The Ediacaran to Cambrian Rift System of Southeastern South America: Tectonic Implications

Renato P. Almeida, Liliane Janikian,[1] *Antonio Romalino S. Fragoso-Cesar, and Gelson L. Fambrini*[2]

Instituto de Geociências, Universidade de São Paulo, Rua do Lago, 562, Cidade Universitária, São Paulo, SP CEP 05508-080, Brazil (e-mail: rpalmeid@usp.br)

ABSTRACT

The tectonic evolution of southeastern South America from the Middle Ediacaran to the Early Cambrian is marked by a series of small fault-bounded siliciclastic and volcaniclastic basins and voluminous coeval granites traditionally associated with the compressional or transpressional tectonics of the late stages of the Pan-African-Brasiliano orogeny. Most existing models consider these basins separately, with distinct tectonic evolutionary histories according to local geological settings. However, new and recently published age constraints, lithological similarities, and structural aspects point to the correlation of all Ediacaran to Cambrian basins in southeastern South America within a common basin system more than 1500 km long. The interpretation of a common origin for all Ediacaran to Cambrian basins of southeastern South America implies that all the different terranes of the Brasiliano orogenic collage in the region were already united in a single plate at approximately 600 Ma. An extensional origin for this basin system is interpreted from the recognition of basin-forming normal faults (later reactivated as strike-slip or inverse) feeding alluvial fans and from expressive basic to acidic volcanic successions in several basins. The occurrence of basic, intermediate, and acidic volcanic rocks and voluminous coeval granites indicates that mantle and crustal fusion were simultaneous with the extensional event. Raised temperatures may have caused the thermal weakening of the lithosphere, enabling both extensional deformation and recurring strike-slip deformation that formed major shear zones in the region. This strike-slip deformation has been mistaken for basin-forming tectonics, but it occurred in the Early Cambrian, after the formation of the basins, and most probably was the result of the far-field propagation of compressional stresses originating in younger collisional orogens at the plate margins.

Online enhancements: color versions of figures 4 and 5.

Introduction

The tectonic evolution of the Neoproterozoic fold belts related to the amalgamation of Gondwana is continuously being debated, mainly with respect to the style and timing of the plate interactions responsible for their final configurations. In southeastern South America, the main tectonic elements of these fold belts are extensive granitic plutons and high dip shear zones that affect Paleoproterozoic and Archean high-grade terranes and low- to medium-grade metasedimentary units of Mesoproterozoic to Early Neoproterozoic age. Another important element of this evolution is a system of small, fault-bounded basins formed from Middle Ediacaran to Early Cambrian that are filled up with unmetamorphosed siliciclastic successions (mainly conglomerates, arkoses, and mudstones). Some of these basins comprise voluminous acid and intermediate volcanic and volcaniclastic rocks, enabling the geochronological dating of their successions.

Ediacaran basins occur from southern Uruguay to southern Minas Gerais State in Brazil, forming a more than 1500-km-long NE-trending system. Most previous works consider these basins separately, and their tectonic settings have been inter-

Manuscript received May 13, 2009; accepted October 20, 2009.

[1] Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, Rua do Matao, 1226, Cidade Universitária, São Paulo, SP CEP 05508-090, Brazil.

[2] Instituto de Geociências, Universidade Federal de Pernambuco, Avenida Acadêmico Hélio Ramos s/n, Sala 510, Cidade Universitária, Recife, PE CEP 50740-530, Brazil.

[The Journal of Geology, 2010, volume 118, p. 145–161] 0022-1376/2010/11802-0003$15.00. DOI: 10.1086/649817

preted in different ways in each segment of the system, depending on age constraints and local tectonic models. These interpretations can be grouped under three main models: late to postcollisional foreland basins in either peripheral (e.g., Fragoso-Cesar 1991; Rostirolla et al. 1999; Basei et al. 2000) or retroarc settings (e.g., Gresse et al. 1996), postcollisional strike-slip basins (e.g., Brito Neves et al. 1999), and intracontinental rift basins (Fragoso-Cesar et al. 2000, 2001; Almeida 2001, 2005; Janikian 2001, 2004; Fambrini 2003). In several cases, more than one model has been proposed for the same basin.

Despite the divergent tectonic models, the available geochronological data reveal that the major volcanic events preserved within the basins were coeval and that ages of deposition overlap, with successions ranging from 605 to 530 Ma. The Camaquã Basin is the most complete and best preserved of these basins, recording several subsidence events in this time span, and can be used as a reference for the correlation among the smaller basins. In light of recent reappraisals of the tectonic setting of the granites that are coeval to the basin system, recently published geochronological data from volcanic rocks, and comparisons among the stratigraphic evolutions of several basins of the system, the existing models for the origin of those basins are reviewed, and a new, integrating model is proposed.

Geological Setting

The Mantiqueira Province (Almeida et al. 1981) comprehends the mobile belts of Neoproterozoic age that occur from southeastern Brazil to Uruguay. The southern and central parts of the province include geological units formed or affected by orogenic processes of Neoproterozoic age, with peak metamorphism at 630–620 Ma (Silva et al. 2005), as well as Ediacaran to Cambrian postorogenic units, including small fault-bounded basins and voluminous granites.

The pre- and synorogenic units of the province comprise Archean to Paleoproterozoic blocks with varying degrees of Neoproterozoic reworking, metasedimentary successions deformed during the collisional events, and a juvenile terrane of probable island arc origin (fig. 1). The older blocks include the Rio de La Plata Craton at the southern part of the province and the Joinvile Block, which is disposed between two metasedimentary fold belts: the Dom Feliciano Belt (Fragoso-Cesar 1980) to the south and the southern part of the Ribeira Belt (Almeida et al. 1973) to the north (Paranapiacaba Orogen of Silva et al. [2005]). The interpreted ages for the peak metamorphism of these mobile belts are somewhat different: 640–620 Ma for the southern one (Basei et al. 2000; Silva et al. 2005) and 610–600 Ma for the northern one (Silva et al. 2005). In both belts, the collisional events affected precollisional granites and sedimentary basins as well as their basement. A Criogenian accreted intraoceanic terrane (Rio Vacacaí Terrane of Fragoso-Cesar [1991]; São Gabriel Block of Babinski et al. [1996]) is recognized north of the Rio de La Plata Craton, characterizing a suture west of the Dom Feliciano Belt. Major strike-slip shear zones, mostly with NNE to NE trends, juxtapose and deform these units and the Ediacaran to Cambrian postorogenic granites and basins.

The tectonic setting of the Ediacaran to Cambrian basins is controversial, and a series of different models has been proposed for each of the major basins of the system and for the system as a whole. The currently accepted models are mostly published in Portuguese in publications of restricted circulation and can be grouped into three main types: (1) models that consider a synorogenic setting, mainly of peripheral foreland basins (e.g., Fragoso-Cesar 1991; Gresse et al. 1996; Rostirolla et al. 1999; Basei et al. 2000); (2) models that consider a late orogenic setting of postcollisional strike-slip basins (Oliveira and Fernandes 1991, 1992; Machado and Sayeg 1992; Sommer et al. 2006); and (3) models that consider an extensional origin unrelated to the previous orogeny (Fragoso-Cesar et al. 2000, 2001; Almeida 2001, 2005; Janikian 2001, 2004; Fambrini 2003; Fragoso-Cesar 2008). Some authors also propose an evolution from syn- to postorogenic settings, recorded in the stratigraphic column of a single basin (e.g., Fragoso-Cesar 1991; Gresse et al. 1996; Paim et al. 2002; Teixeira et al. 2004). The coexistence of such conflicting models is the result of the scarcity of studies on the tectonic record preserved within the basins, since most of the hypotheses are based on models derived from the surrounding metamorphic and plutonic rocks.

Tectonic models for the voluminous granitic plutons that are spatially and chronologically related to the basin system are often the main argument in the interpretation of the tectonic setting of the basins. The interpretation of these Late Neoproterozoic granites of southern Brazil and Uruguay as the core of a magmatic arc (Fragoso-Cesar et al. 1986; Fragoso-Cesar 1991; Basei et al. 2000, 2005, 2008*b*) has been questioned in several recent works, which consider a postcollisional setting for all granites of Ediacaran age (e.g., Philipp and Machado

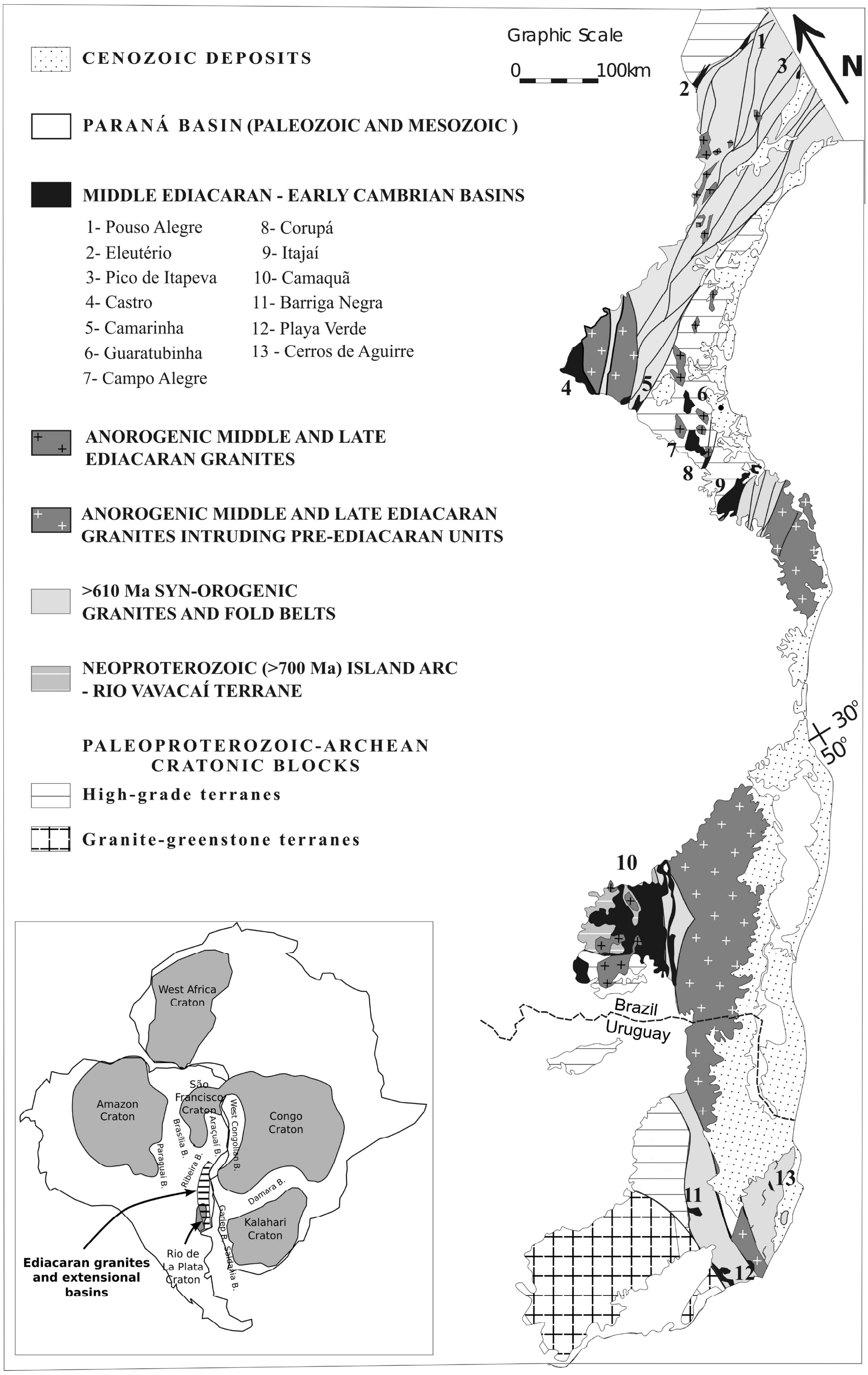

Figure 1. Schematic map of the Ediacaran to Cambrian system of basins of southeastern South America and major divisions of the southern Mantiqueira Province.

2005; Silva et al. 2005; Oyhantçabal et al. 2007) or at least for the post-570-Ma plutons (e.g., Janasi et al. 2001). In fact, the granites that are coeval to the Ediacaran System of basins are mostly A-type in all occurrences from Uruguay to the São Paulo State in Brazil (fig. 1). A-type granites of similar age are reported from southern Uruguay (Oyhantçabal et al. 2007), the Pelotas Batholith in southernmost Brazil (Philipp and Machado 2005), the Graciosa Province of Paraná (Gualda and Vlach 2007*a*, 2007*b*), and the Agudos Grandes Batholith of São Paulo (Janasi et al. 2001). Those granites commonly occur in association with syenites (e.g., Gualda and Vlach 2007*a*, 2007*b*; Nardi et al. 2008) and are considered as the record of the transition from post-orogenic into anorogenic settings by several authors (e.g., Philipp and Machado 2005; Oyhantçabal et al. 2007; Veevers 2007). Related volcanic and subvolcanic rocks, mainly of rhyolitic composition, have also been interpreted as of postcollisional nature (e.g., Philipp and Machado 2005; Sommer et al. 2006). Syntectonic (strike-slip) granites, mostly formed before 605 Ma, are systematically older than the A-type granites (e.g., Frantz and Botelho 2000).

The basin system overlies indiscriminatingly cratonic blocks, Neoproterozoic fold belts, and syn-orogenic granitic batholiths, indicating that the processes of basin formation were not restricted to any particular tectonic setting of the orogenic collage and suggesting that they had no direct causal connection with the orogenic processes.

Camaquã Basin

The Camaquã Basin is the best preserved and exposed basin of the Ediacaran to Cambrian system of basins of southeastern South America, cropping out in an area of more than 3200 km^2 in the southern Mantiqueira Province. Models for the origin of the basin include peripheral foreland settings (e.g., Fragoso-Cesar 1991), postcollisional strike-slip basins (Oliveira and Fernandes 1991, 1992; Machado and Sayeg 1992; Sommer et al. 2006), and extensional basins (Fragoso-Cesar et al. 2000, 2001; Almeida 2001, 2005; Janikian 2001, 2004; Fambrini 2003). Detailed published stratigraphic descriptions (e.g., Janikian et al. 2003, 2005; Fambrini et al. 2005*b*, 2006, 2007) and recently acquired geochronological data from several volcanogenic units (Janikian et al. 2008) enable better constraints on the chronology of the depositional and deformational events. Data from the other basins are here interpreted by means of correlation and comparison with the established chronostratigraphic framework of the Camaquã Basin.

The Camaquã Supergroup (Fragoso-Cesar et al. 2003; Janikian et al. 2003) is the lithostratigraphic unit that includes all sedimentary and volcanic successions of the Camaquã Basin, being composed, from base to top, of the following units: Maricá Group (fluvial sandstones and pebbly sandstones; marine fine-grained sandstones and siltstones), Bom Jardim Group (deep to shallow lacustrine sandstones, conglomerates, rhythmites, and mudstones; intermediate, basic and acid volcanic and volcaniclastic rocks), Acampamento Velho Formation (acid volcanic and volcaniclastic rocks), Santa Bárbara Group (alluvial sandstones, conglomerates, and sand-mud rhythmites), and Guaritas Group (alluvial sandstones and conglomerates; aeolian sandstones). Basic and intermediate hypabyssal rocks of the Rodeio Velho Intrusive Suite cut across the Camaquã Supergroup, frequently occurring as shallow sills that intrude the Guaritas Group. Angular unconformities bound these major units, and variations in the thickness of each unit in different areas of exposition suggest changes in depocenter, related to a complex history of subsidence and uplift of inner highlands (Almeida 2001; Borba et al. 2002).

The prevailing deformational style is the same in all units of the Camaquã Supergroup: highly dipping normal, oblique, and strike-slip faults, defined by discrete planes, commonly presenting striations and locally constituting fault bundles, sometimes related to drag folds, upturning of bedding planes and rare tectonic breccias. Despite that, the density of faults is greater in the lower stratigraphic units (Maricá and Bom Jardim groups and Acampamento Velho Formation). This fact is interpreted as the result of the recurrence of tectonic events along the depositional history of the Camaquã Supergroup, which are possibly related to the origin of angular unconformities. Reverse faults are observed only locally, without specific stratigraphic position. They are interpreted as the result of the same compressional events responsible for the main strike-slip faults.

Fault orientations are related to anisotropy directions of the basement of the Camaquã Basin. Prevailing faults show NE-SW to NNE-SSW trends, parallel to the metamorphic Neoproterozoic and Paleoproterozoic schistosities found in the Dom Feliciano Belt and in the northern and eastern portions of the Rio Vacacaí Terrane. Other faults show WNW-ESE trends, being controlled by metamorphic schistosity and shear zones at the southern border of the Rio Vacacaí Terrane, near its contact with the Valentines Block (northern Rio de La Plata Craton). Several different events of tectonic activation were recognized through paleostress analysis of faults with striations (Almeida 2005), the main ones being the basin-forming NW-SE and ENE-WSW extensional events and the strike-slip reactivation of the faults by NE-SW compression, causing basin inversion. Additional evidence for an extensional origin for the basin comes from provenance analysis of various stratigraphic levels (Fambrini et al. 1992; Fambrini 1998, 2003; Fragoso-Cesar et al. 2000, 2001; Almeida 2001, 2005; Janikian et al. 2003, 2005; Janikian 2004; Almeida et al. 2009), which reveals that alluvial fans and fan deltas were fed from active normal faults, without major lateral tectonic displacement between the deposits and their sources. This evidence suggests that strike-slip deformation was not related to the basin-forming events but only to postdepositional reactivation of faults with small individual displacements. The presence of voluminous volcanic successions also corroborates the hypothesis of extensional origin.

The age of the Camaquã Basin is constrained by several analyses of volcanic and intrusive rocks, which indicate an evolution from 605 to 535 Ma. The lowest sedimentary unit has a minimum age of 600.5 ± 2.4 Ma, given U-Pb zircon dating of a granitic apophysis (Janikian et al. 2008). The mainly intermediate volcanic rocks of the Hilário Formation indicated Ar-Ar crystallization ages of pagioclase of 590 ± 6, 586 ± 8, and 588 ± 7 Ma (Janikian et al. 2008). A correlatable lapilli tuff level yielded a U-Pb zircon age of 590.5 ± 5.7 Ma (Janikian et al. 2008), and a tuff level intercalated in fine-grained sediments that overlay the main volcanic interval was dated at 580 ± 3.6 Ma through the U-Pb SHRIMP method in zircon crystals (Janikian et al. 2008). The mainly acid Acampamento Velho Formation shows U-Pb crystallization ages of 574 ± 7 Ma (Janikian et al. 2008) and 573 ± 18 Ma (Chemale 2002), and younger rhyolitic rocks yielded ages of 544 ± 5 Ma (L. Janikian, unpublished data) and 549 ± 5 Ma (Sommer et al. 2005).

Whole-rock samples of basic rocks of the Rodeio Velho Intrusive Suite of the Camaquã Basin were dated by ^{40}Ar-^{39}Ar systematics following Vasconcelos et al. (2002). Samples were irradiated at the Instituto de Pesquisas Energéticas e Nucleares/ Comissão Nacional de Energia Nuclear IEA-R1 nuclear reactor. Neutron flux gradients were monitored using Fish Canyon sanidine standards. The samples were then stepwise degassed using an argon laser system, and the argon isotopic ratios were measured using a MAP-215–50 mass spectrometer at the University of São Paulo. Blanks were run between each heating step. These hypabyssal rocks were placed as shallow sills in the Guaritas Group and yielded an age of 535.2 ± 1.1 Ma (fig. 2). Soft sediment deformation features found in the contact of these sills with sandstones of the Guaritas Group indicate that the age of deposition of this last unit of the basin was close to the age of the intrusions.

Other Basins in the Southern Mantiqueira Province

Besides the Camaquã Basin, the southern Mantiqueira Province also includes smaller occurrences of volcanic and immature sedimentary rocks that represent the partial preservation of other basins of the system. These occurrences are found mainly in Uruguay, including the Barriga Negra, Cerros de Aguirre, and Playa Verde basins (the last including the Playa Hermosa, Las Ventanas, and San Carlos formations).

The Barriga Negra Basin comprises arkoses, conglomerates, and breccias that overlay metasediments of the Dom Feliciano Belt. Some authors include the Barriga Negra Formation in the evolution of the precollisional passive margin successions of the Dom Feliciano Belt (e.g., Gaucher 2000; Gaucher et al. 2005; Pecoits et al. 2008). Nevertheless, the Barriga Negra Formation comprises alluvial fan deposits with clasts derived from fault scarps that exposed those previous units, strongly suggesting that a tectonic event uplifted the previous metasedimentary deposits while promoting the subsidence of the Barriga Negra Basin (Fambrini et al. 2005*a*). In addition to the alluvial fan deposits, Fambrini et al. (2005*a*) identified fan delta, braided river, and storm-dominated shallow marine deposits. An arid climate is inferred from the abundance of marble clast in the alluvial fan deposits (Fambrini et al. 2005*a*). A maximum age of 566 ± 8 Ma is constrained by U-Pb dating of detritic zircon (Blanco et al. 2009) and corroborated by the fossil content of the underlying carbonate rocks (e.g., Gaucher 2000; Gaucher et al. 2003, 2005).

The Cerro de Aguirres Basin exposes acid volcanic rocks (mainly dacites) with a U-Pb SHRIMP crystallization age of 571 ± 8 Ma (Hartmann et al. 2002). The Playa Verde Basin is composed of three isolated expositions, each one comprising a different formation: the Playa Hermosa, San Carlos, and Las Ventanas formations (Pazos et al. 2003), grouped in the Maldonado Group (Pecoits et al.

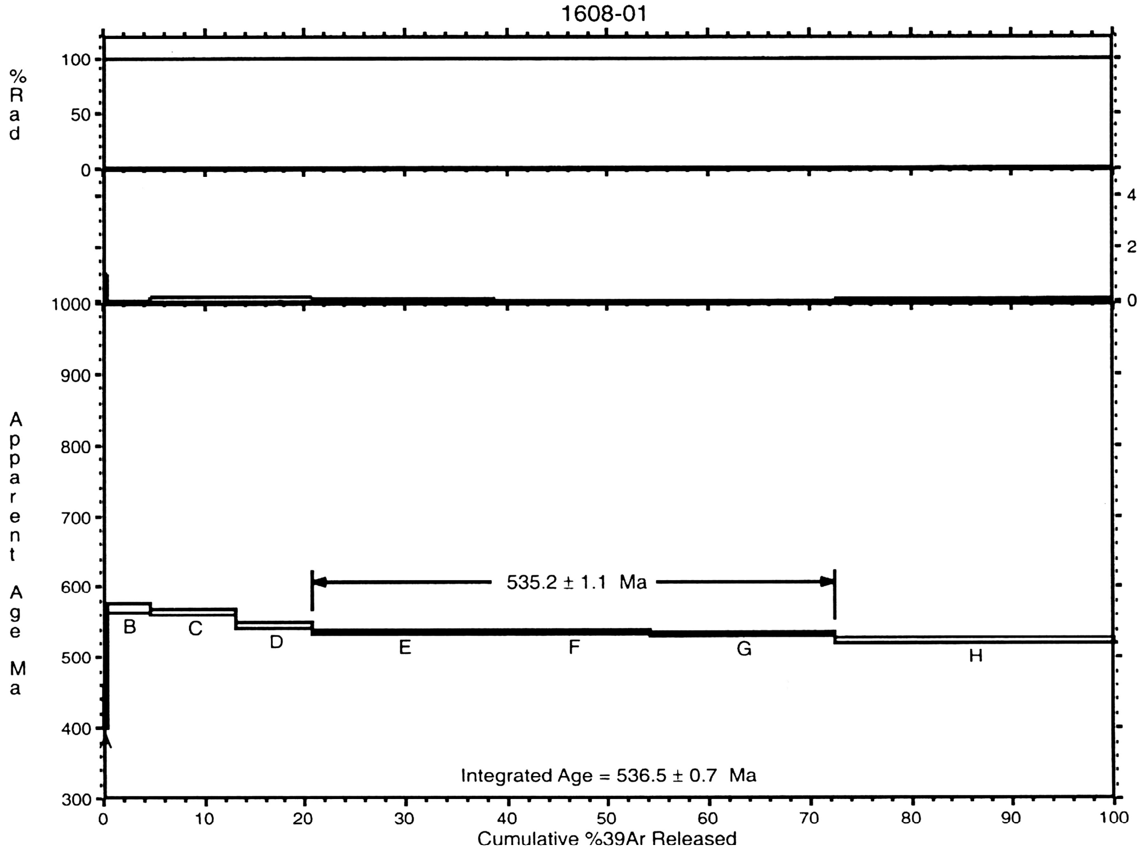

Figure 2. Graphic showing results of whole-rock step-heating Ar-Ar radiometric dating of sample of basic rock from the Rodeio Velho Intrusive Suite. Note plateau at 535.2 Ma, interpreted as the crystallization age of the rock.

2008). The Playa Hermosa Formation comprises a lower succession of conglomerates, sandstones, and rhythmites of interpreted marine origin, possibly with glacial influence (e.g., Fambrini et al. 2003; Pazos et al. 2003, 2008; Pecoits et al. 2008), and an upper succession of bimodal volcanic rocks (e.g., Pazos et al. 2003; Sánchez-Bettucci et al. 2009) related to the Sierra de Las Animas volcanic complex. An age of approximately 580 Ma is attributed to the unit (Sánchez-Bettucci et al. 2009). The San Carlos Formation comprehends alluvial fan conglomerates with granitic provenance and may be correlated to the Santa Bárbara Formation of the Camaquã Basin (Pazos et al. 2003). According to Gaucher et al. (2008), the Las Ventanas Formation is an up to 5000-m-thick volcanosedimentary succession characterized by basic volcanic rocks overlain by a fining-upward succession of conglomerates, sandstones, and siltstones. Alluvial fans and shallow marine deposits are interpreted for the clastic succession (e.g., Blanco and Gaucher 2005), and a depositional age between 615 and 579 Ma is interpreted for the unit on the basis of paleontological content and available geochronological data (Gaucher et al. 2008). An extensional rift setting was proposed by Blanco and Gaucher (2005) for the Las Ventanas Formation, and the same model was applied for the whole Maldonado Group by Pecoits et al. (2008).

Itajaí Basin

The Itajaí Basin is the second largest basin of the system, with approximately 1200 km^2 of exposed area and a preserved sedimentary record more than 10,000 m thick (Teixeira et al. 2004), including alluvial, daltaic, and turbiditic successions (e.g., Rostirolla et al. 1992*a*; Fonseca et al. 2003; Basilici 2006). This basin overlies the Joinvile Cratonic Block and is considered by many authors as a foreland basin related to the collisional tectonics of the Brasiliano Orogeny in the region (e.g., Fragoso-

Cesar et al. 1982*a*, 1982*b*; Rostirolla and Soares 1992; Rostirolla et al. 1992*a*, 1992*b*, 1999; Gresse et al. 1996; Basei et al. 2000), but there is no clear evidence to support a synorogenic origin. Indeed, the preservation of more than 10,000 m of sedimentary rocks after the exhumation of the orogenic load would imply a very small elastic restoration of the lithosphere, which is very unlikely.

The Itajaí Basin is characterized by the recurrence of conglomerates, sandstones, sandstone-mudstone rhythmites, and mudstones in cycles that compose four depositional sequences (Teixeira et al. 2004). There is no accepted formal division for the sedimentary successions of the basin, but several studies have been carried out on the depositional systems evolution, particularly on the well-exposed turbidites (e.g., Rostirolla et al. 1992*a*; Fonseca et al. 2003; Basilici 2006). Rhyolitic tuffs occur at some stratigraphic levels, and the basin is intruded by a granite stock.

The Itajaí Basin is elongated in the NE to ENE direction, parallel to the main ductile structures of its metamorphic basement, and is bounded by a high dip fault in its southeastern border. Tectonic structures include open folds with NE axis, NE-trending reverse to oblique faults, and E-W-trending right-slip faults, reactivated to left-slip in a latter tectonic event (Rostirolla et al. 1992*b*). There is no clear evidence of active synsedimentary tectonism, since the modern basin border faults were formed during latter deformational events and the original proximal deposits are not preserved. Paleostress fields analysis (e.g., Rostirolla et al. 1992*b*, 1999) points to two main compressional events, the first with NW-SE-oriented and the second with NE-SW-oriented maximum horizontal stresses.

Basei et al. (2008*a*) obtained a U-Pb SHRIMP zircon age of 584 ± 27 Ma for a tuff level in the lower arkosic succession, which constraints the depositional age of the lower unit. The maximum age of the basin was constrained by Guadagnin et al. (2008), who found a detrital zircon population of 563 ± 3 Ma in tuffaceous siltstones and volcanogenic sandstones, and Silva et al. (2005), who obtained a U-Pb SHRIMP age of 606 ± 8 Ma for a probably reworked zircon crystal also from a tuff level. The age of the acid intrusive rocks constraints the minimum age of the succession at approximately 550 Ma; Basei et al. (1999) published a U-Pb zircon age of 560 Ma for granites and intrusive rhyolites that cut through the whole basin fill, and Basei et al. (2008*a*) confirmed this result with a U-Pb SHRIMP zircon age of 559 ± 9.5 Ma for an acid intrusion, while Guadagnin et al. (2008) found an age of 549 ± 4 Ma for similar rocks. The recrystallization of zircon during deformation was dated by Basei et al. (2008*a*) at 535 ± 11 Ma.

Other Basins in the Joinvile Block

Two other basins occur in the Joinvile Block: the Guaratubinha and Campo Alegre–Corupá basins, both of which contain thick volcanosedimentary successions.

The Guaratubinha Basin contains mainly acid volcanic and volcaniclastic rocks, with subordinated intermediate volcanic rocks (e.g., Fuck et al. 1967; Reis Neto et al. 2000). Coarse-grained siliciclastic rocks, mainly polimictic conglomerates, are restricted to the southwestern basin border (Reis Neto et al. 2000), indicating the presence of a north-south scarp at the time of basin formation. The preserved area of the basin is in excess of 200 km^2, but the exposed thickness of the strata is difficult to estimate. Basei et al. (1998) obtained a U-Pb zircon age of 605 ± 9 Ma for the crystallization of acid volcanic rocks in the Guaratubinha Basin.

The Campo Alegre Basin has a preserved area of approximately 500 km^2 and exposes up to 1000 m of conglomerates, sandstones, pyroclastic, and volcanic rocks, including basalts, andesites, dacites, riodacites, trachytes, and rhyolites (e.g., Waichel et al. 2000; Citroni et al. 2001). The lower unit of conglomerates and sandstones is interpreted as the deposits of alluvial fans and braided rivers, and the overlaying fine-grained facies as subaqueous deposits (Citroni et al. 2001). The volcanogenic succession shows an alkaline affinity (Waichel et al. 2000) and has been correlated to the Castro and Guaratubinha basins (Ebert and Brochini 1971) and to the Camaquã Basin (Waichel et al. 2000). U-Pb zircon data for the volcanic rocks of the Campo Alegre Basin indicate crystallization ages of 595 ± 16 Ma (Cordani et al. 1999) and 598 ± 29 Ma (Basei et al. 1998; Siga et al. 2000).

Castro Basin

The Castro Basin is the third largest basin of the system, with more than 800 km^2 of exposed area overlying the southern part of the Ribeira Fold belt. It is composed of feldspathic sandstones, siltstones, and conglomerates, as well as acid volcanic rocks, disposed in a more than 3000-m-thick succession. Its tectonic setting is also controversial, being interpreted as either a postorogenic molasse basin (Trein and Fuck 1967) or a transtentional strike-slip basin (Soares 1987, 1988).

The stratigraphic column of the basin is not yet well established because of the intense faulting and

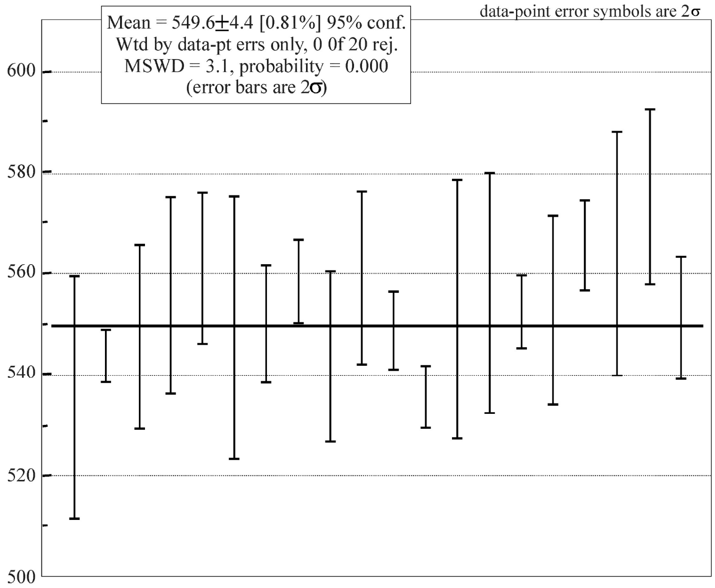

Figure 3. Results of zircon U-Pb laser ablation inductively coupled plasma mass spectrometry radiometric dating of sample from acid rock of the Castro Basin.

compartmentalization of the exposed successions. Published works diverge about the relative position of the lithostratigraphic units (e.g., Moro 1993; Moro et al. 1993, 1994). Our field observations suggest the following stratigraphic column for the basin (from base to top): extrusive and pyroclastic basic to intermediate rocks, turbiditic sedimentary rocks and associated subaqueous volcaniclastic rocks, alluvial fan conglomerates with volcanic provenance, micaceous sandstones of distal alluvial plains, and finely subaerial acid volcanic and pyroclastic rocks, including rhyolitic tuffs and lapilli tuffs.

The Castro Basin is bounded by a high dip NNE-trending fault that is parallel to the metamorphic foliation of the basement. The deformational structures that affect the Castro Basin are very similar to those that affect the Camaquã Basin, with high dip faults with NE to NNE strikes juxtaposing different stratigraphic units and a set of NW-trending structures that show small displacements. In the Castro Basin, these NW structures are intruded by numerous basic dikes that fed the Early Cretaceous volcanism in the region. The occurrence of alluvial fan deposits in the sedimentary succession suggests the presence of active synsedimentary fault scarps, but the correlation between the tectonic events and the basin evolution is not yet well established. Preliminary paleostress data reveal that the two main deformational events were a NW-SE extension and a NE-SW compression that caused strike-slip movement on high dip faults.

Cordani et al. (1999) obtained a U-Pb zircon age of 543 ± 12 Ma for the upper rhyolites. A new U-Pb laser ablation inductively coupled plasma mass spectrometry age of 549.6 ± 4.4 Ma for the same unit was obtained at the Universidade de Brasília, following the procedure described by Bühn et al. (2009), and confirms an Early Cambrian age for the uppermost succession (fig. 3).

Other Basins in the Ribeira Belt

Besides the Castro Basin, several other small occurrences of Ediacaran deposits are found in the Ribeira Belt, resulting from partial preservation of very similar basins. These basins are bounded by reactivated strike-slip faults, preserving several hundreds of meters of siliciclastic deposits. They are characterized by basin border conglomerates that grade into arkoses, rhythmites, and mudstones toward the depocenter. The depositional environments interpreted for these successions are the same in all basins: alluvial fans and fan deltas reworked by tides and storm waves. Among these occurrences are the Pouso Alegre, Eleutério, Pico do Itapeva, and Camarinha basins (Teixeira et al. 2004).

The preserved area of the Pouso Alegre Basin is only 5 km^2, exposing more than 1000 m of conglomerates, arkoses, and siltstones of alluvial fan, wave-dominated fan delta, and marine environments (Teixeira and Petri 2001). The basin is limited by postdepositional strike-slip faults of ENE-WSW direction, which reactivated basement structures. The presence of alluvial fan deposits fed from the northern basin border (Teixeira et al. 2004) indicates that the basin was originally bounded by active faults.

The Eleutério Basin has a small preserved area (approximately 15 km^2) and an exposed thickness of more than 700 m (Teixeira et al. 2004). The basin is limited by strike-slip faults of NE-SW direction, which reactivated basement structures. Teixeira et al. (2004) identified basin border alluvial fan deposits, dominated by conglomeratic facies, grading to braided-plain deposits, coarse-grained deltas, and fine-grained marine deposits. Teixeira (1995) considered the modern basin boundary faults as the original basin-forming structures, proposing a pull-apart model for the basin. A rhyolite clast was dated by Teixeira et al. (1999) through the U-Pb SHRIMP method, giving a maximum age of 606 ± 13 Ma for the basin. K-Ar age of similar clasts revealed a thermal event at 530.5 ± 14.5 Ma (Teixeira 1995), constraining the minimum age of the succession.

The Pico do Itapeva Basin has a preserved area of approximately 20 km^2, bounded by reactivated strike-slip faults, and is composed of more than 1300 m of conglomerates, arkoses, sandstones, and mudstones deposited in alluvial fans and coastal environments (Coimbra and Riccomini 1996).

The Camarinha Basin has a preserved area of more than 100 km^2 and is composed of two separated occurrences, bounded by NE-SW strike-slip faults. The basin exposes approximately 4000 m of conglomerates, arkoses, sandstones, and rhythmites (Moro 2000). Alluvial fan, fan delta, and wave-dominated coastal environments have been recognized (e.g., Teixeira et al. 2004).

Regional Correlation

Age constraints, lithological similarities, and structural aspects point to the correlation of all Ediacaran to Cambrian basins of southeastern South America in a common basin system (fig. 5), with recurrent events of subsidence, magmatic activity, and brittle deformation from 605 to 530 Ma. Lithological similarities among basins are striking, with all being dominated by immature siliciclastic rocks, acid volcanic rocks (with varied contribution of intermediate and basic rocks), or both. Coarse-grained facies, especially alluvial fan and fan delta deposits, indicate the presence of basin border scarps in all basins of the system.

Despite the prevalence of inverse faults in some basins, such as the Itajaí Basin, and of strike-sip faults in others, such as the Camaquã and Castro basins, the same paleostress fields were responsible for the deformation of the system (fig. 4). The main deformational event recognized in all basins is a NW-SE compression, which reactivated the structures that are oblique to the main stress vector as strike-slip faults and reactivated the structures that are perpendicular to this vector as inverse faults, as seen in the Itajaí Basin (fig. 4). Age constraints for this compressional deformation point to an Early Cambrian age (e.g., Teixeira 1995; Basei et al. 2008*a*). NW-SE extension is recognized in all three major basins, and there is evidence for a basin-forming NW-SE extension at least in the Camaquã Basin (e.g., Almeida 2005). NE-SW compression reactivating strike-slip faults with movement opposite to the main compressional event has been recognized in the Camaquã and Itajaí basins.

Age constraints reveal that all basins were formed between 605 and 530 Ma, recording four periods of volcanic activity: the first from 605 to 580 Ma, the second at approximately 575 Ma, the third from 550 to 545 Ma, and the last at 535 Ma. At least two main phases of regional basin formation and volcanism can be identified (fig. 5): a first one characterized by thick volcanosedimentary successions related to basic and intermediate volcanic rocks, with minor acid volcanics, and a second one characterized by thick siliciclastic successions and discrete events of acid volcanism. The first phase is recorded in the Playa Verde, Camaquã, Campo Alegre–Corupá, and Guaratubinha basins, all of which contain basic to intermediate volcanic rocks in the 605–580 Ma range. The second phase is recorded in the Barriga Negra, Cerros de Aguirre, Camaquã, Itajaí, Camarinha, Castro, Pico do Itapeva, Eleutério, and Pouso Alegre basins. Acid volcanic rocks of approximately 570 Ma occur in the Cerros de Aguirre and Camaquã basins, and acid volcanism of approximately 550 Ma is recorded in the Camaquã, Itajaí, and Castro basins.

Discussion

The interpretation of a common origin for all basins of Ediacaran to Cambrian age of southeastern South America implies that all different terranes involved in the collisional stage of the Brasiliano Orogeny

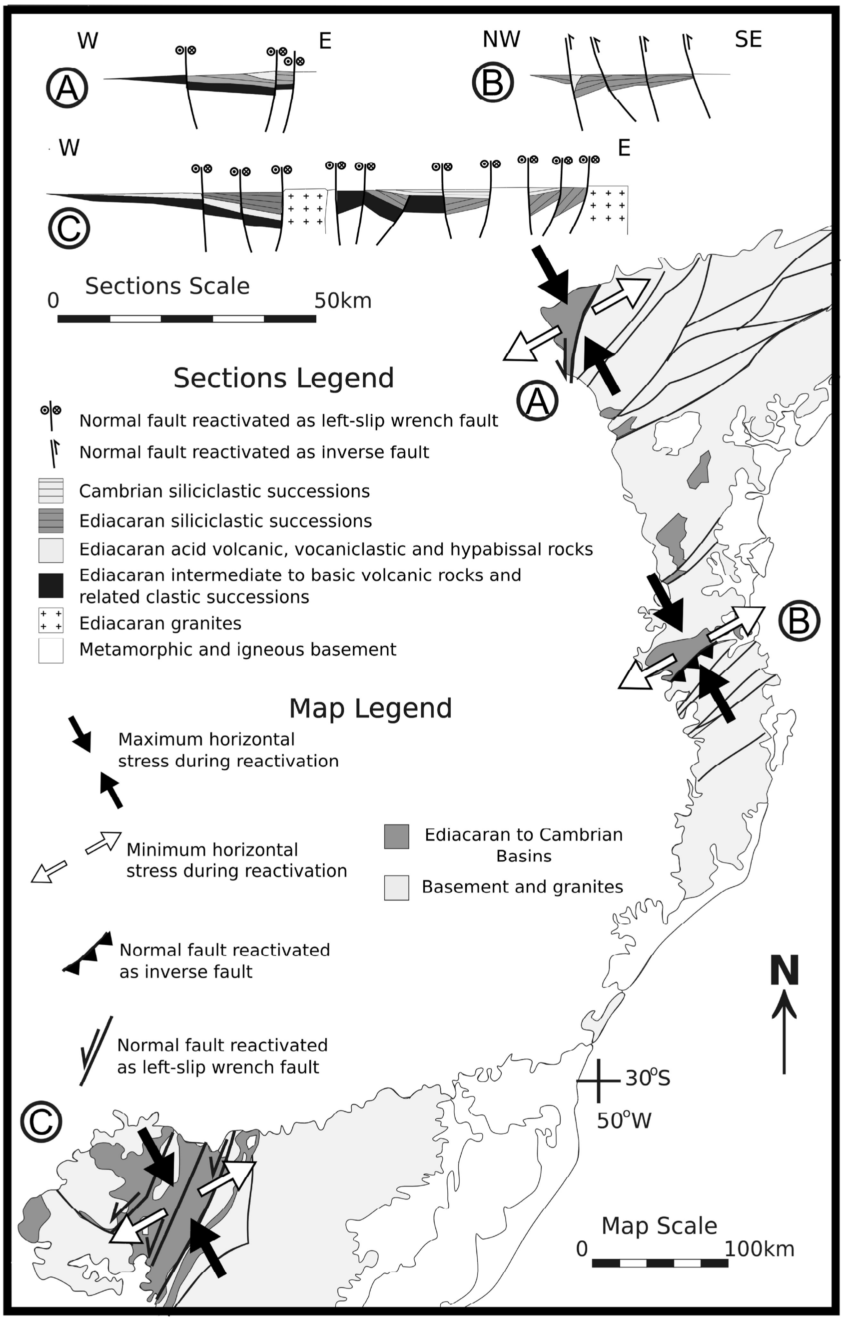

Figure 4. Schematic cross sections of the three main basins of the Ediacaran to Cambrian system of basins of southeastern South America, showing the original normal faults reactivated by NW-SE compression in the Early Cambrian, either as strike-slip or inverse faults, depending on the preexisting fault direction. A color version of this figure is available in the online edition of the *Journal of Geology*.

in the region were already united in a single plate at approximately 600 Ma (fig. 6). Alternative models that consider superposed orogenic events after 600 Ma are based on the interpretation of strike-slip shear zones as syncollisional features, but they fail to explain the common evolution of the whole region from the Middle Ediacaran on, with the synchronous formation of A-type granites and similar basins. Strike-slip deformation occurred in distinct phases, both before and after the development of

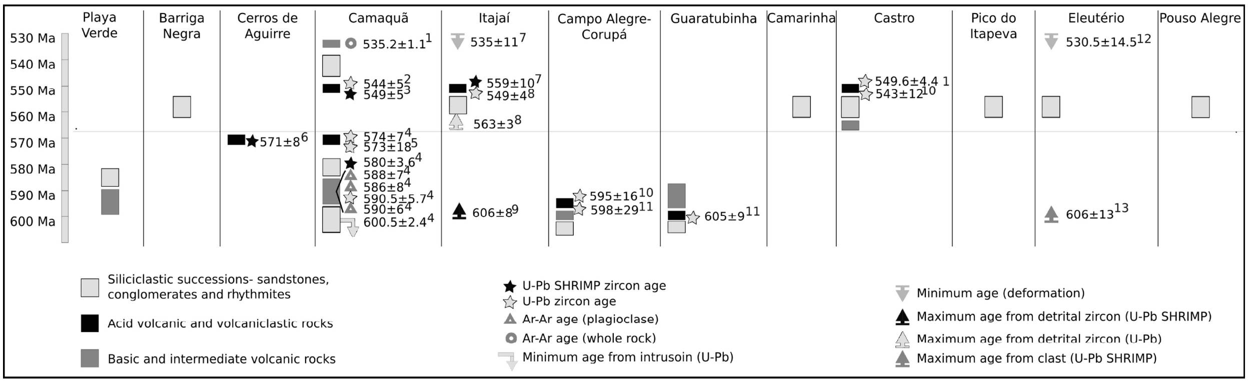

Figure 5. Correlation among the Ediacaran to Cambrian basins of southeastern South America. Ages are given in millions of years before present. References (superscript numbers): *1*, this work; *2*, L. Janikian, unpublished data; *3*, Sommer et al. 2005; *4*, Janikian et al. 2008; *5*, Chemale 2002; *6*, Hartmann et al. 2002; *7*, Basei et al. 2008*a*; *8*, Guadagnin et al. 2008; *9*, Silva et al. 2005; *10*, Cordani et al. 1999; *11*, Basei et al. 1998; *12*, Teixeira 1995; *13*, Teixeira et al. 1999; *14*, Blanco et al. 2009. A color version of this figure is available in the online edition of the *Journal of Geology*.

the basin system. Therefore, the Ediacaran shear zones are most likely related to the far-field propagation of compressional stresses during younger collisional events at the plate margins (such as the East Gondwana–West Gondwana collision).

Several contrasting models have been proposed for the origin of individual basins, with most of them based on the interpretation of the postdepositional strike-slip and locally inverse faults as related to basin-forming tectonics. Nevertheless, the identification of extensional faults formed before the strike-slip deformation (e.g., Almeida 2005), with some of them considered as synsedimentary (Fragoso-Cesar et al. 2001); the identification of normal fault scarps feeding alluvial fans; and the occurrence of expressive volcanic units in several basins point to an extensional origin for the basin system.

This extensional deformation may be related to the decrease in lithospheric strength caused by raising temperatures and magmatic activity. Some of this effect may be due to low lateral heat loss in the wide collisional orogens of the Mantiqueira Province. This sort of thermal weakening may reach its maximum several million years after the end of collision (Gaudemer et al. 1988), potentially explaining the time gap between collision and extension in the Mantiqueira Belt. On the other hand, the voluminous regional magmatic activity coeval to the formation of the basin system may indicate an additional heat source, possibly from mantle anomalies or magma underplating.

Gravitational collapse of the orogenic edifice may have contributed as a driving force for extension, but the inferred extension of the whole lithosphere necessarily depends on forces acting at the plate margins (e.g., Rey et al. 2001; Tirel et al. 2006). Moreover, the great preserved thickness of the successions contrasts with the style of basins formed mainly by gravitational collapse, such as the extensional basins of the Himalayas, which are rarely more than 1000 m deep (e.g., Armijo et al. 1986; Cogan et al. 1998; Garzione et al. 2003) and thus have low preservation potential, since the basement of the basins is thousands of meters above sea level. The characterization of an extensional basin system coeval to voluminous anorogenic granites brings similarities with the mesozoic extensional basin province of southeastern China (e.g., Gilder et al. 1991; Goodell et al. 1991; Qiu et al. 1991; Li et al. 2007; Shu et al. 2009), which developed after compressional deformation due to low angle subduction (Li and Li 2007).

The northern part of the Mantiqueira Province has no preserved basin of Ediacaran age, possibly because of a deeper level of erosion, indicated by the abundance of high-grade metamorphic rocks. In this same region, Late Ediacaran granites are interpreted as synorogenic (e.g., Pedrosa-Soares et al. 2001; Silva et al. 2005), but they intrude a deformed basin surrounded by the São Francisco–Congo craton to the east, north, and west in a clear intraplate position. Trying to solve this paradox, Pedrosa-Soares et al. (1998, 2001) proposed a model of opening and closure of a small oceanic embayment that never completely separated the Congo and São

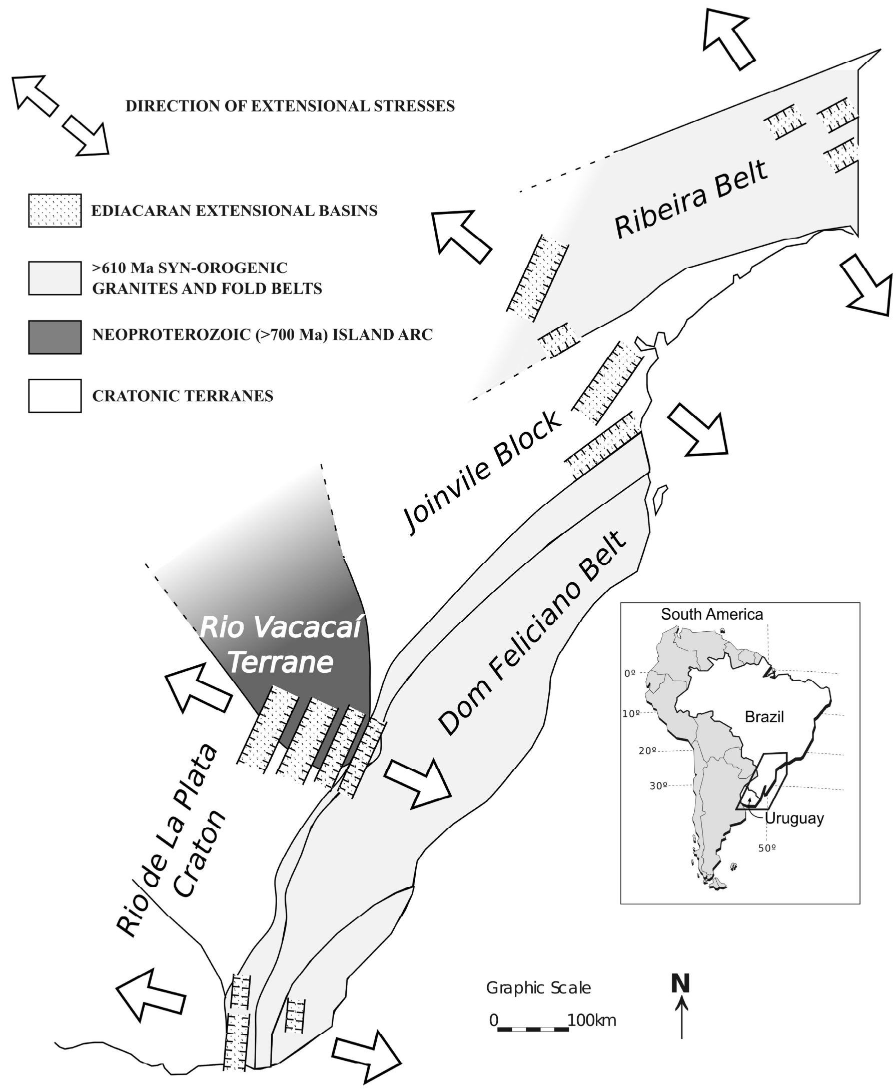

Figure 6. Reconstruction of the Middle to Late Ediacaran extensional event of southeastern South America, affecting indiscriminately all the elements of the Criogenian to Early Ediacaran orogenic collage in the region.

Francisco cratons. The connections between the southern and northern Mantiqueira Province during the Late Ediacaran remain uncertain.

Other Ediacaran units of western Gondwana include successions of the Nama Group of Namibia and the Corumbá Group of the Paraguay Belt at the border of the Amazon Craton in Brazil. Both these units are marine in origin and present Late Ediacaran fossils in carbonate successions, being deposited in a completely different paleogeography than the basin system of southeastern South America, which comprised isolated volcanicastic basins with elevated flanks.

Conclusions

The major geologic features formed between 600 and 530 Ma in southeastern South America are a system of fault-bounded basis and several coeval granites that have been traditionally related to the compressional or transpressional tectonics of the late stages of the Pan-African-Brasiliano Orogeny. Despite previous models that consider different tectonic settings for each of these basins, recent geochronological data strongly support the correlation of the volcaniclastic and siliciclastic basins of Ediacaran to Cambrian age in a continuous system more than 1500 km long. Individual basins overlie indiscriminatingly cratonic blocks, Neoproterozoic thrust and fold belts, a juvenile island arc terrane, and synorogenic granites, revealing that the whole southern Mantiqueira Province has been part of the same plate since approximately 600 Ma.

The characterization of an extensional origin for the basin system reveals that regional extension took place approximately 20 million years after the last Brasiliano collisional event in the region, making it difficult to argue for a direct causal relationship. The occurrence of basic, intermediate, and acid volcanic rocks and voluminous coeval granites indicates that mantle and crustal fusion were simultaneous with the basin-forming extension. Raised temperatures may have caused the thermal weakening of the lithosphere, enabling both the extensional deformation and the recurring strike-slip deformation that reactivated the orogenic structures. This strike-slip deformation has been mistaken for the basin-forming tectonics, but it occurred after basin formation, in the Early Cambrian, and most probably is the result of the far-field propagation of compressional stresses originated in younger collisional orogens at the plate margins.

ACKNOWLEDGMENTS

We thank the Fundação de Amparo à Pesquisa do Estado de São Paulo for graduate scholarships and research grants (98/04510-1, 98/03682-3 , 00/07510-4, 01/01439-9, 05/53522-8, 05/57939-0, 06/50655-0). We also thank the comments and reviews by P. F. Hoffman and D. Rowley.

REFERENCES CITED

Almeida, F. F. M.; Amaral, G.; Cordani, U. G.; and Kawashita, K. 1973. The Precambrian evolution of the South American cratonic margin south of Amazon River. *In* Nairn, A. E., and Stehli, F. G., eds. The ocean basins and margins (vol. 1). New York, Plenum, p. 411–446.

Almeida, F. F. M.; Hassui, Y.; Brito Neves, B. B.; and Fuck, R. A. 1981. Brazilian structural provinces: an introduction. Earth-Sci. Rev. 17:1–21.

Almeida, R. P. 2001. Evolução tectono-sedimentar da Formação Santa Bárbara na Sub-bacia Camaquã Ocidental. MS thesis, Instituto de Geociências, Universidade de São Paulo.

———. 2005. Tectônica e sedimentação do Ediacarano ao Ordoviciano: exemplos do Supergrupo Camaquã (RS) e do Grupo Caacupé (Paraguai Oriental). PhD thesis, Instituto de Geociências, Universidade de São Paulo.

Almeida, R. P.; Janikian, L.; Fragoso-Cesar, A. R. S.; and Marconato, A. 2009. Evolution of a rift basin dominated by subaerial deposits: the Guaritas Rift, Early Cambrian, southern Brazil. Sediment. Geol. 217:30–51.

Armijo, R.; Tapponnier, P.; Mercier, J. L.; and Han, T. L. 1986. Quaternary extension in southern Tibet: field observations and tectonic implications. J. Geophys. Res. 91:13,803–13,872.

Babinski, M.; Chemale, F., Jr.; Hartmann, L. A.; Van Schmus, W. R.; and Silva, L. C. 1996. Juvenile accretion at 750–700 Ma in southern Brazil. Geology 24: 439–442.

Basei, M. A. S.; Citroni, S. B.; and Siga, O., Jr. 1998. Stratigraphy and age of Fini-Proterozoic basins of Paraná and Santa Catarina states, southern Brazil. Bol. IG-USP Ser. Cient. 29:195–216.

Basei, M. A. S.; Drukas, C. O.; Santos, P. R.; Osako, L.; and Arcaro, N. P. 2008*a*. Estratigrafia, idade e proveniência dos sedimentos da Bacia do Itajaí, SC, Brasil. *In* 44 Congresso Brasileiro de Geologia, Anais. Curitiba, SBG.

Basei, M. A. S.; Frimmel, H. E.; Nutman, A. P.; and Preciozzi, F. 2008*b*. West Gondwana amalgamation based on detrital zircon ages from Neoproterozoic Ribeira and Dom Feliciano belts of South America and comparison with coeval sequences from SW Africa. Geol. Soc. Lond. Spec. Publ. 294:239–256.

Basei, M. A. S.; Frimmel, H. E.; Nutman, A. P.; Preciozzi, F.; and Jacob, J. 2005. A connection between the Neoproterozoic Dom Feliciano (Brazil/Uruguay) and Gariep (Namibia/South Africa) orogenic belts: evidence from a reconnaissance provenance study. Precambrian Res. 139:195–221.

Basei, M. A. S.; Siga, O., Jr.; Cordani, U. G.; Sato, K.; and Lima, P. S. 1999. The magmatism of the Itajaí Basin, SC, southern Brasil, and its importance to define the Proterozoic-Phanerozoic limit. *In* Simposio Sudamericano de Geologia Isotopica. II. Córdoba, Argentina, Actas, p. 287–290.

Basei, M. A. S.; Siga, O., Jr.; Masquelin, H.; Harara, O. M.; Reis Neto, J. M.; and Preciozzi, F. P. 2000. The Dom Feliciano Belt of Brasil and Uruguay and its foreland domain, the Rio de La Plata Craton: framework, tectonic evolution and correlation with similar provinces of southwestern Africa. *In* Cordani, U. G.; Milani, E. J.; Thomaz Filho, A.; and Campos, D. A., eds. Tectonic evolution of South America. Rio de Janeiro, 31st Int. Geol. Cong., p. 311–334.

Basilici, G. 2006. Depositional mechanisms and architecture of a pre–Early Cambrian mixed sand-mud deepwater ramp (Apiuna Unit, south Brazil). Sediment. Geol. 187:183–204.

Blanco, G., and Gaucher, C. 2005. Estratigrafia, paleontologia y edad de la Formacion Las Ventanas (Neoproterozoico, Uruguay). Latin Am. J. Sediment. Basin Anal. 12:109–124.

Blanco, G.; Rajesh, H.; Gaucher, C.; Germs, G. J.; and Chemale, F., Jr. 2009. Provenance of the Arroyo del Soldado Group (Ediacaran to Cambrian, Uruguay): implications for the paleogeographic evolution of southwestern Gondwana. Precambrian Res. 171:57–73.

Borba, A. W.; Vignol-Lelarge, M. L. M.; and Mizusaki, A. M. P. 2002. Uplift and denudation of the Caçapava do Sul granitoids (southern Brazil) during Late Paleozoic and Mesozoic: constraints from apatite fission-track data. J. S. Am. Earth Sci. 15:683–692.

Brito Neves, B. B.; Campos Neto, M. C.; and Fuck, R. 1999. From Rodinia to eastern Gondwana: an approach to the Brasiliano–Pan African cycle and orogenic collage. Episodes 22:155–166.

Bühn, B.; Pimentel, M. M.; Matteini, M.; and Dantas, E. L. 2009. High spatial resolution analysis of Pb and U isotopes for geochronology by laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS). An. Acad. Bras. Cienc. 81:99–114.

Chemale, F., Jr. 2002. Evolução Geológica do Escudo Sulrio-grandense. *In* Holz, M., and De Ros, L. F., eds. Geologia do Rio Grande do Sul. Porto Alegre, CIGO/UFRGS, p. 13–52.

Citroni, S. B.; Basei, M. A. S.; Siga, O., Jr.; and Reis Neto, J. M. 2001. Volcanism and stratigraphy of the Neoproterozoic Campo Alegre Basin, SC, Brazil. An. Acad. Bras. Cienc. 73:581–597.

Cogan, M. J.; Nelson, K. D.; Kidd, W. S. F.; and Wu, C. 1998. Shallow structure of the Yadong-Gulu rift, southern Tibet, from refraction analysis of Project INDEPTH common midpoint data. Tectonics 17:46–61.

Coimbra, A. M., and Riccomini, C. 1996. Stratigraphy of the Pico do Itapeva Basin (Neoproterozoic-Cambrian, southeastern Brazil). An. Acad. Bras. Cienc. 68:602.

Cordani, U. G.; Basei, M. A. S.; Siga, O., Jr.; and Nutman, A. 1999. Idades U-Pb (SHRIMP) de rochas vulcânicas das bacias de Campo Alegre, Itajaí e Castro (SC e PR). An. Acad. Bras. Cienc. 71:835.

Ebert, H. D., and Brochini, M. F. 1971. A Formação Campo Alegre, Santa Catarina (vol. 25). São Paulo, Resumos e Comunicações, p. 181–182.

Fambrini, G. L. 1998. O Grupo Camaquã (Transição Proterozóico-Fanerozóico) na região das Minas do Camaquã, RS: análise estratigráfica de fácies, proveniência e paleocorrentes. MS thesis, Instituto de Geociências, Universidade de São Paulo.

———. 2003. O Grupo Santa Bárbara (Neoproterozóico III) da Bacia do Camaquã, Rio Grande do Sul. PhD thesis, Instituto de Geociências, Universidade de São Paulo.

Fambrini, G. L.; Almeida, R. P.; and Fragoso-Cesar, A. R. S. 2006. Estratigrafia e evolução paleogeográfica do Grupo Santa Bárbara (Ediacarano) na sub-bacia Camaquã Ocidental, Rio Grande do Sul, Brasil. Rev. Bras. Geocienc. 36:550–565.

Fambrini, G. L.; Almeida, R. P.; Riccomini, C.; and Fragoso-Cesar, A. R. S. 2003. Tempestitos com influência glacial da formação Playa Hermosa (Neoproterozóico), Piriápolis, Uruguai. Rev. Bras. Geocienc. 33:1–12.

Fambrini, G. L.; Fragoso-Cesar, A. R. S.; Almeida, R. P.; and Riccomini, C. 2005*a*. A Formação Barriga Negra (Ediacarano do Uruguai): caracterização estratigráfica e correlação com unidades do estado do Rio Grande do Sul, Brasil. Rev. Bras. Geocienc. 35:515–524.

Fambrini, G. L.; Janikian, L.; Almeida, R. P.; and Fragoso-Cesar, A. R. S. 2005*b*. O Grupo Santa Bárbara (Neoproterozóico III) na sub-bacia Camaquã Central, RS: sistemas deposicionais, paleogeografia e implicações tectônicas. Rev. Bras. Geocienc. 35:227–238.

———. 2007. Evolução estratigráfica e paleogeográfica do Grupo Santa Bárbara na Sub-bacia Camaquã Central, RS. Geol. USP Ser. Cient. 7:1–24.

Fambrini, G. L.; Sayeg, H. S.; and Fragoso-Cesar, A. R. S. 1992. Variação de áreas-fonte da Formação Arroio dos Nobres (Cambriano) no Vale do Arroio Boici, RS: análise estratigráfica de proveniência e de paleocorrentes. *In* XXXVII Congresso Brasileiro Geologia, Boletim de Resumos Expandidos (vol. 2). São Paulo, SBG, p. 441.

Fonseca, M. M.; Silveira, A. S.; D'ávila, R. S. F.; Zucatti da Rosa, A. L.; Appi, C. J.; and Paim, P. S. G. 2003. Arquitetura deposicional e fácies sedimentares do complexo turbidítico de Apiúna (Bacia do Itajaí-SC). *In* Paim, P. S. G.; Faccini, U. F.; and Netto, R. G., eds. Geometria, arquitetura e heterogeneidades de corpos sedimentares: estudo de casos. UNISSINOS, p. 122–146.

Fragoso-Cesar, A. R. S. 1980. O Cráton Rio de La Plata e o Cinturão Dom Feliciano no Escudo Uruguaio-Sul-Riograndense. *In* XXXI Congresso Brasileiro de Geologia, Anais (vol. 5). Camboriú, SBG, p. 2879–2892.

———. 1991. Tectônica de Placas no Ciclo Brasiliano: as orogenias dos Cinturões Dom Feliciano e Ribeira no Rio Grande do Sul. PhD thesis, Instituto de Geociências, Universidade de São Paulo.

———. 2008. Novas Considerações sobre o Ciclo Brasiliano. *In* 44 Congresso Brasileiro de Geologia, Anais. Curitiba, SBG, p. 28.

Fragoso-Cesar, A. R. S.; Almeida, R. P.; Fambrini, G. L.; Pelosi, A. P. M. R.; and Janikian, L. 2003. A Bacia Camaquã: um sistema intracontinental anorogênico de rifts do Neoproterozóico. III. Eopaleozóico no Rio Grande do Sul. *In* I Encontro sobre a Estratigrafia do Rio Grande do Sul, Boletim de Resumos. Porto Alegre, SBG, p. 139–144.

Fragoso-Cesar, A. R. S.; Fambrini, G. L.; Almeida, R. P.; Pelosi, A. P. M. R.; Janikian, L.; Riccomini, C.; Machado, R.; Nogueira, A. C. R.; and Saes, G. S. 2000. The Camaquã extensional basin: Neoproterozoic to Early Cambrian sequences in southernmost Brazil. Rev. Bras. Geocienc. 30:438–441.

Fragoso-Cesar, A. R. S.; Fambrini, G. L.; Riccomini, C.; Janikian, L.; Almeida, R. P.; Pelosi, A. P. M. R.; and Machado, R. 2001. Estruturas induzidas por abalos sísmicos na Formação Santa Bárbara (Neoproterozóico

III-Eocambriano), Bacia do Camaquã, RS: o exemplo do Passo da Capela. Rev. Bras. Geocienc. 31:155–162.

Fragoso-Cesar, A. R. S.; Figueiredo, M.; Soliani, F., Jr.; and Faccini, U. F. 1986. O Batólito Pelotas (Proterozóico Superior/Eo-Paleozóico) no Escudo do Rio Grande do Sul. *In* XXXIV Congresso Brasileiro de Geologia, Anais, vol. 4. Goiânia, SBG, p. 1322–1342.

Fragoso-Cesar, A. R. S.; Wernick, E.; and Soliani, F., Jr. 1982*a*. Associações petrotectônicas do Cinturão Dom Feliciano (SE da Plataforma Sul-Americana). *In* XXXII Congresso Brasileiro de Geologia, Anais, no. 1. Salvador, SBG, p. 1–12.

———. 1982*b*. Evolução geotectônica do Cinturão Dom Feliciano: uma contribuição através da aplicação do modelo da Tectônica de Placas. *In* XXXII Congresso Brasileiro de Geologia, Anais, no. 1. Salvador, SBG, p. 13–23.

Frantz, J., and Botelho, N. 2000. Neoproterozoic granitic magmatism and evolution of the eastern Dom Feliciano Belt in southernmost Brazil: a tectonic model. Gondwana Res. 3:7–19.

Fuck, R. A.; Marini, O. J.; and Trein, E. 1967. A Fromação Guaratubinha. Bol. Parana. Geocienc. 23:237–255.

Garzione, C. N.; DeCelles, P. G.; Hodkinson, D.; Ojha, T. P.; and Upetri, B. N. 2003. East-west extension and Miocene environmental change in the southern Tibetan Plateau: Thakkhola graben, central Nepal. Geol. Soc. Am. Bull. 115:3–20.

Gaucher, C. 2000. Sedimentology, palaeontology and stratigraphy of the Arroyo del Soldado Group (Vendian to Cambrian, Uruguay). Beringeria 26:1–120.

Gaucher, C.; Blanco, G.; Chiglino, L.; Poiré, D.; and Germs, G. J. 2008. Acritarchs of Las Ventanas Formation (Ediacaran, Uruguay): implications for the timing of coeval rifting and glacial events in western Gondwana. Gondwana Res. 13:488–501.

Gaucher, C.; Boggiani, P. C.; Sprechmann, P.; Sial, A. N.; and Fairchild, T. 2003. Integrated correlation of the Vendian to Cambrian Arroyo del Soldado and Corumbá groups (Uruguay and Brazil): palaeogeographic, palaeoclimatic and palaeobiologic implications. Precambrian Res. 120:241–278.

Gaucher, C.; Poiré, D. G.; Gómez Peral, L.; and Chiglino, L. 2005. Litoestratigrafía, bioestratigrafía y correlaciones de las sucesiones sedimentarias del Neoproterozoico-Cámbrico del Cratón del Rio de la Plata (Uruguay y Argentina). Latin Am. J. Sediment. Basin Anal. 12:145–160.

Gaudemer, Y.; Jaupart, C.; and Tapponnier, P. 1988. Thermal control on post-orogenic extension in collision belts. Earth Planet. Sci. Lett. 89:48–62.

Gilder, S. A.; Keller, G.; Luo, M.; and Goodell, P. 1991. Eastern Asia and the Western Pacific timing and spatial distribution of rifting in China. Tectonophysics 197:225–243.

Goodell, P.; Gilder, S.; and Fang, X. 1991. A preliminary description of the Gan-Hang failed rift, southeastern China. Tectonophysics 197:245–255.

Gresse, P. G.; Chemale, F., Jr.; Silva, L. C.; Walraven, F.; and Hartman, L. A. 1996. Late- to post-orogenic basins of the Pan-African-Brasiliano collision orogen in southern Africa and southern Brazil. Basin Res. 8:157–171.

Guadagnin, F.; Chemale, F., Jr.; Santos, M. N.; Borba, M.; Dussin, I. A.; Justino, D.; and Losangela, A. 2008. Geocronologia U-Pb e geoquímica isotópica de Sm-Nd e Pb-Pb da Bacia do Itajaí: Santa Catarina. *In* 44 Congresso Brasileiro de Geologia, Boletim de Resumos Expandidos. SBG, Curitiba.

Gualda, G. A. R., and Vlach, S. R. F. 2007*a*. The Serra da Graciosa A-type granites and syenites, southern Brazil. 1. Regional setting and geological characterization. An. Acad. Bras. Cienc. 79:405–430.

———. 2007*b*. The Serra da Graciosa A-type granites and syenites, southern Brazil. 2. Petrographic and mineralogical evolution of the alkaline and aluminous associations. Lithos 93:310–327.

Hartmann, L. A.; Porcher, C. C.; and Remus, M. V. D. 2002. Evolução das rochas metamórficas do Rio Grande do Sul. *In* Holz, M., and De Ros, L. F., eds. Geologia do Rio Grande do Sul. Porto Alegre, CIGO/UFRGS, p. 79–118.

Janasi, V. A.; Leite, R. J.; and van Schmus, W. R. 2001. U-Pb chronostratigraphy of the granitic magmatism in the Agudos Grandes Batholith (west of São Paulo, Brazil): implications for the evolution of the Ribeira Belt. J. S. Am. Earth Sci. 14:363–376.

Janikian, L. 2001. Evolução paleoambiental do Grupo Camaquã na região de Bom Jardim, Sub-Bacia Camaquã Central, RS. MS thesis, Instituto de Geociências, Universidade de São Paulo.

———. 2004. Seqüências deposicionais e evolução paleoambiental do Grupo Bom Jardim e da Formação Acampamento Velho, Supergrupo Camaquã, Rio Grande do Sul. PhD thesis, Instituto de Geociências, Universidade de São Paulo.

Janikian, L.; Almeida, R. P.; Fragoso-Cesar, A. R. S.; Corrêa, C. R. A.; and Pelosi, A. P. M. R. 2005. Evolução paleoambiental e seqüências deposicionais do Grupo Bom Jardim e Formação Acampamento Velho (Supergrupo Camaquã) na porção norte da Sub-Bacia Camaquã Ocidental. Rev. Bras. Geocienc. 35:245–256.

Janikian, L.; Almeida, R. P.; Fragoso-Cesar, A. R. S.; and Fambrini, G. L. 2003. Redefinição do Grupo Bom Jardim (Neoproterozóico III) em sua área-tipo: litoestratigrafia, paleogeografia e significado tectônico das sucessões vulcano-sedimentares do Supergrupo Camaquã, RS. Rev. Bras. Geocienc. 33:349–362.

Janikian, L.; Almeida, R. P.; Trindade, R. I. F.; Fragoso-Cesar, A. R. S.; D'Agrella-Filho, M. S.; Dantas, E. L.; and Tohver, E. 2008. The continental record of Ediacaran volcano-sedimentary successions in southern Brazil and their global implications. Terra Nova 20: 259–266.

Li, X.-H.; Li, Z.-X.; Li, W.-X.; Liu, Y.; Yuan, C.; Wei, G.; and Qi, C. 2007. U-Pb zircon, geochemical and Sr-Nd-Hf isotopic constraints on age and origin of Jurassic I- and A-type granites from central Guangdong, SE China: a major igneous event in response to foundering of a subducted flat-slab? Lithos 96:186–204.

Li, Z.-X., and Li, X.-H. 2007. Formation of the 1300-km-wide intracontinental orogen and postorogenic magmatic province in Mesozoic south China: a flat-slab subduction model. Geology 35:179–182.

Machado, R., and Sayeg, H. S. 1992. Aplicação da análise geométrica e cinemática nos falhamentos que condicionaram a bacia molássica do Arroio Boici, RS. *In* I Workshop Sobre as Bacias Molássicas Brasilianas, Boletim de Resumos Expandidos. São Leopoldo, SBG/UNISINOS, p. 73–76.

Moro, R. P. X. 1993. A Bacia Ordoviciana do Grupo Castro, PR. PhD thesis, Instituto de Geociências, Universidade de São Paulo.

———. 2000. Propostas de origem, evoução e contexto da Bacia da Formação Camarinha: transição Neoproterozóico-Eocambriano do Estado do Paraná. PhD thesis, Instituto de Geociências, Universidade de São Paulo.

Moro, R. P. X.; Bonacim, E.; and Soares, P. C. 1993. Grupo Castro: conteúdo de uma bacia molássica pós-orogênica no cambro-ordoviciano paranaense. Acta Geol. Leopold. 37:119–134.

———. 1994. Geologia da Bacia de Castro. Bol. Parana. Geocienc. 42:43–58.

Nardi, L. V. S.; Plá-Cid, J.; Bitencourt, M. F.; and Stabeli, L. Z. 2008. Geochemistry and petrogenesis of post-collisional ultrapotassic syenites and granites from southernmost Brazil: the Piquiri Syenite Massif. An. Acad. Bras. Cienc. 80:353–371.

Oliveira, J. M. M. T., and Fernandes, L. A. D. 1991. Estágios finais da evolução do Cinturão Dom Feliciano: tectônica e sedimentação da Formação Arroio dos Nobres. *In* III Simpósio Nacional de Estudos Tectônicos, Boletim de Resumos Extensos. Rio Claro, SBG, p. 58–59.

———. 1992. Bacias molássicas brasilianas, mito ou realidade? *In* I Workshop Sobre as Bacias Molássicas Brasilianas, Boletim de Resumos Expandidos. São Leopoldo, SBG/UNISINOS, p. 97–105.

Oyhantçabal, P.; Siegesmund, S.; Wemmer, K.; Frei, R.; and Layer, P. 2007. Post-collisional transition from calc-alkaline to alkaline magmatism during transcurrent deformation in the southernmost Dom Feliciano Belt (Braziliano-Pan-African, Uruguay). Lithos 98:141–159.

Paim, P. S. G.; Chemale, F., Jr.; and Lopes, R. C. 2002. A Bacia do Camaquã. *In* Holtz, M., and De Ros, L. F., eds. Geologia do Rio Grande do Sul. Porto Alegre, CIGO/UFRGS, p. 231–274.

Pazos, P. J.; Bettucci, L. S.; and Loureiro, J. 2008. The Neoproterozoic glacial record in the Rio de la Plata Craton: a critical reappraisal. Geol. Soc. Lond. Spec. Publ. 294:343–364.

Pazos, P. J.; Sánchez-Bettucci, L.; and Tofalo, O. R. 2003. The record of the Varanger Glaciation at the Río De La Plata Craton, Vendian-Cambrian of Uruguay. Gondwana Res. 6:65–77.

Pecoits, E.; Gingras, M.; Aubet, N.; and Konhauser, K. 2008. Ediacaran in Uruguay: palaeoclimatic and palaeobiological implications. Sedimentology 55:689–719.

Pedrosa-Soares, A.; Noce, C.; Wiedemann, C.; and Pinto, C. 2001. The Araçuaí-West-Congo Orogen in Brazil: an overview of a confined orogen formed during Gondwanaland assembly. Precambrian Res. 110:307–323.

Pedrosa-Soares, A.; Vidal, P.; Leonardos, O.; and De Brito-Neves, B. 1998. Neoproterozoic oceanic remnants in eastern Brazil: further evidence and refutation of an exclusively ensialic evolution for the Aracuai–West Congo Orogen. Geology 26:519–522.

Philipp, R. P., and Machado, R. 2005. The Late Neoproterozoic granitoid magmatism of the Pelotas Batholith, southern Brazil. J. S. Am. Earth Sci. 19:461–478.

Qiu, Y.; Wu, Q.; Ji, X.; Li, J.; Zhong, H.; and Sheng, Z. 1991. Meso-cenozoic taphrogeny and dispersion in the continental margin of southeast China and adjacent seas. Tectonophysics 197:257–269.

Reis Neto, J. M.; Vasconcelos, E. M. G.; and Bittencourt, C. 2000. Guaratubinha Formation: petrographic characterization of the volcaniclastic rocks. Rev. Bras. Geocienc. 30:371–373.

Rey, P.; Vanderhaeghe, O.; and Teyssier, C. 2001. Gravitational collapse of the continental crust: definition, regimes and modes. Tectonophysics 342:435–449.

Rostirolla, S. P.; Ahrendt, A.; Soares, P. C.; and Carmignani, L. 1999. Basin analysis and mineral endowment of the Proterozoic Itajaí Basin, south-east Brazil. Basin Res. 11:127–142.

Rostirolla, S. P.; Alkmim, F. F.; and Soares, P. C. 1992*a*. O Grupo Itajaí, Estado de Santa Catarina, Brasil: exemplo de sedimentação em uma bacia flexural de antepaís. Bol. Geocienc. PETROBRAS 6:109–122.

Rostirolla, S. P., and Soares, P. C. 1992. Bacia do Itajaí: evolução tectonossedimentar de uma bacia molássica precoce. *In* I Workshop Sobre as Bacias Molássicas Brasilianas, Boletim de Resumos Expandidos. São Leopoldo, SBG/UNISINOS, p. 124–128.

Rostirolla, S. P.; Soares, P. C.; and Alkmim, F. F. 1992*b*. Análise estrutural da tectônica deformadora da Bacia de Itajaí, Estado de Santa Catarina, Brasil. Bol. Geocienc. PETROBRAS 6:123–147.

Sánchez-Bettucci, L.; Koukharsky, M.; Pazos, P. J.; and Stareczek, S. 2009. Neoproterozoic subaqueous extrusive-intrusive rocks in the Playa Hermosa Formation in Uruguay: regional and stratigraphic significance. Gondwana Res. 16:134–144.

Shu, L.; Zhou, X.; Deng, P.; Wang, B.; Jiang, S.; Yu, J.; and Zhao, X. 2009. Mesozoic tectonic evolution of the Southeast China Block: new insights from basin analysis. J. Asian Earth Sci. 34:376–391.

Siga, O., Jr.; Basei, M. A. S.; Sato, K.; Cordani, U. G.; and Citroni, S. B. 2000. U-Pb and Sm-Nd isotopic studies of Campo Alegre and Guaratubinha volcanosedimentary basins, southern region. *In* 31st International Geological Congress, Rio de Janeiro.

Silva, L. C.; McNaughton, N. J.; Armstrong, R.; Hartmann, L. A.; and Fletcher, I. R. 2005. The Neoproterozoic Mantiqueira Province and its African connections: a zircon-based U-Pb geochronologic subdivision for the Brasiliano-Pan-African systems of orogens. Precambrian Res. 136:203–240.

Soares, P. C. 1987. Seqüências tecto-sedimentares e tectônica deformadora no centro-oeste do Escudo Paranaense. *In* III Simpósio Sul-Brasileiro de Geologia, Atas, vol. 2. Curitiba, SBG, p. 743–771.

———. 1988. Tectônica colisional em torno do Bloco Paraná, Brasil. *In* VII Congresso Latino-Americano de Geologia, Anais, vol. 1. Belém, SBG, p. 63–79.

Sommer, C. A.; Lima, E. F.; Nardi, L. V. S.; Figueiredo, A. M. G.; and Pierosan, R. 2005. Potassic and low- and high-Ti mildly alkaline volcanism in the Neoproterozoic Ramada Plateau, southermost Brazil. J. S. Am. Earth Sci. 18:237–254.

Sommer, C. A.; Lima, E. F.; Nardi, L. V. S.; Liz, J. D.; and Waichel, B. L. 2006. The evolution of Neoproterozoic magmatism in southernmost Brazil: shoshonitic, high-K tholeiitic and silica-saturated, sodic alkaline volcanism in post-collisional basins. An. Acad. Bras. Cienc. 78:573–589.

Teixeira, A. L. 1995. Ambientes geradores dos sedimentos da Bacia de Eleutério. MS thesis, Instituto de Geociências, Universidade de São Paulo.

Teixeira, A. L.; Cordani, U. G.; and Nutman, A. 1999. Idades U/Pb (SHRIMP) de seixo rioítico em metacongomerado da Bacia Eleutério, estado de São Paulo. An. Acad. Bras. Cienc. 71:837–838.

Teixeira, A. L.; Gaucher, C.; Paim, P. S. G.; Fonseca, M. M.; Parente, C. V.; Silva Filho, W. F.; and Almeida, A. R. 2004. Bacias do Estágio da Transição da Plataforma Sul-Americana. *In* Mantesso Neto, V.; Bartorelli, A.; Carneiro, C. D. R.; and Brito Neves, B. B., eds. Geologia do Continente Sul-Americano: evolução da obra de Fernando Flávio Marques de Almeida. São Paulo, Beca, p. 487–537.

Teixeira, A. L., and Petri, S. 2001. Estratigrafia e correlações estratigráficas da Bacia Pouso Algre, transição Neoproterozóico-Cambriano, Minas Gerais, Brasil. Rev. Inst. Geol. 22:5–26.

Tirel, C.; Brun, J.-P.; and Sokoutis, D. 2006. Extension of thickened and hot lithospheres: inferences from laboratory modeling. Tectonics 25:TC1005.

Trein, E., and Fuck, R. A. 1967. O Grupo Castro. Bol. Parana. Geocienc. 23:257–305.

Vasconcelos, P. M.; Onoe, A. T.; Kawashita, K.; Soares, A. J.; and Teixeira, W. 2002. ^{40}Ar-^{39}Ar geochronology at the Instituto de Geociências, USP: instrumentation, analytical procedures, and calibration. An. Acad. Bras. Cienc. 74:297–342.

Veevers, J. 2007. Pan-Gondwanaland post-collisional extension marked by 650–500 Ma alkaline rocks and carbonatites and related detrital zircons: a review. Earth-Science Rev. 83:1–47.

Waichel, B. L.; Lima, E. F.; Nardi, L. V. S.; and Sommer, C. A. 2000. The alkaline post-collisional volcanism of the Campo Alegre Basin, southern Brazil: petrogenetic aspects. Rev. Bras. Geocienc. 30:393–396.