ULTRAMAFIC K-ALKALINE AND CARBONATITIC ROCKS FROM PLANALTO DA SERRA, MATO GROSSO, BRAZIL

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ABSTRACT

The Planalto da Serra lithotypes are represented by 600 Ma plugs and necks of glimmerites and carbonatites. Phlogopite and/or tetraphlogopite are the most abundant minerals of the glimmerites. Carbonatites comprise granular hypidiomorphic alvikites and breccied beforsites. Diopside and melanitic garnet are restricted to the glimmerites, whereas pyroclore occur only in carbonatites. Perovskite, tremolite, magnetite, pyrite, apatite, titanite, chlorite and serpentine are common accessories of both lithologies. Under high CO₂ and H₂O activity glimmerites and carbonatites gave rise to hydrotermalites, in which chlorite and serpentine are the predominant minerals (up to 70%). They derived from tremolite, diopside and sometimes from olivine. Pyrite is a common accessory. Glimmerites, alvikitic dykes and hydrotermalites have kamafugitic affinity. Sr-Nd isotopes and incompatible trace-element data, characterized high LREE/HREE fractionation suggest that the K-ultramafic alkaline and carbonatite rocks originated from a varied metasomatized source mantle, characterized by Sr radiogenic enrichment. Crustal contamination is negligible or absent. Geochronological data of the Planalto da Serra rocks and its relationship with the low-grade metamorphic rocks of the Cuiabá Group make improbable the presence of the Clymene Ocean in this area. The age determination also rules out the geochronological relationship between the Planalto da Serra intrusions and the Mesozoic alkaline bodies from the Azimuth 125° lineament, and makes possible to relate its emplacement with to one of the most important extensional periods of Neoproterozoic times, which is characterized by the separation of Laurentia and the Amazonian Craton. The TDM model ages suggest that the Planalto da Serra melts derived from the remobilization of subcontinental lithospheric mantle that had been enriched by small-volume K-rich melt fractions at the Early to Late Neoproterozoic, which makes highly improbable the hypothesis of mantle plume tail, given that a subcontinental mantle enrichment, controlled by an Early Neoproterozoic event, produced similar ultramafic alkaline products at 600 and 80-90 Ma.

INTRODUCTION

Neoproterozoic rocks are found at the southern margin of the Amazonian Craton. They belong to the Paraguay Belt (PB, Fig. 1A), a tectonic feature crossed by the Azimut 125° lineament after Bardet (1977) and along which some important Brazilian alkaline provinces of Mesozoic age also occur (Fig. 1B).

The Paraguay belt (Fig. 2) is geographically divided by Neogene sediments of the Pantanal Basin into two segments named northern and southern Paraguay Belt (Alvarenga et al., 2010). The first segment was developed during the Brasiliano Cycle (Boggiani and Alvarenga, 2004; Manzano et al., 2008) and your stratigraphy mainly consists of the following groups: 1) a lower unit, i.e. the Cuiabá Group (850-630 Ma), which comprises the Nova Xavantina metavolcanic-sedimentary Formation and eight low-grade metasedimentary units; 2) carbonatic rocks of the Araras Group (about 580 Ma); 3) four low-grade metasedimentary formations of the Alto Paraguay Group (590-545 Ma), i.e. the upper unit (Lacerda Filho et al., 2004; Riccomini et al., 2007; Alvarenga et al., 2010).
More recently, the Paraguayan Belt was interpreted as linked to the closing of the Goiás-Pharusian Ocean, due to successive continental collisions, dated roughly between 600 and 650 Ma, which sutured the West African Craton against the Saharan Metacraton in the north, and the Amazonian against the São Francisco Craton in the south (Cordani et al., 2012). Several Brasiliano-Pan African orogenic belts were created in this process and are aligned along a very long area of South America and Africa (more than 6000 Km long) dominated by one of the major tectonic elements of the world, the Transbrasiliano-Kandi lineament (cf. Fig. 1 and Fig. 3 of Cordani et al., 2012).

In particular, at the northeastern side of the northern Paraguay Belt, i.e. in the Planalto da Serra region, some ultramafic and carbonatitic rocks occur intruding low-grade metasedimentary rocks of the Cuiabá Group along the Rio dos Cavalos Rift (Figs. 3 and 4, and Alvarenga et al., 2010).

![Fig. 1. A) Map of South America (modified after Almeida and Hasui, 1984, Heinz et al., 2005 and Cordani et al., 2009) showing cratonic areas, Neoproterozoic provinces and Phanerozoic covers. PB, Paraguay Belt; TB, Transbrasiliano huge continental shear zone (or a mega-suture). B) Two main Brazilian lineaments, Transbrasiliano and Azimut 125° (after Bardet, 1977, and Biondi, 2005), the latter including the alkaline provinces of 1, Poxoréu (age 84 Ma); 2, Rio Verde-Iporá and Goiás (age 80-90 Ma); 3, Alto Paranaíba (age 85 Ma); 4, Serra do Mar (age 85-55 Ma), according to Gibson et al. (1995, 1997).](image)

**THE PLANALTO DA SERRA INTRUSIVE SUITE: GEOLOGIC OUTLINES.**

The Planalto da Serra K-alkaline ultramafic and carbonatitic rocks are located at the central part of the South American Plate, lying to Northeast of the city of Cuiabá in Mato Grosso state, western Brazil (Fig. 3). They represent some of the numerous bodies cropping out near the Azimut 125° lineament (cf. Biondi 2005), around the margins of the Paraná Basin (Comin-Chiaramonti and Gomes, 2005). These rocks were emplaced during Late Neoproterozoic, along a NE-SW trending extensional zone, the Rio dos Cavalos Rift (cf. Fig. 4, and De Min et al., 2012). This rift was developed between the northeastern part of the Paraná Basin and the southeastern margin of the Amazonian Craton, within the Late-Proterozoic Paraguay mobile belt (cf. Figs. 2 and 3).
The rock types from the Planalto da Serra are represented by dykes, plugs and brecciod necks (diatremes) of glimmeritic and carbonatitic affinity. Although the regional metamorphism of greenschist facies, which is associated with the end of the Brasiliano Orogeny (540-520 Ma, cf. Trindade et al., 2003) or being as late as 490 Ma (cf. Tohver et al., 2010), may have changed their original mineralogy, the age of the Planalto da Serra rocks is well constrained at about 600 Ma on the basis of Ar-Ar radiometric determinations carried out on phlogopite (De Min et al., 2012).
Fig. 3. Geological setting of the Mato Grosso State, after Sousa et al. (2005), showing part of the northern Paraguay belt and the Planalto da Serra area.

Fig. 4. Sketch map showing the Planalto da Serra area and the Rio dos Cavalos Rift in the Paraguay Belt (Mato Grosso State). Ultramafic and carbonatitic outcrops (after Ormond, 2006) and analyzed samples are indicated.

PETROGRAPHY

Glimmeritic rocks

The term glimmeritic rocks is applied to ultramafic alkaline dykes and plugs in which phlogopite and/or tetaferriphlogopite are the most abundant mineral (Fig. 5 I-II). They are inequigranular rocks, with coarse to fine texture, made of prevailing phlogopite-tetaferriphlogopite (up to 60 vol%) and subordinate amphibole and/or clinopyroxene, magnetite and primary carbonate (calcite). Clinopyroxene (and sometimes phlogopite) appears partially or completely replaced by amphibole (Fig. 5). Accessories are apatite, titanite, perovskite, garnet and pyrite. Garnet can be an important phase (up to 15 vol.%) in some plugs. Chlorite and serpentine (replacing original olivine) may be present in the plugs as secondary accessories. Representative modal analyses are in Table 1A.
Table 1. Estimated modal mineral abundances of the main rock-types (vol.% and calculated out of 1000 counted points; tr: trace) from Planalto da Serra (for the localities cf. Fig. 4). A: glimmeritic rocks; B: carbonatitic types; C, hydrothermalized samples. Glass*: isotropic material with n < 1.5 (opal?).

<table>
<thead>
<tr>
<th>Sample/Locality</th>
<th>A: Glimmeritic rocks</th>
<th>B: Carbonatitic rocks</th>
<th>C: Hydrothermalite</th>
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<tbody>
<tr>
<td></td>
<td>MT-1</td>
<td>MT-2</td>
<td>MT-3</td>
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<td></td>
<td>Dyke Massao</td>
<td>Dyke Massao</td>
<td>Dyke Massao</td>
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<tr>
<td>Phlogopite</td>
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</tr>
<tr>
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<td>15</td>
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<tr>
<td>Dolomite</td>
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<tr>
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<tr>
<td>Serpentinite</td>
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</table>

Fig. 5. I. MT-3 glimmeritic dyke (Phl, phlogopite ~ 50 vol%) showing clinopyroxene (Cpx) partially replaced by amphibole (Amph); N//. II. MT-16 glimmeritic plug characterized by tetraphlogopite (Phl, ~ 60 vol%); N//. III. MT-15 glimmeritic plug (Phl, ~ 51 vol%) with relics of probable olivine (Ol) replaced by chlorite (Chl); N X. IV. MT-1 showing relics of olivine (Ol) completely replaced by serpentine (Serp); N X.

Carbonatitic rocks

The characteristic feature of the alvikitic dykes (MT-5, Fig. 6.I) is its granular, hypidiomorphic, medium to fine-grained texture. The other carbonatites (cf. representative modal analyses of Table 1B) are beforsitic breccioid necks, coarse to medium-grained in texture. Euhedral to subhedral
dolomite is predominant (Fig. 6.III), occurring associated with clasts of quartz and glass. Amphibole, phlogopite, apatite, opaque minerals (magnetite and pyrite), perovskite, pyrochlore and titanite constitute the complementary mineral assemblage. In few samples chlorite and serpentine pseudomorphs after mafic minerals are also observed (Figs. 6.II-IV). Phlogopite is normally euhedral, but can also form irregular and interstitial aggregates, sometimes in contact with opaque minerals and apatite. Perovskite is subhedral, in general disseminated in the rock, but in some samples is found as irregular aggregates in association with opaque minerals. Chlorite is present as interstitial fibrous aggregates, or as thin (millimetric) veins together with carbonates. Opaque minerals are represented by magnetite and pyrite. Pyrochlore is present in some samples, the grains being brownish, euhedral to subhedral and associated with apatite and opaque minerals. Some dykes are rich in primary carbonate (calcite up to 26 vol%) and have hydrothermalized chilled margins (cf. samples MT-9 and MT-10 of Table 1C) where clinopyroxene is completely uralitized.

Hydrothermalites

Some samples, i.e. MT-9 and MT-10 from Mutum dyke show a prevailing hydrothermal association of chlorite-serpentine-carbonate, and then may be defined as “hydrothermalites”.

MINERAL CHEMISTRY

A systematic mineralogical investigation of the Planalto da Serra rocks was undertaken with the main aim of characterizing the typical minerals of the different assemblages. Microprobe analyses were carried out on polished sections at the São Paulo, Modena and Padova Universities, utilizing various equipments: at São Paulo, a JEOL model JXA-8600, having as analytical conditions 15 kV, 20 nÅ and beam diameter variable from 5 to 10 µm; at Modena, an ARL-SEM-Q operating at 15 kV and 20 nÅ; at Padova, an energy dispersive spectrometer EDS EG IG connected to a SEM AUTOSCAN microprobe operating at 15 kV. There a MAGIC program (ORTEC IV M version) was used to convert count rates into oxides wt%. On the whole oxides or simple silicate compounds were used as standards. The reported analyses are averaged by at least three point-analyses and the results are considered accurate within 2-3% for major elements and about 10% for the minor ones.
**Phlogopite**

Mica is a very important mineral of the Planalto da Serra rocks, being mainly represented by *phlogopite* and *tetraferriphlogopite*. The latter minerals occur as intercumulus primary phase, but can be also found as small aggregates of secondary origin, showing *chlorite* as the most common alteration product. Chemical analyses are reported in Table 2, with the structural formulae calculated assuming the positive charges balanced on 10 oxygen atoms and 2(OH+F+Cl) atoms; tetrahedral sites are believed to be completely filled by Si, Al and Ti to an occupancy of 4. Where the sum Si+Al+Ti is lower than 4.00 a.f.u., Fe$^{3+}$ should be occupying the tetrahedral position. The octahedral sites are filled with Ti, Fe, Mg and Mn, whereas Na, K, Ca and Ba were assigned to the interlayered positions (cf. Brigatti et al., 2001).

Chemical analyses plotted on the conventional Al-Mg-Fe$^{2+}$ diagram (Fig. 7A) show some overlapping for micas from the glimmeritic and carbonatitic rock types, with the phlogopite from carbonatites tending towards eastonite compositions. In general, early phlogopite can be found grading progressively into tetraferriphlogopite as a result of Al-deficiency during the magmatic crystallization. This particular feature has been also observed e.g. in other Brazilian alkaline-carbonatite occurrences (Araxá, cf. Traversa et al., 2001), kamafugitic and kimberlitic rocks from Alto Paranaiba, Brazil (Melluso et al., 2008) and in Uganda kamafugites (Scordari et al., 2012). Notably, the MT-9 and MT-10 dykes, display crystal rims strongly enriched in Ba, probably due to a highly localized influx of residual oxidized carbonatitic fluid (cf. Kopylova et al., 2010).

**Table 2.** Representative chemical compositions of phlogopites from Planalto da Serra. Structural formulae calculated on the basis of 24(O,H,F) and H$_2$O estimated assuming (OH, F)=4.000 a.f.u. Italics: analyses from Tab 5 of De Min et al. (2013).
Fig. 7. A) Composition of micas plotted on the conventional Al-Mg-Fe diagram (Bailey, 1984). Full circles, glimmeritic rocks; open squares, carbonatitic rocks; open diamond, hydrothermalite. B) Clinopyroxene compositions (full circles, dykes; open circles, plugs) projected on the Wo-En-Fs ternary system. Nomenclature after Morimoto (1988).

Carbonates

Carbonate minerals correspond to 2-15 vol% of the whole composition of the glimmeritic rocks. Calcite shows low MgO and relatively high SrO (0.38-1.52 wt%), whereas dolomite is the main constituent of the beforitic rocks (cf. Tables 1 and 3). In the MT-5 alvikitic sample the calcite content can reach up to 51% (Table 1). Other carbonate phases as ankerite, siderite, strontianite and magnesite were not observed. REE carbonates as primary or secondary phases may be also present (ΣREE up to 192 ppm in carbonatic phases). Notably in MT-19 sample, dolomite (51 vol%) coexists with exsolved calcite (3 vol%).

Table 3. Average microprobe analyses of carbonates. CO₂ calculated as from stoichiometry. The end members are also reported (wt%).

<table>
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<tr>
<th>SAMPLE</th>
<th>MT-1</th>
<th>MT-2</th>
<th>MT-3</th>
<th>MT-5</th>
<th>MT-9</th>
<th>MT-10</th>
<th>MT-11</th>
<th>MT-13</th>
<th>MT-14</th>
<th>MT-15</th>
<th>MT-16</th>
<th>MT-17</th>
<th>MT-19</th>
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<td>0.06</td>
<td>0.05</td>
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<td>0.27</td>
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<td>0.21</td>
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</table>

Clinopyroxenes

Clinopyroxenes, diopsidic in composition (Table 4 and Fig. 7B), occur only in the glimmeritic rocks. In the dykes (e.g. MT-3) the mineral is found as relict crystals in association with amphibole, phlogopite and carbonates (cf. Fig. 5.1); on the other hand, cumulus diopside is present in the plugs. Notably, in the carbonatitic rocks, ghosts of clinopyroxene appear to be completely replaced by amphibole and/or chlorite/serpentine.
the textural characteristics of the MT

\[ \text{FeO} \]

and FeO assuming charge balance and a theoretical formula containing 4 cations and 6 oxygens.

### Table 5

Representative microprobe analyses of amphiboles. Fe\(^{3+}\) and Fe\(^{2+}\) repartition according to Leake et al. (1997). Structural formulae calculated on the basis of 2\((O,OH,F)\) and H\(_2\)O estimated assuming \((OH,F)=2.000 \text{ a.f.u.}\)

#### Amphiboles

Amphiboles are mainly tremolitic in composition (Table 5) and usually replace the clinopyroxene. As matter of fact, in some glimmeritic samples diopside relics can be found yet, but conversely in alvikitic dykes and in hydrothermalites the original clinopyroxene is completely substituted by tremolite.

Notably, the replacement of anhydrous by hydrous minerals is commonly used to infer infiltration of a rock by warm H\(_2\)O-rich fluids (cf. Welch and Pawley, 1991), as also suggested by the textural characteristics of the MT-10 hydrothermalite.
shown in Fig. 8) is also present. Sometimes the magnetite is altered into hematite.

Table 6. Representative microprobe analyses of opaques. Fe₂O₃ and FeO (wt%), ulvöspinel (mol%) and end members calculated according to Carmichael (1967) and stoichiometry, respectively.

<table>
<thead>
<tr>
<th>Sample</th>
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<th>MT-3</th>
<th>MT-5</th>
<th>MT-6</th>
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Opaques

Pyrite is a common accessory phase in all the samples, being an important phase (content up to 4-5 vol%) only in hydrothermalitic samples (MT 9 and MT-10) and in the beforisitic neck MT-19 (cf. Table 1). Probably the mineral represents a later phase, as indicated in sample MT-10 where pyrite includes titanomagnetite having the same composition of the groundmass magnetite.

All the specimens contain titaniferous magnetite (ulvöspinel from 4 to 43 mol%; Table 6), the main differences being the Cr content (Fig. 8). In dykes and necks plus plugs, the Cr/(Cr+Al) ratios range from 0.5-0.9 to 0.0-0.4, respectively. Noteworthy, in the MT-5 alvkistic dyke, other than late Ti-magnetite, a subordinate xenocrystals rich in spinel (47 mol%) and Mg-chromite (31 mol%, not shown in Fig. 8) is also present. Sometimes the magnetite is altered into hematite.
Garnet

Garnet is restricted to the glimmeritic rocks and constitutes an important phase only in the Chibata plug (MT16 and MT-17 samples: 6 and 15 vol%, respectively) and, subordinately, in the Massao dyke (MT-1: < 1 vol%). It is brownish fine-grained and subidiomorphic to idiomorphic crystals. On the whole the mineral shows melanitic composition (Deer et al., 1992) and fits the equilibrium cooling trend of Kjarsgaard (1998) at temperature and pressure of 900°C and 0.2 GPa, respectively (Fig. 9).

Table 7. Representative microprobe analyses of garnets. Structural formulae on 24 oxygen basis and Fe$_2$O$_3$ as from charge balance.

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Fig. 8. Fe$^{2+}$/Fe$^{3+}$(+Mg) vs. Ti/(Ti+Cr+Al), Fe$^{3+}$/Fe$^{3+}$(+Cr+Al) and Cr/(Cr+Al) planes through the spinel prism (Deer et al., 1992) illustrating magnetite variations in the Planalto da Serra specimens (cf. Table 6).

Fig. 9. Compositions of melanitic garnets (grey squares) from Planalto da Serra, as represented on the Al-Fe$^{3+}$-Ti triangular plot (atom%, cf. Table 7). Temperatures (°C) and equilibrium cooling trends at 0.2 GPa are also shown (cf. Kjarsgaard, 1998).
**Perovskite and Nb-rich oxides.**

Perovskite microphenocrystals and microlites are ubiquitous and may be an important accessory phase (up to 2-3 vol%; cf. Table 1) in some glimmeritic and carbonatitic rocks (e.g. MT-5, MT-16 MT-19). Representative chemical analyses are reported in Table 8, from which appears possible to apply the oxygen barometer based on the Fe and Nb content of CaTiO$_3$ perovskite to estimate the oxygen fugacity ($f$O$_2$) during the crystallization and emplacement of the rock types (ΔNNO of Bellis and Canil, 2007, relative to the nickel-nickel oxide buffer). The ΔNNO values obtained for the Planalto da Serra rocks vary from 0.63 to 2.50. Notably, the Ca/Ti ratios are slightly over the unity (1.022±0.004 a.f.u.), and some quantity of REE (Σ=2.4-4.7 wt%), (Nb,Ta)$_2$O$_5$ (0.6-0.7 wt%), other than Th (up to 0.60 wt%) and Fe$_2$O$_3$ 1.38-1.96 wt%) are present (cf. Doctor and Boyd, 1979). These results are very similar to those of $f$O$_2$ (ΔNNO) conditions for Lac de Gras pipes (Chakhmouradian and Mitchell, 2001; Canil and Bellis, 2007).

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<td>H$_2$O</td>
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<td>0.63</td>
<td>0.63</td>
<td>0.63</td>
<td>0.63</td>
<td>0.63</td>
<td>0.63</td>
<td>0.63</td>
<td>ΔNNO</td>
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<td>1.57</td>
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</table>

Nb-rich phases are present as accessory microlites (≤1 vol%) in the groundmass of the carbonatitic rocks. Representative chemical analyses relative to the MT-5 alvikitic and MT-19 beforsitic rocks are listed in Table 8 where the more abundant elements are Nb (Nb$_2$O$_5$ 63-65 wt%), CaO (~14 wt%) and Na$_2$O (~7.4 wt%). On the basis of the Ti-Nb-Ta relationships these phases can be classified as pyrochlore (cf. Černý and Erict, 1986). Similar compositions are reported by Simandl et al. (2001) for pyrochlore from Blue River carbonatites, British Columbia.

**Titanite and apatite**

Titanite and apatite are also ubiquitous accessory minerals and occur as microlites and more scarcely as microphenocrysts. Major element contents in titanite are relatively constant, i.e. SiO$_2$=29.8±0.3, TiO$_2$=36.2±0.5, CaO=26.1±0.3 wt% (cf. Table 9).

In apatite the following ranges in F and Sr contents were detected: F, 3-4.7 wt%; Sr, <0.1-0.3 wt%. Notably, these variations closely match those registered in Leucite Hills and in Paraguayapatites (Mitchell and Bergmann, 1991, and Comin-Chiaromonti and Gomes, 1995).

**Secondary accessories**

Secondary accessory minerals are mainly represented by chlorite and serpentine. They occur as alteration products of phlogopite and tremolite and are particularly abundant in the MT-10 hydrothermalite (chlorite 29 vol%, serpentine 27 vol%).

Sometimes chlorite and serpentine are found replacing original phases that have clearly the shape of olivine (cf. Figs. 5.III and 6.IV):
According to Tomkins et al. (1984), high calcium contents implies chloritization under high CO₂ activity. The chlorites are compositionally distinctive, high in SiO₂ and MgO and low in Al₂O₃, and plot inside the field of the chlorites of kimerlites from Sierra Leone (cf. Fig. 10). On the other hand, the diatreme facies, explosive and H₂O enriched (e.g. MT-10; cf. Table 1), resulted in the formation of serpentine+chlorite. Moreover, there are also textural evidences of transformation to serpentine of tremolite as a probable precursor.

Table 9. Representative microprobe analyses of titanites (a.f.u. on the basis of 4Si), and apatites: a.f.u. on the basis of 26(O,F).

<table>
<thead>
<tr>
<th>Titanite</th>
<th>MT-1</th>
<th>MT-9</th>
<th>MT-10</th>
<th>MT-17</th>
<th>Mt-19</th>
<th>Apatite</th>
<th>MT-1</th>
<th>MT-5</th>
<th>MT-15</th>
<th>MT-19</th>
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<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
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<td>5.00</td>
<td>5.00</td>
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<td>15.32</td>
<td>15.32</td>
<td>15.32</td>
<td>15.32</td>
<td>Al₂O₃</td>
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<td>1.01</td>
<td>1.01</td>
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<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
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<td>10.02</td>
<td>10.02</td>
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</table>

Table 10. Representative microprobe analyses of chlorites (a.f.u. on the basis of 28 O), and of serpentine (a.f.u. on the basis of 7 O).

<table>
<thead>
<tr>
<th>Chlorite</th>
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<th>MT-5</th>
<th>MT-10</th>
<th>MT-11</th>
<th>Serpentine</th>
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<tr>
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<td>8.00</td>
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<td>Sum</td>
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</table>
Fig. 10. A: Chlorite analyses plotted as a function of Mg-Fe$^{2+}$-Al. B: Si-NCFM(Fe$^{2+}$+Mg+Mn+Ca+2Na+2K-Ti)-A(Al+Fe$^{3+}$+Cr+2Ti), after Robinson et al. (1982). Variations of kimberlitic chlorites from Sierra Leone are also shown (grey fields; cf. Tomkins et al., 1984). Full circles, chlorites; squares, serpentines.

SIGNIFICANCE OF THE MINERALOGY

The mineralogy of the Planalto da Serra rocks when compared to other alkaline occurrences from the AZ 125° lineament (cf. Fig. 1) is, to some extent, similar to the Late Cretaceous glimmerites and carbonatites from APIP described by Gibson et al. (1995, 1997) and Thompson et al. (1998), for the following reasons: 1) the very abundant phlogopite, primary carbonates (cf. glimmerites, sōvites and beforsites, after Gomes and Comin-Chiaramonti, 2005) and olivine; 2) the compositions of diopside, phlogopite (tetraferriphlogopite), carbonates, opaques (titanomagnetite and chromium-spinel) and accessory apatite, titanite, perovskite and pyrochlore (cf. Bizzi and Araújo, 2005; Comin-Chiaramonti et al., 2005). The presence of primary melanitic garnet is indicative of equilibrium at 900°C and 2-5 Kb pressure (cf. Kjarsgaard, 1998). On the other hand, the presence of the tremolitic amphibole may be referred to hydration, nucleation and growth of amphibole, accompanied by continuous dissolution of diopside at 800-850°C (about 5 Kb; cf. Welch and Pawley, 1991; Jenkins et al., 1991; Bozhilov et al., 2004). Finally, hydrothermal alteration affecting the pre-existing parageneses is responsible for the formation of chlorite, serpentine and pyrite.

PETROCHEMISTRY

The glimmeritic rocks (Table 11, with major oxides wt% recalculated on a water-free basis) fit the kamafugitic field and/or the TAT (Toro- Ankole type) and II fields of Barton (1979) and Foley et al. (1987), respectively (Fig. 11). Even the glass in the beforsitic neck (MT-13) shows a kamafugitic affinity.

It is interesting to note that, on the basis of the classification shown by Fig. 11, the Planalto da Serra samples specifically refers to rock types considered ultrapotassic (i.e., K$_2$O/Na$_2$O>2, K$_2$O>3 wt% and MgO>3 wt%), plotting in the Toro Ankole Group (Group II of Foley et al., 1987) and that even the carbonatic rocks can be considered to some extent as strongly potassic, having K$_2$O/Na$_2$O ratio 14.4±12.3 and K$_2$O 1.38±0.15.

On the whole the variation diagrams MgO vs. major oxides (Fig. 12) confirm the kamafugitic affinity of the non-carbonatitic samples.
Table 11. Chemical analyses of Planalto da Serra rocks. Major elements were analyzed by XRF fluorescence techniques using a PW1400 automatic spectrometer and pressed-powder pellets. FeO was determined by volumetric titration, using the ammonium metavanadate. Glass as taken from microprobe analyses. Glimm.: glimmeritic rocks. CO₂ and H₂O⁺ were determined by wet chemical analyses (cf. also Galle and Runnel method, 1960). Italics: data from Table 1 of De Min et al. (2013).

<table>
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<tr>
<th>Sample (location)</th>
<th>MT-1 (Massao)</th>
<th>MT-2 (Massao)</th>
<th>MT-3 (Massao)</th>
<th>MT-15 (Chibato)</th>
<th>MT-16 (Chibato)</th>
<th>MT-17 (Chibato)</th>
<th>MT-13 (CLASS)</th>
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<td>Beforistic neck</td>
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<tr>
<td>MgO</td>
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<td>MT-13 (Big Valley)</td>
<td>MT-14 (Big Valley)</td>
<td>MT-19 (Dentiaza)</td>
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<td>Beforistic neck</td>
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<td>2.43</td>
<td>4.23</td>
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Italics: data from Table 1 of De Min et al. (2013).
Fig. 11. Planalto da Serra rocks: molar \((K_2O+Na_2O)/Al_2O_3\) vs. SiO\(_2\) (wt\% on a water-free basis: LHT, Leucite Hills; TAT, Toro-Ankole; RPT, Roman Province lavas type after Barton, 1979) and CaO vs. Al\(_2O_3\) (Group I, LHT; Group II, TAT; Group III, RPT; after Foley \textit{et al.}, 1987) diagrams. APIP kamafugite and kimberlite fields are after Fig. 2 of Gomes and Comin-Chiaramonti (2005).

Fig. 12. MgO vs. major oxides and trace elements relationships, where the grey fields represent yhe APIP kamafugites. In the Zr vs. Cr diagram the heavy line represents the liquid descent of the APIP rock types \((Zr_0=240;\ cf. Gomes\ and Comin-Chiaramonti, 2005)\). Symbols as in Fig. 11.
Table 12. Concentrations of trace elements of Planalto da Serra rocks (and carbonate fractions) determined by ICP-mass spectrometer at Actlabs (1336 Sandhill Drive, Ancaster, Ontario L9G 4V5; cf. Table 1). Italics: data from Table 1 of De Min et al., 2013.

<table>
<thead>
<tr>
<th>Sample ppm</th>
<th>MT-1 (Masson)</th>
<th>MT-2 (Masson)</th>
<th>MT-3 (Masson)</th>
<th>MT-3 CF</th>
<th>MT-5 (Los)</th>
<th>MT-5 CF</th>
<th>MT-9 (Masson)</th>
<th>MT-10 (Masson)</th>
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<tr>
<td>Co</td>
<td>60.3</td>
<td>57.4</td>
<td>68.9</td>
<td>601</td>
<td>76.4</td>
<td>76.4</td>
<td>359</td>
<td>359</td>
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<tr>
<td>Cr</td>
<td>108.9</td>
<td>115.4</td>
<td>119.4</td>
<td>160</td>
<td>160</td>
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<td>187.4</td>
<td>68.9</td>
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<td>7.1</td>
<td>7.1</td>
<td>1.8</td>
<td>1.8</td>
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<tr>
<td>La</td>
<td>909</td>
<td>1652</td>
<td>940</td>
<td>6310</td>
<td>1069</td>
<td>2752</td>
<td>1665</td>
<td>1219</td>
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<tr>
<td>Mg</td>
<td>218.0</td>
<td>169.9</td>
<td>220</td>
<td>&lt;0.03</td>
<td>159.4</td>
<td>&lt;0.03</td>
<td>220.4</td>
<td>314.3</td>
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<tr>
<td>Ni</td>
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<td>6.4</td>
<td>6.8</td>
<td>6.2</td>
<td>7.1</td>
<td>8.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sr</td>
<td>7.5</td>
<td>7.7</td>
<td>7.7</td>
<td>7.4</td>
<td>14.0</td>
<td>14.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Also the pairs of major and trace elements of the glimmeritic rocks exhibit ranges for incompatible elements in-or near the kamafugitic fields (Fig. 11). In particular there are apparent correlations between Nd vs. Sm, Th vs. U, La vs. Yb and Sr vs. Rb (Fig. 12); however, correlations are not so evident for the rocks of carbonatic affinity (cf. Table 12). Zr vs. Cr diagram in the previous figure defines for the glimmeritic rocks a liquid with an initial Zr content of about 240 ppm, similarly to the APIP lithotypes (cf. Gomes and Comin-Chiaramonti, 2005), suggesting for a
comparable mantle source, comparable melting degrees.

Incompatible elements, normalized to a primitive mantle composition (Fig. 13A) for both petrographic associations and single occurrences, show different behaviours. In fact, the glimmeritic rocks, and even the MT-5 alvikitic dyke and the hydrothermalites, displaying a kamafugitic affinity, are characterized by negative anomalies in K, Sr-P, Hf and Ti, and positive ones in Th, La, Nd, Eu, Tb. Ba and Rb show both negative or positive anomaly. On the other hand, the beforsitic rocks exhibit strong negative Rb-Ba anomalies and relative enrichment in Th, U, K, La, Ce.

Chondrite-normalized REE distribution (Fig. 13B) displays similar behaviours with strong LREE/HREE fractionation, i.e. (La/Yb)C: 65.0±1.3 (glimmeritic dykes), 56.6±2.2 (glimmeritic plugs), 90.3±8.7 (rocks with hydrothermalitic tendency), 56.1±11.7 (beforsitic rocks), 76 (rock with alvikitic affinity, MT5), and 40.3±6.9 (carbonate fraction of MT-3 and MT-5 samples). These latter ones also show Eu/Eu* (Sm-Gd normalization) negative anomalies, i.e. 0.29 (MT-3) and 0.47 (MT-5), probably due to previous crystallization of Ca-rich phases (clinopyroxene-amphibole?). Alternatively this behaviour could have been acquired from the country rock during the hydrothermal event.

Considering the high MgO contents, reaching up to 19 wt% in the glimmeritic rocks, the REE distribution likely represents the products of partial melts of a veined mantle source, strongly enriched in incompatible elements and C, H (e.g. phlogopite-amphibole-carbonate-rich veins).
Fig. 13. A) Incompatible elements normalized to primitive mantle concentrations (after Sun & McDonough, 1989). B) Chondrite-normalized (after Boynton, 1984) REE distribution for the various rock types and occurrences from the Planalto da Serra region. Data source in Tables 11 and 12.

ISOTOPIC SYSTEMATICS

Age of the rocks intruding the Rio dos Cavalo Rift.

A complete discussion of this subject is provided by De Min et al. (2013). Here are summarized the main results: 40Ar/39Ar (phlogopite and tetraferriphlogopite) yielded an age around 600 Ma (602±16 as average); Rb/Sr systematics, relative to the MT-19 beforitic rocks (whole rock, carbonate fraction and insoluble residue) defines an isochron Rb/Sr of 598±10 Ma, similar to the Sm/Nd age (errorchron for all the samples) of 601±73. Notably, new data relative to the Rb/Sr systematic (Table 13 A,B), excluding MT-10 hydrothermalite and MT-16 carbonate fraction, give an age of 599 ± 8 (cf. Fig. 14), confirming the previous dates of De Min et al. (2013).

Concluding, from the available dates, it can be state that the K-alkaline-carbonatite rock types of the Rio de Cavalo Rift have an age of about 600 Ma, and that this event can be associated with the Brasiliano Cycle (cf. Cordani et al., 2012).

Table 13. A) Rb, Sr contents (ppm), 87Rb/86Sr and 87Sr/86Sr isotopic ratios for the magmatic rocks from Planalto da Serra. Rb, initial 88Sr/86Sr ratios calculated at 600 Ma, WR, whole rock; Ce calcite; IR, insoluble residue; Dol, dolomite; Cc Fr: carbonate fraction.. B) Sm, Nd contents (ppm), 143Sm/144Nd and 143Nd/144Nd isotopic ratios for the same samples. Isotopic ratios were determined at the Department of Mathematics and Geosciences, University of Trieste: NBS987: 86Sr/88Sr=0.710250 (2o: 0.000008) n=20; La Jolla: 143Nd/144Nd=0.511853 (2o: 0.000015) n=21. Italics: A, Rb/Sr systematics (MT-19), B, Sm/Nd systematics, data from Table 3 and 4 of De Min et al. (2013), respectively.

<table>
<thead>
<tr>
<th>A</th>
<th>Rb (ppm)</th>
<th>Sr (ppm)</th>
<th>87Rb/86Sr</th>
<th>87Sr/86Sr</th>
<th>Rock-type</th>
<th>Carbonatic vol%</th>
<th>Rb (600Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MT-4 WR</td>
<td>58.5</td>
<td>999</td>
<td>0.1862</td>
<td>0.700201 (22)</td>
<td>Glimmeritic dyke</td>
<td>5 Cr</td>
<td>0.70668</td>
</tr>
<tr>
<td>MT-3 WR</td>
<td>107.3</td>
<td>941</td>
<td>0.3255</td>
<td>0.711106 (24)</td>
<td>Glimmeritic dyke</td>
<td>6 Cr</td>
<td>0.706655</td>
</tr>
<tr>
<td>MT-5 Cc Fr</td>
<td>1.675</td>
<td>6130</td>
<td>0.0788</td>
<td>0.702789 (21)</td>
<td>Albitic dyke</td>
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<td>0.706625</td>
</tr>
<tr>
<td>MT-6 WR</td>
<td>71.9</td>
<td>1069</td>
<td>0.1946</td>
<td>0.70294 (25)</td>
<td>Albitic dyke</td>
<td>5 Cr</td>
<td>0.706625</td>
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<tr>
<td>MT-7 Cc Fr</td>
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<td>7232</td>
<td>0.037</td>
<td>0.706463 (24)</td>
<td>Albitic dyke</td>
<td>5 Cr</td>
<td>0.706625</td>
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<td>MT-9 WR</td>
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<td>1865</td>
<td>0.0379</td>
<td>0.707022 (25)</td>
<td>Carbonated dyke</td>
<td>26 Cr</td>
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<tr>
<td>MT-10 WR</td>
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<td>1219</td>
<td>0.0427</td>
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<td>Hydrothermalite</td>
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<tr>
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<td>200</td>
<td>0.2648</td>
<td>0.708964 (24)</td>
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<td>59 Dd, 3 Cc</td>
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<tr>
<td>MT-11 Dd+Cc Fr</td>
<td>0.045</td>
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<td>0.709104 (25)</td>
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<td>153</td>
<td>1067</td>
<td>0.4159</td>
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<td>2 Cr</td>
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<td>95</td>
<td>0.0022</td>
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<td>MT-16 B</td>
<td>153</td>
<td>1053</td>
<td>0.476</td>
<td>0.708109 (24)</td>
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<td>MT-19 Dd+Cc Fr</td>
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<td>0.0066</td>
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<th>Nd (ppm)</th>
<th>147Sm/144Nd</th>
<th>143Nd/144Nd</th>
<th>Initial (600 Ma)</th>
<th>εNd</th>
<th>εSr</th>
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<td>115.7</td>
<td>0.03818</td>
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<td>0.03532</td>
<td>0.517209 (20)</td>
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<td>1.38</td>
<td>0.0973</td>
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<td>MT-6 Cc Fr</td>
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<td>1.54</td>
<td>0.0999</td>
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<td>0.511864</td>
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<td>0.1193</td>
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<td>0.09933</td>
<td>0.522259 (20)</td>
<td>0.511864</td>
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<td>38.2</td>
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</table>

Sr-Nd isotopes

In general, the high concentration of most I.E. in all the Planalto da Serra rocks suggests that the effects of crustal contamination on the Nd isotopic systems were negligible and that the parental magma compositions are more likely linked to mantle-enriched sources, related to variable degrees of metasomatism (veined mantle). The data are plotted on Fig. 15 (time-integrated ε-notations of Table 13B), being the values concentrated in the enriched quadrant, with εNd = 0.41 ± 0.05 and εSr extending from 4 to 32-41. Notably, the lowest Sr values refer to the hydrothermalite and to the carbonate component (Sr = 195ppm) of a glimmeritic plug (εSr wr = 32) to suggest a reopening of
the system by less enriched fluids, rather than a selective crustal contamination.

In any case, the isotopic systematics testify a distribution which appears quite distinct from that corresponding to the APIP kamafugites, as indicated in the Fig.15.

**Fig. 14.** Errorchron relative to the new data of $^{87}\text{Rb}/^{86}\text{Sr}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ from the Planalto da Serra samples (cf. Table 13), excluding MT-10 sample and carbonate fraction from MT-16 sample.

**Fig. 15.** Time integrated, $\varepsilon$ notations, $^{87}\text{Sr}/^{86}\text{Sr}$ ($\varepsilon_{\text{Sr}}$) vs. $^{144}\text{Nd}/^{143}\text{Nd}$ ($\varepsilon_{\text{Nd}}$) correlation diagrams. Squares represent the samples from Planalto da Serra (grey squares are the carbonate fractions; cf. Table 13). Grey field represents the composition of APIP kamafugites (Gomes and Comin-Chiaramonti, 2005). Inset: histogram relative to the Nd model ages ($T_{\text{DM}}$) for the APIP kamafugites (grey areas) and for Planalto da Serra samples (black areas, PdS); $T_{\text{DM}}$ values: calculation of model dates relative to a depleted reservoir, $^{143}\text{Nd}/^{144}\text{Nd}=0.513114$ and $^{147}\text{Sm}/^{144}\text{Nd}=0.222$ (cf. Faure, 1986; Dickin, 2005).

Moreover, the almost constant behaviour of the Sm/Nd ratio in the rocks (0.13±0.003; cf. Fig. 12 and Table 13) allows to consider the Nd model ages (De Min et al., 2012) as indicative of the main metasomatic event affecting the lithospheric sources beneath the Planalto da Serra region. These ages (calculated in relation to the depleted mantle, $T_{\text{DM}}$, cf. Table 13; Dickin, 2005) for the whole PdS population (12 samples) fit 1.05±0.08 Ga, roughly similar to those calculated for the APIP kamafugites, i.e. $T_{\text{DM}} = 0.97±0.09$ (44 samples, cf. inset of Fig.15) and Rio Verde-Iporá alkaline province (0.98±0.10, cf. Fig. 1, and Gomes and Comin-Chiaramonti, 2005), defining an Early Neoproterozoic age.

On the other hand, the “uncontaminated trachybasaltic dykes” from the Poxoréu area (cf. Fig. 1...
and Gibson et al., 1997) display $T_{DM} = 643\pm 52$ Ma. Thus, in spite of the different age among the Rio dos Cavalos Rift lithotypes (about 600 Ma) compared to the APIP, Rio Verde-Iporá and Poxoréu rocks (about 84 Ma; cf. Gibson et al., 1995, 1997), the model ages seem to reflect the time when the fluids were “extracted” metasomatizing the lithospheric mantle.

CONCLUDING REMARKS

Along the AZ 125° lineament, where alkaline magmatic rocks are also present in Poxoréu, Rio Verde-Iporá and APIP areas (cf. Fig. 1B), the Rio dos Cavalos Rift, in the Planalto da Serra region, was intruded by dykes and necks of ultramafic and carbonatitic rocks within an extensional zone in the Late-Proterozoic Paraguay mobile belt (Cuiabá Group; cf. Figs. 2 and 3). The Planalto da Serra lithotypes (PdS) are represented by glimmerites of kamafugitic affinity, by carbonatitites having alvikitic and beforisitic characteristics and also by petrographic varieties showing evidences of late hydrothermalization. These hydrothermalization processes, responsible for the lowest isotopic Sr values, suggest that a successive event partially reopened the system by less enriched fluids.

On the whole, the PdS lithologies present petrochemical features similar to those from the Late Cretaceous alkaline rocks from the APIP region. On the other hand they yielded Ar-Ar, Rb/Sr and Sm/Nd similar ages, around 600 Ma. Notably, the 600 Ma date represents an Ediacaran age (630-542 Ma), at the eastern margin of the Amazonian Craton that was fragmented at the beginning of the Neoproterozoic time (cf. Cordani et al., 2012).

The sedimentation of the units of the Paraguay mobile belt occurred in a passive margin, at the onset of the Brasiliano Cycle (cf. Cordani et al., 2009). The whole stratigraphy of the Northern Paraguay Belt is divided into: 1) Alto Paraguay Group, which is the upper unit, 2) the Araras Group, and 3) the Cuiabá Group, the lower unit, which formed presumably between 850 and 600 Ma (Lacerda Filho et al., 2004). According to Alvarenga et al. (2010), the older stratigraphic units of the belt represent the passive margin and the younger ones are typical of a foreland related to the Brasiliano Cycle (cf. Figs 1-3).

As matter of fact, the PdS ultramafic rocks intruding low-grade metasedimentary rocks of the Cuiabá Group indicate that the onset of the deformation and the low-grade metamorphism of the group is older than 600 Ma, and probably taking place at the transition of the Cryogenian and the Ediacaran Periods (630 Ma; cf. Campos Neto et al., 2011).

This age, together with other geochronological and tectonic data (cf. Cordani et al., 2012) indicates that it is highly improbable the existence of a large oceanic domain in this area (the Clymine ocean), as postulate by Trindade et al. (2006), and rules out the possible geochronological relationship between the Planalto da Serra intrusions and the alkaline bodies from the Azimuth 125° lineament (Bardet, 1977; Biondi, 2005), which is characterized by the occurrence of ultramafic and alkaline-carbonatite rocks and kimberlites, ranging in age from 80 to 90 Ma.

According to Pimentel et al. (2000), the final amalgamation of Western Gondwana would have occurred at 620 Ma or slightly later, which means that Laurentia, still attached to the Amazonian Craton, was, for a short time, part of the Gondwana Supercontinent. The opening of the Iapetus ocean characterized the separation between Laurentia and the Amazonian Craton. It is unknown when this ocean opened, but it could have been just after 600 Ma. Basins were opened, deformed and metamorphosed around 520 Ma (Trompette, 1997). On the other hand, paleomagnetic measurements indicate that the opening occurred at ca. 580 Ma (Cordani et al., 2009). Taking into account these factors, it is possible that the emplacement of the ultramafic and carbonatitic rocks from Planalto da Serra is related to one of the most important extensional periods of Neoproterozoic times, which is characterized by the separation of Laurentia and the Amazonian Craton.

Considering the Nd model ages (depleted mantle, $T_{DM}$) as indicative of the main metasomatic events affecting the lithospheric sources beneath the AZ 125° lineament, the values are $1.05\pm 0.07$ Ga for the PdS population, $0.97\pm 0.09$ Ga for the APIP kamafugites and $0.98\pm 0.10$ Ga for the Rio
Verde-Iporá alkaline volcanics, defining on the whole an Early Neoproterozoic age episode, which reflects the time when the fluids were “extracted” metasomatizing the lithospheric mantle.

In conclusion, the TDM model ages suggest that the Planalto da Serra magmas were derived by the remobilization of subcontinental lithospheric mantle that had been enriched by small-volume K-rich melt fractions at the Early to Late Neoproterozoic, well corresponding to the aggregation of Western Gondwana (cf. Scotese, 2009). This severely hampers any hypothesis of mantle plume tail, as proposed by Gibson et al. (1995), given that a subcontinental mantle enrichment, controlled by an Early Neoproterozoic event, produced similar ultramafic alkaline products at 600 and 80-90 Ma.

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