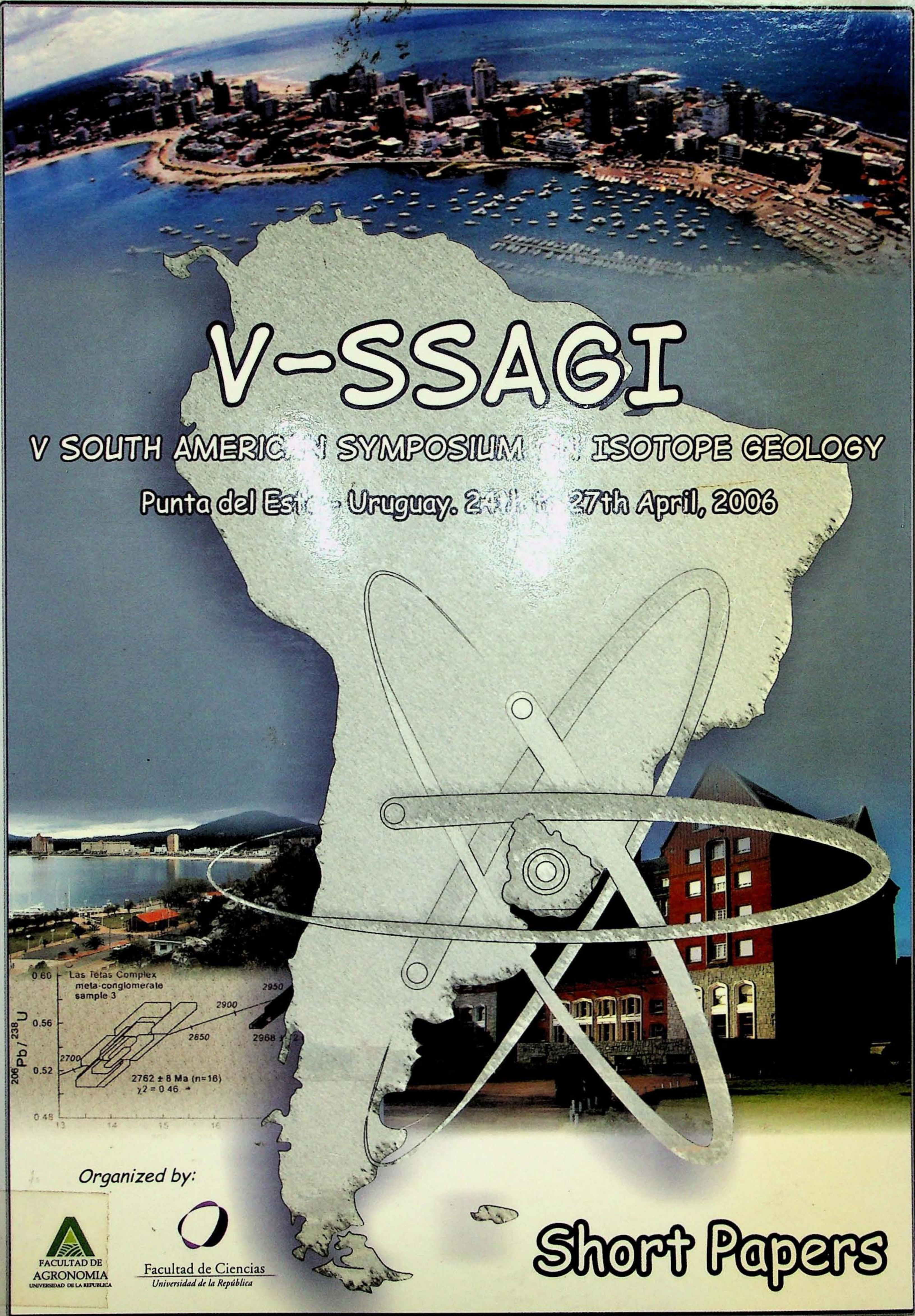

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A REVIEW OF THE CARBONATITIC MAGMATISM IN THE PARANÁ-ANGOLA-NAMIBIA PROVINCE

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The Paraná Basin is part of the Paraná-Angola-Namibia (Etenkeda) Province (PAN; PAEP cf. Comin-Chiaramonti et al., 1997) characterized by Early Cretaceous tholeiitic flood basalts and dyke swarms (133 Ma; cf. Renne et al., 1992, 1997) occurring in close association with alkaline and alkaline-carbonatitic complexes that range in age from Mesozoic to Paleocene (Comin-Chiaramonti and Gomes, 1996, 2005; Comin-Chiaramonti et al., 2006). Specifically, the carbonatite occurrences can be placed into three main chronogroups: Early Cretaceous, Late Cretaceous and Paleocene, the latter only represented in southwestern Namibia (Dicker Willem carbonatite, 49 Ma, cf. Cooper and Reid, 1998). The emplacement of the alkaline and alkaline-carbonatitic complexes is clearly controlled by main tectonic lineaments of the South American platform (Fig. 1), active at least since Early Mesozoic and reaching up to present times, as suggested by the distribution of earthquakes in southern Brazil (Berrocal and Fernandes, 1996). A similar tectonical situation is recognized for the Angolan (e.g. Moçâmedes Arch) and Namibian (e.g. Damara belt) occurrences in Africa.

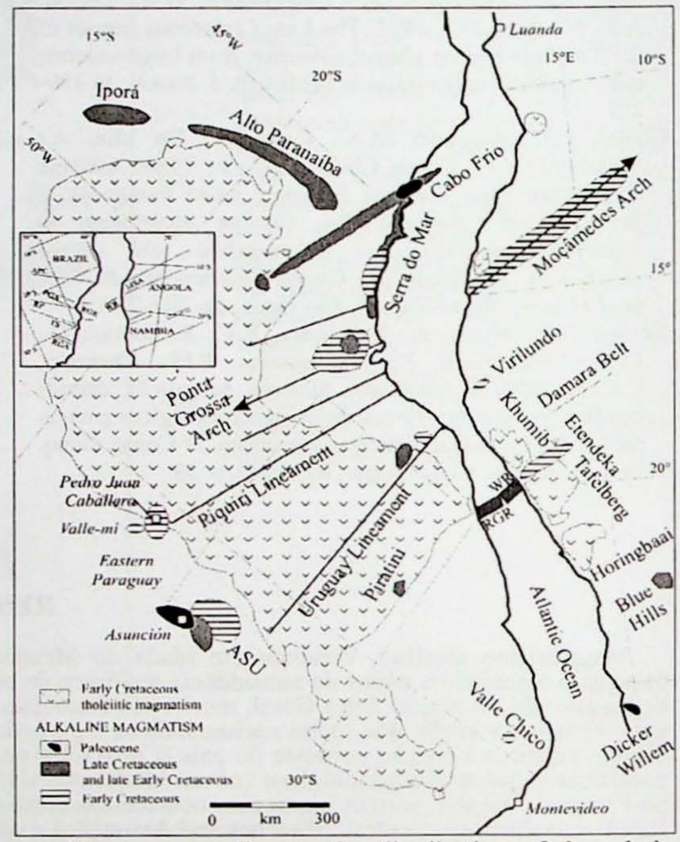

Figure 1. Schematic distribution of the magmatism in the Paraná-Angola-Namibia Province (South American and African plates, Western Gondwana, arranged at about 110 Ma; modified after Comin-Chiaramonti et al., 1997, 2005), and location of the main alkaline-carbonatitic occurrences: Ja, Jacupiranga; Ju, Juquiá; BdI, Barra do Itapirapuã; MP, Mato Preto; RA, Rio Apa; C-S, Cerros Chiriguelo and Sarambí; ASU, Asunción-Sapucai. Other abbreviations: RGR, Rio Grande Rise; WR, Walvis Ridge. Inset: lineaments across Africa and Brazil corresponding to the main lineaments of the alkaline complexes.

In general, the alkaline-carbonatitic complexes display intrusive/subintrusive, circular/subcircular to oval shaped structures, where the carbonatites are roughly found at the core of the intrusions, testifying their high upwelling energy. The South American carbonatites are rarely "effusive" (lava flows, single and dyke networks) with the associated extrusive rocks poorly exposed, probably as a result of the intense erosion responsible for their removal. Weathering processes led to the formation in some complexes of large supergenic and residual deposits of economical importance, particularly as source of phosphate, niobium and vermiculite.

Brazilian carbonatites (Santa Catarina Province: Anitápolis and Lages; Ponta Grossa Arch Province: Barra do Itapirapuã, Jacupiranga, Juquiá and Mato Preto; Alto Paranaíba Province: Catalão, Salitre and Tapira) are quite variable in major elements composition, ranging from calcio- to magnesio- and ferrocarbonatites (Figs. 2A-B), although these three rock-types are not commonly found in the same complex. Angolan carbonatites (Bailundo, Langonjo, Lupungola, Sulina and Tchivira-Bonga, cf. Alberti et al., 1999) show a compositional variation wider than that of the Brazilian analogues for each complex, roughly corresponding to the distribution of the whole population (Fig. 2A). Namibian carbonatites (Dicker Willem, Kalkfeld, Okurusu, Ondurakorume, Osongombo and Otjisaku, cf. Milner and Le Roex, 1996; Le Roex and Lanyon, 1998; Kurszlaukis et al., 1999; Bühn and Trumbull, 2003) are represented by ferrocarbonatites and scarce calciocarbonatites (Early Cretaceous, Fig. 2A) and by magnesiocarbonatites (Late Cretaceous, Fig. 2B). In general, ferrocarbonatites appear to be systematically related to low-temperature hydrothermal stages.

Early Cretaceous carbonatites from Angola (Alberti et al., 1999), Brazil (cf. Gomes et al., 1990; Comin-Chiaramonti et al., 2005), Eastern Paraguay (Rio Apa Province: Valle-mí; Amambay Province: Cerro Chiriguelo and Cerro Sarambí; Central Province: Sapucai, cf. Censi et al., 1989; Comin-Chiaramonti and Gomes, 1996) are usually associated with potassic alkaline rocks of "plagioleucitic" affinity, following Foley's (1992) classification. In Namibia, they are also related to lamprophyric rock-types, both of potassic and sodic filiation (Le Roex and Lanyon, 1998). On the other hand, the Brazilian Late Cretaceous carbonatites are characterized by kamafugitic-kimberlitic associations (Gibson et al., 1995; Traversa et al., 1994, 1996; Brod et al., 2005). Less evolved rock-types (gabbro-basalt clans) and cumulatic assemblages (e.g. dunite, clinopyroxenite, phoscorite, etc.) are relatively common to both Early and Late complexes. The Eocene Dicker Willem carbonatite in Namibia is associated with alkaline sodic rocks (melanite ijolite; Cooper and Reid, 1998).

In general terms, there are large variations in the normalized values from one carbonatite complex to another for any given incompatible and rare earths element, with the remarkable scattering mainly due to: 1) the control of accessory phases, e.g. apatite, pyrochlore, fluorcarbonates and fluorite, and 2) the repeated overprinting of hydrothermal over magmatic processes. Oxygen ($\delta^{18}O$‰ V-SMOW) and carbon ($\delta^{13}C$‰ PDP-1) isotope data for some carbonatites (Fig. 3) mainly range between 5.5. and 24%, and between -8.5 and +1.5%, respectively, with values typical of "primary carbonatites", such as those displayed by the Jacupiranga rocks and believed to represent a primary isotopic signature of the mantle (Huang et al., 1995), along with a number of samples with higher $\delta^{18}O$‰ and $\delta^{13}C$‰ values. Two trends ranging from magmatic to hydrothermal temperatures, at variable CO_2/H_2O ratios, are suggested in the below figure. The enrichment in heavy isotopes is probably related to post-magmatic and deuteric-groundwater processes. As evidenced by field relationships and geochemical characteristics, processes of liquid immiscibility from trachytic-phonolitic liquids, starting from parental alkaline mafic magmas, are believed to have generated the PAN carbonatites.

The bulk of the geochemical data indicate that mostly of the alkaline-carbonatitic associations have an enriched isotopic signature (Fig. 4) and that, on the whole, they show a well-defined array, with the Early and Late occurrences varying from close to the Bulk Earth to the enriched quadrant, respectively. The data also demonstrate that those associations, even in the late stages of fluid-rock interaction (i.e. hydrothermal environment; cf. Castorina et al., 1997; Speziale et al., 1997), have the same isotopic $^{87}Sr/^{86}Sr$ (Sr_i) and $^{143}Nd/^{144}Nd$ (Nd_i) initial ratios in comparison to the associated silicate alkaline rocks. Sr-Nd-Pb systematics highlight the importance of the HIMU and EMI mantle components to the genesis of the PAN magmatism.

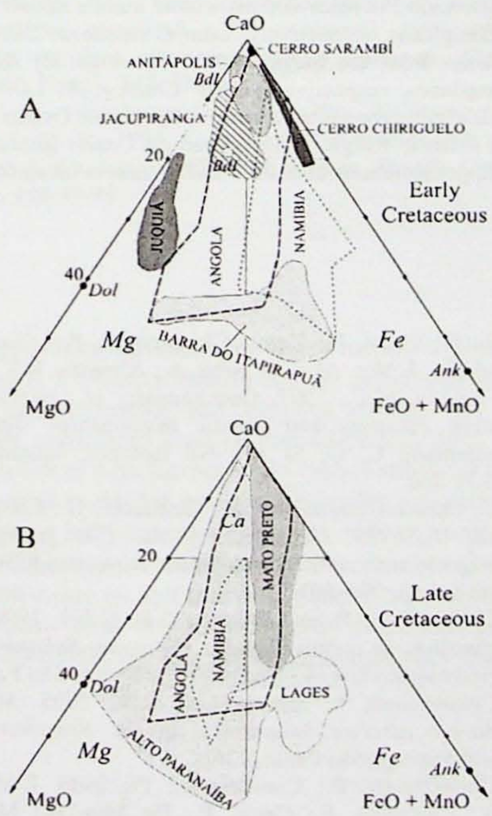

Figure 2. Classification of the carbonatitic associations (after Woolley and Kempe, 1989) in the various complexes and regions from the PAN. Abbreviations: Dol, dolomite; Ank, ankerite. For data source see Comin-Chiaramonti et al. (2005, 2006).

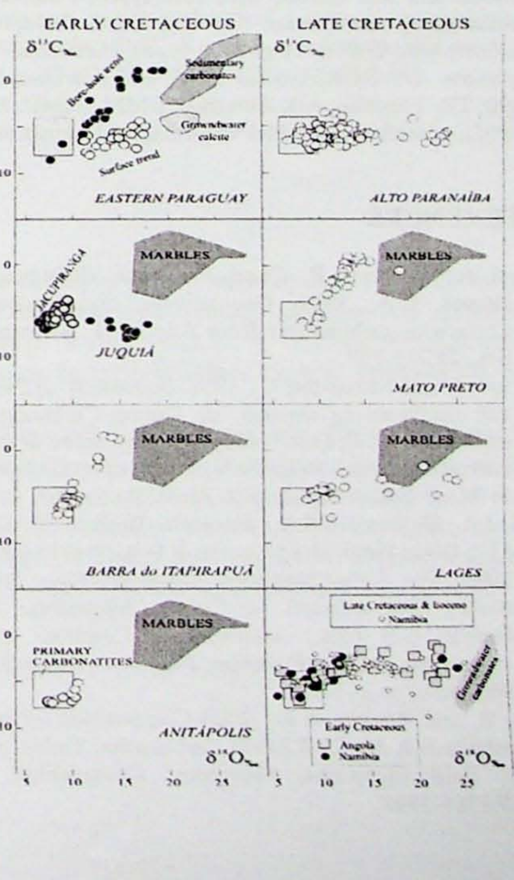

Figure 3. Plot of $\delta^{18}O$‰ (V-SMOW) and $\delta^{13}C$‰ (PDB-1) for the carbonatites from the PAN. For comparison the fields relative to sedimentary rocks, groundwater calcite and marbles are also shown (for data source see Comin-Chiaramonti et al., 2005). "Primary carbonatites" field, PC, after Taylor et al. (1967) and Hoefs (1987).

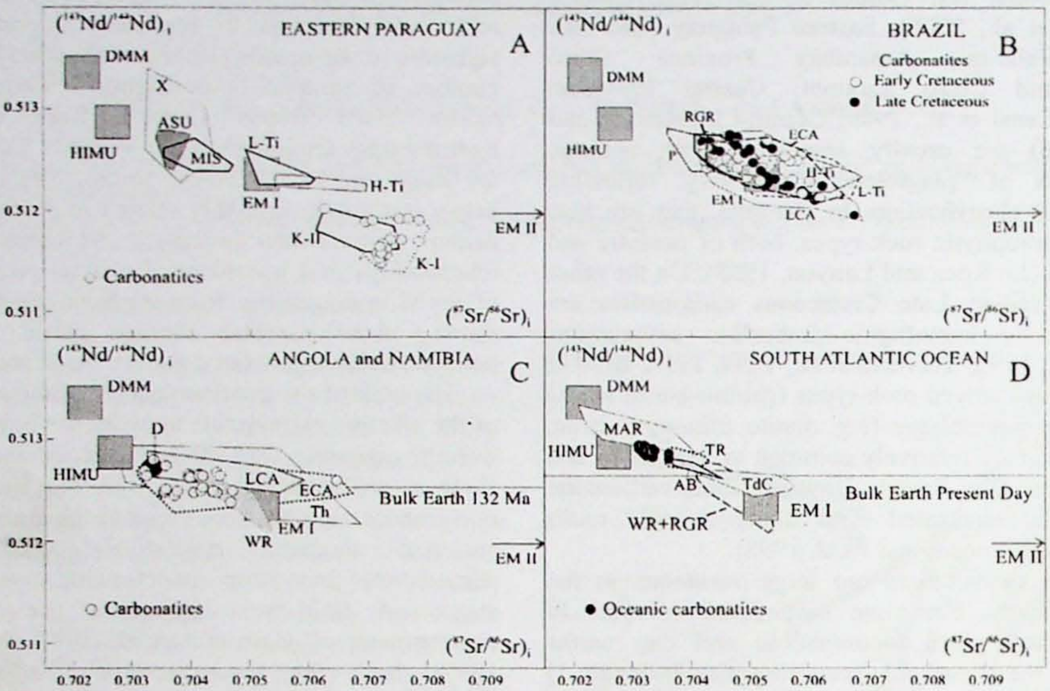

Figure 4. Initial $^{87}Sr/^{86}Sr$ (Sr_i) vs. initial $^{144}Nd/^{143}Nd$ (Nd_i) correlation diagrams for alkaline and tholeiitic associations from Eastern Paraguay, Brazil and African occurrences and basaltic rocks of oceanic islands. For general data source see Comin-Chiaramonti et al. (2006). A) **Eastern Paraguay** *Early Cretaceous*: K-I and K-II potassic alkaline complexes, pre- and post-tholeiites, respectively; H-Ti and L-Ti, high- and low-Ti tholeiitic basalts, respectively; *Late Early Cretaceous*: MIS, sodic alkaline complexes from the Misiones Province; *Paleocene:* ASU, sodic alkaline complexes from the Asunción Province and associated mantle xenoliths (X); B) **Brazil.** *Early Cretaceous*: H-Ti, L-Ti and ECA, tholeiitic and alkaline complexes, respectively; *Late Cretaceous*: LCA, alkaline complexes and Rio Grande Rise rock-types; *Paleocene:* alkaline complexes from the Serra do Mar Province. C) **Angola and Namibia.** *Early Cretaceous:* Th and ECA, tholeiitic and alkaline complexes, respectively; *Late Cretaceous*: LCA, alkaline complexes; WR, Walvis Ridge rock-types; *Paleocene*: D, Dicker Willem alkaline-carbonatitic complex; D) **Atantc Ocean** volcanic associations. WR-RGR, Walvis Ridge and Rio Grande Rise; MAR, Mid Atlantic Ridge; TdC, Tristan da Cunha (Inacessible and Gough); TR, Trindade; AB, Abrolhos. DMM, HIMU, EM I and EM II are approximations of mantle end-members taken from Hart et al. (1992); oceanic carbonatites according to Hoernle et al. (2002).

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RESUMO

O magmatismo alcalino-carbonatítico da Província Paraná-Angola-Namibia (PAN) acha-se distribuído ao longo de alinhamentos tectônicos reativados do embasamento, seja no continente americano quanto africano. Os carbonatitos ocorrem principalmente nas porções centrais de complexos exibindo forma circular a ovalada e encontram-se comumente associados com rochas silicáticas mais evoluídas. Processos de imiscibilidade líquida parecem ter sido o fator responsável pela formação do carbonatitos em toda a província.

As grandes variações nas concentrações dos elementos incompatíveis e das Terras Raras parecem estar relacionadas com processos hidrotermais, como sugerido pelo comportamento dos isótopos de C e O. O conjunto dos dados químicos obtidos indica que a maioria das ocorrências alcalina-carbonatíticas investigadas apresenta-se enriquecida em Sr radiogênico e que os carbonatitos, mesmo aqueles atingidos pelos últimos estágios de interação rocha-fluido, mostram razões iniciais de Sr e Nd similares às das rochas silicáticas associadas. Os dados para Sr-Nd-Pb procuram chamar a atenção para a contribuição dos componentes mantélicos HIMU e EM I na geração do magmatismo da província.