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# On the origin and tectonic significance of the intra-plate events of Grenvillian-type age in South America: A discussion

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ABSTRACT

The objective of this article is to examine the available evidence of intra-plate tectonic episodes of “Grenvillian-type age”, affecting the South-American continent, assessing their possible causal correlation with the tectonic processes occurring within the orogenic belts active at their margins. For the Amazonian Craton, the active margin is represented by the Rondonian-San Ignacio and Sunsas belts. However, active margins of similar age are not recognized for the São Francisco and the Rio de La Plata Cratons, and the intra-plate events over them could be reflections of the Kibaran, Irumide or Namaqua orogenic collisions in Africa. Grenvillian-type age events over the Amazonian Craton can be described in four different aspects: shearing and tectonic reactivation along zones of weakness, cratogenic granitic magmatism, alkaline ring complexes, and pervasive regional heating in some localized regions. The first of them may reflect the compressional stresses at active margins, however the others may have different origins. Within the type-region of the K’Mudku tectono thermal episode, mylonites and pseudotachylites cut across the regional granitoid and metamorphic rocks. These shear belts developed under low-to-moderate temperature conditions, that induced resetting of K–Ar and Rb–Sr mineral ages. In the São Francisco Craton, extensional and compressional events of Grenvillian-type age are well registered by the structural features exhibited by the sedimentary rocks of the Espinhaço Supergroup. For example, in Bahia state, an Appalachian-style structure is observed, with large synclines and anticlines extending along hundreds of kilometers. The major difference between the Amazonian and the Congo-São Francisco Cratons is related to heat originated from the Earth’s interior. Amazonia exhibits very large areas heated up to 350–400 °C, where the K’Mudku thermo-tectonic episodes were detected. In addition, Amazonia comprises a large amount of cratogenic granitic intrusions, and some alkalic complexes of Mesoproterozoic age, whose origin could be attributed, at least partially, to deeper sources of heat. This is not reported for the São Francisco Craton, and also for its African counterpart, the Congo Craton. Moreover, the Grenvillian-type age intra-plate features over South America demonstrate that while many cratonic fragments were colliding to build Rodinia, rifting was already occurring in parts of the Amazonian and the Congo-São Francisco Cratons.

## 1. Introduction

Rodinia, the Mesoproterozoic supercontinent, was formed by the agglutination of the existing cratonic fragments during accretionary events and continental collisions more or less contemporary worldwide. It was conceived by Hoffman (1991), and the original reconstruction is shown in Fig. 1, in which Laurentia makes up its central part, and the other cratonic units are surrounding it. Amazonia, São-Francisco-Congo, Kalahari, Rio de La Plata and other minor cratonic fragments are part of Rodinia. The suturing orogenic belts that formed Rodinia vary in space and time, as tectonic guides for the successive processes of plate convergence leading to the final agglutination of the supercontinent. They were active during most of the Mesoproterozoic, and especially within the 1200–1000 Ma time interval, typical of the “Grenvillian orogeny” of Canada. Rodinia is considered to finally agglutinate at about 1000 Ma, at the end of this continental collisional orogeny, so characterized by Gower and Krogh (2002), in the so-called Grenville Tectonic Province of Canada.

The objective of this article is to examine the available evidence of intra-plate tectonic episodes of “Grenvillian-type age”, affecting the South-American continent in areas located far from the active margins of that time. The development of important intra-plate

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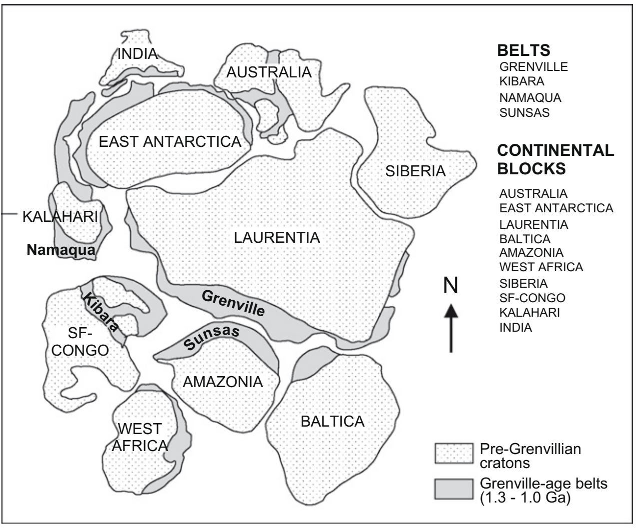


**Fig. 1.** Reconstruction of Rodinia, adapted from Hoffman (1991). The Grenville age belts dealt with in this article are indicated: **Grenville** in North America; **Kibara** in Central Africa; **Namaqua**–Natal in southern Africa; **Sunsas** in South America.

structures is frequently related to collisional tectonics at plate margins. Continental lithosphere can then undergo large-scale intra-plate failure, during reactivation of previous structures or reworking of segments of the continents, in this case involving repeated deformation, together with the associated metamorphism and magmatism. In this work we will try to assess the significance of the intra-plate type tectonic events affecting the Amazonian, the São Francisco and the Rio de La Plata Cratons of South America, and establish a possible causal correlation with the tectonic processes occurring within the orogenic belts active at their margins.

The time frame considered in this article will be the transition between the Meso and Neoproterozoic, roughly the 1400–900 Ma age-span, that was selected in order to encompass the development in time of all the orogenic belts connected with Rodinia's agglutination, as indicated by Hoffman (1991), and reported schematically in Fig. 1. In addition to the Grenville Province of Canada, considered to be the counterpart of the Rondonian and Sunsas belts of South America, we will also address in this work the other orogenic belts important for the formation of West Gondwana, which are now included in the African continent.

Li et al. (2008) presented a comprehensive synthesis of the current state of knowledge of Rodinia. If we agree with these authors, assuming that Rodinia assembled through worldwide events between 1300 and 900 Ma, we have also to take into account that plate convergence started much earlier, since at least Paleoproterozoic times, closing oceanic domains formed by the disruption of previous supercontinents, such as Atlantica or Columbia. For example, within the Grenville Province, successive accretion of magmatic arcs is reported during the entire Mesoproterozoic (Gower and Krogh, 2002), affecting the proto-Laurentian margin. These magmatic arcs are reported as related to the Labradorian (1710–1600 Ma) and Pinwarian (1520–1460 Ma) tectono-magmatic events, and form a parautochthonous belt along a few segments of the Grenville Front, the major tectonic zone of northeastern North America. A collection of many recent works related to the Grenville Orogen of North America is included in GSA Memoir 197, a comprehensive volume edited by Tollo et al. (2004).

Within the Grenville Province, several classical works on the regional tectonic evolution were produced, among which the synthesis by Rivers (1997). In that work, three orogenic pulses were proposed, the Elzevirian (starting at about 1350 Ma), Ottawan (about 1150 Ma) and Rigolet (about 1000 Ma). The last two correspond to the "Grenvillian orogeny" of Gower and Krogh (2002), and the last episode (Rigolet) seems to have been the only tectono-magmatic event effectively "pan-Grenvillian", affecting the entire tectonic province.

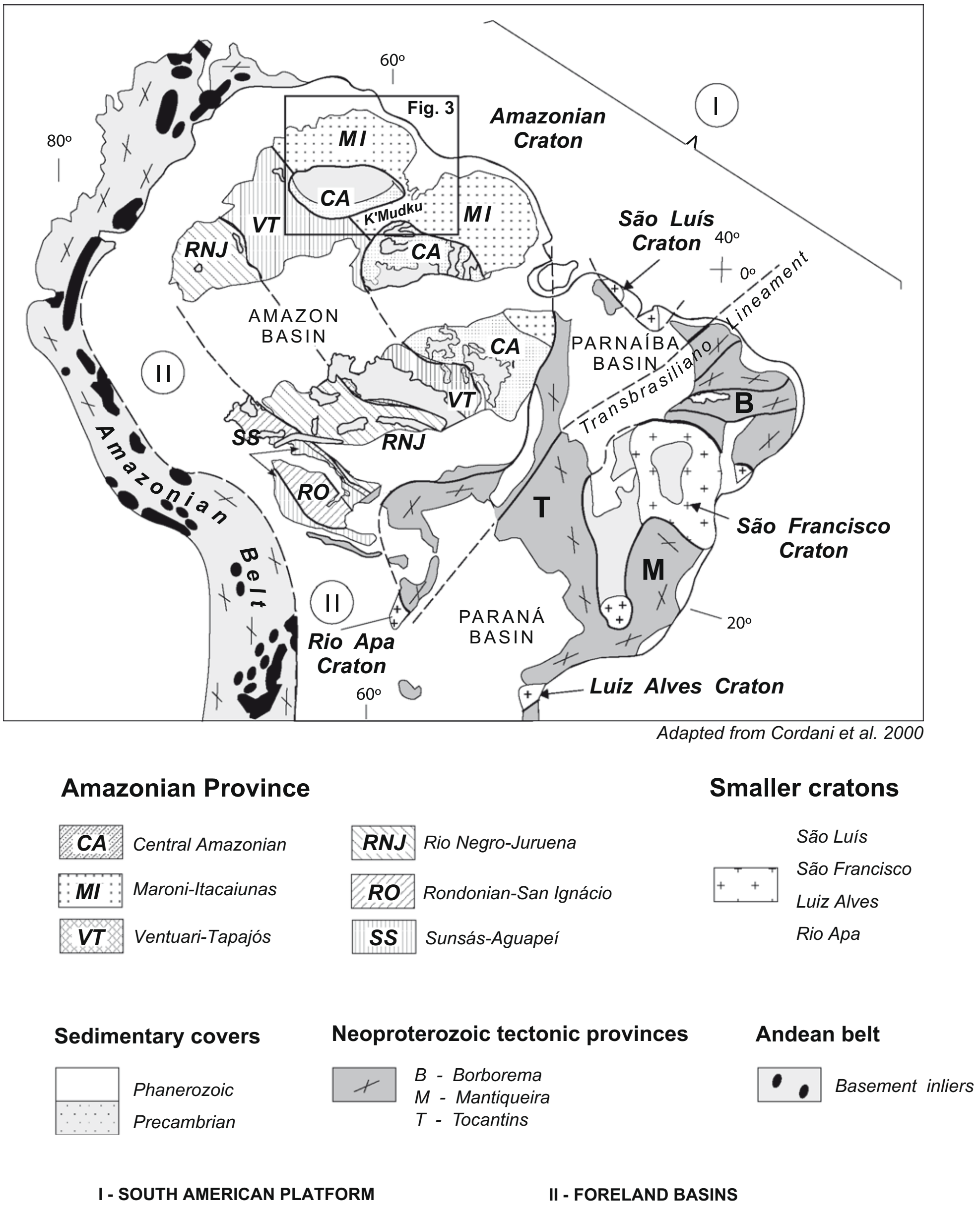
After the seminal work by Hoffman (1991), many other reconstructions for Rodinia were proposed later. In all of them it is represented as the assemblage of the cratonic masses and fragments existing at that time, connected by a strip of Grenvillian-type age orogenic belts. Since the initial works, such as the one by Powell et al. (1993), this supercontinent is considered as a long-standing feature, from about 1000 Ma until at least 750 Ma. In their comprehensive synthesis, although recognizing that many aspects still require to be discovered, Li et al. (2008) conclude suggesting that the final formation of the supercontinent mainly occurred through successive continental collisions between 1100 and 1000 Ma, and that it was complete at about 900 Ma.

As reported by Li et al. (2008), in most reconstructions Rodinia includes all continental blocks known to exist at about 1000 Ma. However, Cordani et al. (2003), Kroener and Cordani (2003), Pisarewsky et al. (2003) and Tohver et al. (2006), present some evidence for a large oceanic domain separating Laurentia (plus Amazonia and West Africa) from a series of large continental masses such as the Congo-São Francisco, Rio de La Plata, Kalahari, plus other smaller cratonic fragments. Because of this, in this work we will present our discussion into two separated parts. The first will deal with Amazonia, where the active Meso-Neoproterozoic active margin is represented by the Rondonian-San Ignacio and Sunsas belts. Cordani and Teixeira (2007) bring a summary of the interactions between Amazonia and Laurentia, a key issue for supercontinent reconstructions for the Mesoproterozoic. The second part will deal with the São Francisco-Congo, Rio de La Plata and Kalahari Cratons, whose active margins shall be examined in Africa. They are the Kibaran and Irumide belts, at the eastern margin of the Congo Craton, and the Namaqua–Natal belt of southern Africa, at the northern margin of the Kalahari Craton. A short outline for these belts is given by Kroener and Cordani (2003).

## 2. Events of Grenvillian-type age in Amazonia

The relative positions of Laurentia and Amazonia for Mesoproterozoic time are subjected to intense debate. In most reconstructions, (e.g. Sadowski and Bettencourt, 1996; Weil et al., 1998; Keppie and Ortega-Gutierrez, 1999, among others), Amazonia is placed against the eastern side of Laurentia by matching the Grenville and Sunsas belts (Fig. 1). Different reconstructions, although keeping the general correlation for the ~1000 Ma mobile belts, are designed to accommodate other smaller cratonic fragments such as Oaxaquia of southern Mexico, or the Grenvillian age basement inliers of the northern Andes in South America.

Fig. 2, adapted from Cordani and Teixeira (2007), brings the subdivision of the Amazonian Craton into two Archean nuclei and five Proterozoic tectonic provinces, which show coherent structural and geochronological patterns. According to these authors, the Amazonian Craton contains four important and well-recognizable tectonic domains of different age: (1) a relatively small Archean nucleus, the Carajás granite-greenstone terrain, with ages around 2.8 Ga; (2) the younger Maroni-Itacaiunas province, including a variety of greenstone belts and associated calc-alkaline granitoids, stretching along the northern coast of South America for over 1500 km, with ages around 2.2–2.0 Ga, typical for the Transamazonian orogeny, as defined by Hurley et al. (1967); (3) accretionary belts that formed along the southwestern margin of this nucleus (Cordani et al., 2000; Tassinari and Macambira, 1999; Santos et al., 2004, among others), beginning at ca. 2.0 Ga and giving rise to the Ventuari-Tapajós (2000–1800 Ma)



Adapted from Cordani et al. 2000

**Fig. 2.** Tectonic provinces of northern South America, adapted from Cordani and Teixeira (2007). The area covered by Fig. 3 is indicated.

and the Rio Negro-Juruena (1780–1550 Ma) tectonic provinces, made up by essentially by granitoid rocks, many of them with Nd isotopic signatures indicating accretion of juvenile continental crust; and (4) two major Mesoproterozoic tectonic provinces, the Rondonian-San Ignacio (1550–1300 Ma), and the Sunsas (1250–1000 Ma) orogenic belts, at the southwestern corner of the Amazonian Craton, whose orogenic evolution has been compared to that of the North American Grenvillian Province.

Important intra-plate shearing events of Grenvillian-type age, accompanied by thermal overprint of the basement rocks, have been recognized for a long time as a separate tectonic episode far beyond the Mesoproterozoic belts themselves (e.g. Priem et al., 1971). During the Sunsas collisional event, the Amazonian Craton behaved as a rigid block, and the resulting deformation was mostly concentrated on pre-existing major shear zones, cross-cutting the entire cratonic area. Moreover, the structural, petrographic and geochronological data collected during the first large-scale geological mapping works on the Guyana Shield has led to the recognition of a ~1.2 Ga old tectono-thermal event named K'Mudku Episode in Guyana (Barron, 1969), Nickerie Metamorphic Episode in Suriname and Colombia (Priem et al., 1971), and Orinoquean Event in Venezuela (Martin-Bellizzia, 1972). The terminology proposed first is favored in this work.

Within the Guyana Shield, the K'Mudku Episode has been recognized in many regions, and has been described as related to the reactivation of older Paleoproterozoic structures (Berrangé, 1977; Gibbs and Barron, 1993; Fraga and Reis, 1996). The main evidence of it is the production of large mylonite belts, associated to low-grade metamorphism and resetting of K–Ar and Rb–Sr mica ages (Barron, 1969; Priem et al., 1971). Teixeira (1978), taking into account observations obtained for the entire area of the Amazonian Craton, suggested that this episode would be a tectonic reflection, over the craton, of the orogenic pulses (1.30–0.90 Ga) occurring at its south-western margin. A similar idea was elaborated later by Kroonenberg (1982) that correlated, in addition, the Garzon massif and the basement inliers within the northern Colombian Andes.

### 2.1. The orogenic belts of Grenvillian-type age at the SW active margin

In a large region at the southwestern part of the Amazonian Craton, rocks belonging to the Rondonian-San Ignacio and Sunsas orogenic provinces are exposed. Their tectonic development occurred at the end of the Mesoproterozoic, roughly between 1500 and 1000 Ma.

The older one, the Rondonian-San Ignacio orogenic belt, comprises a very complex orogenic system, including supracrustal metamorphic belts, gneisses, granites and related intrusives, as well as metavolcanic rocks. Large parts of the province correspond to accretionary complexes, formed by a sequence of magmatic arcs, many of which exhibiting juvenile isotopic signature, (Cordani and Teixeira, 2007; Geraldes et al., 2001). The age of the principal metamorphism within the Rondonian-San Ignacio orogenic belt is about 1300–1350 Ma, of the same range of the arc-continent type Elzevirian orogeny of Rivers (1997) in Canada. In addition, the best approximation for the time of the tectonic stabilization of the province seems to be provided by the youngest K–Ar mica dates (ca. 1250 Ma) obtained in Bolivia (Litherland et al., 1986, 1989), and by the $^{40}$Ar/$^{39}$Ar muscovite and hornblende ages for the Colorado schists of Rondonia (Brazil), slightly older than 1300 Ma (Rizzotto et al., 2002).

The collisional type Sunsas orogen consists of supracrustal rocks, deposited, deformed and intruded by syntectonic granitoids during the Sunsas orogeny at roughly 1250–1000 Ma (Tassinari and Macambira, 1999; Cordani and Teixeira, 2007; Teixeira et al., 2010). It comprises low-to-medium grade metamorphic belts and a reactivated crystalline basement (e.g. Litherland et al., 1989; Boger et al., 2005). The limits of this belt are structurally marked by shear and mylonitic fronts (Litherland et al., 1986) and widespread post-tectonic magmatism followed the orogenic pulses.Isotopic age determinations of the granitic suites of the Sunsas belt are included in the 1150–1000 Ma time interval, matching almost precisely the time interval of the Grenville orogeny, in the sense of Gower and Krogh (2002), in Canada. Moreover, over the cratonic area, in Brazil, rift-type structures occur, affected by later transpression, variable degrees of metamorphism, and crustal shortening, dated at about 1160 Ma (Rizzotto et al., 2001; Santos, 2003). They were considered by Teixeira et al. (2010) to be a response to the Sunsas collisional dynamics.

The above description deals with continued plate convergence at the southwestern extremity of the Amazonian Craton at the end of the Mesoproterozoic, and it shall be considered within the context of the continental collision between Laurentia and Amazonia in the process of agglutination of Rodinia.

### 2.2. Tectonic framework of the central Guyana Shield as the type locality for the K'Mudku tectono-thermal episode

The main region originally connected with the K'Mudku or Nickerie tectono-thermal episode (Barron, 1969; Priem et al., 1971), is the central part of the Guyana Shield. In this region, Kroonemberg (1976) proposed the existence of a large granulite belt, including the Kanuku mountains in southern Guyana. This belt was splitted into two arms, towards the Bakhuis mountains at NE, and towards the Coeroeni high-grade rocks of Suriname, to SE. Later, Gibbs and Barron (1993) modified and simplified the high-grade unit, keeping a Central Guyana belt, a 1000 km long NE–SW belt of mainly granulitic rocks, bounded by prominent fault zones, stretching from western Suriname into northern Brazil.

Delor et al. (2003) showed aeromagnetic evidence supporting the continuation of the high-grade belt into the southeastern branch, forming an arcuate structure which is also confirmed by the work of Fraga et al. (2008) in northern Roraima State of Brazil. The result is the sinuous large-scale structure shown in Fig. 3, the Cauarane-Coeroeni belt, that marks the approximate limit between two entirely distinct domains: the Transamazonian granite-greenstone domain in the north, with rocks older than 2000 Ma, and a southern domain, where extensive volcano-plutonic magmatism younger than 1900 Ma is largely dominant.

Bosma et al. (1983) stated that in Suriname the K'Mudku Episode was responsible for low-grade metamorphism and mylonitization along E–NE-trending zones. The ancient structures of the Bakhuis Belt, characterized by NE–SW trending banding/foliation, developed under granulite facies conditions at about 2060 Ma ($^{207}$Pb/$^{206}$Pb evaporation on single zircon crystals, De Roever et al., 2003), have been partially reactivated. The Bakhuis Mountains display a horst structure reflecting the K'Mudku reactivation enhanced by Mesozoic brittle reactivation. Priem et al. (1971) emphasized the thermal effects of the K'Mudku Episode in the resetting the K–Ar and Rb–Sr mica ages at 1200 ± 100 Ma.

In the classical area where Barron (1969) recognized the K'Mudku Episode, in southern Guyana, stripes of K'Mudku mylonites and pseudotachylites cut across the regional high-grade supracrustal metamorphic rocks and also the granitoid rocks south of the belt. The mylonite–pseudotachylite stripes recognized in Guyana extend through the Roraima state in Brazil, as shown by the maps of Berrangé (1977) and CPRM (1999). The mylonite–pseudotachylite belts developed under low (to moderate) temperature conditions and conform to pre-existing E–W to NE–SW high-temperature structural patterns imprinted in the country rocks during Paleoproterozoic times (Fraga et al., 2009 and references therein).

Fraga et al. (2009) have elaborated the up-to-date geological sketch map of Fig. 3 for the central part of the Guyana Shield. The main tectonic feature of that area corresponds to the Cauarane-Coeroeni belt, the already described peculiarly sinuous NW–SE/NE–SW/NW–SE structure, formed at around 2000 Ma, connecting amphibolite to granulite facies supracrustal rocks.

A high-K, calc-alkaline, I-type, post-collisional volcano-plutonic magmatism dated at 1980–1960 Ma (U–Pb SHRIMP and conventional U–Pb zircon ages, Schobbenhaus et al., 1994; Reis et al., 2000; Santos, 2003) extends along the northern border of the Cauarane-Coeroeni belt. It corresponds to the Surumu Group in Brazil, the Cuchivero Group in Venezuela, the Iwokrama Group in Guyana, and the Dalbana Group in Suriname. The Paleoproterozoic intracratonic sedimentary sequences of the Roraima Supergroup, dated at 1798 Ma by the $^{40}$Ar/$^{39}$Ar method (Onstott et al.,1984), and at 1870 Ma by U–Pb SHRIMP on zircon (Santos et al., 2003), cover large areas of the central portion of the shield.

The basement rocks of the south-central to south-eastern part of the shield, south of the Cauarane-Coeroeni belt, have been significantly obliterated by an extensive felsic plutonism and volcanism in the 1.89–1.81 Ga interval (U–Pb SHRIMP on zircon, Santos, 2003) during the widespread Uatumã Event. Mesoproterozoic sedimentary sequences and A-type granites, including some with rapakivi texture (Surucucus-type), as well as associated mafic rocks, are also present therein.

In the western and south-western part of the shield the basement comprehends rock units younger than 1830 Ma (U–Pb SHRIMP ages by Santos et al., 2000, and conventional U–Pb zircon ages by Gaudette and Olszewski, 1985), with decreasing ages toward southwest, as suggested by the poorly dated granitoid rocks of the Imeri Domain, characterized by Almeida (2006 and references therein). The evolution of this domain, corresponding approximately to the Rio Negro-Juruena Province of Tassinari and Macambira (1999, 2004), was attributed to subduction processes with formation of a great deal of juvenile magmatic arcs.

In the central part of Roraima, south of the Cauarane-Coeroeni belt, the Mesoproterozoic Mucajaí Anorthosite-Mangerite-rapakivi Granite Complex, whose location is indicated in Fig. 3, is an excel-

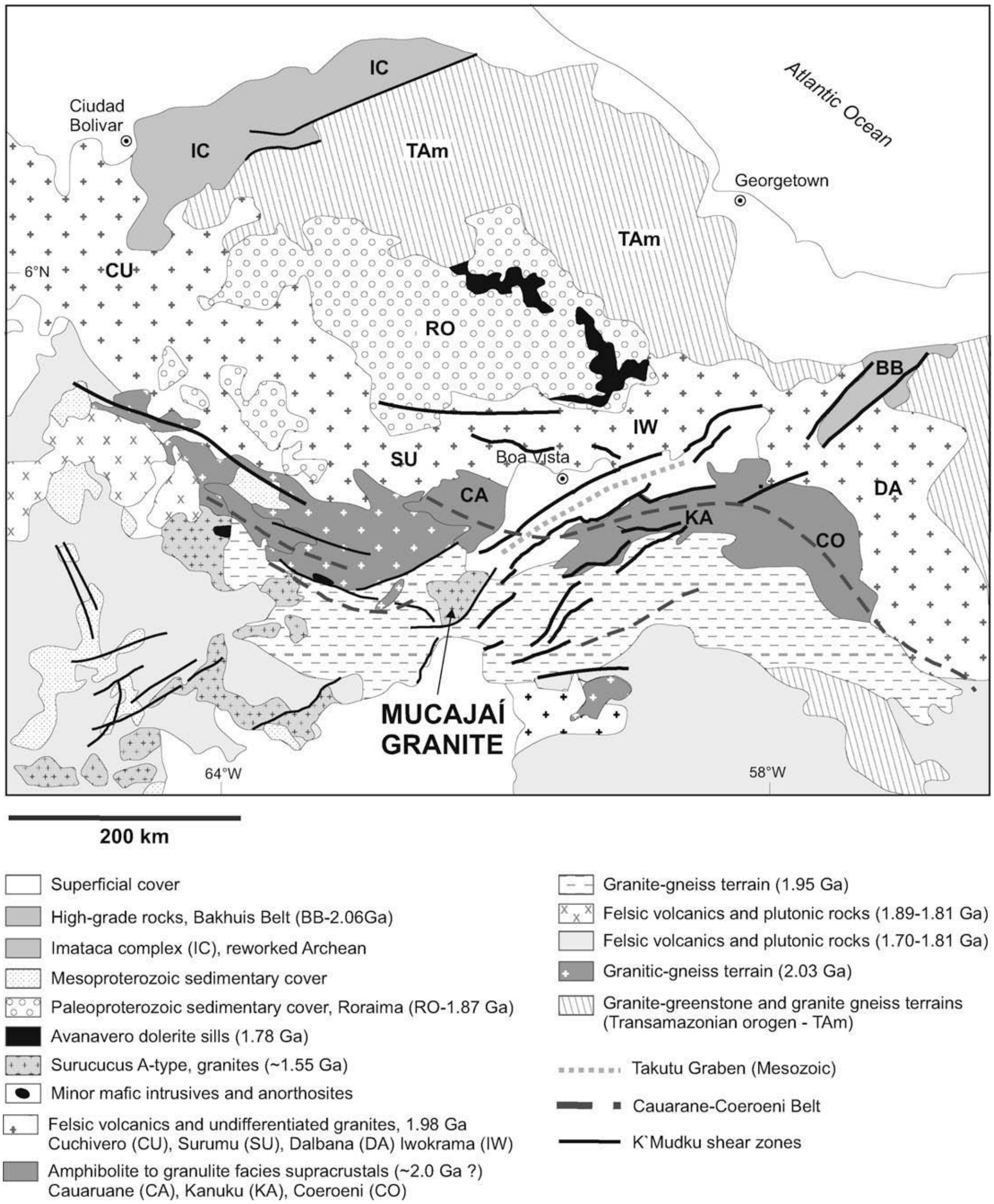


**Fig. 3.** Geological sketch map of the central part of the Guyana Shield, adapted from Fraga et al. (2009), showing the principal shear zones affected by the K'Mudku tectonic reactivation.

lent marker to characterize the K'Mudku Episode. Fraga (2002) reports the available geochronological control for the complex. The anorthosite was dated at 1527 Ma (U–Pb SHRIMP age on baddeleyite), a quartz-mangerite yielded an age of 1538 Ma ($^{207}$Pb/$^{206}$Pb evaporation on single zircon crystals), and the rapakivi granite yielded an age of 1544 Ma (U–Pb conventional method on zircon). The rapakivi granite lacks the tectonic fabrics of the Paleoproterozoic country rocks, but exhibits a strong deformation along a large shear zone that limits the body to south and southeast (Fraga, 2002). Along this shear zone, the igneous textures of the granite have been superposed by mylonitic fabrics recording low-to-moderate temperature conditions typical of brittle–ductile transition. In the mylonites, fragmented porphyroclasts of feldspar and hornblende, as well as recrystallized quartz aggregates and ribbons, are distributed in a fine-grained matrix (Fig. 4). During the K'Mudku event, while quartz undergone ductile deformation and recrystallized, feldspars behaved in a brittle–ductile manner, displaying abundant features such as internal microfractures, tapering deformation twins, undulose extinction, kink bands, flame perthites and some recrystallization by grain-boundary migration.

The foliation along the K'Mudku mylonite–pseudotachlyte belt of the central part of the shield, controlled by the original Paleoproterozoic structures of the Cauarane-Coeroeni belt, is oriented accordingly to them and exhibits steep dips (usually more than 70°), frequently associated with steep dipping lineation. The association of steep mylonitic foliation with down-dip stretching lineation is interpreted as resulting from transpression, following the main evidence given by microstructural analyses (Fraga, 2002).

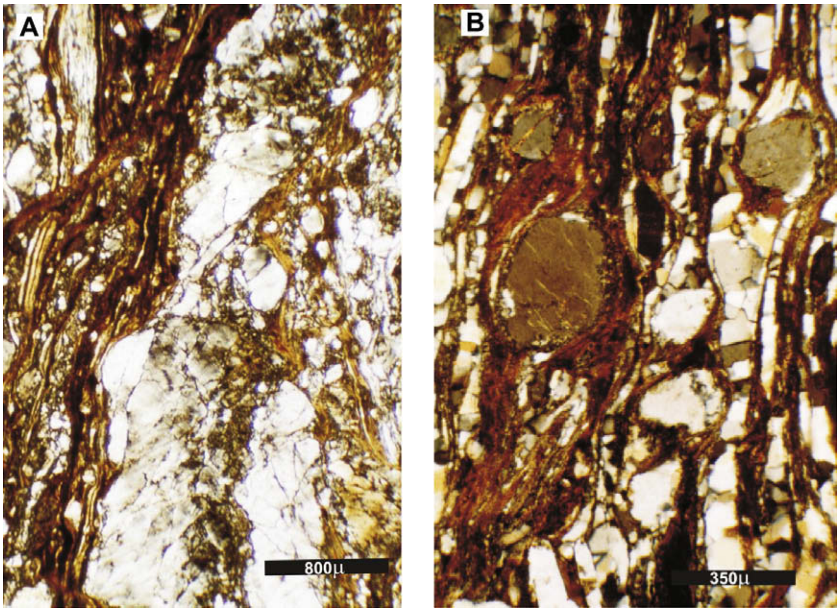


**Fig. 4.** Mylonitic textures of the Mucajai Rapakivi Granite along one of the principal K'Mudku shear zones (from Fraga et al., 2009). (A) Feldspar porphyroclasts exhibiting internal microfracturing and undulose extinction; (B) rounded feldspar porphyroclasts, some of which exhibiting tails in a $\delta$ geometry, as well as recrystallized quartz aggregates and ribbons distributed in a fine-grained matrix. See text for structural interpretation.

### *2.3. Intra-plate tectonic reactivations of Grenvillian-type age over the entire Amazonian Craton*

In the previous item, a complex tectonic evolution was demonstrated for the Central Guyana Shield, where the K'Mudku tectonothermal episode was described. In particular, the cratogenic Mucujaí rapakivi granite was clearly deformed and heated along a K'Mudku shear zone. Moreover, the entire region was obviously affected by both intense shearing and regional heating, the latter responsible for the isotopic rejuvenation of micas. Such evidence, valid for the Central Guyana Shield, is here extrapolated to other areas of the Amazonian Craton, where similar tectonic evolution could be envisaged.

In this way, intra-plate events of Grenvillian-type age in Amazonia can be described in a few different categories: (1), deformation along fracture zones; (2), occurrence of mafic dike swarms; (3), emplacement of alkaline igneous complexes; (4), cratogenic intrusions of granitic character; and (5), thermal events producing isotopic rejuvenation on micas. These events may not be necessarily related with each other. The first ones could be attributed without too much difficulty to a response of the stable and rigid continental mass to the major stresses involved in the Laurentia-Amazonia collision at the end of the Mesoproterozoic. However, at least the latter two other events would need anyway additional sources of energy, such as heat produced in the subjacent mantle.

### *2.3.1. Shear zones, tectonic reactivations with associated mafic magmatism, and alkaline ring complexes*

Intra-plate deformation and associated mafic magmatism of Grenvillian-type age was mostly concentrated along pre-existing major NE–SW or NW–SE shear zones, which cross-cut the entire cratonic area (see Fig. 5). In addition to the already described tectonic deformation in the Central Guyana Shield, large mylonitic zones are reported in many places, covering the entire cratonic unit. Differential displacements along the main shear zones are observed, allowing uplift of the intervening blocks, and in many cases generating rift basins, while conditioning the emplacement of bi-modal volcanism. Along the zones that concentrated the deformation, cleavage may have been developed in the volcanic and sedimentary rocks, like in the case of the Tepequem hill, where Luzardo and Milliotti (2007) have proposed that the sedimentary rocks were affected by folding and very low-grade metamorphism. Tectonic reactivation is observed along many of them, and extensional fractures were filled by mafic dike swarms. Although the radiometric control is still rare, the mafic dikes, as well as minor intrusions, are normally considered to be related to the K'Mudku tectono-thermal event. Table 1 reports some examples and some general areas in which radiometric dating was carried out, yielding Grenvillian-type ages, roughly between 1400 and 950 Ma. It was made taking into account the compilations of the available K–Ar and Rb–Sr dates elaborated by Teixeira (1978) and Tassinari (1996), plus some more recent and significant results (Santos et al., 2002; Tohver et al., 2002).

Fig. 5 brings the location of the main tectonic lineaments, believed to be due to shearing events, and a few of them were indicated with their local or regional name. They may have been reactivated, after their initial formation, by successive transpressional pulses, or by later extensional events, frequently associated with mafic magmatism. The principal tectonic zones, with NE–SW trends, are, among many others, the Guri, Takutu, Cachorro, Jari-Falsino, and Tapajós lineaments. The compressional episodes of the Rondonian-San Ignacio orogeny, and especially the continental collision related to the Sunsas orogen, are considered responsible for the shearing deformation spread over the Amazonian Craton. Because of their assumed age, the shear belts are interpreted as due to indentation tectonics caused by the Amazonia-Laurentia collision (Teixeira, 1978; Kroonenberg, 1982; Tohver et al., 2005). Moreover, younger tectonic reactivations of extensional character, during Neoproterozoic and Phanerozoic time, produced in some cases the onset of sedimentary basins. A good example is the large Takutu graben, about 300 km long and 30–50 km wide, where the obvious post-Grenvillian tectonic reactivation is controlled by Meso-Cenozoic radiometric dating (Vaz et al., 2007 and references therein). It is shown in Fig. 5, included between a NW and a SE Takutu lineaments, and its basin displays about 7000 m of sediments.

A few ring alkaline complexes with Grenvillian-type ages, between 1300 and 1000 Ma, sometimes associated with mafic magmatism, are known in the Amazonian Craton. They occur as

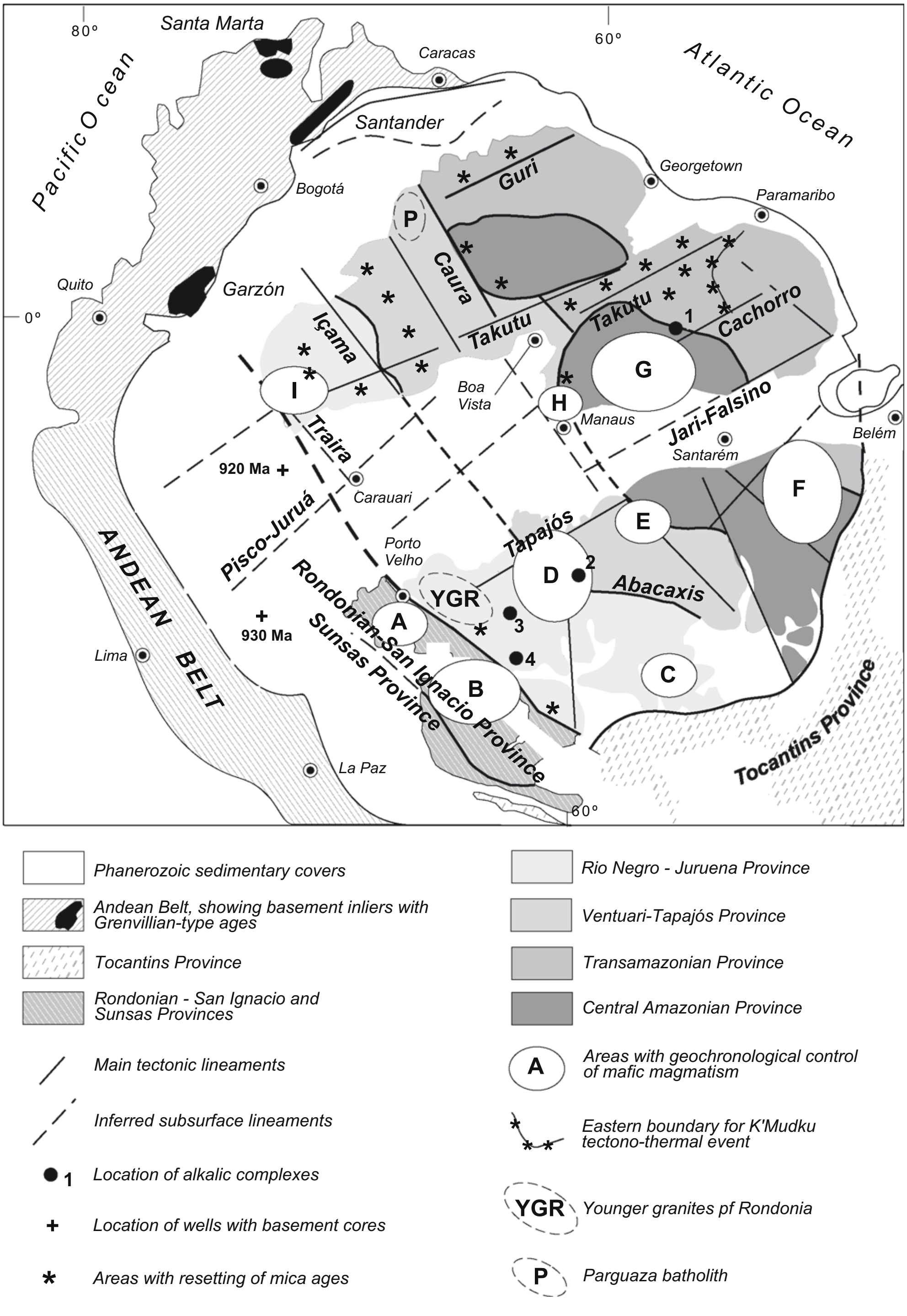


**Fig. 5.** Main tectonic lineaments over the Amazonian Craton; some lineaments from subsurface interpretation are outlined. This figure brings the location of some areas with geochronological control of the mafic magmatism, as well as some of the principal Mesoproterozoic alkaline igneous complexes (1 = Mutum 2 = Sucunduri; 3 = Guariba; 4 = Canamã). Moreover, areas (*) with resetted mica ages in Grenvillian time are indicated, as well as the location of wells with dated basement cores, after Kovach et al. (1976).

relatively small, scattered plutons that encompass a wide range of compositions including quartz syenites, syenites, monzonites, and alkaline/peralkaline granites. Four of the principal ones are listed in Table 1, and their approximate geographical site is indicated in Fig. 5. They are located usually along some of the shear zones attributed to the break up of the stable continental crust, and were considered by Tassinari et al. (2000) as a reflection of the orogenic pulses at the active margin. If a genetic link could be established, it is possible to envisage a process of lithosphere fragmentation and deformation, along the main zones of weakness, providing channels for the ascent of melts from the asthenosphere or from the lithospheric mantle.

### 2.3.2. Cratogenic granitic magmatism

Granitoid rocks generally non-deformed are described, exhibiting mineralogical and geochemical characteristics common to A-

**Table 1**
Some critical areas of the Amazonian Craton with significant geochronological control for intra-plate magmatic events of Mesoproterozoic age. 1 – Teixeira (1978); 2 – Tassinari (1996); 3 – Tohver et al. (2002); 4 – Santos et al. (2002).

| Location | Rock type and geologic setting | Age (Ma) | Method | Reference |
|---|---|---|---|---|
| A – Northern Rondonia State of Brazil | Dolerite dikes, gabbros and alkaline intrusions | 1050–1200 | K–Ar Rb–Sr | 1 and 2 |
| B – Southern Rondonia State of Brazil | Dolerite dike swarms | 1000–1100 | K–Ar | 1 and 2 |
| B – Nova Floresta | Rift related basalt | 1200 | $^{40}$Ar/$^{39}$Ar | 3 |
| C – Teles Pires river | Dolerite dikes | 1270–1330 | K–Ar. | 1 and 2 |
| D – Roosevelt river | Dolerite dikes | 1170–1370 | K–Ar | 1 and 2 |
| E – Jamanxin river | Dolerite dikes | 1050–1070 | K–Ar | 1 and 2 |
| F – Cachoeira sea, Pa | Alkaline gabbro | 1190 | U–Pb | 4 |
| F – Tocantins river area | Dolerite dikes | 950–1040 | K–Ar | 1 and 2 |
| G – Northern Amazonas State of Brazil | Dolerite dikes | 1330–1400 | K–Ar | 1 and 2 |
| H – North of Manaus, Am | Gabbro intrusion | 1100 | K–Ar | 1 and 2 |
| I – Serra Traira, NW Brazil | Dolerite dikes | 940–980 | K–Ar | 2 |
| 1 – Boundary between Brazil and Suriname | Mutum alkaline igneous complex | 1130 | K–Ar | 1 and 2 |
| 2 – Sucunduri dome area, Amazonas State of Brazil | Alkaline intrusion and dikes | 1200 | K–Ar | 1 and 2 |
| 3 – Northern Rondonia State | Guariba alkaline complex | 1250 | Rb–Sr | 1 and 2 |
| 4 – Northern Rondonia State | Canamã alkaline complex | 1170 | Rb–Sr K–Ar | 1 and 2 |

type granites, many of them with rapakivi-type textures (DalÍAgnol et al., 1999). If we exclude those which are evidently late-to-post orogenic of the Transamazonian orogeny, within the Guyana Shield, with ages around 2000 Ma, the older ones (1550–1580 Ma) are widespread over Amazonia, and the younger ones (1000–970 Ma) are located near the Brazilian–Bolivian border. They intrude the basement rocks in various pulses, at shallow crustal levels, and show often well-defined discordant contacts (Dall'Agnol et al., 1994, 1999; Bettencourt et al., 1999 and references therein). These A-type, anorogenic or cratogenic granites are widespread, from the very large batholith of the Parguaza rapakivi granite found at the Venezuelan–Colombian border (Mendoza, 1977), to the so-called Younger Granites of Rondonia (Priem et al., 1989). Their approximate location is indicated in Fig. 5. In many cases, during field regional mapping, it is very difficult to distinguish among the regional basement granitoids, especially when they are little or not deformed, and the younger cratogenic granitic intrusive bodies.

A good description of these cratogenic granites is given by Kroonenberg and De Roever (in press). They indicate the Parguaza granite, dated at about 1540 Ma (Gaudette et al., 1978) as a typical one, a huge batholith which extends for about 300 km, and consists of wyborgite and pyterlite, characterized by ovoid alkali feldspar crystals surrounded by plagioclase rims. Granites with similar textures are included in the general designation rapakivi granite, and show specific geochemical features such as metaluminous to peraluminous character and an A-type granite signature. Several other cratogenic granites yielded similar ages, such as the biotite granites from the Vaupés river in the Colombian Amazonas (Priem et al., 1982), and the Surucucus and Mucajaí granites in the Roraima state of northern Brazil (DalÍAgnol et al., 1999). Moreover, for the southern part of the Amazonian Craton, within the so-called Rondonian Tin Province, Kroonenberg and De Roever (in press) ratified the work of Bettencourt et al. (1999) that recognized seven age groups for the cratonic granites of that region, cutting through basement belonging to the Rio Negro-Juruena and the Rondonian-San Ignacio tectonic provinces. The related radiometric determinations are robust U–Pb zircon ages. The oldest group yielded ages between 1610 and 1530 Ma, four groupings yielded ages between 1410 and 1310 Ma, and the two younger between 1080 and 970 Ma. Only the last ones, the Younger Granites of Rondonia, are tin-mineralized. Bettencourt et al. (1999) indicated that, for the first five age groups, their relation with orogenic events is difficult to establish because of the absence of associated meta-sedimentary or supracrustal belts. Moreover, the close spacing of the magmatic pulses suggests that they form rather a magmatic continuum than a series of discrete events.

### *2.3.3. Pervasive regional heating in some localized regions, accompanied by isotopic rejuvenation of micas*

K–Ar and $^{40}$Ar/$^{39}$Ar radiometric ages between 1300 and 1000 Ma on separated minerals, especially micas, from "basement" metamorphic rocks, are evidence of isotopic resetting caused by intra-plate geological activities, over the Amazonian Craton. The original work on this subject was carried out by Priem et al. (1971), dealing with rocks from Suriname, where regional heating is observed affecting the Kanuku Complex and the Bakhuis Mountains. In these regions, K–Ar, Rb–Sr and more recently $^{40}$Ar/$^{39}$Ar dates on micas from older rocks were obviously isotopically rejuvenated (Priem et al., 1971; Teixeira, 1978, and several other papers). Priem et al. (1971) indicated an eastern limit for what they called "Nickerie tectono-thermal event", shown in Fig. 5, and this limit was later confirmed by successive works, and especially those of Delor et al. (2003) in French Guiana, and of Rosa-Costa et al. (in press) in Amapá, where several $^{40}$Ar/$^{39}$Ar determinations made in micas and amphiboles showed that these areas were not thermally affected after the termination of the Transamazonian orogeny.

K–Ar or Rb–Sr ages in micas, whose physical significance is the time of cooling below a critical temperature (about 300–350 °C), may be interpreted in two ways. They could be related to some thermal event during their lifetime, or to the normal regional uplift after the cratonization of a certain area. Isotopic rejuvenation of micas is obvious when the host rock can be dated by other methods, like in the example described in this work, the Mucajai Granite (item 2.2), and also in the case of many dated rocks in the Guyana Shield. However, regional cooling age, after cratonization, is not easy to characterize in our case, because the coverage of radiometric ages over the Amazonian Craton is still quite scanty, very far from complete, and very irregular in areal distribution. Moreover, magmatic events of all types, such as the described mafic and alkaline intrusions, as well as the cratogenic granites, may be the sources of local heating and rejuvenation due to contact metamorphism.

Looking at the southern part of the Amazonian Craton, it is possible to attribute (1), a general 1500–1600 Ma age for the regional cooling of the Rio Negro-Juruena tectonic province (Cordani et al., 1979; Tassinari et al., 1996); (2), an age of about 1300 Ma for the cooling of the Rondonian-San-Ignacio province (Cordani et al., 1979; Teixeira and Tassinari, 1984), and (3), an age of 1000–1100 Ma for the cooling if the Sunsas belt (Litherland et al., 1986). Given that the regional cooling of the Rio Negro-Juruena province can be attributed to 1500–1600 Ma, younger apparent ages, such as the K–Ar and $^{40}$Ar/$^{39}$Ar plateau ages between 1.3 and 1.0 Ga recorded on it, shall be considered as produced by younger tectono-thermal events. Because of the proximity, they may be interpreted as responding to the active tectonics within the neighboring Rondonian-San Ignacio and Sunsas orogenic belts. Such apparent ages were obtained on mica and hornblende from several kinds of rocks of the regional basement and of some intrusive granitic bodies (Bettencourt et al., 1996; Tassinari 1996; Tohver et al., 2002). A good example of this seems to be the polycyclic basement rocks of the south-western Amazonian Craton, where Tohver et al. (2005) obtained $^{40}Ar/^{39}Ar$ mineral ages between 1120 and 1200 Ma. Moreover, Santos et al. (2005) dated by the U–Pb SHRIMP method detrital zircons and xenotime of the Aguapei intra-continental rift, located over the Rondonian-San Ignacio Province, and constrained its age close to 1160 Ma, right within the time-interval of the Sunsas orogen.

The work by Teixeira et al. (2006) is a good example of the of successive heating events in a region close to the Rio Negro-Juruena and Rondonian-San Ignacio tectonic boundary. To the north, minerals from the basement rocks of an area close to the Serra da Providencia intrusive Suite, dated by the $^{40}Ar/^{39}Ar$ method, yielded ages of about 1550 Ma, coherent with the regional exhumation and cooling of the Rio Negro-Juruena Province. In contrast, to the south of the tectonic boundary, metamorphic rocks yielded by the same method mineral ages close to 1320 Ma, considered related to the regional cooling of the Rondonian-San Ignacio Province.

Looking at the western limit of the Guyana Shield, the widespread occurrence of Grenville-type K–Ar and Rb–Sr ages on micas, from the works by Barrios (1983) in Venezuela and Priem et al. (1982) in Colombia, has to be taken into account. The first age dating in this area was produced by Pinson et al. (1962), a 1200 Ma biotite age of a granitic rock at San José del Guaviare, Colombia. Later, Priem et al. (1982), also in eastern Colombia, dated by the same methods more than 30 biotites, most of them yielding ages near 1200–1300 Ma, more or less synchronous with the regional cooling of the Rondonian-San Ignacio Province. A few U–Pb zircon ages of 1780–1560 Ma on the same rocks allows to correlate them to the Rio Negro-Juruena Province. Priem et al. (1982) suggested two main possibilities for the interpretation of these Grenvillian-type ages: (1), a prolonged regional cooling after a widespread regional heating, perhaps related to the emplacement of the very large Parguaza batholith, and of other anorogenic granites of similar age, and (2), the preferred alternative of those authors, the effect of the Nickerie (K'Mudku) tectono-thermal episode in a very regional scale.

In the Amazonas territory of Venezuela, Barrios (1983), and later Barrios et al. (1985), reported a great deal of K–Ar ages in micas in the 1200–1300 Ma range, in a similar way to the situation found by Priem et al. (1982) in eastern Colombia. Moreover, in the same general area, Urbani et al. (1977) studied a few samples from metasedimentary rocks attributed to the Roraima Supergroup. They found textural and mineralogical evidence of a low to medium grade either thermal or burial metamorphism, with strong recrystallization and neoformation of pyrophyllite, muscovite and in some cases andaluzite. These rocks, in many places, like the Cerro Druida, exhibit conspicuous folding and late deformation. In this area, the low-grade formations unconformably overlie Mesoproterozoic rocks, like the Parguaza granite, and must be much younger than the Roraima Supergroup of the Roraima plateau, where rocks of this lithostratigraphic unit yielded a fairly robust Paleoproterozoic age.

### *2.4. Discussion on the interpretation of the intra-plate Grenvillian-age events in the Amazonian Craton*

In the previous items, several intra-plate events found affecting the Amazonian craton were described. Several authors, such as Tassinari and Macambira (1999), Tassinari et al. (2000), Cordani and Teixeira (2007), among others, related them to a still poorly defined K'Mudku Episode, and considered them to be formed as reflections of the development of the Rondonian-San Ignacio and Sunsás orogenies at the south-western active margin of the craton. This may be the case of the major lineaments, easily visible in the satellite images which were indicated in Fig. 5. They may be important sites of intra-plate failure, most probably controlled by spatial and temporal strength variations of the lithosphere Mobility along such mega-fault systems may have produced a great diversity of features, allowing uplift of the intervening blocks, formation of rift-type sedimentary basins and association with bi-modal volcanism and mafic dike swarms.

However, since his first characterization by Barron (1969) the K'Mudku is characterized as a tectono-thermal episode, which may bear a quite different origin. The P–T conditions of this very important event in the tectonic evolution of the central Guyana Shield, as well as the time interval that brackets its tectonic development, remain a case of debate, and the geodynamic significance of it is still obscure. Moreover, the complete distribution of the main structural features, and the relation of these features to the tectonic framework of the shield, has not yet been achieved. Based on K–Ar and Rb–Sr ages on muscovite and biotite, Barron (1969) attributed to the K'Mudku episode an age around 1240 ± 100 Ma. Fraga (2002) obtained a Rb–Sr mineral isochron age of 1264 ± 155 Ma using biotite, alkali feldspar and whole-rock from the mylonitized Mucajaí Rapakivi Granite. In the same work, an $^{40}Ar/^{39}Ar$ age of 1080 ± 90 Ma was obtained on a biotite from a gneissic country rock, lacking structural evidence of shearing deformation, located 12 km far from the contact with the Mucajaí Granite, therefore showing that the K'Mudku thermal event also affected rocks far apart from the known mylonite belts.

In the case of the A-type cratogenic granites, although the works by Dall'Agnol et al. (1994, 1999) and by Bettencourt et al. (1999) are quite comprehensive, the intra-plate tectonic processes involved in such major episode, very large in space and very long in time, are not completely understood. The granites seem to have been produced mainly by melting of the lower crust, although their isotopic signature indicates protoliths formed not much before (Cordani and Teixeira, 2007). Moreover, heating of the lower crust could be related to the location of Amazonia, during the Proterozoic, in the interior of a large and thick supra-continental-size mass.

Intra-plate tectonic processes, such as release of stress and extensional thinning of the lithosphere along mega-fractures, with the consequent rising of the boundary between lithosphere and asthenosphere, may cause pressure release at depth and influx of volatiles into the crust from the asthenosphere. With the rise of the isotherms, and the consequent warming of the lower crust, these processes will facilitate partial melting, leading to the production of A-type magmas of granitic composition. In this case, if the tectonic processes along mega-fractures are essential for the genesis of the granitoid magmas of Grenvillian-type age, the intrusion of the correspondent intra-plate cratogenic granites could still be considered as far off reflections of the Rondonian-San Ignacio and Sunsas orogenies over the stable foreland.

When dealing with the formation of alkaline magmas, however, deep mantle contribution must be considered more relevant. These magmas originate in deeper regions of the mantle, and to be formed they need additional heat sources, such as those linked to hot spots and plumes, or to poorly characterized thermal anomalies. In this case, the association of the magmas with the fracture zones in the upper crust is only indirect, meaning that, in their ascent, these magmas make profit of the existent zones of weakness of the lithosphere.

Based essentially on a few U–Pb zircon data, Santos (2003) and Santos et al. (2008), interpreted the very large area of heating and intra-plate Grenvillian reactivation, corresponding roughly to the

Central Guyana belt of Gibbs and Barron (1993), as a distinct tectonic domain of the Sunsas orogenic belt, named "K'Mudku Province", active within the 1.250–1.480 Ma time interval, and comprehending a high-grade metamorphic belt. To us this is a serious conceptual mistake, because the available geotectonic evidence bears no relationship with the possible existence, in the Guyana Shield, of an orogenic system of that age. In that region, microstructural analyses are needed to properly interpret the structural evolution. For instance, among other examples, the geological scenario of the Mucajaí region, considered earlier (Fraga, 2002), indicates that the Mucajai granite is a cratogenic intrusion dated at 1.530 Ma, emplaced in upper crustal level. It is not affected by high-grade metamorphism, and its country rocks are Paleoproterozoic. Fraga (2002) and Fraga et al. (2009) have shown that the Central Guyana belt is not a coherent tectonic feature and joins NE–SW segments with tectonic structures generated during different periods of the evolution of the Guyana Shield. The K'Mudku Episode highlighted the NE–SW lineaments across the shield, but is certainly not responsible for the evolution of previous high-temperature features recorded in the Paleoproterozoic rocks.

In Fig. 5, the envisaged boundaries of the Rondonian-San Ignacio and Sunsas belts are shown, as well as their supposed continuation under the Solimões and Acre basins. The position of a few critical wells and the K–Ar biotite ages from their basement cores (Kovach et al., 1976) are indicated in that figure. In addition, asterisks mark the area where the K'Mudku event was observed, and also the areas in eastern Colombia (Priem et al., 1982) and western Venezuela (Barrios, 1983; Tassinari et al., 2004), where widespread rejuvenation of micas was observed.

If we consider the distribution of the available K–Ar and Rb–Sr mineral ages, those between 1200 and 1400 Ma are much more abundant than those of 1000–1200 Ma. Therefore, although the Sunsas collision is the one considered to be the critical for the final agglutination of Rodinia, it seems that intra-plate heating over the Amazonian Craton could be more related to the events of the Rondonian-San Ignacio orogeny. Intra-plate heating with Grenvillian-type age is especially conspicuous at the southern part of the craton, along the boundary of the Rio Negro-Juruena and Rondonian-San Ignacio Provinces. In addition, it is also important along the westernmost areas of the shield, adjacent to the Andean foreland basins. Such location obviously stimulate speculations in the way of envisaging the Rondonian-San Ignacio and Sunsas belts bending to the north along the western limit of the craton, therefore making up most of the basement to the mentioned foreland basins. This line of thinking brings back the idea of Kroonenberg (1982), about a possible existence of a long and continuous Grenvillian-age belt below the central and eastern Andes, and enhance the correlation of the rejuvenated areas over the Amazonian Craton with the Garzon massif and other inliers of the northern Andes (Cordani et al., 2005). A mountain belt in the region where now there are the Llanos foreland basins may well explain the very large amount of detrital zircon of Grenvillian-type age encountered in the Paleozoic meta-sedimentary rocks of the Marañon Complex, in the Eastern Cordillera of Peru (Cardona et al., 2009). K–Ar and Ar–Ar dating of the basement cores in the Venezuelan and Colombian Llanos may help in testing the idea here presented.

## 3. Grenvillian-type age events in the São Francisco-Congo, Rio de La Plata and Kalahari Cratons

Cordani et al. (2003) presented an unusual reconstruction of the position of continents and oceans for the time slice 1000 Ma, in which a few cratonic fragments now included in South America or Africa didn't take part in the formation of Rodinia. Tohver et al. (2006) reached a similar conclusion on the basis of their review of the available paleomagnetic data from Africa and South America. Such reconstruction places the large cratonic masses of São Francisco-Congo, Kalahari and Rio de La Plata more or less united, and close to many other smaller cratonic fragments and microcontinents. These tectonic units seem to have been part of the same continental mass, that was agglutinated during orogenic episodes more or less at the same time as the formation of Rodinia.

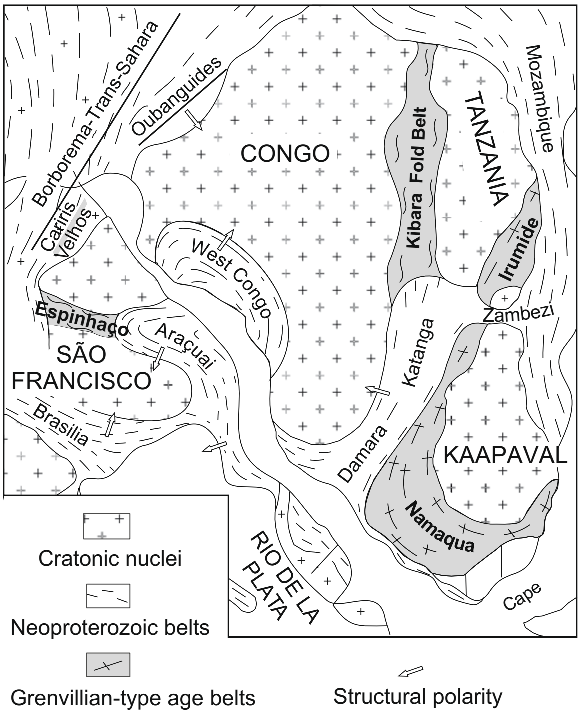


**Fig. 6.** Schematic geotectonic map of part of Western Gondwana, adapted from Trompette (1994), showing the location of the African orogenic belts discussed in this article.

Fig. 6, adapted from Trompette (1994) shows a sketch map indicating the large-scale Brazil–Africa links before the formation of the South Atlantic Ocean, in Mesozoic times. The Neoproterozoic belts that took part in the agglutination of Gondwana are indicated, as well as the Mesoproterozoic Kibara and Namaqua belts. The Kibaran belt is shown in its position between the Congo and Tanzanian Cratons. The Namaqua belt occupies a southern position in relation to the Kaapvaal Craton, and is considered to extend to Natal, along the Indian Ocean, below the sedimentary cover of the Karoo basin. The position of the Cariris Velhos tectonic domain within northeast Brazil, is also indicated.

### 3.1. Grenvillian-type age belts in Africa

The various mobile belts of central and southern Africa, namely the Kibaran, Irumide, Namaqua, Natal, Lurio, and others, are collectively known as Kibaran (Tack et al., 1994), and were formed roughly within the 1400–1000 Ma time interval. They were largely ignored in the Mesoproterozoic reconstruction models of Rodinia, and their age and evolution is quite varied. For instance, the first accretionary events in the type Kibaran belt (Kokonyangi et al., 2006) in eastern Africa took place at about 1380 Ma, pre-Grenvillian times, whilst juvenile crust formed between 1300 and 1200 Ma within the Namaqua belt (Eglington, 2006) and deformation and metamorphism within the Irumide belt in Zambia is dated at about 1000 Ma (De Waele et al., 2006).

The Kibaran mobile belt, at the eastern edge of the Congo Craton, extends for more than 1500 km from Katanga to Uganda and consists of multiply deformed suprscrustals and large volume of syn-kinematic granitoids with isotopic ages close to 1380 Ma (Kokonyangi et al., 2006). These authors concluded that the orogen developed as an accretionary belt starting at about 1400 Ma on the eastern margin of the Congo Craton, and plate convergence continued until the end of the Mesoproterozoic. The unit was intensely deformed between 1200 and 1100 Ma, and a large fold and trust belt was formed as a result of the collision between the SF-Congo and the Tanzanian Craton. Moreover, Kokonyangi et al. (2006), indicated that the final suture, accompanied by the intrusion of tin granites, occurred at about 1000 Ma.

The northeast trending Irumide belt of Zambia, located at the northern and northeastern edge of the Zimbabwe Craton, includes syn to post-kinematic intrusions of granitoid rocks with ages between 1050 and 950 Ma (De Waele et al., 2006). These authors conclude that the arc related magmatic rocks (Katongo et al., 2004) have developed inboard an active plate margin located to the southeast.

The Namaqua–Natal orogenic belt of southern Africa, at the southern margin of the Kalahari Craton, is interrupted by the sedimentary basins of the Cape-Karoo Supergroups. McCourt et al. (2006) interpreted the evolution of the Natal region at the eastern corner as an oceanic arc setting, followed by accretion of arc terranes to the continental margin of the Kaapvaal Craton at about 1150 Ma. Eglington (2006) presented an interpretation of the crustal evolution of the entire Namaqua–Natal belt that includes major periods of granitoid formation between 1150 and 1030 Ma, when terrane accretion was completed. The collisional tectonics is indicated by UHT and granulite facies metamorphism (Jacobs et al., 1997; Robb et al., 1999). The Sinclair Group of high-K calc-alkaline rocks of about 1200 Ma age (Becker et al., 2006), located in Namibia at the western edge of the Kalahari Craton, is normally correlated with the Namaqua belt, however it is weakly deformed and metamorphosed, and seems not to have been related to collisional events.

Over both cratonic areas, Congo and Kalahari, intra-plate magmatic rocks of Mesoproterozoic age are found in many places. For example, the huge Kunene anorthosite complex in Angola, over the Congo Craton, was found to be about 1380 Ma (Mayer et al., 2004), and the Umkondo igneous province, over the Kalahari Craton, was dated at about 1100 Ma (Hanson, 2003).

### 3.2. Intra-plate events of Grenvillian-type age in north-eastern and eastern South America

The São Francisco Craton, in South America, is an extension of the much larger Congo Craton of central Africa, to which it was attached prior to the South Atlantic opening. Both cratonic units are composed essentially by Archean nuclei, amalgamated by Paleoproterozoic orogenic belts (Cordani et al., 2000). Cratonization occurred at about 2000 Ma, time of consolidation of the last conventional orogen, that in the case of the São Francisco Craton is the Jacobina-Contendas belt in Bahia State. Fig. 7, adapted from Trompette (1994) brings the main tectonic features of the São Francisco Craton discussed in this work. Grenvillian-type orogenic belts do not occur over or adjacent to this cratonic unit. However, extensional features such as mafic dike swarms of this age in several sites, and compressional features, visible in the Mesoproterozoic cratonic sequences that overlie the craton, were found and are shortly described below.

Mafic dikes related to fissural processes are widespread. In contrast to the apparently synchronous 800–750 Ma break-up recorded in many Rodinian continental fragments, South America and Africa continental masses have experienced almost simultaneous rifting in the 1000–750 Ma interval. An early attempt to break up the Congo-São Francisco junction is recorded by a voluminous set of 1.1–0.9 Ga old mafic dykes, which crop out along the border of these blocks (Renne et al., 1990; D'Agrella-Filho et al., 1990; Tupinambá et al., 2007). The oldest ones belong to the dike swarm of the Olivença-Ilhéus region in Bahia (Corrêa-Gomes and Oliveira, 2000), very significant for the correlation Brazil–Africa and for the related paleomagnetic reconstructions. These extensional features, with Grenvillian-type ages, are constituents of the important Tonian taphrogenesis that affected large parts of eastern Brazil and western and southern Africa. They are associated with continental rifting, and this process has led further to the development of the Neoproterozoic Adamastor Ocean, from which ophiolitic remnants are described (Pedrosa-Soares et al., 2001; Tack et al., 2001), and that later was closed in the agglutination of Gondwana. In the case that the São Francisco-Congo Craton was indeed part of Rodinia, as in the more conventional reconstructions, these extensional events can be attributed to the initial splitting of that supercontinent.

Two layered mafic intrusive complexes with similar ages, around 1000 Ma, were also described in Minas Gerais State, at the localities of Ipanema (Angeli et al., 2004) and Alvarenga (Paes, 1999). Isolated mafic dikes, with apparent K–Ar ages around 900–930 Ma were detected in a few other places in Bahia and Minas Gerais. Looking at Africa, extensional events of similar ages can be easily correlated, such as the intrusive mafic magmatism affecting the basement of the West Congo belt (Tack et al., 2001).

An important additional tectonic-magmatic event that affected South America is the Cariris Velhos belt, located within the Borborema Province in northeastern Brazil, a domain in which Neoproterozoic orogenic elements of the Brasiliano Cycle are blended with large areas of basement with Archean and Paleoproterozoic ages. The Cariris Velhos tectonic unit is dealt with in another article of this volume (Santos et al., 2010 and references therein) and will not be discussed here in detail. The belt includes felsic magmatism with ages in the 980–930 Ma interval, related to an initial extension, and also mafic rocks interpreted as parts of ophiolites. It could be a result from the operation of a short-lived Wilson Cycle, with a closure of a restricted oceanic domain. In addition, it was affected by a strong deformational episode that occurred much later, as a response of the lithospheric shortening associated to the Brasiliano orogeny, in the process of agglutination of Gondwana.

### 3.3. Compressional tectonic events over the São Francisco Craton

Compressional events of Grenvillian-type age are well registered by structural features exhibited by the meta-sedimentary rocks of the Espinhaço Supergroup. This major tectono-stratigraphic unit covers extensive areas of the Bahia and Minas Gerais states of Brazil, and its sedimentation is attributed to the formation of large continental rifts, or aulacogenic type basins (Da Costa and Inda, 1982; Brito-Neves et al., 1979). It includes several cratonic-type sedimentary sequences that cover the São Francisco Craton, showing variable thickness that could reach a few kilometers. The first stage of the units includes essentially siliciclastic rocks, with some felsic volcanics (Rio dos Remedios Group) interbedded within its basal sequence, yielding radiometric ages between 1700 and 1760 Ma (Turpin et al., 1988; Cordani et al., 1992; Danderfer et al., 2009). The successive stages encompass a large time interval, lasting through the entire Mesoproterozoic. The Espinhaço Supergroup is covered by the Neoproterozoic São Francisco Supergroup, composed basically by two main stratigraphic units: the Macaubas and Bambuí Groups, whose deposition is entirely Neoproterozoic (Thomaz-Filho et al., 1998).

In the Northern Espinhaço range, in Bahia state, an Appalachian-style structure is observed, with large synclines and anticlines extending along hundreds of kilometers, with N–S to

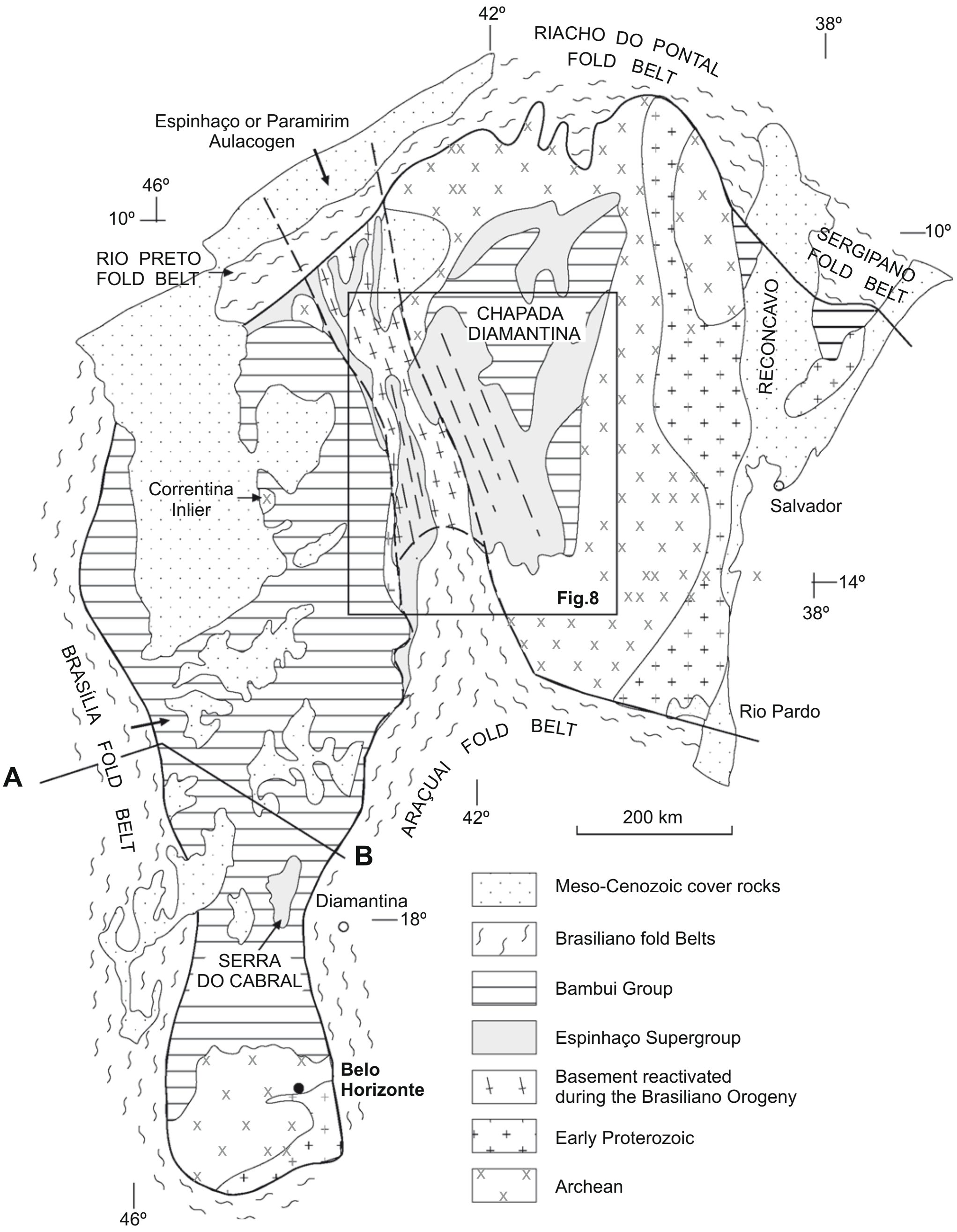


**Fig. 7.** Main tectonic features of the São Francisco Craton, adapted from Trompette (1994). The area covered by Fig. 8 is indicated, as well as the location of the geophysical profile of Fig. 9.

NNW–SSE trends, as shown in Fig. 8. In this region, Pedreira and De Waele (2008) indicated a succession in which the Rio dos Remedios Group, including a great deal of felsic volcanics, is overlain by the Paraguaçu Group, essentially siliciclastic. The Chapada Diamantina Group, basically formed by pelitic and carbonatic rocks, covers the lower sequences by means of an important angular unconformity, whose age is not completely determined, but shall be close to 1000–1100 Ma according to some imprecise age determinations (Brito-Neves et al., 1979; Cordani et al., 1992). Moreover, in the western part of that region, Danderfer et al. (2009) have described a series of depositional discontinuities along the entire sedimentary column, including some angular unconformities. Three important and robust U–Pb zircon ages were obtained in felsic volcanic intercalations. The older (1730 Ma) confirms previous results obtained in the correlative units of the Rio dos Remedios Formation. The two younger yielded ages near 1580 Ma, and are intercalated with sedimentary rocks correlative of the Paraguaçu Group, demonstrating the large time interval involved in the deposition of the Espinhaço Supergroup.

A younger major regional angular discordance, located in time close to the Precambrian–Cambrian boundary, is also evident when the São Francisco Group is taken into attention. Fig. 8 shows clearly that the N–S to NNW–SSE trends of the Espinhaço Supergroup sharply contrasts with the nearly E–W trends of the younger São Francisco tectono-stratigraphic unit. The structural polarity of the latter is due to the active margin of the São Francisco Craton, and the age of this structural feature is related to the agglutination of Gondwana at about 550–600 Ma.

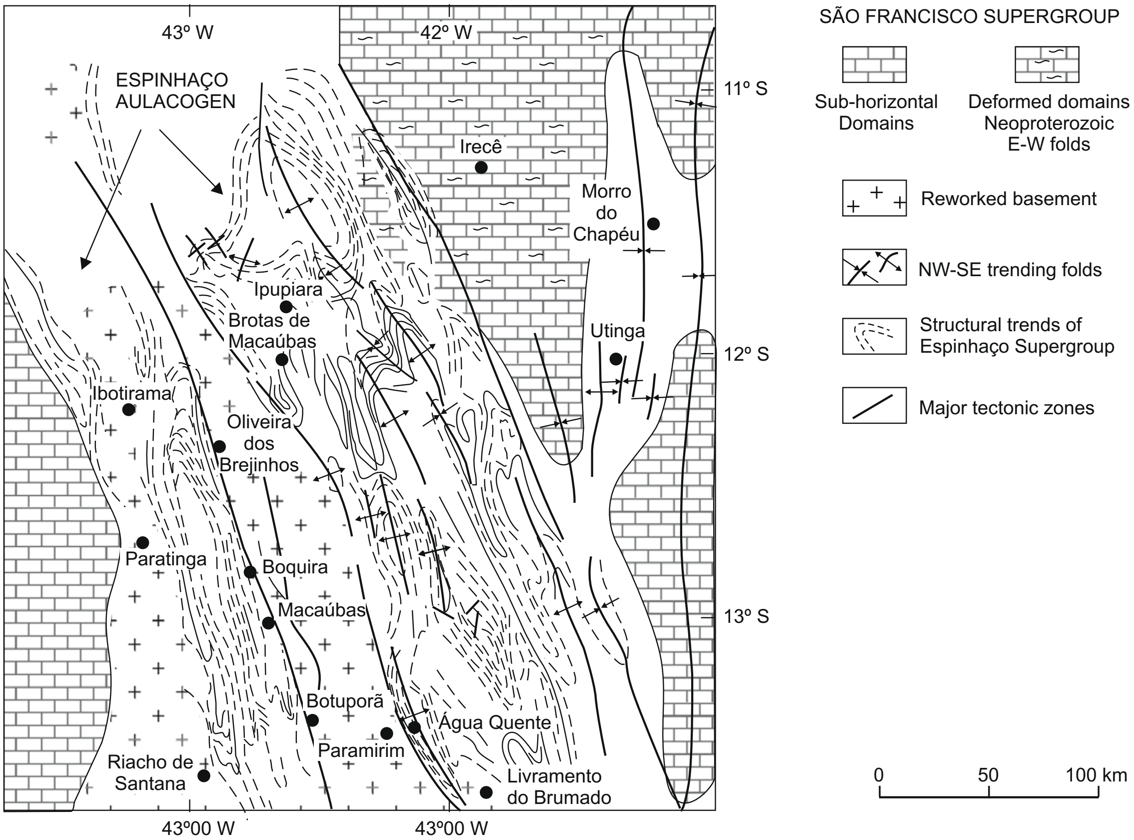


**Fig. 8.** Principal tectonic features of central Bahia State of Brazil.

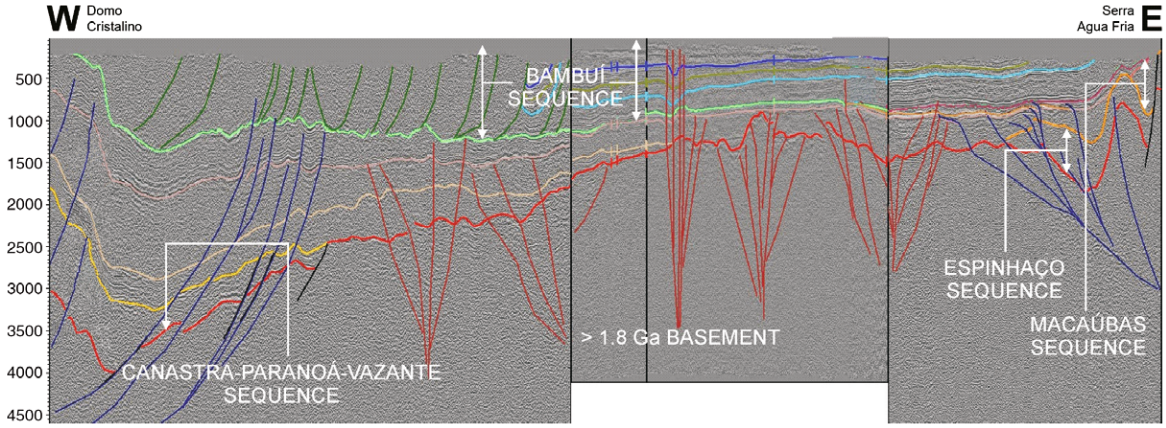


**Fig. 9.** Sismotectonic profile at the southern part of the São Francisco Craton, in Minas Gerais State of Brazil, adapted from Zalán and Silva (2007).

In the southern part of the region, in Minas Gerais, the Neoproterozoic deformation was imposed at significantly deeper crustal levels, attaining up to amphibolite facies metamorphic grade, making very difficult the observation of previous metamorphic structures. Alkmin et al. (2006 and references therein), considered as entirely Neoproterozoic the deformation of the Espinhaço Supergroup. However, the geophysical profile obtained by the Petrobrás Brazilian oil company (Zalán and Silva, 2007) right across the São Francisco Craton in Minas Gerais (Fig. 9, location of the profile in Fig. 7) shows clearly that there are compressional structures in the sediments of the Espinhaço Supergroup preceding both deposition and later deformation of the Neoproterozoic units of the São Francisco Supergroup.

The tectonic significance of the Espinhaço deformation and folding is not completely clear. It is certainly not an orogenic event, connected with a nearby active margin, because there is no evidence whatsoever in the regional context. Several attempts were made to date the Espinhaço deformation, with disappointing results. It is possible that the U–Pb dates obtained in zircon by Turpin et al. (1988), and the Rb–Sr results obtained by Cordani et al. (1992), on basement gneisses from central Bahia, in both cases close to 1500–1550 Ma, could be significant and linked to a still not clearly understood medium grade metamorphic episode. Other Rb–Sr and K–Ar ages in the 1300–1000 Ma range were obtained in the low-grade meta-sedimentary rocks of the Chapada Diamantina Group, or on cross-cutting basic dikes (Mascarenhas and Garcia, 1989).

### 3.4. Comments on the origin of the intra-plate events in eastern South America

As it was already mentioned, Grenvillian age active margins are not recognized in the area of the São Francisco and Rio de La Plata Cratons. Consequently, the intra-plate deformational events of that age affecting them are considered to be reflections of the Mesoproterozoic Kibaran, Irumide or Namaqua orogenic collisions occurring in Africa. The tectonic features with about 1000–1100 Ma age observed over the São Francisco Craton, such as the mafic dikes, or the compressional features of the Espinhaço Supergroup, can be attributed to the collisional episodes related to the amalgamation of the Tanzanian cratonic fragment against the eastern size of the Congo Craton, then attached to the São Francisco Craton. Tectonic features older than 1100 Ma could still be linked to the first orogenic episodes of the Kibaran belt, dated at about 1300–1400 Ma.

Up to the present, no counterpart was found in South America of the Namaqua–Natal orogenic belt of southern Africa, and the only feature that is worth while to be mentioned seem to be the occurrence of a high-grade basement inlier of Grenvillian-type age within the Don Feliciano belt (Basei et al., 2005). Moreover, Mesoproterozoic intra-plate events, like the ones described for the Kalahari Craton, suck as the Umkondo igneous complex (Hanson, 2003) are rare over the Rio de La Plata Craton. However, a thermal event is registered by Teixeira et al. (1999) on the Paleoproterozoic mafic dikes of southern Uruguay, whose age was established by $^{40}$Ar/$^{39}$Ar dating at about 1200 Ma. These event affecting the Rio de La Plata Craton, in a similar way to those of the São Francisco Craton, may be considered as a tectonic reflection of some orogenic episode within the Namaqua–Natal belt.

## 4. Final remarks – similarities and differences between the Amazonian and São Francisco Cratons regarding intra-plate phenomena, and their separation in Grenville time

The intra-plate tectonic events dealt with in this work are covering the interval 1400–1000 Ma. Within this time frame, important similarities and differences are observed between the Amazonian and the São Francisco Cratons. Among clear similarities, we may indicate the compressional features shown in some of the practically non-metamorphic sedimentary covers of both Amazonian and São Francisco Cratons, and also the widespread extensional fracturing, reactivating older zones of weakness, often associated with mafic dike swarms. As reported in the previous chapters, many structural features are interpreted as tectonic reflections of the collisional pulses occurring within the active orogenic belts at the margins of each of the cratonic areas.

Regarding differences, the major one between Amazonia and the Congo-São Francisco Craton, in our view, is related to heat originated from the Earth's interior. Amazonia exhibits very large areas heated up to at least 350–400 °C, such as the many already described sites where the K'Mudku tectono-thermal episodes were detected. In addition, Amazonia comprises a large amount of cratogenic granitic intrusions, witnesses of a great deal of heat production within the lower crust, since the beginning of the Mesoproterozoic, and continuing during Grenvillian times. The presence of similar areas of persistent heat production is found in other continental masses included in Rodinia, located near Amazonia in the reconstructions, such as Laurentia and Baltica (Hoffman, 1991; Li et al., 2008; Cordani et al., 2009, among other works). The source of such relevant amount of heat at the core of Rodinia may be connected with the low thermal conductivity of material making up the continental lithosphere. The consequent low heat dissipation would lead to temperature increase at the base of the crust, beyond the limits for crustal anatexis. This is not reported for the São Francisco Craton, and also for its African counterpart, the Congo Craton, making up a fundamental difference between these cratonic fragments and the other constituents of Rodinia. Another difference between the two cratonic areas is the fact that, within the Amazonian Craton the influence of the Neoproterozoic orogenic events that produced Gondwana were minor and apparently affected only its eastern border. In contrast, the Brasiliano–Pan African orogeny making up West Gondwana was very important for the São Francisco and the Rio de La Plata Cratons.

Spontaneous mantle dynamics, related to thermal anomalies located at depth, is a possible good alternative for intra-plate tectonic events associated with heat. For example, the formation of alkaline complexes of Grenvillian-type age, and perhaps also some features of the K'Mudku tectono-thermal episode, could be attributed, at least partially, to deeper sources of heat, such as hot spots and plumes, and shall not be considered as a response to the active margins of the lithospheric plates. This applies to all alkalic intrusions that affect Amazonia, as well as the SF-Congo and Kalahari Cratons, where they exhibit Grenvillian-type ages. Nevertheless, the tectonic processes occurring at the active margins may well have contributed to the formation and widening of weakness zones, facilitating the emplacement of the magmas.

The younger events, especially those aged at about 900–1000 Ma, although may be produced as a tectonic response to the active orogenic belts, may also be originated by extensional tectonism. In this way, they could be witnesses of the contrasting diachronic character shown in different parts of the same continental unit. In other words, while many cratonic fragments were colliding along the sites of the Grenvillian belts to build Rodinia, rifting was already occurring in some parts of it, such as the Amazonian and Congo-São Francisco Cratons.

Rodinia is considered to have been tectonically stable for more than 200 Ma, and its major phase of break up is taken as the formation of the large rift-related basins followed by passive margins on both sides of Laurentia, at about 750 Ma (Li et al., 2008, and references therein). However, by that time, the convergent process that would lead to the agglutination of Gondwana was already occurring since at least 300 Ma earlier. Rodinia's break up must be understood as a long duration process, starting, in our view, not longer after the final formation of the supercontinent. The younger of the Grenvillian-type age intraplate events discussed in this work, aged close to 950–1000 Ma, seem to be the initial manifestations of such large-scale continental fracturing. During the entire Neoproterozoic, the dispersion of many fragments of different size was enhanced, many of them downsized to microcontinents, which were later reassembled during successive collisions, in the processes of agglutination of Gondwana. Even later, already within the early Paleozoic, the convergent process went on, to produce Pangea. Fig. 10 shows a paleogeographic reconstruction for the time of the final agglutination of Gondwana, with the concomitant formation of the Iapetus Ocean. Amazonia and Congo-São Francisco, which were always somewhat separated, and were finally brought together through the closing of the Pharusian–Goias Ocean.

The Goiás Magmatic Arc (Pimentel et al., 2000) includes large areas with intra-oceanic magmatic arcs, formed by subduction of oceanic lithosphere, whose isotopic signatures indicate juvenile mantle-related derivation. It is the main evidence for the existence of a huge portion of an oceanic domain, dated at about 900–1000 Ma, that occupied what is now central Brazil, and extended into the Pharusian Ocean to the northeast (Trompette, 1994; Fetter et al., 2003, among others). This implies that, when the main nucleus of Rodinia formed around Laurentia, including Amazonia and West Africa, a large ocean was separating from this nucleus

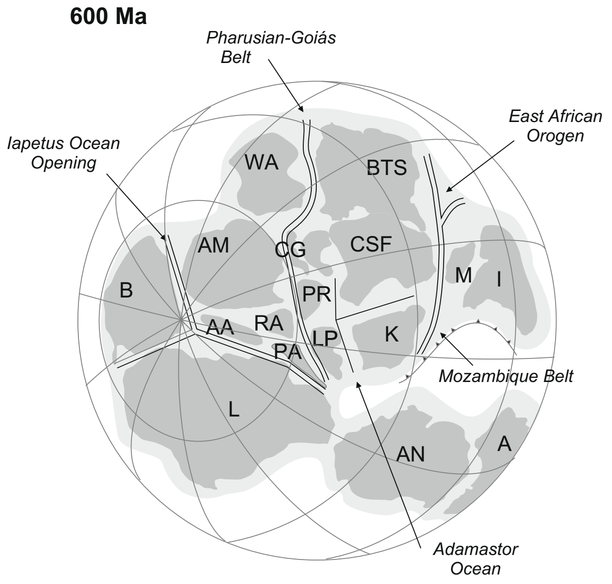


**Fig. 10.** Paleogeographic reconstruction at 600 Ma, when the final agglutination of Gondwana was going on, with the concomitant separation of Laurentia and Baltica, and formation of the Iapetus Ocean. Adapted from Cordani et al. (2009). L = Laurentia; B = Baltica; AM = Amazonia; AA = Arequipa/Antofalla: RA = Rio Apa; PA = Pampia; WA = West Africa; CG = Central Goias Massif; PR = Paranapanema; LP = Rio de La Plata; BTS = Borborema/Trans-Sahara; CSF = Congo:São Francisco; K = Kalahari; M = Madagascar; I = India; AN = Antarctica; A = Australia.

a few continental masses and fragments, including the São Francisco-Congo, Rio de La Plata, and Kalahari Cratons. Cordani et al. (2003) and Kroener and Cordani (2003) used this observation, valid for the time of Rodinia's agglutination, to propose that these cratonic fragments were never parts of Rodinia.

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