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An overview of the Mesozoic-Cenozoic magmatism and tectonics in Eastern Paraguay and central Andes (western Gondwana): implications for the composition of mantle sources.

by

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PREFACE

The paper is dedicated to Ricardo Héctor Omarini, full professor at the Salta University and president of the “Centro de Estudios Geologicos Andinos”. He planned this publication in January 2015 together with Piero Comin-Chiaramonti. Unfortunately, Ricardo passed away on June 28, 2015, but always remains in our hearts.

ABSTRACT

The amalgamation of the Western Gondwana (including the Greater Gondwana supercraton) occurred at 600 Ma during the Brazilian – Pan African orogeny. A plate junction related to this event is marked by the Transbrazilian lineament which separates the South American continent into two sectors: the Eastern Paraguay-Brazilian and Central Andean domains. An overview of the geodynamic data from these two sectors indicates that the two domains were subjected to distinct evolutions from the Proterozoic to the present. The Andean domain is characterized by long-lived subduction processes linked to the convergence and consequent collision of microplates since the Middle Proterozoic (western Amazonian Craton) with a peak at about 600-580 Ma. The Paraguay-Brazilian domain remained relatively stable but was affected by extension episodes that reactivated ancient (Early and Middle Proterozoic) suture zones. These different geodynamic evolutions seem to reflect broadly distinct mantle compositions. In the subduction zones of the Andean domain the mantle was deeply modified by metasomatic processes following the subduction of oceanic plates. Consequently, the Andean type magma sources show a clear HIMU imprint inherited from the MORB, whereas the Paraguay-Brazilian sector shows a prevalent EMI and subordinate EMII character. The petrological data mainly from Mesozoic and Cenozoic magmatic events in the two sectors are reviewed to investigate the current mantle plume and mantle dome models for the uprising of the asthenospheric (or sub-lithospheric) material.

Key Words: Magmatism; South America; Eastern Paraguay; Mantle Plumes; End-member source.

1. Introduction

This paper presents a revision of petrological, geological, geochemical and geophysical studies of continental magmatism in the central sector of Eastern Paraguay and the central Andes (South American Platform) during the Mesozoic-Cenozoic time, to elucidate the parental mantle sources (Cristiani et al., 2005 and Comin-Chiaramonti et al., 2009). The area considered in this paper is characterized by potassic, sodic and alkaline-peralkaline continental magmatic rocks associated to the continental tholeiitic basalts of two LIPs (large igneous provinces), namely the Central Atlantic Magmatic and the Parana Etendeka provinces exposed over different geographic domains from eastern to western sides of the Transbrazilian lineament (TBL of Cordani et al., 2013 and references therein; see also Figure 1).

The largest volume of tholeiitic and alkaline rocks are located on the eastern sector of the TBL, parallel to the continental margin of the South American (Atlantic) domain. Magmatic activity in the western sector of the TBL is minor in volume and developed within or close to a series of rift basins parallel to the western border of the South America Continent (proto-Andean domain). Notably, the magmatism, developed within the late Proterozoic to Early Paleozoic basement, contains also marine and continental sediments of
Jurassic/Cretaceous ages. The opening of the Atlantic Ocean, in the context of the breakup of the Gondwana continent, has controlled the magmatic activity in these sectors. In terms of chemical and petrological relationships, these areas have been rarely considered together with the exception of a study on lavas carrying mantle xenoliths (Comin-Chiaramonti et al., 2009).

The eastern TBL sector has been extensively studied by Piccirillo and Melfi (1988), Hawkesworth et al. (1992, 2000), Comin-Chiaramonti and Gomes (1996, 2005), Gibson et al. (2006), Velázquez et al. (2006), Comin-Chiaramonti et al. (2007a) and Foulger and Judy (2007). The main reviews of the western sector of the TBL (Central Andean domain) are those of Viramonte et al. (1999), Tawackoli et al. (1999), Jaillard et al. (2000), Sempere et al. (2002), Lucassen et al. (2002, 2005), Schultz et al. (2004), Cristiani et al. (2005), Hauser et al. (2010a,b), Omarini et al. (2013) and Rocha Junior et al. (2013).

The aim of this review is to propose and illustrate a new interpretation of the Mesozoic-Cenozoic magmatism in the Brazilian Platform and Central Andes domains, and to explore their geochemical and petrological differences in terms of mantle sources.

2. Geodynamic background

The tectonic development of the South American platform (20-28°S) (Western Gondwana) includes five major events (Figures 1 and 2):

(a) Gondwana amalgamation between 850 and 480 Ma (Trompette, 1994; Unrug, 1996; Grunow, 1999; Cordani et al., 2000, 2003a,b, 2013; Almeida et al., 2000; Fuck et al., 2008, 2014);
(b) development of the extensive Central Atlantic tholeiitic magmatic province (at about 200 Ma; Marzoli et al., 1999);
(c) development of the large igneous provinces in connection with the Serra Geral flood tholeiites at 135-133 Ma (Bellieni et al., 1986; Rocha-Campos et al., 1988; Renne et al., 1992);
(d) emplacement of potassic magmatism and sodic mafic-ultramafic magmatism in southeast and central Paraguay at 138-59 Ma (Comin-Chiaramonti et al., 1986, 2001, 2005a,b, 2007a,b; Velázquez et al., 2002, 2006);
(e) development of rift-related alkaline-peralkaline magmatism and tholeiitic basaltic sills in the central Andes at 184-60 Ma (Viramonte et al., 1999; Sempere et al., 2002; Schultz et al., 2004; Hauser et al., 2010a,b; Cristiani et al., 2005; Lucassen et al., 2005; Comin-Chiaramonti et al., 2009; Omarini et al., 2013).

The geodynamic evolution of Western Gondwana during the late Precambrian-early Paleozoic times reflects the paleogeographic reorganization centered on the San Francisco craton that involved the consumption of inter-oceanic ensialic basins during the Brazilian and Panafarian orogeny (Plumb and James, 1986; Trompette, 1994; Unrug, 1996; Brito Neves et al., 1999; Cordani et al., 2000; Figure 1b). The Brazilian cycle, in its original definition (Almeida, 1945, 1968), describes the tectonic activity on the flanks of the Archean and Early Proterozoic proto-South American shields (i.e., Amazonia, Arequipa, Antofalla, Pampa, Río de la Plata, Luis Alves, Río Apa and San Francisco) between 890 and 480 Ma (Cordani et al., 2000 and references therein). In northwestern Argentina, the time-equivalent Pampean cycle (Aceñolaza and Toselli, 1976) defines the late Precambrian reorganization as a consequence of the accretion of the Arequipa-Antofalla microplates (Omarini et al., 1999). The accretion history in the central Andes region during this time (Figure 1 c) is equivalent to the closure of the sutures recognized between 580 and 530 Ma in many Laurentian and proto-Gondwanan terranes (Condie, 1989; Keppie and Dostal, 1998; Omarini et al., 1999).
Fig. 1
The origin of Gondwana is a Paleozoic event involving the amalgamation of the western and eastern proto-Gondwana continents. The timing of initial Gondwana configuration is related to the closure of the Mozambique ocean (550-480 Ma, Figure 1A) up to the Pangea fragmentation (Unrug, 1996; Grunow, 1999; Trouw and de Wit, 1999; Hoffman, 1999). The continental margin of Gondwana was affected in the Paleozoic by the accretion of some continental terranes. The last terranes, named Chilenia by Ramos et al. (1984), were accreted to the proto-margin of the Andes during the late Devonian-early Carboniferous. This collisional event is connected with the emplacement of the plutonic bodies (397-264 Ma) over the Pampa and Antofalla cratons (Damm et al., 1990; Sims et al., 1998; Ramos et al., 2010; Spagnuolo et al., 2012; Ramos et al., 2015). During the Triassic-lower Jurassic, the southern Gondwana margin was affected by magmatism (230-180 Ma) with huge volcanic eruptions and pluton emplacement (Kay et al., 1989; De Wit et al., 1999; Turner, 1999). The magmatic activity that predates the western Gondwana fragmentation took place during the late Permian-middle Triassic times in the Brazilian platform and western South America. Evidence of the early rifting in the central Andes, from Peru to Bolivia, includes alkaline rocks associated to marine and continental sediments deposited in subsiding basins (Hegarty et al., 1996; Jaillard et al., 2000; Sempere et al., 2002; Schultz et al., 2004). The main axis of the rift system approximately coincides with the ancient suture zone between the Arequipa-Antofalla craton and the Amazonia craton (Figures 1B and 1C; Jaillard et al., 2000; Sempere et al., 2002). In the Brazilian platform the main cratonic fragments, originally belonging to the Pangea, are surrounded by the Neoproterozoic Brazilian-Panafrian mobile belt (Figure 1B). These peripheral areas have been orogenically active, and crustal reworking has generated large volumes of magmatic rocks during the Precambrian and Phanerozoic, with their distribution controlled by active suture zones (Cordani et al., 2000, 2003a,b; Kröner and Cordani, 2003). The most important example of a long-lived active mega-suture is the Transbrazilian lineament (TBL) that crosses the entire region from South America to west Africa (Figure 1B; Pedrosa-Soares et al., 1998; Cordani et al., 2013; Curto et al., 2014). In this context, the magmatism was driven by the extensional regime caused by the relative movements (compressive-transpressive) of the ancient blocks. A notable example of this mechanism is the Alto Paraguay Triassic alkaline magmatism at the border of the Rio Apa block. This area was affected by rifting at about 241 Ma, probably induced by counter-clockwise and clockwise movements (north and south, respectively) hinged at about 20° latitude south and taking place during the Cabo-Laventana orogeny (Prezzi and Alonso, 2002; Velázquez et al., 2006).

The genesis of the Brazilian magma type (bmt) is linked to the geodynamic processes that promoted the opening of the south Atlantic and the rift systems to east of the TBL (Figure 1C). According to Chang et al. (1988) and Nürberg and Müller (1991), the sea-floor spreading in the south Atlantic at the bmt latitudes started at ~125-127 Ma (chron m4). Nürberg and Müller (1991) proposed that the opening of the south Atlantic is younger (~113 Ma) to the north of the Walvis-Rio Grande ridges (Latitude >28°; Figure 1C). The alkaline and alkaline-carbonatitic complexes in the bmt are commonly considered to be associated with this opening. They are therefore sub-coeval with the main flood tholeiites of the Paraná basin emplaced in the early stages of the rifting and before the continental separation. On the other hand, the Late Cretaceous analogues were emplaced during advanced stages of Africa-South America continental separation.

Rift propagation is not random, but tends to follow the trend of the orogenic fabric of the plates, suggesting reactivation of ancient lithospheric sutures (e.g., Tommasi and Vauchez, 2001; Cristiani et al., 2005). In southern Brazil, the alkaline and alkaline-carbonatitic magmatism is concentrated in regions showing positive gravimetric anomalies (Ernesto et al., 2002; Molina and Ussami, 1999; Ernesto, 2005), probably related to dense deep materials, as evidenced also by gravity observations (GOCE, Gravity field and steady-state Ocean Circulation Explorer of Mariani et al., 2013). Probably the different westward angular velocities of the ancient lithospheric continental blocks, as well as the different rotational trends at 19-20° latitude south, may favour the decompression and melting of metasomatized (wet spots) portions of
the lithospheric mantle at different times and thus with variable isotopic signatures (Turner et al., 1994; Comin-Chiaramonti et al., 1999). Consistent with this hypothesis, it has been proposed that the combined presence of even small amount of water and carbon dioxide in the upper mantle can lower the melting temperature of the primitive source(s) even by some hundreds of degrees (Thybo, 2006). This scenario could explain the presence of late Cretaceous to Cenozoic sodic magmatism in the bmt, even at the Eastern Paraguay longitudes, where there is evidence of active rifting (Comin-Chiaramonti et al., 1992a,b,c; 1999).

Relationships among low velocity anomalies of p-waves and the distribution of late Cretaceous alkaline provinces in SE Brazil were observed by Assumpção et al. (2010) and interpreted as related to a weak lithosphere, evidenced by high temperatures associated with the ponding of the Trindade plume head beneath the lithosphere. Van Decar et al. (1995) and Schimmel et al. (2003) identified a "cylindric" low-velocity volume in the upper mantle and mantle transition zone beneath the northeastern Paraná basin (Iporá late Cretaceous magmatic province - San Francisco craton), and this was interpreted as a thermal anomaly corresponding to the "fossil" Tristan da Cunha plume that had moved with the lithospheric plate. In contrast, Liu et al. (2003) suggested that the thermal anomaly does not extend into the mantle transition zone or, alternatively, that the observed anomaly is not primarily thermal, but dominantly compositional in origin (e.g., "veined mantle").

Fig. 2. Time-space diagram for the study area, showing the correlation of ages and magmatic events between the western and eastern sector of the Transbrazilian lineament (see Figure 1 for more details).

Considering that the lithosphere has a typical time constant of about 60 Ma for dissipating heat and consequently attenuating topography (Gallagher and Brown, 1997, 1999), it is quite unlikely that heat from a plume that reached the base of the lithosphere more than 130 Ma ago could still persist (Ernesto, 2005, p. 698). Moreover, neither a geoid anomaly nor a surface expression of the Tristan da Cunha thermal anomaly has been recognized in this region (Molina and Ussami, 1999; Ernesto et al., 2002). Schimmel et al. (2003) argued that low velocities of seismic waves at lithospheric depths in South America characterize all the areas with late Cretaceous post-rift alkaline intrusions. If this is correct, the late Cretaceous alkaline intrusions may extend to the Apoyaya complex (NW Bolivia; Schultz et al., 2004) through the regions of Goiás and Mato Grosso in Brazil (Sousa et al., 2005) and southeastern Bolivia (Comin-Chiaramonti et al., 2005b). This magmatic activity could be linked to an extensive lineament corresponding to the "125°Azimut" (Bardet, 1977; De Min et al., 2013).

3. Mantle plumes or mantle domes?

According to the plate tectonic theory, actively upwelling mantle plumes are responsible for the genesis of the oceanic islands and intra-continental magmatism (McKenzie and Bickle, 1988; Foulger et al., 2005;
The concept of mantle plumes, however, remains controversial, to the point that some researchers even deny their existence (Burov and Gerya, 2014). This concept is supported by recent advances in various disciplines (e.g., seismic tomography, convection simulations in the mantle, experimental and computational mineral physics, petrology and techniques to infer temperatures in the mantle). The new results from these methodologies, however, are in disagreement with previous concepts (Nolet et al., 2007; Anderson, 2007; Burov and Gerya, 2014). To date, the existing model of mantle plumes cannot explain the majority of continental flood basalts and the recurrent intraplate alkaline magmatism (Marzoli et al., 1999). In particular, it remains difficult to reconcile the geological data with mantle plume models for the sodic magmatism of Eastern Paraguay, Asunción (58.4 Ma) and Misiones (118.3 Ma). A strong argument against a mantle plume origin of these magmatic events is their possible connection with a SSE drift of the Paraguay block. This drift would correspond to a change in the movement of South America at about 80 Ma (Velázquez et al., 2006). According to Ernesto et al. (2000, 2002) and Ernesto (2005), the thermal source that gave rise to the Eastern Paraguay magmatism is in the upper mantle, with no evidence for material transfer from the core-mantle boundary or the lower mantle to the lithosphere. Besides the indications from the geoid anomalies (Ernesto et al., 2002), the existence of long-lived thermal anomalies or compositional differences in the mantle have already been demonstrated by velocity distribution models based on seismic tomography techniques, using both P- and S-waves (Zhang and Tanimoto, 1993; Li and Romanovicz, 1996; Van der Hilst et al., 1997; Liu et al., 2003).

Based on paleomagnetic and gravimetric studies, Ernesto et al. (2002; 2005) provide the following evidences for thermal or compositional mantle heterogeneity independent on the existence of a mantle plume:

1) Paleogeographic reconstructions of the Paraná-Tristan da Cunha (TC) system, assuming that the TC hotspot is a fixed point in the mantle, indicate that the TC plume was located ~800-1000 km south of the Paraná Magmatic Province (PMP). Therefore, plume mobility would be required in order to maintain the PMP-TC relationship.

2) Assuming that the TC hotspot was located in the northern portion of the PMP (~20° from its current position), the plume would have migrated southward from 134-130 Ma (the main magmatic phase in the area) to 80 Ma at a rate of about 40 mm/yr. From 80 Ma to the present, the plume remained virtually fixed, leaving a track compatible with the African plate movement. Notably, the southward migration of the plume is opposed to the northward migration of the main Paraná magmatic phases (Ernesto et al., 2002).

3) Regional thermal anomalies in the deep mantle, mapped by geoid and seismic tomography data, offer an alternative non-plume-related heat source for the generation of intracontinental magmatic provinces. Following the interpretation of Ernesto et al. (2002), the "hotspot tracks" of Walvis Ridge and Rio Grande Rise, as well as the Victoria-Trindade chain, may thus reflect the accommodation of stresses in the lithosphere during rifting (Ferrari and Riccomini, 1999), rather than continuous activity induced by mantle plumes beneath the moving lithospheric plates.

Fig. 3. (a) Diagram showing the depth vs. temperature for xenoliths of the Brazilian Platform and Andean Domain, modified after Comin-Chiaramonti et al. (2009). Sky blue: Asunción low potassic suite; pale brown: Asunción high potassic suite; green: carbonatized peridotites; orange: xenoliths from the Andean domain; (1) and (2): mantle-crust boundary according to Lucassen et al. (2005) and Gibson et al. (2006), respectively; dashed line (g): inferred geotherm (Petrini et al., 1994). (b) Sketch illustrating...
data, the thermal lithospheric anomaly associated with the upwelling of asthenospheric mantle (Figure 3) is generated at shallow depth above the asthenosphere - lithosphere boundary (~2.3 GPa, ~80 km depth and ~1300°C) in the spinel lherzolite field, according to the geothermal curves proposed by Pollark and Chapman (1977; see also Lucassen et al., 2005, Comin-Chiaramonti et al., 2009). In agreement with these data, the thermal lithospheric anomaly associated with the upwelling of asthenospheric mantle (Figure 3) is an efficient mechanism to produce OIB basaltic melts via partial melting of a primitive source. The fluids resulting from this process, accumulated at the base of the lower crust (source (II) in Figure 3b), were homogeneous or only slightly modified during the passage through the lithosphere. A notable characteristic of this magma, consistent with this source, is the high contents of relatively sodic plagioclase (modal and normative) and clinopyroxene associated to mantle xenolith suites (spinel facies; Comin-Chiaramonti et al., 2009).

Paleomagnetic constraints are necessary for paleogeographic reconstructions that can provide a more realistic position of the presumed Tristan da Cunha plume in relation to the Paraná flood basalts and surrounding alkaline rocks. There are sufficient good-quality paleomagnetic data (Renne et al., 1992, 1993, 1996; Ernesto, 2005; Ernesto et al., 1996, 2000, 2002) to delineate the Mesozoic apparent polar wandering in South America, and many of these data derive from igneous rocks of the Paraná Magmatic Province. All these data indicate that South America was describing a clockwise rotation, and a slight north-south movement from the Late Jurassic to the Early Cretaceous. In contrast, Gibson et al. (2006) followed the interpretation of O’Connor and Duncan (1990), which is completely based on the assumption that the hotspot formed a fixed frame, and proposed a displacement towards the northwest in the 139-133 Ma interval. Therefore there is no independent evidence for the motion of South America at this time, and plate movements have been reconstructed to match the Rio Grande Rise-Walvis Ridge hotspot tracks, the geodynamic meaning of which has been questioned by some authors (e.g., Ernesto et al., 2002 and references therein). On the other hand, the plate velocity necessary to place the Tristan da Cunha plume in the two consecutive positions (139 and 133 Ma, respectively) outlined in the model of Gibson et al. (2006) exceeds by almost three times the 3.5 cm per year velocity estimated by O’Connor and Duncan (1990).

Overall, existing research indicates that the pre-existing lithospheric structure plays a major role in local tectonics. For example, Tommasi and Vauchez (2001) suggest that preservation within the lithospheric mantle of a lattice preferred orientation of olivine crystals may induce a large-scale mechanically anisotropy of the lithospheric mantle. Consequently, the olivine crystals formed during the major tectonic episodes that shaped the plates (e.g., Transamazonic, Uruaçuño, Brasiliano cycles with the preservation of a structural memory at the lithospheric scale), leads to a directional strain softening, explaining the “perennial” nature of plate boundaries and their systematic reactivation.

Both the Late Archean-Proterozoic and Mesozoic tholeiites from the South American Platform (SAP) are characterized by high- and low-Ti (TiO₂ > 2 and < 2 wt%, respectively) and by high and low contents of incompatible elements, respectively (Piccirillo and Melfi, 1988; Iacumin et al., 2003). According to these authors, the Precambrian and Mesozoic SAP tholeiites reflect heterogeneous mantle sources, including EMI (e.g., fluids, small volumes of melts) and EMII (e.g., ancient subduction-related metasomatism) components, and the existence of heterogeneity in the mantle source of SAP since at least the Late Archean. Notably, all the tholeiites have similar compositional features irrespective of their age, and their distribution in the vicinity of craton/mobile belt boundaries suggests that the upper mantle “edge drive convection” plays an important role in their genesis.

The spinel-peridotite mantle xenoliths entrained in the Mesozoic and Tertiary melanephelinites-anakaritrites from the Brazilian Platform (e.g., Misiones and Asunción in Paraguay) and in the Central Andes, (e.g., El Sapo- Las Conchas valley) (Figure 1c) support the geophysical and geochemical results: in spite of distinct tectonic settings, generally compressive in the Central Andes (but extensional in a back-arc environment), and extensional in Eastern Paraguay (riifting environment in an intercratonic area), lavas and host xenoliths are similar in terms of geochemical and isotopic characteristics (De Marchi et al., 1988; Petrini et al., 1994; Princivalle et al., 2000; Lucassen et al., 2002; 2005; Antonini et al., 2005; Comin-
Further evidence against the classic mantle plume hypothesis is provided by the low thermal gradient beneath the Brazilian Platform and Andean Domain (Figure 3a). The bulk chemistry of the alkaline magmas in both regions indicates a temperature ranging from 980 °C to 1150 °C (for geothermometric results, see Table 3 and Figure 11 of Comin-Chiaramonti et al., 2009). These values are significantly lower than the temperature of approximately 1450 °C suggested by McKenzie and Bickle (1988) and Davies (2005) for a mantle plume. Thus, it is plausible that the thermal perturbation of the continental crust be the consequence of the upwelling of shallow asthenospheric mantle material located along the major active extensional-transtensive shear zones. In this context, the adiabatic decompressional melting of the sub-lithospheric mantle at a depth of about 60-70 km can be an efficient mechanism to produce basaltic melts and associated alkaline rocks (Aldamaz et al., 2005; Comin-Chiaramonti et al., 2009; Omarini et al., 2013). This is consistent with a “passive” model of “upper” mantle geodynamics where the unstable buoyancy of “supercontinents” (e.g., Anderson, 1994; 2007) played an essential role in approaching isostatic stabilization through the Pangea break-up.

In summary, and as an alternative to the more widely-accepted mantle plume model, the genesis and temporal evolution of the Brazilian magmatic events discussed above may be attributed to the existence of thermal anomalies resulting from mantle “incubation” under the continental domains of the lithosphere.

4. Magma source(s)

Previous studies on the geology, petrology, geochemistry, and isotope geochemistry of Mesozoic-Cenozoic magmatic rocks of the Eastern and Western Transbrazilian lineament have indicated a marked compositional diversity due to complex evolution processes and different geological settings (De Mine et al., 2003; Schultz et al., 2004; Cristiani et al., 2005; Deckart et al., 2005; Comin-Chiaramonti et al., 2007a,b; Hauser et al., 2010a,b).

![Fig. 4. 87Sr/86Sr vs. 143Nd/144Nd diagram showing the minerals and whole rock data from Paraguay and Andes relative to MORB, DMM, HIMU, and EMI. Open circles: clinopyroxenes in low potassic Asunción suite; full circles: clinopyroxenes in high potassic Asunción suite. Open and full diamonds: clinopyroxenes and orthopyroxenes, respectively, in xenoliths hosted in alkaline lavas from Central Andes. Coloured fields are the same as in Figure 3a. Data sources: Comin-Chiaramonti et al., (1991; 2005a,b); Antonini et al., (2005); Lucassen et al., (2002, 2005, 2007). MORB, DMM, HIMU, and EMI components after Hart (1988) and Zindler and Hart (1986). Filled star is the average composition of 41 basanitic lavas from Central Andes (Lucassen et al., 2002, 2007); open star is the average compositions of 67 basanitic lavas from Paraguay (Petrini et al., 1994; Marques et al., 1999a,b; Antonini et al. 2005; Comin-Chiaramonti et al., 2007a,b). Paraguay array is from Comin-Chiaramonti et al. (1997). Database available in Comin-Chiaramonti and Gomes (2005) and Comin-Chiaramonti et al. (2007b, 2009 and references therein). Inset: Calculated SCUM (sub continental upper mantle) isotopic composition at 1.8 Ga ago, projected to 130 Ma. Parental melts with various Rb/Sr and Sm/Nd ratios are assumed for K, Na (potassic and sodic rocks from Paraguay, respectively; Comin-Chiaramonti et al., 1997) and Th (PAN tholeiitic basalts; Piccirillo and Melfi, 1988). It should be noted that the compositions of metasomatized rocks formed from a single metasomatizing melt vary with the evolution of the melt. Consequently, the veins will define a trend of shallow slope, and the mixing curves between...](image-url)
the vein and the matrix will define an array towards the matrix. Model DMM: \( Rb = 0, \text{Sr} = 0.133, \text{Sm} = 0.314, \text{Nd} = 0.628 \); present day Bulk Earth: \( ^{87} \text{Sr}/^{86} \text{Sr} = 0.70475, \text{Rb}/\text{Sr} = 0.0816, ^{143} \text{Nd}/^{144} \text{Nd} = 0.512638, ^{147} \text{Sm}/^{144} \text{Nd} = 0.1967 \); (Rb/Sr)_{dipside} \approx 0.125, (Sm/Nd)_{dipside} \approx 1.5; K: Rb/Sr = 0.0957, Sm/Nd = 0.1344; Na: Rb/Sr = 0.0732, Sm/Nd = 0.2295; Th: Rb/Sr = 0.0733, Sm/Nd = 0.2082.

In particular, the studies carried out on mantle lherzolites and mantle-derived peridotites (Schultz et al., 2004; Lucassen et al., 2005, 2007; Comin-Chiaramonti et al., 1991, 1997, 2001; Antonini et al., 2005) have highlighted the heterogeneity of the lithospheric mantle in both regions. The differences among the well-known HIMU, EMI and EMII mantle end-members (Zindler and Hart, 1986; Hannan and Graham, 1996; Hofmann, 1997; Jackson and Dasgupta, 2008; Niu et al., 2012) are linked to differences in their radioactive parent/daughter ratios (Rb/Sr, Sm/Nd, Lu/Hf, U/Pb and Th/Pb) with respect to their “pristine OIB” source. According to Hofmann and Hart (1978) and Niu et al. (2012), the fractionation of parent/daughter ratios is unlikely in the deep mantle, due to extremely slow diffusion rates of the processes. In areas affected by subduction, however, mantle diffusion is more efficient due to the dehydration of the subducting slab and metasomatism of the asthenospheric wedge. In this context, many authors have emphasized that recycled subducted terrigenous sediments or ancient continental crust may be responsible for the enriched OIB signatures for the mantle-derived magmas (Kogiso et al., 1997; Hofmann, 1997; Willbold and Stracke, 2006; Jackson et al., 2007). Other authors have identified mantle metasomatism as responsible for the enriched signature of OIB in terms of their incompatible trace element and isotopes “fingerprints” (Niu and O’Hara, 2003; Donnelly et al., 2004; Niu 2009; Niu et al., 2012).

Figure 4 shows the Sr and Nd isotopic correlations for whole rocks and minerals in xenoliths from Eastern Paraguay and the central Andes magmatic rocks. \( \text{Sr}_i \) (initial isotopic ratio) ranges from 0.70418 to 0.70329 in the basanitic lavas from the central Andes, with a variation of Nd, (initial isotopic ratios) between 0.51267 and 0.51274. The average (41 samples) gives a value of 0.70339 for \( ^{87} \text{Sr}/^{86} \text{Sr} \) and 0.51274 for \( ^{143} \text{Nd}/^{144} \text{Nd} \), respectively, with the strongest HIMU signature. On the contrary, basanitic lavas from Paraguay show highly variable Sr and Nd isotopic ratios ranging from 0.70367 to 0.70711 (\( ^{87} \text{Sr}/^{86} \text{Sr} \)) and from 0.512680 to 0.511856 (\( ^{143} \text{Nd}/^{144} \text{Nd} \)). The average \( ^{87} \text{Sr}/^{86} \text{Sr} \) of these lavas are 0.70515 and 0.51227, respectively, showing a strong EMI signature (Comin-Chiaramonti et al., 2001; Antonini et al., 2005; Lucassen et al., 2005). The minerals (clino-orthopyroxenes) from xenoliths hosted in low and high potassic lavas from Paraguay (Figure 4) also show a wide range of \( ^{87} \text{Sr}/^{86} \text{Sr} \) (0.70326-070404) and \( ^{143} \text{Nd}/^{144} \text{Nd} \) (0.51248-0.51322) values. In the central Andes the range in \( ^{87} \text{Sr}/^{86} \text{Sr} \) and \( ^{143} \text{Nd}/^{144} \text{Nd} \) values (0.70264-0.70498 and 0.51258-0.51310, respectively) for clinopyroxenes from the basanite lavas was interpreted as due to heterogeneity in their mantle source linked to the presence of volatiles (Lucassen et al., 2005).

In order to test the potential mantle end member source beneath the central Andes and Eastern Paraguay, the average isotopic ratios for basanites have been plotted in the \(^{87} \text{Sr}/^{86} \text{Sr} \) initial vs \(^{206} \text{Pb}/^{204} \text{Pb} \) initial and \(^{87} \text{Sr}/^{86} \text{Sr} \) initial vs \( K_2 \)O diagrams proposed by Willbold and Stracke (2006) and Jackson and Dasgupta (2008), respectively (Figures 5a and 5b). Notably, Figure 5 shows that the average composition of basanitic rocks from Eastern Paraguay displays a strong EMI signature, while a HIMU affinity predominates in the central Andes.

**Fig. 5.** Mantle affinity of the average composition of basanitic lavas from the Central Andes (open star) and Paraguay (filled star) in the (a): \( ^{87} \text{Sr}/^{86} \text{Sr} \) vs. \(^{206} \text{Pb}/^{204} \text{Pb} \) diagram (modified after Willbold and Stracke, 2006) and (b): \( K_2 \)O (wt %) vs. \( ^{87} \text{Sr}/^{86} \text{Sr} \) diagram (modified after Jackson and Dasgupta, 2008). References as in Figure 4.
5. Concluding Remarks

OIB-type basalts are predominant in the Brazilian platform and, to a lesser extent, in the Andean domain (see Figure 2). As an alternative to the mantle plume model, we envisage that these rocks are linked to the uplift of an asthenospheric dome with consequent partial melting caused by adiabatic decompression (see Figure 3b). The OIB compositions may be locally modified during uplift through the lithosphere or the crust. These magmas can also be stored in the continental crust and become differentiated through crystal fractionation, giving rise to the intrusive stocks commonly observed in the two domains.

The geochemical and isotopic features of the magmatic products in the two domains considered in this study involve participation of two main sources: HIMU for the central Andes domain and EMI for the Paraguay domain. The two potential mantle end members share the same original OIB signature. This implies that the differences in major and trace element compositions and isotopic ratios between the partial melts of the two “pristine” fertile peridotitic sources are mainly due to different processes of mantle modification in the two different geological domains.

5.1. Central Andean Domain

A petrological problem in the western sector of TBL (Andean domain of Figure 1c) is to determine when and how the asthenosphere and/or the sub-continental lithospheric mantle acquired the \(^{208}\text{Pb}/^{204}\text{Pb}\) HIMU signature that characterizes the Mesozoic magmatic rocks. Considering the long-lived subduction process that affected the proto-western Gondwana margin during the late Precambrian-lower Paleozoic times, it is conceivable that the mantle was deeply modified by this subduction process during that period. The geodynamic evolution of the Andean domain may thus be summarized as follows:

1: 580-517 Ma. At this time, the continental margin of proto-Gondwana, composed of the Pampean-Amazonian cratons, was affected by the subduction of the paleo-Pacific plate that was responsible for the build-up of the Andean-type magmatic arc. The following collision of the Arequipa-Antofalla and the Pampean-Amazonian cratons gave rise to the Pampean orogeny (Omarini et al., 1999; Ramos, 2008; Escayola et al., 2011; Ramos et al., 2015).

2: 515-490 Ma. This period was characterized by stretching of the continental lithosphere, collapse of the Puncoviscana orogenic belt and generation of rift basins with E-MORB magma genesis. Stratiform lead-zinc deposits have been found in sedimentary formations within these basins (Sureda and Martin, 1990; Sureda and Omarini, 1999; Hauser et al., 2010b).

3: 490-440 Ma. The continental margin of Gondwana became accreted to the Antofalla-Arequipa craton, and was affected by a subduction process with the build-up of a magmatic arc, and by the subsequent collision with the Precordillera-Mejillonia craton (Famatinian orogeny; Ramos, 1988; Sureda and Omarini, 1999; Ducea et al., 2015). The docking of the Argentine Precordillera terrane (Cuyania) and its relationship to Laurentia and Gondwana in the Late Ordovician were constrained by Rapalini and Cingolani (2004) using palaeomagnetic evidence, and Ramos (2004) supported the hypothesis of its derivation from Laurentia, drift towards Gondwana as a separate microcontinent, and amalgamation to the protomargin of western Gondwana in the Middle to Late Ordovician.

4: 440-300 Ma. A new active continental margin (Figure 6; see also Figure 1), formed by the Antofalla-Arequipa and Precordillera-Mejillonia cratons, developed following the subduction of the paleo-Pacific plate and by the subsequent collision with the Chilenia craton (Achalian orogenesis according to Ramos et al., 1986; Thomas et al., 2004; Finney, 2007).

5: 300-170 Ma. Two main stages are proposed by Charrier et al. (2007). The first stage is represented by a rift phase, developed in Palaeozoic units, and resulting in a transgression-regression sedimentary cycle, initially associated with local volcanism of Permian age and followed by thermal subsidence deposits. The second stage resulted in continental and marine deposits, followed by a thermal subsidence phase lasting until the early Jurassic with a predominantly marine facies.

6: 170 Ma to present (Andean cycle). The formation of the Andean cordillera began 170 Ma ago with the successive subduction of the Nazca plates and the eastward migration of the magmatic arc (Ramos and Aleman, 2000; Kramer et al., 2005; Oliveros et al., 2006). During this period, stretching of the continental lithosphere and rifting beyond the arc promoted the emplacement of alkaline magmatism.

The long-lived subduction of oceanic plates under the Western Gondwana margin may have been responsible for the thorough modification of the upper mantle through metasomatic processes, resulting in the HIMU signature of the Mesozoic volcanic rocks in the central Andean domain. According to Niu et al.
(2012), the continuous subduction process overtime may have led to an enrichment in incompatible elements and U/Pb ratios in the asthenosphere and sub-continental lithosphere relative to the primitive mantle. Evidence of mantle metasomatism in the Andean domain are found in Mesozoic mantle xenoliths (Figure 6) hosted in basanitic lavas and in the alkaline lamprophyric dykes (Lucassen et al., 2005; Comin-Chiaramonti et al., 2001; Hauser et al., 2010a).

5.2. Eastern Paraguay Domain

In the last 580 Ma the eastern sector of TBL has been virtually stable. Only at the beginning of the opening of the Atlantic ocean at 134 Ma the important transversal lineaments of Uruguay, Piquiri, Ponta Grossa etc. (Figure 1c) were formed due to the clockwise rotation of South America with respect to the African continent. These lineaments mainly controlled the magmatic activity in this domain, which is characterized by widespread Mesozoic-Cenozoic tholeiitic to alkaline volcanism (Figure 2). Major and trace elements heterogeneity, as well as isotopic systematics, reflect the compositional diversity of the parental mantle sources. In terms of the OIB sources, the main end-members are EMI, EMII, and minor HIMU associated to various domains, modified during the Transamazonian (2.2 – 1.9 Ga) and Brazilian (0.80 – 0.48 Ga) events. Evolution of the different mantle sources led to the formation of a wide variety of silicate rocks, including melts enriched in H-C-O-F (Bell, 1998 and references therein).

The conditions for magma genesis in the Eastern Paraguay domain are summarized below:

1. Tectonic lineaments controlled the emplacement of the alkaline and alkaline-carbonatitic magmas, both in the American and the African continents (Figure 1). The carbonatites mainly occur in the inner parts of circular/oval shaped alkaline-carbonatitic complexes, usually associated with evolved silicate rocks (Comin-Chiaramonti and Gomes, 1996 and references therein; Comin-Chiaramonti et al., 2015). Notably, liquid immiscibility processes played an important role in the genesis of the Brazilian (BMT) alkaline-carbonatitic complexes (Comin-Chiaramonti and Gomes, 2005).

2. Field relationships, geochemistry and new high-quality ⁴⁰Ar/³⁹Ar ages show that several distinct
magmatic events took place in Eastern Paraguay since the Triassic in a region strongly characterized by extensional tectonics. The oldest magmatic activity, characterized by evolved rocks of sodic affinity, occurred during the Triassic along the Paraguay River, at the boundary between the Chaco-Pantanal and Paraná basins (Comin-Chiaramonti et al., 2015).

During the Early Cretaceous, potassic alkaline rock-types outcrop in the Rio Apa-Amambay region and Central Provinces, pre- and post-dating (139 and 127 Ma, respectively) the eruption of the Paraná Basin flood tholeiites (both high- and low-Ti variants with ages from 134 to 130 Ma, according to Piccirillo and Melfi, 1988). Only sodic magmatism occurred in Eastern Paraguay from the Lower Cretaceous to the Paleocene, and this was concentrated in the Asunción and Misiones Provinces, roughly along the Paraguay River.

3. The potassic rocks show a compositional continuum from moderately to strongly potassic, with two well distinct suites: alkali basalt to trachyte and basanite to phonolite. Both suites started from different parental magmas, evolving through fractional crystallization, and are associated with carbonatitic bodies or carbonate rich rock-types.

The sodic rocks from Asunción and Misiones Provinces include mainly ankararites, melanephelinites and phonolites. Notably, the ultramafic rocks contain very abundant mantle xenoliths (spinel facies), in turn represented by two suites, high and low in potassium, showing imprinting of a variably metasomatized lithospheric mantle (Demarchi et al., 1998).

4. Initial Sr-Nd isotopic ratios define an array from a depleted end-member for the sodic rocks and associated mantle xenoliths, to an enriched end-member for the potassic rocks and associated carbonatites, with the tholeiites having intermediate compositions (Figure 4). The carbonatites and primary carbonates in the host rock-types show the same isotopic ratios of the associated alkaline silicate rocks.

The large variations in incompatible elements and REE of the carbonatites appear to be in many cases mainly related to hydrothermal processes. This interpretation is also supported by the O-C isotope systematics and by the calcite-dolomite isotopic equilibrium temperatures that indicate complex trends from magmatic to hydrothermal environments at variable CO₂/H₂O ratios. On the other hand, some O-C isotopic ratios fall into the primary carbonatite field strictly linked to orthomagmatic phases, possibly representing the primary isotopic signature of the mantle (see Comin-Chiaramonti et al., 2005b,c).

Crustal contamination does not appear significant in the generation of all the investigated rock-types, especially with respect to the high contents of radiogenic U, Sr and Nd in the carbonatitic rocks.

5. The different magma types and the calculated parent liquid derived from different degrees of partial melting indicate that the Early Cretaceous alkaline magmatism in the Paraná-Angola-Etendeka area is related to heterogeneous mantle sources ranging in composition from DM-HIMU to time-integrated enriched-mantle components (Comin-Chiaramonti and Gomes, 2005).

The enriched isotopic signature of the Early Cretaceous alkaline magmatism decreases from the West (Paraguay) to the East (SE-continental margin of Brazil, Angola and Namibia). A similar decreasing isotopic shift as a function of the age of magmatism, from Early - Late Cretaceous to Paleogene, is also observed in Paraguay and Brazil. These results suggest a connection between magmatic activities in Paraná and Angola-Namibia, with large- and small-scale heterogeneities in the mantle sources (Comin-Chiaramonti et al., 2005c and references therein).

6. In the eastern sector of the TBL, the close association of potassic and sodic suites requires that their parental magmas derived from a sub-continen tal heterogeneous and enriched mantle sources, isotopically similar to a MORB source.

7. The T<sup>DM(Nd)</sup> model ages of clinopyroxenes and host rocks record earlier events of fluid-infiltrations (Comin-Chiaramonti et al., 2001). These appear defined by an average age of 0.47±0.18 Ga, with more than 60% model ages spanning the Brazilian cycle (0.80 – 0.48 Ga). The compositional variations in some xenoliths and host lavas could reflect small-scale sampling of the lithospheric mantle, and different interactions between fluids and overlying peridotites.

8. T<sup>DM(Nd)</sup> model ages show that the magmatic series follow roughly two main "enrichment" events of the sub-continental upper mantle estimated at 2.0-1.4 Ga in a cratonic block and 1.0-0.5 Ga in mobile blocks from Eastern Paraguay and Brazil (Cordani et al., 2000, 2001, 2003a,b, 2005). This would have preserved isotopic heterogeneities over a long period of time, suggesting a non-convective lithospheric mantle beneath different cratons or intercratonic regions.

9. The over-simplified model of mantle plumes is not a satisfactory explanation for the genesis of most continental flood basalts and the recurrent intraplate alkaline magmatism, especially based on fluid dynamic considerations. Therefore, following Ernesto et al. (2002), an alternative mechanism and thermal
sources may exist in the mantle, and these processes may not require direct mass transfer from the core-mantle boundary or from the lower mantle to the lithosphere. Besides the indications from geoid anomalies, as previously mentioned, the existence of long-living thermal anomalies or compositional differences in the mantle have already been demonstrated by velocity distribution models based on seismic tomography using both p- and s-waves (Zhang and Tanimoto, 1993 Li and Romanovicz, 1996; Van der Hilst et al., 1997; Liu et al., 2003).

**Data sources**

Geochronological and isotopic data for rocks and minerals from the Mesozoic-Cenozoic magmatism of Paraguay and the central Andes domains discussed in this article can be found in Piccirillo and Melfi (1988), Comin-Chiaramonti and Gomes (1996, 2005), Lucassen et al. (2002, 2005), Schultz et al. (2004), Cristiano et al. (2005), Hauser et al. (2010a) and Comin-Chiaramonti et al. (2015).

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AN OVERVIEW OF THE MESOZOIC-CENOZOIC MAGMATISM AND TECTONICS IN EASTERN PARAGUAY AND CENTRAL ANDES (WESTERN GONDWANA): IMPLICATIONS FOR THE COMPOSITION OF MANTLE SOURCES.

Highlights:

1. Distinct mantle sources in Mesozoic-Cenozoic South America
2. Different geodynamic evolution for the Andean and the Paraguay-Brazil domains
3. HIMU mantle signature in the Andean domain, EMI and EMII in Paraguay-Brazil
4. Existing mantle plume model is inconsistent with South American magmatism