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Magmatism, rifting and sedimentation related to Late Paleoproterozoic mantle plume events of Central and Southeastern Brazil

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Abstract

Domal uplift, a giant tholeiitic mafic dyke swarm, anorogenic bimodal volcanism and plutonism and extensive intracontinental rift sedimentary sequences are recorded at the Late Paleoproterozoic of the Central and Southeastern Brazil. Mantle plume events at 1.77 Ga and around 1.72 Ga are thought as an unifying concept for these geological features.

Keywords: Brazil; Mantle plumes; Late Paleoproterozoic

1. Introduction

The Brazilian Shield (Almeida and Hasui, 1984; inset map in Fig. 1) shows cratonic blocks (Amazonian, São Francisco and little ones else) surrounded by Proterozoic mobile belts. These belts belong to different structural provinces (Tocantins, Mantiqueira, Borborema), all with complex geological evolution. Large volcanic and sedimentary Phanerozoic basins are found in the Brazilian territory (Amazonas, Parnaíba and Paraná) as well.

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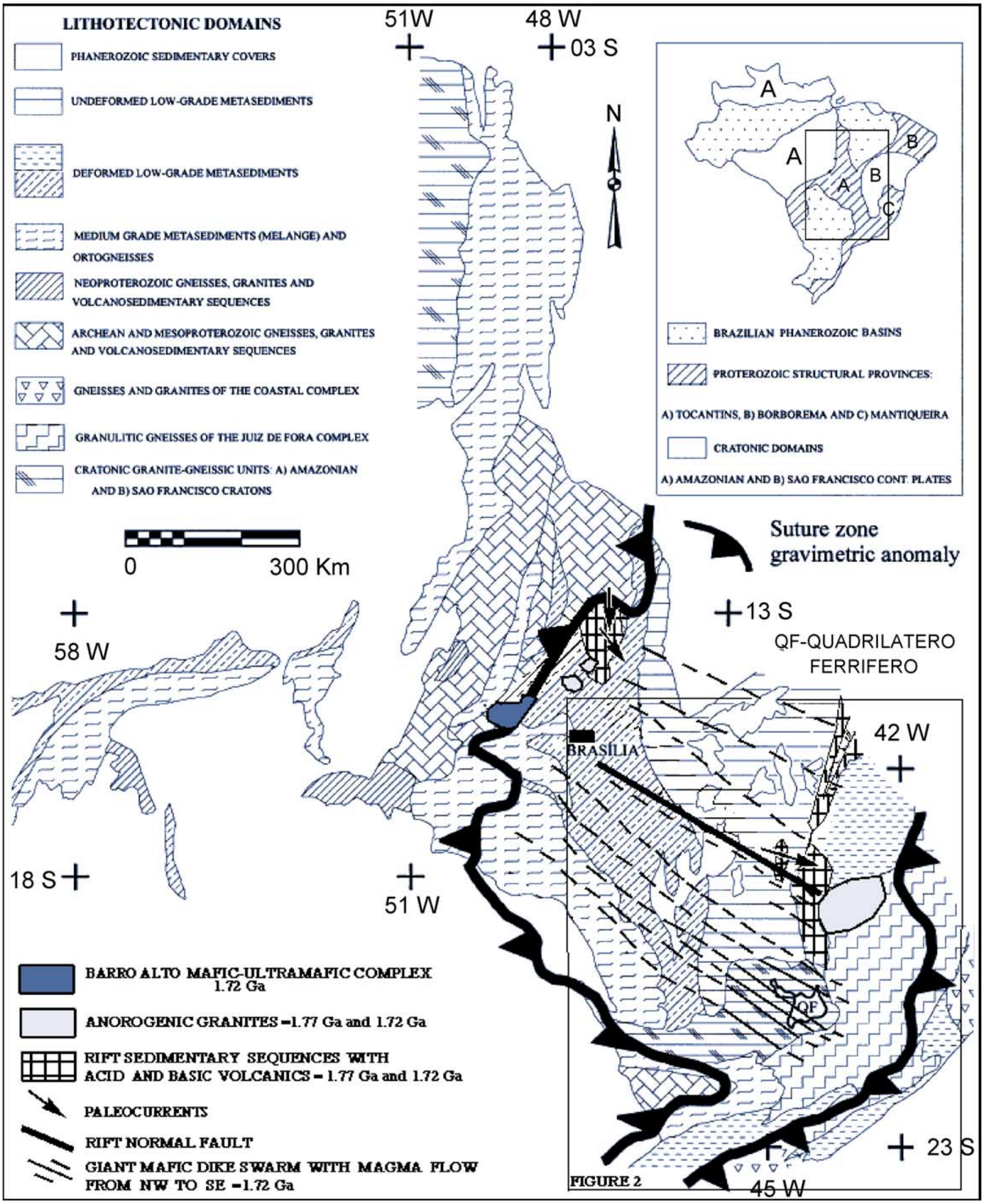

Fig. 1. Lithotectonic domains of the study area. The geological features at 1.77 and 1.72 Ga from Central and Southeastern Brazil are summarized in the lower legend (modified from Strieder and Suita, 1999). The rift-related normal fault and the majority of the mafic dykes are covered by younger metasediments. The location of Fig. 2 is inserted to help the reader.

The Tocantins Proterozoic Structural Province and the São Francisco Craton (SFC) are situated in Central and Southeastern Brazil. Their lithotectonic domains are presented in Fig. 1. Meso (Uruaçuano Orogeny) to Neoproterozoic (Brasiliano Orogeny) fold and thrust belts on the west side of the SFC show deformed low to medium grade metasediments and orthogneisses. These mobile belts were developed over the SFC with folds and faults striking NNE-SSW. The tectonic vergence is from west to east. The Neoproterozoic gravimetric anomaly of the suture zone is located farther west from these belts (Fig. 1, Strieder and Suita, 1999).

A lot of radiometric data between 1.8 and 1.7 Ga have been published for acid and basic igneous/metaigneous rocks of Central and Southeastern Brazil, which record an important bimodal anorogenic magmatism of that time (e.g. Brito Neves et al., 1979; Pimentel et al., 1991; Dussin, 1994; Silva et al., 1995). Extensive intracontinental rift sedimentary sequences belonging to the basal formations of the Araí Group and southern Espinhaço Supergroup are coeval with this magmatism. Araí and Espinhaço are located on the west and east borders of the SFC, respectively, 600 km apart from each other. These facts could indicate that intraplate rift systems affected large areas of a continental mass at the end of the Paleoproterozoic, suggesting its break-up attempt. Thus, the arising question is—what originated this extensional geodynamic setting?

The present article aims to summarize 1.8–1.7 Ga magmatic, tectonic, and sedimentological events of Central and Southeastern Brazil, to review models of the origin of this geological activity and of the global intraplate magmatism, and finally to demonstrate how (?) two mantle plumes affected the region at that time.

2. The 1.8–1.7 Ga magmatic, tectonic and sedimentological events of Central and Southeastern Brazil

A giant tholeiitic dyke swarm, designated Pará de Minas swarm (1714 ± 5 Ma, U-Pb by Silva et al., 1995), is found cutting migmatitic gneiss, granitoids and supracrustal rocks in the southernmost part of the SFC. It is also seen under the Neoproterozoic cover and Meso to Neoproterozoic thrust-belts west of this Craton in the aeromagnetic chart of Fig. 2. Even though this swarm extends along 800 km in this chart, it reaches ca. 1400 km up to its NW end in the Transbrasiliano Lineament at the Mato Grosso State (Borges and Drews, 2001).

Most of anisotropy of magnetic susceptibility (AMS) data from 1.72 Ga Pará de Minas dykes reveals subhorizontal magma flow, since ca. 70% of the K_{max} inclination values oscillate between 0 and 25° for normal and intermediate AMS fabrics (Raposo et al., 2004). Dyke/wall rock contact features presented in Fig. 3 (explanation given in the legend), match with AMS results and show magma flow from NW to SE (Chaves, 2001). These facts seem to indicate a magma source centered at the NW end of the Pará de Minas swarm. Furthermore, the central region of porphyritic dykes shows tabular plagioclase phenocrysts with its principal axes oriented with the same trend as those of dykes. This feature is in agreement with the subhorizontal magma flow.

In the neighborhood of the Brazilian's Capital, dioritic/gabbronoritic rocks of the Barro Alto mafic–ultramafic complex (Fig. 1) were dated at 1721 ± 29 Ma using the U-Pb methodology (Suita et al., 1994). Although this complex has been affected by Neoproterozoic Brasiliano Orogeny (770–795 Ma), the age based on Barro Alto zircon studies seems to be reliable (Takehara et al., 1999).

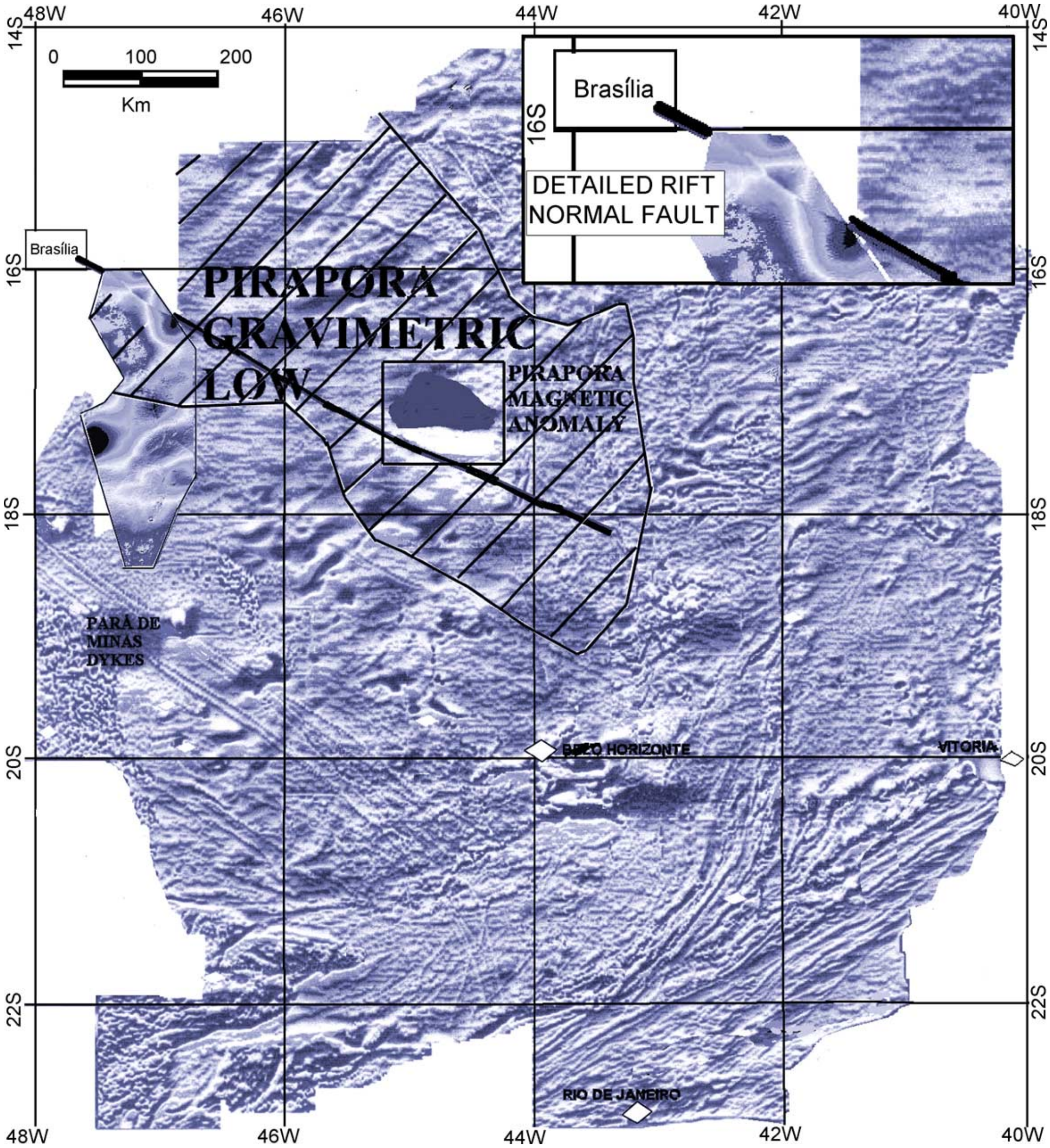

Fig. 2. Aeromagnetic chart (first vertical derivative of the total magnetic field; Prakla-Seimos GMBH, 1972) of the Southeastern Brazil. The thin linear structures trending NW-SE represent Pará de Minas dykes. The Pirapora gravimetric Low is demarcated over the magnetic chart (black hatched area). The detailed total magnetic field chart of the area below Brasília City is area 1 from Lasa S/A (2001) and was added to show isogams disrupted by the rift-related normal fault presented in Fig. 1 (best seen in zoom area).

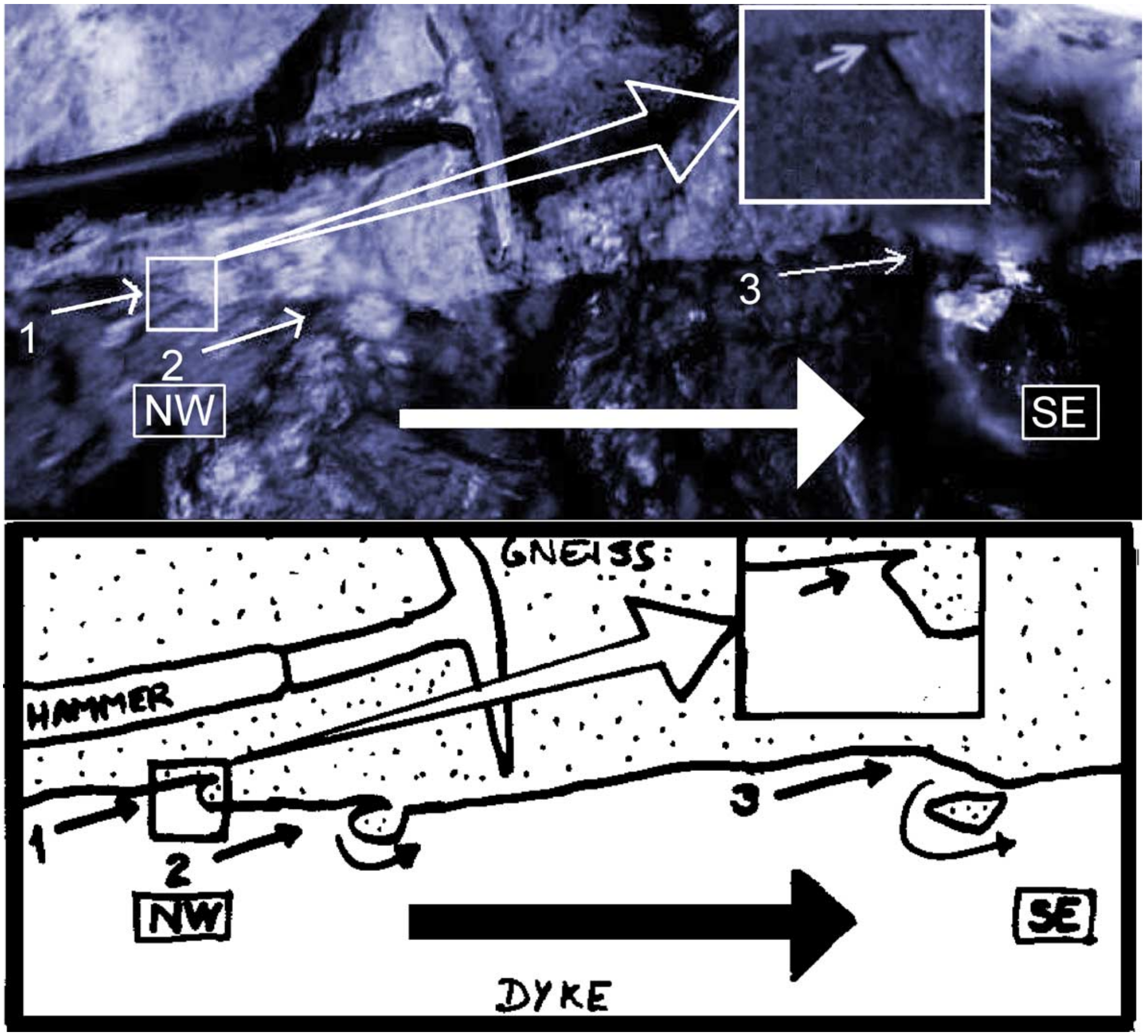

Fig. 3. Geological contact between a mafic dyke of the Pará de Minas swarm and the gneissic country-rock. The photo on the top was obtained from the ground. The bottom drawing represents our interpretation of the mafic magma flow: it originates a horn-shaped injection in the gneiss (1), best seen in the zoom detail; yields the counterclockwise rotation of a gneissic rock fragment (2) and pulls out, embraces and counterclockwise rotates another gneissic fragment (3). The bold arrow indicates the lateral magma flow from NW to SE. The hammer is the scale.

Bimodal volcanic rocks near Brasília City (Fig. 1) associated with the rift-related sedimentation of the Araí Group are also found. This group is a 1500 m thick sedimentary sequence made up of continental to shallow marine sediments (Alvarenga et al., 2000). The volcanic rocks are represented by 1771 ± 2 Ma alkali-rich basalts and rhyolites near the base of this sedimentary pile. Furthermore, 1.77 Ga Soledade and Sucuri anorogenic undeformed granites are known in the surroundings of Brasilia City as well and correspond to the plutonic equivalents of the Araí volcanics (Pimentel et al., 1991, U-Pb). Recent Nd isotopic data obtained by Pimentel and Botelho (2001) for these granites show a very large spread in $\varepsilon_{\mathrm{Nd}}(T)$ values. They interpreted this fact in two different ways: (i) the original magmas were the product of mixing between 1.8–1.7 Ga mafic magmas and felsic crust-derived melts, or (ii) the sialic source was very heterogeneous in terms of age and isotopic characteristics. They also considered a combination of these two explanations.

An expressive gravimetric low trending NW-SE in the Central-South SFC (Pirapora Low, Fig. 2), is found in the Bouguer map from Alkmim and Martins-Neto (2001). It corresponds to a surface area of ca. 120,000 km^2. Souza Filho (1995) has interpreted this feature as a giant graben that keeps at least 5000 m of sediments. The oldest sediments were generated during the southern Espinhaço Supergroup deposition, around 1.8–1.7 Ga, and they are coeval with the Araí Group sedimentation. Seismic profiles along this trough suggest the occurrence of Araí and southern Espinhaço sediments in its deep sections (Teixeira, 1993). The sedimentary pile of this NW-SE trough also includes Neoproterozoic sedimentary rocks of the São Francisco Supergroup Meso/Cenozoic sedimentary rocks (Brito Neves et al., 1995). Also with this NW-SE trend, a prominent normal fault near the axis of this graben is suggested in the aeromagnetic chart of Lasa S/A (2001, area 1). This fault is probably a rift master fault and can be recognized by disrupted isogams presented in the aeromagnetic chart in Fig. 2.

The basal sequence of the Paleo/Mesoproterozoic southern Espinhaço Supergroup situated in the east side of the SFC (Fig. 1), whose thickest sediment pile is located in Pirapora Gravimetric Low (Dupont et al., 2004), is equivalent to that of the Araí Group. The paleocurrent studies of the Araí Group show sediments coming from north and northwest to the south and southeast (Martins, 1999). The paleocurrents of the southern Espinhaço basal sequence, intruded by the Pará de Minas mafic dykes, come from WNW to ESE (Martins-Neto, 1998). Thus, Araí and Espinhaço paleocurrents come from northwest to southeast approximately (Fig. 1). This fact suggests a maximum domal uplift in the surroundings of Brasília City preceding the emplacement of the Pará de Minas dykes. The present N-S Espinhaço trend seems to result from the Neoproterozoic Brasiliano Orogeny, whose tectonic vergence against the SFC was from E to W.

Metarhyolites and Fe-rich metavolcanics dated at 1.77 by Brito Neves et al. (1979, U-Pb) and 1.71–1.72 Ga by Machado et al. (1989, U-Pb) and Dussin (1994, Pb-Pb) are found interbedded in the southern Espinhaço basal sequence. They are associated with greenschists, chemically classified as continental rift tholeiitic basalts (Chula, 1996). Furthermore, Almeida Abreu and Renger (2001) referred to maar craters containing diamond-bearing vent breccias intruding the basal sequence of the southern Espinhaço.

The 1729 ± 14 Ma (Dossin et al., 1993; Pb-Pb) and 1770 ± 30 Ma (Fernandes, 2001, U-Pb) anorogenic granites of the Borrachudos Suite are found near the southern Espinhaço rocks as well. They can be considered the plutonic equivalent of the rhyolites (Fig. 1). In the central SFC region, exactly in the Lagoa Real Uranium Province region, another anorogenic alkaline granite dated at 1725 ± 5 Ma (Turpin et al., 1988, U-Pb) was found, the São Timóteo Granite.

3. Models for the origin of the 1.8–1.7 Ga geological activity in Central and Southeastern Brazil and for the global intraplate magmatism

Several Brazilian geoscientists have suggested models to explain the origin of the 1.8–1.7 Ga tensional tectonics and the associated igneous activity in Central and Southeastern Brazilian Provinces. Dussin (1994), Pimentel and Botelho (2001) and Fernandes (2001) proposed that the 1.8–1.7 Ga anorogenic volcanism and plutonism in Central and Southeastern Brazil, coeval with the Araí and Espinhaço rifting, represent a post-orogenic event following the Paleoproterozoic orogeny. They consider a model in which, after the Transamazonian Orogeny (2.1–1.9 Ga), a considerable time interval elapsed before the continental crust (amalgamated blocks) became gravitationally unstable and the crustal extension leadind to upwelling/diapirism and decompression melting of the mantle took place. Mantle mafic magmas invaded and eventually passed over the crust. Their heat triggered the crust melting, yielding felsic magmas. This was the model used by the last authors to explain the bimodal magmatism and rifting.

Suita and Chemale Jr. (1997, 1998) believe that the bimodal magmatism observed in Tocantins and São Francisco Provinces during the Paleo/Mesoproterozoic transition could be assigned to the presence of picritic-tholeiitic magmatism affecting a hot Transamazonian lithosphere. The mafic magmatism was possibly caused by a giant plume event at that time. This plume-related event included underplating so enabling the heat conduction and the partial melting of the lower crust. According to these authors, this process originated a widespread felsic and mafic magmatism in the aforementioned provinces. During the rift phase, sites for the deposition of thick and extensive intracontinental volcano-sedimentary sequences developed.

These two models agree in that the felsic magmatism was generated from the crust melting by heat transfer from deep mafic magmas. However, they are different in terms of the geodynamic mechanism that triggered the tensional tectonics and the huge magmatic activity. The first one is probably linked to the plate tectonics and the last one to a mantle plume.

Conceived in the 1960s (Wilson, 1963), the basic idea of mantle plumes has been used by some authors to explain, among other things, the significant amount of magmatism located far from plate boundaries (e.g. Richards et al., 1989). Mantle plumes represent buoyant material that separates itself from a thermal (perhaps partly compositional) boundary layer either at the base of the mantle or at the 660 km boundary, ascending through the mantle with the typical head and tail structure. Upon reaching the base of the lithosphere, the head flattens against the last one (Davies, 1998). Deep mantle seismic tomography seems to confirm the occurrence of thermal mantle plumes (Zhao, 2001). According to Ernst and Buchan (2003), mantle plumes can be recognized by domal uplift, triple junction rifting and especially by the presence of a large igneous province (LIP), dominated in the Phanerozoic by flood basalts and, in the Proterozoic, by the exposed plumbing system of dykes, sills and layered intrusions.

However, athermal mechanisms have been alternatively proposed to explain the oceanic plateaus and the continental flood basalts. Athermal mechanisms would include edge-driven convection in a partially molten shallow mantle, which occurs where thick, cold continental lithosphere is adjacent to warmer oceanic mantle (King and Anderson, 1998).

Lithospheric delamination is believed to be another mechanism responsible for intraplate magmatism. Elkins-Tanton and Hager (2000) proposed that when the lower lithosphere delaminates, the mantle might melt adiabatically. The dome left in the lithosphere has a horizontal temperature gradient across its edges, from the hot asthenosphere now located at the center to the cool adjacent lithosphere, which did not delaminate. Horizontal temperature gradients drive convection, and the dome is soon filled with an umbrella-shaped convection cell, pulling hot material up from depth.

Furthermore, the theory of plate tectonic processes (PTP) proposes that volcanic anomalies are “by products” of the plate tectonics. In short, volcanism occurs where lithospheric extension allows melting material to rise up to the surface. The stress field in the plate governs volcanism location, and the amount of melt is controlled by the fusibility of the mantle beneath. This theory regards the magmatic activity as a result of lithospheric processes rather than of a heat influx from below, at the core-mantle boundary (Foulger and Natland, 2003).

Table 1
Summary of the 1.77 and 1.72 Ga geological events in Central and Southeastern Brazil

~1.77 Ga event	
	Domal uplift of the lithosphere in Brasília City surroundings deduced from paleocurrent data.
	Bimodal magmatism represented by basalts and anorogenic rhyolites (1771 ± 2 Ma, 1770 Ma) and granites (1769 ± 2 Ma, 1767 ± 10 Ma, 1770 ± 30 Ma) yielded by deep hot mafic magmas/crust interaction.
	Sedimentation of the southern Espinhaço Supergroup basal sequence accompanied by the formation of maar craters containing diamond-bearing vent breccias and deposition of the Araí Group.
	Kimberlite intrusions?
	Continental flood basalts? (Pirapora magnetic anomaly)
~1.72 Ga event	
	Emplacement of the Pará de Minas dyke swarm (1714 ± 5 Ma), with the magma flowing from NW to SE.
	Rift-related normal faulting with NW-SE strike.
	Main phase of the NW-SE Araí-Espinhaço Graben development and linked sedimentation.
	Crust melting yielding anorogenic rhyolites (1711 ± 8 Ma, 1715 ± 2 Ma) and granites (1729 ± 14 Ma, 1725 ± 5 Ma).
	Emplacement of a mafic–ultramafic complex (1721 ± 29 Ma).

Based on geological and geochronological data, the 1.8–1.7 Ga events of Central and Southeastern Brazil presented in the previous item can be grouped in two well-defined periods. The first one occurred at 1.77 Ga and the last one around 1.72 Ga. Both are summarized in Table 1. The explanation of these two episodes could require plume and non-plume models, but we believe that the plume model is more consistent with the data available, as we discuss below.

4. Discussions

The importance of mantle plumes in geodynamic processes has been widely recognized. Plumes are thought to play a role in uplift, triple-junction rifting, continental break-up, continental and oceanic flood basalt provinces, giant dyke swarms, magmatic underplating, lithospheric thinning, as well as in some carbonatites and kimberlites (e.g. Davies, 1998; Condie, 2001; Ernst and Buchan, 2003).

The 1.77 Ga domal uplift in Central Brazil, deduced from the paleocurrent data of the Araí and Espinhaço basal sequences, represents a typical feature of mantle plume activity. The 1.77 Ga basalts and rhyolites interbedded in these sedimentary piles as well as the 1.77 Ga anorogenic undeformed granites found in Central and Southeastern Brazil are probably related to mantle plume mafic magmas that passed over and extensively melted the crust. During the plume-related initial rift phase sites for the deposition of the Araí and Espinhaço sedimentary basal sequence were developed along the NW-SE Pirapora Graben.

Many examples worldwide show a very close relationship of carbonatitic and kimberlitic rocks to mantle plume magmatism (Bell, 2001; Heaman and Kjarsgaard, 2000; Haggerty, 1999). The diamonds found in metaconglomerates of the southern Espinhaço basal pile are probably related to kimberlitic/lamproitic volcanism affecting this basin. This basal pile also keeps maar craters containing diamond-bearing vent breccias generated generally by phreatomagmatic activity, which increased its explosive action (Nixon, 1995). Thus, although Paleoproterozoic primary diamondiferous rocks in southern Espinhaço have not been located precisely, its probable that diamonds were brought to the sedimentary basin surface by kimberlitic (or lamproitic) magmatism related to the 1.77 Ga mantle plume.

Although there is no confirmation from drill core, the enigmatic large Pirapora magnetic anomaly clearly shown inside the Pirapora Gravimetric Low (Fig. 2) can be interpreted as plume-related continental flood basalts interbedded in the basal sediments of the NW-SE Pirapora Graben.

The aforementioned features seem to point out to the 1.77 Ga mantle plume activity in Central and Southeastern Brazil. Since the mantle plume/lithosphere interaction is usually shorter than 20 Myr (Ernst and Buchan, 2002), another plume should have affected this region around 1.72 Ga. This fact would mean the difference between our two-plume model and the single-plume model proposed by Suita and Chemale Jr. (1997, 1998).

Previously we have seen that when a mantle plume reaches the base of the lithosphere with its head and conduit (tail) structure, its head flattens against the lithosphere. Far away from the plume center, the mafic magma spreads laterally in the lithosphere as dykes. The anisotropy of magnetic susceptibility data and dyke/wall rock contact features (Fig. 3) regarding the giant Pará de Minas swarm reveal the lateral spreading of the mafic magma 1400 km away from the magmatic source. This can be explained by the activity of a ∼1.72 Ga mantle plume in the Central and Southeastern Brazil rather than by plate tectonics processes, edge-driven convection and lithospheric delamination models. The slightly high initial $^{87}Sr/^{86}Sr$ (0.70562) found by Chaves and Correia Neves (2004) for Pará de Minas dykes suggests that they were contaminated during their crustal emplacement.

Ernst and Buchan (1997) proposed that mafic–ultramafic complexes can be fed from the system of a plume-related giant radiating dyke swarm and that they may be located either near or far from the plume center. Probably there is a correlation between the Pará de Minas swarm and dioritic/gabbronoritic rocks of the Barro Alto mafic–ultramafic complex, taking into account their ages and trace element chemistry (chemical data of Oliveira, 1993 and Chaves, 2001).

Rubin (1992) refers to close relationship between graben subsidence and dyke-induced faulting in Hawaiian volcanic rift zones. Mege et al. (2000) and Ernst et al. (2001) also describe graben development related to dyke emplacement on Mars and Venus. The parallelism between the plume-related Pará de Minas dykes and the NW-SE Pirapora Graben (Fig. 2) suggests that the last one resulted from normal faulting induced by Pará de Minas dykes, taking into account that the interpretations from Hawaiian and extra-terrestrial dykes can be applied to our intracontinental dyke swarm. The prominent normal fault shown in Fig. 2 near the axis of the Pirapora Graben is probably a rift master fault developed at this time. The real density of the Pará de Minas dykes is not shown in Fig. 2 due to the aeromagnetic resolution used. On average, they are 5 km apart from each other in southern SFC keeping the same pattern under the cratonic cover in the Pirapora Graben (Chaves, 2001).

The Pirapora Graben subsidence certainly was accompanied by an increasing sedimentation rate both in Araí and southern Espinhaço. In the deep crustal sections of this Graben the heat transfer from the plume-related rising mafic magmas and probably the regional decompression (deflation) under the Graben yielded extensive crustal melting and generated the acid anorogenic volcanism and plutonism around 1.72 Ga, which were sometimes accompanied by plume-related basic volcanics.

5. Conclusions

The 1.77 and 1.72 Ga plume events in Central and Southeastern Brazil are certainly responsible for extensive anorogenic bimodal magmatism, the intrusion of a large mafic dyke swarm, as well as rifting and generation of the Pirapora Graben. These events can also be related to the emplacement of dioritic/gabbronoritic rocks of the Barro Alto mafic–ultramafic complex and diamond-bearing rocks. The possibility of the occurrence of Late Paleoproterozoic continental flood basalts in the studied area can be presumed taking into account the large magnetic anomaly inside the NW-SE Pirapora Graben. The rift sedimentary sequences of the southern Espinhaço Supergroup and Araí Group accumulated in this trough during the Late Paleoproterozoic/Mesoproterozoic transition. Therefore, the widespread magmatism, rifting and sedimentation yielded by these two endogenic events insert them among the most prominent geodynamic processes of the Brazilian Precambrian Geology.

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