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Recurring extensional and strike-slip tectonics after the Neoproterozoic collisional events in the southern Mantiqueira province

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ABSTRACT

In Eastern South America, a series of fault-bounded sedimentary basins that crop out from Southern Uruguay to Southeastern Brazil were formed after the main collisional deformation of the Brasiliano Orogeny and record the tectonic events that affected the region from the Middle Ediacaran onwards. We address the problem of discerning the basin-forming tectonics from the later deformational events through paleostress analysis of more than 600 fault-slip data, mainly from the Camaquã Basin (Southern Brazil), sorted by stratigraphic level and cross-cutting relationships of superposed striations, and integrated with available stratigraphic and geochronological data. Our results show that the Camaquã Basin was formed by at least two distinct extensional events, and that rapid paleostress changes took place in the region a few tens of million years after the major collision (c.a. 630 Ma), probably due to the interplay between local active extensional tectonics and the distal effects of the continued amalgamation of plates and terranes at the margins of the still-forming Gondwana Plate. Preliminary paleostress data from the Castro Basin and published data from the Itajaí Basin suggest that these events had a regional nature.

Key words: Camaquã Basin, Earth Sciences, Neoproterozoic, Paleostress Analysis, Rift Basin, Southern Brazil.

INTRODUCTION

The tectonic evolution of Precambrian terrains has long been a major theme of scientific research, but the tectonic record present in the unmetamorphosed and low-grade sedimentary and volcanic successions of the Proterozoic and Archean is frequently underestimated. Studies focused on the paleostress analysis of Precambrian sedimentary basins using fault slip data are scarce, possibly due to the complexity brought by the superposition of several tectonic events during the long geological history of these regions.

In this context, the Ediacaran to Early Cambrian system of fault-bounded basins that crops out from Southern Uruguay to Southeastern Brazil is an ideal object for paleostress analysis since these

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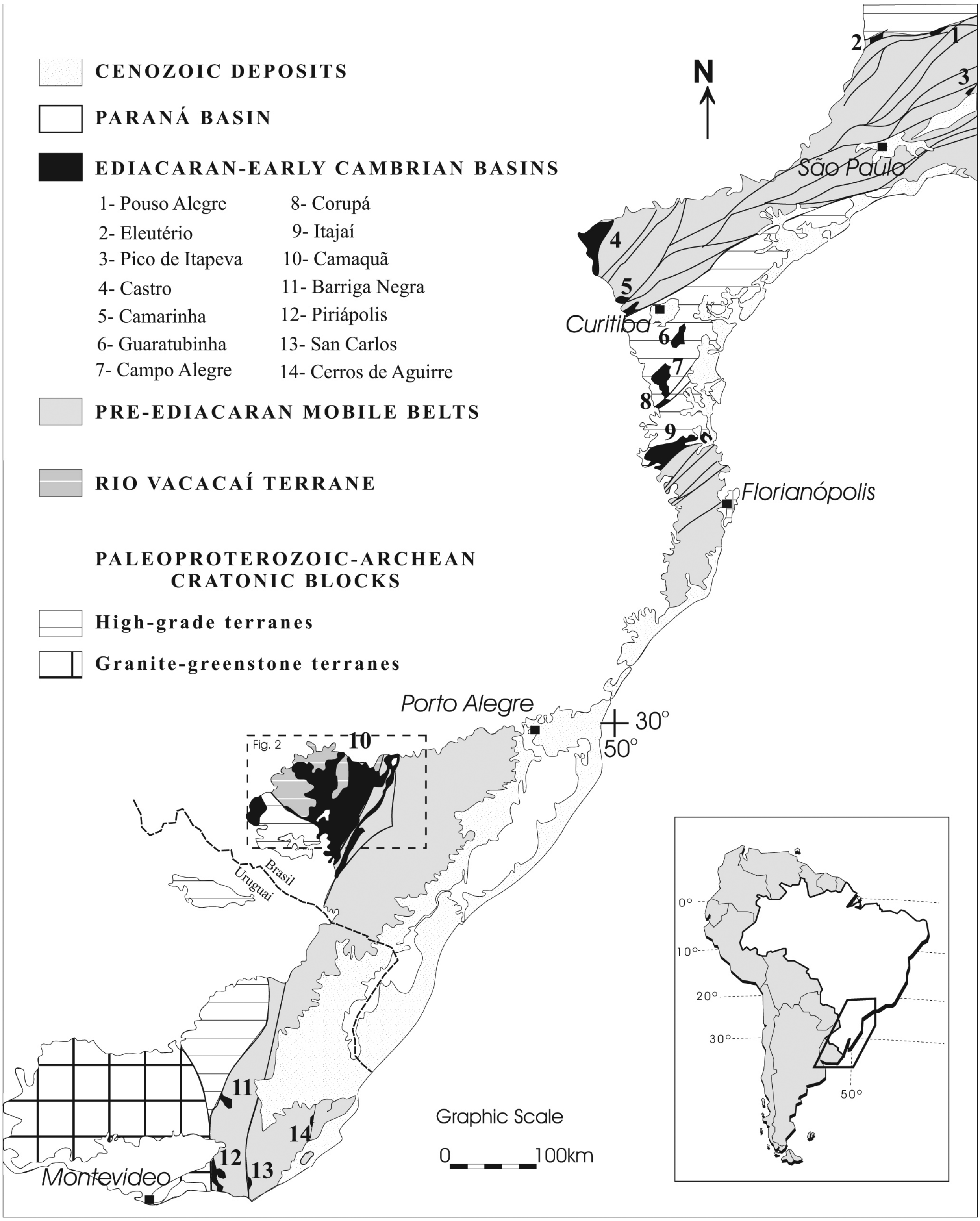

Figure 1: Geological sketch map of southern Brazil and Uruguay showing the location of the Ediacaran-Cambrian basins and the major tectonic division of their basement.

basins show no regional metamorphism or ductile deformation, and it is possible to identify and date, through geochronological analysis of several volcanic units, distinct events of subsidence bounded by unconformities. This brings the possibility of determining an absolute chronology for the tectonic events that occurred during the basin evolution.

The basin system is more than 1,500 km long (Fig. 1), encompassing several discontinuous basins bounded by steeply dipping brittle faults and filled with immature terrigenous sedimentary successions with volcanic and volcaniclastic intercalations. The basins are aligned parallel to the major structures of the underlying Dom Feliciano and Ribeira fold belts, which were formed during the main collisional event of the Brasiliano-Pan African Orogeny in the region. This orogenic event affected most of eastern South America, forming several fold and thrust belts around the São Francisco and the Rio de La Plata Cratons (Almeida 1969, Almeida et al. 1973, 1981, Cordani and Brito Neves 1982). The basins were formed soon after the main collisional deformation of the Brasiliano Orogeny, and their origin is often attributed to the last stages of orogenic evolution, being interpreted either as peripheral foreland basins (e.g. Fragoso-Cesar 1991, Gresse et al. 1996, Rostirolla et al. 1999) or post-collisional strike-slip basins (Oliveira and Fernandes 1991, 1992, Machado and Sayeg 1992). These interpretations are based mostly on the presence of strike-slip and inverse faults affecting the sedimentary successions, but no evidence for a syn-depositional nature of this deformation has been presented to date.

In order to test the current models of tectonic evolution of Southeastern South America from the Ediacaran to the Cambrian, we reconstructed the stress evolution of the best preserved basin of the system: the Camaquã Basin, which comprises more than 10,000 m of sedimentary and volcanogenic successions that record the paleogeographic evolution of the region between ca. 610 Ma and 535 Ma. We present orientation data on brittle faults with slickensided fibers and striations of each major unit of the Camaquã Basin, as well as some younger units, in order to establish the chronology of the deformational events and to distinguish the directions of paleostress axes related to basin formation from those that were responsible for its later deformation. The other two major basins of the system were also considered, leading to a regional characterization: the Itajaí Basin, for which we analyzed published paleostress data, and the Castro Basin, for which we collected preliminary data.

The resulting characterization of the basin-forming and basin-deforming tectonic events brings new insights on the nature of post-orogenic tectonics. The present work also shows that, given adequate stratigraphic and geochronological controls, paleostress analysis of sedimentary basins can be a powerful tool in the reconstruction of the tectonic history of Precambrian terrains.

Geological Setting

The Ediacaran to Cambrian basins of Southeastern South America are part of the Mantiqueira Province (Almeida et al. 1981), occurring mainly in its southern part. The Southern Mantiqueira Province comprehends pre-Ediacaran geological units affected by Brasiliano orogenic processes, with peak metamorphism at 630 to 620 Ma (Silva et al. 2005), as well as Ediacaran to Cambrian post-Orogenic units, including the here discussed basins and voluminous granites of alkaline affinity (e.g. Philipp 1998, Philipp and Machado 2001, Janasi et al. 2001, Campos Neto 2000, Trouw et al. 2000, Philipp et al. 2002, Nardi and Lima 2002, Leite 2003, Heilbron et al. 2004, Silva et al. 2005, Gualda and Vlach 2007a, b, Oyhantçabal et al. 2007). The pre-Ediacaran units of the province comprise Archean to Paleoproterozoic blocks with varyied degrees of Neoproterozoic reworking. These include the Rio de La Plata Craton (Almeida et al. 1973) at the southernmost part of the province, an accreted intraoceanic terrane of Criogenian age (Rio Vacacaí Terrane of Fragoso-Cesar 1991, São Gabriel Block of Babinski et al. 1996) and a collisional mobile belt (Dom Feliciano Belt, Fragoso-Cesar 1980) with peak metamorphism at the Criogenian – Ediacaran boundary (Basei et al. 2000, Silva et al. 2005), affecting pre-collisional granites and sedimentary basins, as well as their basement. Major strike-slip shear zones, mostly with NNE to NE trends, juxtapose and deform the above described units, including the Ediacaran ones.

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 basin of the system. The currently accepted models can be grouped into three main types: (i) models that consider a syn-orogenic setting, mainly of peripheral foreland basins (e.g. Fragoso-Cesar 1991, Gresse et al. 1996, Rostirolla et al. 1999); (ii) models that consider a late orogenic setting of post-collisional strike-slip basins (Oliveira and Fernandes 1991, 1992, Machado and Sayeg 1992); and (iii) models that consider an extensional origin, unrelated to the previous orogeny (Fragoso-Cesar et al. 2000, 2001, Almeida et al. 2010, Janikian 2001, 2004, Fambrini 2003). Some authors also propose an evolution from syn- to post-orogenic 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. Indeed, very few paleostress data on these Ediacaran to Cambrian basins have been published (Rostirolla et al. 1992b, Bonacim et al. 1994, for the Itajaí and Castro Basin, respectively).

Despite the potential of the Camaquã Basin to elucidate some important issues concerning the nature of the latest stages of the Brasiliano Orogeny, very few works have focused on the structural analysis of its sedimentary units (e.g. Silva Filho 1997, Fambrini 1998), and the majority of the published tectonic interpretations are based on assumptions of the supposed role of the Camaquã Basin in regional tectonic models (e.g. Fragoso-Cesar 1991, Oliveira and Fernandes 1991, 1992, Gresse et al. 1996). On the basis of stratigraphic analysis of individual units of the Camaquã Basin, recent works (e.g. Fragoso-Cesar et al. 2000, Almeida 2001, Janikian 2001, 2004, Janikian et al. 2003, 2005, Fambrini 2003, Fambrini et al. 2005, Almeida 2005) demonstrated the influence of the syn-sedimentary basin border faults on the depositional architecture. These works revealed the absence of large-scale strike-slip displacement between source-areas and the nearby alluvial-fan deposits, suggesting that the basin border faults were mainly normal during extensional basin-forming tectonic episodes. The here presented characterization of the deformational events that affected the basin brings additional evidence supporting an extensional origin for the Camaquã and coeval basins, which was recently synthesized by Almeida et al. (2010).

METHODS

For the reconstitution of the paleostress fields, we have collected more than 600 data on faults with striations distributed in more than 100 outcrops (table I) of the volcanic and sedimentary successions of the Camaquã Supergroup (Ediacaran to Cambrian) and the Castro Group, as well as Permian and Triassic successions found near the Camaquã Basin (respectively the Tubarão and the Rosário do Sul groups). In some situations, the data of outcrops within a radius of less than 2 km were grouped in order to constraint the paleostress tensor with bigger data sets, achieving more accurate results. The successive tectonic events were sorted using relative chronology criteria based on stratigraphic data from the Camaquã Basin and superimposition of slickensided fibers and striations. Correlation among basins was based on the available geochronological data (Almeida et al. 2010). We used the TENSOR software (Delvaux and Sperner 2003) to reconstruct the orientation of the paleostress tensors, which is based on the Angelier (1979, 1984, 1990) method of inversion.

Camaquã Basin

The Camaquã Basin is the largest and best known basin of the system, with an area in excess of 3,200 km^2 divided into three sub-basins. Detailed published stratigraphic descriptions (e.g. Janikian et al. 2003, 2005, Fambrini et al. 2005, 2006, 2007, Paim and Scherer 2007, Marconato et al. 2009, Almeida et al. 2009) and available geochronological data from several volcanogenic units in different stratigraphic positions (Janikian et al. 2008, 2011, Almeida et al. 2010) are the basis for choosing the Camaquã Basin as the main target for the paleostress analysis. Data from the other basins were interpreted by means of correlation and comparison with the established chronostratigraphic framework of the Camaquã Basin.

The Camaquã Basin (CB) has been studied by many authors, and the evolution of its major units was recognized and related to subsidence and deformation events. Paim (1994) and Paim et al. (2002) divided the CB into five unconformity-bounded units (allogroups) gathered in the Camaquã Allosupergroup. They interpreted, based on regional tectonic models, the following subsidence events and related deposits: a foreland succession (Maricá Allogroup); a transpresional strike-slip basin succession presenting inverse faults and folds (Bom Jardim Allogroup); two successions formed during transtensional events (Cerro do Bugio and Santa Bárbara Allogroups); and, finally, a transtensional subsidence event represented by the Guaritas half-graben, which is interpreted as a consequence of the reactivation of NE-SW regional faults (Allogroup Guaritas).

The here adopted stratigraphic column is similar to those proposed by Ribeiro et al. (1966) and Paim et al. (2002), considering published formal lithostratigraphic units (Fragoso-Cesar et al. 2003, Janikian et al. 2003, Pelosi and Fragoso-Cesar 2003, Fambrini et al. 2005, 2006, Fambrini and Fragoso-Cesar 2006, Almeida et al. 2009). The composing units of the Camaquã Supergroup (Fragoso-Cesar et al. 2003) had different depocenters resulted from the activation of distinct syn-depositional faults. This Supergroup is composed of sedimentary and volcanic successions deposited between ~ 600 and 530 Ma that are divided into the following units, from base to top: Maricá Group (fluvial sandstones and pebbly sandstones; marine fine-grained sandstones and siltstones), Bom Jardim Group (deep to shallow lacustrine sandstone, conglomerate, rhythmite and mudstone; intermediate, basic and acid volcanic and volcaniclastic rocks), Acampamento Velho Formation (acid volcanic and volcaniclastic rocks), Santa Bárbara Group (alluvial sandstone, conglomerate and sand-mud rhythmite), and Guaritas Group (alluvial sandstone and conglomerate; aeolian sandstone). Basic and intermediate subvolcanic rocks of the Rodeio Velho Intrusive Suite cut across the Camaquã Supergroup, frequently occurring as shallow sills that intrude the Guaritas Group.

Structural Geology

The Camaquã Basin developed on a complex basement, composed of three structures generated during the Brasiliano event (Fragoso-Cesar 1991): (1) the Rio de La Plata Craton, (2) the Dom Feliciano Belt and (3) the Rio Vacacaí Terrane.

The Rio de La Plata Craton crops to the southwest of the basin and is composed of high grade metamorphic neoarchean and paleoproterozoic rocks (Hartmann et al. 2000). It presents NW/SE banding and highly varied, steep dips.

The craton is bordered to the East by the Dom Feliciano Belt (Ribeiro and Fantinel 1978, Porada 1979, Fragoso-Cesar 1980, 1991, Jost 1981,

TABLE I

Calculated orientation of stress axes for each measured site. N=number of measurements. Φ = (σ2-σ3)/(σ1-σ3) with σ1>σ2>σ3 (Angelier, 1984). α= average angle between computed shear stress and observed slickensided striations (in degrees). Stress tensor noted as trend/plunge, in degrees.

Outcrop	Stratigraphic Unit	Coordinates	N	σ1	σ2	σ3	ϕ	α	Tectonic Event
1	Maricá Group	30° 21' 46" S	5	05/348	66/245	23/080	0.33	3.48	Post-Early Cambrian strike-slip
		53° 31' 02" W							
2	Bom Jardim Group	30° 25' 06" S	9	06/136	70/028	16/228	0.89	15.37	Middle Ediacaran extension
		53° 22' 20" W	17	83/165	05/029	05/299	0.25	10.77	Late Ediacaran extension
			13	01/225	62/314	28/134	0.67	9.70	Ediacaran-Cambrian strike slip
3	Bom Jardim Group	30° 35' 10" S	12	76/268	05/166	13/076	0.35	13.18	Middle Ediacaran extension
		53° 22' 54" W							Late Ediacaran extension
4	Bom Jardim Group	30° 26' 54" S	6	83/111	08/311	05/217	0.65	9.25	Middle Ediacaran extension
		53° 21' 46" W							
5	Bom Jardim Group	30° 32' 12" S	5	61/090	07/343	26/250	0.38	8.08	Post-Early Cambrian strike-slip
		53° 22' 32" W							
6	Bom Jardim Group	30° 55' 14" S	8	15/016	56/130	28/277	0.47	10.84	Middle Ediacaran extension
		53° 37' 44" W							
7	Bom Jardim Group	30° 35' 06" S	13	87/006	02/144	02/234	0.22	8.43	Middle Ediacaran extension
		53° 23' 23" W	12	18/008	26/270	57/128	0.14	9.59	Ediacaran-Cambrian strike slip
8	Acampamento V. Fm.	30° 21' 46" S	5	87/274	01/018	02/109	0.04	0.94	Late Ediacaran extension
		53° 31' 02" W							
9	Bom Jardim Group	30° 21' 46" S	18	81/167	09/342	00/072	0.37	11.66	Middle Ediacaran extension
		53° 22' 30" W	7	44/099	43/298	09/199	0.72	14.37	Late Ediacaran extension
10	Lavras do Sul Granite	30° 47' 30" S	8	12/042	76/255	07/135	0.14	5.43	Ediacaran-Cambrian strike slip
		53° 49' 52" W							
11	Lavras do Sul Granite	30° 48' 12" S	16	00/154	66/244	24/065	0.40	16.63	Post-Early Cambrian strike-slip
		53° 52' 07" W							
12	Santa Bárbara Gr.	30° 54' 21" S	38	16/336	65/207	18/071	0.67	11.31	Post-Early Cambrian strike-slip
		53° 26' 35" W	50	14/229	76/026	05/138	0.62	12.10	Post-Early Cambrian strike-slip
			26	09/097	81/298	04/187	0.39	12.18	Post-Early Cambrian strike-slip

TABLE I (continuation)

Outcrop	Stratigraphic Unit	Coordinates	N	σ1	σ2	σ3	ϕ	α	Tectonic Event
14	Santa Bárbara Gr.	30° 43' 12" S 53° 40' 37" W	21	41/345	48/176	05/081	0.70	8.05	Early Cambrian extension
15	Santa Bárbara Gr.	30° 32' 56" S 53° 35' 05" W	12	01/318	52/049	38/227	0.04	11.98	Post-Early Cambrian strike-slip
16	Santa Bárbara Gr. (sin- sedimentary)	30° 52' 45" S 53° 04' 30" W	11	58/360	32/178	01/091	0.16	8.29	Late Ediacaran extension
17	Santa Bárbara Gr.	30° 44' 55" S 53° 45' 47" W	12	01/138	43/050	47/227	0.09	9.34	Cretaceous extension
18	Guaritas Group	30° 46' 41" S 53° 33' 40" W	14	83/019	07/198	00/109	0.57	13.90	Early Cambrian extension
20	Rodeio Velho I.S.	30° 51' 52" S 53° 13' 40" W	8	17/326	08/058	72/172	0.07	17.48	Post-Early Cambrian strike-slip
21	Rodeio Velho I.S.	30° 46' 36" S 53° 39' 14" W	19	75/064	02/318	14/228	0.16	11.78	Cretaceous extension
22	Rodeio Velho I.S.	30° 41' 53" S 53° 28' 26" W	14	07/149	82/289	06/058	0.56	10.42	Post-Early Cambrian strike-slip
24	Tubarão Group	30° 22' 00" S 52° 25' 31" W	7	89/162	01/324	00/054	0.08	8.86	Cretaceous extension
27	Sanga do Cabra Fm.	31° 05' 02" S 52° 58' 54" W	10	88/097	01/323	02/233	0.10	4.71	Cretaceous extension
28	Sanga do Cabra Fm.	30°51' 11" S 52° 59' 05" W	32	83/112	07/300	01/210	0.14	13.22	Cretaceous extension
31	Castro B. rhyolite	24° 47' 02" S 50° 01' 24" W	7 11	28/339 82/007/	14/242 01/103	58/129 07/194	0.01 0.09	14.90 4.99	Post-Early Cambrian strike-slip Cretaceous extension

Fragoso-Cesar et al. 1982b, Fernandes et al. 1992). It is interpreted as an intracontinental mobile belt with paleoproterozoic basement, composed of a suite of plutonic-mylonitic rocks with a plataformal covering that presents subordinate volcanism of mesoproterozoic and late proterozoic age, as well as low grade metamorphism. It is affected by large scale folding and shear zones of NE/SW direction. Fernandes et al. (1992) divided the Dom Feliciano Belt into two large-scale continental shear zones: one presenting linear structures with a general E-W trend and a planar fabric with an overall flat-lying attitude, and another with NE-trending sinistral strike-slip structures.

The Rio Vacacaí Terrain (Fragoso-Cesar 1991) presents Tonian and Cryogenian rocks of basic/ultrabasic composition, low grade volcano-sedimentary metamorphics and TTG complexes. Its occurrences are located to the northwest of the Camaquã Basin and are limited in the south by the WNW/ESE, dextral and steeply dipping Ibaré Shear Zone (Fragoso-Cesar 1991).

The brittle tectonic events that formed and deformed the Camaquã Basin activated these previous structures, most notably the main deformational event that activated the NNE to NE-trending structures of the Rio Vacacaí Terrane and the Dom Feliciano Belt (Fig 2) as left-lateral steeply dipping faults. This main event obliterated most (but not all) of the previous brittle deformational structures.

The composing units of the Camaquã Supergroup occur in structural blocks limited by steeply dipping faults and, with the exception of the Guaritas Group, generally present dips between 16° and 60°, with varying but mainly NE-SW strikes (Figs 3, 4, 5 and 6). Locally, at the vicinity of major faults such as the Andradas and Minas do Camaquã fault zones, the beds have higher dips, reaching 90°. Despite the descriptions of previous authors (e.g. Ribeiro et al. 1966), this intense deformation near the fault zones also affects the Guaritas Group and is clearly seen near the Minas do Camaquã Fault Zone, south of the Camaquã River, where a thick succession of fluvial and eolian deposits of the Guaritas Group occurs as near vertical beds due to fault dragging. Open folds with north-south axes affect the whole succession, being more evident in areas where the fault-induced tilting is less prominent (Figs 5 and 6).

The map distribution of the composing units of the Camaquã Supergroup is strongly controlled by later tectonic events, and the basin itself is divided into three sub-basins (Fig 3), called eastern, central and western Camaquã sub-basins, separated by basement highlands (Caçapava do Sul and Serra das Encantadas highlands). These two basement highs are limited by steeply dipping NNE-SSW-trending faults or fault zones. This NNE-SSW system is the Irapuá Fault System (Ribeiro et al. 1966), and includes faults within the sub-basins, some of them with displacements big enough to juxtapose successions of different groups. A common feature in the NNE-SSW faults is the inversion of apparent vertical displacement along their strike, caused by successive reactivation and strike-slip movement cutting tilted blocks. Another important set of brittle structures is composed of steeply dipping faults with approximately WNW-ESE trends, called Cerro da Vigia Fault System by Ribeiro et al. (1966). These structures rarely juxtapose different units of the Camaquã Supergroup, but some of the fault zones are responsible for intense deformation, marked by verticalization of beds and abundant minor faults. Evidence of successive reactivation is also present in this system.

Both fault systems are related to anisotropy directions of the basement of the Camaquã Basin (Fig. 2). The NE-SW to NNE-SSW fault system reactivates metamorphic Neoproterozoic and Paleoproterozoic schistosities found in the Dom Feliciano Belt and in the northern and eastern portions of the Rio Vacacaí Terrane. The faults with WNW-ESE trends are controlled by metamorphic schistosity and shear zones at the southern border

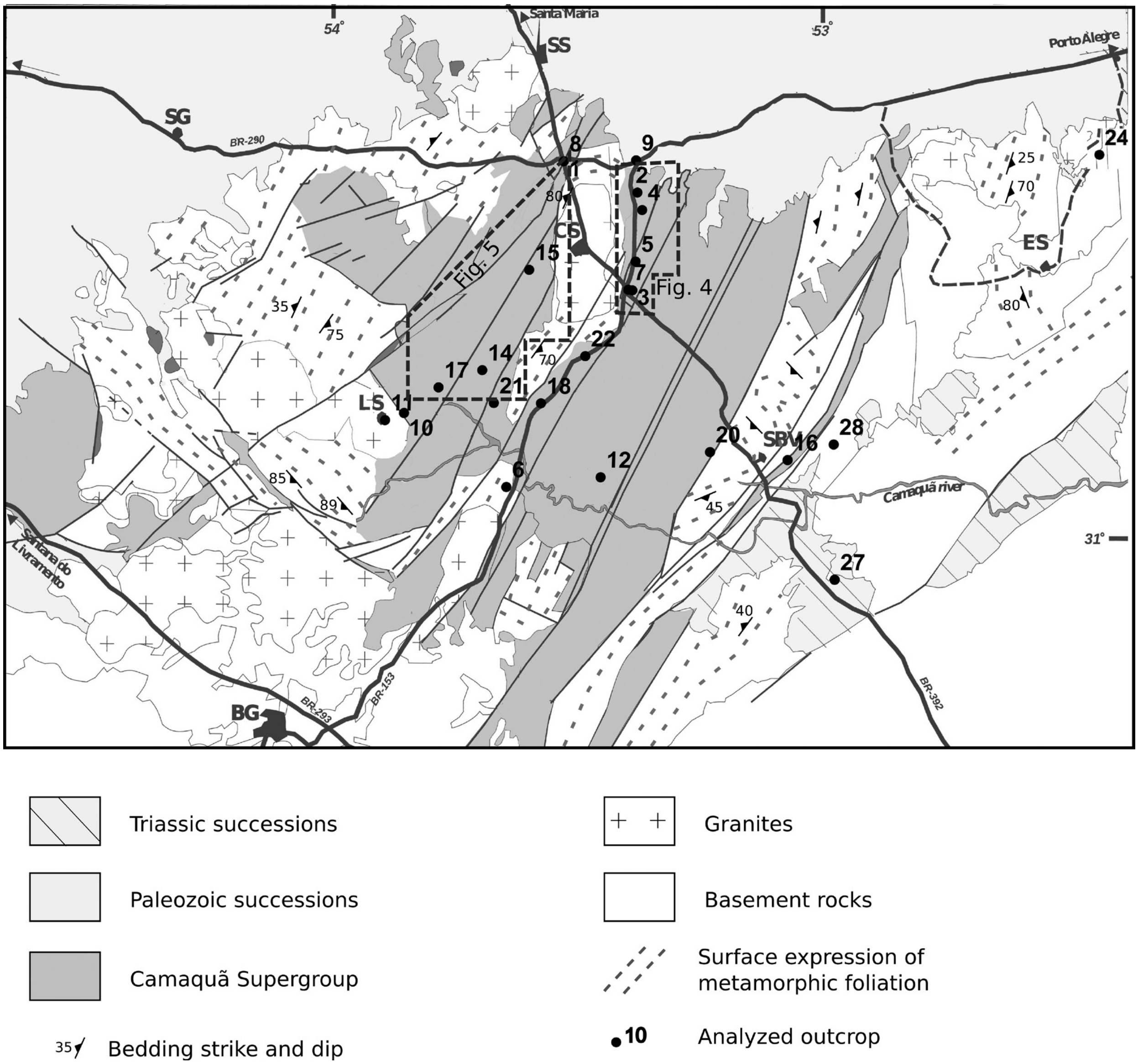

Figure 2: Location of analyzed outcrops of the Camaquã Basin region and map distribution of the main structures of its basement.

of the Rio Vacacaí Terrane, near its contact with the Valentines Block (northern Rio de La Plata Craton).

The steep dips and the great lateral continuity of the faults of both systems, which are typically more than 30 km long, suggest the predominance of strike-slip displacement. Despite that, the provenance analysis of deposits of alluvial fans and fan-deltas in 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) shows that strike-slip displacement between the deposits and their sources is not greater than a few hundred meters. This evidence suggests that strike-slip deformation was not related to the basin-forming events, but only to post-depositional activation of faults with small individual displacements.

Detailed geological mapping of selected areas of the basin reveals that the prevailing deformational style is the same in all units of the Camaquã Super-

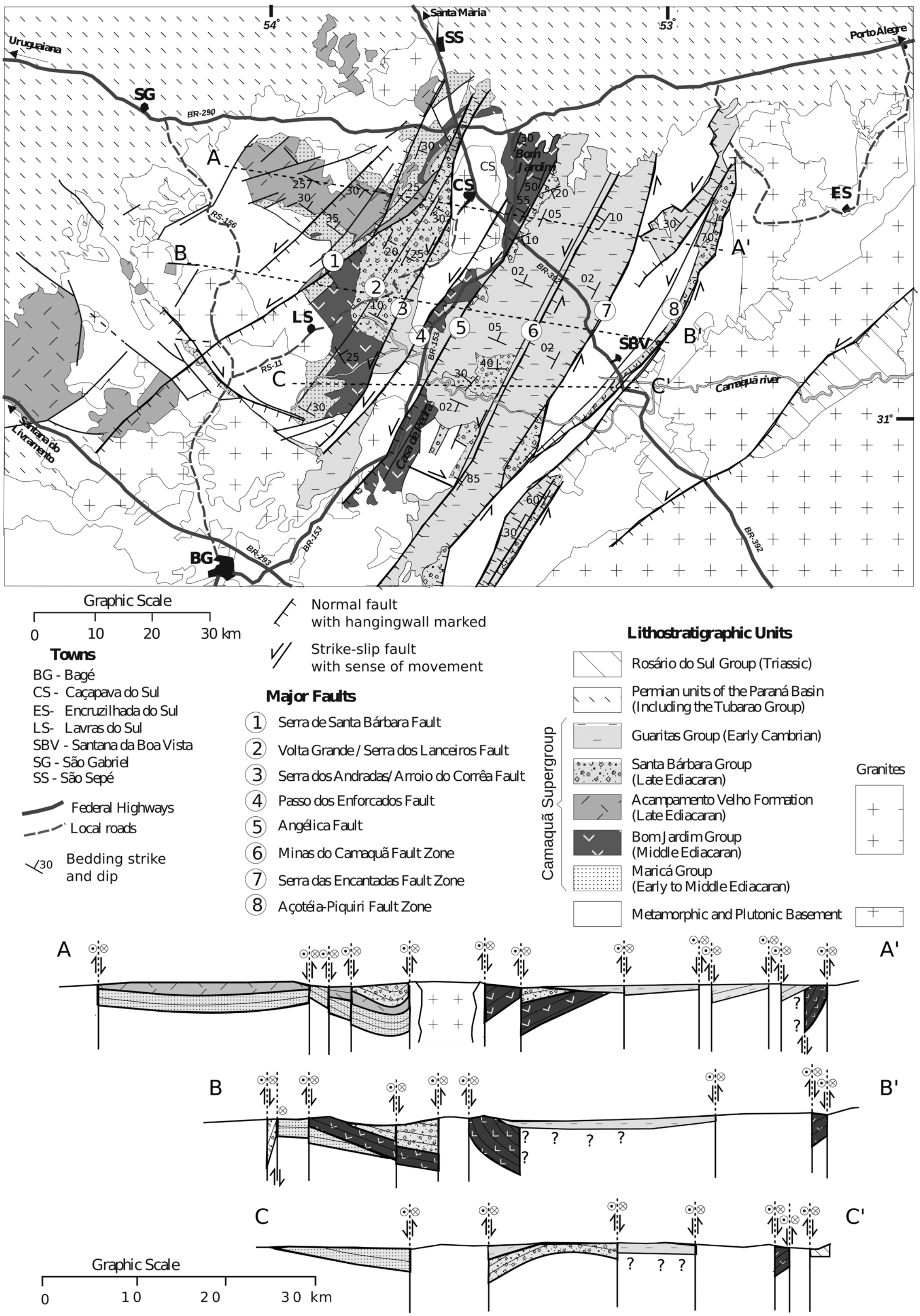

Figure 3: Geological sketch map and sections of the Camaquã Basin and nearby areas. Modified from Fragoso-Cesar et al. (2000). See location on Figure 1.

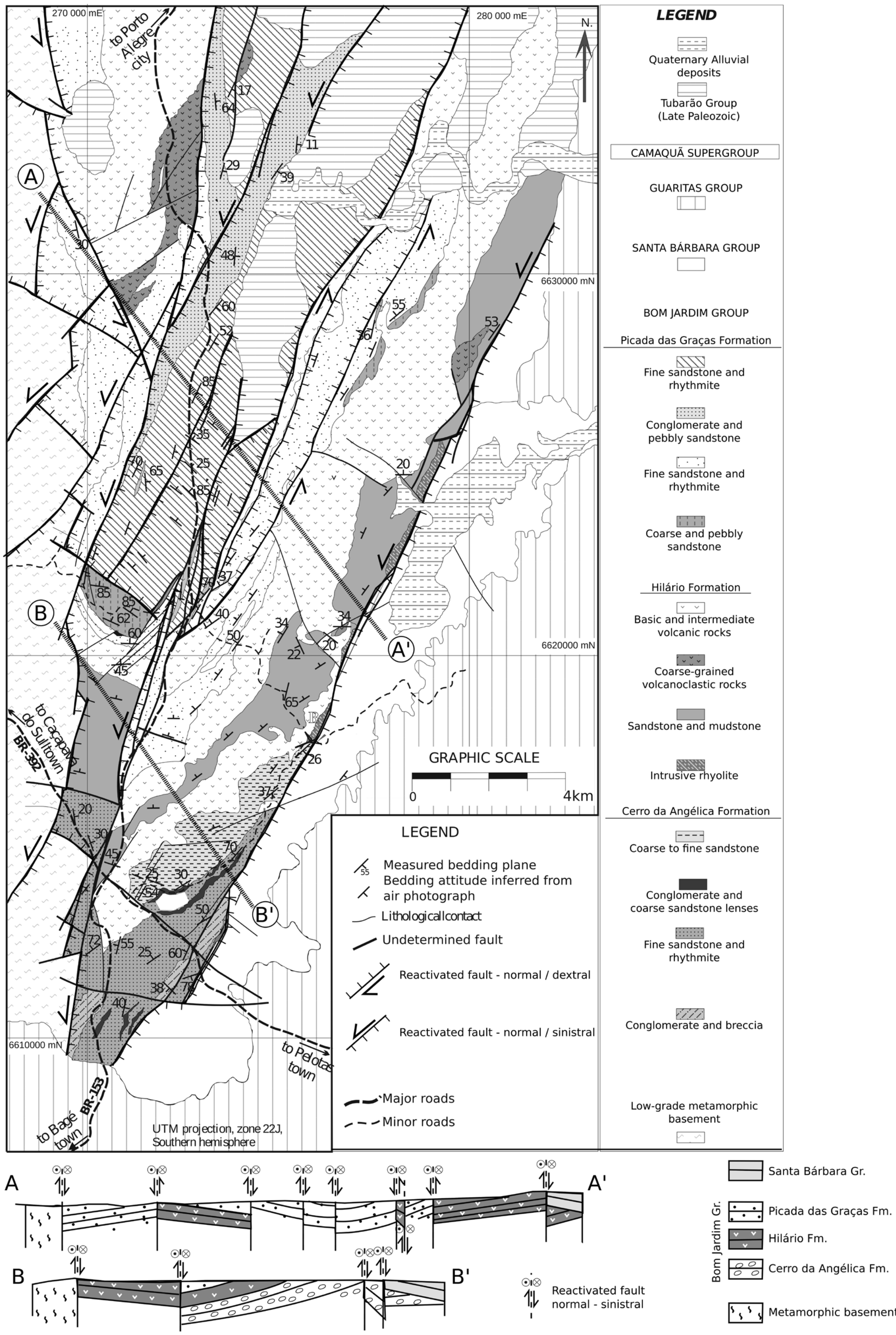

Figure 4: Geological sketch map and sections of the type area of the Bom Jardim Group and nearby areas. Modified from Janikian et al. (2003). For location see Figure 2.

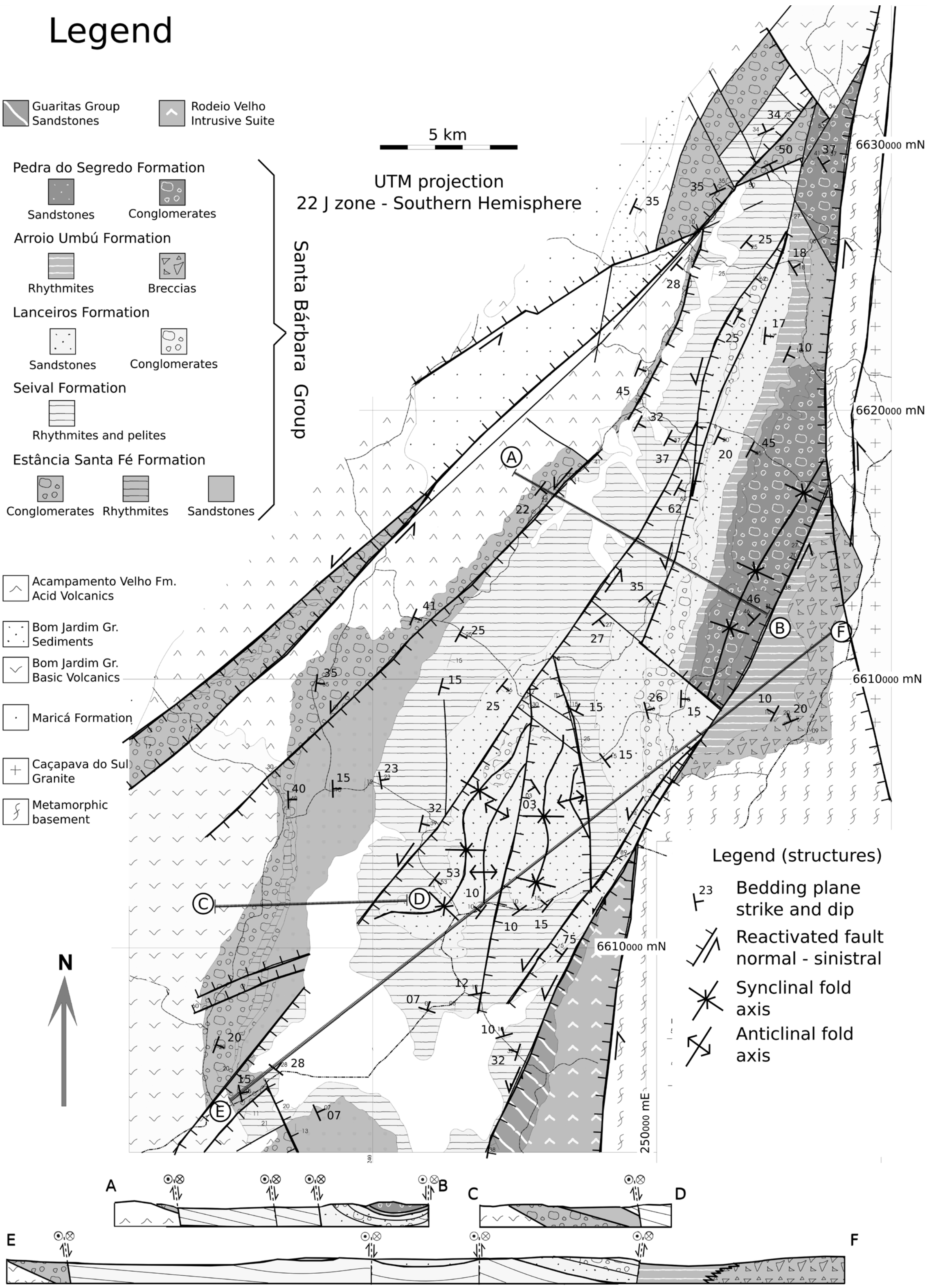

Figure 5: Geological sketch map and sections of the type area of the Santa Bárbara Group and nearby areas. Modified from Almeida (2005). For localization, see Figure 2.

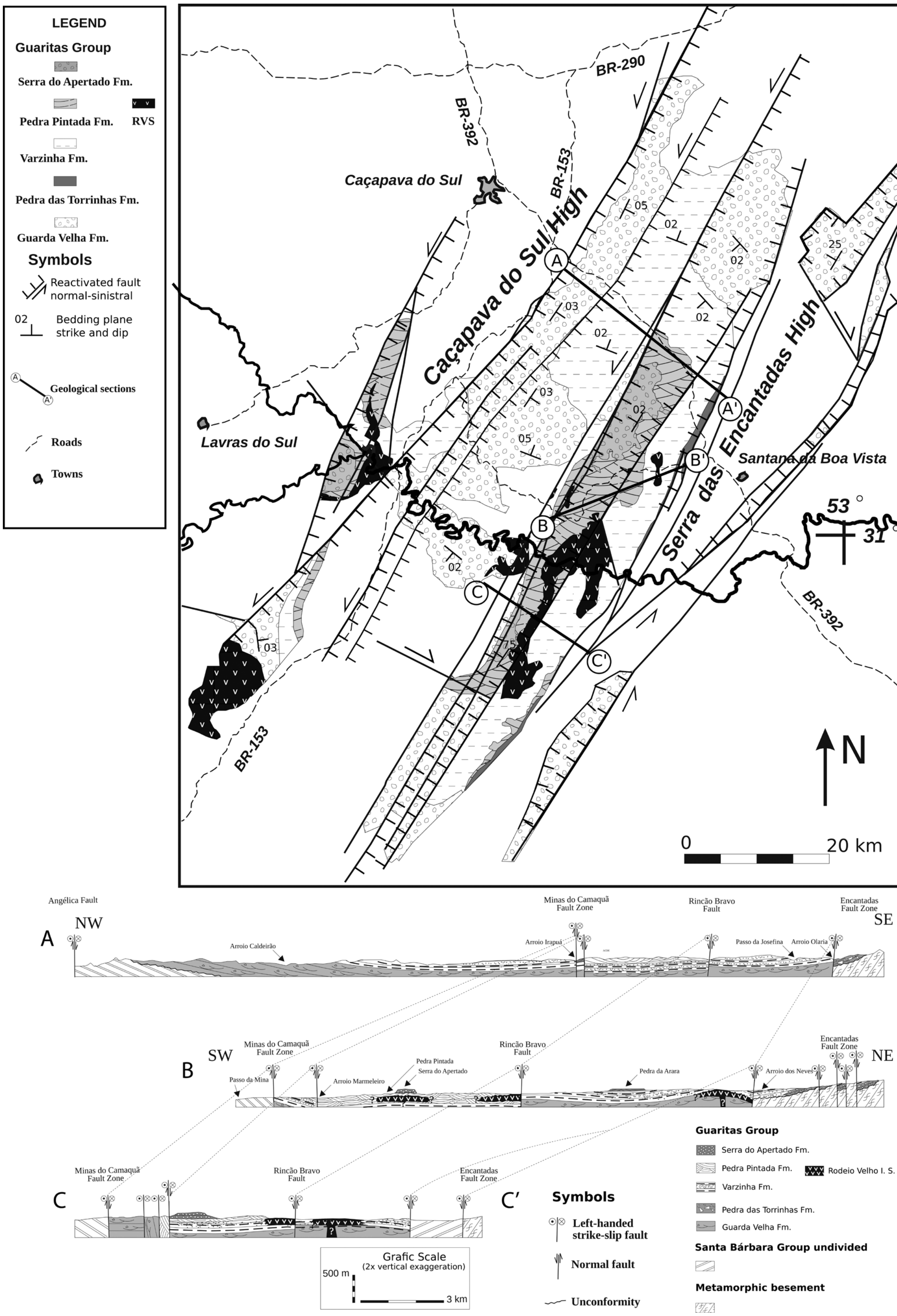

Figure 6: Geological sketch map and sections of the Guaritas Group. Modified from Almeida (2005).

group (Figs 3, 4, 5 and 6): steeply dipping normal, oblique and strike-slip brittle faults, defined by discrete planes, commonly presenting striations and locally constituting fault bundles, sometimes related to drag folds, verticalization of bedding planes and rare tectonic breccias. The resulting movement observed on the major NE-trending faults is always a composition of early NE-SW extension and later left-lateral activation, reflecting the main tectonic events (Fig. 5). Despite that, the density of faults is greater in the lower stratigraphic units (Maricá and Bom Jardim Groups and Acampamento Velho Formation), and the bedding planes tend to be steeper in those older successions, as clearly seen in the type-area of the Bom Jardim Group (Fig. 4). 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 were 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.

Paleostress Fields

The paleostress inversion of brittle faults with slickenside fibers and striations from each major unit of the Camaquã Supergroup, as well as Paleozoic and Mesozoic units that crop out in the same region, led to the recognition of five distinct stress fields (Table I), two of them interpreted as related to the basin-forming tectonics and the other three to later deformation. A sixth event is recognized regionally, but could not be identified in our dataset. The relative chronology of the events was established through stratigraphic control of fault families and, where possible, cross-cutting relationships of striations (Fig. 7). Age constraints are based on available geochronological data for the Bom Jardim Group and the Acampamento Velho Formation (Janikian et al. 2008, 2011), as well as for the Rodeio Velho Intrusive Suite (Almeida et al. 2009).

Although the paleostress analysis was carried out from the younger units to the older ones, the main identified tectonic events are described below in order of occurrence, to clarify their chronology.

Middle to Late Ediacaran extension

The Bom Jardim Group is the older unit of the Camaquã Basin that clearly shows the influence of active basin-border faults during its deposition (Janikian 2004). Therefore, the Maricá Group was not considered in the present work given its scarcity of outcrops showing faults and the uncertanties regarding its role in the tectonic evolution of the basin. The sedimentation age of the Bom Jardim Group has been determined through geochronological analysis of several stratigraphic levels of volcanoclastic and volcanic rocks (Janikian et al. 2008), ranging from 600 to 580 Ma. This unit is affected by a set of steeply

	600 to 545 Ma	545 Ma	535 Ma	530 Ma?	Cretaceous
Units affected	ENE $\sigma 3$	NNE $\sigma 1$	NW $\sigma 3$	NW $\sigma 1$	NE $\sigma 3$
Rosário do Sul Group (Triassic)					
Itararé Group and Rio Bonito Fm. (Permian)					
Rodeio Velho Intrusives (Cambrian)					
Guaritas Group (Cambrian)			Basin-forming		
Santa Bárbara Group (Late Ediacaran)	Basin-forming				
Acampamento Velho Fm. (Ediacaran)					
Bom Jardim Group (Ediacaran)	Basin-forming				
Lavras do Sul and Caçapava granites					
Maricá Group					

Figure 7: Chronology of tectonic events sorted by stratigraphic criteria and cross-cutting relationships of slickensided striations on the same plane. Dark gray rectangles indicate proved stratigraphic occurrence of each event, while light gray rectangles indicate supposed occurrence.

dipping brittle faults formed by a stress field with vertical σ1 and horizontal σ3 in the NE quadrant, characterizing an ENE-WSW to NE-SW extension (Fig. 8). Although faults compatible with a NE-SW extension are found in all studied units, affecting even Triassic successions (see below), the structures affecting the Bom Jardim Group present much higher density of occurrence than those found in higher stratigraphic levels, which are clearly post-Triassic. Where this later (possibly Cretaceous, see below) extension affects the Bom Jardim and Santa Bárbara groups, it reactivates strike-slip faults.

Feeder dikes of the Bom Jardim Group volcanic rocks are oriented mainly around NNW (Fig 8), suggesting that the ENE-WSW extensional paleostress field is related to the basin-forming tectonics during the deposition of the Bom Jardim Group. Paleogeographic reconstructions based on stratigraphic analysis and detailed mapping (Janikian 2001, 2004, Janikian et al. 2003, 2005) reveal a north-south oriented basin axis for the Bom Jardim Group, which is compatible with the interpreted paleostress field.

The Late Ediacaran basin-forming tectonics is recorded in the Camaquã Basin as the Acampamento Velho Formation (acid volcanic and pyroclastic rocks) and the post-volcanic Santa Bárbara Group. The Acampamento Velho Formation overlies the Bom Jardim Group and shows crystallization ages of 573±18 (U-Pb SHRIMP - Chemale Jr. 2002) and 574±7 (U-Pb zircon age - Janikian et al. 2005). Sommer et al. (2005) obtained an age of 549±3 Ma (U-Pb SHRIMP) in samples of acid intrusive rock that was interpreted as correlated to the Acampamento Velho Formation.

The Santa Bárbara Group, which is here considered as Late Ediacaran, overlies the Acampamento Velho Formation and is overlain, in angular unconformity, by the Early Cambrian Guaritas Group. The present analysis could not identify any compressional event related to the angular unconformity between Santa Bárbara and Bom Jardim Groups, and this is interpreted as an evidence that this unconformity resulted from local uplifting due to the continuity of the extensional tectonics.

Dikes related to the Acampamento Velho extrusive rocks show ENE-WSW average directions (Fig 8), suggesting a NNW-SSE minimum horizontal stress axis at approximately 570 Ma, but no consistent set of faults with striations compatible with this stress field was obtained in our study. Syn-sedimentary normal faults with NNW-SSE to NE-SW strikes are found in the overlying Santa Bárbara Group (Fragoso-Cesar et al. 2001, Fambrini et al. 2001, Fambrini and Fragoso-Cesar 2006), and the paleostress inversion of these structures gives an extensional stress field with E-W σ3, which is not very different from the paleostress field interpreted as related to the basin subsidence during the deposition of the Bom Jardim Group. Despite that, both events are separated by an angular unconformity (between the Bom Jardim and Santa Bárbara groups) and are recorded in the Bom Jardim Group, where cross-cutting relationships of striations can be attributed to this succession of events. A set of meso-scale normal faults affecting the Santa Bárbara Group and older units also gives a paleostress field with ENE-WSW σ3 (Fig. 4), corroborating the interpretation of a Late Ediacaran extensional event.

Paleogeographic reconstructions based on depositional systems mapping, as well as paleocurrent and provenance analyses (Fambrini et al. 2005, Fragoso-Cesar et al. 2000, 2001, Almeida 2001, 2005, Janikian 2001, 2004, Janikian et al. 2003, 2005, Fambrini 2003), suggest the presence of a roughly N-S trending basin-border normal fault during the deposition of the Santa Bárbara Group, thus corroborating the interpretation of an ENE-WSW extension in the Late Ediacaran.

Given the uncertainties regarding the actual strike of the original main faults during sedimentation, it is purely speculative to discuss weather there was a transtensional (oblique) component

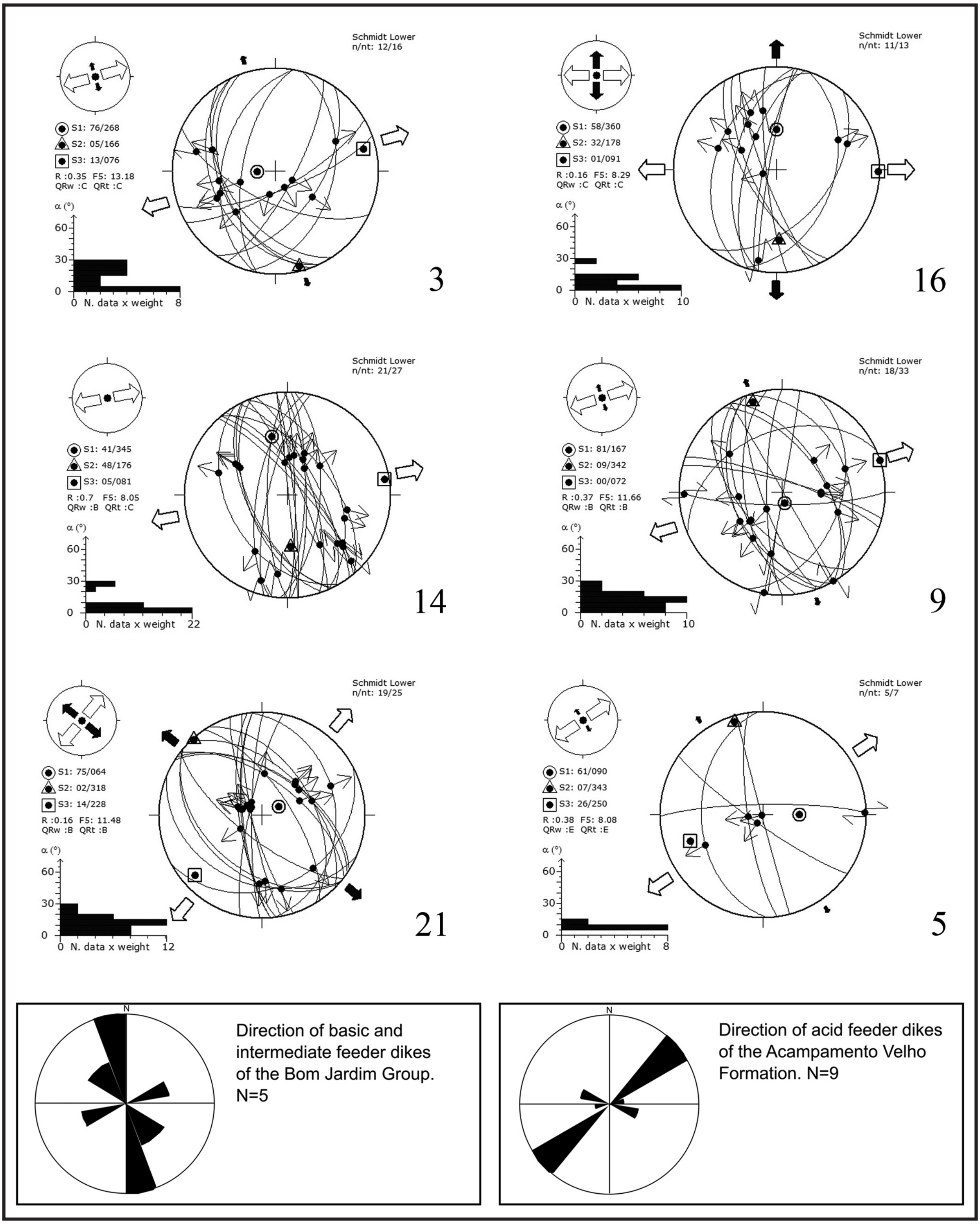

Figure 8: Characteristic examples of stereographic projections corresponding to data measurements of the first and second recognized paleostress fields (ENE extension), Schimidt projection, lower hemisphere. Fault planes are great circles; slickensided lineations are small centrifugal traces (normal faults) or double traces (strike-slip faults).

in their movement or not. The vertical nature of σ_1 can be emphasize, which contradicts models considering a strike-slip origin for the basin.

Late Ediacaran - Early Cambrian strike-slip faulting

A major angular unconformity separates the Guaritas Group (Early Cambrian) from the older units of the Camaquã Supergroup. This unconformity is related to a strike-slip faulting event that generated ENE-WSW to WNW-ESE left-slip and NNE-SSW to NNW-SSE right-slip faults affecting all the units of the Camaquã Supergroup but the Guaritas Group. Paleostress field inversion of this fault group gives a NE-SW to NNE-SSW oriented horizontal σ1 and a near vertical σ2 (Fig. 9). The stratigraphic position of this event suggests that it occurred near the Precambrian-Cambrian boundary.

Early Cambrian extension

The Guaritas Group and the Rodeio Velho Intrusive Suite (mainly basic to intermediate shallow sills) record the youngest basin-forming tectonic events of the Camaquã Supergroup, which generated NE-SW to NNW-SSE-trending normal faults. The paleostress field obtained for these faults gives a WNW-ESE to NW-SE σ_3, characterizing an event of NW-SE extension (Fig. 10). Faults attributed to this event are not found in younger units. The presence of alluvial fan deposits in the Guaritas Group next to the eastern NNE-SSW-striking basin-border fault reveals that this fault was active during the deposition of the unit (e.g. Marconato et al. 2009). Therefore, this event can be considered as syn-depositional to the Early Cambrian succession, thus postdating the first strike-slip fault event and predating the second one. Intense extensional deformation of the Guaritas Group suggests ongoing extension during sedimentation. This deformation includes open fault-drag folds with N-S axis.

The depositional age of the Guaritas Group is constrained by dating of the Rodeio Velho Intrusive Suite (Almeida et al. 2009) obtained in a sample of a shallow sill that caused fluidization of then unconsolidated host sediment of Guaritas Group. Thus, the crystallization age obtained for the Rodeio Velho Intrusive Suite (535.2±1.1 Ma) by Almeida et al. (2009) is interpreted to be very close to the sedimentation age of the Guaritas Group. As the second NW-SE extensional event is considered to be coeval to the deposition of the Guaritas Group and related to the subsidence tectonics, this age determination also constrains the tectonic event.

Post-Early Cambrian strike-slip faulting

The main post-depositional deformational event that affected the Camaquã Supergroup is characterized by intense strike-slip faulting, mainly left-slip NE-SW to NNW-SSE faults and right-slip ENE-WSW to WNW-ESE faults, including the major faults that juxtapose different units of the Camaquã Supergroup and its basement. This fault group affects the Guaritas Group and the Rodeio Velho Intrusive Suite, but has not been found in younger Phanerozoic deposits in the region and hence was generated after Early Cambrian and before Early Permian. Paleostress field inversion of this fault population gives a NW-SE oriented horizontal σ_1 and a near vertical σ_2 (Fig. 11). Fault-drag folds are found near the major faults. Cross-cutting relationships of striations corroborate the interpretation of this set of structures being younger than those generated by a NE-SW compression.

The copper mineralization found in deposits of the Santa Bárbara Group in the Minas do Camaquã region may be related to this tectonic event since the mineralization is associated to WNW-ESE-trending faults that behaved as extensional structures during this event, which is compatible with the T-fractures of the conjugate system (Santos et al. in press).

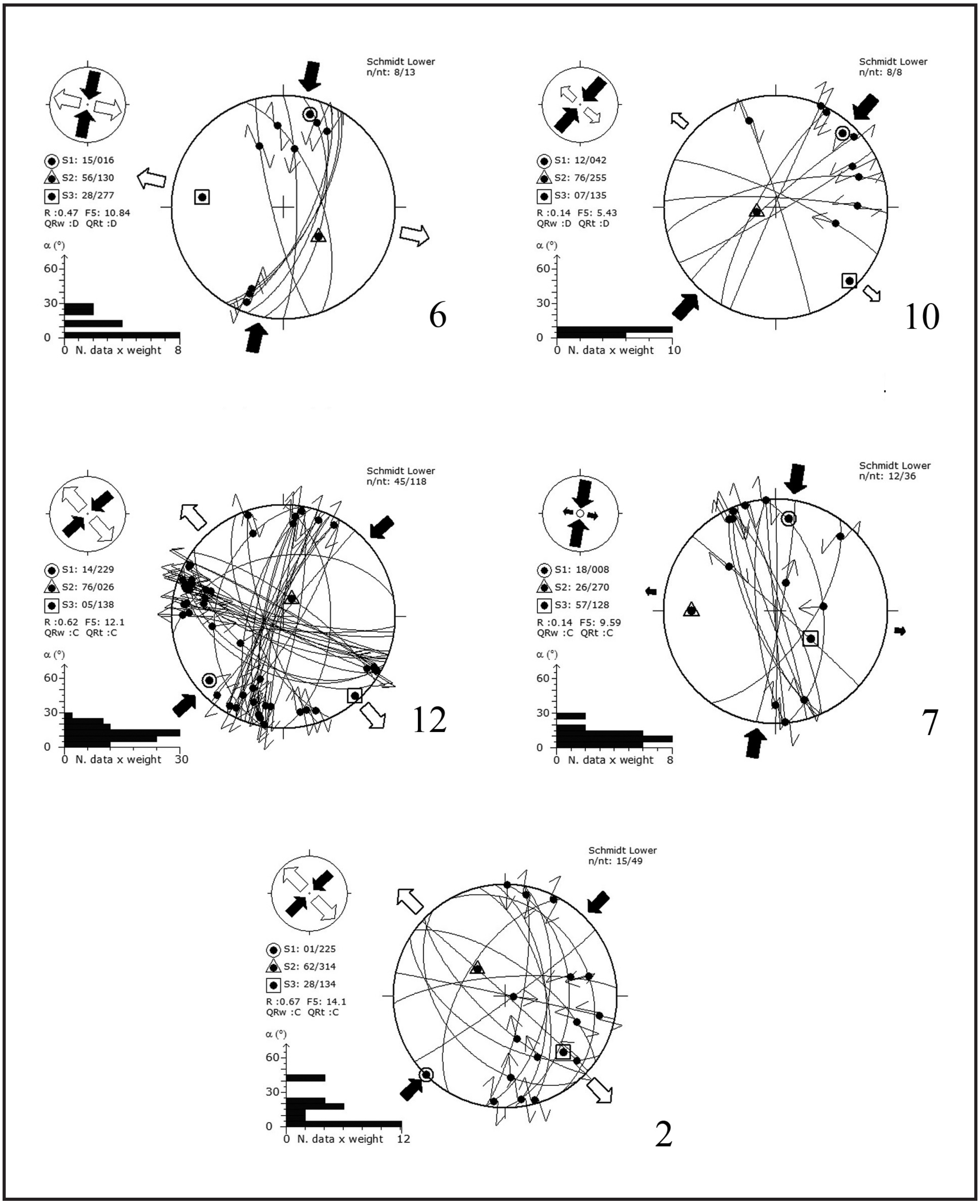

Figure 9: Characteristic examples of stereographic projections corresponding to data measurements of the second recognized tectonic event (NE compression), Schimidt projection, lower hemisphere. Fault planes are great circles; slickenside lineations are small centrifugal traces (normal faults), centripetal traces (reverse faults) or double traces (strike-slip faults).

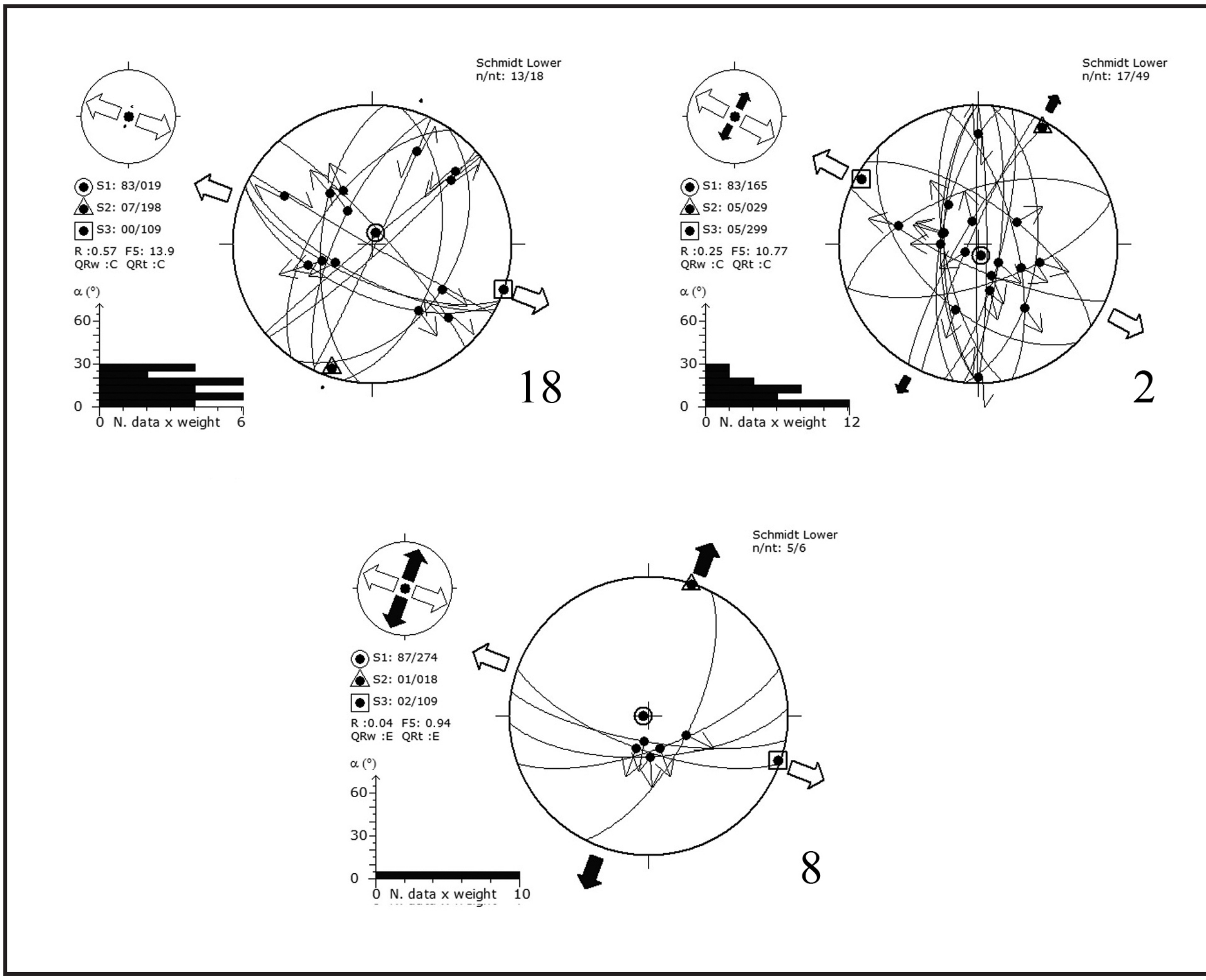

Figure 10: Characteristic examples of stereographic projections corresponding to data measurements of the third recognized tectonic event (NW extension), Schimidt projection, lower hemisphere. Fault planes are great circles; slickenside lineations are small centrifugal traces (normal faults) or double traces (strike-slip faults).

Post-Early Triassic strike-slip faulting

This deformation event is characterized by strike-slip faulting and affected sedimentary successions of the Tubarão Group (Permian), as well as the Sanga do Cabral Formation of the Rosário do Sul Group (Tomba 2006), which are considered to be of Early Triassic Age (Zerfass et al. 2003, 2004, 2005), in isolated occurrences directly above the Precambrian basement. We do not have enough data to obtain a consistent paleostress field for this event. Data presented by Tomba (2006) suggest a paleostress field with NE-SW oriented horizontal σ1 and a near vertical σ_2. This paleostress orientation is interpreted as a repetition of the Ediacaran-Cambrian strike-slip event, though it was not as intense as the first one.

Cretaceous extension

The youngest event of brittle faulting observed in the studied successions is characterized by normal faults with average NW-SE strikes, as well as related oblique faults, formed by a stress field with near vertical σ_1 and NE-SW oriented horizontal σ_3 (Fig. 12). These structures affect all the units of the Camaquã Supergroup, the Tubarão Group

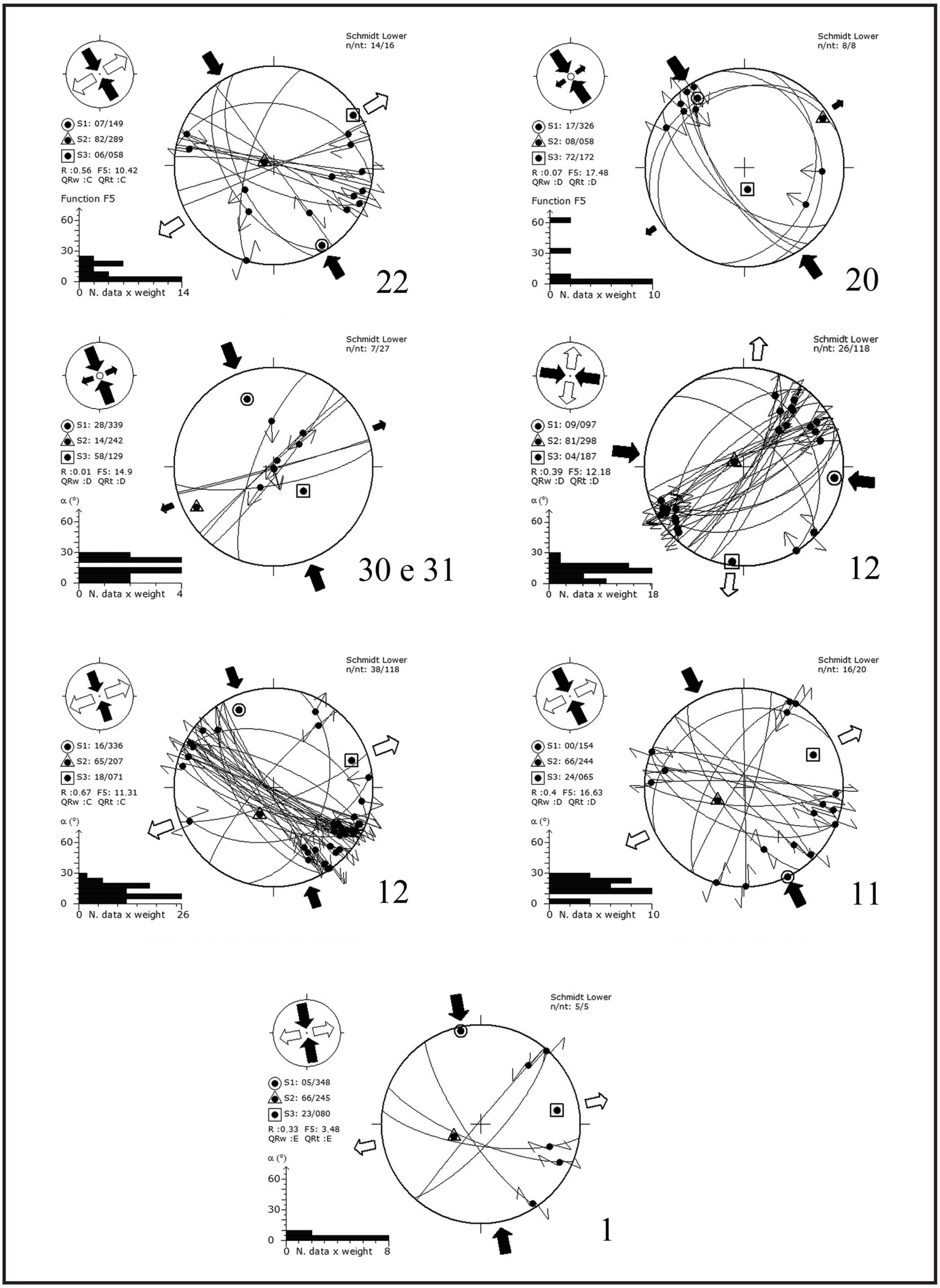

Figure 11: Characteristic examples of stereographic projections corresponding to data measurements of the fourth recognized tectonic event (NW compression), Schimidt projection, lower hemisphere. Fault planes are great circles; slickenside lineations are small centrifugal traces (normal faults) or double traces (strike-slip faults).

(Permian) and the whole Rosário do Sul Group (Triassic), characterizing a post-Triassic event. The distinction of this event from the Middle to Late Ediacaran event of similar paleostress field is often difficult. Nevertheless, some outcrops of the older units show mainly oblique faults, which are most likely reactivated strike-slip faults of the compressional events, later submitted to the Cretaceous extensional field.

Two Cretaceous magmatic events may be related to this extensional event: the vast Early Cretaceous basic volcanism of the Serra Geral Formation whose feeder dikes show, in the region, directions compatible with a NE-SW extension, and the Late Cretaceous alkaline dikes that occur in the studied area (Ribeiro and Teixeira 1970) and also have compatible directions.

Castro Basin

The Castro Basin is filled by feldspathic sandstones, siltones and conglomerates, as well as acid volcanic rocks, disposed in a more than 3,000 m thick succession, with more than 800 km^2 of exposed area (Moro et al. 1993, 1994, Moro 2003). Controversy regarding the tectonic setting of its origin also exists for the Castro Basin, with concurring models of post-orogenic molasse basin (Trein and Fuck 1967) and transtentional strike-slip basin (Soares 1987, 1988).

The style and directions of the faults that affect the Castro Basin are the same as those of the structures that affect the Camaquã Basin. Steeply dipping faults with NE to NNE strikes are the main structures, presenting large normal displacements, including the basin-border fault, which is parallel to the NNE-trending metamorphic foliation of the basement. NW trending faults are also present, showing smaller displacements and frequently being intruded by basic dikes of Early Cretaceous age. The presence of alluvial fan deposits suggests active syn-sedimentary faulting at the basin borders.

Paleostress Fields

Previous paleostress data for the Castro Basin are restricted to less then 25 faults with striations grouped in a strike-slip event with NE σ_1 and an extensional event with NE σ_3 (Bonacim et al. 1994). Our data, although also very scarce, reveal a more complex structural evolution with mutually incompatible fault sets attributed to two different tectonic events:

- A NW compression activating NE trending faults with reverse and oblique left-lateral movement.
- A NNE extension, revealed by ENE to WNW striking normal and oblique faults.

Although there are no clear cross-cutting relations among striations of different events, the correlation of these paleostress fields with those interpreted for the Camaquã Basin suggests that the NW compression is correlatable to the main strike-slip deformation of the Camaquã Basin, possibly of Early Cambrian age. The NNE extension is very likely related to the Cretaceous magmatism, as basic dikes of this age intrude many of the NW structures.

Itajaí Basin

The Itajaí Basin contains more than 10,000 m of alluvial, deltaic and turbiditic successions (e.g. Rostirolla et al. 1992a, Fonseca et al. 2003, Basilici 2006) in an area of approximately 1,200 km^2. Several authors consider this basin as a foreland basin of the Brasiliano Orogeny (e.g. Fragoso-Cesar et al. 1982a, b, Rostirolla and Soares 1992, Rostirolla et al. 1992a, b, 1999, Gresse et al. 1996, Basei et al. 2000), but there is no convincing evidence for the alleged syn-depositional nature of the described thrust faults, nor for the supposed syn-orogenic context of the basin. The Itajaí Basin is coeval to part of the Camaquã Basin (Almeida et al. 2010), which suggests a common geotectonic setting for both basins.

The Itajaí Basin contains conglomerate, sandstone, sandstone-mudstone rhythmite and mudstone organized in four depositional sequences (Teixeira et al. 2004). Rhyolitic tuffs occur at some

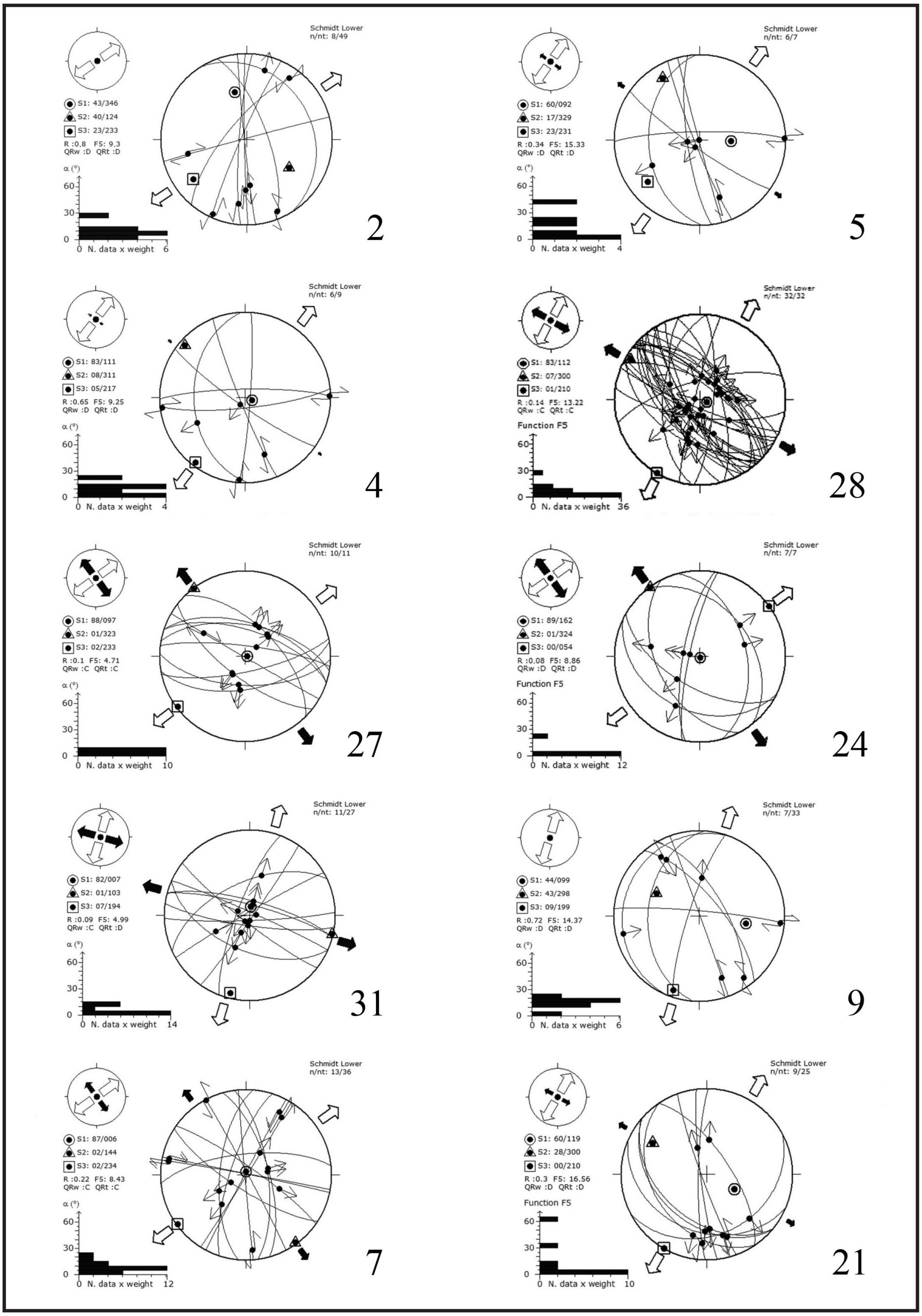

Figure 12: Characteristic examples of stereographic projections corresponding to data measurements of the last recognized tectonic event (NE extension), Schimidt projection, lower hemisphere. Fault planes are great circles; slickenside lineations are small centrifugal traces (normal faults) or double traces (strike-slip faults).

stratigraphic levels and the basin is intruded by a granite stock (e.g. Basei et al. 1999, Cordani et al. 1999). The basin is bounded by a steeply dipping post-sedimentary reverse fault in its southeastern border, which activated ductile structures of the basement. Other structures are NE trending reverse to oblique faults and E-W trending right-slip faults, reactivated to left-slip in a younger tectonic event (Rostirolla et al. 1992b), as well as open folds with NE axis.

Paleostress Fields

Rostirolla et al. (1992b) recognized two main deformational events in the Itajaí Basin: a first and more intense NW compression, forming the open folds and the NE to E-W trending right-lateral, oblique and reverse faults, and a younger NW compression, reactivating these same structures with the opposite movement.

Although the paleostress interpretation of Rostirolla et al. (1992b) was based on less then 30 data for the whole basin, the recognition of a main NW-SE compressional event is in accordance with the paleostress analysis of the Camaquã Basin, as is the recognition of a younger NE-SW compression. Considering that the main NW-SE compressional event is the same in all basins of the system, the deformation would be dominated by strike-slip faults in the NNE-SSW trending Camaquã and Castro basins, and by oblique to reverse faults in the ENE trending Itajaí Basin. Hence we interpret that the apparently conflicting structural styles of the Ediacaran successions of the system are the result of a single main deformation acting upon different previous anisotropies of basement rocks.

DISCUSSION

Most of the current tectonic models for eastern South America consider that the geological evolution of the region between 600 Ma and 530 Ma records the last collisional episodes of the Brasiliano Orogeny (e.g. Ribeiro and Fantinel 1978, Fragoso-Cesar 1991, Brito Neves et al. 1999, Basei et al. 2000, Campos Neto 2000, Pedrosa-Soares and Wieldmann-Leonardos 2000, Trouw et al. 2000, Heilbron and Machado 2003, Heilbron et al. 2004, Silva et al. 2005). In this context, the Ediacaran to Cambrian basins of the region have been considered as syn- to post-collisional, with their origin related either to supposed flexural loading during crustal thickening or to late-orogenic strike-slip deformation.

The here presented chronology of the deformational events that are preserved within the sedimentary and volcanic successions of the Camaquã Basin (Fig. 7), and its correlation to the Itajaí and Castro basins, point to an alternative interpretation previously deduced from provenance, paleocurrent and stratigraphic data: that of an extensional origin for this basin system.

The stratigraphic record of the deformational events of the Camaquã Basin reveals the recurrence of strike-slip and extensional episodes (Fig. 13) with no major thrust fault-generating compression. Thus, the paleostress fields do not support a syn-collisional peripheral foreland basin model for the Camaquã Basin. Independent evidence suggests that the extensional events were responsible for the subsidence cycles, and that the strike-slip faulting events are related to younger deformation: (1) the oldest extensional event, with ENE-WSW to NE-SW σ_3, is found only in the lower stratigraphic levels and predates the first identified strike-slip event, as revealed by dikes feeding syn-depositional volcanism; (2) a similar extensional event, with E-W $\sigma 3$, was responsible for syn-sedimentary faulting in the Late Ediacaran Santa Bárbara Group; (3) the units generated during the last subsidence cycle of the basin, in the Early Cambrian, are not affected by the main compression and also record an extensional event prior to an event of strike-slip faulting, which shows a different orientation of stress axes from the previous.

The occurrence of volcanic or pyroclastic successions in all three major basins of the system (the Camaquã, Itajaí and Castro basins) suggests that they were formed during a period of enhanced thermal gradient. This hypothesis is corroborated by the presence of several voluminous granitic intrusions coeval to the basins. Thus, it is not likely that the basins formed due to extensional collapse of thickened crust caused by the collision that had taken place more than 30 Ma before. In the Camaquã Basin, the major intermediate to basic volcanism occurred in the time-span of the first extension, suggesting that this event was related to mantle upwelling.

The recurrence of extensional and strike-slip events suggests that a persistent tendency to extension, maybe due to a mantle thermal anomaly after the major continental collision of the Brasiliano-Pan-African Orogeny in the region, was repeatedly interrupted by compressional events, possibly the far-field response to the latest collisions at the margins of the still-forming Gondwana Plate.

The first identified compression, with NE-SW σ_1, occurred around the Ediacaran-Cambrian boundary and may be related to the deformational event recorded in the Gariep Belt of Southwestern Africa (Frimmel and Frank 1998). The second, post-Early Cambrian compressional event, with NW-SE

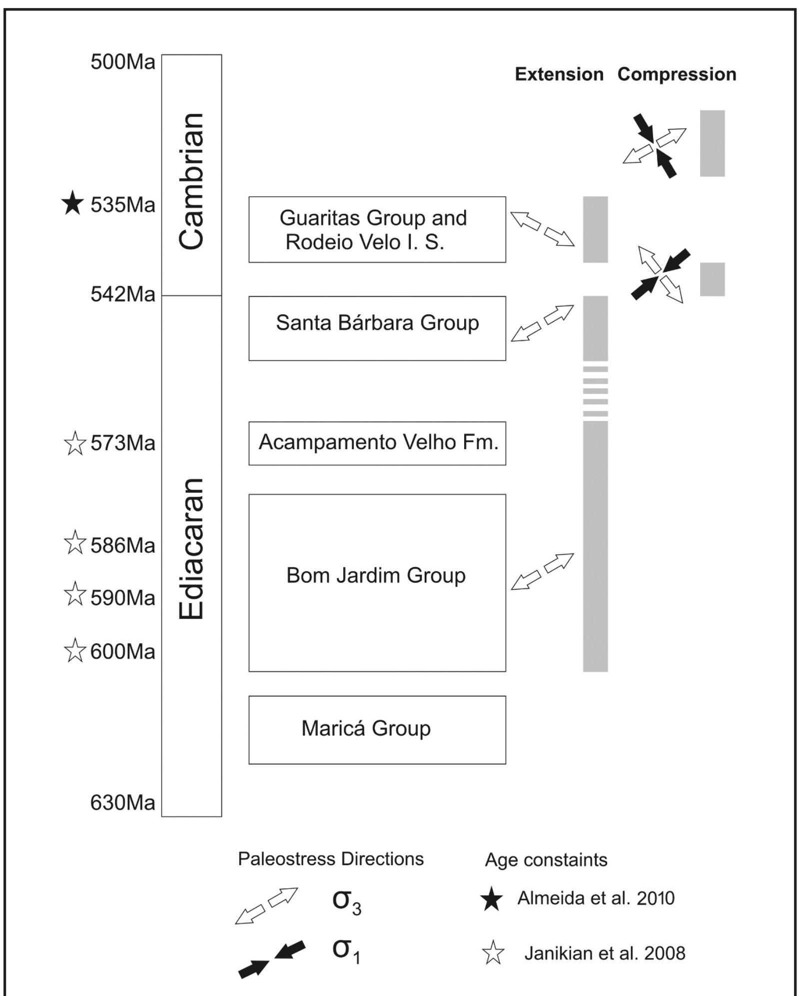

Figure 13: Summary of the paleostress evolution of the Camaquã Basin from Ediacaran to Cambrian.

σ_1, is compatible with the last deformational events in the Paraguay Belt (Pimentel et al. 1996, Tohver et al. 2010), south of the Amazon Craton, and also with the final collision between eastern and western Gondwana around 530 Ma (Meert 2001). Most of the post-collisional ductile strike-slip deformation that affects rocks of deeper crustal levels in the same region – the Southern Mantiqueira Province - may be related to the intense brittle strike-slip deformation of the basins due to these two compressional events at shallower crustal levels.

Our results suggest that the intense post-orogenic strike-slip deformation recognized in the Neoproterozoic fold belts of Southeastern South America may be a response to later distal collisions and not the consequence of ongoing compression since the orogenic stage. The rapid paleostress changes identified on unmetamorphosed sedimentary and volcanic successions deposited after the main collision would be much more difficult to recognize in rocks of deeper crustal levels, where ductile deformation prevails, and there is no possible stratigraphic control enabling us to distinguish among superposed events.

CONCLUSIONS

The paleostress analysis of the Camaquã Supergroup and overlying Phanerozoic units revealed five main deformational events responsible for normal, strike-slip and oblique brittle faults found in the region. These events caused the reactivation of former basement structures, mainly with NNE-SSW and WNW-ESE strikes, in response to regional tectonic episodes from the Ediacaran to the Cretaceous.

The basin-forming tectonic events of the Camaquã Basin are mainly extensional, firstly with two phases of ENE-WSW to NE-SW σ_3 during the deposition of the Bom Jardim Group (600 Ma to 580 Ma), the Acampamento Velho Formation (575 Ma) and the Santa Bárbara Group (550 Ma to 545 Ma), and later with a NW-SE σ_3 during the formation of the upper units of the Camaquã Supergroup, including, the Guaritas Group (535 Ma) and the subvolcanic Rodeio Velho Intrusive Suite.

Besides these basin-forming tectonic events, three deformational tectonic events were recognized. The first occurred during the formation of the angular unconformity between the Santa Bárbara and Guaritas groups, thus near the Precambrian-Cambrian boundary. This event is characterized by strike-slip and oblique faults formed during NE-SW compression.

The second, more intense, deformational event, is characterized by a NW-SE compression causing the major strike-slip and oblique faults that control the map distribution of the geological units of the Camaquã Basin and nearby areas. This event also affects the Guaritas Group and the Rodeio Velho Intrusive Suite, but not the Permian and Triassic units of the region, and thus occurred between 535 Ma and the Permian. We suggest a relationship between this event and the compressional stress fields caused by the collision of Eastern and Western Gondwana, around 530 Ma, or the collision of the Amazon Plate to the northwest. This event caused the cessation of the subsidence in the Camaquã Basin.

A third deformational event caused a NE-SW extension generating normal and oblique faults found in all studied units, from the lower levels of the Camaquã Supergroup to the Triassic deposits. Late Cretaceous alkaline dikes related to the reactivation of WNW-ESE faults are compatible with this NE-SW extension, as are basic Early Cretaceous dikes related to the opening of the South Atlantic Ocean.

The characterization of the tectonic events responsible for the subsidence of the Camaquã Basin as extensional ones suggests that the basin was an interior rift formed after the Brasiliano orogenic episodes. The abundant strike-slip and rare reverse faults affecting the basin are related to the cessation of subsidence and, in some cases, basin inversion, bringing no relation with the origin of the basin. Preliminary data from the Itajaí and Castro basins, which are the two other largest basins of the system (Almeida et al. 2010), indicate compatible paleostress fields and suggest a regional nature for the recognized tectonic events.

The characterization of four events of brittle faulting with different paleostress fields in the time span between 600 and 530 Ma reveals that the tectonic evolution of Southeastern South America after the main collisional episode of the Brasiliano Orogeny (c.a. 630 Ma) was far more complex than the previously accepted model of continued post-orogenic compression causing strike-slip deformation. The rapid paleostress changes are most probably the consequence of the interplay between local extensional stresses possibly caused by thermal anomalies and the distal propagation of the compressional stresses induced by younger episodes of continental collision at the plate margins.

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RESUMO

No Leste da América do Sul, um conjunto de bacias sedimentares que afloram do sul do Uruguai ao sudeste do Brasil formou-se após os eventos colisionais da Orogenia Brasiliana, registrando os eventos tectônicos que afetaram a região a partir do Mesoediacarano. O problema da distinção entre a tectônica formadora das bacias e os eventos deformacionais posteriores é aqui abordado através da análise de paleotensões de mais de 600 dados de falhas com estrias, obtidos principalmente na Bacia Camaquã (Sul do Brasil), que foram classificados por nível estratigráfico e relações de corte entre estrias sobrepostas, e intergrados a dados estratigráficos e geocronológicos disponíveis. Nossos resultados revelam que a Bacia Camaquã teve origem em ao menos dois eventos distensivos, e que modificações rápidas no campos de tensões ocorreram na região alguns poucos milhões de anos após a colisão principal (c.a. 630 Ma), provavelmente em decorrência da interação entre esforços distensivos locais e os efeitos distais da contínua amalgamação de placas e terrenos nas margens da placa Gondwana, ainda em formação. Dados preliminares de paleotensões da Bacia de Castro e dados publicados da Bacia Itajaí sugerem que esses eventos tiveram um caráter regional.

Palavras-chave: Bacia do Camaquã, Ciências da Terra, Neoproterozoico, Análise de Paleotensões, Bacia Rift, Sul do Brasil.

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