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INVITED REVIEW

The Brasiliano collage in South America: a review

A colagem Brasiliana na América do Sul: uma revisão

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ABSTRACT: Analysis of recent geological and geochronological data from the basement of the South American platform indicates that the Brasiliano orogenic collage took place in four distinct pulses: a) Early Cryogenian (ca. 800 – 740Ma); b) Late Cryogenian-Early Ediacaran (ca. 660 – 610 Ma); c) Early-Middle Ediacaran (c. 590 – 560 Ma); and d) Late Cambrian (520 – 500 Ma). The first three pulses are well represented in most Neoproterozoic structural provinces in West Gondwana. The youngest orogenic phase/pulse, however, is only seen in Argentina (Pampean Orogeny) and Brazil, in eastern Rio de Janeiro State (Búzios Orogeny). The period between ca. 750 and 500 Ma is comparable to that reported for the amalgamation of various continental fragments in East (Arabian-Nubian, Mozambique, Kuunga) and North Gondwana (Cadomian). However, important differences in the nature and ages of events are recognized, which can be expected in view of the magnitude of Gondwana agglutination and the diversity of paleogeographic and tectonic scenarios. West Gondwana shows an interesting peculiarity: lithologically and tectonically diversified Tonian terranes underlie Brasiliano orogenic buildups. They were strongly reworked during most of the orogenic pulses. The Tonian terranes (1000 – 900 Ma) and their relation with Rodinia or with the processes of Gondwana fusion remains an open question. Indications of their presence in East Gondwana are still poorly documented.

KEYWORDS: West Gondwana; Cryogenian; Ediacaran; orogenic collage; orogenic pulses; Tonian terranes.

RESUMO: Consoante os mais recentes dados geológicos e geocronológicos do embasamento da Plataforma Sul-Americana, a colagem orogênica Brasiliana se deu em quatro pulsos distintos: a) eocriogeniana (ca. 800 – 70Ma); b) tardicriogeniana-eoediacarana (ca. 660 – 610 Ma); c) eo-médio ediacarana (ca. 590 – 560 Ma) e d) tardicambriana (520 – 500 Ma). Os três primeiros pulsos da colagem apresentam boa representatividade na maioria das províncias estruturais do Neoproterozóico, em todo Gondwana Ocidental. O último e mais jovem pulso orogênico constitui casos específicos locais registrados na Argentina (Orogenia Pampeana) e no Brasil, no leste do Rio de Janeiro (Orogenia Búzios). No cômputo geral, o intervalo de tempo (ca. 750 – 500 Ma) é comparável com o que é conhecido sobre o conjunto mais oriental (Árabe -Nubiano, Moçambique, Kuunga) e norte de Gondwana (Cadomiano), nos vários segmentos derivados deste supercontinente. No detalhe são encontradas diferenças importantes de eventos e idades entre os vários segmentos de Gondwana, o que é esperável diante da magnitude territorial da aglutinação do supercontinente e da natural diversidade dos cenários paleogeográficos e tectônicos. Em Gondwana Ocidental observa-se peculiaridade interessante: sotoposta aos edifícios orogênicos do Brasiliano e retrabalhada fortemente nos quatro pulsos principais, é encontrada série muito diversificada de terrenos do Toniano, em termos de rochas e proveniência tectônica. Estes terrenos (1000 – 900 Ma) e sua relação tanto com os processos da fusão de Rodinia como com os de aglutinação de Gondwana constituem um problema em aberto. Há algumas outras indicações, ainda muito pouco documentadas, da presença de tais terrenos em Gondwana Oriental.

PALAVRAS-CHAVE: Colagem orogênica; Gondwana Ocidental; Criogeniano; Ediacarano; pulsos orogênicos; terrenos tonianos.

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INTRODUCTION

Over the last five decades the word "Brasiliano" has been loosely used to refer to many aspects of the Neoproterozoic geology of Brazil (e.g. cycle, orogeny, tectonic evolution, metamorphism, mobile belts, cratons, etc.).

When the first formal definitions were proposed (Cordani *et al*. 1968, Cordani *et al*. 1973, Almeida *et al*. 1973; Almeida e Hasui 1984), the term appeared as "Brasiliano cycle" ("Ciclo Brasiliano"), comprising the period from 700 to 450 Ma. These authors separated it from the pre-Neoproterozoic cycles, also defined in the early 70s (*e.g.* the "Uruaçuano", "Espinhaço", and "Transamazonian" cycles). These seminal concepts were heavily based on Rb-Sr and K-Ar geochronology, the only methods available at that time. The poor dating was made worse by the non-uniform availability of the data over the South American territory. These definitions were also strongly biased by poor geological and geotectonic knowledge, associated to the need to establish the timing of geological/geotectonic processes in South America (see a synthesis of original definitions in Brito Neves *et al*. 1990, and in Tab. 1).

With the progress of systematic geological mapping, strongly supported by recent aerogeophysical surveys, and introduction of new isotopic and geochronological methods, especially Sm-Nd and U-Pb (Pb-Pb evaporation, TIMS, LA-ICPMS, SHRIMP), those concepts adopted during the last decades of the past century need to be reviewed and updated. As new data is being rapidly produced, new reviews may be necessary in the near future

The misuse of one of the older designations, the "Transamazonian" cycle (ca. 2,100 – 1,800 Ma), is persistent in Brazilian literature. With the improvement of geological knowledge in the last decades, it has been recognized that all systems of the Paleoproterozoic era are well represented in the continent (Brito Neves, 2011). Therefore, choosing a single unifying rack (the "Transamazonian") to include all the different systems is both undesirable and inconsistent, although understandable in the past. Even for Amazonia, in northern South America, the accumulated geological knowledge — according to Santos 2003; Tassinari and Macambira 2004; Rosa Costa *et al*. 2006; Cordani and Teixeira 2007, among many others — is sufficient to place the initial concept of "Transamazonian" in a untenable position, since isotopic determinations originally labeled as "Transamazonian" (ca. 2,000 Ma) are restricted to a small area in the northeastern part of the Amazonian craton. Likewise, using the same designation in other basement blocks (*e.g.* São Francisco Craton, Rio de La Plata Craton, São Luis Craton, basement of Neoproterozoic provinces, etc.), is inadequate, given that these blocks, or plates, were — probably — distant from each other, and unlikely to have shared a single cycle of plate interaction.

The "Uruaçuano cycle" (ca. 1,300-1,100 Ma) proposal was consolidated in the same publication of Almeida *et al*. (1973), although it was present in several earlier studies, in other structural provinces of South America. This was an interpretive mistake of geological and isotopic data (mostly Rb-Sr and K-Ar), which gradually disappeared from the scientific archive of the continent, due to the growth in the geological knowledge of the region.

At that time, it was a common practice to take a few groups of age and "validate" them as a tectonic "cycle". This was done without the necessary commitment to paleogeographic and paleotectonic scenarios. Concepts such as "cycle", "phase", "orogeny", and "tectonic event" were used loosely, without commiting to a ruling principle. Additionally, there was the widespread unduly idea of a continent (South America) always acting as a large monolithic continental mass, which is not adequate.

As far as the Brasiliano "cycle" and the Neoproterozoic structural provinces are concerned, new information is continuously being produced. A few subdivisions have been proposed (*e.g.* Campos Neto 2000; Schobbenhaus & Brito Neves 2003; Silva *et al.* 2005), with very good scientific support, providing valuable aid to the approach proposed in the present paper.

Scientific progress is instrumental to challenge inadequate concepts and subdivisions. In addition to that, advances in geological knowledge have gradually demonstrated the existence of other major tectonic events associated to the concept of interaction of several paleocontinents (e.g. those from the Siderian, Tonian, Cambrian, among others), barely hypothesized or imagined during the last quarter of the past century.

The interesting question posed by Collins *et al.* (2011), in the XIV Gondwana Symposium, about the final assembly of Gondwana ("Where and when did Gondwana finally amalgamate?") seems to have a good answer based on the most remarkable record in South America. A review of the different main phases (pulses) of convergent plate interactions during the Neoproterozoic and the final fusion of West Gondwana in late Cambrian times are the main objectives of this work.

PREVIOUS STUDIES

Since the late 1960s several authors (e.g. Cordani *et al.* 1968) have attempted to summarize and organize the available geological and geochronological information, trying to subdivide the pre-Ordovician in the South American platform. In the 1970s, several classic papers were published (Almeida 1971, 1978; Almeida *et al.* 1973; Cordani 1973), in which the Neoproterozoic orogenic activity was encompassed in the so-called "Brasiliano" (between 700 and 450 Ma, Almeida *et al.* 1973). This is a sequence of relevant contributions, each successively taking advantage of the progress of the knowledge (Tab. 1).

Contributions by Schobbenhaus and Campos (1984) and Almeida and Hasui (1984), although sticking to the rules of international committees, and taking hold of the continent as a whole, brought about advances to the proposals of the previous decade. As mentioned above, Brito Neves *et al.* (1990) presented a synthesis of these classifications and systematizations (Tab. 1).

Table 1. A review of the main proposed schemes of chrono- and lithostratigrafic evolution for the basement of the South American Platform during the last 50 years

Almeida, 1971	Almeida et al., 1973	Almeida et al., 1973	Almeida et al., 1978	Martin, 1978 (coord.)	
0.57 Ga UPPER PRECAMBRIAN Late Brasiliano Cycle (0.62 – 0.57 Ga) Brasiliano Cycle (0.9 – 0.62 Ga) Uruaçuano/Minas Cycle (1.3 – 0.9 Ga) Espinhaço Cycle (1.8 – 1.3 Ga) 1.8 Ga Transamazonian Cycle (2.2 – 1.8 Ga) MIDDLE PRECAMBRIAN 2.6 Ga LOWER PRECAMBRIAN	Brasiliano Cycle (0.7 – 0.45 Ga) Uruaçuano Cycle (1.4 – 0.9 Ga) Transamazonian Cycle (2.2 – 1.8 Ga) Middle and Lewer Precambrian >2.2 Ga)	Brasiliano Cycle (0.65 – 0.50 Ga) 1.4 – 1.1 Ga Orogenic events Transamazonian Cycle (2.2 – 2.8 Ga) Pre-Transamazonian events	Cambrian – Ordovician Events 0.65 – 0.62 Ga Brazilian Cycle 1.0 Ga 1.4 Ga Parguasa – Paraense events Uruaçuano structures 1.8 Ga Transamazonian Cycle (2.2 – 2.8 Ga) 2.6 Ga Jequié event 2.8 Ga	0.65 – 0.55 Ga Brazilian events 1.2 Ga Orinocan tectonism (K´Mudku – Nigerie) 1.5 Ga Parguazan event 2.2 – 1.8 Ga Transamazonian events 2.7 – 2.5 Ga Carichapdan events 2.7 Ga Ardan events 3.4 – 3.3 Ga Gurian events	PROTEROZOIC ARCHENZOIC

Inda& Barbosa, 1978 Brito Neves et al., 1980	Schobbenhaus et al.,1984 (Coord.)		Almeida & Hasui, 1984 Events/Cycles		Brito Neves et al., 1990 Pre-Brasilian Domain	Brito Neves et al., 1990 Brasilian Domain
0.57 Ga Brasiliano Cycle 1.1 Ga Espinhaço Cycle 1.8 Ga Transamazonian Cycle 2.6 Ga Jequié Cycle	Transition stage Brasiliano Cycle Rodonian-Espinhaço-Uruçuan-K´mudku (Parguazense) (Uatumã) 2.0 Ga Transamazonian Cycle 2.6 Ga Jequié-Aruense Cycle 3.2 Ga Guriense Cycle	PAL PROTEROZOIC ARCHENZOIC	0.45 Ga Brasiliano 0.68 Ga 1.0 Ga Uruaçuan 1.3 Ga 1.8 Ga Transamazonian 2.1 Ga 2,55 Ga Jequié 2.9 Ga ? > 3.4 Ga	0.45 Ga Brasiliano Cycle ? 1.0 Ga Uruaçuan Cycle ? 1.8 Ga Transamazonian Cycle ? 2.5 Ga Jequié Cycle ? 3.3 Ga	LATE PROTER MIDI PROTER 0.57 Ga Brasiliano Cycle (>0.5 Ga) 0.9 Ga Guajará Mirim – D – Sunsás Cycle (1.3/1.28-0.9) "Caiabis" – C – S. Ignacio Rondonian Cycle (1.5-1.3) "Beneficiente" – B – Rio Negro Cycle (1.75-1.55) "Uatumã" – A 1.9 Ga Trans-amazonian Cycle (2.25-1.9-1.8) Early Proterozoic 2.5 Ga Archean III 2.9 Ga Archean II 3.5 Ga Archean I	0.5-0.48 Ga 0.57 Ga Brasiliano Cycle Late Proterozoic 0.9 Ga Events 1.0 Ga Middle Proterozoic Espinhaço-Uruçuano Cycle (1.75-1.2) 1.3 Ga Trans-Amazonian Cycle (2.2-1.8) Early Proterozoic 2.4 Ga Events Jequié Cycle (2.7-2.6-2.5 Ga)

Continue...

Table 1. Continuation

Schobbenhaus & Bellizzia, 2000		Age
		0.54 Ga
Brasiliano Cycle		
		0.95 Ga
Cariris V elhos Sunsas Uruaçuano		
		1.3 Ga
San Ignçacio Rodinian		
		1.5 Ga
Rio Negro-Juruena Cycle	Taphrogenic Processes	
		1.8 Ga
Ventuari-Tapajós		
		1.9 Ga
Transamazonian Cycle		
		2.2 Ga
		2.5 Ga
Jequié Cycle		
		2.6 Ga

	Silva *et al.*, 2005*
Brasiliano III	Syn – collisional 530 – 500 Ma (S and I types)
	Araçuaí Orogeny
	Post – Collisional 560 – 490 Ma Syn – Collisional 580 – 560 Ma Pre – Collisional 630 – 570 Ma
Brasiliano II	Dom Feliciano, Rio Piên, Paranapiacaba and Costeiro Granitic Belt 600 – 560 Ma Late to post – Collisional 640 – 600 Ma Pre to Syn – Collisional
Brasiliano I 810 – 700 Ma	São Gabriel Orogeny
	Tuffs, Metatrondhjemites, metadiorites, tonalite – gneiss

(*Based only on Mantiqueira Province)

Subsequent works — by Pimentel *et al.* 1997; Campos Neto 2000, among others —, brought to light new data from mapping and geochronological data using new isotopic methods, and made it clear that previous schemes could not prevail. From then on, the number of relevant contributions grew and led to rapid progress.

The new data represented the starting point for new schemes of geological time subdivision in the continent (Schobbenhaus & Brito Neves 2003; Delgado *et al.* 2003). In both cases, Neoproterozoic tectonic events were considered with particular care, including the previous proposals to subdivide the "Brasiliano" *sensu lato*. Silva *et al.* (2005), considering the development of the Mantiqueira Province, attempted to improve and update the scheme proposed by Delgado *et al.* (2003). These contributions provide excellent synthesis of geochronological data available for the Proterozoic of the continent. In addition, they provided the first attempts to organize the "Brasiliano" geological record in space and time.

Defining orogenic processes, taking into account geological time subdivision and main stages supported by tectonic events, is a complex and demanding exercise, and it needs to be carried out permanently. Timely revisions are necessary to keep track of knowledge advancement.

PLATE INTERACTIONS, OROGENY, OROGENIC COLLAGE, FUSION (ASSEMBLY)

There is no consensus in the international literature concerning the definition of the concepts above. They are simply overlooked, or in some cases, treated frivolously. However, in our view and experience, attempts to understand the geotectonic development of continents, following the initial assumptions of Mitchell and Reading (1969), Dewey and Bird (1970) and Dewey and Burke (1973), as suggested by Helwig (1974), and again by Sengör (1990), is very useful in the systematization of tectonic processes. According to Helwig (1974) and Sengör (1990), orogenesis is defined as a plate interaction (development of a Wilson cycle), orogenic collage is a concatenated sequence of orogenies, and fusion is the sum of these processes, leading to the formation of a large continental mass or a supercontinent.

As mentioned above, several geoscientists, including authors of textbooks, do not follow any robust systematics, and the consolidation of these concepts is usually missing — see Moores and Twiss 1995; der Pluijm and Marshak 2004; Kearey *et al.* 2009, among other more recent textbooks —, which leaves room for many inferences and counterintuitive "concepts". For instance, in the case of the several orogenies of the Appalachian Mountains involving distinct terranes, arcs and plates, no discrimination is proposed, and the term orogeny persists until the end of a long and complex evolution. Orogenic collage should have been used, since the assembly of Pangaea was the final result of the processes. Indeed this oversimplification ("orogenesis") has been common practice, especially when some linearity of orogenic processes persists.

In cases where co-linearity and/or contiguity of successive orogenic processes are absent, and where interacting participants (basement inliers, terranes, "structural highs", shear belts, etc.) are abundant, the simplistic treatment has not been possible or is usually confusing. This is the case of the branching systems of orogens or "mosaic-like folded regions" present not only in Proterozoic terrains (e.g. Neoproterozoic structural provinces in Brazil, Baikalian provinces of Asia, etc.), but also in Phanerozoic terrains (e.g. European Hercynian, Ural-Mongolia, Alps). In every case there is then the necessity to investigate each of the belts, their paleogeographic framework, as well as their lithostructural and isotopic records, and perform comparison exercises in order to achieve meaningful syntheses.

Even recognizing the disregard of formal nomenclature and definitions in the Geotectonic literature, for which the necessity of formalization equals that of the stratigraphic nomenclature code, we decided to follow the "Helwig (1974)–Sengör (1990)" proposal, aiming to understand the problems presently posed for South America. We hope to establish a basis for the better appreciation of the problem and for its future solution.

PRE-TONIAN IN SOUTH AMERICA

Archean

Eoarchean rocks have not been found in South America up to now, although there are some indirect records from Sm-Nd model ages and from rare U-Pb ages of detrital zircon grains.

Exposures of Paleoarchean high- and low-grade rocks are recognized within the main cratonic nuclei (São Francisco, Amazonian), in basement inliers within and between mobile belts, and eventually in detrital zircon grains from Proterozoic metasedimentary rocks. The oldest rocks (> 3.4 Ga) were identified in the central and northern domains of the São Francisco craton (Nutman & Cordani 1993), and in the São José do Campestre block (Dantas *et al.* 2004, 2010, 2013), in the Borborema province. Up to this date, there is no sufficient data to try to establish workable tectonic subdivisions for this era in South America.

Mesoarchean records are far more abundant in cratons, basement of Proterozoic mobile belts, as well as in detrital material of Proterozoic metasedimentary rocks. However, in spite of the available data, it seems still early to suggest subdivisions. Occasionally, some denominations of orogenic nature are used — *e.g.* "Guriense cycle (Schobbenhaus & Campos, 1984) — to distinguish between different tectonic/metamorphic peaks. Although the increasing volume of geological and geochronological data is recognized, formal classifications should wait until additional data are available. In addition to that, many Mesoarchean terranes were variably reworked during Proterozoic orogenies, requiring caution when making new propositions.

In general, among the Archean eras, Neoarchean records are the most frequent in the basement of the cratons and the Proterozoic mobile belts. The wealth of data has lead researchers to propose some local designations, such as the "Jequié cycle" (Cordani 1973), "Jequié-Aroense" (Schobbenhaus & Campos, 1984), and "Rio das Velhas" (Noce *et al.* 1998). Such designations express the necessity of knowledge systematization, and are understandable, acceptable, and should be stimulated. However, caution should be exercised when such designations are extended from a specific geological domain to the whole continent.

With the necessary caution, possible Neoarchean continental nuclei in Brazil should be confronted with what is known about Neoarchean rocks worldwide. Indeed, several neoarchean continental reconstruction scenarios have been suggested in the literature (e.g. Bleeker 2003):

- a single continent (Kenoran);
- two or three large continental masses (Sclavia, Superia, Vaalbara); or
- many different masses, plates and nuclei, which appears to be the less probable solution, according to Bleeker (2003).

In our point of view, this xcenario considered as the "less probable solution" (Bleeker, 2003), involving many different neoarchean masses, appears to be the most realistic model (taking into consideration the data of the South American Platform).

PALEOPROTEROZOIC

There are good lithological and structural records of all Paleoproterozoic periods recognized in South America, both from orogenic and anorogenic processes, also including basin-forming tectonics (Brito Neves 2011).

Siderian rock units (2,500 – 2,300 Ma) were recently identified in the cratonic basement of the Amazonian and Luis Alves cratons, and in basement inliers of Proterozoic belts, including volcano-sedimentary formations (Brito Neves 2011).

The Rhyacian (2,300 – 2,050 Ma), mainly in its middle part (ca. 2,150 – 2,200 Ma), is the Paleoproterozoic time interval with the largest number of tectonic, magmatic and sedimentary events recorded in the diverse components of the basement in South America, particularly in its central and eastern sectors.

The Orosirian (2,050 – 1,800 Ma) runs second place in terms of record wealth, comprising independent orogenies, all well constrained in their time intervals, but also representing the final stages of orogenies that started in the Rhyacian. Aside from the orogenic processes, important granite plutonism and abundant volcanic and sedimentary sequences have been identified. In eastern Amazonia, these processes were extensive, representing a large igneous province (LIP), covering an area that exceeds 1 million km^2, in five different countries (Brito Neves 2011; Klein *et al.* 2013).

During the Statherian (1,800 – 1,600 Ma), there is a single orogen in the central sector of the Amazonian craton, known as the Rio Negro-Juruena belt, exposed to the west of an Orosirian belt. Nd-Sr isotopic evidence points to juvenile accretion processes in the origin of this orogen (Tassinari & Macambira 2004; Cordani & Teixeira 2007). This orogen is believed to continue into North America (Transcontinental-Labrador) and northern Europe (Gothian-Kongsbergian), according to continental reconstructions put forward by several authors (Brito Neves 2005). However, the most outstanding feature of the Statherian in South America is taphrogenesis, with many examples in all sectors of the continent. This is represented by plutonism, volcanism, and sedimentation, including precursors of large intracratonic sedimentary basins ("steer's head basins" or koilogens). In part, these extensive covers continued to form well into the Mesoproterozic, for example the Espinhaço Supergroup in the São Francisco craton. Some of the basins were formed in large rift zones, deformed later on during the Late Mesoproterozoic and Neoproterozoic orogenic processes (e.g Espinhaço, Orós-Jaguaribe, Araí).

MESOPROTEROZOIC

There are two large geological domains in South America, the Amazonian (or pre-Brasiliano, or north-west domain) and the "Brasiliano" (or central-east domain) ones, according to Brito Neves and Fuck (2013, 2014). Their distinction is easily recognized when analyzing Mesoproterozoic and younger rock assemblages (Table 2).

In the Amazonian domain, the Mesoproterozoic (1,600 – 1,000 Ma) is represented in several NNW-ESE mobile belts that developed between 1,590 and 1,000 Ma (Tab. 2), organized from northeast to southwest in a chelogenic pattern (Tassinari & Macambira 2004; Bettencourt *et al.* 2010, among others). The continuity of these belts into North America is a frequent matter of debate (Brito Neves 2005; Bettencourt *et al.* 2010; Brito Neves & Fuck 2014, among others), especially among researchers investigating the history of supercontinents.

Mesoproterozoic magmatic and sedimentary processes have been recorded within the Brasiliano domain. However, so far, no true mobile belt has been recognized, except, perhaps, for the Ceres-Rialma belt, exposed along the high course of the Tocantins River, in central Brazil (Moraes *et al.* 2004, 2006). Most units generated during the Mesoproterozoic were strongly affected by Neoproterozoic orogenic events. Some restricted cratonic covers escaped this, for instance the central part of the Chapada Diamantina Group, in the São Francisco craton (Süssenberger *et al.* 2014). Several examples of Mesoproterozoic rift deposits were involved in younger Brasiliano mobile belts, many hundreds of million years later (e.g. part of Espinhaço, Orós-Jaguaribe, Araí, etc.).

Available geological and geochronological information indicate that the Mesoproterozoic time scale for the successive orogenic events in Amazonia is distinct from that recorded in the extra-Amazonian portion of the continent (Tab. 2). It is not an overstatement to say that the end of the Mesoproterozoic marks the end of the history of Precambrian orogenies in Amazonia, since Neoproterozoic events are scarce (Brito Neves & Fuck 2013). On the other hand, Neoproterozoic systems are of utmost importance outside Amazonia, in the so-called Brasiliano domain.

NEOPROTEROZOIC

Tonian Terranes/Orogenies

The progress of the geological knowledge arising from 1:100.000 and larger scale mapping of almost the whole area of the Brasiliano domain and also from abundant isotopic studies, led to the establishment of a much more complete scenario of crustal evolution than that described by the pioneering authors mentioned above.

Tonian terranes, in the sense of Howell (1995), have been identified in all Neoproterozoic structural provinces of South America. They usually represent fractions of Early-Middle Tonian accretionary — some juvenile in nature — and collisional orogens, including volcanic-sedimentary associations metamorphosed under low- to high-grade conditions. Rock assemblages, typical of active continental margins, magmatic island arcs and remnants of ocean floor have been recognized in these units (e.g. Pimentel & Fuck 1992; Pimentel

Table 2. Generalized scheme of evolution and main events of the Amazonian (Pre-Brasiliano, north and northwest parts) and Brasiliano (central and eastern parts) domains of the basement of the South American platform. Based on Saes and Leite (1993), Geraldes *et al.* (2000), Ruiz *et al.* (2004), Tassinari and Macambira (2004), Bettencourt *et al.* (2010), Rizzotto and Hartmann (2012), Rizzotto *et al.* (2013), Brito Neves and Fuck (2013), Brito Neves and Fuck (2014), among others.

AMAZONIAN DOMAIN (Pre-Brasiliano)	BRASILIANO DOMAIN	(Ga)
First cratonic sedimentary sequences of western Gondwana	SILURIAN – EARLY DEVONIAN CAMBRO – ORDOVICIAN	0.40 0.50
Absence of orogenic events	Diversified late to post tectonic processes: / Transition stage	0.55
	CAMBRIAN OROGENIC BELTS (0.55 – 0.52 Ga)	0.60
	MIDDLE EDIACARAN OROGENIES (0.59 – 0.56 Ga)	
	LATE CRYOGEN – EARLY EDIACARAN OROGENIES(0.66 – 0.62 Ga)	0.65
	MAIN EVENTS OF TAPHROGENESES / + LOCAL PRECURSOR OROGENIC EVENTS (0.85 – 0.75 Ga)	0.80
	TONIAN OROGENIES / TERRANES (1000 – 0.920 Ma)	1.00
SUNSÁS AGUAPEÍ/ HUANCHACA Orogenie and cover sequences (1200 – 1000 Ma) / ANOROG. GRANITES	Vulcanic, plutonic (felsic and mafic) cratogenic processes + Cratonic sedimentary sequences	1.20
RONDONIAN – SAN IGNACIO Accretionary, collisional and cratogenic processes (1510 – 1320 Ma)		1.40
STA. HELENA OROGEN (1440±15Ma)		
CACHOEIRINHA OROGEN (1590±1530Ma)		1.60
RIO NEGRO – JURUENA ACCRET. PROCESSES (1.75 – 1.60 Ga)	STATHERIAN TAPHROGENIC PROCESSES	
RORAIMA PLATEAU	OROSIRIAN OROGENIC CYCLES	1.80
UATUMÃ (LIP)/ VOLCANISM/PLUTONISM	+ ANOREGENIC CRATONIC PLUTONISM	
	RHYACIAN – OROSIRIAN OROGENIES RHYACIAN OROGENIES	2.05
SIDERIAN OROGENIC PROCESSES AND PLUTONIC		2.30
IMPORTANT OCCURRENCES (GRÃO PARÁ,"JEQUIÉ" /"RIO DAS VELHAS" CYCLE)		2.50
SPARSE OCCURRENCES		2.86
FEW, SPARSE, SMALL NUCLEI		3.20
SOME ISOTOPIC INDICATIONS		3.60
FEW ISOTOPIC TRACES		4.00

et al. 1997, 2000, 2004; Pankhurst *et al.* 2008; Santos *et al.* 2010; Siga Jr. *et al.* 2009, 2011; Van Schmus *et al.* 2011). It is not always possible to reconstruct the paleogeography of these terranes, as they were disrupted during subsequent Neoproterozoic orogenies. In all cases, it has been hard to discriminate them from younger Neoproterozoic lithostructural and tectonic units, and they have frequently been interpreted as basement inliers. In general, time lapses of hundreds of million years have been recognized between these Tonian terrains and the younger Neoproterozoic processes. The plate configurations and duration of these periods still need to be accurately established.

Borborema province (NE South America)

Tonian terranes, apparently the largest in the continent, occupy wide areas within the Borborema Province (Fig. 1). They extend along ca. 1,000 km from the north of João Pessoa to SW Piauí, forming a belt up to ca. 100 km wide (the so-called Alto Pajeú terrane + Riacho Gravatá "subterrane") and in some other minor occurrences in the Transversal (central) and southern domains of the province. Volcanic-sedimentary associations, including felsic, mafic and restricted ultramafic rock associations, as well as orogenic and collisional granites, are dominant. In some cases, arc magmatism displays juvenile geochemical and isotopic signatures (Accioly *et al.* 2010; Santos *et al.* 2010; Van Schmus *et al.* 2011). These rocks formed largely between 1,050 and 930 Ma. Tonian rocks are also exposed in the north (Belém do São Francisco, Cabrobó) and south (Marrancó, Poço Redondo) of the Pernambuco-Alagoas massif, in the northern portion of the Sergipano belt, between the post-Cryogenian supracrustals and the Paleoproterozoic basement of the massif (Oliveira *et al.* 2010). A wealth of data is available for the Borborema Tonian rock assemblages (Santos 2010; Van Schmus *et al.* 2011; Caxito *et al.* 2014a, 2014b). According to De Wit *et al.* (2005, 2008), it is likely that these Tonian units of the Borborema Province have also been recognized in the Pan African domains, from Cameroon to the south of Sudan.

Tocantins province

The Goiás Magmatic arc is one of the most important tectonic features of the Brasília Belt, in central Brazil. It is exposed for approximately 1,000 km in the NNE-SSW direction along the western part of the belt. It comprises two sectors, separated by the Archean terranes of the Goiás massif (see Pimentel *et al.* 2004 and Figs. 2 and 3).

The southern sector is known as the Arenópolis arc, and the northern sector, as the Mara Rosa arc (Pimentel *et al.* 2000; Laux *et al.* 2004, 2005). In both sectors, early evolution of the arc took place in Tonian intra-oceanic island arcs, between ca. 930 and 810 Ma, with the crystallization of very primitive tholeiitic to calc-alkaline volcanics and associated tonalites/granodiorites (Fig. 3). The rocks display positive $\varepsilon_{Nd(T)}$ values and Nd T_{DM} model ages mostly between 0.8 and 1.1 Ga (Pimentel & Fuck 1992; Pimentel *et al.* 1997, 2000). Geochemical and isotopic data suggest that some of

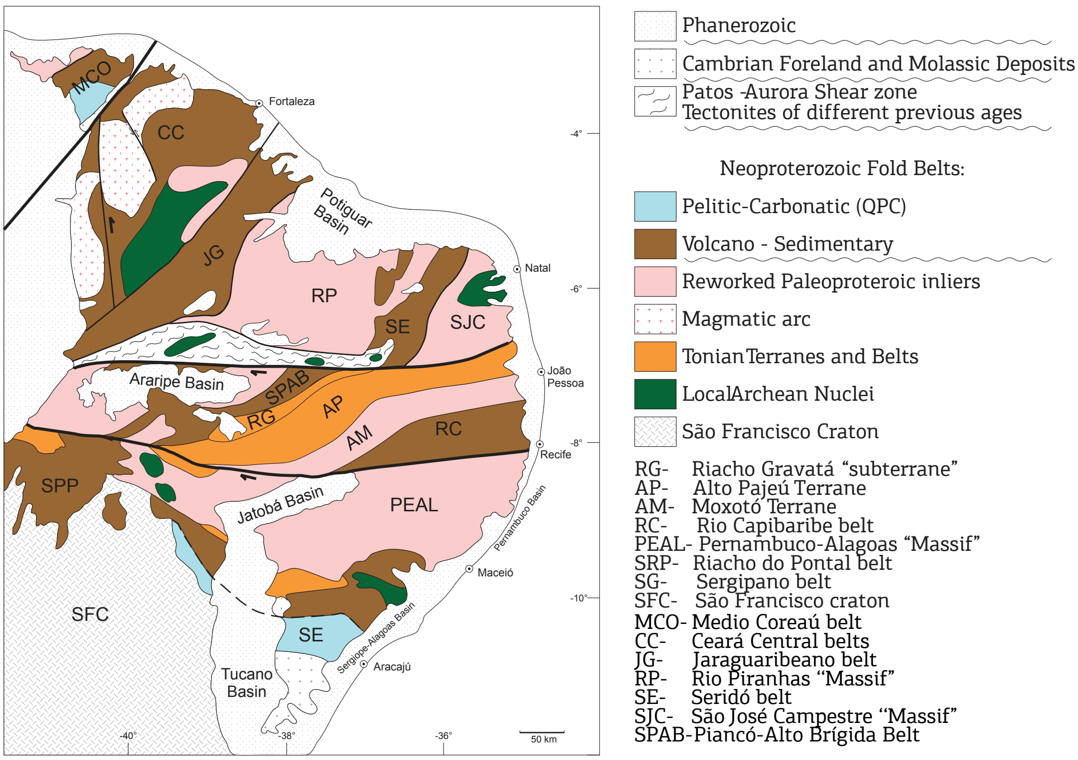


Figure 1. The Borborema Province, northeast of South America. Scheme of the main basement inliers and fold belts (including cryogenian-ediacaran magmatic arcs). Modified from Brito Neves and Santos (2000) and from Oliveira (2008), among others.

the original tonalite/andesite magmas were similar to modern adakites (Pimentel *et al.*, 1997).

A younger cycle of magmatic activity took place between ca. 670 and 600 Ma (Laux *et al.* 2005; Fuck *et al.* 2006; Oliveira *et al.* 2006). This second cycle also comprises volcanic-sedimentary sequences, calc-alkaline tonalite-granodiorite intrusions, as well as bi-modal intrusions comprised of gabbro/diorite/granite. Sm-Nd data produced T_{DM} values varying in a much wider range, from ca. 0.9 to 2.2 Ga, suggesting a higher contribution/contamination with older continental crust and indicating that this second event took place in a continental arc. Metamorphism under greenschist to amphibolite facies took place at ca. 630-620 Ma. This was followed by the emplacement of a large volume of post-tectonic bimodal intrusions formed by gabbros and granites dated between ca. 600 and 540 Ma.

Although these two main phases of arc magmatism are recognized on the basis of geochronological and, locally, geophysical data, their spatial distribution is still not clear for most of this geotectonic unit. In a large part, both sectors of the Goiás Magmatic Arc have been strongly affected by dextral strike-slip shear zones of the Transbrasiliano-Kandi lineament (Schobbenhaus *et al.* 1975; Cordani *et al.* 2013b). This is a striking geologic feature that corresponds to a wide (approximately 200-100 km wide) tectonic corridor of continental dimensions, cutting through most of South America and extending into Africa. The strike-slip faults have disrupted the arc rock units, causing important displacements in the NNE-SSW direction, obliterating the original spatial, structural, and stratigraphic relationships between the two different phases of arc magmatism. In addition, younger and older tonalite and granodiorite intrusions, preserved or not from strong deformation, are virtually identical petrographically, hampering their distinction in the field. Therefore, one has to rely on tools such as geochronology and airborne geophysics to distinguish between them. This was partially achieved in the Mara Rosa arc, where an appropriate amount of Sm-Nd isotopic data allied with U-Pb zircon ages seem to indicate that the Tonian rocks (930-800 Ma) dominate the eastern part of the arc (here informally called the Amaralina

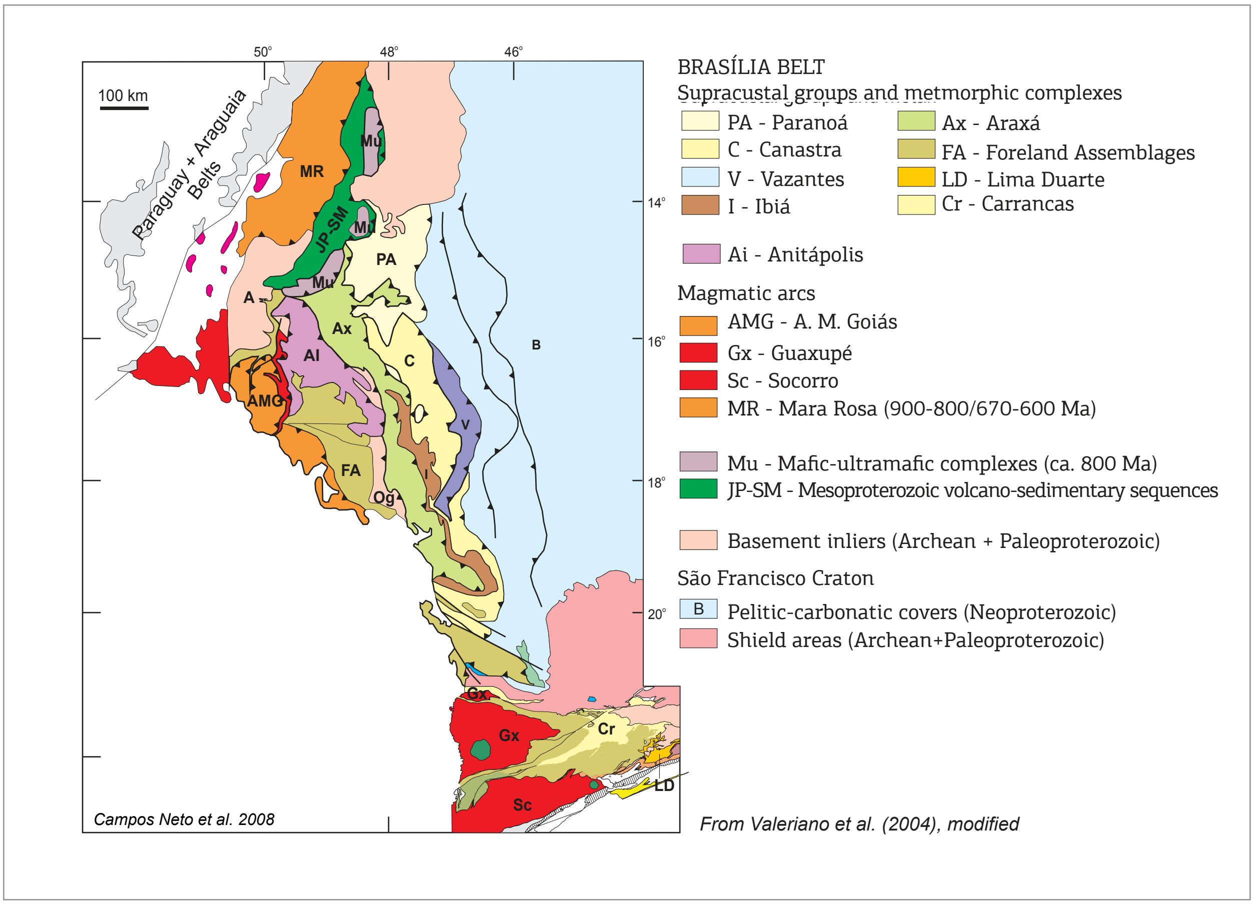


Figure 2. Sketch map of the Tocantins Province (central part of the basement of South American platform). Based on Pimentel *et al.* 2004, among others. See Fig. 3 for the detail of the Mara Rosa arc (Tonian in age) and surroundings.

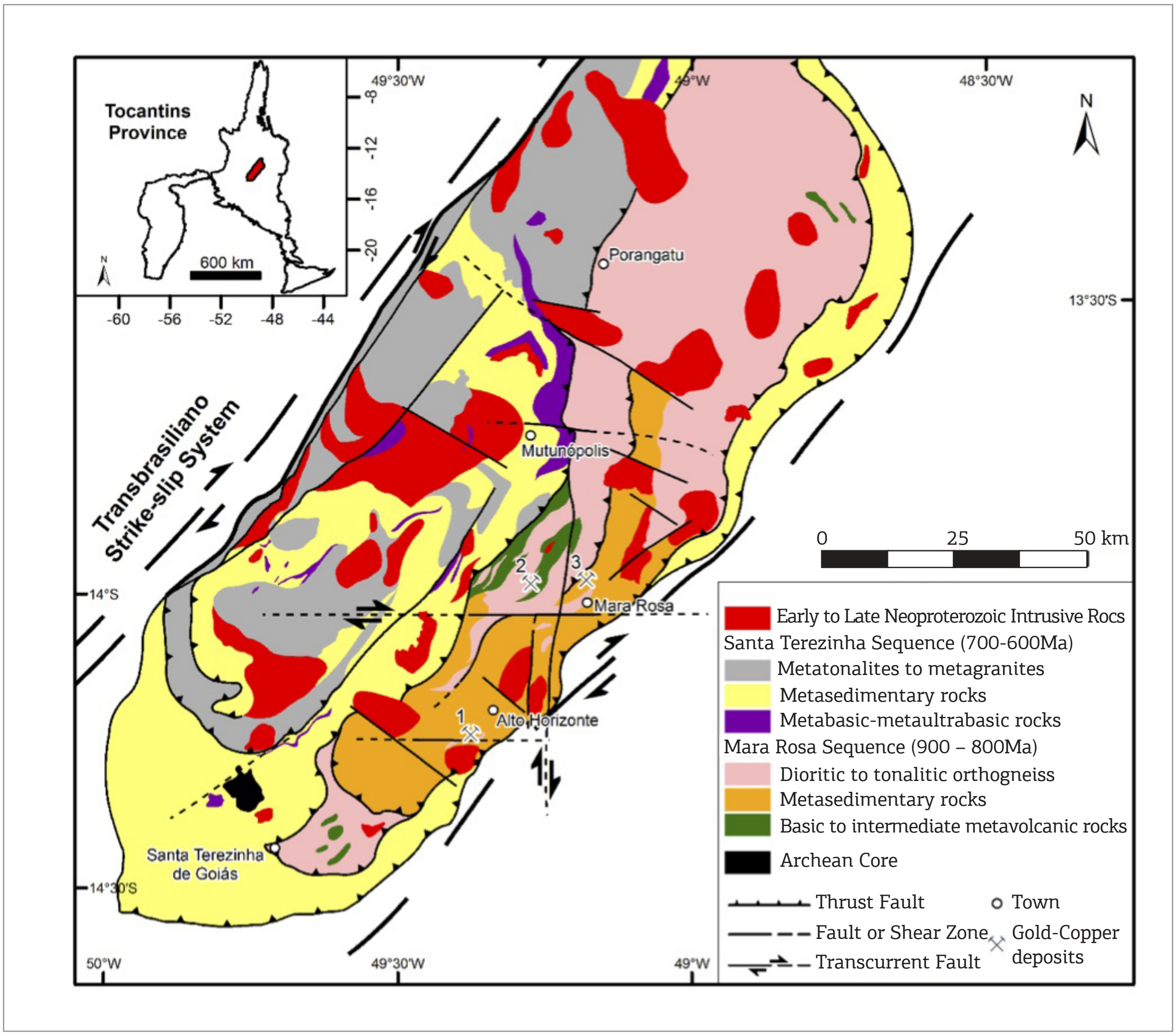


Figure 3. Schematic map of the Mara Rosa arc, the Tonian terrane (pre-Brasiliano evolution, island arc) of the northern central part of the Tocantins Province. Based on Junges *et al.* (2008), Pimentel *et al.* (2014), Oliveira *et al.* (2014), among others.

domain), whereas the western and southern parts of it (the Santa Terezinha de Goiás domain, see Figure 3) comprises mainly 670-600 Ma old rocks. One metavolcanic rock interlayered in fine-grained metasedimentary rocks of the Santa Terezinha de Goiás Sequence yielded the U-Pb zircon age of ca. 670 Ma, whereas associated metatonalites have intrusion ages of ca. 630 – 600 Ma.

In the Arenópolis arc (the southern part of the Goiás magmatic arc, Figs. 2 and 3) strike slip faults separate regions where the Tonian juvenile rocks dominate from regions dominated by the Ediacaran phase. However, the available geological and geochronological data do not allow their representation in geological maps at an appropriate scale. Small ultramafic bodies consisting of serpentinite, metaperidotite, and amphibolite are not rare and have been interpreted as remnants of oceanic basins, separating different island arc terranes. Similar rocks have also been recognized in the Mara Rosa arc. They may represent former suture zones between colliding magmatic arc systems, which have been obliterated by later deformational events (Pimentel *et al.* 2000).

Mantiqueira province

a) Italva Klippe/Terrane

Rock assemblages of the Italva terrane, including tonalite and granodiorite gneiss, marble, amphibolite, intercalated with rocks of the Rio Negro arc, occur in a large synform (a probable klippe, Peixoto & Heilbron 2010), within the "Oriental terrane", in the central northern part of Rio de Janeiro (Fig. 4). They strike NNE-SSW following the superposed trends of the Neoproterozoic orogenic association (Rio Negro arc and surroundings).

Geochemical data of the Italva rocks indicate extensional magmatism in a back arc-type environment, filled up with detritus derived from a neighboring basement (Peixoto and Heilbron 2010). Geochronological data of amphibolites, intercalated with marbles, indicate the crystallization age of 848 ± 11 Ma for the original mafic magmatism (Heilbron and Machado 2003). This is ca. 50 Ma older than the oldest age recorded so far in the Rio Negro arc, and more than 200 Ma older than the main magmatic activity within the magmatic arc. Metamorphism of the Italva rocks took place at higher P-T conditions than that seen in the younger rocks, and their contacts are tectonic in nature.

b) Itaiacoca Group

The Itaiacoca Group occurs in the westernmost area of the Mantiqueira Province, in Paraná and São Paulo. It is a ca. 180 km long and > 15 km wide metavolcanic-sedimentary sequence, exposed between the ca. 620 Ma old Cunhaporanga and Três Córregos magmatic arcs (Fig. 5). The metamorphic belt is covered in the north and south by Phanerozoic deposits of the Paraná Basin. It is composed of a QPC-type (quartzite-pelite-carbonate) metasedimentary association. Stromatolitic dolomite marble, frequently rich in talc, and phyllite make up the lower part of the sequence, followed by quartzite and metavolcanic rocks, with phyllite at the top (Siga Jr. *et al*. 2009, 2011). The U-Pb zircon age of the Itaiacoca metavolcanics is set at 934 ± 36 Ma, and detrital zircon ages vary from late Stenian to Early Tonian (Siga Jr. *et al*. 2009, 2011). The sequence is thought to represent continental passive margin deposits related to the Paranapanema microplate (Mantovani & Brito Neves 2009). Cryogenian orogenic processes later truncated it, and it is covered locally by metaconglomerate, metarkose, metagraywake and metavolcanics of the Cryogenian Abapã Formation, dated at 628±18 Ma.

INTERCONTINENTAL INTEGRATION

As previously mentioned, a recent contribution, by Brito Neves and Fuck (2014) showed that the basement of the South American Platform is divided into two distinct major geological and geotectonic domains, the Amazonian or pre-Brasiliano domain and the Brasiliano domain, which are separated by the transcontinental Transbrasiliano lineament (Tab. 2). These domains are separated from each other by the Transcontinental Kandi-Transbrasiliano lineament. The distinction between the two domains is underlined by the striking differences in stratigraphic organization in both domains, especially when the tectonic events in the Brasiliano domain are considered. From the Mesoproterozoic onwards the two domains display very distinct geological features and tectonic evolution. In Table 3, the different tectonic events comprising the Brasiliano collage are listed and detailed.

Tonian Terranes

The presence of Tonian terranes within the Brasiliano collage is well documented. However, based on the available data, it has been difficult to recognize them as representative of an independent (post-Stenian, pre-Brasiliano) phase of crustal evolution. Although there is evidence of structural discontinuity between the Tonian and the Brasiliano rock assemblages in some areas, the precise meaning of this break is hard to understand due to the strong overprint of Brasiliano orogenic events.

As far as geological knowledge and lithostructural context of each province go, there is no evidence to link the Tonian occurrences in Brazil to those of the classic Meso-Neoproterozoic Grenvillian orogenies of the northern and southern hemispheres. Also, there are fundamental differences in age and composition, and it has been truly difficult to provide paleographic reconstruction, even following several different models.

In relation to Africa, based on previous reconstitutions and age data, the Meso-Neoproterozoic Namaqua–Natal belt is possibly the most interesting orogen (candidate) to be correlated to South American Tonian terrains. Some similarities have been pointed out during the analysis of the literature. However, many difficulties are also evident as, for instance, the lack of paleomagnetic support. Meso-Neoproterozoic geological units in Nigeria, Chad and southern Sudan, comparable with those in Brazil, have been reported (de Wit *et al*. 2005, 2008), but they have been strongly reworked by the Pan-African orogeny. If this supposed correlation will be confirmed, the Tonian terranes in West Gondwana may extend along strike for several thousands of kilometers. Actually, the presence of Tonian terranes in Rodinia, Western (and Eastern) Gondwana has been neglected, and this is persisting as a challenging open question.

Tonian processes and orogenies were absent and have not been considered in the Rodinia concept; this supercontinent was formed at ca. 900 Ma ago (Li *et al*. 2008). It is still an open question whether the Tonian processes precede (or follow) Rodinia amalgamation, and this has important implications for the configuration of this supercontinent. It appears that, in general, awareness of this problem is absent in the international scientific community.

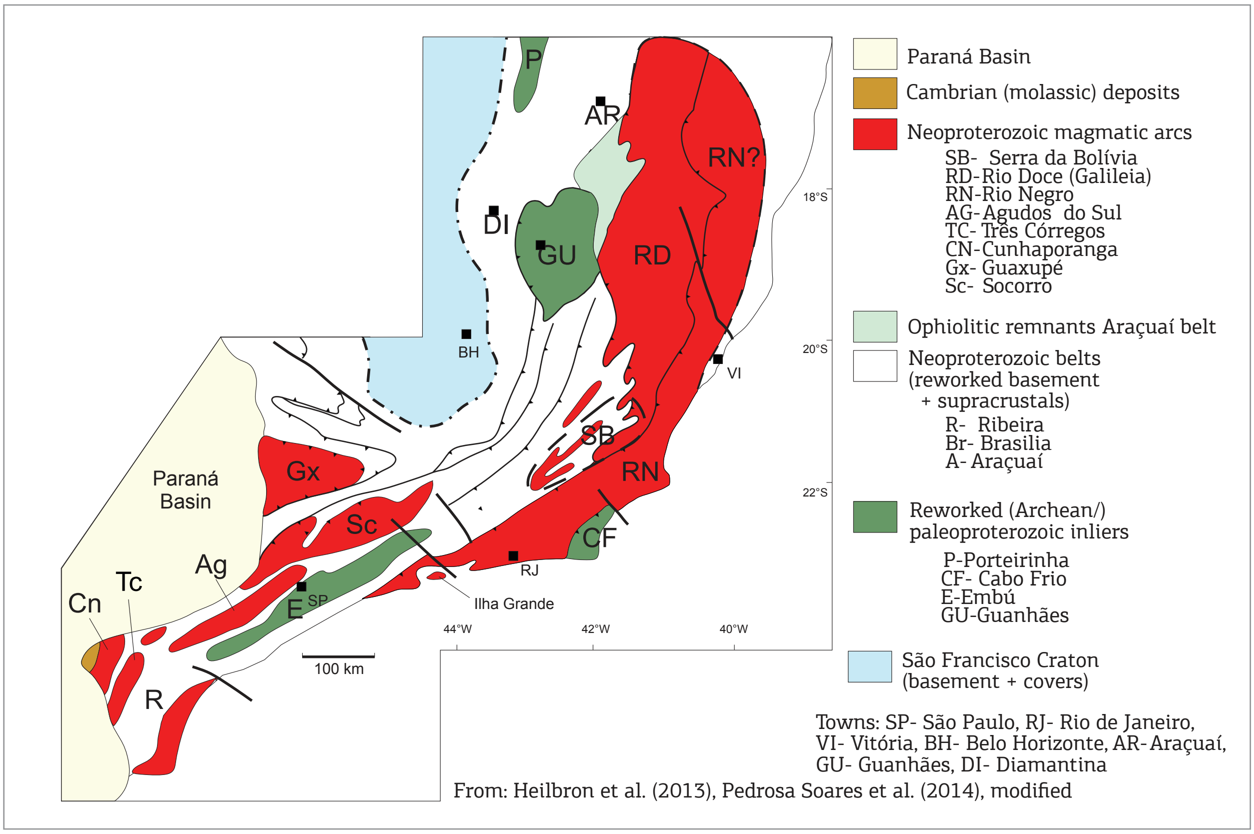


Figure 4. Sketch tectonic map of the northern part of the Mantiqueira Province (north of the 25ºS parallel). Based on Heilbron *et al.* (2013), Heilbron *et al.* (2004), Pedrosa Soares *et al.* (2014), among others.

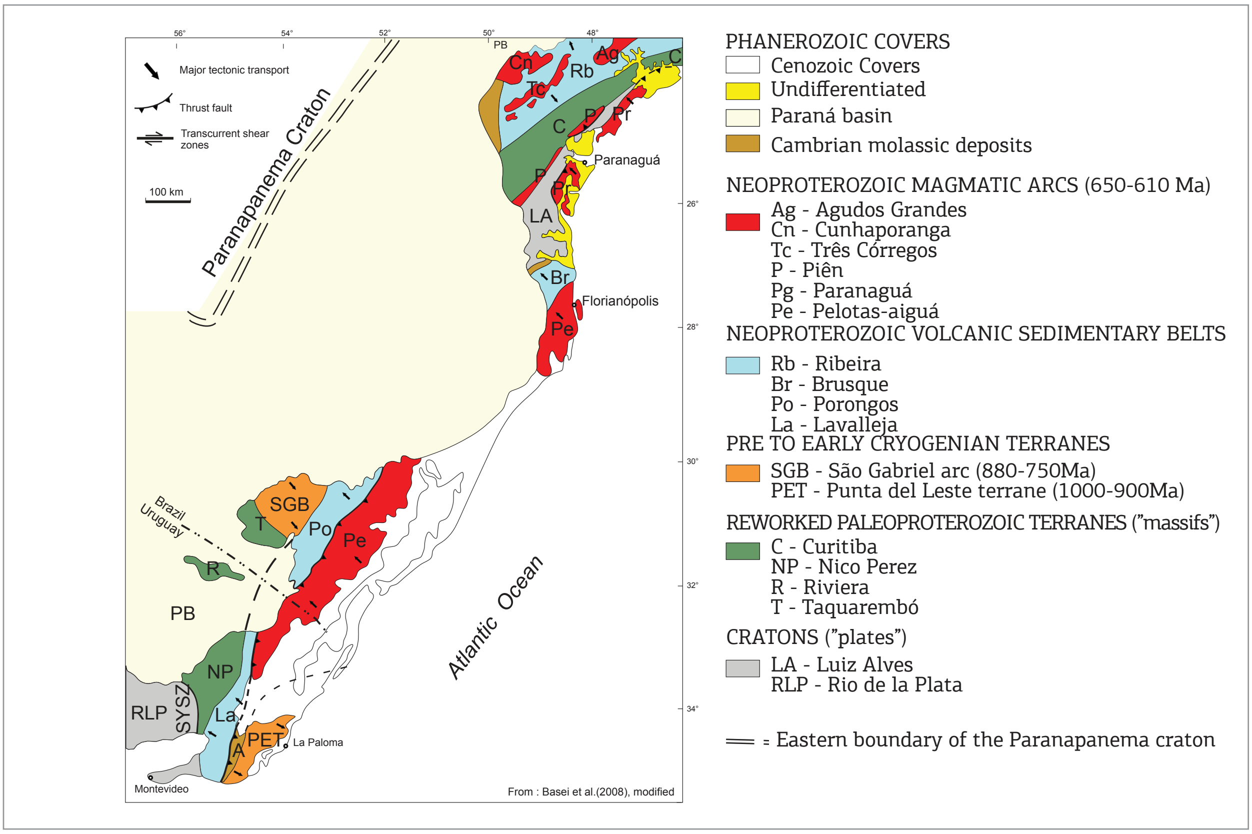
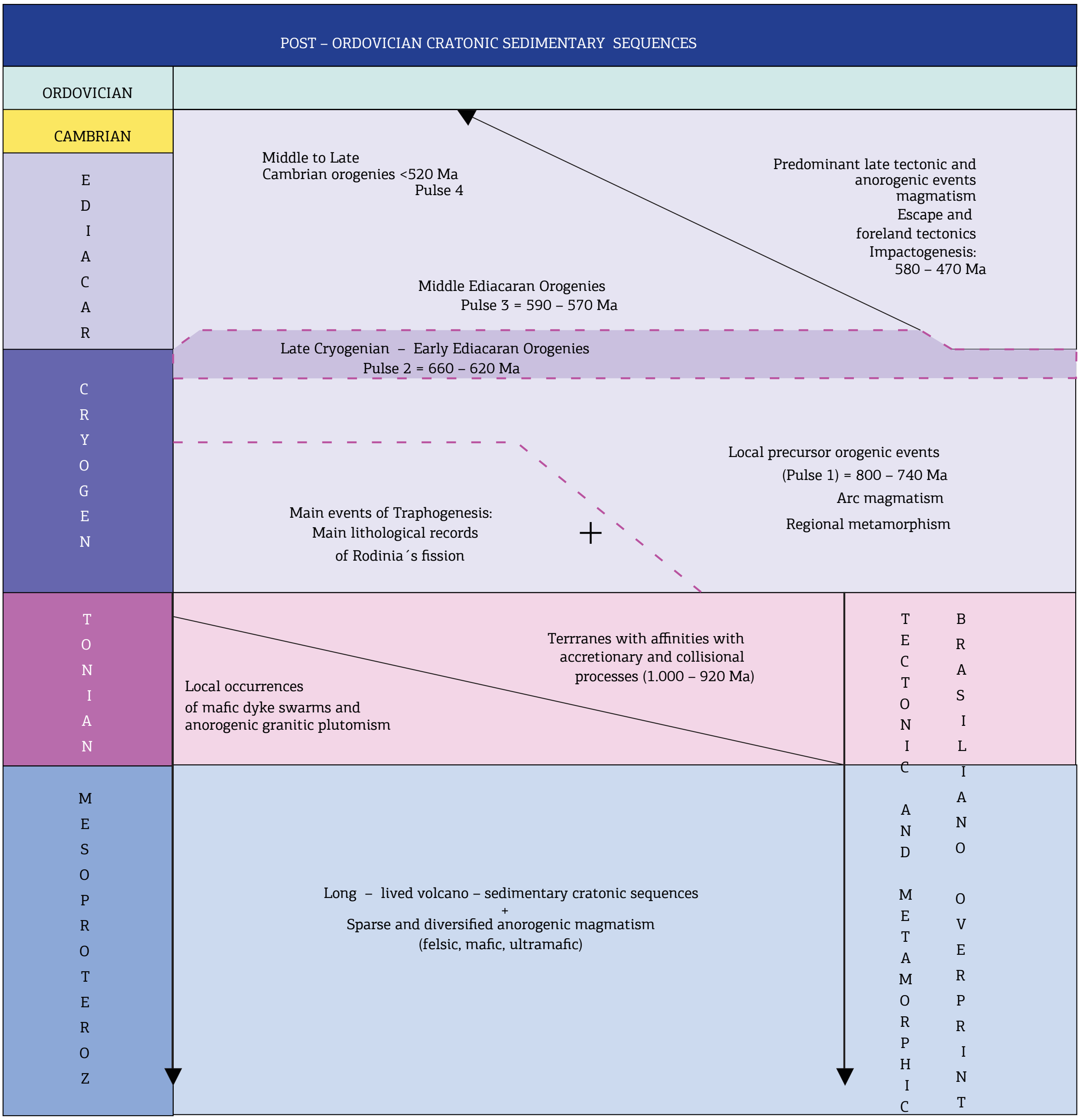


Figure 5. Sketch tectonic map of the central and southern part of the Mantiqueira Province (south of the parallel 25ºS). Based on Heilbron *et al.* (2004), Basei *et al.* (2008), among others.

Table 3. Generalized scheme of evolution for the Brasiliano domain, emphasizing the most important recognized pulses and aspects. See the text in order to follow this scheme. Based on Bizzi *et al.* (2003), Mantesso Neto *et al.* (2004), Basei *et al.* (2010), Brito Neves and Fuck (2013), among others.



Post-Tonian: The Brasiliano Orogenies

Early Criogenyan, ca. 840 – 750 Ma. ("Pulse" 1 of the Brasiliano collage)

The first events of convergent plate interaction of the Brasiliano collage are believed to have taken place in the Early Cryogenian (≥750 Ma), as recorded in most of the structural provinces, except for the Pampean Orogen. Investigation of the initial events may be hampered by the superposition of younger magmatic or tectonic events, or by the lack of outcrops, access problems or even by the lack of geochronological data.

Furthermore, the initial convergent processes are coeval with taphrogenic events (elsewhere) linked to the breakup of Rodinia, which appear to have more evidence due to a wealth of geological and isotopic data (850 – 740 Ma, Silva *et al.* 2005; Brito Neves and Fuck 2013). In other words, these extensional processes are dominant and more easily observed. In consequence, there are some obvious problems in recognizing the earliest orogenic events of the Brasiliano collage, which will be here discussed.

São Gabriel Arc

The best-documented examples of Early Cryogenian accretionary processes are from the São Gabriel arc, in western Rio Grande do Sul. The arc is partially hidden below Eopaleozoic deposits (Maricá Group, Camaquã basin) and by the Paraná cratonic basin, underlying an area of ca. 5,000 km^2, limited by the NW-SE Ibaré and NNE-SSW Irapuá faults.

The São Gabriel arc comprises calc-alkaline granite-gneiss (Cambaí Group, 890 – 730 Ma), metavolcanic-sedimentary sequence (Vacacaí Group, 760 – 730 Ma), ophiolite remnants (Cerro Mantiqueira, 740 Ma), and late 720 – 685 Ma old intrusions (Laux *et al.* 2010; Lena *et al.* 2014).

Recently, Philipp *et al.* (2014) reported some older ages in the southern part of the São Gabriel terrane. Tonalite orthogneis from the Imbicuí rock unit was dated at 875 ± 5 Ma. Intrusive diorite was dated at 745 ± 1.2 Ga. According to the authors, this may represent an older arc, possibly related with the Tonian terrains discussed above.

Cerro Bori orthogneisses

Early Cryogenian rocks are exposed in Cerro Bori, Uruguay, east of the southernmost tip of the Pelotas-Aiguá batholith. Tonalite and granodiorite gneisses, mafic and felsic granulites and amphibolite are the dominant rock types (Lenz *et al.* 2011). Petrological, geochemical and isotopic data confirm magmatic arc affiliation.

U-Pb SHRIMP data of mafic granulites indicate ages between 770 and 796 Ma. Gneisses samples were dated between 770 and 802 Ma. Regional metamorphism was dated at ca. 676 Ma, implying in a complete accretionary and collisional history before the emplacement of the Pelotas–Aiguá batholith, preceding, therefore, all other accretionary processes related with the climax of the Brasiliano orogeny. Lenz *et al.* (2011) suggested an early Brasiliano event (or Brasiliano I), following the earlier proposal by Silva *et al.* (2005). Despite the small size of this area (ca. 300 km^2), this is an important occurrence that should be remarked. Relations with the almost coeval São Gabriel arc exposed to the west side of the Pelotas-Aiguá batholith still have to be investigated.

The "Embu terrane"

The "Embu terrane" is exposed in the central Mantiqueira Province, to the northwest and north of the Curitiba terrane up to the northern part of the province (Figs. 4 and 5), striking NE-SW for more than 250 km and up to 40 km wide (Heilbron *et al.* 2004; Campos Neto *et al.* 2007; Alves *et al.* 2013; Trouw *et al.* 2013). The Embu terrane is recognized as a continental fragment docked at the Ribeira belt during the Ediacaran, when the Paranapanema and São Francisco plates collided. It comprises Paleoproterozoic gneiss (shown as a basement inlier in Figs. 4 and 5), medium- to high-grade supracrustal rocks, as well as Cryogenian gneiss, and granite intrusions dated at 600-590 Ma.

Early Cryogenian tonalite and granodiorite gneisses with magmatic arc affinities exposed to the south of São Paulo were dated at 811 ± 13 Ma (Cordani *et al.* 2002) while muscovite leucogranites from the western "Embu terrane" were dated at 760 – 740 Ma (Passarelli *et al.* 2004). Xenotime and monazite from the Mogi das Cruzes granite yielded ages of ca. 790 Ma (Vlach 2001), similar to the age of regional metamorphism.

Orogenic and anorogenic granite magmatism took place between 650 and 500 Ma, with the main peak between 590 and 540 Ma (Alves *et al.* 2013). The available data suggest that the "Embu" is a Brasiliano terrane, although early Cryogenian, as well as Meso- and Paleoproterozoic events have also been identified (Alves *et al.* 2013). However, connections with coeval events in neighboring terranes and belts have yet to be investigated. There are some unpublished data pointing out the occurrence of some pre-Proterozoic rock units (at its northernmost part).

The Ceres-Rialma Metamorphic Belt

A high-grade metamorphic belt is exposed along the headwaters of the Tocantins River in central Brazil, east of the Mara Rosa arc and Goiás massif. It extends for more than 350 km, striking NNE-SSW, and was formed in the Early Cryogenian (Moraes & Fuck 1994; Moraes *et al.* 2004, 2006, among others).

The western part of the belt comprises sedimentary and volcanic rocks of the Juscelândia, Indaianópolis and Palmeirópolis sequences and the Serra da Malacacheta and Serra dos Borges gabbro-anorthosite complexes, formed in a rift environment that evolved to ocean floor at ca. 1,270 Ma. These rocks overlie tectonically the eastern part of the belt that is made of the Barro Alto, Niquelândia and Cana Brava mafic-ultramafic layered complexes (Moraes *et al.* 2004; Ferreira Filho *et al.* 2010, among others). It has been suggested that the layered complexes are originally related to the taphrogenesis processes that led to the Rodinia breakup (Brito Neves & Fuck 2013), at about 800 Ma (Pimentel *et al.* 2004; Della Giustina *et al.* 2011).

Although the original igneous stratigraphy and mineralogy of the complexes were disturbed by late Eocryogenian tectonic-metamorphic processes (750 – 770 Ma, Ferreira Filho 1994; Moraes *et al*. 2006), it has been possible to retrieve petrological and geochemical data. These suggest that they may have been a single large body, representing an Eocryogenian LIP (Moraes *et al*. 2004), an inference which appears to be supported by geophysical data (Soares 2005; Soares *et* al. 2010). The two parts of the belts are singularly different in origin and age, but were juxtaposed tectonically, deformed and metamorphosed together under high-grade conditions of high-T amphibolite and granulite facies. They form an unusual high-grade belt between the Goiás massif and the Paleoproterozoic Natividade-Cavalcante block, basement to the external zone of the Brasília belt. Another notable feature of the high-grade belt is that its metamorphic gradient is opposite to that of the Brasília belt: it increases from west to east.

Despite the numerous investigations carried out on the belt, several questions are still pending. The age of closure and inversion of the western Ectasian rift is still debatable, although Moraes *et al*. (2006) present preliminary data suggesting metamorphism between ca. 0.75 – 0.76 Ga, as indicated by U-Pb analysis of metamorphic zircon and Sm-Nd garnet-whole rock isochrons on rocks of the Juscelândia sequence. The causes of orogeny and high-grade metamorphism are still poorly understood. Subsequent Neocryogenian tectonics and magmatism are rather complex, and hamper the understanding of previous events. It seems likely that the orogenic process may have been caused by compressive far-field stresses resulting from the inversion of the large rift that led to the intrusion of the layered mafic-ultramafic complexes. So far, no obvious connection could be established with the other Cryogenian terrains discussed above.

Neocryogenian-Early Ediacaran (650/600 – 600/590 Ma)— "Pulse" 2 of the Brasiliano collage

The Neocryogenian-Early Ediacaran time interval is marked globally by post-Rodinia and pre-Gondwana events, and by diachronic accretionary and collisional processes in all of the Neoproterozoic structural provinces in South America. Large orogenic chains with important crustal accretion events were then developed. They also include important recycling of Mesoproterozoic to Paleoarchean crustal material. Narrow and wide oceans (Campos Neto 2000; Schobbenhaus & Brito Neves 2003; Basei *et al*. 2008) were consumed in a varied and complex scenario of plate interaction and continent formation. Collisional processes were followed soon after (late Cryogenian-early Ediacaran) by the intrusion of typically collisional syenite and granite bodies emplaced in thickened crust. In other cases — e.g., SE of Brasilia belt, north of Mantiqueira province —, the collision was entirely confined within the early Ediacaran.

Tocantins Province

In the Tocantins Province (Figs. 2 and 3), the Brasiliano part of the Goiás magmatic arc (Pimentel *et al*. 2000, 2004; Fuck *et al*. 2006; Oliveira *et al*. 2006; Dantas *et al*. 2006) and of the Socorro-Guaxupé nappe, further south (Campos Neto & Caby 2000), are relatively well studied, with reference to interacting plates, closed ocean realms, as well as to their accretion history (650 – 630 Ma) and subsequent collision (ca. 625 Ma). Metamorphic processes and post-collisional events are relatively well constrained.

The Araguaia (Rokelide) orogenic system further north within the Tocantins Province displays good geological and geochronological records of ocean closure (770 – 550 Ma), as attested by the Quatipuru, Serra do Tapa and Tucuruí ophiolites (Paixão *et al*. 2008). So far, there is no clear evidence of related arc magmatism. However, based on positive gravity Bouguer anomalies observed in the basement, it has been suggested that the Goiás magmatic arc might branch out northwards below the Parnaíba basin (Castro *et al*. 2014).

Borborema Province

An important accretionary event has been recorded in the western Borborema Province (Fig. 1). The Santa Quitéria-Tamboril system is ca. 380-km-long, striking north-south, and up to 110-km-wide (Fetter *et al*. 2003; Santos *et al*. 2008, 2009; Araújo *et al.* 2012; Costa *et al*. 2013; Vasconcellos *et al*. 2013). Several aspects of arc formation and evolution are still unknown, due to the lack of data and to the superimposed extrusion tectonics. Recent magnetotelluric data display evidence of double convergent subduction below the Santa Quitéria arc (Padilha *et al*. 2014), corroborated by remnants of eclogite/retroeclogite and high-pressure granulite on both sides of the arc (Santos *et al.* 2009; Amaral *et al*. 2011, 2012).

In the "Zona Transversal" of the Borborema Province, and in several other areas, there are references of granites formed in magmatic arcs (e.g. "Conceição", "Brejinho", "Riacho do Icó", "Timbaúba", "Caboclo-Nova Olinda", "Curral de Cima", etc. (Brito Neves *et al*. 2003; Ferreira *et al*. 2004; Sial *et al*. 2008), the majority of which were dated between 650 and 620 Ma.

These granites of the "Zona Transversal" domain (central-western part) are mostly piercing rock assemblages of the Piancó-Alto Brígida (SPAB), Riacho Gravatá (RG) and Alto Pajeú terranes (AP) (See Fig. 1). This group of granites deserves further investigation, and, informally, they have been grouped as part of the "Alto Sertão Magmatic Arc".

Accretionary orogenic evolution has also been proposed for the northern part of the Sergipano belt, on the southern border of the Pernambuco-Alagoas massif (Oliveira *et al.* 2010), where ages are well constrained between 630 and 617 Ma.

In the African Dahomeyan-Trans-Saharan counterpart of the Borborema Province, Caby (2011) reports that the main calk-alkaline plutonic phase of active continental margin took place at 640 – 630 Ma, followed by regional metamorphism at 620 – 600 Ma.

Mantiqueira Province

Accretionary processes have also been recognized in the Mantiqueira Province, from eastern Minas Gerais to eastern Uruguay (Figs. 4 and 5), forming different branches for more than 1,500 km along the eastern margin of the continent, between 18ºS and 34ºS (Cordani *et al.* 2000; Bizzi *et al.* 2003; Mantesso Neto *et al.* 2004; Silva *et al.* 2005, among others). The accretionary systems are not continuous along the strike of the province, but are supported by a wealth of geological, geochemical and geochronological data. These include:

- Rio Doce, in Minas Gerais, Espírito Santo and Rio de Janeiro (Heilbron *et al.* 2004; Pedrosa Soares *et al.* 2006, 2014), possibly extending to the coastal Serra Mar in São Paulo (Campos Neto 2000): 630 – 590 Ma < 580 – 570 Ma (main accretionary phases).
- Serra da Bolívia, from southern Espírito Santo to the south of Rio de Janeiro (Heilbron *et al.* 2013): 620 – 595 Ma.
- Rio Negro, in Rio de Janeiro and São Paulo (Tupinambá *et al.* 2007, 2010; Heilbron *et al.* 2004): 792 Ma, 650 – 630 Ma.
- Cunhaporanga, Três Córregos and Agudos Grandes, in São Paulo and Paraná (Prazeres Filho *et al.* 2003; Siga Jr. *et al.* 2011): 630 – 610 Ma.
- Pien, in Paraná (Basei *et al.* 2008): 615 Ma.
- Florianópolis, Pelotas-Aiguá, in Santa Catarina, Rio Grande do Sul and Uruguay, respectively (Silva *et al.* 2005; Basei *et al.* 2008): 635 – 590 Ma.

The scheme of plate interactions is not fully understood. In the northern part of the Mantiqueira Province, the western "São Francisco plate" represents the lower plate. The upper plate to the east was possibly the "Congo plate", but this is still an open question (also, there are some objections). Other authors envisage collision in a broader scenario, such as the "nutcracker model" proposed by Alkmim *et al.* (2006).

In the central part of the province, several lithospheric fragments have been mentioned as interacting plates/microplates/microcontinents; these include the Paranapanema, Curitiba, and Luis Alves blocks (Figs. 4 and 5). However, the proposed models need additional tectonic and geophysical support in order to be validated (Basei *et al.* 2008). The model developed for the southern part of the province suggests that the "Rio de La Plata" represents the lower plate (to the west) and the Kalahari (to the east), would be the upper plate (Basei *et al.* 2008). Many of the difficulties in identifying the plates involved are related to the post-collisional shear systems resulting from Neoediacaran-early Ordovician escape tectonic processes, which hamper paleogeographic reconstructions. Additionally, evolution of the South Atlantic continental margin and the Cenozoic uplift and other brittle tectonic events also mask some of the (former) Brasiliano features.

Some local and precursor events of the Neocryogenian-early Ediacaran processes and/or inheritance — Preceding "pulse" 2

In some cases, initial accretionary events have been discriminated from the dominant Neocryogenian ones, due to reliable isotopic data, although the lack of appropriate field data may hamper their interpretation.

In the Santa Quitéria magmatic arc, W Ceará (Borborema Province), the large majority of age determinations are in the 640-610 Ma interval. However, in the eastern part of the arc, granodiorite, metatexite and diatexite have crystallization ages between 876 and 831 Ma (Araujo *et al.* 2012), this means ca. 200 Ma older than the main phase of arc building.

In the Rio Negro arc, Rio de Janeiro (Mantiqueira Province), the main rock assemblages were formed mainly between 630 and 590 Ma. A granodiorite gneiss sample was recently dated at 792 ± 12 Ma and a granite sample at ca. 845 Ma, interpreted as the product of initial arc magmatism (Heilbron *et al.* 2004). Although additional isotopic data are needed, the new ages are duly noted.

Early – Middle Ediacaran (590 – 560 Ma) — "Pulse" 3 of the Brasiliano collage

Several tectonic events took place during the 590 – 560 Ma time interval, including accretionary orogenic processes.

As mentioned previously, rocks representing "pulse" 3, aside from those of the so-called "Rio Doce arc" in Minas Gerais and Espírito Santo, according to Campos Neto and Figueiredo (1995) and Campos Neto (2000), are exposed in the coastal zone of Rio de Janeiro and São Paulo, along the Serra do Mar ("Serra do Mar terrane", Campos Neto 2000). According to this peculiar concept of the "Rio Doce arc" (590 – 570 Ma), its rock forming events overlap those of the preceding orogenic pulse represented by the Rio Negro arc, exposed eastwards. According to Campos Neto and Figueiredo (1995) and Campos Neto (2000), these events have (some type of) connection with those of the Rio Doce orogeny in the Araçuaí belt, further north in the Mantiqueira Province. So, a precise separation of the orogenic "pulses" (arc magmatism) 2 and 3 along the coastal zone of the Mantiqueira Province is still uncertain (Heilbron *et al.* 2013).

In the Borborema Province, granite magmatism, including high-K, peralkaline, ultrapotassic, and rarely shoshonitic magmatism, took place mainly in the time interval between 590 and 570 Ma (Ferreira *et al.* 2004; Sial *et al.* 2008). These magmatic events followed the emplacement of epidote-bearing tonalite and granodiorite (of the "pulse 2"), these probably related with arc magmatism ("Alto Sertão Magmatic Arc"), between ca. 650 and 620 Ma.

In addition to the successive accretionary events, there are several indications of intraplate orogenic processes without any evidence of previous subduction. Collisional/metamorphic events (ca. 590 – 560 Ma) have been recorded in some particular cases of the Brasiliano structural provinces (e.g. part of the northern Mantiqueira Province, to the north of the Patos lineament in the Borborema province, etc.).

The identification of truly orogenic events occurring during the Early-Middle Ediacaran has been difficult, due to concurrent post-orogenic tectonic and magmatic events, as well as anorogenic magmatism, which overlap in time and space with the orogenic rocks.

According to Tupinambá *et al.* (2007, 2010), the accretionary phase of the Rio Negro arc ended around 600 Ma ago, and the collisional phase started soon after, including several syn-collisional magmatic events until 560 Ma. These authors admitted also that another magmatic arc may have been accreted at the beginning of the collisional phase, reiterating previous observations by Campos Neto (2000).

Post-collision processes have been recorded in many places, such as granite and syenite magmatism (e.g. Itu and Graciosa suites, Teixeira-Terra Nova tectonic zone, late granites of the Rio Doce and Rio Negro arcs, Araguaia and Brasilia belts granites, granite magmatism piercing through basement inliers in the Borborema Province, etc.). Given the widespread occurrence of processes and their record, this is clearly a time interval composed of a diversified plethora of tectonic and magmatic activities. The distinction between the events of this time interval, late and post-collisional processes, from the previous ones, arc magmatism and metamorphism, still needs to be completed with new and better geological field data and isotopic information. It is also useful to bear in mind that escape- (extrusional) tectonic processes and foreland tectonics affecting the South American Platform as a whole (in fact a large part of West Gondwana) started soon after 580 Ma. These processes obliterated some of the original geological relationships.

Cambrian Orogenies (530 – 490 Ma) — "Pulse" 4 of the Brasiliano collage

From the late Ediacaran to the early Ordovician, the most remarkable tectonic events in South America are related to post-collisional processes, marking the transition from unstable to stable tectonic conditions. They mainly include escape tectonics and associated sedimentary processes, foreland tectonics, extension-related intrusions and isostatic adjustments.

While such processes were underway, two local minor orogenic developments were in process in the eastern and southwestern parts (Búzios and Pampean orogenies, respectively) of the continental area that soon after became Western Gondwana.

Búzios orogeny

The Cambrian Búzios orogeny, the youngest event of the Ribeira belt in the Mantiqueira Province, is recognized in the coastal zone of Rio de Janeiro (Região dos Lagos, Schmitt *et al.* 2008; Schmitt & Armstrong 2014).

The tectonic evolution started with the history of a small (residual?) ocean basin from 610 Ma onwards, where volcanic-sedimentary sequences accumulated. These rocks were deformed and metamorphosed under high-grade conditions, and transported to the northwest at ca. 520 Ma. The hypothesis is a process of subduction of the "Angola plate" (to the east) under the "Terreno Oriental" (to the west). This is estimated to have taken place between 590 and 530 Ma, which was followed by collision at ca. 530 – 520 Ma. Late igneous and tectonic activity took place between 520 and 490 Ma (Schmitt *et al.* 2008). The authors compare this complete Wilson cycle with the products of Pan-African orogeny in the Kaoko belt in Angola and Namibia. Schmitt and Armstrong (2014) admit that the orogeny extended until ca. 490 Ma in a stepwise process that progressed to a poorly understood Ordovician orogenic collapse, until middle Ordovician times.

Pampean orogeny

The Pampean orogenic belt, east of Cordoba, Argentina (Fig. 6), developed in response to the subduction of the lower "Pampia microplate" to the west, made of high-grade "Grenvillian" rocks, under the Rio de La Plata upper plate in the east (Rapela *et al.* 1998; Escayola *et al.* 2007; Schwartz *et al.* 2008). The orogen comprises two parallel belts, the eastern one comprising mostly calc-alkaline magmatic rocks, and the western made of metasedimentary rocks and peraluminous granites. Calc-alkaline magmatism was active between 555 and 525 Ma, whereas peraluminous intrusions associated with regional metamorphism took place in the Early Cambrian (525 – 515Ma). Ophiolite remnants were dated by the Sm-Nd method at 647 ± 70 Ma (Escayola *et al.* 2007).

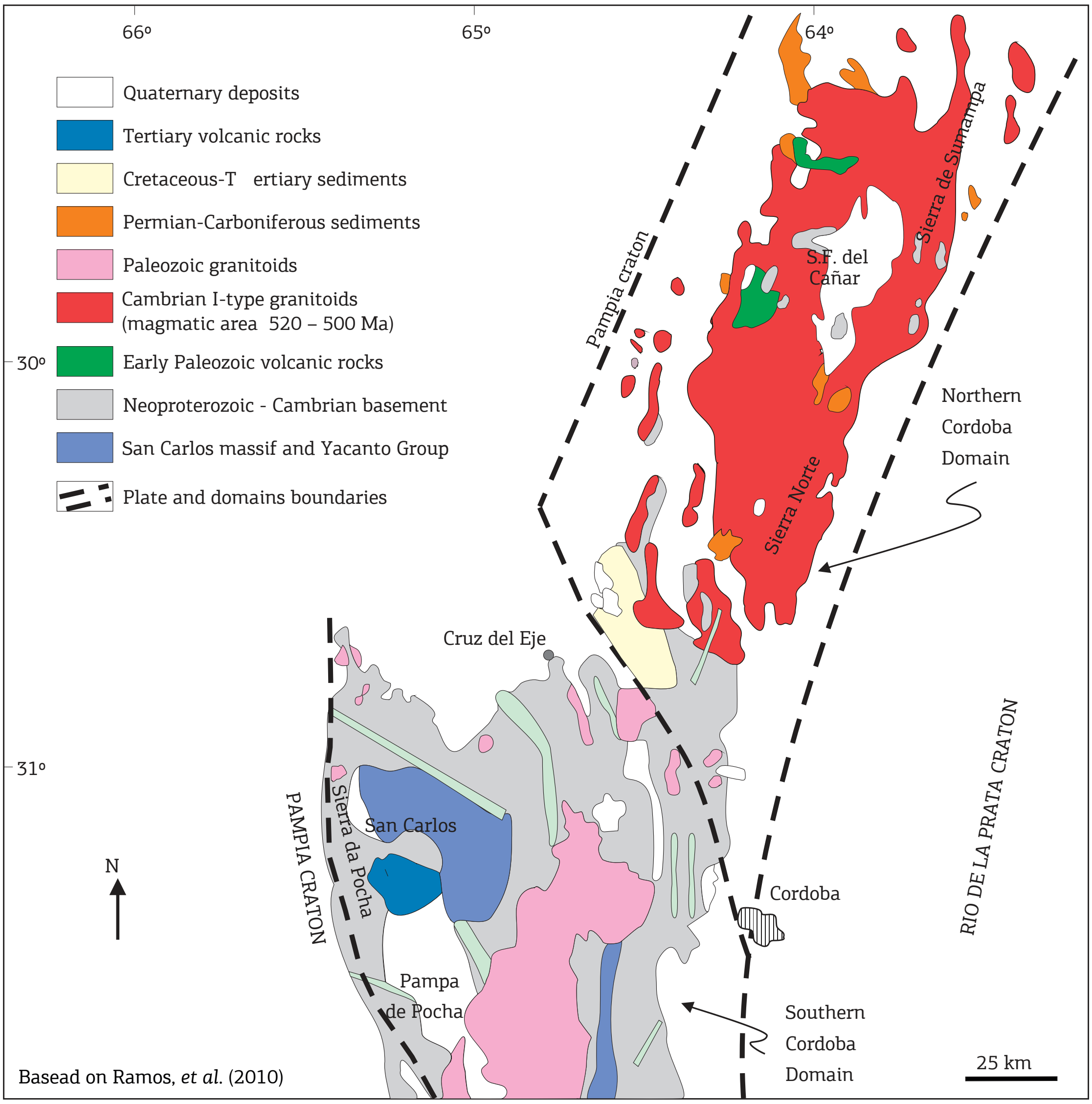


Figure 6. The Pampean orogen, west of Cordoba, Argentina. Modified of Escayolla *et al.* (2007), Schwartz *et al.* (2008), Ramos and Vujovich (2010).

Schwartz *et al.* (2008) proposed a possible connection with the "Terra Australis orogen", along the closing paleo-Pacific Ocean. In a regional perspective, there is the possibility of a northward connection with the Paraguay belt (south-western border of the Amazonian plate), although there is no evidence for subduction of ocean lithosphere in the latter. Additional geological and geophysical data are necessary to test this model.

PRELIMINARY CONSIDERATIONS ABOUT GONDWANA AMALGAMATION

Processes leading to amalgamation of supercontinental masses are complex, long lasting, and accomplished according to amalgamation fronts of distinct paleogeography. Eventually, amalgamation processes in one province or front concur in time with taphrogenesis or breakup processes taking place in other areas. These are fundamentally diachronic processes from one amalgamation front to another and from one province to another. Therefore, understanding supercontinent formation requires a large amount of geological, tectonic, paleomagnetic and isotopic data. Additionally, it should be remembered that supercontinents are not the final product of configuration, therefore improvement of tectonic models are necessary.

Several distinct models for the assembly and evolution of Gondwana have been proposed, but the problem is far from resolved. Many questions still remain, demanding different levels of geological and geophysical investigations in different continents.

According to the recent proposal by Collins *et al.* (2011), processes took place along three different fronts of present day southern continents. Should this be the case, two of these fronts are represented in the South America basement, in addition to Mediterranean-Middle East-Arabia, East Africa-Madagascar-India-Sri Lanka-Antarctica, with ramifications to Zambezi and Damara, and Rokelides-Araguaia-Paraguay-Pampean.

There are other models/versions of Gondwana formation, e.g. Stern (1994), Meert (2003) (Kuunga and East Africa orogenies); Zulauf *et al.* (2004) (Cadomian orogeny), Meet and Lieberman (2008), Linnemann *et al.* (2008, 2014) (North Africa, Cadomian orogeny), etc. See discussions in the next item of this paper. Consensus seems to be hard to achieve, and it will certainly take time to better understand amalgamation of Gondwana.

Independent of academic dissent, and aware of the need for new data, it can be stated that the Brasiliano collage in South America (and in part of westernmost Africa) comprises four distinct phases (main "pulses"), from the early Cryogenian (Neoproterozoic) to the early Ordovician (in some special cases, up to the upper Ordovician, ca. 440 Ma). The latest processes of collage fronts that ended up in Western Gondwana amalgamation are recorded in South America, and some similar and coeval events have been recorded in westernmost Africa (e.g. Schmitt *et al.* 2008; Schmitt & Armstrong 2014).

From Bahia to Uruguay, the Mantiqueira Province displays the most complete record of the main tectonic-magmatic events referred to above, including the Tonian terranes and the four Neoproterozoic pulses. None of the other provinces present such a complete record. However, as mentioned previously, there are some unsolved questions related to the adequate and precise discrimination of the pulses discussed above (pre-740 Ma; 650 – 630 Ma; 590 – 560 Ma; 530 – 490 Ma). Also, it will be necessary to refine time interval limits, as well as to search for additional magmatic and metamorphic records. It should be noted that in the Araçuaí belt, northern portion of the Mantiqueira Province, late-collisional granites were intruded from 590 to 530 Ma. Similar intrusions were reported from the Borborema Province and other areas. However, robust isotopic data are lacking.

Where and when did Gondwana finally amalgamate?

In general, the orogenic processes that led to Gondwana amalgamation (Collins *et al.* 2011) are somewhat similar and coeval (~ 750Ma ± Δx – 500 Ma ± Δx), in its western as well as in its eastern portion. Early phases, nevertheless, display some important time differences. On the other hand, late- to post-orogenic events tend to overlap in the late Ediacaran, or in the middle Cambrian, occasionally extending into the Ordovician. This most important set of geotectonic processes coincides with one of the most dynamic periods of Earth evolution, involving all its geospheres and their components. The overall time lapse comprised in this long, complex and polyphase assembly process (ca. 280 – 250 Ma) is comparable to that of the assembly of Pangea, between 500 and 230 Ma ago (270 Ma), for which scientific foundation (Stratigraphy, Paleontology, Paleomagnetism) is much more reliable.

Similarities notwithstanding, detailed analysis of each portion of the continent shows that the orogenic collage pulses are quite distinct in time and importance. It should be noted that the polyphase development of Gondwana (Tab. 4) bears many similarities with the formation of Pangaea, where several phases (e.g. Caledonian, Alleghenian, etc.), are constantly highlighted. However it is well known that they are not exclusive.

Northern part of Gondwana

In northern Gondwana, three main orogenic phases have been distinguished (Linnemann *et al.* 2008, 2014; Pereira *et al.* 2012, among others), the last, related to the evolution of the Rheic ocean, and the initial development of Pangaea:

- Mid-Ediacaran, > 590 – 570 Ma, magmatic arc stage (Avalonian) and formation of backarc basins;
- Late-Ediacaran, 570/560 – 545/543 Ma, oblique collision between the Cadomian arc and the hinterland, closing the Cadomian backarc basin and other related basins;
- Cambrian-early Ordovician, 540 → 500/485 Ma. There is no abrupt break between the Cadomian orogeny and Cambro-Ordovician rifts, which led to the Rheic ocean opening. After collision, slab break-off is thought to have taken place from 540 Ma onwards, overlapping rifting and new ocean opening. U-Pb age data between 522 and 499 Ma of the sedimentary deposits (Serra Negra succession, Pereira *et al.* 2012) indicate that they are part of a new post-discontinuity cycle above the Early Cambrian unconformity of 542 Ma.

Eastern Gondwana

Several distinct, although not necessarily opposite, digressions apply to eastern Gondwana evolution, from the Arabian–Nubian shield, to India, western Australia and Antarctica.

a) Collins and Pisarevsky (2005) provided an excellent synthesis based on rich paleogeographic documentation and paleomagnetic data of the whole evolutionary process, starting at 750 Ma. The authors display the continental masses involved, as well as the intervening oceans (Mozambique, "Adola", Adamastor, "Braziliano", "Pacific"). Three orogenic phases of the collage are recognized:

- The first orogenic phase (c. 630 Ma) is recorded between east Africa ("Azania") and the "Congo/Tanzania/ Bangweulu" ("CTB") masses, and between these and the continental masses of the "Saharan metacraton", including closure of several minor ocean basins between them;
- Early Ediacaran (ca. 570 Ma), when "CTB" collided with the São Franciscano block. There is no record of this collision in South America, or of its continuity into the collision with "Azânia";
- Early Cambrian (540 – 530 Ma), encompassing a series of collision processes east and west of India with "Austrália–Mawson", and "Azânia", and of "CTB" with Kalahari (including northern Mantiqueira Province?) and Rio de La Plata (Don Feliciano belt?). Associated with these processes, high-grade metamorphism took place in several of the resulting mobile belts.

b) Based on geochronological and other databases, Meert (2003) and Meert and Lieberman (2008) present different concepts and syntheses, displaying several noticeable and well-documented phases for the 750 – 530 Ma time interval:

East African orogeny:

- ca. 750 Ma (between 780 and 720 Ma): important accretion phase, arc magmatism from northern Africa (Arabia-Nubian shield) to Antarctica.
- ca. 640 Ma (between 700 and 610 Ma): important phase of collisions, high-grade metamorphism, and in some cases initiation of escape tectonics (Arabia-Nubian shield, Somalia, Eritrea).
- ca. 550/540 Ma (between 590-520 Ma) — Kuunga orogeny —: collision, high-grade metamorphism and post-orogenic magmatism in several belts. Structures related to the Kuunga orogeny strike orthogonally to those of the East African orogen, between the southwest coast of Africa (Damara), southern India and western Australia.

Meert (2003) has suggested that the 500 Ma old Ross-Delamerian belt (Australia-Antarctica-South Africa) should be ascribed to a later event that took place after final suturing of Gondwana, adding to the controversy about the belt. This suggestion is a matter of dispute.

West Gondwana

As discussed above, and previously highlighted by Brito Neves and Fuck (2013), four main orogenic pulses are recorded

Table 4. A review of the main proposed schemes for the geochronological evolution of Gondwana at different sectors.

WEST GONDWANA	NORTH GONDWANA	EAST GONDWANA	SOUTH GONDWANA
East Brazil/ West Africa	North America/ North Africa/ Eurasia	East Africa India/ Antarctica	Antarctica/ Australia
Brasiliano/ Pan-African	Avalonian/ Cadomian	Eastern Gondwana "EAO	Ross Delamerian
This paper	Pereira *et al.* (2012)	Meert (2003) Meert and Lieberman . (2008)	Foster *et al.* (2005) Goodge . (2007)
0.590 – 0.560 Ga	*Rift-drift processes* 0.500 – 0.480 Ga	*Kuunga Orogeny* 0.570 – 0.530 Ga	~ 0.540 Ga
Main phases of orogenic processes			
0.660 – 0.610 Ga	0.653 – 0.545 Ga Late Cadomian. 0.700 – 0.653 Ga Early Cadomian	0.650 – 0.620 Ga	0.650 – 0.600 Ga
Local precursor events			
0.850 – 0.750 Ga	0.850 – 0.700 Ga	~ 0.750 Ga	0.800 – 0.750 Ga
Tonian terranes			
1.000 – 0.920 Ga	– – – – – – – – – – –	1.000 – 0.900 Ga	– – – – – – – – – – – –

in the Gondwana portion of South America. Further considerations on the final orogenic processes (Pampean and Búzios) are presented below.

Buzios Orogeny

In the central-northern portion of the Mantiqueira Province, another Cambrian orogen is recognized, as discussed above. The orogenic belt appears to correspond to the closing of a small oceanic basin or back-arc, which remained between the "Terreno Oriental", the upper plate of the Ribeira orogenic belt, and a colliding continental fraction (Cabo Frio terrane), in the east, interpreted by some authors as a slice from the Congo craton/plate.

The collisional process probably closed a remnant fraction of the Adamastor Ocean, and led to intense low-angle deformation and high-T amphibolite to granulite facies metamorphism. Geological and geochronological studies (Schmitt *et al*. 2008; Schmitt & Armstrong 2014) identified Cambrian ages of 530 – 510 Ma for the orogeny, which was followed by collapse and extrusion between 510 and 480 Ma. Geological and geochronological equivalents were found in western Africa, within the Kaoko belt (Schmitt *et al*. 2008). Recently, Schmitt and Armstrong (2014) presented new data, reiterating the Middle to Late Cambrian age of 515 – 510 Ma, possibly extending up to 490 Ma, for the Búzios orogeny. Still not well-understood collapse processes occurred until the Mid Ordovician (c. 440 Ma).

Pampean

Escayola *et al*. (2007) reported the Sm-Nd isochron age 647 ± 77 Ma for ophiolite remnants and interpreted it as the best age estimate for the development of oceanic lithosphere in the belt. Early Cambrian ages of 530 – 514 Ma were recorded for the calk-alkaline arc magmatism and subsequent metamorphism (collision).

Schwartz *et al*. (2008) concluded that subduction started at 555 Ma, in the Ediacaran, establishing ages of 555 – 525 Ma for the arc magmatism, partially overlapping with the data of Escayola *et al*. (2007). They pointed out 525 Ma as the age of collision and metamorphism, revealing the record of Early Cambrian amalgamation of Gondwana in southwest South America.

Recent data (Rapela *et al*. 2014) added new information to the age of the Pampean orogeny. Metasedimentary rocks affected by the orogeny include a 525 Ma old detrital zircon peak among Neo- and Mesoproterozoic and older zircon grains. Therefore, ages younger than 525 Ma should be expected for the orogeny, allowing the possibility of ages from the Middle to Late Cambrian (< 530 Ma).

It is also possible that these orogenic processes reached farther north, encompassing the southern branch of the Paraguay belt (MacGee *et al*. 2012). This proposition has been challenged by Cordani *et al*. (2013a).

Although remote, there is the possibility of a connection between the Pampean and the Ross-Delamerian orogens (positioned to the south of Gondwana, south of Antartica and Australia). Lack of data hampers discussion at this time.

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