolution of carbonates of carbonatites. As a result, large supergenic and

residual deposits of apatite, pyrochlore, vermiculite, anatase and REE carbonates and phosphates can be present (Biondi 2005). Fresh rocks are usually scarce or even inexistent at surface, and samples for petrological studies are obtained mostly from drill cores. Jacupiranga is the only exception, presently mined for phosphate (Morro da Mina) with good local exposures that allow for sampling of fresh rock.

PETROGRAPHIC AND MINERALOGICAL CONSIDERATIONS

The carbonatites are characterized by a large variation in grain-size and texture, that grades from equi- to inequi-granular and hypidiomorphic to allotriomorphic or even seriate. Other common features include structural flow with alignment of elongated crystals (e.g. apatite), presence of brecciated and xenolithic material, and typical banding from differential concentration of minerals, particularly apatite, phlogopite, olivine and magnetite, as well evidenced in Jacupiranga carbonatites (Melcher 1966, Morbidelli *et al.* 1986, Chmyz *et al.* 2017).

The carbonatites are associated (or spatially rather than genetically associated, as postulated by Gittins & Harmer 2003) with silicate rock types of varied composition, mainly cumulates of different petrographic and compositional characteristics. They are found in close contact with ultrabasic-ultramafic lithologies having dunites, peridotites and pyroxenites as their main representative variants (Tab. 1). These rocks are abundant and well-exposed at surface in the Jacupiranga (Melcher 1966, German *et al.* 1987) and Juquiá (Born 1971, Beccaluva *et al.* 1992) complexes, but are also present in a large number of occurrences. Other cumulates associated with carbonatites are glimmerites, especially in Ipanema (Guarino *et al.* 2012) and Catalão (Machado Jr. 1991, Carvalho & Bressan 1997, Cordeiro *et al.* 2010); bebedourites in Alto Paranaíba complexes, notably in Salitre (Barbosa 2009, Barbosa *et al.* 2012a, 2012b) and Tapira (Brod *et al.* 2013); phoscorites in Anitápolis (Furtado *et al.* 1986, Scheibe *et al.* 2005), Ipanema (Guarino *et al.* 2012) and several bodies in Alto Paranaíba (Cordeiro *et al.* 2010, Guarino *et al.* 2017); kamaflagites, kimberlites, lamproites and picrites. All these rock types are practically restricted to occurrences in Minas Gerais and Goiás (Danni 1994, Meyer *et al.* 1994, Gibson *et al.* 1995a, 1995b, Brod *et al.* 2000, 2005, Sgarbi *et al.* 2000, Junqueira-Brod *et al.* 2000, 2002, Melluso *et al.* 2008, Guarino *et al.* 2013, 2017), except for the presence of kimberlites in Lages (Scheibe *et al.* 2005) and kimberlites and

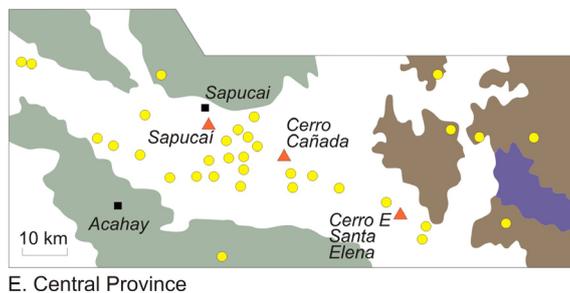
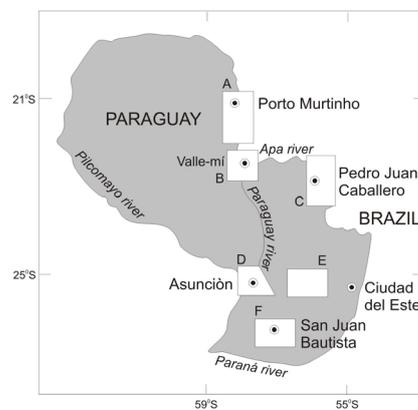
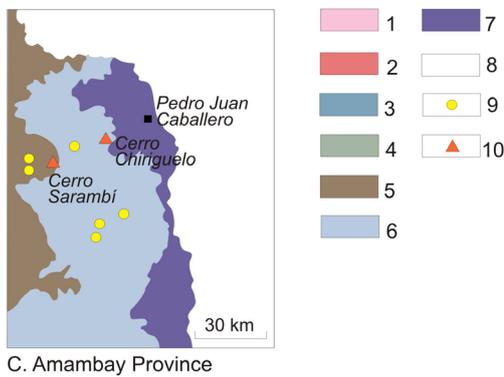
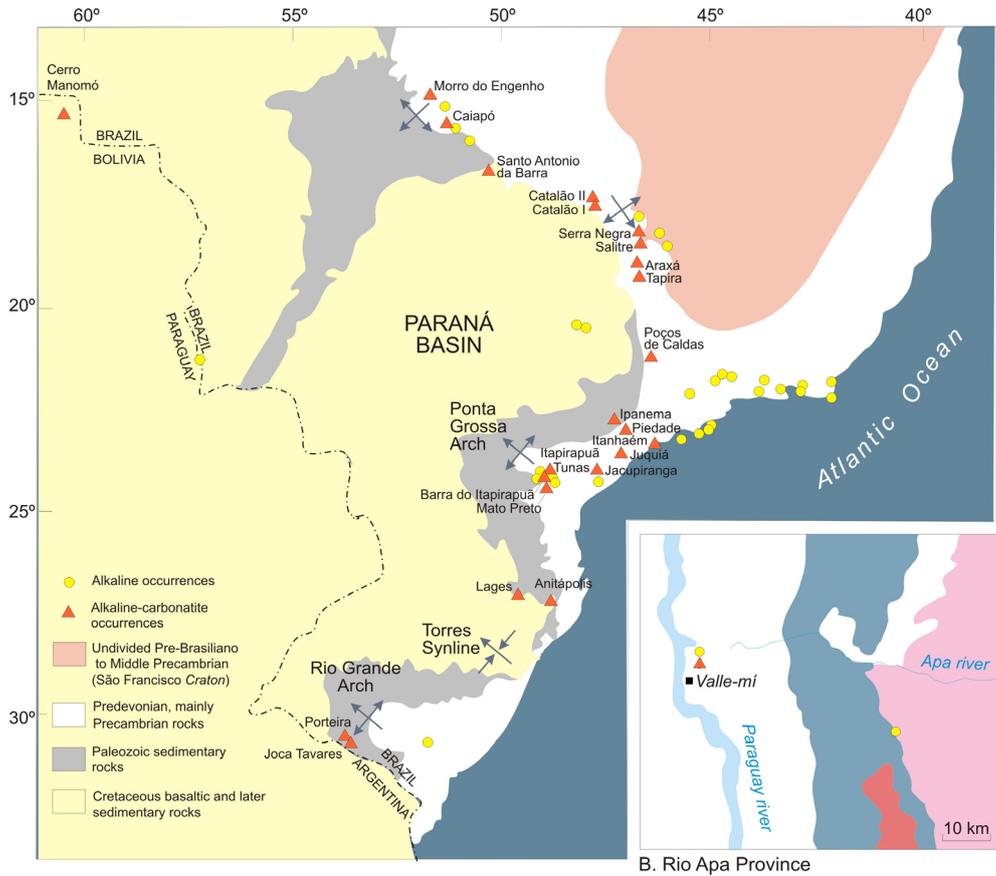


Figure 1. Schematic maps showing the distribution of alkaline and alkaline-carbonatite occurrences in Brazil (after Ulbrich & Gomes, 1981, modified) and Paraguay (after Gomes *et al.* 2013, simplified). Also, indicated is the location of the Cerro Manomó in Bolivia. Captions for the Paraguayan rocks: (1) Lower Precambrian, Rio Apa Complex; (2) Upper Precambrian, Alumiador Intrusive Suite; (3) Cambrian Sediments, Itapucumi Group; (4) Silurian Sediments, Caacupé Group; (5) Carboniferous Sediments, Cerro Corá Group; (6) Triassic Sediments, Misiones Formation; (7) Cretaceous Tholeiitic Magmatism, Alto Paraná Formation (Serra Geral Formation in Brazil); (8) Tertiary and Quaternary Sediments; (9) Alkaline occurrences; (10) Alkaline-carbonatite occurrences.

lamproites in Rio Grande do Sul (Philipp *et al.* 2005). Monomineralic cumulatic rocks (apatites, magnetites, phlogopites) were described in a few complexes (e.g., Anitápolis, Ipanema and Catalão) as small segregations forming decimetric to metric irregular bands.

Association of carbonatites and alkaline gabbros of the melteigite-ijolite-urtite series is quite frequent. It chiefly characterizes the alkaline-carbonatites of southeastern Brazil, especially in the Ribeira Valley, being particularly frequent in Jacupiranga and Juquiá and of subordinate presence in other districts (Ruberti *et al.* 2005, Gomes *et al.* 2011a). Association with lithologies of syenitic composition represented by coarse-grained (nepheline syenites, syenites) and fine-grained (phonolites, trachytes) rock types (Beccaluva *et al.* 1992, Ruberti *et al.* 2002) is also frequent. The presence of fenites, mostly of syenitic composition, is notable. Syenodioritic and dioritic fenites are scarce. Fenites are described in many carbonatitic bodies as forming irregular masses in the inner parts of the alkaline intrusions or being concentrated along their borders. Fenitization processes are occasionally responsible for aureoles in country rock that can reach tens of meters wide (e.g., 2.5 km in Araxá, Rodrigues & Lima 1984; 2.0 km in Jacupiranga, Gaspar 1989). Fenites do not usually constitute individual mappable units. They are interpreted as metasomatic bodies originated by either magmatic fluids enriched in Na and/or K and F from carbonatitic or alkaline silicatic magmas acting on the associated alkaline rocks and country rocks. Such processes can be of sodic or potassic nature, as suggested by changes in the chemical composition and texture of the rocks and by mineralogical evidences, notably the presence of sodic pyroxene and/or amphibole in the first case, and the appearance of alkali potassic feldspar in the second case (Le Bas 2008). Evidence of fenitization has been reported for a large numbers of alkaline-carbonatite complexes, especially where carbonatites are in direct contact with ultrabasic rocks (e.g., Morbidelli *et al.* 1986, Guarino *et al.* 2012). Jacupiranga is the best example of such an association, with pyroxenites (jacupirangites) and carbonatites forming reaction bands from fenitization of older ultrabasic rocks by alkali-enriched metasomatic fluids derived from carbonatite magma. This type of reaction bands was investigated in detail by Morbidelli *et al.* (1986), who distinguished among concentric, centimeter-to-decimeter layers consisting of alternating carbonate and silicate material. Amphibolitization and phlogopitization of the pyroxenitic protolith by alkali-enriched fluids associated with carbonatitic magmas seem to be a constant feature in almost all Brazilian and Paraguayan carbonatite complexes (Haggerty & Mariano 1983, Gomes *et al.* 1990).

Petrographic associations allow the major alkaline-carbonatite complexes to be identified as *primary* or *magmatic carbonatites*, as defined by Mitchell (2005) and Woolley and Kjarsgaard (2008). Yet, they allow most carbonatites to be included in at least two different clans that conform in general terms the geographic distribution areas of the occurrences.

The *nephelinite-clan carbonatites* (Mitchell 2005) or *carbonatite occurrences with melteigite-ijolite-urtite (no nephelinite extrusive rocks*, Woolley & Kjarsgaard 2008) are a classical association, ijolite being the predominant rock type. They represent about 20% of the magmatic carbonatite occurrences known to the latter authors worldwide. Ultramafic bodies (pyroxenites or olivinites or both), interpreted as cumulates, correspond to 60% of the occurrences, whereas nepheline syenites and syenites, along with rocks of the melteigite-ijolite-urtite series, are present in 84% of the cases. Considering the occurrences reviewed in the present study, this is the most abundant association, being represented mainly by the Lower Cretaceous complexes of the Ribeira Valley (Ipanema, Itapirapuá, Jacupiranga, Juquiá), Santa Catarina (Anitápolis) and Paraguay (Cerro Sarambí) and the Upper Cretaceous intrusions of Mato Preto, also in the Ribeira Valley and, apparently, Caiapó and Morro do Engenho in Goiás.

Melilite-clan carbonatites (Mitchell 2005) and *carbonatite occurrences with melilite-bearing (melilitolite) intrusive rocks* (Woolley & Kjarsgaard 2008) associations are not very common, even at global scale. Only 13 (3%) of a total 403 published occurrences are listed by the latter authors, some of them bearing rocks of the melteigite-ijolite-urtite series, nepheline syenites or syenites (or both) and, frequently, phoscorites. Mitchell (2005) included the Upper Cretaceous Alto Paranaíba complexes of Araxá, Catalão and Tapira in this clan, stressing that Minas Gerais is one of the three regions in the world characterized by extensive development of melilitolite-bearing complexes. The author also emphasized the paucity of nepheline syenite and ijolite-urtite as a representative feature that distinguishes melilitolite complexes from plutonic rocks of the nephelinite clan. Apparently, only the Tapira occurrence is known to include melilite-bearing rocks. Guimarães *et al.* (1980) reported the presence of a dike of uncomphgrite (an ultramelilitolite according to Dunworth & Bell 1998) in which the modal content of the mineral reaches up to 63%. The inclusion of Tapira in this clan was also confirmed by Woolley and Kjarsgaard (2008). However, the other Alto Paranaíba complexes were included in a new clan, the *carbonatite occurrences with only olivinite and pyroxenite as ultramafic rocks (± syenite)*. This clan is characterized by a broad spectrum of ultramafic rocks including olivinites (dunites), peridotites, pyroxenites, amphibolites and glimmerites among the carbonatite complexes. Additional

rock types are phoscorites, nepheline syenites and syenites (or both). In some localities, carbonatites form km-scale diameter ore-hosting bodies with Nb (pyrochlore), phosphate and vermiculite. Rocks of the melteigite-ijolite-urtite series are missing. Guarino *et al.* (2017) emphasized the close relationship of Alto Paranaíba carbonatites and phlogopite picrites and ultramafic lamprophyres.

Although not mentioned by either Mitchell (2005) or Woolley and Kjarsgaard (2008), melilite-bearing rocks are also found in an Upper Cretaceous alkaline-carbonatite occurrence in Lages, State of Santa Catarina (Traversa *et al.* 1994, 1996, Gibson *et al.* 1999). Their occurrence is of very complex composition, consisting of large amounts of syenitic rocks (predominantly phonolites and peralkaline phonolites), carbonatites, ultrabasic types that occur mainly as dikes, and kimberlites. Outcrops of olivine melilitites are described in various places in Lages, Cerro Alto de Cima, a semiring, 50 m wide dike being the most significant body (Scheibe 1986).

More recently, Beccaluva *et al.* (2017) noticed the presence of melilite with modal content higher than 10% in ijolitic rocks of the Jacupiranga carbonatites.

Additionally, the overall petrographic association allows to distinguish a new group of carbonatites, the *hydrothermal* ones (also referred to as carbothermals by Mitchell 2005; or carbohydrothermals by Woolley & Kjarsgaard 2008). These latter authors define carbohydrothermal carbonatites as formed by precipitation at subsolidus temperatures, from a mixed CO₂-H₂O fluid that can be either CO₂-rich (i.e., carbothermal), or H₂O-rich (i.e., hydrothermal). Mitchell (2005) added variable proportions of F to the composition of the low-temperature fluids. A statistical study performed by Woolley and Kjarsgaard (2008) indicated that carbohydrothermal carbonatites amounted to 74 out of the 477 occurrences (magmatic carbonatites included) in the world, 54 of them being predominantly associated with intrusive alkali silicate rocks. Their research also made evident that syenitic rocks (feldspathoidal syenites, syenites and quartz syenites) constitute the dominant silicate rock in this association. Also according to Woolley and Kjarsgaard (2008), these occurrences typically consist of calcite ± barite ± fluorite ± quartz ± sulfides ± K-feldspar ± zeolites. However, the hydrothermal stages can also have involved enrichment in elements such as Th, REE and F, as reflected in the mineralogical assemblage, that bears REE fluorocarbonates, fluorite and other fluoride phases. Based on chemical and mineralogical evidence, notably the presence of rare accessory phases like ancylite, bastnäesite, synchysite, parisite, etc., Barra do Itapirapuã (Ruberti *et al.* 2002, 2008), Cerro Chiriguelo (Haggerty & Mariano 1983, Censi *et al.* 1989) and Cerro Manomó (Fletcher *et al.* 1981, Comin-Chiaramonti *et al.* 2005d, 2011) complexes fall within the hydrothermal group.

No data is presently available on the Piedade (SP), Jocas Tavares (RS) and Porteira (RS) carbonatites, but, considering the occurrence of alkaline rocks in Rio Grande do Sul, represented by the phonolitic suite of Piratini (Barbieri *et al.* 1987), it is possible that both bodies correlate with the aforementioned volcanism event. Woolley and Kjarsgaard (2008) described the occurrence of carbonatite with only phonolite or feldspathoidal syenite, without any ultramafic cumulates or members of the melteigite-ijolite-urtite series or melilite-bearing rocks. This association is considered to be the third most significant one, with carbonatite intrusions forming small dikes into larger bodies.

Other carbonatitic occurrences are represented by small dikes in Itanhaém (Coutinho & Ens 1992) and in an island on the coast of the State of São Paulo (Ilhas, Coutinho 2008); dikes and ultramafic silico-carbonatitic plugs and carbonatitic fragments within volcanoclastic deposits in the Poços de Caldas alkaline complex (Ulbrich *et al.* 2002, 2005, Vlach *et al.* 2003, Alves 2003); and as minor aggregates (*ocelli*) in association with fine-grained (Valle-mí) and coarse-grained (Cerro Cañada and Cerro E Santa Elena) silicate alkaline rocks in Paraguay (Castorina *et al.* 1997, Comin-Chiaramonti *et al.* 2007a, Gomes & Comin-Chiaramonti 2017).

Carbonatites are predominantly calcic (sövites-alvikites) and, even in more magnesian (beforsites) intrusions (e.g., Araxá, Barra do Itapirapuã, Juquiá, etc.), calcite is an important constituent. A more iron-rich composition with ankerite as the chief mineral form is present in Lages and Cerro Manomó, for example (Comin-Chiaramonti *et al.* 2002, 2011). The three primary end-member minerals are not usually found in the same complex, Barra do Itapirapuã and Juquiá being the most noticeable exceptions, with such phases present in different stages of intrusion. More commonly, carbonate minerals exhibit a complex and varied chemical composition, due mainly to post-magmatic changes induced by hydrothermal and deuteric-groundwater processes, as described by Comin-Chiaramonti *et al.* (2007a) in many occurrences of Lower Cretaceous (e.g., Barra do Itapirapuã, Cerro Chiriguelo) and Upper Cretaceous (e.g., Lages, Mato Preto). A secondary, hydrothermal mineralogical assemblage is the main characteristic of some complexes bearing heterogeneous and complex chemical composition phases enriched in Nb, Ti, Zr, Th, U, F, Ba, and REE. Araxá and Barra do Itapirapuã are good examples of a mineral assemblage consisting of REE-bearing carbonates, fluorocarbonates and phosphates, which was intensively investigated by Traversa *et al.* (2001) and Ruberti *et al.* (2008), respectively. Additional mineral information is also found in the studies by Fletcher *et al.* (1981, on Cerro Manomó), Haggerty and Mariano (1983, on Salitre, Cerro Chiriguelo and Cerro Sarambí) and Menezes Jr. and Martins (1984, on Jacupiranga). Table 7.1

of Gomes and Comin-Chiaramonti (2017) compiles a great number of less common and even exotic minerals related to alkaline-carbonatite complexes, including sorosilicates (*lamprophyllite*, *rosenbuschite*, *Sr-chevkinite*), cyclosilicates (*eudialyte*, *wadeite*), inosilicates (*pectolite*, *serandite*, *wollastonite*), phyllosilicates (*neptunite*), oxides and hydroxides (*baddeleyite*, *loparite*, *menezesite*, *perovskite*, *pyrochlore*, *zirconolite*), carbonates (*alstonite*, *ancylite*, *bastnäesite*, *breunnerite*, *burbankite*, *cordyllite*, *magnesite*, *norsethite*, *olekminskite*, *parisite*, *remondite*, *shortite*, *strontianite*, *synchysite*, *witherite*), and phosphates (*britholite*, *galgenbergite*, *gorceixite*, *monazite*). Although not cited in Table 7.1, the following should be also mentioned: carbonates (*ankerite*, *kutnehorite*, *rodochrosite*, *siderite*), fluorides (*fluorite*), oxides (*calzirtite*, *geikielite*, *uranopyrochlore*), phosphates (*dahlite*), sulphates (*barite*, *celestine*), and sulfides (*chalcopyrite*, *galena*, *phylotite*, *pyrite*, *sphalerite*).

AGES

Except for a small number of occurrences such as Barra do Itapirapuá, Jacupiranga and Poços de Caldas (Ruberti *et al.* 1997, Chmyz *et al.* 2017, Vlach *et al.* 2003, respectively), whose ages were determined directly from carbonatites and their mineral constituents, most available data resulted from analysis of associated silicate alkaline rocks (whole-rock and mineral concentrates of different minerals). Data for all presently known alkaline-carbonatite occurrences indicates that these rocks are of Cretaceous age, with two clearly distinguished formation intervals, 120–140 Ma and 70–90 Ma, Lower Cretaceous and Upper Cretaceous (Ulbrich & Gomes 1981, Rodrigues & Lima 1984, Berbert 1984, Gomes *et al.* 1990, Gibson *et al.* 1995a, Ruberti *et al.* 2005, Comin-Chiaramonti *et al.* 2007a, 2007b, Gomes *et al.* 2011a, 2011b, 2013, Gomes & Comin-Chiaramonti 2017). Preferred ages for the occurrences are shown in Figure 2.

Lower Cretaceous

Although some results are yet to be confirmed by new analytical methods, this interval is apparently represented by three distinct generation episodes. The oldest age of ~139 Ma is suggested for the Amambay (Cerro Chirigué and Cerro Sarambí), Rio Apa (Valle-mí) occurrences in northern Paraguay and Cerro Manomó in southeastern Bolivia. An average approximately 130 Ma age characterizes the Ribeira Valley complexes (Barra do Itapirapuá, Ipanema, Itanhaém, Jacupiranga, Juquiá and Piedade) in southeastern Brazil and also Anitápolis to the south, in the State of Santa Catarina. Carbonatite flows cropping out nearby the village of Sapucaí and ijolitic rocks of Cerro Cañada and Cerro E Santa Elena, all in central-eastern Paraguay, are probably

related to the same magmatic event. The Itapirapuá massif, also in the Ribeira Valley, seems to represent the youngest Lower Cretaceous episode, with ages in the 100–110 Ma range, as suggested by old K-Ar results (Gomes & Cordani 1965) confirmed by recent Ar-Ar and U-Pb SHRIMP determinations (Gomes *et al.* 2018).

Upper Cretaceous

The Alto Paranaíba (Araxá, Catalão I and II, Salitre, Serra Negra and Tapira) and Goiás (Santo Antônio da Barra) complexes in central-western Brazil, together with Mato Preto and Lages complexes in the south, have ages that fall within the 70–90 Ma interval. The Joca Tavares and Porteira bodies in the State of Rio Grande do Sul probably belong to the same interval.

It is also important to notice that three of the above ages fit the chronogroups of 133 Ma, 108 Ma and 84 Ma proposed by Ulbrich *et al.* (1991) to define peaks of alkaline magmatism along the borders of the Paraná Basin. These chronogroups are believed to represent different phases of evolution of the basaltic and alkaline magmatism in the South Atlantic Plate. They stress the coherent relationship of this volcano-tectonic cycle to important changes in the position of rotation poles and spreading rates of the South American and African plates (Herz 1977, Sadowski 1987).

GEOCHEMISTRY

Major elements

Chemical data indicates that the carbonatites range in composition from calciocarbonatites to magnesiocarbonatites to ferrocarnatites. However, association of these different petrographic types in a same complex is rare (e.g., Araxá, Barra do Itapirapuá, Juquiá). Plottings of whole-rock chemistry data in CaO-MgO-(FeO + MnO) classification diagrams (Woolley & Kempe 1989) are discussed in various papers (e.g., Comin-Chiaramonti *et al.* 2001, 2002, 2005c, 2007a, Gomide *et al.* 2016). They usually stress the large chemical variation of carbonatites, analyses covering the three, Ca, Mg and Fe compositional fields. Calciocarbonatites are the most abundant types, followed by magnesiocarbonatites. Calciocarbonatites constitute the main lithology in Anitápolis, Cerro Chirigué, Ipanema, Itapirapuá, for instance, whereas magnesiocarbonatites predominate in complexes like Araxá, Barra do Itapirapuá, and Juquiá. Ferrocarnatites are of subordinate occurrence, being more significant only in Lages (Scheibe *et al.* 2005) and Cerro Manomó (Comin-Chiaramonti *et al.* 2002, 2011, respectively). The Bolivian Cerro Manomó complex represents the most striking occurrence of ferrocarnatites, with 40.5 wt% of FeO, 7.7 wt%

of CaO, 0.34 wt% of MgO and 7.1 wt% of MnO (Comin-Chiaramonti *et al.* 2011). However, it is important to consider that in some complexes like Barra do Itapirapuã, Jacupiranga and Juquiá, the evolution of carbonatite magmas resulted in rocks of wide variation in chemical composition representing different stages of intrusion. Thus, early stage carbonatites of the Jacupiranga and Alto Paranaíba complexes tend to show a more calcic composition, that evolved to more magnesian in latter stages of crystallization (Gomide *et al.* 2016). This calciocarbonatites→magnesiocarbonatites evolution trend, reaching up to ferrocarnatites in a few

cases, has been described in Barra do Itapirapuã (Ruberti *et al.* 2002), Cerro Chirigué (Censi *et al.* 1989) and Juquiá (Walter *et al.* 1995) complexes. In some occurrences (e.g., Mato Preto, Santo Antônio da Barra, etc.), the carbonatitic association also includes silicocarbonatites, carbonatites with > 20% SiO₂ occurring mostly as dikes.

The Lower Cretaceous carbonatites of southern Brazil seem to be chemically related to a potassic magmatism of plagioclitic composition in Foley's (1992) classification (Comin-Chiaramonti & Gomes 1996b), chiefly represented by evolved rock types of syenitic filiation. On the other

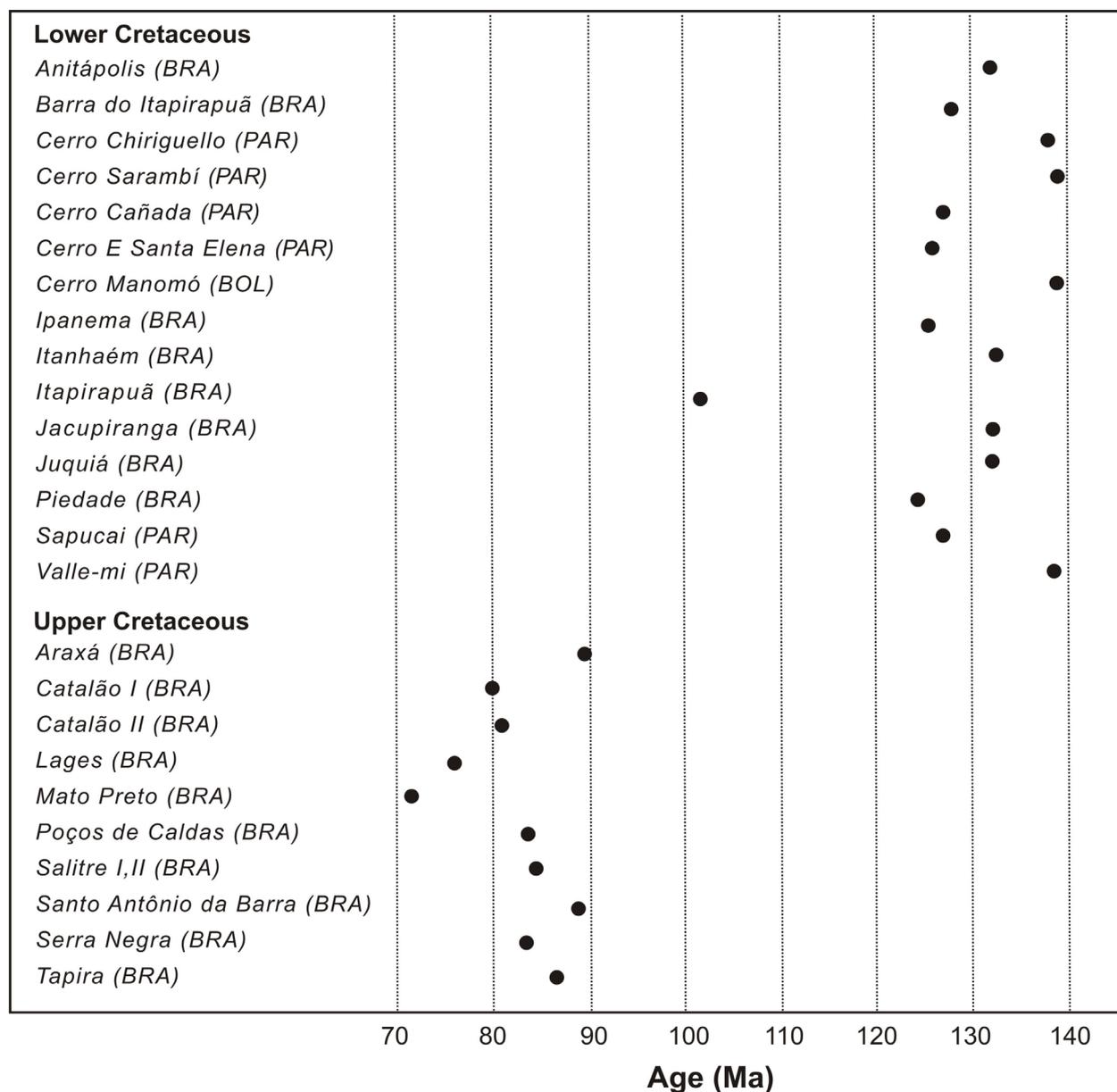


Figure 2. Reference age diagram for carbonatite occurrences in the southern Brazilian Platform. Data source follows references listed in Table 1.

hand, the Upper Cretaceous carbonatites of central-western Brazil are characterized by ultrapotassic-kamafugitic associations (Junqueira-Brod *et al.* 2002, Guarino *et al.* 2017). Usually, also included in the Lower and Upper Cretaceous occurrences are less evolved lithologies of gabbroic-basaltic affinity and cumulates of diverse nature (e.g., dunites, pyroxenites, phoscorites).

Trace and rare earth elements

Incompatible elements (IE) diagrams normalized to primitive mantle concentration (Sun & McDonough 1989) for Brazilian Lower Cretaceous carbonatites (Anitápolis, Barra do Itapirapuá, Jacupiranga, Juquiá) and Paraguay (Cerro Chiriguelo, Cerro Sarambí, Sapucaí, Valle-mí) and for Upper Cretaceous Brazilian complexes (Alto Paranaíba, Lages, Mato Preto) were compiled in review papers by Comin-Chiaramonti *et al.* (2005c, 2007a). Additional multielement diagrams are also found for other areas: the Ponta Grossa Arch (Gomes *et al.* 2011a, Azzone *et al.* 2013, Beccaluva *et al.* 2017, Chmyz *et al.* 2017), Amambay (Gomes *et al.* 2011b, Comin-Chiaramonti *et al.* 2014), and the Alto Paranaíba province (Gomide *et al.* 2016).

For any given incompatible element, there is a large variation in normalized values from one carbonatite complex to another. Scatters for the different carbonatites seem to reflect, to some extent, the variable distribution and the concentration of phases, IE occurring mainly as accessory minerals such as phosphates (e.g., apatite and monazite: rare earth elements — REE), oxides (e.g., pyrochlore: Nb, Th, U; calzirtite: Nb, Zr; zirconolite: Ti, Nb, Zr; loparite: Ti, Nb, REE) and REE-carbonates and fluorocarbonates (e.g., ancylite, bastnaësite, burbankite, parisite, synchysite). In comparison to associated silicate alkaline rocks, the carbonatites follow a general tendency to higher abundances in practically all of the incompatible trace elements. Even considering variable composition and stage of intrusion, they are usually characterized by the presence of negative anomalies for Rb, K, P, Hf-Zr and Ti and positive spikes for Ba, Th-U and La-Ce. The behavior of Nb-Ta and Sr appears to be less regular, but pointing mostly to positive anomalies. Although based only on little data available (e.g., Anitápolis, Lages, Mato Preto, cf. Gibson *et al.* 1999, Comin-Chiaramonti *et al.* 2005c, 2007a), no significant difference is noticed in the chemical behavior of IE in early and late carbonatites of a same complex, except for a clear tendency of the latter rocks to be more enriched in all the elements.

REE display remarkable scatters even within a single complex. This is particularly evident for samples from areas that involve different stages of formation, i.e., magmatic, late-magmatic or hydrothermal conditions. Similar to the IE, scatters are mainly attributed to the presence of accessory

minerals such as apatite, REE fluorocarbonates, fluorite and barite. REE fluorocarbonates are relatively abundant in late stage carbonatites (e.g., Barra do Itapirapuá, Cerro Manomó). Chondrite-normalized (Thompson 1982, Boynton 1984, McDonough & Sun 1995) REE distribution diagrams for various carbonatite complexes are discussed in several papers (e.g., Comin-Chiaramonti *et al.* 2005c, 2007a, 2014, Gomes *et al.* 2011a, 2011b, Azzone *et al.* 2013, Gomide *et al.* 2016, Beccaluva *et al.* 2017, Chmyz *et al.* 2017). Patterns are in general marked by high REE concentration and variable LREE/HREE fractionation degrees. A strong increase from Lu to La is observed in Cerro Chiriguelo, Jacupiranga, Lages (both early and late carbonatites) and Mato Preto complexes, and also Alto Paranaíba occurrences that characterizes different stages of fractional crystallization (C1 to C5, cf. Gomide *et al.* 2016). Flat REE or patterns with a smooth decrease from La to Lu are characteristic of Anitápolis, Barra do Itapirapuá (late calciocarbonatites), Ipanema, Jacupiranga (calciocarbonatites) and Juquiá (magnesian- and calciocarbonatites) rocks. In these occurrences, the REE distribution seems to be related to the apatite composition. Concave patterns with a HREE plateau and a steady increase from Dy to LREE are typical of Valle-mí and Barra do Itapirapuá carbonatitic rocks. Ferrocarnatites are generally more enriched than calcio- and magnesiancarbonatites, mainly as evidenced in Lages. Comin-Chiaramonti *et al.* (2007a) gave especial attention to the stockwork of Barra do Itapirapuá, that includes four generations of carbonatite dikes of similar, parallel and slightly enriched LREE pattern. As a result from the presence of REE fluorocarbonate minerals, the dikes more intensely subject to hydrothermal alteration show higher LREE concentrations (Andrade 1998).

C and O isotopes

The behavior of carbon and oxygen isotopes derived mainly from carbonates of Brazilian and Paraguayan carbonatitic rocks has been discussed in detail by many authors over the last decades (e.g., Nelson *et al.* 1988, Censi *et al.* 1989, Santos *et al.* 1990, Santos & Clayton 1995, Huang *et al.* 1995, Toyoda *et al.* 1994, Walter *et al.* 1995, Castorina *et al.* 1996, 1997, Speziale *et al.* 1997, Andrade *et al.* 1999, Comin-Chiaramonti *et al.* 2001, 2002, 2005b, 2005c, 2007a, Ruberti *et al.* 2002, Gomide *et al.* 2013, 2016, Gomes & Comin-Chiaramonti 2017). In general, $\delta^{18}\text{O}$ data available in literature for such occurrences covers a wide interval, from about 5 to 25‰ (V-SMOW notation per thousand, cf. Deines 1989). For approximately 50% of the analyses, however, results lie between 6 and 10‰. In contrast, $\delta^{13}\text{C}$ values show a more restricted variation, with 91% of the analyses falling between -2‰ and -8‰ (PDB-1 notation per thousand, cf. Deines 1989). Ranges

of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ between 6 and 10‰ and between -4 and -8‰, respectively, correspond to the field defined by Taylor *et al.* (1967) and Keller and Hoefs (1995) for primary carbonatites. The plot of $\delta^{18}\text{O}$ vs. $\delta^{13}\text{C}$ (Fig. 3), including some Brazilian Lower Cretaceous and Upper Cretaceous and Paraguayan Lower Cretaceous carbonatite occurrences, makes evident that:

- a clear primary signature of the Lower Cretaceous complexes in southeastern Brazil, as exemplified mainly by the Jacupiranga rocks plotting entirely inside the range of mantle values;
- two well-distinct linear enrichment trends of heavy isotopes are present.

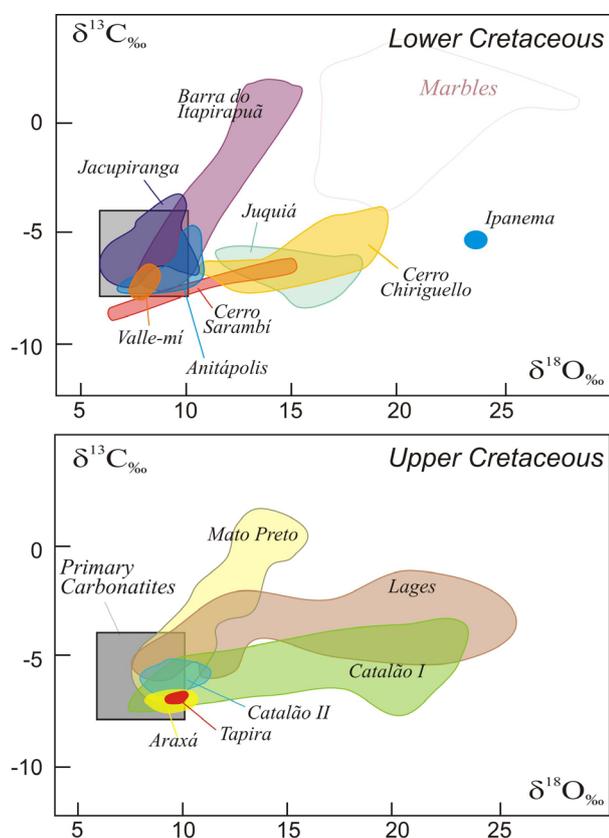


Figure 3. Fields of $\delta^{18}\text{O}$ ‰ (V-SMOW) vs. $\delta^{13}\text{C}$ ‰ (PDB-1) for Lower Cretaceous (Jacupiranga, Juquiá, Barra do Itaipapuá, Anitápolis) and Upper Cretaceous (Araxá, Catalão I, Catalão II, Tapira, Mato Preto, Lages) carbonatites of Brazil and for Lower Cretaceous carbonatites of Eastern Paraguay (Cerro Chiriguello, Cerro Sarambí, Valle-mi). Data sources: Comin-Chiaramonti *et al.* (2005c and therein references), Cordeiro *et al.* (2011), Guarino *et al.* (2012, 2017), Gomes and Comin-Chiaramonti 2017). PC, field for primary carbonatites from Taylor *et al.* (1967) and Keller and Hoefs (1995); field for marbles is also from Comin-Chiaramonti *et al.* (2005c).

Enrichment of heavy isotopes is interpreted as resulting from mantle source heterogeneity (Nelson *et al.* 1988), contamination processes by country rocks, especially limestone (Santos & Clayton 1995), or magmatic vs. hydrothermal evolution at shallow levels (Censi *et al.* 1989). The first trend is characterized by a shift to positive values of both $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ (e.g., Barra do Itaipapuá, Jacupiranga, Mato Preto), and it appears to be an extension of the Jacupiranga carbonatites, which are believed to have a primary signature (Huang *et al.* 1995). A similar isotopic evolution from magmatic fractionation also characterizes early stage carbonatites (C1) of the Alto Paranaíba province (Gomide *et al.* 2016). Other carbonatites representing intermediate (C2, C3) and later (C4, C5) stages of the same region also show isotopic evolution consistent with magmatic fractionation, but with additional interaction with carbohydrothermal fluids and hydrothermal alteration. The second trend shows a $\delta^{18}\text{O}$ increase for similar values of $\delta^{13}\text{C}$ typical of the Juquiá, Lages, Cerro Chiriguello and some Alto Paranaíba (e.g., Catalão I, Catalão II, Tapira) complexes.

As stressed in literature (e.g., Deines 1989), the large variation in the content of oxygen and carbon isotopes in carbonatitic complexes results from magmatic (crystal fractionation, degassing, crustal contamination) and post-magmatic (hydrothermal) processes. Systematic investigation of carbonatites of the Paraná Basin points out that most occurrences have enriched isotopic composition and negligible or absent crustal signature, and that fractional crystallization and liquid immiscibility processes cause little effect on oxygen and carbon isotopic values (Santos & Clayton 1995, Castorina *et al.* 1997, Comin-Chiaramonti *et al.* 2005b, Gomes & Comin-Chiaramonti *et al.* 2017). Also, according to these authors, the main variations in $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ could be explained by isotopic exchange between these rocks and H_2O - CO_2 rich fluids at different temperatures and $\text{H}_2\text{O}/\text{CO}_2$ ratios in a hydrothermal environment (e.g., below 300°C for the first two authors, and in the range of 400–80°C and fluids with a 0.8–1 $\text{CO}_2/\text{H}_2\text{O}$ ratio for the others). The two paths of $\delta^{18}\text{O}$ - $\delta^{13}\text{C}$ fractionation previously mentioned are attributed to different emplacement levels, that reflect sub-volcanic and surface conditions, respectively. Weathering and groundwater fluids are locally important factors, as is meteoric water, that yielded samples strongly enriched in light carbon due to contamination by a biogenic component (Castorina *et al.* 1997, Comin-Chiaramonti *et al.* 2005b). Crustal contamination by limestone country rocks of the Açungui Group ($\delta^{18}\text{O} = +25.0$ to $+24.4$ ‰ and $\delta^{13}\text{C} = +3.5$ to -8.6 ‰), as suggested by Santos and Clayton (1995) for Mato Preto carbonatites, does not seem necessary to explain the enrichment in both heavy oxygen and carbon isotopes of some hydrothermally altered samples of the complex, based

on considerations by Speziale *et al.* (1997) and Comin-Chiaramonti *et al.* (2005b). This interpretation is also supported by the initial $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic ratios of some selected carbonatites, that present the same values as their associated alkaline rocks (Comin-Chiaramonti *et al.* 2005c). Speziale *et al.* (1997) pointed out that, in terms of radiogenic isotopes, Barra do Itapirapuá and Mato Preto carbonatites preserve mantle source characteristics, even where original O-C isotopic signatures were in part modified by low temperature post-depositional hydrothermal fluids. A more complex situation is apparently associated with the wide $\delta^{18}\text{O}$ (between 8.58 to 23.11%) and $\delta^{13}\text{C}$ (between -3.55 and -7.88%) values shown by Catalão I carbonatitic rocks (Cordeiro *et al.* 2011, Oliveira *et al.* 2017). There, the original isotopic composition of carbonates was modified by at least two events of magmatic fractionation (1 — Rayleigh fractionation, with carbonate signatures being related to the isotopic fractionation between carbonates and other minerals as well as to the temperature and the isotopic composition of the initial melt, and 2 — degassing) and three fluid fractionation (fluid degassing, H_2O percolation and CO_2 - H_2O fluid percolation) episodes.

Apparently, sulfur and carbon isotopic data from sulphides is only available in studies by Gomide *et al.* (2013, 2016) on the Alto Paranaíba complexes (Araxá, Catalão I, Catalão II, Salitre, Serra Negra and Tapira) and Jacupiranga in the Ribeira Valley. In these occurrences, almost all carbonatite intrusions present an isotopic composition of sulfur that is compatible with values for the mantle and carbonatites around the world. Exceptions are a few Catalão I and Tapira samples showing distinctly negative ^{34}S values more consistent with sulfur degassing and/or hydrothermal alteration processes (Gomide *et al.* 2013).

Gomide *et al.* (2013) also noted that in Jacupiranga sulphides have relatively narrow ^{34}S ranges and more primitive ^{34}S values than in minerals of the Alto Paranaíba occurrences for the same rock type, which suggests that the Jacupiranga magmas are less evolved and/or that they intruded deeper levels than in the aforementioned complexes.

Sr and Nd isotopes

In Brazil and Paraguay, carbonatites are characterized by initial $^{87}\text{Sr}/^{86}\text{Sr}$ (Sr_i) and $^{143}\text{Nd}/^{144}\text{Nd}$ (Nd_i) ratios similar to those of their associated alkaline rocks, even in late stages of fluid-rock re-equilibration (i.e., hydrothermal environment), as already established by Castorina *et al.* (1997) and Speziale *et al.* (1997). However, the wide ranges of Nd_i isotopes for a narrow Sr_i interval reported for the Catalão I complex by Cordeiro *et al.* (2011) are indicative that magmatic and/or carbohydrothermal processes were able to fractionate Nd, leaving Sr isotopes unaffected. Thus, caution should be

taken when analyzing carbonatites submitted to post-magmatic modifications.

In general, the Sr_i and Nd_i isotopic values for Brazilian Lower Cretaceous carbonatites presented by Comin-Chiaramonti *et al.* (1999) range from 0.70425 to 0.70595 (mean $\text{Sr}_i = 0.70527 \pm 0.00034$) and from 0.51213 to 0.51280 (mean $\text{Nd}_i = 0.51224 \pm 0.00011$), respectively. Values of $\text{Sr}_i = 0.70538$ and $\text{Nd}_i = 0.51253$ for a sample of a carbonatite intrusion from Jacupiranga were more recently given by Beccaluva *et al.* (2017). Average values for Upper Cretaceous alkaline occurrences of different regions are: Alto Paranaíba, $\text{Sr}_i = 0.70527 \pm 0.00036$ and $\text{Nd}_i = 0.51224 \pm 0.00006$ (Bizzi *et al.* 1994, Gibson *et al.* 1995a, 1995b, and references therein); Taiúva-Cabo Frio and Serra do Mar, $\text{Sr}_i = 0.70447 \pm 0.00034$ and $\text{Nd}_i = 0.51252 \pm 0.00008$ (Thompson *et al.* 1998); Lages, $\text{Sr}_i = 0.70485 \pm 0.00053$ and $\text{Nd}_i = 0.51218 \pm 0.00022$ (Traversa *et al.* 1996, Comin-Chiaramonti *et al.* 2002). Guarino *et al.* (2017) postulated that the Sr-Nd isotopic composition of the Alto Paranaíba carbonatites is markedly different from rocks of the southernmost parts of Brazil, suggesting regional-scale heterogeneity in mantle sources underneath the Brazilian Platform. In the initial ($^{87}\text{Sr}/^{86}\text{Sr}$)_i vs. ($^{143}\text{Nd}/^{144}\text{Nd}$)_i correlation diagram (Fig. 4A), values for Lower and Upper Cretaceous carbonatites display the same trend defined for Lower Cretaceous tholeiitic lavas of the Paraná Basin (H-Ti and L-Ti), Upper Cretaceous volcanics of the Rio Grande Rise and Paleocene alkaline rocks of the Serra do Mar province (Comin-Chiaramonti *et al.* 2005c, 2007a).

Lower Cretaceous potassic alkaline rocks of Paraguay (both pre- and post- tholeiitic lavas) and associated carbonatites yield Sr_i and Nd_i values within 0.70612-0.70754 and 0.51154-0.51184, respectively (Fig. 4B). These higher Sr_i and lower Nd_i values are distinct when compared with those relative to late Lower Cretaceous (Misiones province) and Paleocene (Asunción province, ASV) Na-alkaline rocks, i.e., $\text{Sr}_i = 0.70362$ -0.70524 and $\text{Nd}_i = 0.51225$ -0.51277. Together, they define a trend similar to the Low Nd array of Hart *et al.* (1986), i.e., Paraguayan array according to Comin-Chiaramonti *et al.* (1995). Figure 4B also makes evident that sodic alkaline rocks and associated xenolith plots are close to Bulk Earth (BE) values, and that the high and low TiO_2 tholeiites are intermediate between K- and Na-alkaline rocks.

The alkaline and alkaline-carbonatite occurrences in Figure 4 follow well-defined trends involving depleted and enriched mantle components (Gomes & Comin-Chiaramonti *et al.* 2017). The Lower Cretaceous and Upper Cretaceous Brazilian complexes range from close to BE to the enriched quadrant, falling within uncontaminated tholeiitic lavas of the Paraná-Angola-Namibia (Etendeka) province

(Comin-Chiaramonti *et al.* 1997). On the other hand, isotopically Sr-enriched alkaline and alkaline-carbonatites of Paraguay are not easily explained by crustal contamination processes, because that would require high percentages of

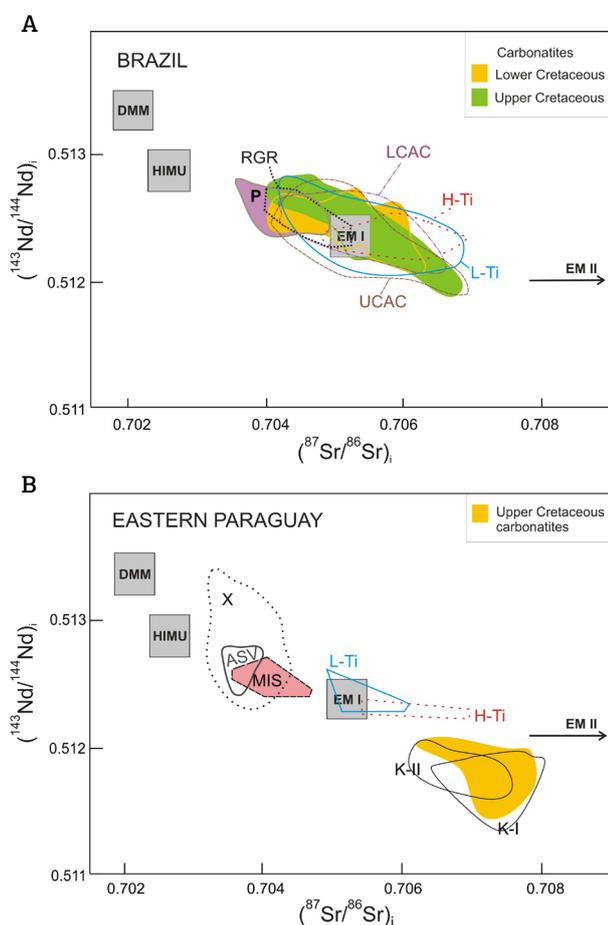


Figure 4. Correlation diagrams for $^{87}\text{Sr}/^{86}\text{Sr}$ (Sr_i) vs. $^{143}\text{Nd}/^{144}\text{Nd}$ (Nd_i) initial ratios for Brazilian and Paraguayan alkaline-carbonatites after Comin-Chiaramonti *et al.* (2005c, modified). Basalts and andesi-basalts are represented by poorly crustally contaminated or uncontaminated rocks (Piccirillo & Melfi 1988). (A) Brazil: H-Ti, L-Ti and LCAC, Lower Cretaceous high- and low-TiO₂ flood tholeiites and alkaline complexes, respectively; RGR and UCAC, Upper Cretaceous Rio Grande Rise volcanic rock types and alkaline complexes, respectively; P, Paleocene alkaline complexes in the Serra do Mar region. (B) Eastern Paraguay: K-I and K-II, Lower Cretaceous potassic alkaline complexes, pre- and post-tholeiites, respectively; H-Ti and L-Ti as in (A); MIS, late Lower Cretaceous sodic alkaline complexes in the Misiones province; ASV, Paleocene sodic alkaline complexes in the Asunción province and associated mantle xenoliths (X). Data sources for both diagrams are given in Comin-Chiaramonti *et al.* (2005c). DMM, HIMU, EM I and EM II are approximations of mantle end-members taken from Hart *et al.* (1992).

crustal components, up to 90% according to those authors. Thus, following Castorina *et al.* (1996, 1997), the Sr-Nd systematics for Paraguayan rocks seems to be related to an isotopically enriched source, where chemical heterogeneities reflect a depleted mantle metasomatized by small-volume melts and fluids rich in incompatible elements.

The $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $^{143}\text{Nd}/^{144}\text{Nd}$ diagram in Figure 5 shows that the carbonatites extend across the field of Lower Cretaceous Hi-Ti tholeiites of northern Paraná and are intermediate between the two groups of kimberlites (Type I, Gibeon, Namibia, cf. Davies *et al.* 2001; type II, cf. Smith 1983 and Clark *et al.* 1991). In the ϵSr vs. ϵNd inset of the figure, isotopic data ranges widely in the enriched quadrant, with the kamafugite field overlapping all lithological types. In the other inset, model ages T^{DM} for the overall Alto Paranaíba population fit to 0.99 ± 0.10 Ga. The constant Sm/Nd ratio in these rocks allows considering Nd ages as indicative of the main metasomatic event that affected the lithosphere beneath the Alto Paranaíba region.

Nd-model ages

Despite their limited petrological meaning, Nd ages are useful indicators of metasomatic events that affected tholeiites and alkaline rocks of different regions of Brazil and Paraguay. Data on volcanic rocks of the Paraná Basin indicates T^{DM} (Nd) ages that range mainly from 0.5 to 2.1 Ga for Hi-Ti flood tholeiites and dikes, with a mean peak at 1.1 ± 0.1 Ga. Values for L-Ti tholeiites span between 0.7 and 2.4 Ga for L-Ti tholeiites, with a mean peak at 1.6 ± 0.3 Ga (Comin-Chiaramonti *et al.* 2014). Regarding specifically the tholeiitic rocks of Paraguay, T^{DM} (Nd) ages vary from 0.9 to 1.4 Ga for Hi-Ti and from 0.7 to 2.8 for L-Ti, respectively. Apparently, an age increase is observed from North to South and West to East (Comin-Chiaramonti *et al.* 2007a). T^{DM} (Nd) ages for the whole Paraná-Angola-Namibia (Etendeka) system reported by these authors vary from 0.8 to 2.4 Ga for Hi-Ti and from 0.8 to 2.7 Ga for L-Ti, respectively.

Age histograms for Brazilian and Paraguayan tholeiites, alkaline rocks and carbonatites are grouped together in studies by Castorina *et al.* (1997) and Comin-Chiaramonti *et al.* (1997). Nd model age values listed more recently (e.g., Gomes & Comin-Chiaramonti 2005, Bizzi & Araújo 2005, Ruberti *et al.* 2005, Scheibe *et al.* 2005, Comin-Chiaramonti *et al.* 2007a, 2014, Carlson *et al.* 2007, Gomes *et al.* 2011b) allow distinguishing among chronological events in the alkaline magmatism. Thus, the Lower Cretaceous alkaline potassic magmatism includes pre- and post-tholeiite rock types, the first group being only recognized in northern Paraguay. Nd model ages

for the pre-tholeiite rocks display two peaks, one at 1.1 Ga (Valle-mí region) and the other at 1.4 Ga (Amambay region), respectively. The Lower Cretaceous syn- and post-tholeiitic magmatism Nd model ages vary from 0.6 to 0.9 Ga. The Upper Cretaceous alkaline rocks and carbonatites, represented mainly by the Alto Paranaíba complexes in Brazil, as well as the late Lower Cretaceous Misiones and Paleocene Asunción volcanics in Paraguay, yield Nd model ages within the 0.6–1.0 Ga interval. The youngest T^{DM} ages are related to the Asunción Tertiary sodic alkaline rocks.

The large variation in model ages seems related to different metasomatic events that took place from Paleoproterozoic to Neoproterozoic. The resulting isotopically distinct alkaline and tholeiitic magmas follow two main subcontinental lithospheric mantle enrichment episodes, at 2.0–1.4 and 1.0–0.5 Ga (Castorina *et al.* 1997, Comin-Chiaramonti *et al.* 1997). These metasomatic events, characterized by strong

chemical differences in Ti, LILE and HFSF concentrations, may have been precursors to the genesis of tholeiitic and alkaline magmatism in the Paraná Basin.

Pb isotopes

Only a few studies present initial Pb isotopic compositions for $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios in alkaline-carbonatite complexes of the southeastern Brazilian Platform (e.g., Antonini *et al.* 2005, Comin-Chiaramonti *et al.* 2005c, 2007a, Bizzi & Araújo 2005, Beccaluva *et al.* 2017, Gomes & Comin-Chiaramonti *et al.* 2017). Values are reported for Lower Cretaceous occurrences of Brazil and Paraguay and for some Brazilian Upper Cretaceous complexes in the Alto Paranaíba province (Figs. 6A and 6B). In general, isotopic values vary significantly with the different ages. Brazilian and Paraguayan Lower Cretaceous rocks values range in 17.033–19.968, 15.380–15.641 and 37.373–39.011

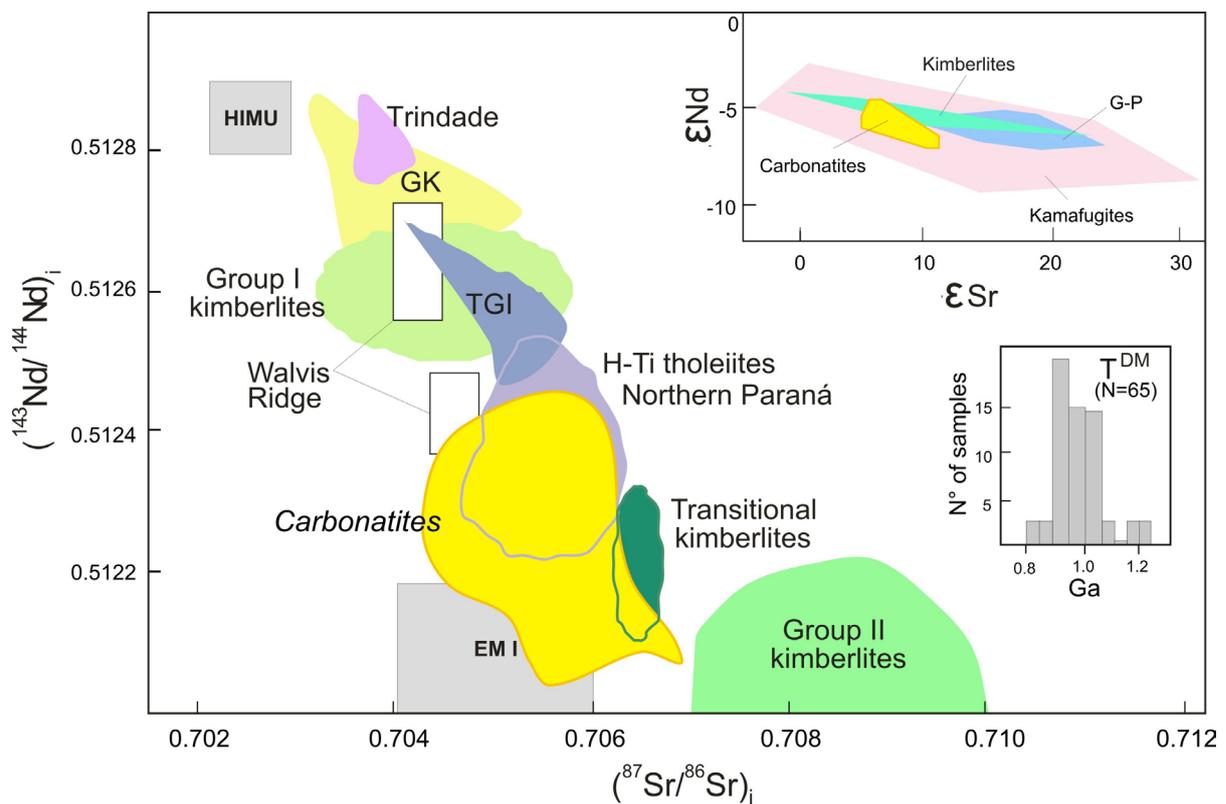


Figure 5. Correlation diagrams for $^{87}\text{Sr}/^{86}\text{Sr}$ (Sr_i) vs. $^{143}\text{Nd}/^{144}\text{Nd}$ (Nd_i) initial ratios of rock types from the Alto Paranaíba province after Bizzi and Araújo (2005; modified by Comin-Chiaramonti *et al.* 2005c). Data sources: GK, Gibeon kimberlites (Davies *et al.* 2001); TGI, Tristan da Cunha, Gough and Inaccessible islands (Le Roex 1985; Le Roex *et al.* 1990); Walvis Ridge (Richardson *et al.* 1984); Group I, Group II and transitional kimberlites (Smith 1983, Clark *et al.* 1991), Trindade (Siebel *et al.* 2000, Marques *et al.* 2000). Paraná uncontaminated high-Ti tholeiites (Comin-Chiaramonti *et al.* 1997). HIMU and EM I (Zindler & Hart 1986, Hart & Zindler 1989). Insets: Nd model ages (T^{DM}) histograms for Alto Paranaíba rock associations (Gomes & Comin-Chiaramonti 2005) and fields for different alkaline petrographic types (kamafugites, kimberlites, carbonatites and G-P: glimmerites and mica peridotites) in the time integrated ϵSr vs. ϵNd diagram (Bizzi & Araújo 2005, modified). T^{DM} values calculated relative to a depleted mantle: $^{143}\text{Nd}/^{144}\text{Nd} = 0.513114$ and $^{147}\text{Sm}/^{144}\text{Nd} = 0.222$, cf. Faure (1986).

intervals for $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios, respectively. Higher values for $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios are typical of a basanite dike that crops out in the Rio Apa region (Valle-mí) in northern Paraguay (K-I, Figs. 6A and 6B). Brazilian Upper Cretaceous occurrences, in turn, show $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios that vary within narrow intervals: 17.51–18.52, 15.44–15.55 and 38.20–38.76, respectively. These variations are well-evidenced in correlation diagrams involving $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, and Sr_i and Nd_i vs $^{206}\text{Pb}/^{204}\text{Pb}$ initial ratios, respectively, especially for the Brazilian rocks. In the diagrams, Lower Cretaceous carbonatites superpose tholeiites of the Paraná Basin, suggesting a common geodynamic evolution for both alkaline and tholeiitic magmatisms, yet emphasizing the more Sr-enriched composition of coeval Paraguayan rocks and the scatter caused mainly by the values for samples from Valle-mí (K-I). Investigating Sr-Nd-Pb-isotopes of some selected Paraguayan Cretaceous to Tertiary alkaline-carbonatites, Antonini *et al.* (2005) postulated that two main mantle components were involved in the genesis of these rocks: an extreme and heterogeneous EM I, which was prevalent in the Lower Cretaceous potassic alkaline magmatism (K-I and K-II), and a HIMU component, which become more important in the late Lower Cretaceous and Paleocene sodic magmatism (LEC-P).

More recently, Beccaluva *et al.* (2017) provided isotopic data for some intrusions of the Jacupiranga complex. The northwestern body includes alkali gabbros, syenodiorites and syenites around dunites, while the southeastern body consists of clinopyroxenites and rocks of the melteigite-ijolite-urtite series and associated carbonatites. $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios for the former petrographic association range from 17.34 to 17.94, from 15.49 to 15.59 and from 37.94 to 38.93, respectively. For the latter association, values vary from 17.70 to 17.87, from 15.47 to 15.50 and from 38.03 to 38.41, respectively. The carbonatite intrusion shows $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios of 17.21, 15.42 and 37.87, respectively. According to these authors, the silicate and carbonatite intrusions have markedly different Sr-Nd-Pb isotopic compositions, which support derivation of the relative parental magmas from independent mantle sources.

Diagrams for Pb isotopes (Fig. 7A) define linear arrays that are subparallel to both Lower Cretaceous Paraná tholeiites (Marques *et al.* 1999a) and the Northern Hemisphere Reference Line (NHRL, cf. Hart 1984). Notably, some kimberlites appear to approach the HIMU mantle component. The Alto Paranaíba rocks fall within the Brazilian Upper Cretaceous alkaline-carbonatite complexes (Fig. 4A), which contain all the magmatic petrographic types of the Paraná Basin. Considering the $^{206}\text{Pb}/^{207}\text{Pb}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ and

$^{143}\text{Nd}/^{144}\text{Nd}$ initial ratio diagrams (Fig. 7B), it should be noticed that the majority of the Alto Paranaíba rocks correspond to peridotite xenoliths, some kimberlites excluded. These latter lithologies show less radiogenic Nd in comparison to other Upper Cretaceous kimberlites (e.g., Gibeon, cf. Davies *et al.* 2001).

Re-Os isotopes

Carbonatite complexes strictly associated with highly potassic mafic-ultramafic rocks of kamafugitic-kimberlitic affinity may represent useful sources of information on the behavior of platinum group elements. Analytical isotopic data on Re, Os and platinumoids for rocks from the Alto Paranaíba province are discussed by Bizzi *et al.* (1994, 1995), Carlson *et al.* (1996), Araújo *et al.* (2001), Bizzi and Araújo (2005) and Comin-Chiaramonti *et al.* (2007a).

The Re-Os isotope systematics (Gomes and Comin-Chiaramonti *et al.* 2017) does not seem to allow for a clear distinction among rock types in the Alto Paranaíba province, although data provided by Comin-Chiaramonti *et al.* (2007a) indicates that glimmerites have the highest $^{187}\text{Os}/^{188}\text{Os}$ and $^{187}\text{Re}/^{188}\text{Os}$ ratios (Fig. 7C). Radiogenic $^{187}\text{Os}/^{188}\text{Os}$ ratios for kimberlites and kamafugites range from 0.11 to 0.13 (av. 0.122 ± 0.005) and from 0.11 to 0.15 (av. 0.134 ± 0.013), respectively. T^{RD} (Os) model ages reported by Bizzi and Araújo (2005) for the Alto Paranaíba petrographic association vary between 1.39 and 1.64 Ga, correlating these lithologies to an older event with respect to the Nd model ages (0.99 ± 0.10).

Hf isotopes

Hafnium isotopic composition is only available for baddeleyite separates from cumulatic rocks (magnetitites and apatitites) of Catalão I. Data reported by Guarino *et al.* (2017) depict a narrow range of initial $^{176}\text{Hf}/^{177}\text{Hf}$ of 0.28248 to 0.28249 and ϵHf_i of -10.3 to -10.9. ϵHf_i values are distinct with respect to those of peridotite xenoliths hosted by kamafugites of the Goiás province (Carlson *et al.* 2007), confirming mantle heterogeneities in the Alto Paranaíba province. Calculated hafnium model ages (T^{DM} Hf = 1.0–1.1 Ga) are coherent to regional tectonomagmatic events that affected the central-southern Brazil.

Noble gases

Only a few carbonatites in the world have been analyzed for noble gases. In Brazil, only two occurrences have so far been investigated: Lower Cretaceous Jacupiranga calciocarbonatites for forsterite and apatite, and Upper Cretaceous Tapira calciocarbonatites for apatite. Analytical data for Ar, Xe, Kr, Ne, and He is presented in Sasada *et al.* (1997) and discussed in a review paper by Comin-Chiaramonti *et al.* (2007a). A summary provided by the latter authors suggests that:

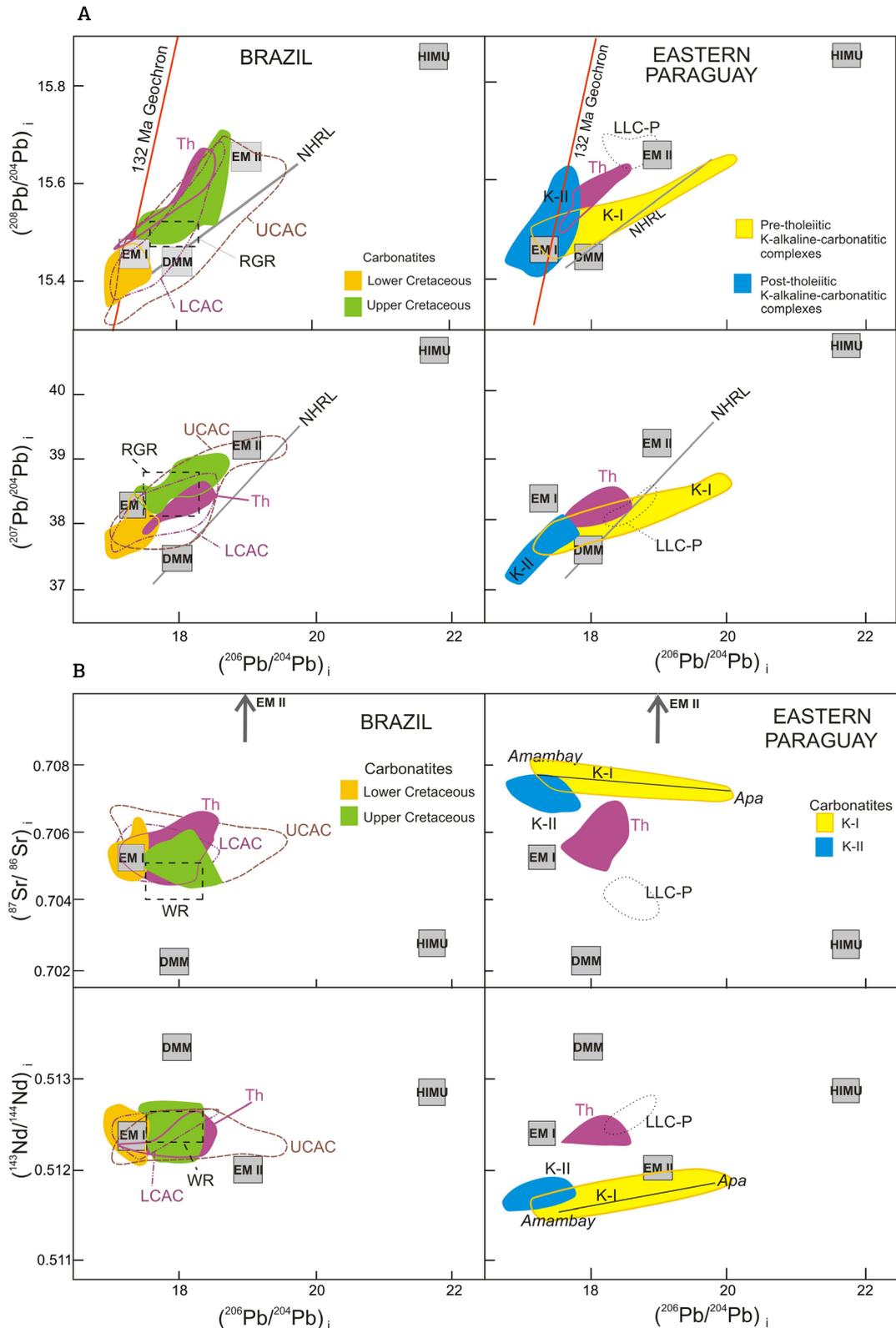


Figure 6. Correlation diagrams for (A) $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ initial ratios and for (B) $^{206}\text{Pb}/^{204}\text{Pb}$ initial ratios vs. Sr_i and Nd_i of rock types of southern Brazil and eastern Paraguay (after Comin-Chiaramonti et al. 2005c, modified). Brazil: LCAC and UCAC, Lower Cretaceous and Upper Cretaceous alkaline-carbonatite magmatism, respectively. Eastern Paraguay: LLC-P, late Lower Cretaceous-Paleocene sodic alkaline magmatism. NHRL, North Hemisphere Reference Line (Hart 1984); Th, Paraná tholeiites; WR, Walvis Ridge; 132 Ma geochron according to Ewart et al. (2004). Data sources are given in Comin-Chiaramonti et al. (2005c). Further information as in Figure 4.

- apatites from both carbonatite complexes are in the same range of possible derived sources (e.g., HIMU and MORB);
- sources are enriched in F;
- carbonatites are unlikely to derive from subduction-related carbon, whereas they support a C-O fractionation model of mantle-derived sources.

PETROLOGICAL CONSIDERATIONS

Carbonatite melts from all over the world are currently assigned to some main processes:

- immiscibility of silicate and carbonatite liquids (e.g., Baker & Wyllie 1990, Kjarsgaard & Hamilton 1988, 1989, Lee & Wyllie 1996, 1997, 1998b);

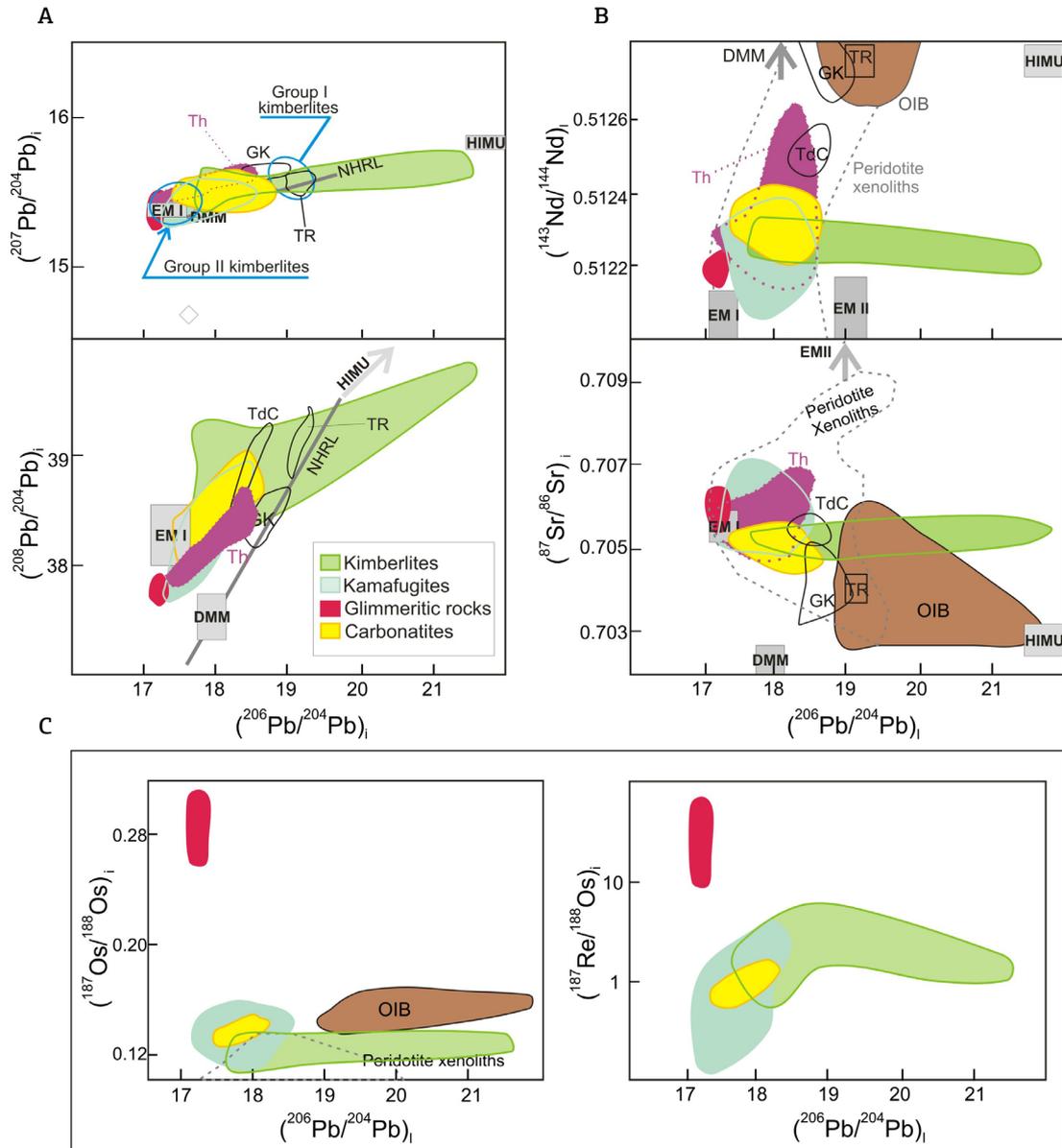


Figure 7. Graphical representation of rock samples from the Alto Paranaíba province in correlation diagrams involving isotopic ratios: (A) $(^{206}\text{Pb}/^{204}\text{Pb})_i$ vs. $(^{207}\text{Pb}/^{204}\text{Pb})_i$ and $(^{208}\text{Pb}/^{204}\text{Pb})_i$; (B) $(^{206}\text{Pb}/^{204}\text{Pb})_i$ vs. $(^{143}\text{Nd}/^{144}\text{Nd})_i$ and $(^{87}\text{Sr}/^{86}\text{Sr})_i$; (C) $(^{206}\text{Pb}/^{204}\text{Pb})_i$ vs. $(^{187}\text{Os}/^{188}\text{Os})_i$ and $(^{187}\text{Re}/^{188}\text{Os})_i$ (after Bizzi & Araújo 2005, modified; cf. also Gomes & Comin-Chiaramonti 2017). OIB, Ocean islands basalts and peridotite xenoliths (Smith 1983; Smith *et al.* 1985; Clark *et al.* 1991); TdC, Tristan da Cunha-Gough-Inaccessible islands (Le Roex *et al.* 1990); TR, Trindade island (Marques *et al.* 2000). Further information as in Figures 4, 5 and 6.

- extreme fractionation from carbonate-rich silicatic magma (e.g., Otto & Wyllie 1993, Lee & Wyllie 1994, Church & Jones 1995);
- a primary mantellic origin such as melting of metasomatized source (Chakhmouradian 2006) or melting of recycled oceanic crust components under mantle conditions (Hoernle *et al.* 2002, Song *et al.* 2017).

Petrogenetic studies performed on a selected number of prominent Cretaceous complexes, as exemplified by Barra do Itapirapuá (Ruberti *et al.* 2002), Ipanema (Guarino *et al.* 2011), Juquiá (Beccaluva *et al.* 1992, Azzone *et al.* 2013) and Lages (Traversa *et al.* 1996) in Brazil and by Cerro Chiriguelo (Castorina *et al.* 1996, 1997) and Cerro Sarambí (Gomes *et al.* 2011b) in Paraguay indicate that processes of fractional crystallization and liquid immiscibility from parental alkaline mafic magmas are the main responsible for the generation of carbonatitic liquids, as suggested by field relationships and geochemical characteristics (cf. also Comin-Chiaramonti *et al.* 2014).

A very consistent hypothetical model for the origin of the Juquiá carbonatites was discussed by Beccaluva *et al.* (1992) that considers multistage evolution under nearly closed system conditions involving:

- assemblage fractionation closely comparable to olivine clinopyroxenite and subordinate olivine alkali gabbro cumulates from parental basanitic melt leading to the formation of essexitic magma;
- derivation of least differentiated mafic nepheline syenite from essexitic magma by withdrawal of cumulitic syenodiorites;
- exsolution of carbonate fluid from a CO₂-enriched mafic nepheline syenite magma, the magma itself being also submitted to continued fractionation to form melteigite-ijolite-urtite cumulates;
- formation of residual nepheline syenitic rocks (and phonolitic dikes) leaving out orthocumulates of nepheline syenites.

Based on field, petrographic, mineralogical, chemical and isotopic evidence, Brod *et al.* (2013) consider the Tapira occurrence as resulting from the complex interplay of several petrogenetic processes: liquid immiscibility, crystal fractionation, and degassing/metasomatism. Their study strongly supports silicate-carbonate liquid immiscibility from decoupling of geochemical pairs such as Nb/Ta and Zr/Hf, rotation of REE patterns, which cross over the patterns of the primitive liquids, and matching and opposite enrichment-depletion trace elements relationships in spider diagrams of conjugate immiscible liquids.

In spite of the isotopic data support to the interpretation that the Cretaceous alkaline-carbonatites are mostly

formed by processes related to immiscibility and fractional crystallization from a common parental magma, higher ⁸⁷Sr/⁸⁶Sr initial ratios found in samples from a few occurrences (e.g., Barra do Itapirapuá, Ipanema, Jacupiranga, Juquiá, etc.) seem to indicate that contamination processes should not be discarded, particularly in some complexes where border facies are in contact with granitic country rocks in the latest stage of carbonatite intrusion. In the past, Roden *et al.* (1985) and Gaspar (1989), investigating the Jacupiranga complex, also interpreted isotopic heterogeneities of some rocks as due to crustal contamination. In contrast, based on isotopic data, Huang *et al.* (1995) refuted any significant contribution of contamination processes affecting the evolution of the carbonatites and clinopyroxenites. In a recent study, Chmyz *et al.* (2017) provided mineralogical, textural and geochemical evidence of crustal contamination in the formation of the weakly silica-undersaturated rocks of Jacupiranga.

A complex model combining crustal assimilation, fractional crystallization and fluid immiscibility processes was proposed for the carbonatites of Catalão I by Cordeiro *et al.* (2011). A compositional trend is assigned to multiple batches of immiscible and/or residual melts derived from fractional crystallization of a carbonated-silicate parental magma (phlogopite picrite) contaminated to a variable amount with continental crust material. A second trend involved interaction of previously-formed magmatic carbonatites with late-stage or post-magmatic carbohydrothermal fluids.

Conversely, Beccaluva *et al.* (2017) suggested that in the Jacupiranga complex carbonatitic and silicatic rocks originated from independent rather than common mantle sources. Different isotopic data trends indicate that these petrographic types do not exhibit any evidence of being genetically related among themselves. The authors mention the absence of carbonatite *ocelli* in the associated silicate rocks and the presence of fluid and melt inclusions in apatites from carbonatites (suggestive of high depth trapping) as features indicative of origin at mantle depths. Based on geochemical evidence (patterns for REE and isotopic data for sulphur and iron indicating a primitive nature), Beccaluva *et al.* (2017) also advocated that the hypothesis of carbonatites being associated with shallow level immiscibility is less plausible.

A phlogopite-bearing carbonate-metasomatized heterogeneous peridotite source is assigned to different domains of the Brazilian Platform (e.g., Gibson *et al.* 1995b, 1999, 2006, Comin-Chiaramonti *et al.* 1997, 2014, Thompson *et al.* 1998, Brotzu *et al.* 2005, Guarino *et al.* 2017). Such mantle source heterogeneities were recognized at regional scale, the isotopic signatures of the Alto Paranaíba rocks being distinct

from those of the Goiás province and the Ponta Grossa Arch, as demonstrated by Guarino *et al.* (2017).

The geodynamic models regarding the Cretaceous carbonatitic and alkaline magmatism of the Brazilian Platform are related:

- to mantle plume and subcontinental lithospheric mantle (SCLM) interactions;
- to low-degree partial melts of metasomatized SCLM due to the reactivation of ancient fault zones (cf. Gomes & Comin-Chiaramonti, 2017).

Gibson *et al.* (1995a, 1995b, 1999), Thompson *et al.* (1998) and Natali *et al.* (2018) suggested for the alkaline and tholeiitic magmatism an origin associated with the interaction of melts from asthenospheric sources attributed to different mantle plumes (i.e. Tristan da Cunha and Trindade mantle plumes) with melts derived of a previously metasomatized lithospheric mantle source. On the other hand, Comin-Chiaramonti *et al.* (1997, 1999, 2002, 2005c, 2007a), Castorina *et al.* (1997), Alberti *et al.* (1999), Ernesto *et al.* (2002) and Riccomini *et al.* (2005) proposed for the alkaline-carbonatite events in the Paraná-Angola-Namíbia system an origin from metasomatized lithospheric mantle sources without the contribution of plume-derived components.

ECONOMIC ASPECTS

The economic importance of carbonatites in Brazil results from the intense weathering of alkaline rocks, mainly of ultrabasic and carbonatic composition. Lateritic soils thus formed can reach more than 200 m thick, especially in complexes of the Ribeira Valley and Alto Paranaíba regions. Mineral deposits formed by either supergene alteration or residual concentration of primary minerals during long periods (Gomes *et al.* 1990). A few sources of mineralization in contact with eluvial material and, more scarcely, fresh rocks are described. Mineral deposits of major importance include phosphate, niobium and vermiculite, whereas subordinate mineralizations are represented by titanium, rare earths, barite, bauxite, fluorspar, etc. Economic aspects of carbonatites are presented by Berbert (1984), Rodrigues and Lima (1984) and Gomes *et al.* (1990). However, such aspects are discussed in more detail in a compilation work by Biondi (2005), one of the most valuable and comprehensive sources of economic data on carbonatites. The author distinguishes among various types of alkaline rock associations containing economic or potentially economic mineral deposits. The most important mineral ores are

represented by miaskitic alkaline complexes with syenites + pyroxenites + ijolites + carbonatites, and/or their effusive equivalents as main petrographic types. Recently, Oliveira *et al.* (2017) observed that the distinct evolution trends reaching late-stage rocks from Catalão I coincide with a shift from a Nb-rich to a REE- and Ba-rich mineralization environment.

Finally, in Cerro Manomó, Bolivia, extensive and important enrichments in U and Th are associated with carbonatite blocks (Fletcher *et al.* 1981, Comin-Chiaramonti *et al.* 2011).

CONCLUDING REMARKS

In the southeastern Brazilian Platform, Lower Cretaceous and Upper Cretaceous episodes of alkaline-carbonatite magmatism took place along tectonic lineaments genetically related to regional structural features like the Ponta Grossa Arch and the Alto Paranaíba Uplift in Brazil and the Ponta Porã Arch in Paraguay. The carbonatites occupy inner parts of circular/oval-shaped complexes or appear as dikes and veins that cut across associated alkaline and regional rocks. In some complexes, they result from multistage intrusions of varied composition. Carbonatites are usually found in contact with cumulates of large compositional variation such as ultrabasic (dunites, peridotites, pyroxenites) lithologies, members of the melteigite-ijolite-urtite series, nepheline syenites and syenites, glimmerites, kamafugites, kimberlites, phoscorites, and unimineralic rock types such as apatite, magnetite and flogopite in a few complexes. The country rocks were in most cases deeply affected by fenitization, giving origin mainly to syenitic types. Such processes promoted flogopitization, amphibolitization and aegirization of pyroxenitic rocks due to the action of highly concentrated alkalis, together with CO₂ and H₂O enriched fluids derived from carbonatitic and syenitic magmas, as well evidenced in Ribeira Valley and Alto Paranaíba complexes.

In an overall classification, Cretaceous carbonatites can be placed into two major groups: primary or magmatic, and hydrothermal. The major Brazilian complexes of the Ribeira Valley and Alto Paranaíba correspond to the first group, whereas Barra do Itaipapuã in Brazil, Cerro Chiriguelo in Paraguay, and Cerro Manomó in Bolivia, are included in the second group. Additional occurrences are represented by small dikes and aggregates of carbonate material (*ocelli*) present in the interior of fine- and coarse-grained alkaline silicate rocks, namely basanite and ijolite. However, it must be stressed that, in

some magmatic occurrences, carbohydrothermal events were also registered.

Carbonatites vary considerably in major oxide concentrations, from calciocarbonatites to magnesiocarbonatites to ferrocarbonatites, but the three rock types are rarely associated in the same complex. Besides their richness in elements such as K, Ba, Th, U, Sr, P and REE, and F and Cl as well, and their high LREE content and La/Lu ratio, carbonatites exhibit, in general, a strongly fractionated pattern for REE, mostly controlled by the presence, concentration and variable distribution of accessory phases represented by phosphates, oxides, REE-carbonates and fluorocarbonates minerals (e.g., apatite, monazite, pyrochlore, ancyllite, bastnäesite, synchysite, etc.). In spite of some scatter observed, the behavior of incompatible elements points to negative Rb, K, P, Hf-Zr and Ti anomalies, contrasting with positive Ba, Th-U and La-Ce peaks. A remarkable scattering also characterizes the REE distribution, REE-fluorocarbonates being relatively abundant in late ferrocarbonatites. Different behaviors can be distinguished: a strong increase from Lu to La, flat REE with a relative weakly decrease from La to Lu, and concave patterns with a HREE plateau followed by a steady increase from Dy to LREE.

Notably, significant differences in C-O isotope compositions are observed in primary carbonates of alkaline rocks and associated carbonatites. The variations are interpreted as due mainly to isotope exchange between carbonates and H₂O-CO₂ rich fluids, with the isotopic modifications occurring at low temperatures (400–80°C) in a hydrothermal environment with CO₂/H₂O fluids ranging from 0.8 to 1. Two main paths of δ¹⁸O and δ¹³C fractionation associated with different emplacement levels (i.e., deep-seated up to near surface, or near-surface environments) are distinguished. Agents such as weathering and groundwater fluids, that seem to have also influenced post-magmatic changes, could explain the secondary isotopic variations, as indicated by the largest enrichment in heavy oxygen.

In general, Sr-Nd isotopes and trace-element data for the alkaline rocks shows that coeval carbonatites and primary carbonates reflect the composition of the mantle source. In particular, Sr and Nd isotopic data indicate that the carbonatite system was dominated by mantle component(s) without appreciable crustal contamination. Model ages also evidence that the alkaline rocks and associated carbonatites experienced two chemically different episodes of mantle enrichment in Proterozoic times, at 2.0–1.4 Ga and 1.0–0.5 Ga, respectively.

Significant H₂O, CO₂ and F are also expected in the mantle source, as suggested by the occurrence of the carbonatitic rocks.

Combined Pb, Sr and Nd isotopic data reveal the contribution of two mantle components as source:

- an extreme and heterogeneous EM I component, which was active in the formation of the Lower Cretaceous alkaline potassic rocks;
- a depleted component, which is believed to have played an important role in the sodic magmatism, spanning in age from Permotriassic to Paleocene.

Mixing processes mainly involving HIMU and EM I end-members, DMM and EM I subordinate, as well as crustal *latu sensu* components (e.g., EM II) were also proposed. For the overall occurrences of the Paraná-Angola-Namibia system, data emphasizes carbonatite plots that fall close to EM I/DMM-HIMU mixing lines for both Pb-Sr and Pb-Nd.

Os isotopic results for silicate alkaline rocks (kama-fugites, kimberlites) associated with carbonatites of the Alto Paranaíba province are indicative of lithospheric mantle sources that experienced LILE enrichment by fluid/melt metasomatism at ~1 Ga, probably during the mobile belt formation along the western border of the São Francisco Craton.

Fractional crystallization and liquid immiscibility processes from parental alkaline mafic magmas are thought to be the main responsible for the generation of Cretaceous carbonatite fluids in the Brazilian Platform, crustal contamination being considered to have played a minor role. Degassing, metasomatism and post-magmatic interaction with carbohydrothermal fluids were also recognized in various occurrences. However, some carbonatites do not present a clear genetic association with silicate rocks, which suggests the possibility of a primary mantle origin for the carbonatites. For the generation of alkaline-carbonatite magmatism, a heterogeneous phlogopite-bearing carbonate-metasomatized mantle source is assigned to different domains of the Brazilian Platform.

ACKNOWLEDGMENTS

The authors thank Fapesp for the financial support to this research (Grants: 2016/23399-4, CBG; 2012/06082-6, ER; 2017/03768-8, RGA). They also thank for the reviewers L. Beccaluva and E.S.R. Barbosa for the valuable suggestions to improve the manuscript.

REFERENCES

- Alberti A., Castorina F., Censi P., Comin-Chiaramonti P., Gomes C.B. 1999. Geochemical characteristics of Cretaceous carbonatites from Angola. *Journal of African Earth Sciences*, **29**(4):735-759. [https://doi.org/10.1016/S0899-5362\(99\)00127-X](https://doi.org/10.1016/S0899-5362(99)00127-X)
- Algate J.P. 1972. A influência dos arqueamentos cratônicos no condicionamento das alcalinas dos estados de São Paulo e Paraná. In: Congresso Brasileiro de Geologia, 26., Belém. *Anais...*, p. 65-69.
- Almeida F.F.M. 1971. Condicionamento Tectônico do Magmatismo Alcalino Mesozóico do Sul do Brasil e do Paraguai Oriental. *Anais da Academia Brasileira de Ciências*, **43**:835-836.
- Almeida F.F.M. 1983. Relações tectônicas das rochas alcalinas mesozoicas da região meridional da Plataforma Sul-Americana. *Revista Brasileira de Geociências*, **13**:139-158.
- Alves A.D. 2003. *Rochas vulcanoclásticas do complexo alcalino de Poços de Caldas – MG/SP*. MS Dissertation, Universidade de São Paulo, São Paulo, 106 p.
- Amaral G. 1978. Potassium-argon studies on the Jacupiranga alkaline district, state of São Paulo, Brazil. In: International Symposium on Carbonatites, 1., Poços de Caldas. *Proceedings...*, p. 297-302.
- Amaral G., Bushee J., Cordani U.G., Kawashita K., Reynolds J.H. 1967. Potassium-argon ages of alkaline rocks from Southern Brazil. *Geochimica et Cosmochimica Acta*, **31**:117-142. [https://doi.org/10.1016/S0016-7037\(67\)80041-3](https://doi.org/10.1016/S0016-7037(67)80041-3)
- Andrade F.R.D. 1998. *Geoquímica do sistema de alteração do carbonatito de Barra do Itaipirapuã*. PhD Thesis, Universidade Estadual de São Paulo, Rio Claro, 136 p.
- Andrade F.R.D., Möller P., Höndorf A. 1999a. The effect of hydrothermal alteration on the Sr and Nd signatures of the Barra do Itaipirapuã carbonatite. *Journal of Geology*, **107**:177-191. <https://doi.org/10.1086/314339>
- Andrade F.R.D., Möller P., Lüders V., Dulski P., Gilg H.A. 1999. Hydrothermal rare earth elements mineralization in the Barra do Itaipirapuã carbonatite, southern Brazil: behavior of selected trace elements and stable isotopes (C, O). *Chemical Geology*, **155**:91-113.
- Antonini P., Gasparon M., Comin-Chiaramonti P., Gomes C.B. 2005. Post-Palaeozoic magmatism in Eastern Paraguay: Sr-Nd-Pb isotope compositions. In: Comin-Chiaramonti P. & Gomes C.B. (eds.), *Mesozoic to Cenozoic alkaline magmatism in the Brazilian Platform*. São Paulo, Edusp/Fapesp, p. 57-70.
- Araújo A.L.N., Carlson R.W., Gaspar J.C., Bizzi L.A. 2001. Petrology of kamafugites and kimberlites from the Alto Paranaíba Alkaline Province, Minas Gerais, Brazil. *Contributions to Mineralogy and Petrology*, **142**:163-177. DOI: 10.1007/s004100100280
- Azzone R.G., Enrich G.E.R., Gomes C.B., Ruberti E. 2012. An olivine gabbro-norite occurrence associated with the Jacupiranga mafic-ultramafic alkaline-carbonatite complex (SE Brazil). In: 34th International Geological Congress, Brisbane. *Abstract Book*, p. 495.
- Azzone R.G., Enrich G.E.R., Gomes C.B., Ruberti E. 2013. Trace element composition of parental magmas from ultramafic cumulates determined by *in situ* mineral analysis: the Juquiá mafic-ultramafic alkaline-carbonatite massif, SE Brazil. *Journal of South American Earth Sciences*, **41**:5-21. <https://doi.org/10.1016/j.jsames.2012.07.005>
- Baker M.B. & Wyllie P.J. 1990. Liquid immiscibility in a nephelinite-carbonate system at 25 kbars and implications for carbonatite origin. *Nature*, **346**:168-170. DOI: 10.1038/346168a0
- Barabino G., Gomes C.B., Traversa G. 2007. The Lages diatremes: mineral composition and petrological implications. *Anais da Academia Brasileira de Ciências*, **79**:473-501. <http://dx.doi.org/10.1590/S0001-37652007000300010>
- Barbieri M., Beccaluva L., Brotzu P., Conte A., Garbarino C., Gomes C.B., Loss E., Macciotta G., Morbidelli L., Scheibe L.F., Tamura R.M., Traversa G. 1987. Petrological and geochemical studies of alkaline rocks from continental Brazil. *Geochimica Brasiliensis*, **1**:109-138.
- Barbosa E.S.R. 2009. *Mineralogia e petrologia do complexo carbonatítico-foscorítico de Salitre, MG*. PhD Thesis, Universidade de Brasília, Brasília, 257 p.
- Barbosa E.S.R., Brod J.A., Cordeiro P.F.O., Junqueira-Brod T.C. 2012a. Variações composicionais de olivinas do complexo alcalino-carbonatítico de Salitre, MG. *Revista Brasileira de Geociências*, **42**:729-743. <http://dx.doi.org/10.5327/Z0375-75362012000400006>
- Barbosa E.S.R., Brod J.A., Junqueira-Brod T.C., Dantas E.L., Cordeiro P.F.O., Gomide C.S. 2012b. Bebedourite from its type area (Salitre 1 complex): a key petrogenetic series in the Late Cretaceous Alto Paranaíba kamafugite-carbonatite-phoscorite association, Central Brazil. *Lithos*, **144-145**:56-72. <https://doi.org/10.1016/j.lithos.2012.04.013>
- Beccaluva L., Barbieri M., Born H., Brotzu P., Coltorti M., Conte A., Garbarino C., Gomes C.B., Acciotta M., Morbidelli L., Ruberti E., Siena F., Traversa G. 1992. Fractional crystallization and liquid immiscibility processes in the alkaline-carbonatite complex of Juquiá (São Paulo, Brazil). *Journal of Petrology*, **33**:1371-1404. <https://doi.org/10.1093/petrology/33.6.1371>
- Beccaluva L., Bianchini G., Natali C., Siena F. 2017. The alkaline-carbonatite of Jacupiranga (Brazil): magma genesis and mode of emplacement. *Gondwana Research*, **44**:157-177. <https://doi.org/10.1016/j.gr.2016.11.010>
- Berbert C.O. 1984. Carbonatites and associated mineral deposits in Brazil. Report of International Research and Development Cooperation – ITIT Projects n. 8316. *Research on Mineral Deposits Associated with Carbonatite in Brazil*. International Research and Development Cooperation. p. 131-152.
- Berrocal J. & Fernandes C. 1996. Seismicity in Paraguay and neighbouring regions. In: Comin-Chiaramonti P. & Gomes C.B. (eds.), *Alkaline magmatism in central-eastern Paraguay*. Relationships with coeval magmatism in Brazil. São Paulo, Edusp/Fapesp, p. 57-66.
- Biondi J.C. 2005. Brazilian mineral deposits associated with alkaline and alkaline-carbonatite complexes. In: Comin-Chiaramonti P. & Gomes C.B. (eds.), *Mesozoic to Cenozoic alkaline magmatism in the Brazilian Platform*. São Paulo, Edusp/Fapesp, p. 707-750.
- Bizzi L.A. & Araújo A.L.N. 2005. Dynamic of mantle-derived magmatism in the southwestern São Francisco Craton, Brazil. In: Comin-Chiaramonti P. & Gomes C.B. (eds.), *Mesozoic to Cenozoic alkaline magmatism in the Brazilian Platform*. São Paulo, Edusp/Fapesp, p. 341-365.
- Bizzi L.A., De Wit M.J., Smith C.B., McDonald I., Armstrong R.A. 1995. Heterogeneous enriched mantle materials and Dupal-type magmatism along the southwestern margin of the San Francisco Craton, Brazil. *Journal of Geodynamics*, **20**:469-491.
- Bizzi L.A., Smith C.B., De Wit M.J., McDonald I., Armstrong R.A. 1994. Isotope characteristics of the lithospheric mantle underlying the SW San Francisco craton margin, Brazil. In: International Symposium on the Physics and Chemistry of the Upper Mantle, São Paulo. *Invited Lectures...*, p. 227-256.

- Born H. 1971. *O complexo alcalino de Juquiá*. PhD Thesis, Universidade de São Paulo, São Paulo, 177 p.
- Boynton W.V. 1984. Cosmochemistry of the Rare Earth Elements: meteorite studies. In: Henderson P. (ed.), *Rare Earth Element geochemistry*. Amsterdam, Elsevier, p. 63-114.
- Brod J.A. 1999. *Petrology and geochemistry of the Tapira alkaline complex, Minas Gerais State, Brazil*. PhD Thesis, University of Durham, Durham. 486 p.
- Brod J.A., Barbosa E.S.R., Junqueira-Brod T.C., Gaspar J.C., Diniz-Pinto H.S., Sgarbi P.B.A., Petrinovic L.A. 2005. The Late-Cretaceous Goiás alkaline province (GAP), Central Brazil. In: Comin-Chiaramonti P. & Gomes C.B. (eds.), *Mesozoic to Cenozoic alkaline magmatism in the Brazilian Platform*. São Paulo, Edusp/Fapesp, p. 261-340.
- Brod J.A., Gibson S.A., Thompson R.N., Junqueira-Brod T.C., Seer H.J., Moraes L.C., Boaventura G.R. 2000. The kamafugite-carbonatite association in the Alto Paranaíba Igneous Province (APIP), Southeastern Brazil. *Revista Brasileira de Geociências*, **30**:408-412.
- Brod J.A., Junqueira-Brod T.C., Gaspar J.C., Petrinovic I.A., Valente S.C., Corval A. 2013. Decoupling of paired elements, crossover REE patterns, and mirrored spider diagrams: Fingerprinting liquid immiscibility in the Tapira alkaline-carbonatite complex, SE Brazil. *Journal of South American Earth Sciences*, **41**:41-56. <https://doi.org/10.1016/j.jsames.2012.04.013>
- Brotzu P., Melluso L., D'Amelio F., Lustrino M. 2005. Mafic/ultramafic potassic dykes and felsic intrusions of the Serra do Mar igneous province (SE Brazil): a review. In: Comin-Chiaramonti P. & Gomes C.B. (eds.), *Mesozoic to Cenozoic alkaline magmatism in the Brazilian Platform*. São Paulo, Edusp/Fapesp, p. 443-472.
- Carlson R.W., Araújo A.L.N., Junqueira-Brod T.C., Gaspar J.C., Brod J.A., Petrinovic I.A., Hollanda M.H.B.M., Pimentel M.M., Sichel S. 2007. Chemical and isotopic relationships between peridotite xenoliths and mafic-ultrapotassic rocks from Southern Brazil. *Chemical Geology*, **242**:415-434. <https://doi.org/10.1016/j.chemgeo.2007.04.009>
- Carlson R.W., Esperança S., Svisero D.P. 1996. Chemical and Os isotopic study of Cretaceous potassic rocks from Southern Brazil. *Contributions to Mineralogy and Petrology*, **125**:393-405.
- Carvalho W.J. & Bressan S.R. 1997. Depósitos de fosfatos, nióbio, titânio, terras raras e vermiculita de Catalão I, Goiás. In: Schobbenhaus C., Queiroz E.T., Coelho C.E.S. (eds.), *Principais depósitos minerais brasileiros – Rochas e minerais industriais*. Departamento Nacional da Produção Mineral. v. VI, parte C, p. 69-93.
- Castorina F., Censi P., Barbieri M., Comin-Chiaramonti P., Cundari A., Gomes C.B., Pardini G. 1996. Carbonatites from Eastern Paraguay: a comparison with coeval carbonatites from Brazil and Angola. In: Comin-Chiaramonti P., Gomes C.B. (eds.), *Alkaline magmatism in central-eastern Paraguay*. Relationships with coeval magmatism in Brazil. São Paulo, Edusp/Fapesp, p. 231-248.
- Castorina F., Censi P., Comin-Chiaramonti P., Piccirillo E.M., Alcover Neto A., Gomes C.B., Almeida T.I.R., Speziale S., Toledo M.C.M. 1997. Carbonatites from Eastern Paraguay and genetic relationships with potassic magmatism: C, O, Sr and Nd isotopes. *Mineralogy and Petrology*, **61**:237-260.
- Censi P., Comin-Chiaramonti P., Demarchi G., Longinelli A., Orúé D. 1989. Geochemistry and C-O isotopes of the Chirigué carbonatite, Northeastern Paraguay. *Journal of South American Earth Sciences*, **3**:295-303. [https://doi.org/10.1016/0895-9811\(89\)90035-7](https://doi.org/10.1016/0895-9811(89)90035-7)
- Cerva-Alves T., Remus M.V.D., Dani N., Basei M.A.S. 2017. Integrated field, mineralogical and geochemical characteristics of Caçapava do Sul alkalic and beforite intrusions: a new Ediacaran carbonatite complex in southernmost Brazil. *Ore Geology Reviews*, **88**:352-369. <https://dx.doi.org/10.1016/j.oregeorev.2017.05.017>
- Chakhmouradian A.R. 2006. High-field-strength elements in carbonatitic rocks: geochemistry, crystal chemistry and significance for constraining the sources of carbonatites. *Chemical Geology*, **235**:138-160. <https://doi.org/10.1016/j.chemgeo.2006.06.008>
- Chmyz L., Arnaud N., Biondi J.C., Azzone R.G., Bosch D., Ruberti E. 2017. Ar-Ar ages, Sr-Nd isotope geochemistry and implications for the origin of the silicate rocks of the Jacupiranga ultramafic-alkaline complex (Brazil). *Journal of South American Earth Sciences*, **77**:286-309. <https://doi.org/10.1016/j.jsames.2017.05.009>
- Church A.A. & Jones A.P. 1995. Silicate-carbonate immiscibility at Oldoinyo Lengai. *Journal of Petrology*, **36**:869-889. <https://doi.org/10.1093/petrology/36.4.869>
- Clark T., Smith C.B., Bristow J.W., Skinner E.M.W., Viljoen K.S. 1991. Isotopic and geochemical variation in kimberlites from the S-Western Craton Margin, Prieska area, South Africa. In: International Kimberlite Conference, 5., Araxá, *Proceedings...*, p. 46-48.
- Comin-Chiaramonti P. & Gomes C.B. (eds.). 1996. *Alkaline magmatism in central-eastern Paraguay*. Relationships with coeval magmatism in Brazil. São Paulo, Edusp/Fapesp, 464 p.
- Comin-Chiaramonti P., Castorina F., Cundari A., Petrini R., Gomes C.B. 1995. Dykes and sills from Eastern Paraguay: Sr and Nd isotope systematics. In: Baer G. & Heimann A. (eds.), *Physics and chemistry of dykes*. Rotterdam, Balkema, p. 267-278.
- Comin-Chiaramonti P., Censi P., Cundari A., Gomes C.B. 1992. A silico-beforsitic flow from the Sapucaí complex (Central-Eastern Paraguay). *Geochimica Brasiliensis*, **6**:87-91.
- Comin-Chiaramonti P., Cundari A., DeGraff J.M., Gomes C.B., Piccirillo E.M. 1999. Early Cretaceous-Tertiary magmatism in Eastern Paraguay (Western Paraná Basin): geological, geophysical and geochemical relationships. *Journal of Geodynamics*, **28**:375-391. [https://doi.org/10.1016/S0264-3707\(99\)00016-2](https://doi.org/10.1016/S0264-3707(99)00016-2)
- Comin-Chiaramonti P., Cundari A., Piccirillo E.M., Gomes C.B., Castorina F., Censi P., De Min A., Marzoli A., Petrini R., Speziale S., Velázquez V.F. 1997. Potassic and sodic igneous rocks from Eastern Paraguay: their origin from a lithospheric mantle and genetic relationships with the associated Paraná flood tholeiites. *Journal of Petrology*, **38**:495-528. <https://doi.org/10.1093/ptroj/38.4.495>
- Comin-Chiaramonti P., De Min A., Girardi V.A.V., Gomes C.B. 2014. Carbonatites and primary carbonates in the Rio Apa and Amambay regions, NE Paraguay. *Lithos*, **188**:84-96. <https://doi.org/10.1016/j.lithos.2013.10.027>
- Comin-Chiaramonti P., Girardi V.A.V., De Min A., Boggiani P.C., Correia C.T. 2011. Iron-rich formations at the Cerro Manomó region, southeastern Bolivia: remnant of a BIF? *Episodes*, **34**:177-185.
- Comin-Chiaramonti P., Gomes C.B., Castorina F., Censi P., Antonini P., Furtado S., Ruberti E., Scheibe L.F. 2002. Anitápolis and Lages alkaline-carbonatite complexes, Santa Catarina state, Brazil: geochemistry and geodynamic implications. *Revista Brasileira de Geociências*, **32**:43-58.
- Comin-Chiaramonti P., Gomes C.B., Censi P., Gasparon M., Velázquez V.F. 2005a. Alkaline complexes from the Alto Paraguay province at the border of Brazil (Mato Grosso do Sul State) and Paraguay. In: Comin-Chiaramonti P. & Gomes C.B. (eds.), *Mesozoic to Cenozoic alkaline magmatism in the Brazilian Platform*. São Paulo, Edusp/Fapesp, p. 71-148.
- Comin-Chiaramonti P., Gomes C.B., Censi P., Speziale S. 2005b. Carbonatites from Southeastern Brazil: a model for the Carbon and Oxygen isotope variations. In: Comin-Chiaramonti P. & Gomes C.B. (eds.), *Mesozoic to Cenozoic alkaline magmatism in the Brazilian Platform*. São Paulo, Edusp/Fapesp, p. 629-649.

- Comin-Chiaramonti P., Gomes C.B., Cundari A., Castorina F., Censi P. 2007a. A review of carbonatitic magmatism in the Paraná-Angola-Etendeka (PAN) system. In: Castelli D. & Compagnoni R. (eds.), *Periodico di Mineralogia, Special Issue*, **76**:25-78.
- Comin-Chiaramonti P., Gomes C.B., Demin A., Ernesto M., Gasparon M. 2015. Magmatism along the High Paraguay river at the border of Brazil and Paraguay: a review and new constraints on emplacement ages. *Journal of South American Earth Sciences*, **58**:72-81. <http://dx.doi.org/10.1016/j.jsames.2014.12.010>
- Comin-Chiaramonti P., Gomes C.B., De Min A., Ernesto M., Marzoli A., Riccomini C. 2007b. Eastern Paraguay: an overview of the Post-Paleozoic magmatism and geodynamical implications. *Rendiconti Lincei, Scienze Fisiche e Naturali*, **18**:139-192. DOI: 10.1007/BF02974464
- Comin-Chiaramonti P., Gomes C.B., Marques L.S., Ruberti E., Antonini P. 2005c. Carbonatites from Southeastern Brazil: geochemistry, O-C, Sr-Nd-Pb isotopes. Relationships with the magmatism from the Paraná-Angola-Namibia Province. In: Comin-Chiaramonti P. & Gomes C.B. (eds.), *Mesozoic to Cenozoic alkaline magmatism in the Brazilian Platform*. São Paulo, Edusp/Fapesp, p. 657-688.
- Comin-Chiaramonti P., Gomes C.B., Ruberti E., Antonini P., Castorina F., Censi P. 2001. Mato Preto alkaline-carbonatite complex: geochemistry and isotope (O-C, Sr-Nd) constraints. *Geochimica Brasiliensis*, **15**:23-34.
- Comin-Chiaramonti P., Gomes C.B., Velázquez V.F., Censi P., Antonini F., Comin-Chiaramonti F., Punturo R. 2005d. Alkaline complexes from southerneastern Bolivia. In: Comin-Chiaramonti P. & Gomes C.B. (eds.), *Mesozoic to Cenozoic alkaline magmatism in the Brazilian Platform*. São Paulo, Edusp/Fapesp, p. 159-211.
- Comin-Chiaramonti P., Marzoli A., Gomes C.B., Milan A., Riccomini C., Velázquez V.F., Mantovani M.M.S., Renne P., Tassinari C.C.G., Vasconcelos P.M. 2007c. The origin of Post-Paleozoic magmatism in Eastern Paraguay. In: Foulger R.G. & Jurdy D.M. (eds.), *Plates, plumes and planetary processes. Geological Society of America, Special Paper*, **430**:603-633.
- Comte D. & Hasui Y. 1971. Geochronology of Eastern Paraguay by the potassium-argon method. *Revista Brasileira de Geociências*, **1**:33-43.
- Cordeiro P.F.O., Brod J.A., Dantas E.L., Barbosa E.S.R. 2010. Mineral chemistry, isotope geochemistry and petrogenesis of niobium-rich rocks from the Catalão I carbonatite-phoscorite complex, Central Brazil. *Lithos*, **118**:223-237. <https://doi.org/10.1016/j.lithos.2010.04.007>
- Cordeiro P.F.O., Brod J.A., Santos R.V., Dantas E.L., Oliveira C.G., Barbosa E.S.R. 2011. Stable (C, O) and radiogenic (Sr, Nd) isotopes of carbonates as indicators of magmatic and post-magmatic processes of phoscorite-series rocks and carbonatites from Catalão I, central Brazil. *Contributions to Mineralogy and Petrology*, **161**:451-464. <https://doi.org/10.1007/s00410-010-0542-y>
- Costa A.F.U., Fernandes L.A.D., Shukowsky W., Nardi L.V.S., Bittencourt M.F. 1995. Teste dos modelos tectônicos e de posicionamento do complexo granítico de Caçapava do Sul através de estudos de modelagem gravimétrica 3-D. *Revista Brasileira de Geofísica*, **13**:91-101.
- Coutinho J.M.V. 2008. Dyke swarms of the Paraná Triple Junction, Southern Brazil. *Geologia USP, Série Científica*, **8**:29-52.
- Coutinho J.M.V. & Ens H.H. 1992. Diques lamprofíricos e diferenciados carbonatíticos da região de São Sebastião e Itanhaém, SP (Resultados preliminares). In: Congresso Brasileiro de Geologia, 37., São Paulo. *Resumos Expandidos...*, **1**:512-513.
- Danni J.C.M. 1994. Os picritos alcalinos da região de Iporá: implicações na gênese dos complexos do tipo central do sul de Goiás. *Revista Brasileira de Geociências*, **24**:112-119.
- Davies G.R., Driggs A.J., Nixon P.H. 2001. A non-cognate origin for the Gibeon kimberlite megacryst suite, Namibia: implications for the origin of Namibian kimberlites. *Journal of Petrology*, **42**:159-172. <https://doi.org/10.1093/ptrology/42.1.159>
- Davino A. 1975. Geologia da Serra de Araçoiaba, Estado de São Paulo. *Boletim do Instituto de Geociências da USP*, **6**:129-144.
- Deines P. 1989. Stable isotope variations in carbonatites. In: Bell K. (ed.), *Carbonatites: genesis and evolution*. London, Unwin Hyman Ltd., p. 301-359.
- Dunworth E.A. & Bell K. 1998. Melilitolites: a new scheme of classification. *The Canadian Mineralogist*, **36**:895-903.
- Ernesto M., Marques L.S., Piccirillo E.M., Molina E.C., Ussami N., Comin-Chiaramonti P. & Bellieni G. 2002. Parana Magmatic Province-Tristan da Cunha plume system: Fixed versus mobile plume, petrogenetic considerations and alternative heat sources. *Journal of Volcanology and Geothermal Research*, **118**(1-2):15-36. [https://doi.org/10.1016/S0377-0273\(02\)00248-2](https://doi.org/10.1016/S0377-0273(02)00248-2)
- Ewart A., Marsh J.S., Milner S.C., Duncan A.R., Kamber B.S., Armstrong R.A. 2004. Petrology and geochemistry of Early Cretaceous bimodal continental flood volcanism of the NW Etendeka, Namibia. Part i: introduction, mafic lavas and re-evaluation of mantle source components. *Journal of Petrology*, **45**:59-105. <https://doi.org/10.1093/ptrology/egg083>
- Faure G. 1986. *Principles of isotope geology*. New York, John Wiley & Sons.
- Fletcher C.J.N., Appleton J.D., Webb B.C., Basham I.R. 1981. Mineralization in the Cerro Manomó carbonatite complex, Eastern Bolivia. *Transaction Institution of Mining and Metallurgy, Section B, Applied Sciences*, **90**:37-50.
- Foley S.F. 1992. Petrological characterization of the source components of potassic magmas: geochemical and experimental constraints. *Lithos*, **28**:187-204. [https://doi.org/10.1016/0024-4937\(92\)90006-K](https://doi.org/10.1016/0024-4937(92)90006-K)
- Furtado S.M.A. 1989. *Petrologia do maciço alcalino de Anitápolis, SC*. PhD Thesis, University of São Paulo, São Paulo. 245p.
- Furtado S.M.A., Gomes C.B., Scheibe L.F. 1986. Ocorrência de foscritos no maciço alcalino de Anitápolis. In: Congresso Brasileiro de Geologia, 34., Goiânia. *Anais...*, **4**:1604-1614.
- Gaspar J.C. 1989. *Geologie et mineralogie du complexe carbonatique de Jacupiranga, Brésil*. PhD Thesis, U.E.R. de Sciences Fondamentales et Appliquées, Université d'Orléans, Orléans, 344 p.
- Gaspar J.C. & Danni J.C.M. 1981. Aspectos petrográficos e vulcanológicos da província alcalino-carbonatítica de Santo Antônio da Barra, sudoeste de Goiás. *Revista Brasileira de Geociências*, **11**:74-83.
- Germann A., Marker A., Friedrich G. 1987. The alkaline complex of Jacupiranga, São Paulo, Brazil. *Zentralblatt für Geologie und Paläontologie*, **1**:807-818.
- Gibson S.A., Thompson R.N., Day J.A. 2006. Timescales and mechanisms of plume-lithosphere interactions: 40Ar/39Ar geochronology and geochemistry of alkaline igneous rocks from the Paraná-Etendeka large igneous province. *Earth and Planetary Science Letters*, **251**(1-2):1-17. <http://doi.org/10.1016/j.epsl.2006.08.004>
- Gibson S.A., Thompson R.N., Dickin A.P., Leonardos O.H. 1995a. High-Ti and low-Ti mafic potassic magmas: key to plume-lithosphere interactions and continental flood-basalt genesis. *Earth Planetary Science Letters*, **136**:149-165. [https://doi.org/10.1016/0012-821X\(95\)00179-G](https://doi.org/10.1016/0012-821X(95)00179-G)

- Gibson S.A., Thompson R.N., Leonardos O.H., Dickin A.P., Mitchell J.G. 1995b. The Late Cretaceous impact of the Trindade mantle plume: evidence from large-volume, mafic, potassic magmatism in SE Brazil. *Journal of Petrology*, **36**:189-229. <https://doi.org/10.1093/petrology/36.1.189>
- Gibson S.A., Thompson R.N., Leonardos O.H., Dickin A.P., Mitchell J.G. 1999. The limited extent of plume-lithosphere interactions during continental flood-basalt genesis: geochemical evidence from Cretaceous magmatism in Southern Brazil. *Contributions to Mineralogy and Petrology*, **137**:147-169. <https://doi.org/10.1007/s004100050588>
- Gittins J. & Harmer R.E. 2003. Myth and reality in the carbonatite-silicate rock association. *Periodico di Mineralogia*, **72**(1):19-26.
- Gomes C.B. 1970. Petrologia do maciço alcalino de Itapirapuã, São Paulo. *Boletim do Instituto de Geociências e Astronomia*, **1**:77-188. <http://dx.doi.org/10.11606/issn.2316-9001.v1i0p77-197>
- Gomes C.B. & Comin-Chiaramonti P. 2005. Some notes on the Alto Paranaíba Igneous Province. In: Comin-Chiaramonti P. & Gomes C.B. (eds.), *Mesozoic to Cenozoic alkaline magmatism in the Brazilian Platform*. São Paulo, Edusp/Fapesp, p. 317-340.
- Gomes C.B. & Comin-Chiaramonti P. (eds.). 2017. *Magmatismo alcalino continental da região meridional da Plataforma Brasileira*. São Paulo, Edusp/Fapesp, 608 p.
- Gomes C.B., Comin-Chiaramonti P., Velázquez V.F., Orué D. 1996b. Alkaline magmatism in Paraguay: a review. In: Comin-Chiaramonti P. & Gomes C.B. (eds.), *Alkaline magmatism in central-eastern Paraguay. Relationships with coeval magmatism in Brazil*. São Paulo: Edusp/Fapesp, p. 35-56.
- Gomes C.B. & Cordani U.G. 1965. Geocronologia do maciço alcalino de Itapirapuã (SP). *Anais da Academia Brasileira de Ciências*, **37**:497-501.
- Gomes C.B. & Dutra C.V. 1969. A short note about the carbonatites from Itapirapuã, São Paulo. *Anais da Academia Brasileira de Ciências*, **41**:195-198.
- Gomes C.B. & Dutra C.V. 1970. Some geochemical features of the alkaline rocks of Itapirapuã, São Paulo. *Anais da Academia Brasileira de Ciências*, **42**:521-534.
- Gomes C.B., Comin-Chiaramonti P., Velázquez V.F. 2013. A synthesis on the alkaline magmatism of Eastern Paraguay. *Brazilian Journal of Geology*, **43**:745-761. DOI: 10.5327/Z2317-488920130004000012
- Gomes C.B., Morbidelli L., Ruberti E., Comin-Chiaramonti P. 1996a. Comparative aspects between Post-Palaeozoic alkaline rocks from the western and eastern margins of the Paraná Basin. In: Comin-Chiaramonti P. & Gomes C.B. (eds.), *Alkaline magmatism in central-eastern Paraguay. Relationships with coeval magmatism in Brazil*. São Paulo, Edusp/Fapesp, p. 249-274.
- Gomes C.B., Ruberti E., Azzone R.G., Vasconcelos P.M., Sato K., Enrich G.E.R. 2018. New age determinations for the Banhadão and Itapirapuã complexes in the Ribeira Valley, southern Brazil. *Brazilian Journal of Geology*, in press.
- Gomes C.B., Ruberti E., Comin-Chiaramonti P., Azzone R.G. 2011a. Alkaline magmatism in the Ponta Grossa Arch, SE Brazil: a review. *Journal of South American Earth Sciences*, **32**:152-168. <https://doi.org/10.1016/j.jsames.2011.05.003>
- Gomes C.B., Ruberti E., Morbidelli L. 1990. Carbonatite complexes from Brazil: a review. *Journal of South American Earth Sciences*, **3**:51-63. [https://doi.org/10.1016/0895-9811\(90\)90017-U](https://doi.org/10.1016/0895-9811(90)90017-U)
- Gomes C.B., Velázquez V.F., Azzone R.G., Paula G.S. 2011b. Alkaline magmatism in the Amambay area, NE Paraguay: the Cerro Sarambí complex. *Journal of South American Earth Sciences*, **32**:75-95. <https://doi.org/10.1016/j.jsames.2011.04.004>
- Gomide C.S., Brod J.A., Junqueira-Brod T.C., Buhn B., Santos R.V., Barbosa E.S.R., Cordeiro P.F.O., Palmieri M., Grasso C.B., Torres M.G. 2013. Sulfur isotopes from Brazilian alkaline complexes. *Chemical Geology*, **341**:38-49. <https://doi.org/10.1016/j.chemgeo.2013.01.006>
- Gomide C.S., Brod J.A., Vieira L.C., Junqueira-Brod T.C., Petrinovic I.A., Santos R.V., Barbosa E.S.R., Mancini L.H. 2016. Stable (C, O, S) isotopes and whole-rock geochemistry of carbonatites from Alto Paranaíba Igneous Province, SE Brazil. *Brazilian Journal of Geology*, **46**:351-376. <http://dx.doi.org/10.1590/2317-4889201620150059>
- Grasso C.B. 2010. *Petrologia do complexo alcalino de Serra Negra*. MG. MSc Dissertation, University of Brasília, Brasília. 209p.
- Guarino V., Azzone R.G., Brotzu P., Gomes C.B., Melluso L., Morbidelli L., Ruberti E., Tassinari C.C.G., Brilli M. 2012. Magmatism and fenitization in the Cretaceous potassium-alkaline-carbonatitic complex of Ipanema, São Paulo State, Brazil. *Mineralogy and Petrology*, **104**:43-61. DOI: 10.1007/s00710-011-0168-4
- Guarino V., Wu F.-Y., Lustrino M., Melluso L., Brotzu P., Gomes C.B., Ruberti E., Tassinari C.C.G., Svisero D.P. 2013. U-Pb ages, Sr-Nd isotope geochemistry, and petrogenesis of kimberlites, kamafugites and phlogopite-picrites of the Alto Paranaíba Igneous Province, Brazil. *Chemical Geology*, **353**:65-82. <https://doi.org/10.1016/j.chemgeo.2012.06.016>
- Guarino V., Wu F.-Y., Melluso L., Gomes C.B., Tassinari C.C.G., Ruberti E., Brilli M. 2017. U-Pb ages, geochemistry C-O-Nd-Sr-Hf isotopes and petrogenesis of the Catalão II carbonatitic complex (Alto Paranaíba Igneous Province, Brazil): implications for regional-scale heterogeneities in Brazilian carbonatite associations. *International Journal of Earth Sciences*, **106**:1963-1989. <https://doi.org/10.1007/s00531-016-1402-4>
- Guimarães I.G., Amaral M.A.M., Garcia I.R.A. 1980. Uncompahgrito de Tapira, MG. In: Congresso Brasileiro de Geologia, 31., Camboriú. *Anais...*, p. 2050-2058.
- Haggerty S.E. & Mariano A.N. 1983. Strontian loparite and strontiochevkinite: two new minerals in rheomorphic tenites from the Paraná Basin carbonatites, South America. *Contributions to Mineralogy and Petrology*, **84**:365-381.
- Hart S.R. 1984. A large-scale isotope anomaly in the Southern Hemisphere. *Nature*, **309**:753-757. DOI: 10.1038/309753a0
- Hart S.R., Gerlach D.C., White W.M. 1986. A possible new Sr-Nd-Pb mantle array and consequences for mantle mixing. *Geochimica et Cosmochimica Acta*, **50**:1551-1557. [https://doi.org/10.1016/0016-7037\(86\)90329-7](https://doi.org/10.1016/0016-7037(86)90329-7)
- Hart S.R., Hauri E.H., Oschmann I.A., Whitehead J.A. 1992. Mantle plumes and entrainment isotopic evidence. *Science*, **256**:517-520.
- Hart S.R. & Zindler A. 1989. Constraints on the nature and the development of chemical heterogeneities in the mantle. In: Peltier W.R. (ed.), *Mantle convection plate tectonics and global dynamics*. New York, Gordon and Breach Sciences Publishers, p. 261-388.
- Hasui Y., Sadowski G.R., Suguio K., Fuck R.A. 1975. The Phanerozoic tectonic evolution of the western Minas Gerais. *Anais da Academia Brasileira de Ciências*, **47**:431-438.
- Herz N. 1977. Timing of spreading in the South Atlantic: information from Brazilian alkali rocks. *Geological Society of America Bulletin*, **88**:101-112.
- Hoernle K., Tilton G., Le Bas M.J., Duggen S., Garbe-Schönberg D. 2002. Geochemistry of oceanic carbonatites compared with continental carbonatites: mantle recycling of oceanic crustal carbonate. *Contributions to Mineralogy and Petrology*, **142**:520-542. DOI: 10.1007/s004100100308

- Huang J.-M., Hawkesworth C.J., Van Calsteren P., McDermott F. 1995. Geochemical characteristics and origin of the Jacupiranga carbonatites. *Chemical Geology*, **119**:79-99. [https://doi.org/10.1016/0009-2541\(94\)00093-N](https://doi.org/10.1016/0009-2541(94)00093-N)
- Issa Filho A., Lima P.R.A.S., Souza O.M. 1984. Aspectos da geologia do complexo carbonatítico do Barreiro, Araxá, MG, Brasil. *Companhia Brasileira de Metalurgia e Mineração*, p. 19-44.
- Jenkis II, R.E. 1987. Geology of the Clugger-fluorite deposit, Mato Preto, Paraná, Brazil. *Revista Brasileira de Geociências*, **17**:288-294.
- Junqueira-Brod T.C., Brod J.A., Gibson S.A., Thompson R.N. 2000. Mineral chemistry of kamafugites and related rocks from Águas Emendadas region, Goiás State. *Revista Brasileira de Geociências*, **30**:403-407.
- Junqueira-Brod T.C., Roig H.L., Gaspar J.C., Brod J.A., Meneses P.R. 2002. A província alcalina de Goiás e extensão do seu vulcanismo kamafugítico. *Revista Brasileira de Geociências*, **32**:559-566.
- Keller J. & Hoefs J. 1995. Stable isotope characteristics of recent natrocarbonatites from Oldoinyo Lengai. In: Bell K. & Keller J. (eds.), *Carbonatite volcanism: Oldoinyo Lengai and the petrogenesis of natrocarbonatites*. Berlin, Springer, p. 113-123.
- Kjarsgaard B.A. & Hamilton D.L. 1988. Liquid immiscibility and the origin of alkali-poor carbonatites. *Mineralogical Magazine*, **52**:43-55. DOI: 10.1180/minmag.1988.052.364.04
- Kjarsgaard B.A. & Hamilton D.L. 1989. The genesis of carbonatites by immiscibility. In: Bell K. (ed.), *Carbonatite: Genesis and Evolution*. London, Unwin Hyman, p. 388-404.
- Knecht T. 1960. Notas preliminares sobre novas ocorrências de rochas alcalinas no Estado de São Paulo. *Boletim da Sociedade Brasileira de Geologia*, **9**:71-76.
- Lapido-Loureiro F.E. & Tavares J.R. 1983. Duas novas ocorrências carbonatíticas: Mato Preto e Barra do Itapirapuã. *Revista Brasileira de Geociências*, **13**:7-11.
- Le Bas M.J. 2008. Fenites associated with carbonatites. *The Canadian Mineralogist*, **46**:915-932. DOI: 10.3749/canmin.46.4.915
- Le Roex A.P. 1985. Geochemistry, mineralogy and magmatic evolution of the basaltic and trachytic lavas from Gough Island, South Atlantic. *Journal of Petrology*, **26**:149-186. <https://doi.org/10.1093/ptetrology/26.1.149>
- Le Roex A.P., Cliff R.A., Adair B.J.J. 1990. Tristan da Cunha, South Atlantic: geochemistry and petrogenesis of a basanite-phonolite lava series. *Journal of Petrology*, **31**:779-812. <https://doi.org/10.1093/ptetrology/31.4.779>
- Lee W.J. & Wyllie P.J. 1994. Experimental data bearing on liquid immiscibility, crystal fractionation, and the origin of calciocarbonatites. *International Geology Review*, **36**:797-819. <https://doi.org/10.1080/00206819409465489>
- Lee W.J. & Wyllie P.J. 1996. Liquid Immiscibility in the join $\text{NaAlSi}_3\text{O}_8\text{-CaCO}_3$ to 2.5 GPa and the origin of calciocarbonatite magmas. *Journal of Petrology*, **37**:1125-1152. <https://doi.org/10.1093/ptetrology/37.5.1125>
- Lee W.J. & Wyllie P.J. 1997. Liquid immiscibility between nephelinite and carbonatite from 2.5 to 1.0 GPa compared with mantle melt compositions. *Contributions to Mineralogy and Petrology*, **127**:1-16. <http://dx.doi.org/10.1007/s004100050261>
- Lee W.J. & Wyllie P.J. 1998a. Petrogenesis of carbonatite magmas from mantle to crust, constrained by the system $\text{CaO-(MgO + FeO*)-(Na}_2\text{O + K}_2\text{O)-(SiO}_2\text{ + Al}_2\text{O}_3\text{ + TiO}_2\text{)-CO}_2$. *Journal of Petrology*, **39**:495-517. <https://doi.org/10.1093/ptetroj/39.3.495>
- Lee W.J. & Wyllie P.J. 1998b. Processes of crustal carbonatite formation by liquid immiscibility and differentiation, elucidated by model systems. *Journal of Petrology*, **39**:2005-2013. <https://doi.org/10.1093/ptetroj/39.11-12.2005>
- Leinz V. 1940. Petrologia das jazidas de apatita de Ipanema. Departamento Nacional da Produção Mineral. Rio de Janeiro, Ministério da Agricultura. 52p.
- Livieres R.A. & Quade H. 1987. Distribución regional y asentamiento tectónico de los complejos alcalinos del Paraguay. *Zentralblatt für Geologie und Paläontologie*, Part I, **7**:791-805.
- Machado Jr. D.L. 1991. *Geologia e aspectos metalogenéticos do complexo alcalino-carbonatítico de Catalão II (GO)*. PhD Thesis, Universidade de Campinas, Campinas, 102 p.
- Maciel L.A.C. 2016. Rochas alcalinas do Rio Grande do Sul: controles tectônicos e mineralização associadas. In: SIMEXMIN, Ouro Preto. *Boletim de Resumos*.
- Mariano A.N. 1989. Economic geology of Rare Earth Elements. *Reviews on Mineralogy*, **21**:309-348.
- Mariano A. & Marchetto M. 1991. Serra Negra and Salitre carbonatite alkaline igneous complex. In: 5th International Kimberlite Conference, Araxá. *Field Guide Book*, p.74-79.
- Marques L.S., Dupré B., Piccirillo E.M. 1999. Mantle source compositions of the Paraná Magmatic Province (Southern Brazil): evidence from trace element and Sr-Nd-Pb isotope geochemistry. *Journal of Geodynamics*, **28**:439-458. [https://doi.org/10.1016/S0264-3707\(99\)00020-4](https://doi.org/10.1016/S0264-3707(99)00020-4)
- Marques L.S., Ulbrich M.N.C., Ruberti E., Tassinari C.C.G. 2000. Petrology, geochemistry and Sr-Nd isotopes of the Trindade and Martin Vaz volcanic rocks (South Atlantic Ocean). *Journal of Volcanology and Geothermal Research*, **93**:191-216. [https://doi.org/10.1016/S0377-0273\(99\)00111-0](https://doi.org/10.1016/S0377-0273(99)00111-0)
- McDonough W.F. & Sun S. 1995. The Composition of the Earth. *Chemical Geology*, **120**:223-253. [https://doi.org/10.1016/0009-2541\(94\)00140-4](https://doi.org/10.1016/0009-2541(94)00140-4)
- Melcher G.C. & Coutinho J.M.V. 1966. Rochas alcalinas e carbonatito de Anitápolis, Estado de Santa Catarina. *Boletim da Sociedade Brasileira de Geologia*, **15**:59-93.
- Melcher G.C. 1966. The carbonatites of Jacupiranga, São Paulo, Brazil. In: Tuttle O.F. & Gittins J. (eds.), *Carbonatites*. New York, Interscience, p. 169-181.
- Melluso L., Lustrino M., Ruberti E., Brotzu P., Gomes C.B., Morbidelli L., Morra V., Svisero D.P., D'Amelio F. 2008. Major- and trace-element composition of olivine, perovskite, clinopyroxene, Cr-Fe-Ti oxides, phlogopites and host kamafugites and kimberlites, Alto Paranaíba, Brazil. *The Canadian Mineralogist*, **46**:19-40. DOI: 10.3749/canmin.46.1.19
- Menezes Jr. L.A.D. & Martins J.M. 1984. The Jacupiranga mine, São Paulo, Brazil. *The Mineralogical Record*, **15**:261-270.
- Meyer H.O.A., Blaine L.G., Svisero D.P., Craig B.S. 1994. Alkaline intrusions in western Minas Gerais. In: International Kimberlite Conference, 5., Araxá. *Proceedings...*, p. 140-155.
- Mitchell R.H. 2005. Carbonatites and carbonatites and carbonatites. *The Canadian Mineralogist*, **43**:2049-2068. <https://doi.org/10.2113/gscanmin.43.6.2049>
- Monteiro C.F., Toniolo J.A., Abram M.B. 2016. Carbonatitos associados ao Escudo Sul-Riograndense, Rio Grande do Sul. In: Abram M.B., Bahiense J.C., Almeida R.C. (eds.), *Projeto Fosfato Brasil – Parte II. CPRM. Informe de Recursos Minerais, Série Insumos Minerais para Agricultura*, **17**:433-449.

- Moraes L.C. 1984. *Petrologia, estratigrafia e potencial diamantífero da suíte vulcânica alcalina da região de Santo Antônio da Barra, Goiás*. MSc Dissertation, Universidade de Brasília, Brasília. 133p.
- Moraes L.C. 1988. Aspectos petrológicos do magmatismo alcalino cretáceo de Santo Antônio da Barra, GO. *Revista Brasileira de Geociências*, **18**:33-42.
- Morbidelli L., Beccaluva L., Brotzu P., Conte A.M., Garbarino C., Gomes C.B., Macciotta G., Ruberti E., Scheibe L.F., Traversa G. 1986. Petrological and geochemical studies of alkaline rocks from continental Brazil. 3. Fenitization of jacupirangite by carbonatite magmas in Jacupiranga complex, SP. *Periodico di Mineralogia*, **55**:261-295.
- Morbidelli L., Gomes C.B., Beccaluva L., Brotzu P., Conte A.M., Ruberti E., Traversa G. 1995. Mineralogical, petrological and geochemical aspects of alkaline and alkaline-carbonatite associations from Brazil. *Earth-Science Reviews*, **39**:135-168. [https://doi.org/10.1016/0012-8252\(95\)00031-3](https://doi.org/10.1016/0012-8252(95)00031-3)
- Morbidelli L., Gomes C.B., Beccaluva L., Brotzu P., Garbarino C., Riffel B. F., Ruberti E., Traversa G. 1997. Parental magma characterization of Salitre cumulate rocks (Alto Paranaíba Alkaline Province, Brazil) as inferred from mineralogical, petrographic and geochemical data. *International Geology Review*, **39**:723-743. <https://doi.org/10.1080/00206819709465298>
- Natali C., Beccaluva L., Bianchini G., Siena F. 2018. Coexistence of alkaline-carbonatite complexes and high-MgO CFB in the Paraná-Etendeka province: Insights on plume-lithosphere interactions in the Gondwana realm. *Lithos*, **296-299**:54-66. <https://doi.org/10.1016/j.lithos.2017.11.001>
- Nelson D.R., Chivas A.R., Chappell B.W., McCulloch M.T. 1988. Geochemical and isotopic systematics in carbonatites and implications for the evolution of ocean-island sources. *Geochimica et Cosmochimica Acta*, **52**:1-17. [https://doi.org/10.1016/0016-7037\(88\)90051-8](https://doi.org/10.1016/0016-7037(88)90051-8)
- Oliveira I.L., Brod J.A., Cordeiro P.F.O., Dantas E.L., Mancini L.H. 2017. Insights into the late-stage differentiation processes of the Catalão I carbonatite complex in Brazil: New Sr-Nd and C-O isotopic data in minerals from niobium ores. *Lithos*, **274-275**:214-224. DOI: 10.1016/j.lithos.2016.12.034
- Otto J.W. & Wyllie P.J. 1993. Relationships between silicate melts and carbonate precipitating melts in CaO-MgO-SiO₂-CO₂-H₂O at 2 kbar. *Mineralogy and Petrology*, **48**:343-365.
- Pena G.S. 1974. Geologia da Área do Projeto Goiânia II, Sudoeste de Goiás. In: Congresso Brasileiro de Geologia, 28., Porto Alegre. *Anais...* **4**:37-50.
- Philipp R.P., Viero A.P., Comin-Chiaramonti P., Gomes C.B. 2005. Mesozoic alkaline rocks of Rio Grande do Sul. In: Comin-Chiaramonti P. & Gomes C.B. (eds.), *Mesozoic to Cenozoic alkaline magmatism in the Brazilian Platform*. São Paulo, Edusp/Fapesp, p. 573-590.
- Piccirilo E.M. & Melfi A.J. 1988. *The Mesozoic flood volcanism of the Paraná Basin*: petrogenetic and geophysical aspects. São Paulo, IAG-USP, 600p.
- Riccomini C., Velázquez V.F., Gomes C.B. 2005. Tectonic controls of the Mesozoic and Cenozoic alkaline magmatism in the Central-Southeastern Brazilian Platform. In: Comin-Chiaramonti P. & Gomes C.B. (eds.), *Mesozoic to Cenozoic alkaline magmatism in the Brazilian Platform*. São Paulo, Edusp/Fapesp, p. 31-56.
- Richardson S.H., Gurney J.J., Erlank A.J., Harris J.W. 1984. Origin of diamonds in old enriched mantle. *Nature*, **310**:198-202. DOI: 10.1038/310198a0
- Rocha A.M.R., Dorneles N.T., Gindri M.D., Vargas F.M., Cerva-Alves T., Benetti F.A. 2013. Descoberta dos carbonatitos Picada dos Tocos e Passo Feio e o potencial para fosfato e ETRs, Caçapava do Sul, Rio Grande do Sul. In: Brazilian Symposium of Metallogeny – The New Brazilian Mineral Deposits, 3., Gramado. *Boletim de Resumos...*
- Roden M.F., Murphy V.R., Gaspar J.C. 1985. Sr and Nd isotopic composition of the Jacupiranga carbonatite. *Journal of Geology*, **93**:212-220. <https://doi.org/10.1086/628943>
- Rodrigues C.S. & Lima P.R.A.S. 1984. *Complexos carbonatíticos do Brasil*: geologia. Araxá, Companhia Brasileira de Metalurgia e Mineração, p. 1-17.
- Rodrigues E.P.O. 1985. *O complexo alcalino de Anitápolis: um estudo petrológico*. PhD Thesis, Universidade de São Paulo, São Paulo. 174p.
- Ruberti E. 1998. *Petrologia e geoquímica das suítes carbonatíticas de Mato Preto (PR) e da Barra do Itaipirapuã (PR/SP), Brasil*. Thesis, University of São Paulo, São Paulo.
- Ruberti E., Castorina F., Censi P., Comin-Chiaramonti P., Gomes C.B., Antonini P., Andrade F.R.D. 2002. The geochemistry of the Barra do Itaipirapuã carbonatite (Ponta Grossa Arch, Brazil): a multiple stockwork. *Journal of South American Earth Sciences*, **15**:215-228. [https://doi.org/10.1016/S0895-9811\(02\)00031-7](https://doi.org/10.1016/S0895-9811(02)00031-7)
- Ruberti E., Castorina F., Censi P., Gomes C.B., Speziale S., Comin-Chiaramonti P. 1997. REE-O-C-Sr-Nd in carbonatites from Barra do Itaipirapuã and Mato Preto (Southern Brazil). In: South American Symposium on Isotope Geology, 1., Campos do Jordão. *Short Papers...*, p. 271-275.
- Ruberti E., Enrich G.E.R., Gomes C.B., Comin-Chiaramonti P. 2008. Hydrothermal REE fluorocarbonate mineralization at Barra do Itaipirapuã, a multiple stockwork carbonatite, Southern Brazil. *The Canadian Mineralogist*, **46**:901-914. <https://doi.org/10.3749/canmin.46.4.901>
- Ruberti E., Gomes C.B., Comin-Chiaramonti P. 2005. The alkaline magmatism from the Ponta Grossa Arch. In: Comin-Chiaramonti P. & Gomes C.B. (eds.), *Mesozoic to Cenozoic alkaline magmatism in the Brazilian Platform*. São Paulo, Edusp/Fapesp, p. 473-522.
- Ruberti E., Marguti R.L., Gomes C.B. 1991. O complexo carbonatítico de Jacupiranga: informações gerais. In: Congresso Brasileiro de Geoquímica, 3./Congresso de Geoquímica dos Países de Língua Portuguesa, 1., São Paulo. *Guia de Excursões...* p. 1-20.
- Ruberti E., Scheibe L.F., Gomes C.B. 1988. The Jacupiranga alkaline complex. In: International Conference on the Geochemical Evolution of the Continental Crust, Poços de Caldas. *Extended Abstracts...* p.11-25.
- Rugenski A., Mantovani M.S.M., Shukowsky W. 2006. Investigação gravimétrica do complexo alcalino de Ipanema, São Paulo, Brasil. *Geologia USP, Série Científica*, **6**:13-24. <http://dx.doi.org/10.5327/S1519-874X2006000200002>
- Sadowski G.R. 1987. A possible relation between pulses of platform activation and plate kinematics. *Tectonophysics*, **143**:43-57. [https://doi.org/10.1016/0040-1951\(87\)90077-1](https://doi.org/10.1016/0040-1951(87)90077-1)
- Santos R.V. 1988. *Geologia e geoquímica do depósito de fluorita do complexo carbonatítico de Mato Preto, Paraná, Brasil*. MSc Dissertation, Universidade de Brasília, Brasília. 144p.
- Santos R.V. & Clayton R.N. 1995. Variations of oxygen and carbon isotopes in carbonatites – A study of Brazilian alkaline complexes. *Geochimica et Cosmochimica Acta*, **59**:1339-1352. [https://doi.org/10.1016/0016-7037\(95\)00048-5](https://doi.org/10.1016/0016-7037(95)00048-5)
- Santos R.V., Dardenne M.A., Matsui E. 1990. Geoquímica de isótopos de carbono e oxigênio dos carbonatitos do complexo alcalino de Mato Preto, Paraná, Brasil. *Revista Brasileira de Geociências*, **20**(1-4):153-158.

- Santos R.V., Dardenne M.A., Oliveira C.G. 1996. Rare Earth Elements geochemistry of fluorite from the Mato Preto carbonatite complex. *Revista Brasileira de Geociências*, **26**:81-86.
- Sasada T., Hiyagon H., Bell H., Edbihara M. 1997. Mantle-derived noble gases in carbonatites. *Geochimica et Cosmochimica Acta*, **61**:4219-4228. [https://doi.org/10.1016/S0016-7037\(97\)00202-0](https://doi.org/10.1016/S0016-7037(97)00202-0)
- Scheibe L.F. 1986. *Geologia e petrologia do distrito alcalino de Lages, SC, Brasil*. PhD Thesis, Universidade de São Paulo, São Paulo, 224 p.
- Scheibe L.F. & Formoso M.L.L. 1982. Contribuição da geoquímica das Terras Raras à caracterização dos carbonatitos da Fazenda Varela, Lages, SC. *Revista Brasileira de Geociências*, **12**:553-561.
- Scheibe L.F., Furtado S.M.A., Comin-Chiaramont P., Gomes C.B. 2005. Cretaceous alkaline magmatism from Santa Catarina State, Southern Brazil. In: Comin-Chiaramontim P. & Gomes C.B. (eds.), *Mesozoic to Cenozoic alkaline magmatism in the Brazilian Platform*. São Paulo, Edusp/Fapesp, p. 523-571.
- Sgarbi P.B.D. 1998. *Mineralogia e petrologia dos kamafugitos da região de Santo Antônio da Barra, Sudoeste de Goiás*. PhD Thesis, Universidade Federal do Rio de Janeiro, Rio de Janeiro. 214p.
- Sgarbi P.B.D., Gaspar J.C., Valença J.G. 2000. Brazilian kamafugites. *Revista Brasileira de Geociências*, **30**:417-420.
- Siebel W., Becchio R., Wolker F., Hansen M.A.F., Viramonte J., Trumbull R.B., Haase G., Zimmer M. 2000. Trindade and Martín Vaz islands, South Atlantic: isotopic (Sr, Nd, Pb) and trace element constraints on plume related magmatism. *Journal of South American Earth Sciences*, **13**:79-103. [https://doi.org/10.1016/S0895-9811\(00\)00015-8](https://doi.org/10.1016/S0895-9811(00)00015-8)
- Smith C.B. 1983. Pb, Sr and Nd isotopic evidence for sources of Southern African Cretaceous kimberlites. *Nature*, **304**:51-54. DOI: 10.1038/304051a0
- Smith C.B., Gurney J.J., Skinner E.M.W., Clement C.R., Ebrahim N. 1985. Geochemical character of Southern African kimberlites: a new approach based on isotopic constraints. *Transactions of the Geological Society of South Africa*, **88**:267-280.
- Song W., Xu C., Chakhmouradian A.R., Kynicky J., Huang K., Zhang Z. 2017. Carbonatites of Tarim (NW China): first evidence of crustal contribution in carbonatites from a large igneous province. *Lithos*, **282-283**:1-9. <https://doi.org/10.1016/j.lithos.2017.02.018>
- Sonoki I.K. & Garda G.M. 1988. Idades K-Ar de rochas alcalinas do Brasil Meridional e Paraguai Oriental: compilação e adaptação às novas constantes de decaimento. *Boletim do Instituto de Geociências USP, Série Científica*, **19**:63-85. DOI: 10.11606/issn.2316-8986.v19i0p63-85
- Souza Filho J.G.C. (1974) Prospecção de urânio nas chaminés alcalinas de Serra Negra e Salitre, MG. *Boletim do Ministério de Minas e Energia*. Rio de Janeiro, Comissão Nacional de Energia Nuclear. v.9. 41p.
- Speziale S., Censi P., Comin-Chiaramont P., Ruberti E., Gomes C.B. 1997. Oxygen and carbon isotopes in the Barra do Itaipirapua and Mato Preto carbonatites (Southern Brazil). *Mineralogica et Petrographica Acta*, **40**:1-21.
- Sun S.S. & McDonough W.F. 1989. Chemical and isotopic systematics of oceanic basalts. In: Saunders D. & Norry M.J. (eds.), *Magmatism in oceanic basins*. *Geological Society of London, Special Publication*, **42**:313-345.
- Taylor Jr. H.P., Frechen J., Degens E.T. 1967. Oxygen and carbon isotope studies of carbonatites from Laacher See district, West Germany and Alnö District, Sweden. *Geochimica et Cosmochimica Acta*, **31**:407-430. [https://doi.org/10.1016/0016-7037\(67\)90051-8](https://doi.org/10.1016/0016-7037(67)90051-8)
- Thompson N. 1982. Magmatism of the British Tertiary Volcanic Province (Carnegie Review Article). *Scottish Journal of Geology*, **18**:49-107. <https://doi.org/10.1144/sjg18010049>
- Thompson R.N., Gibson S.A., Mitchell J.G., Dickin A.P., Leonardos O.H., Brod J.A., Greenwood J.C. 1998. Migrating Cretaceous-Eocene magmatism in the Serra do Mar Alkaline Province, SE, Brazil: melts from the deflected Trindade mantle plume? *Journal of Petrology*, **39**:1493-1526.
- Toniolo J.A., Remus M.V.D., Parisi G.N., Dani N. 2013. Dois eventos carbonatíticos temporalmente distintos no RS: tipos linear e central. In: Simpósio Sul-Brasileiro de Geologia, 8., Foz do Iguaçu. *Resumos...*
- Toyoda K., Horiuchi H., Tokomani M. 1994. Dupal anomaly of Brazilian carbonatites: geochemical correlations with hotspots in the South Atlantic and implications for the mantle source. *Earth and Planetary Science Letters*, **126**:315-331. [https://doi.org/10.1016/0012-821X\(94\)90115-5](https://doi.org/10.1016/0012-821X(94)90115-5)
- Traversa G., Barbieri M., Beccaluva L., Coltorti M., Conte A.M., Garbarino C., Gomes C.B., Macciotta G., Morbidelli L., Ronca S., Scheibe L.F. 1996. Mantle sources and differentiation of alkaline magmatic suite of Lages, Santa Catarina, Brazil. *European Journal of Mineralogy*, **8**:193-208.
- Traversa G., Gomes C.B., Brotzu P., Buraglini N., Morbidelli L., Macciotta G., Morbidelli L., Principato M.S., Ronca S., Ruberti E. 2001. Petrography and mineral chemistry of carbonatites and mica-rich rocks from the Araxá complex (Alto Paranaíba Province, Brazil). *Anais da Academia Brasileira de Ciências*, **73**:71-98. <http://dx.doi.org/10.1590/S0001-37652001000100008>
- Traversa G., Scheibe L.F., Barbieri M., Beccaluva L., Coltorti M., Conte A.C., Garbarino C., Gomes C.B., Macciotta G., Morbidelli L., Ronca S. 1994. Petrology and mineral chemistry of the alkaline district of Lages, SC, Brazil. *Geochimica Brasiliensis*, **8**:179-214.
- Ulbrich H.H. & Gomes C.B. 1981. Alkaline rocks from continental Brazil. *Earth-Science Reviews*, **17**:135-154. [https://doi.org/10.1016/0012-8252\(81\)90009-X](https://doi.org/10.1016/0012-8252(81)90009-X)
- Ulbrich H.H., Garda G.M., Ulbrich M.N.C. 1991. Avaliação das idades K-Ar dos maciços alcalinos do Brasil Sul-Oriental e Paraguai Oriental. *Boletim Instituto de Geociências USP, Publicação Especial*, **9**:87-91. <http://dx.doi.org/10.11606/issn.2317-8078.v0i9p87-92>
- Ulbrich H.H.G.J., Demaiffe D., Vlach S.R.F., Ulbrich M.N.C. 2005. Structure and origin of the Poços de Caldas alkaline massif, SE Brazil. In: Comin-Chiaramont P. & Gomes C.B. (eds.), *Mesozoic to Cenozoic alkaline magmatism in the Brazilian Platform*. São Paulo, Edusp/Fapesp, p. 367-418.
- Ulbrich H.H.G.J., Vlach S.R.F., Ulbrich M.N.C., Kawashita K. 2002. Penecontemporaneous syenitic-phonolitic and basic-ultrabasic-carbonatitic rocks at the Poços de Caldas alkaline massif, SE Brazil: genetic and geochronologic evidence. *Revista Brasileira de Geociências*, **32**:15-26.
- Velázquez V.F., Riccomini C., Gomes C.B., Figueredo L., Figueredo C. 1998. Relações tectônicas do magmatismo alcalino do Paraguai Oriental. *Revista do Instituto Geológico*, **19**:41-48. <http://dx.doi.org/10.5935/0100-929X.19980005>
- Vlach S.R.F., Vilalva F.C.J., Ulbrich M.N.C., Ulbrich H.H.G.J., Vasconcelos P.M. 2003. Phlogopite from carbonatitic veins associated with the Poços de Caldas alkaline massif, SE Brazil: mineralogy and ⁴⁰Ar/³⁹Ar dating by the laser step heating method. In: South American Symposium on Isotope Geology, 6., Salvador. *Short Papers...*, v. 2, p. 702-705.

Walter A.V., Flicoteaux R., Parron C., Loubet M., Nahon D. 1995. Rare-Earth Elements and isotopes (Sr, Nd, O, C) in minerals from the Juquiá carbonatite (Brazil): tracers of a multistage evolution. *Chemical Geology*, **120**:27-44. [https://doi.org/10.1016/0009-2541\(94\)00101-D](https://doi.org/10.1016/0009-2541(94)00101-D)

Woolley A.R. 1987. *Alkaline rocks and carbonatites of the world*. Part I: North and South America. London, British Museum (Natural History), 216 p.

Woolley A.R. & Kempe D.R.C. 1989. Carbonatites: nomenclature, average chemical compositions, and element distribution. *In*:

Bell K. (ed.), *Carbonatites: genesis and evolution*. London, Unwin Hyman Ltd., p. 1-14.

Woolley A.R. & Kjarsgaard B.A. 2008. The paragenetic types of carbonatite as indicated by the diversity and relative abundances of associated silicate rocks: evidence from a global database. *The Canadian Mineralogist*, **46**:741-752. DOI: 10.3749/canmin.46.4.741

Zindler A. & Hart S.R. 1986. Chemical geodynamics. *Annual Review of Earth and Planetary Sciences*, **14**:493-571. <https://doi.org/10.1146/annurev.ea.14.050186.002425>

