Pb, Nd, Sr, and Os ISOTOPIC SYSTEMATICS OF BRAZILIAN CRETACEOUS POTASSIC ROCKS

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ABSTRACT Mafic potassic rocks of the Alto Paranaíba (Minas Gerais), Paranatinga (Goiás), Juína (Mato Grosso), and Pimenta Bueno (Mato Grosso) provinces belong to a large lineament of rocks that crosses from western to southeastern Brazil and have been associated to a hot spot track by several authors. These provinces intruded the Neoproterozoic Brasília and Paraguay fold belts (Alto Paranaíba, Paranatinga), and the Mesoproterozoic Rio Negro-Juruena belt (Juína, Pimenta Bueno). Pb isotopic compositions of the studied provinces show a wide variation. ²⁰⁶Pb/²⁰⁴Pb of kimberlites (18.47-19.23) and kamafugites (17.79-18.71) from the Alto Paranaíba Province are close to the Tristan/Walvis Ridge composition. The ²⁰⁶Pb/²⁰⁴Pb of the Paranatinga (19.38-19.67) and Pimenta Bueno (19.78-21.00) provinces are similar to the South African Group I kimberlite compositional fields, while Juína is displaced to higher Pb isotopic ratios (21.38-22.26), close to those shown by HIMU ocean island basalts (OIB). Although the Pb isotopic composition of the more northern alkaline provinces ranges towards the values seen for HIMU OIB, the Sr and Nd isotopic composition of these samples is not like HIMU, nor in combination with Pb, like any other ocean island basalt. With the exception of the kimberlites from the Alto Paranaíba, which range to quite unradiogenic compositions, most of the samples have ¹⁸⁷Os/¹⁸⁸Os between 0.13 and 0.15. The Nd model ages of Juína kimberlites vary from 1.70-1.73Ga, and could be indicating a prior accretion period into the mobile belt. Nd model ages for Paranatinga kimberlites vary between 0.56 and 0.64Ga and Pimenta Bueno kimberlites from 0.72 to 1.05Ga. Minimum Re depletion model ages for Paranatinga kimberlites vary between 0.74 and 0.93 and Pimenta Bueno kimberlites from 0.9 to 1.3Ga, indicating that the Nd isotopic signatures could have been affected by metasomatic overprint in Neoproterozoic.

Keywords: kimberlites, kamafugites, isotopes.

GEOLOGICAL SETTING The Alto Paranaíba, Paranatinga, Juína, and Pimenta Bueno provinces belong to a NW-SE lineament defined by the late Cretaceous alkaline magmatism in Brazil. The lineament has been attributed to a hot spot track by several authors (Trindade, Gibson et al. 1995 and/or Tristan da Cunha, Bizzi et al. 1993, 1995). These intrusions correspond to kimberlitic and kamafugitic vents and diatremes, kamafugitic lavas, and carbonatite intrusions (Herz 1977, Svisero et al. 1983, Almeida & Svisero 1991, Gibson et al. 1995, Costa 1996, Teixeira et al. 1998, Araujo 2000, Araujo et al. 2001).

The mafic rocks have intruded folded and reworked Proterozoic mobile belts. The Alto Paranaíba Alkaline Province is located in western Minas Gerais and southwest Goiás. The province intruded the Neoproterozoic Brasília belt, which is bounded by the Paraná Basin to the south and the São Francisco Craton to the east (Fig. 1). The region corresponds to one of the volumetrically largest mafic potassic provinces in the world (Gibson et al. 1995). The majority of the radiometric ages for the alkaline magmatism in the region clusters between 80 and 90 Ma (Amaral et al. 1967, Hasui & Cordani 1968, Sonoki & Garda 1988, Bizzi 1993, Gibson et al. 1995). The Brasília Mobile Belt represents a strongly folded terrain for which isotopic data indicate two ages for peak metamorphism, 790 Ma and 630-610 Ma (Ferreira Filho et al. 1994, Suita et al. 1994, Pimentel et al. 1991, 1997). Pimentel et al. (1999), studying the isotopic characteristics of the granitic rocks associated with the mobile belt, suggest that the belt formed through an early rift stage between 1.77-1.60 Ga and collisional stages between 0.90-0.60 Ga.

The Paranatinga Province is located near the southern border of the Amazon Craton (Fig. 1), and is underlain by the Neoproterozoic Paraguay belt and the Mesoproterozoic Rio Negro-Juruena Mobile Belt (1.5-1.75Ga) (Teixeira et al. 1998, Costa 1996). At shallow levels, the kimberlites intrude into sedimentary rocks and sediments related to the cratonic cover (Heaman et al. 1998). U-Pb zircon ages of 123-126 Ma were obtained for the intrusions (Heaman et al. 1998, Crough et al. 1980). The age interval obtained is an obstacle to the association of the magmatism with the Trindade hot spot track (Heaman et al. 1998).

Kimberlites from the Juína Province, at the northern border of the Paleozoic Parecis Basin (Fig. 1), like the Paranatinga Province, intruded the Mesoproterozoic Rio Negro-Juruena Belt (Teixeira et al. 1998). Heaman et al. (1998) obtained U-Pb zircon ages of 92-95 Ma for the intrusions.

The Pimenta Bueno Province, which is located in eastern Rondônia State (Fig. 1), is poorly known. The kimberlitic mineral assemblage in the area was previously reported by Svisero et al. (1983). The bodies intruded through the Mesoproterozoic Rio-Negro Juruena Belt and is composed of kimberlitic and melilitite or/melilitite kamafugitic end member structures (Bitencourt et al. 2001).

PETROGRAPHY The mineralogy of the mafic rocks from the Alto Paranaíba, Paranatinga, Juína, and Pimenta Bueno provinces was studied by several authors (Leonardos et al. 1991, Sgarbi 1991, Sgarbi & Valença 1993, Gibson et al. 1994, 1995, Araujo et al. 1998, Araujo et al. 2001, Teixeira et al. 1998, Svisero et al. 1983, Costa 1996, Teixeira et al. 2001).

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Figure 1 – Distribution of the Cretaceous alkaline igneous provinces in Brazil. Geochronological ages from Teixeira *et al.* (1989), Gibson *et al.* (1995), and Heaman *et al.* (1998).

Kimberlites have the same mineralogical characteristics in all provinces studied and consist of two populations of olivine (macro and phenocrysts) set in fine grained matrix of olivine, ilmenite, phlogopite, spinel, perovskite, monticellite, apatite, garnet (rare in some of the Alto Paranaíba kimberlites), carbonate, and serpentine. Mantle-derived xenoliths (spinel/garnet-lherzolite, wehrlite, dunite, pyroxenite and, in the Juína Province, eclogite) and crustal xenoliths were identified in the kimberlites (Araujo 2000, Costa 1996, Teixeira *et al.* 2001).

Kamafugites from the Alto Paranaíba Province consist of olivine, clinopyroxene, and phlogopite phenocrysts set in a fine-grained matrix of clinopyroxene, olivine, phlogopite, kalsilite and/or leucite, spinel, perovskite, carbonate, apatite, and serpentine. Among the kamafugites, both ugandite (characterized by the presence of leucite as a dominant felsic phase) and mafurite (with kalsilite as a dominant felsic phase) end members have been recognized. Mantle-derived xenoliths include wehrlite, dunite and pyroxenite. Crustal xenoliths have also been recorded (Araujo, 2000). The kamafugite from Pimenta Bueno is composed of olivine, clinopyroxene, spinel, perovskite, and melilite (Bitencourt *et al.* 2001). Mantle related phases like spinel and pyrope garnet are described in these rocks (Bitencourt *et al.* 2001).

ANALYTICAL METHODS Elements were analyzed using MC-ICP-MS (Rb, Sm, Nd and Pb), TIMS (Sr) and negative thermal ionization mass spectrometry at the Department of Terrestrial Magnetism (DTM/Carnegie Institution of Washington).

For Rb, Sr, Sm, Nd, and Pb, 25 mg of powdered sample, with the addition of the respective spikes, were digested using HF and HNO₃. The elements were separated using procedures described previously (Carlson & Irving 1994). A standard solution of Tl was added to the Pb prior to mass spectrometry (e.g. Rehkamper & Halliday 1998).

For Re-Os analysis, 2g of sample and respective spikes were

digested in HCl - HNO₃ in a sealed Pyrex tube held at 240°C overnight. Os was extracted from the aqua-regia into CCl₄ and then back-extracted into HBr. Os was further purified by a microdistillation step from a H₂SO₄-CrO₃ mixture. Re was separated by anion exchange chromatography. Procedures for Re-Os separation follow those described by Carlson *et al.* (1999).

ISOTOPIC SYSTEMATICS The Paranatinga, Pimenta Bueno and Juína provinces are very poorly isotopically studied. Previous Sr, Nd, and Pb isotopic studies of the Alto Paranaíba kimberlites and kamafugites were presented by Bizzi (1993), Gibson *et al.* (1995), and Araujo *et al.* (2001). Previous Re-Os results are shown in Carlson *et al.* (1996) and Araujo *et al.* (2001).

In this study, the lithological control of the samples coupled with the isotopic data (Table 1) provide a new approach to the characterization of the origin of these magmas. Pb isotopic compositions show a wide variation (Fig. 2). The kamafugites from the Alto Paranaíba Alkaline province have relatively low ²⁰⁶Pb/²⁰⁴Pb, varying from 17.79 to 18.71 (Araujo *et al.* 2001). Kimberlites from the Alto Paranaíba show ²⁰⁶Pb/²⁰⁴Pb varying from 18.47 to 19.23 (Araujo *et al.* 2001), Paranatinga from 19.38 to 19.67, Pimenta Bueno from 19.78 to 21.00, and Juína from 21.38 to 22.26. The Pb isotopic compositions of kamafugites and a part of the kimberlites from the Alto Paranaíba Province are close to, or overlap, the Tristan/Walvis Ridge composition (Carlson *et al.* 1996, Araujo *et al.* 2001) (Fig. 2). The Pb isotopic composition of the Alto Paranaíba, Paranatinga, and Pimenta Bueno provinces are near to the South African Group I kimberlite compositional field, but the samples from the Juína Province are displaced to higher Pb isotopic values, close to those shown by HIMU ocean island basalts (OIB) (Fig. 2).

Sr and Nd isotopic compositions show approximately the same range of values for all provinces (Fig. 3 and 4). Although

Figure 2 – Pb isotopic composition diagrams for the alto Paranaíba (AP) (Araújo et al. 2001), Paranatinga, Juína, and Pimenta Bueno alkaline provinces. Kimberlites and orangeites fields from Smith (1983), Paraná Basalts from Hawkesworth et al. (1988) and Piccirillo et al. (21989), Tristan da Cunha from O’Nions et al. (1977), and ocean island basalts from Fraser et al. (1986). Kalwekikorongu are from Davies & Lloyd (1989) and Bufumbira from Vollmer & Norry (1983).

the Pb isotopic composition of the more northern alkalic provinces ranges towards the values seen for HIMU OIB, the Sr and Nd isotopic composition of these samples is not like HIMU, nor in combination with Pb, like any other ocean island basalt. Os isotopic compositions of the samples do not correlate with Pb isotopic variation. Kamafugites from the Alto Paranaíba Province have Pb isotopic compositions closer to the EM1 mantle component, while kimberlites from this province plot closer to the HIMU end member. When compared with other kamafugitic occurrences (as Bufumbira and the Katwe-Kikorongo kamafugites, Africa, Davies & Lloyd 1989, Vollmer & Norry 1983), the Alto Paranaíba kamafugites show lower $^{206}\text{Pb}/^{204}\text{Pb}$. Figure 4 the Brazilian kimberlites and kamafugites isotopic composition is close to the Tristan/Walvis Ridge and Paraná basalts.

With the exception of the kimberlites from the Alto Paranaíba, which range to quite unradiogenic compositions,

most of the samples have $^{187}\text{Os}/^{188}\text{Os}$ between 0.13 and 0.15, with two samples of kimberlites from Pimenta Bueno and one from Paranatinga extending to significantly higher $^{187}\text{Os}/^{188}\text{Os}$.

Nd model ages of Juína kimberlites vary from 1.70 to 1.73 Ga, Paranatinga from 0.56 to 0.64 Ga and Pimenta Bueno from 0.72 to 1.05 Ga. Os model ages for Paranatinga vary from 0.74 to 0.93 Ga and Pimenta Bueno from 0.9 to 1.3 Ga. The Alto Paranaíba Nd depleted mantle model ages (T_{DM}) range from 0.78 to 1.32 Ga for kamafugites and between 0.83 to 0.95 Ga for kimberlites. The Re-depletion model ages in kimberlites are between 1.39 and 1.65 (Araújo et al. 2001).

DISCUSSION The Sr, Nd, and Pb isotopic compositions of alkaline mafic rocks from western Brazil overlap those of the oceanic basalts from Walvis Ridge, and are intermediate between the EM1 and HIMU isotopic components defined for ocean island basalts (Bizzi 1993, Bizzi et al. 1995, Gibson et al. 1995, Carlson et al. 1996, Araújo et al., 2001). Kimberlites from Paranatinga, Juína, and Pimenta Bueno have isotopic compositions close to South African Group I kimberlites (Smith 1983, Meyer et al. 1994, Mitchell 1995). Kamafugites and kimberlites from the Alto Paranaíba Province have isotopic compositions between South African Group I and II kimberlites or orangeites (Bizzi 1993, Bizzi et al. 1995,

Figure 3 – Nd, Sr, Os and Pb isotopic composition. The Alto Paranaíba (AP) samples from Araújo et al. 2001. Fields for peridotite compositions are from Carlson et al. (1999) and Carlson & Irving (1994), for ocean island basalts from Roy-Barman & All-egre (1997) and Reisberg et al. (1993).

Table 1 - Pb, Nd, Sr, and Os isotopic data. Os model ages were calculated with respect to bulk-earth $^{187}\text{Re}/^{188}\text{Os}=0.4243$, $^{187}\text{Os}/^{188}\text{Os}=0.1287$ (Meisel et al. 1996), ^{187}Re decay constant of $1.666 \times 10^{-11} \text{ year}^{-1}$ (Smoliar et al. 1996).

Province	Juína		Paranatinga		Pimenta Bueno				
Sample	C-4	L-1	B-6	P-235	P-24	P-1	P-13	P-22	C-12
$^{206}\text{Pb}/^{204}\text{Pb}$	22.261	21.387	19.673	19.385	19.780	21.000	19.863	20.026	
$^{207}\text{Pb}/^{204}\text{Pb}$	16.050	16.001	15.704	15.704	15.778	15.790	15.824	15.809	
$^{208}\text{Pb}/^{204}\text{Pb}$	40.908	40.331	40.134	39.944	39.874	41.537	39.821	40.011	
Sm(ppm)	7.18	4.63	9.07	4.96	4.90	17.44	8.18	10.99	
Nd(ppm)	38.24	28.52	70.68	61.06	35.63	124.65	63.98	86.43	64.35
$^{147}\text{Sm}/^{144}\text{Nd}$	1.14E-01	9.82E-02	7.76E-02	4.91E-02	8.31E-02	8.46E-02	7.74E-02	7.69E-02	
$^{143}\text{Nd}/^{144}\text{Nd}$	0.511880	0.511729	0.512582	0.512385	0.5124380	0.5124630	0.5121190	0.5122550	0.512353
$^{143}\text{Nd}/^{144}\text{Nd}(i)$	0.511809	0.511668	0.5125180	0.512345	0.5123860	0.5124100	0.5120710	0.5122070	0.512353
$\epsilon\text{Nd}(85\text{ma})$	-12.4	-15.4	2.1	-1.8	-1.5	-1.0	-7.7	-5.1	-3.2
T_{DM}	1.73	1.70	0.56	0.64	0.74	0.72	1.05	0.90	
Rb(ppm)	32.0	12.1	12.7	57.6	5.3	22.8	6.9	50.1	12.4
Sr(ppm)	121.5	85.9	321.4	535.3	250.4	596.5	468.8	241.0	
$^{87}\text{Rb}/^{86}\text{Sr}$		0.394386	0.093017	0.315083	0.0616340	0.1120920	0.0829290	0.3091960	0.077894
$^{87}\text{Sr}/^{86}\text{Sr}$	0.748388	0.743003	0.704249	0.708888	0.707050	0.7053380	0.7071330	0.707149	
$^{87}\text{Sr}/^{86}\text{Sr}(i)$		0.742527	0.704137	0.708507	0.7069760	0.7052030	0.7070330	0.706776	
Os(ppb)	0.3434	0.6073	1.0012	0.1557	0.9087	0.1883	0.7166	0.3327	0.7641
Re(ppb)	0.33	0.08	0.24	0.09	0.15	0.13	0.11	0.02	0.93
$^{187}\text{Re}/^{188}\text{Os}$	4.623	0.650	1.165	2.983	0.785	3.470	0.721	0.357	5.868
$^{187}\text{Os}/^{188}\text{Os}(m)$	0.14572	0.1314	0.13798	0.16884	0.17726	0.17588	0.135320	0.1383600	0.136790
uncertainly	0.00021	0.00017	0.00054	0.00027	0.00018	0.00068	0.00018	0.00024	0.00014
$^{187}\text{Os}/^{188}\text{Os}(i)$	0.13917	0.13048	0.13633	0.16461	0.17615	0.17096	0.13430	0.13785	0.12847
γOs	8.6	1.9	6.4	28.5	37.5	33.5	4.8	7.6	0.3
$^{187}\text{Re}/^{185}\text{Re}$	1.27512	0.72960	1.17845	0.78165	0.93754	0.95176	0.82831	0.33159	1.49306
T_{BE}	0.24	0.71	0.75	0.93		0.92	1.33		0.09

Carlson et al. 1996, Araujo et al., 2001).

Differences in isotopic composition of kimberlites and kamafugites from the Alto Paranaíba Province ($^{187}\text{Os}/^{188}\text{Os}$ of the order of 0.118 in kimberlites and 0.135 in kamafugites) were attributed to differences in mantle sources (old lithospheric peridotite and either pyroxenite/websterite/eclogite or plume signatures, respectively) (Carlson et al. 1996, Araujo et al. 2001). Kimberlites from Paranatinga, Juína, and Pimenta Bueno provinces show $^{187}\text{Os}/^{188}\text{Os}$ varying from 0.130 to 0.149, higher than those found in the Alto Paranaíba kimberlites, but overlapping values seen in the Alto Paranaíba kamafugites. Two of the samples, with $^{187}\text{Os}/^{188}\text{Os}$ near 0.17, have low Os contents suggesting that crustal contamination could have influenced their Os isotopic compositions. On the other hand, one sample from Pimenta Bueno with $^{187}\text{Os}/^{188}\text{Os}$ near 0.18 has almost 800ppt Os suggesting that its radiogenic Os may be a source signature rather than due to crustal contamination. $^{187}\text{Os}/^{188}\text{Os}$ for the studied kimberlites is close to those obtained for South African kimberlites (0.120-0.145, Pearson et al. 1995). The kamafugites show higher $^{187}\text{Os}/^{188}\text{Os}$ than those observed for lamproites (0.113-0.123; Shirey & Walker 1995).

The Nd model age obtained for the Juína kimberlite, 1.7 Ga, could suggest a prior accretion period into mobile belt lithosphere, once considered as a minimum source age formation. The Re depletion ages obtained for Paranatinga and Pimenta Bueno are older (0.7-1.3Ga) when compared the Nd model ages obtained for these provinces, and could indicate

Figure 4 - ϵNd versus $^{87}\text{Sr}/^{86}\text{Sr}(i)$ variation diagram. Kamafugites and kimberlites from the Alto Paranaíba Alkaline Province from Araújo (2000), Araújo et al. (2001), kimberlites and orangeites fields from Mitchell (1995), Western Australia lamproites from Mitchell & Berman (1991), Paraná Basalts from Hawkesworth et al. (1986, 1988), Mantovanni et al. (1985) and Piccirillo et al. (1989), and Tristan da Cunha from O'Nions et al. (1977).

that a metasomatic overprint during the Neoproterozoic could have modified the Nd isotopic signatures.

Due to the overlapping of Sr, Nd, and Pb isotopic compositions of rocks from the four provinces, mainly kamafugites, to the ocean island basalts of the Tristan hot spot and the Paraná flood basalts, the source of the Cretaceous magmatism has been attributed to a mantle plume activity.

Alternatively, another explanation, based on the EM1 mantle component characteristic and supported by the old depleted lithosphere peridotite/pyroxenite-eclogite Os characteristic of these magmas, is delamination of Brazilian lithospheric mantle and its incorporation into the sublithospheric mantle during the opening of the South Atlantic (Hawkesworth *et al.* 1986, Carlson *et al.* 1996, Araujo *et al.* 2001).

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