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ORIGINAL PAPER

Major shear zones of southern Brazil and Uruguay: escape tectonics in the eastern border of Rio de La plata and Paranapanema cratons during the Western Gondwana amalgamation

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Abstract The Mantiqueira Province represents a series of supracrustal segments of the South-American counterpart formed during the Gondwana Supercontinent agglutination. In this crustal domain, the process of escape tectonics played a conspicuous role, generating important NE–N–S-trending lineaments. The oblique component of the motions of the colliding tectonic blocks defined the transpressional character of the main suture zones: Lancinha-Itariri, Cubatão-Arcádia-Areal, Serrinha-Rio Palmital in the Ribeira Belt and Sierra Ballena-Major Gercino in the Dom Feliciano Belt. The process as a whole lasted for *ca.* 60 Ma, since the initial collision phase until the lateral escape phase predominantly marked by dextral and subordinate sinistral transpressional shear zones. In the Dom Feliciano Belt, southern Brazil and Uruguay, transpressional event at 630–600 Ma is recognized and in the Ribeira Belt, despite less coevally, the transpressional event occurred between 590 and 560 Ma in its northern-central portion and between *ca*. 625 and 595 Ma in its central-southern portion. The kinematics of several shear zones with simultaneous movement in opposite directions at their terminations is explained by the sinuosity of these lineaments in relation to a predominantly continuous westward compression.

Keywords Mantiqueira Province · Gondwana agglutination · Suture zones · Escape tectonics · Metamorphic-deformational events

Introduction

Magmatic, metamorphic and structural records of superposed orogeneses can be observed in southeastern Brazil. These records reflect the collage of distinct terranes in a process that culminated with the consolidation of Western Gondwana during the Neoproterozoic–Eopaleozoic transition. The episodes associated with this agglutination are subduction, continental collision and late-collisional transcurrent movements. The latter, which were responsible for the dissipation of great part of the energy generated during the collisional processes, caused the lateral displacement of crustal masses by means of an escape or lateral extrusion tectonic process.

In the Himalayas, this process can be observed as a result of the collision between the Indian and Asian continental tectonic plates, leading to the eastward sinistral transport along the Tian Shan and several other faults (Molnar and Tapponnier 1975; Yeats and Lillie 1991; Jacobs and Thomas 2004; Zhang and Wang 2007). Another important example is the Alpine orogeny, when in its younger stages, especially during the Pliocene-Quaternary, dextral transcurrent faults caused the lateral escape of major crustal fragments (Ratschbacher et al. 1991; Picha 2002; Brückl et al. 2007; Tomljenovic et al. 2008).

The evolution of the accretionary Andean belt, developed in the western margin of the South-American

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continent with significant destruction of oceanic crust, was responsible for the generation of north–south trending, narrow, linear, typical accretionary chains, and also for the creation and deformation of arc-related settings and continental reactivation, with several peaks of orogenic activity since the Upper Triassic (Mégard 1987; Hervé et al. 1987; Stern and Kilian 1996; Ramos and Aleman 2000). Transcurrent movements associated with collision are common during continental evolution. Tectonic escape has been an element in the continental evolution along the whole Earth's geologic history record, leading to (1) rifting and formation of rift-basins accompanied by crustal thinning; (2) late penetrative transcurrent zones that separate mountain chains by shearing and juxtapose sectors that have no connection in transversal section; (3) compressional mountain chains and associated foreland basins (Sengor et al. 1985; Burke and Sengor 1986).

In the Gondwana Supercontinent agglutination, the escape tectonics process took place by means of important lineaments, mainly trending NE–N–S, in the fold belts associated with the collision of the São Francisco, Kalahari, Paranapanema and Río de La Plata cratons (Brito Neves and Cordani 1991; Campos Neto and Figueiredo 1995; Hackspacher and Godoy 1999; Brito Neves et al. 1999). In this context, the structural framework and kinematic patterns of the shear zones are discussed, including brittle–ductile reactivations, thermal-metamorphic pattern characterization, and, when possible, the determination of the absolute age of the metamorphic-deformational events. The focus of this work will be on the Arcádia-Areal (Rio de Janeiro), Lancinha-Cubatão-Itariri and Serrinha-Rio Palmital Shear Zones of the central-southern portion of the Ribeira Belt (São Paulo and Paraná states) and on the Sierra Ballena-Cordilheira-Major Gercino shear belt in the Dom Feliciano Belt, as well as on the significance of these mega-shear zones in the Gondwana agglutination context.

Geological background

The NE–SW-trending Mantiqueira Province (Almeida et al. 1981) stretches out for *ca.* 3,000 km along the Atlantic coast, from Punta del Este (Uruguay) to south of Bahia in Brazil (Fig. 1) bordering the São Francisco, Paranapanema and Rio de la Plata/Paraná cratons and surrounding the Luis Alves and Curitiba microplates (Almeida et al. 1981; Brito Neves and Cordani 1991; Cordani and Sato 1999; Mantovani and Brito Neves 2005, and others). It developed from the end of the Neoproterozoic to the beginning of the Paleozoic, during the Neoproterozoic Brasiliano-Panafrican Orogeny, which resulted in the amalgamation of Western Gondwana (Almeida et al. 2000).

This tectonic province includes the Araçuaí, Ribeira, Dom Feliciano and Rocha fold belts, which developed diachronically by the interaction of the São Francisco–Congo, Kalahari, Paranapanema and Rio de La Plata cratons, as well as minor cratonic fragments such as Luis Alves and Curitiba (Almeida et al. 1981; Brito Neves and Cordani 1991; Heilbron et al. 2004; Mantovani and Brito Neves 2005; Silva et al. 2005a). This orogen resulted from the closure of the Adamastor Ocean due to the convergence of the São Francisco–Congo and partially the Rio de La Plata cratons and the amalgamation of several minor terranes such as the Apiaí, Embu, Curitiba/Registro, Luis Alves and Juiz de Fora to the margin of the São Francisco craton.

The *ca.* 1,500 km-long Ribeira Belt (Hasui et al. 1975; Almeida et al. 1981) is situated in southern Brazil (Fig. 1), extending from south of the Bahia State into the Paraná State. It is the largest geotectonic unit of the Mantiqueira Province (Almeida and Hasui 1984; Silva et al. 2005a). It consists of tectonic domains limited by expressive Neoproterozoic Shear Zones (Fig. 1). In its central-northern portion, the Juiz de Fora, Paraíba do Sul and Coastal terranes stand out. Its southeastern portion is composed of the Embu and Apiaí terranes.

The major geotectonic unit in the southern part of the Mantiqueira Province is represented by the Dom Feliciano Belt (DFB). The tectonic evolution of the DFB is associated with the Neoproterozoic and Early Paleozoic Western Gondwana collage (Fragoso-Cesar 1980; Basei et al. 2000). It forms a roughly NE–SW-trending belt and occupies the entire eastern segment of southern Brazil and Uruguay (Fig. 1). From its southern limit in Uruguay to its termination in Santa Catarina state in Brazil, the DFB is composed of three crustal sectors separated by tectonic contacts: (a) I-type medium to high-K calc-alkaline granitoid rocks of Florianópolis, Pelotas and Aiguá batholiths; (b) Central greenschist to amphibolite-facies metavolcano-sedimentary rocks of Brusque, Porongos and Lavalleja groups; and (c) achimetamorphic sedimentary and volcanic rocks of Itajaí, Camaquã, Arroyo del Soldado and Piriápolis foreland basins.

The Ribeira Belt

The RB central sector is characterized by a series of thrust faults that developed under amphibolite facies conditions and imprinted a northwestward vergence pointing to the São Francisco Craton (Heilbron et al. 1995; Heilbron and Machado 2003). They evolved to transpressional systems, markedly the Rio Paraíba do Sul Shear Belt (Ebert et al. 1996) (Fig. 1). Southeast in the RB, the Lancinha-Cubatão Shear Zones (L-C) separate the Embu/Apiaí terranes (NW)

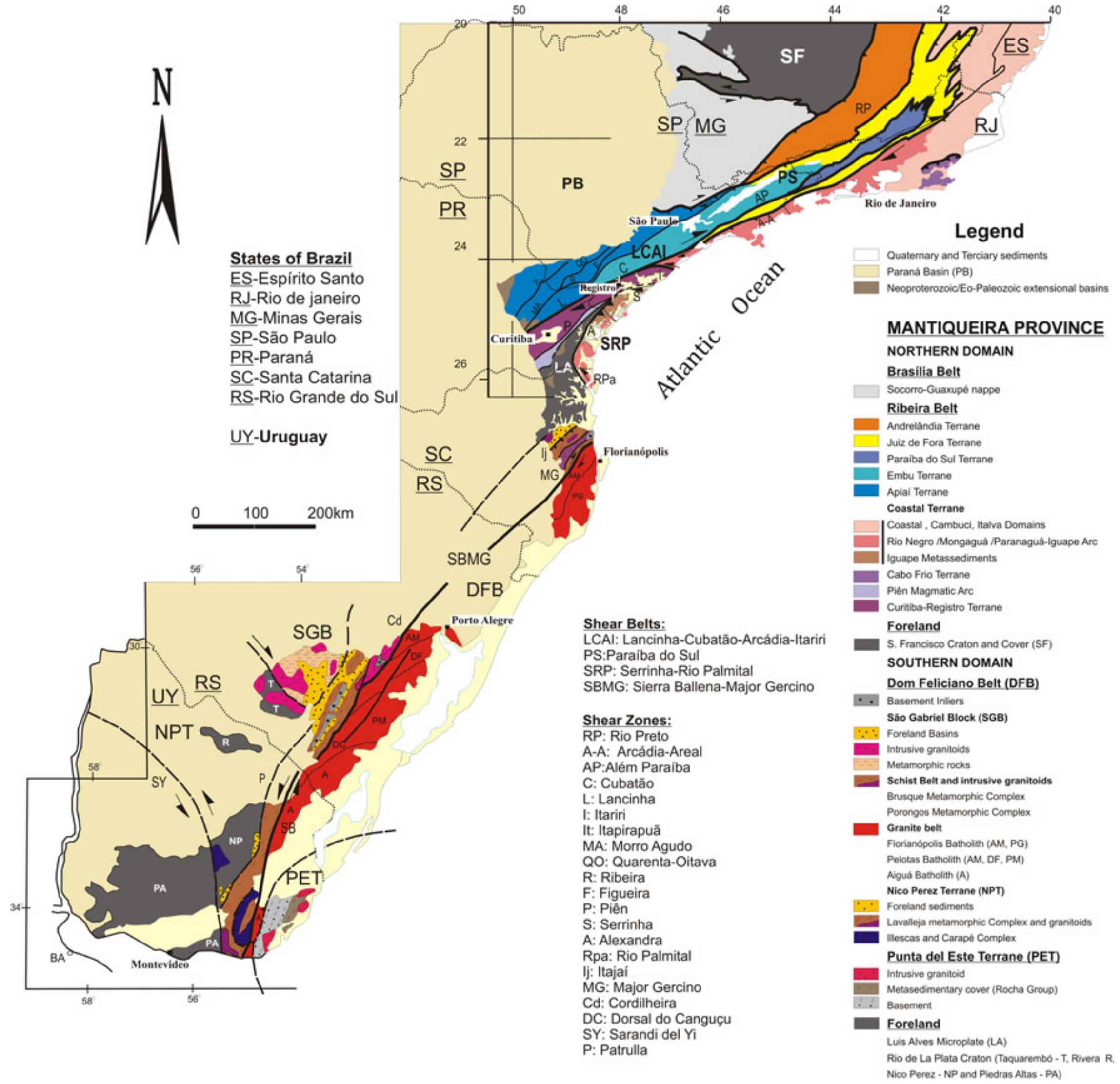

Fig. 1 General outline of the Mantiqueira Province (Brazil-Uruguay) (Simplified from Campos Neto and Figueiredo 1995; Bossi et al. 1998; Basei et al. 1999, 2000; Heilbron et al. 2004; Tupinambá et al. 2007)

from the Curitiba/Registro granitic-gneissic terranes (SE). In turn, the Itariri Shear Zone (I) separates the Curitiba/Registro terranes from the Coastal Terrane. Southwards, between São Paulo and Paraná states, the Serrinha (S), Alexandra (A) and Rio Palmital (RPa) Shear Zones limit the Coastal Terrane (Fig. 1). They represent mega-structures responsible for the structural framework and compartmentation of distinct Precambrian terranes.

The tectonic compartmentation of the central-northern portion

The RB central-northern portion in Rio de Janeiro, Espirito Santo and Minas Gerais states encompasses four main tectono-stratigraphic terranes denominated as Occidental, Oriental, Paraíba do Sul/Embu, and Cabo Frio, by Heilbron et al. (1995, 2000, 2003, 2004). The first two are separated from one another by the Arcádia-Areal Shear Zone, which is complexly re-folded and steeply to moderately northwestwards dips in the central-southern portion of Rio de Janeiro, and southeastwards in the northeastern portion of that state and south of Espírito Santo (Tupinambá et al. 2007). The Occidental Tectonic Terrane includes the Juiz de Fora and Andrelândia Terranes (Heilbron et al. 1998). The Juiz de Fora Terrane (Fig. 1) is composed of a Paleoproterozoic granulite-facies orthogneisses (Machado et al. 1996) and subordinately by high amphibolite- to granulite-facies metasediments, granites and gneisses. The Andrelândia Terrane (Fig. 1) is composed of Neoproterozoic metasedimentary sequence (Sollner and Trouw 1997), which reached the high-pressure, high amphibolite facies that mainly comprises schists, gneisses, quartzites, migmatitic gneisses and calc-silicate rocks. The Paraíba do Sul Terrane (Fig. 1) is characterized by Meso- to Neoproterozoic metasediments (Machado et al. 1996) of the intermediate-pressure, amphibolite facies, which locally underwent partial melting. It consists of gneisses, schists, quartzites, marbles and calc-silicate rocks and is crosscut by syn-tectonic and post-tectonic granitoids. The Coastal Terrane (Fig. 1) includes rocks generated in magmatic arc settings and Neoproterozoic metasediments and was subdivided in the Rio de Janeiro northwestern region in three distinct structural domains: (a) the Cambuci domain (metavolcano-sedimentary sequence with marble and calc-alkaline orthogneisses lenses); (b) the Coastal domain (sediments metamorphosed to the granulite to high amphibolite facies intercalated with impure quartzites and intrusive orthogneisses and metagabbros of the Rio Negro Magmatic Arc); (c) the Italva domain (metavolcano-sedimentary sequence with marbles, amphibolites and paragneisses). The Cabo Frio Terrane (Fig. 1) is represented by Paleoproterozoic orthogneisses, tectonically intercalated with supracrustal rocks, metamorphosed to the amphibolite to granulite facies during the Mid-Cambrian.

The tectonic compartmentation of the south–southeastern portion

The southeastern Ribeira Belt consists of four major tectonic domains limited by significant shear zones associated with Neoproterozoic events. The Embu Terrane is limited to the south from the Registro/Curitiba Terrane by the Cubatão Shear Zone. The Coastal Terrane, represented by the Mongaguá magmatic arc, is limited from the Embu and Registro/Curitiba terranes by the sinistral Itariri Shear Zone, and the Paranaguá magmatic arc from the Registro/Cutitiba Terrane and the Luis Alves Microplate by the Serrinha—Rio Palmital Shear System (Fig. 1).

The Embu Terrane (Fig. 2), in the southeastern portion of São Paulo State, north of the Cubatão Shear Zone (CSZ), is composed of mica schists, partially migmatized paragneiss, quartzite, fine schists, phyllites and subordinately metabasite and calc-silicate rocks. Calc-alkaline and peraluminous granites (Dantas et al. 1987b) crosscut these units. The first records of magmatic processes in this Terrane date from the Cryogenian (810–780 Ma) and were obtained by zircon U–Pb SHRIMP (Cordani et al. 2002) and by U–Pb ID-TIMS dating (Passarelli et al. 2003, 2008). The metamorphic climax was characterized around 780 Ma by monazite in situ dating (Vlach 2001).

The Apiaí terrane is formed by Mesoproterozoic and Neoproterozoic metavolcano-sedimentary sequences (Basei et al. 2003; Weber et al. 2004; Campanha et al. 2004, 2008; Siga et al. 2009) with intrusive calc-alkaline granitoid rocks (Gimenez Filho et al. 2000; Prazeres Filho et al. 2003) and a series of Paleoproterozoic gneiss-migmatitic nuclei related to the Statherian taphrogenesis (Brito Neves et al. 1995; Cury et al. 2002) limited by shear zones, where the Itapirapuã, Morro Agudo, Ribeira, Figueira and Quarenta Oitava stand out (Fig. 1).

Associated gneissic-migmatitic and granitic rocks predominate in the Mongaguá and Paranaguá-Iguape magmatic arcs of the Coastal Complex. The Mongaguá granitoids have been correlated with the Rio Negro magmatic arc in the Rio de Janeiro State by Passarelli et al. (2004a, 2008) being limited by Cubatão Shear Zone to the northwest and by the Itariri Shear Zone to the south (Fig. 2). Gneiss-migmatitic rocks yielded U–Pb zircon ages in the 640–620 Ma range, and late-intrusive granites present zircon TIMS ages around 580 Ma (Passarelli et al. 2003, 2008). The Paranaguá-Iguape domain is largely represented by deformed calc-alkaline granitic rocks of ages between 620 and 570 Ma (Siga et al. 1993; Cury et al. 2008), which are sometimes intruded by two-mica leucogranites. As probable remains of host rocks, meta-rhythmites, quartzites and fine schists with apparent metamorphic grade increase southwards occur.

The Registro-Curitiba Terrane is limited from supracrustal rocks to the north (Embu and Apiaí) and from Mongaguá magmatic arc rocks by the Cubatão—Itariri Shear Zone and from the Paranaguá domain rocks by the Serrinha Shear Zone (Fig. 2). It is formed by Paleoproterozoic gneissic-migmatitic rocks (2.1–2.2 Ga) strongly deformed during the Neoproterozoic (600–580 Ma). Its cover is composed of meta-limestones, meta-sandstones and metapelites and intermediate-greenschist- to amphibolite-grade metamorphic sequence represented by quartzites, schists and paragneisses. The Juréia Massif garnet-biotite gneisses and the cordierite gneisses outcropping north of the Serrinha Shear Zone and correlated with the Cachoeira Sequence show two metamorphic records, an older one around 750 Ma (Passarelli et al. 2007, 2008), interpreted as the metamorphic peak of the paragneissic rocks, and a younger one, around 595 Ma, responsible for the neoformation and recrystallization of monazite, associated with intense granitic magmatism of similar age occurring in this domain. This terrane is separated from the Luis Alves Microplate by the Piên Suture Zone, characterized by the presence of magmatic arc roots of 615 Ma and ophiolitic remains of 630 Ma (Harara et al. 1997; Basei et al. 2000).

The Ribeira Belt tectonics

There exist several tectonic models for the Ribeira Belt central portion that indicate southeastward or northwestward subduction, followed by the collision of the São Francisco, Congo and Paranapanema cratons (Porada 1979; Basei et al. 1992; Trompette 1994; Trouw et al. 2000; Heilbron and Machado 2003). Along its length, the Ribeira

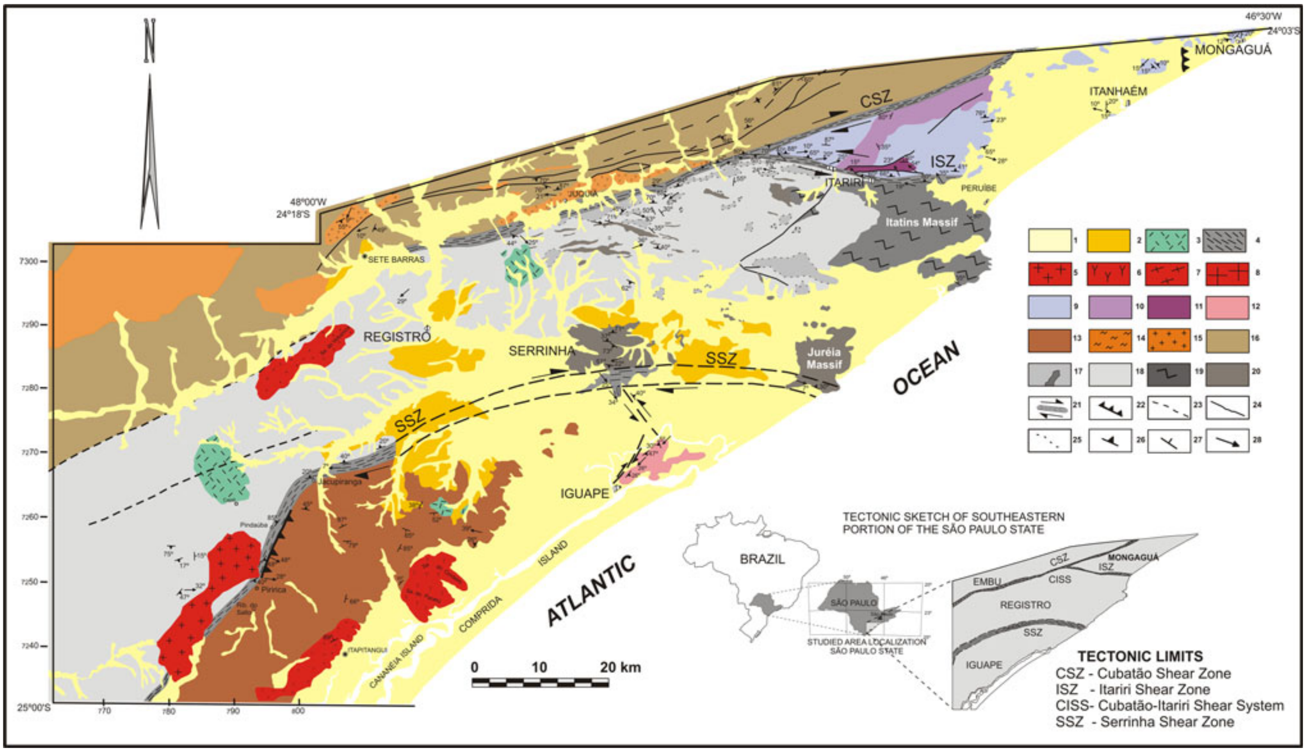

Fig. 2 Geological map of southeastern São Paulo State (modified from Passarelli C 2001). *1* Quaternary sediments. *2* Tertiary sediments. *3* Juquiá Alkaline Complex (Cretaceous). *4* CISS and SSZ: mylonitic rocks. Serra do Mar Granitic Suite: *5* Itapitangui *6* Serra do Cordeiro *7* Serra do Votupoca *8* Guaraú. Mongaguá Domain: *9* Itariri-type granites and gneiss-migmatitic rocks. *10* Areado Granite. *11* Ribeirão do Óleo Granite. Iguape Domain: *12* Iguape Granite. *13* Iguape metasediments. Embu Terrane: *14* Juquiá Granite. *15* Sete Barras Granite. *16* Indiscriminate metasediments. Registro Domain: *17* Granite-gneiss-migmatitic Domain. *18* Gneissic Domain. *19* Itatins Complex. *20* Cachoeira Sequence. *21* Main shear zones. *22* Fault with thrust component *23* Inferred Faults. *24* Lineaments. *25* Gradational geological contact. *26* Mylonitic foliation. *27* Principal foliation. *28* Mineral lineation

Belt shows a clear change in the deformation regime. The southeastern portion is characterized by transpressional deformation with coeval or slightly diachronous northwestward thrusting that evolves to predominantly dextral orogen-parallel transcurrent movements during the final stages (Trompette 1994; Hackspacher and Godoy 1999; Egydio-Silva et al. 2002; Schmitt et al. 2004; Vauchez et al. 2007). The southern portion is characterized by thrusting of allochthonous units on the São Francisco Craton margin (Cunningham et al. 1998; Campos Neto and Caby 2000; Trouw et al. 2000). This change in the dominant deformation regime is probably associated with the interaction between the Ribeira and Brasília Belts at the São Francisco Craton southern termination (Vauchez et al. 1994; Egydio-Silva et al. 2005).

In the northern portion of the Ribeira Belt, in the interface with the Araçuaí Belt, U–Pb ages of 575 Ma represent the time of metamorphic climax with the generation of leucocratic anatexites, as well as the pre- to syn-collisional magmatism (Vauchez et al. 2007). In the RB, central-northern sector the record of four main tectonic phases is better defined: (a) pre-collisional, between 630 and 600 Ma, (b) syn-collisional between 590 and 565 Ma, late-collisional between 540 and 520 Ma and post-tectonic between 520 and 480 Ma (Heilbron et al. 1995; Machado et al. 1996; Heilbron and Machado 2003). The Juiz de Fora, Andrelândia and Paraíba do Sul terranes were amalgamated to the São Francisco Craton SE border between 605 and 580 Ma (Machado et al. 1996; Heilbron and Machado 2003). With a more recent and independent metamorphic-deformational history, the Cabo Frio Terrane was accreted at the end of the orogenic collage, at *ca.* 530–510 Ma (Schmitt et al. 2004). This domain presents the highest-pressure metamorphic paragenesis with kyanite, which differs from the metamorphic pattern predominant in the Ribeira Belt, characterized by high-temperature and low-pressure mineral associations.

In the Embu Terrane, the period between 810 and 780 Ma was characterized as that of the magmatic-metamorphic climax, associated with a convergent tectonic process (Cordani et al. 2000; Vlach 2001). Important calc-alkaline magmatism associated with the syn-collisional phase occurred in this sector of the Ribeira Belt between 620 and 610 Ma (Hackspacher et al. 2000; Janasi et al.

2001, 2003). Lateral escape tectonics with development of several NE–SW-trending shear zones and emplacement of granitic bodies (Hackspacher et al. 2000) occurred around 600 Ma and can be correlated with the late-collisional phase in this sector of the Ribeira Belt (Janasi et al. 2001).

In the Mongaguá Domain of the Coastal Terrane, south–southeastern portion of the Ribeira Belt, four important thermal episodes are recorded: 640; 620–610; 600 and 580 Ma. The deformed granites (Itariri-type) and gneissic-migmatitic rocks yielded U–Pb zircon ages of ca. 640 and 620–610 Ma and are probably associated with the Rio Negro magmatic arc-related rocks, in the central part of Ribeira Belt (Tupinambá et al. 2000; Dias Neto et al. 2002). The Itariri-type granites (Fig. 2) reveal a metamorphic overprint of *ca.* 600 Ma, pointed out by U–Pb monazite ages. In the central part of Ribeira Belt, the 600 Ma event represented by extensive crustal melting that led to leucogranite generation is also well characterized and marks the end of subduction-related magmatism (Tupinambá et al. 2000; Heilbron and Machado 2003).

The collisional phase intrinsically associated with the juxtaposition of Mongaguá, Embu and Registro blocks is associated with a mean E–W compression and probably occurred around 580 Ma (monazite and zircon U–Pb ages). The syn-collisional magmatism is represented by peraluminous foliated and mylonitic granites that occur as NE–SW elongated plutons (Areado Granite—Fig. 2). The tectono-thermal event near 580 Ma is also recognized in the Paraíba do Sul and Coastal domains in Rio de Janeiro (Machado et al. 1996; Heilbron and Machado 2003).

Major shear zones of the Ribeira Belt: geochronology and structural features

The Ribeira Belt, a mobile belt that borders the São Francisco, Paranapanema and part of the Rio de La Plata cratons, contains thrusts and transcurrent shear zones. In this chapter, emphasis will be given to the main transcurrent shear zones, resulting from lateral escape tectonics associated with agglutination in this sector of Gondwana. In general, in the areas to be discussed, two main deformation types were recognized: lateral movements (dextral and sinistral transcurrent faulting) and shortening perpendicular to the shear zones, represented by flattening. The Itariri Shear Zone and its close relationship with the Cubatão-Lancinha-Arcádia-Areal system, with records from the north of Paraná to the north of Rio de Janeiro state, will be treated specifically. The main characteristics of the Serrinha-Palmital shearing system will also be discussed.

Lancinha–Itariri–Cubatão–Arcádia–Areal Shear System

This shear system can be subdivided in two main segments that separate distinct tectonic compartments. It represents suture zones with ductile to ductile–brittle characteristics, developed in the greenschist to low amphibolite facies (Fig. 2). The E–W segment is represented by the sinistral Itariri Shear Zone (ISZ) that strikes predominantly N85W/70NE and has 400- to 700-m of width, composed mainly of protomylonites and mylonites (Sadowski et al. 1978; Silva et al. 1981; Egydio-Silva 1981; Dantas et al. 1987b; Gimenez Filho et al. 1987; Passarelli et al. 2004a, 2008). The NE segment represented by the Lancinha-Cubatão Shear Zone cluster around N70E–N75E/sub-vertical (Sadowski 1984; Dantas et al. 1987b; Passarelli et al. 2004a, 2008).

In the north of the Ribeira Belt, this shear zone was former referred as the Além Paraíba-Cubatão-Lancinha Shear Zone (Sadowski 1984; Machado and Endo 1993). In the Paraná and São Paulo states represents a shear zone of *ca.* 300- to 1,500-m in width, composed mainly of mylonites, protomylonites and phyllonites, predominant dextral movement with brittle–ductile reactivations (Gimenez Filho et al. 1987; Sadowski and Motidome 1987; Sadowski 1991; Passarelli et al. 2004a, 2008).

Southeast of São Paulo State, between Itariri and Juquiá (Fig. 2), two important deformation phases were identified in the Cubatão and Itariri Shear Zones by means of a systematic structural study of the mylonitic rocks. The first deformational phase, of ductile nature, is associated with sinistral movements of a N85W-trending shear zone, with intermediate to strong dips to N–NE and two sets of stretching lineations (Passarelli 2001). The first one dipping E–NE is scarcely preserved (west of Itariri city, Fig. 2), thus giving a thrust component toward the SW. The second one plunging moderately to NW is compatible with an extensional component of the shear zone. Local folds with hinge lines parallel to the second stretching lineations were also observed. The second arrangement of the stretching lineations possibly represents an extensional movement resulting from stress release of the juxtaposition of the Embu and Registro terranes (Passarelli 2001; Passarelli et al. 2005). The first phase represents the peak metamorphic conditions in the evolution of the Itariri Shear Zone, which reached the amphibolite facies, and is characterized by intense feldspar recrystallization and the presence of well-developed polycrystalline quartz ribbons (Boullier and Bouchez 1978; Hongn and Hippertt 2001). To this deformational phase are associated mainly oblate to prolate ellipsoids (Passarelli 2001) with main shortening direction around N20E–N40E (Fig. 3). This deformational phase records sinistral deformation at amphibolite facies

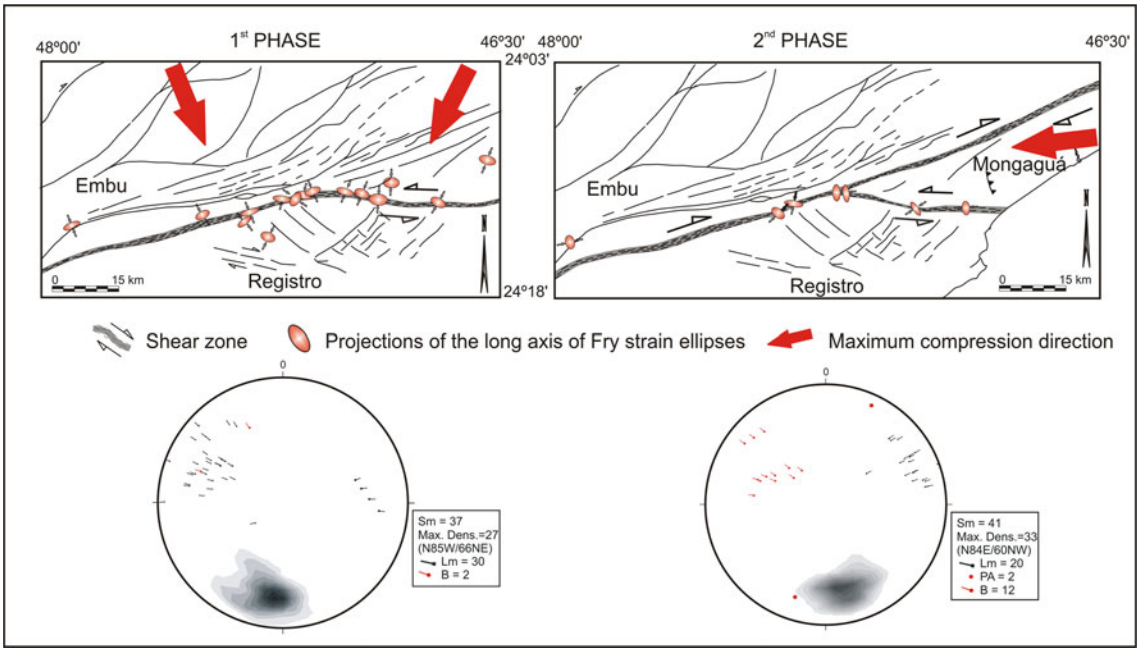

Fig. 3 Deformation phases in the Itariri Shear Zone with the projections of the long axis of Fry strain ellipses. Maximum compression direction and respective structural data plotted in equal area lower hemisphere Schmidt-Lambert stereographic projection. Number of data points (*n*) shown. *Sm* Poles to mylonitic foliation, *PA* poles to fold planes, *Lm* mineral stretching lineation; *B* fold axis. The terranes are discriminated

metamorphic mineral association, corroborated by geothermobarometric analysis (Passarelli unpublished data).

The second deformational phase, with ductile/ductile–brittle characteristics, is associated with an average E–W compression (deformation ellipses with major axis striking N–S), which caused a main sinistral strike-slip displacement with a modest thrust component toward the SW in the 'Itariri E–W branch' (recorded by the oblate deformation ellipsoids) and a dextral strike-slip displacement in the 'Cubatão NE branch' (Fig. 3). This deformational phase associated with sinistral movement in the 'Itariri E–W branch' is represented by a N84E-trending shear zone, with intermediate to strong dips to N–NW and a gently plunging NE mineral stretch lineation and associated folds with axes perpendicular to the mineral stretch lineation. Finite strain ellipsoid analyses show the total prevalence of oblate-type ellipsoids associated with this deformational phase (Passarelli 2001; Passarelli et al. 2005). In this context, the NE–SW 'Cubatão branch', slightly younger than the 'E–W Itariri branch', probably restarted moving in the western portion of the E–W branch, which records a dextral movement close to the junction of the ramifications. From the petrographic data, this phase did not exceed the greenschist facies. This phase is associated with the formation of a 'wedge' characterized by the junction of the 'Itariri and Cubatão branches', forming the Cubatão-Itariri Shear System (CISS), where the Mongaguá terrane is juxtaposed against two other terranes: Embu and Registro (Fig. 3).

In the Lancinha Shear Zone, N60E-striking sinistral movements preceded the dextral shear is also reported (Pierin et al. 2009), but further studies are needed to investigate the correlation between these movements and those recorded in the Cubatão-Itariri Shear System (CISS).

Sinistral reactivation in more brittle conditions is evidenced in CISS by mylonitic foliation and the generation of striations. Later sinistral brittle faulting, trending approximately N40E and NW-trending fracturing are also observed, clearly crosscutting the mylonitic foliation. In the central part of the Ribeira Belt, one of the most important structures is the Rio Paraíba do Sul Shear Belt (Fig. 4) that comprises a anastomosing network of NE–SW trending ductile shear zones extending over 1,000 km of the southeastern coast of Brazil (Ebert et al. 1996).

One of the most important shear zones of this complex system is the granulite-facies mylonites of the deep-crustal Além Paraíba Shear Zone that limits the Paraíba do Sul terrane and partly makes the boundary of the Juiz de Fora and Embu terranes (Fig. 1). It is a 10 km wide, dextral strike-slip vertical shear zone occurring in the north-central portion of Rio de Janeiro State, oriented N70E and N40E, in the southern and northern portions, respectively, and is slightly oblique to the regional orogenic trend (Egydio-Silva and Mainprice 1999; Hippertt et al. 2001; Egydio-Silva et al. 2002). It represents a mega-scale C' shear band that acted as a strain transfer shear zone accommodating the orogen-normal contraction components in a transpressional

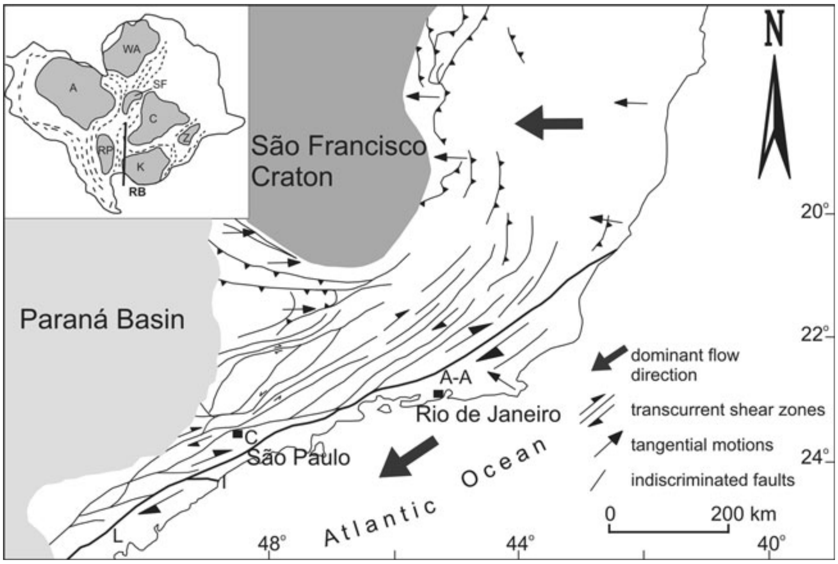

Fig. 4 Schematic structural map of the southern portion of Ribeira-Araçuaí Belt showing the NE–SW-trending dextral transpressional Rio Paraíba do Sul Shear System and adjacent areas with dominant kinematics (*L* Lancinha, *C* Cubatão, *I* Itariri, *A-A* Arcádia-Areal Shear Zones). Modified from Vauchez et al. (1994); Ebert et al. (1996); Egydio-Silva and Mainprice (1999)

regime (Egydio-Silva et al. 2002). This tectonic structure has been considered as a dextral shear zone developed in response to a transpressional regime, which produced wide mylonitic zones (Ebert et al. 1991; Machado and Endo 1993; Vauchez et al. 1994). Determination of stress directions has confirmed the kinematics of this deformation regime, suggesting that pure shear was as important as simple shear (Egydio-Silva and Mainprice 1999; Egydio-Silva et al. 2002). Many authors correlated the Além Paraíba Shear Zone with Cubatão-Lancinha Shear Zone (Fiori 1985a; Machado and Endo 1994; Ebert and Hasui 1998; Campanha and Sadowski 1999; Silva et al. 2005a).

However, in this work, we stress out our opinion that the Cubatão Shear Zone, which is a suture zone because it separates domains with totally distinct tectonic evolutions, continues northeastwards, into the Rio de Janeiro state, as the so-called Arcádia-Areal Shear Zone or Central Tectonic Limit (Almeida et al. 1998; Heilbron et al. 2004), and not as the Além Paraíba or Paraíba do Sul Shear Zone, located *ca*. 20 km northwest (Fig. 1).

The Arcádia-Areal Shear Zone, which represents the continuity of the Cubatão Shear Zone in the Ribeira Belt central sector, Rio de Janeiro State, strikes N65E and steeply to moderately dips northwestwards and locally southeastwards with a maximum in N60E/48 NW and a sub-horizontal and directional stretching lineation around N33E/24° (Almeida et al. 1998). The Arcádia-Areal Shear Zone corresponds to the tectonic limit (Almeida et al. 1998) between the Oriental and Occidental terranes (Heilbron et al. 2000; Trouw et al. 2000), reaching *ca*. 3 km in thickness.

Divergent kinematic indicators are found in the Arcádia-Areal Shear Zone (Almeida et al. 2006). While asymmetric porphyroclasts indicate a sense of shear top down to NE in the metasediments, characterizing a dextral distensional transport, the sigma structures in orthogneisses of the Coastal Terrane indicate top up to SW characterizing a sinistral compressional transport. The authors propose two distinct explanations: a previous west-to northwestward thrusting followed by transpressional dextral shearing that rotates the stretching lineation to NE, or a previous west-to northwestward thrusting and later transtensive dextral shear zone that formed a NE stretching lineation. In both cases, the deformation was partitioned, concentrated in the "softer" and anisotropic metasedimentary rocks, and preserving the more isotropic and "harder" igneous rocks (Almeida et al. 2006). The finite deformation ellipsoids determined for this shear zone are oblate, confirming the importance of pure shearing. The greenschist metamorphic grade observed in the Cubatão Shear Zone contrasts with that of mylonitic rocks of the shear system in the Rio de Janeiro State, which reaches the lower-medium amphibolite or even the granulite facies (Machado et al. 1996; Egydio-Silva et al. 2002).

In the Paraná State, the Lancinha Shear Zone, which is the natural continuity of the Cubatão Shear Zone, shows associated folding, sinistral transtensional reactivation, and is characterized by rare mylonitic rocks and a brittle anastomosed aspect (Fiori 1985a, b; Soares 1987; Salamuni et al. 1993; Salamuni 1995; Fassbinder et al. 1994). The Lancinha Fault would reflect, at the surface, an older and deeper fault, represented by the Cubatão Lineament, reactivated under brittle–ductile conditions (Fiori 1985a; Fassbinder et al. 1994).

Serrinha: Rio Palmital Shear System

The Serrinha-Rio Palmital Shear System separates the Paranaguá-Iguape Arc from the Curitiba-Registro and Luis Alves Microplate (Fig. 1). The Serrinha Shear Zone

(Passarelli 2001) is the northern part of this shear system and changes from a dextral transcurrent ramp in the easternmost portion (Juréia) to a dextral lateral-oblique ramp in the central-western portion (Serrinha and Pariquera-Açu) and to a frontal ramp in the western portion (Piririca area—Fig. 2). It is associated with the juxtaposition of the Paranaguá-Iguape and the Registro-Curitiba Terrane.

In general, the strike of the mylonitic foliation varies from *ca*. N60W/NE low dip in the eastern portion, with a gently plunging mineral stretch lineation, grading in the central portion around E–W with low- to intermediate-angle stretching lineations, and around N80E/NW low dip with low-angle lineations and around N20E/SE intermediate dip with down-dip stretching lineations in the westernmost portion. The transcurrent Alexandra and Palmital Shear Zones represent the southern continuity of this system, indicating sinistral kinematics with oblique component characterized by the co-existence of strike-slip and down-dip lineations (Siga et al. 1993; Cury et al. 2008). Therefore, this system delineates along its whole area a tectonic wedge composed of the Paranaguá Terrane, with preferential westward transport (Fig. 2). The different shear zones that compose this system represent the partition of the main strain associated with the collision of the Paranaguá Terrane with other domains to the west, in the site of the Luis Alves Microplate.

The easternmost sector of Serrinha Shear Zone (SSZ) affects the Juréia paragneissic rocks of Cachoeira Sequence, Registro-Curitiba terrane, with the mylonitic foliation characterized by strong stretching of the quartz-feldspatic portions. The mylonitic foliation has a predominantly N40W–N65W strike and dips 35°–65° to NE, with a subhorizontal to gently NE plunging stretching lineation. In this east sector, the Serrinha Shear Zone represents a dextral lateral ramp (Passarelli et al. 2007). Mylonitic rocks of granitic composition of the central sector of the SSZ are imbricated with granulite-facies metasedimentary rocks of Cachoeira Sequence. The mylonitic foliation shows a general strike around E–W and is associated with a predominant dextral movement with an important pure shear component. The coaxial component is characterized mainly by the presence of dextral and sinistral kinematic indicators, symmetric porphyroclasts and results of Fry analysis (Passarelli 2001). In this area, the Serrinha Shear Zone presents a conspicuous, 1 km—thick, N35W—trending, SE-dipping ramification, (Fig. 2) where sinistral movement is observed associated with a NW thrust component. A frontal thrust ramp with ~N60W transport is characterized in the westernmost sector (Fig. 2) by a N20E striking moderately SE-dipping mylonitic foliation, carrying a well-defined down-dip mineral lineation defined by stretched-out feldspar aggregates.

Ages of main deformation and cooling episodes

In the Lancinha-Itariri Shear Zone, the first deformational phase is associated with the juxtaposition of the Embu and Registro domains. The period between 620 and 600 Ma is suggested in this work as the most probable for this movement and is recorded in rocks of both terranes. In Embu Terrane, protomylonitic granites yielded U–Pb ages of metamorphic epidote around 598 Ma (Passarelli et al. 2008) obtained for the Juquiá Granite (Fig. 5a) and in monazite around 620 Ma (Passarelli et al. 2008) obtained for the Sete Barras Granite (Fig. 5b). A metamorphic overprint at *ca*. 600 Ma in granite-gneissic rocks is record in zircon overgrowths (U–Pb SHRIMP, unpublished data) and from protomylonitic granite monazites by U–Pb ID-TIMS dating from Registro Terrane (Fig. 6).

The oldest age of the second deformation episode, which generated the wedge formed by the Itariri and Cubatão Shear Zones, is 583 ± 3 Ma (Fig. 7), defined by a concordant U–Pb age of a needle-shaped zircon from a mylonite of the Cubatão Shear Zone northern branch and a lower intercept of the Areado and Ribeirão do Óleo Granites of Mongaguá Domain (Fig. 2) and interpreted as syn-kinematic to the Cubatão-Itariri Shear Zone main movement (Passarelli et al. 2008).

According to Machado et al. (1996), the metamorphic climax in the Central Ribeira Belt was reached between 590 and 565 Ma (zircon, monazite and titanite ages). It represents the record of an important tectono-thermal event characterized by partial melting, intrusion of granitic rocks and remobilization of basement gneisses. They correspond to early WNW thrusting that started before 589 ± 8 Ma (monazite and titanite ages) and to the development of dextral shear zones. A slightly lower-grade metamorphic imprint was recorded during the development of the dextral transcurrent shear zones before 535–527 Ma (zircon, monazite and titanite U–Pb ages).

In the Serrinha-Rio Palmital Shear System, in situ U–Pb ages using conventional TIMS analyses (Passarelli et al. 2009) and EPMA chemical dating (unpublished data) were obtained. Monazite crystals extracted from mylonitic granitic rocks and from the Juréia Massif mylonitic paragneisses, respectively, located in the central and eastern portions of the Serrinha Shear Zone, were dated. An average age of 575 ± 5 Ma (Passarelli et al. 2008) was obtained by both methods (Fig. 8a, b), which is interpreted as the metamorphic peak associated with the movement of the Serrinha Shear Zone, the deformation reaching the amphibolite facies.

Both for the Cubatão-Itariri Shear Zone and the Serrinha Shear Zone, muscovites and biotites extracted from mylonitic rocks analyzed by the K–Ar and Ar–Ar methods yielded cooling ages (McDougall and Harrison 1999;

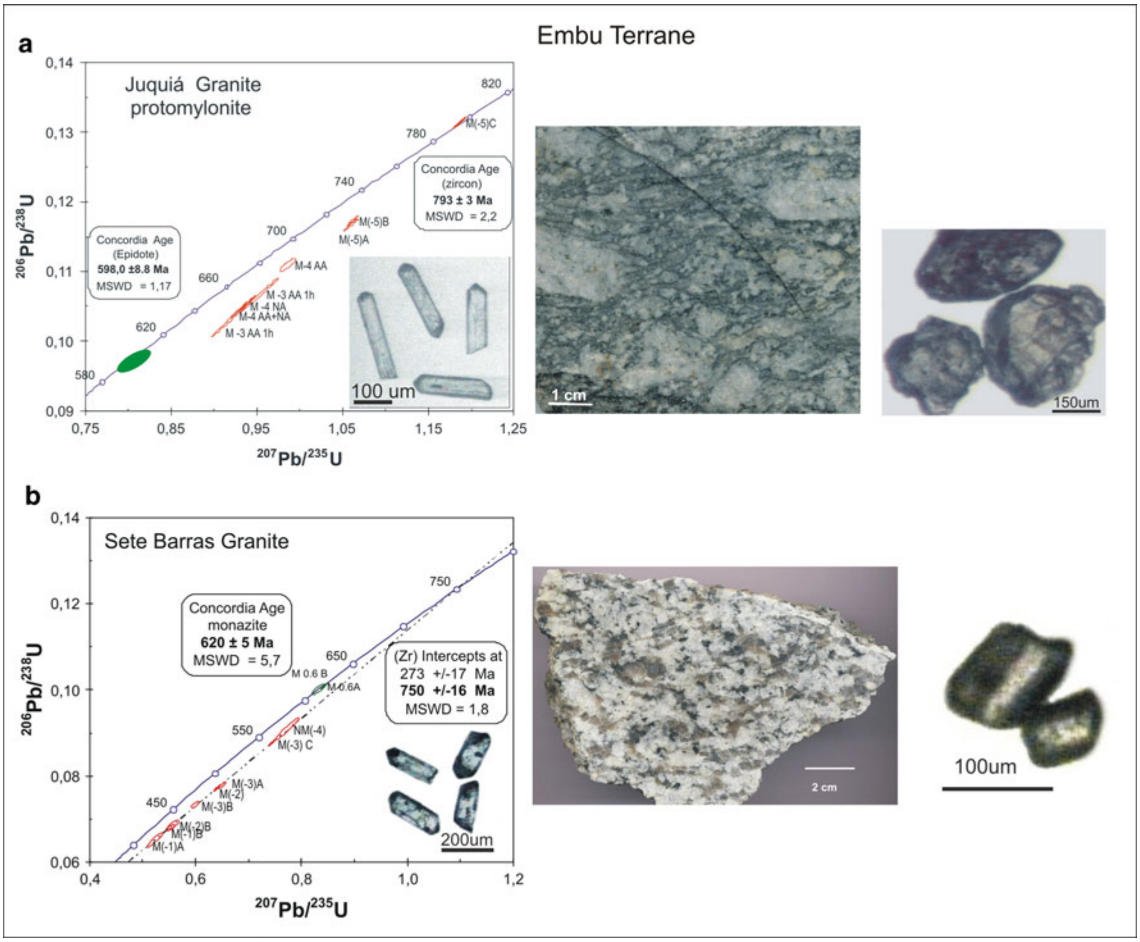

Fig. 5 ^{206}Pb/^{238}U vs. ^{207}Pb/^{235}U Concordia diagram of Embu Terrane granites. **a** Juquiá Granite; **b** Sete Barras Granite. The crystallization age is defined by zircons and the deformation age by epidote and monazite. The photographs of the samples and respective minerals dated are included

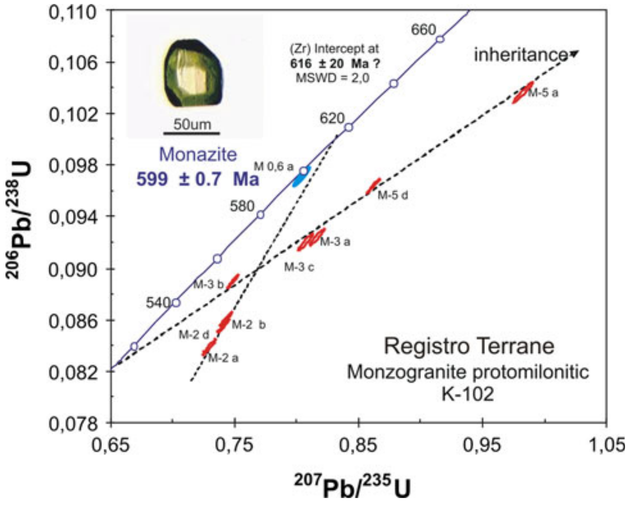

Fig. 6 ^{206}Pb/^{238}U vs. ^{207}Pb/^{235}U Concordia diagram of protomylonite with an uncertain age around 615 Ma and a deformation age of 600 Ma defined by monazite (photo)

Willigers et al. 2001). The K–Ar ages obtained for fine fractions are systematically younger and are interpreted as referring to very low-temperature processes (around 300°C) associated with subsequent reactivation of the shear zones, causing the generation of very fine-grained materials, which can be dated, sensitive to low- to very low-grade thermal events (Wemmer 1991).

Along the Cubatão-Itariri shear system, for which there are a reasonable number of samples dated, a constancy of K–Ar ages between 490 and 500 Ma and Ar–Ar ages between 483 and 499 Ma obtained from biotites is observed. These ages are distinct from those obtained from a sample collected at the junction of the ramifications of these shear zones, which yielded ages around 400 Ma, suggesting that this area remained heated for a longer time than the others. The K–Ar ages obtained for fine fractions are slightly older in the Itariri Shear Zone, between 395 and 425 Ma, than those of the Cubatão Shear Zone, between

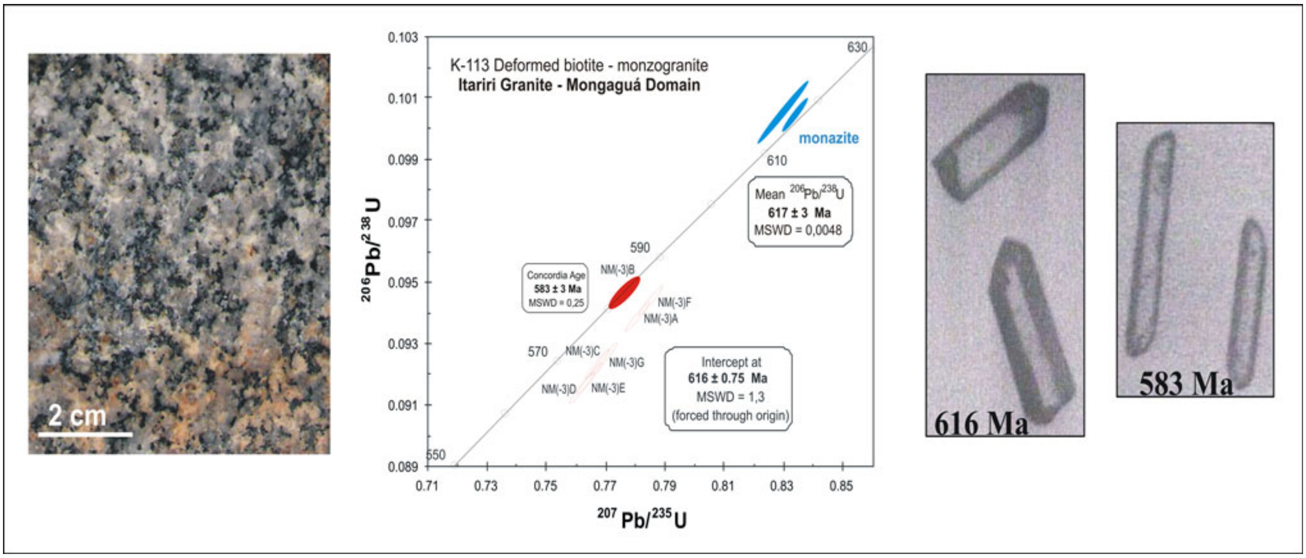

Fig. 7 $^{206}Pb/^{238}U$ vs. $^{207}Pb/^{235}U$ Concordia diagram of the 617 Ma deformed granite of Mongaguá Domain. The crystallization age is defined by zircons and monazite and the deformation age of 583 Ma by needle-shaped zircons. Photographs of the samples and respective dated minerals are included

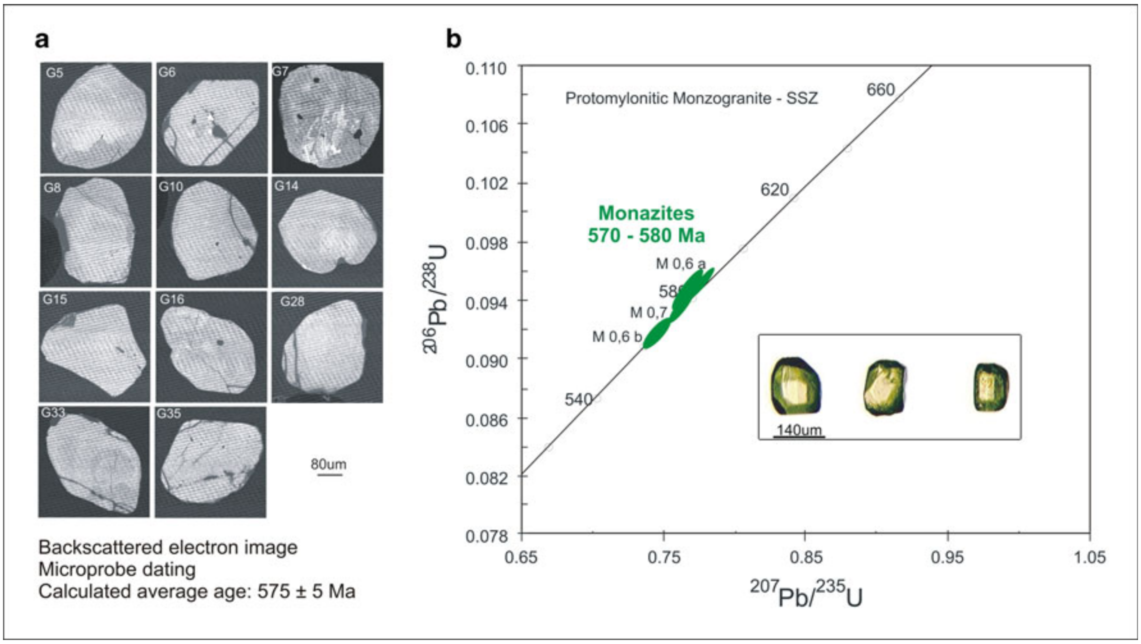

Fig. 8 U–Pb dating of monazite (protomylonite Serrinha Shear zone). **a** Backscattered electron image of Microprobe dating monazite grains: −26 analytical spots over the main crystals gave chemical ages in the range between 550 and 599 Ma with an average of 575 ± 5 Ma. **b** $^{206}Pb/^{238}U$ vs. $^{207}Pb/^{235}U$ Concordia diagram showing data points and error ellipses for concordant populations of monazite with an age range interval 580–570 Ma

375 and 380 Ma. In the Serrinha Shear Zone, the biotite K–Ar and Ar–Ar ages are distributed between 482 and 495 Ma, the muscovite of the eastern sector yielding 501 ± 5 Ma. In the western sector of the Serrinha Shear Zone, ages of 575 Ma yielded by muscovites are concordant with the U–Pb ages obtained for monazites extracted from a Serrinha Shear Zone protomylonite and represent its main period of movement. The K–Ar ages obtained for the fine fractions are distributed between 370 and 425 Ma, with older ages being apparently more characteristic in the eastern sector.

Fission-track dating of apatites resulted in important information on the thermal-tectonic evolution of the Cubatão-Itariri Shear System and the Mongaguá and

Registro terranes, specifically on the low-temperature thermal history, supplying records of the main exhumation events. The uplift of the South-American continent coastal region, associated with the uplift phase of the process that culminated with the continental rupture and opening of the Atlantic (Gallagher et al. 1995; Amaral et al. 1997; Hackspacher et al. 1999, 2004a; Kohn et al. 2002; Tello Sáenz et al. 2003; Godoy et al. 2006; Hackspacher and Tello Sáenz 2006; Hackspacher et al. 2008), is recorded by apatite fission tracks with ages around 120 Ma in rocks of the crystalline basement of the Paraná Basin eastern border (Godoy et al. 2006). Similar values were obtained in the Registro and Mongaguá domains affected by the Cubatão Shear Zone. Neocretaceous cooling ages, around 74 Ma, were also obtained from a rock of the Registro domain affected by the Itariri Shear Zone. In the Paleocene, a predominantly extensional tectonics occurred in the Serra do Mar region, leading to the Continental Rift System of southeastern Brazil (Almeida 1976; Riccomini et al. 1989; Zalán and Oliveira 2005), accelerating the exhumation and denudation processes. This period is recorded in the Areado Granite of the Mongaguá domain.

The available data attest that cooling of the Registro and Mongaguá terranes changed from the 110°C isotherm to the 60°C isotherm at different time periods. The similarity of the values obtained from a sample of the Registro domain and the value obtained for the Cubatão Shear Zone mylonite suggests that around 120 Ma this shear zone was reactivated with important vertical component.

Dom Feliciano Belt

The Dom Feliciano Belt (DFB) represents the major geotectonic unit in the southern part of the Mantiqueira Province (Almeida et al. 1981; Silva et al. 2005a), crop out roughly N–S, and occupies the entire eastern segment of southern Brazil and Uruguay (Fig. 1). Its evolution is associated with the transpressional tectonics related to the Neoproterozoic and Early Paleozoic West Gondwana collage. The Dom Feliciano Belt consists of supracrustal rocks and granitic batholiths with contacts defined by high-angle ductile NE–SW shear zones. Remnants of Paleoproterozoic basement inliers can be found on the eastern border (Basei et al. 2000).

Tectonic compartmentation

From its southern outcrops in Uruguay to its termination in Santa Catarina in Brazil, the DFB is composed of three crustal sectors separated by tectonic contacts (Fig. 1). They are (a) the Granite Belt (Florianópolis and Pelotas Batholiths in Brazil and the Aiguá Batholith in Uruguay), composed of deformed I-type medium to high-K calc-alkaline granites and alkaline granitoid rocks; (b) the Schist Belt (Brusque and Porongos Metamorphic Complexes in Brazil and the Lavalleja Group in Uruguay), constituted by volcano-sedimentary rocks metamorphosed in greenschist to amphibolite facies with associated granitoids; and (c) the foreland basin deposits (Itajaí and Camaquã Basins in Brazil and the Arroyo del Soldado and Piriápolis Basins in Uruguay), composed of anchimetamorphic sedimentary and volcanic rocks, situated between the Schist belt and the Archean-Paleoproterozoic foreland to the West.

The Major Gercino Shear Zone (MGSZ) defined by Trainini et al. (1978) in Santa Catarina state (Fig. 9a) is part of a lithospheric-scale discontinuity in the DFB and is a prominent feature of the Proterozoic terranes in southern Brazil and Uruguay (Hallinan et al. 1993; Basei et al. 2000, 2008). This major lithospheric-scale suture, denominated by Basei et al. (2005) as the Sierra Ballena—Major Gercino Lineament (SBMGL), forms a ~1,400 km-long shear system and is marked by strong linear negative gravity anomalies (Mantovani et al. 1989; Hallinan et al. 1993). The SBMGL is a crustal discontinuity that encompasses several anastomosed shear zones, striking NNE and NE with dominant transcurrent kinematics, which controlled the intrusion of calc-alkaline granites, and in which syn-tectonic calc-alkaline, peraluminous and alkaline granites occurred (Picada 1971; Bitencourt and Nardi 2000, 2004; Oyhantçabal et al. 2007, 2009a).

The DFB schist belt is represented by the Brusque Metamorphic Complex in Santa Catarina (Basei 1985; Silva 1991; Philipp et al. 2004). It is composed of meta-volcano-sedimentary rocks which underwent polyphase deformation resulting in NW-verging nappes formed during the main metamorphic episode in the Neoproterozoic which reached upper greenschist – lower amphibolite facies (Basei et al. 2000). The Schist Belt was intruded by late-tectonic granites: the two mica leucogranites of the São João Batista suite, the porphyritic biotite granites of the Valsungana suite, and the biotite granites of the Nova Trento suite. Similar features are also documented in other parts of the Schist Belt in Rio Grande do Sul, Porongos Metamorphic Complex, and Uruguay, Lavalleja Metamorphic Complex (Basei et al. 2006). The Granite Belt is represented by the Florianópolis Batholith (Fig. 1) composed of three main suites. The deformed tonalites to granodiorites and migmatites of Águas Mornas Suite is the oldest one, the quartz-diorites to quartz-monzonites of São Pedro de Alcântara Suite and the late alkaline leucogranites of Pedras Grandes Suite. The U–Pb ages are in the 640-595 Ma time interval. The Pelotas Batholith in RS state (Fig. 1) comprises the Pinheiro Machado, Erval, Viamão, Encruzilhada do Sul, Cordilheira and Dom Feliciano granitic suites. The suites comprise high-K calc-alkaline to

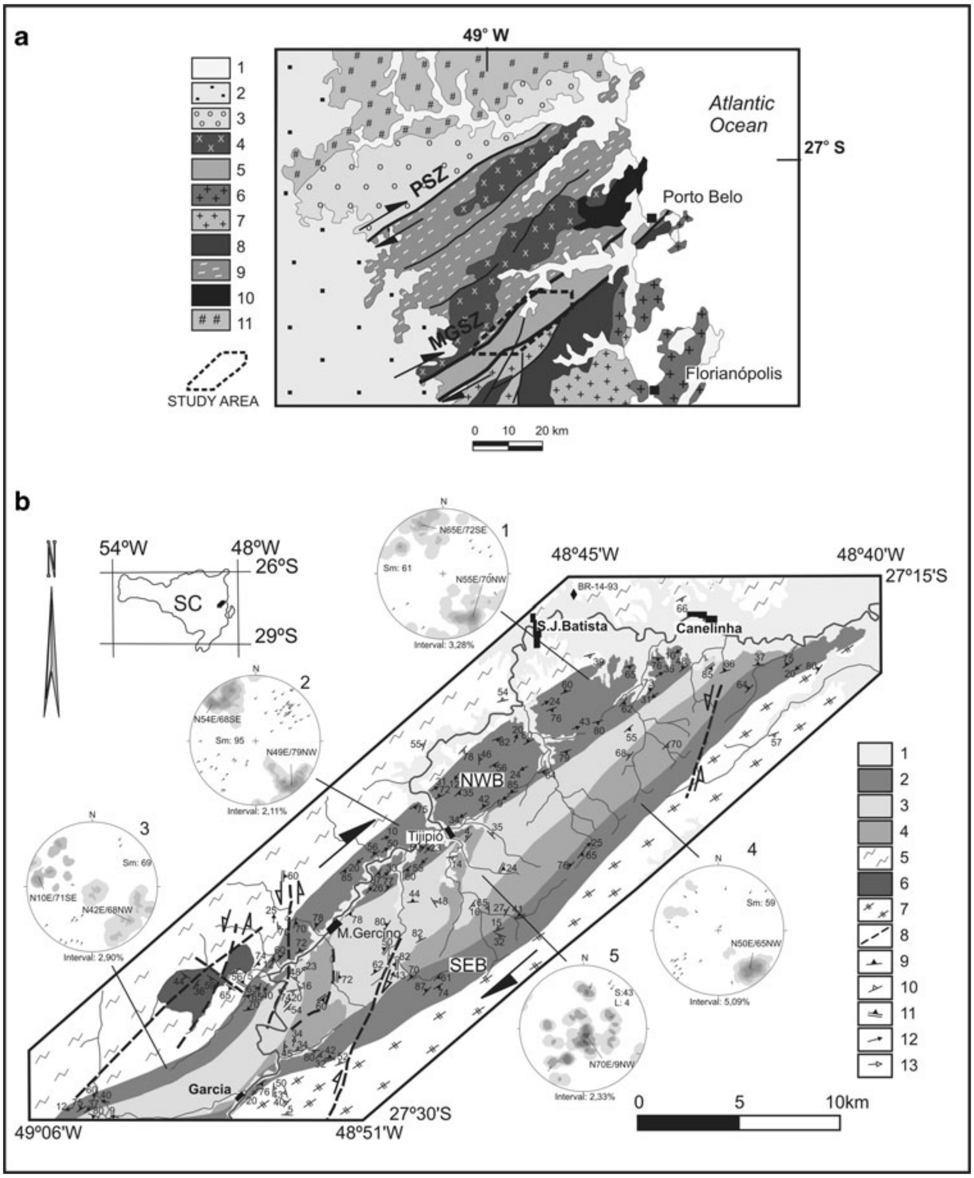

Fig. 9 **a** The southern portion of Dom Feliciano Belt, Santa Catarina, Brazil. *1* Cenozoic deposits; *2* Paleozoic to Mesozoic sediments of Paraná Basin; *3* Late Neoproterozoic-Early Paleozoic Itajaí volcano-sedimentary basin; *4* Neoproterozoic intrusive granites; *5* Central Granitoids (Major Gercino Shear Zone); Neoproterozoic granitoid belt (Florianópolis Batholith): *6* Pedras Grandes Suite, *7* São Pedro de Alcântara Suite, *8* Águas Mornas Complex; *9* Neoproterozoic volcanosedimentary units of Brusque Complex; *10* Neoproterozoic gneisses and intrusive granites of Camboriú Complex; *11* Archean/Paleoproterozoic Santa Catarina Granulitic Complex. *PXZ* Perimbó Shear Zone; *MGSZ* Major Gercino shear zone; *A* Amazonas craton; *RP* Rio de la Plata craton; *SF* São Francisco craton; *K* Kalahari craton; *C* Congo craton; *DFB* Dom Feliciano belt; **b** Geological map of Major Gercino shear zone (MGSZ). (1) Cenozoic deposits; *MGSZ* (2) Northwestern mylonite belt (NWB), Southeastern mylonite belt (SEB); Central Granitoids: (3) Fernandes granitoid association; (4) Rolador granitoid association; Terrains north of MGSZ: (5) Brusque metamorphic complex; (6) Intrusive granitoids; Terrains south of MGSZ: (7) Granite-migmatitic complex (Camboriú complex); (8) principal faults; (9) mylonitic foliation; (10) main foliation; (11) cataclastic foliation; (12) mineral lineation; (13) magmatic lineation

alkaline compositions, with U–Pb ages between 630 and 590 Ma (Philipp and Machado 2005).

Similarly to the southern Brazilian portion, in the Uruguayan Shield, the region east of the Schist Belt (Lavallela Group) is constituted by a domain of granitoid rocks (Bossi et al. 1988; Babinski et al. 1997; Basei et al. 2000) where igneous rocks of different compositions predominate with poly-intrusive calc-alkaline granitoids, subordinately occurring isotropic granitoid bodies of syenogranitic composition. This domain constitutes the Aiguá Batholith, interpreted as the root of a Neoproterozoic magmatic arc. The Aiguá Batholith (A) has been correlated with the Pelotas and Florianópolis Batholiths further to the northeast. The oldest value observed in the Aiguá granitoids is a Pb–Pb age on titanite of 614 ± 3 Ma (Oyhantçabal et al. 2007, 2009a, b). Late-tectonic granitic bodies within the Aigua Batholith yielded slightly younger U–Pb zircon ages between 590 and 570 Ma (Preciozzi et al. 1999, 2001).

The Major Gercino Shear Zone

The MGSZ is a N–NE/S–SW-oriented shear zone that affects the Dom Feliciano Belt as an important suture separating the magmatic arc granites to the East (Granite Belt) and a folded supracrustal belt to the West (Schist Belt). These belts show different model NdTDM ages of 1,290 to 1,690 Ma in the Granite Belt, and around 2,000 Ma in the Schist Belt (Mantovani et al. 1989; Basei 1990). The belts had independent origins and evolutions and achieved their present configuration around 540 Ma, when they were transported northwestwards to the border of the Rio de La Plata Craton which today underlies the Paraná basin (Basei et al. 2000). The syn-tectonic magmatism and the mylonites developed mainly during dextral lateral and oblique movement under compression led to the Granite Belt uplift.

The MGSZ presents a northwestern mylonite belt (NWB) 1 to 3.8 km wide and a 500 m to 2 km wide southeastern mylonite belt (SEB) (Fig. 9b), both striking NE and composed of protomylonites to ultramylonites with mainly dextral kinematics (Passarelli et al. 2010). The mylonitic belts form the limits of two petrographically, geochemically and isotopically different granitoid associations, usually referred to as the Central Granitoids: the Rolador Granitoid Association (RGA) and the Fernandes Granitoid Association (FGA).

A gradation from protomylonite to ultramylonites and phyllonite, passing through mylonite, characterizes the shear-related rocks of these two belts. The dip of NWB mylonitic foliation is mainly sub-vertical and shows a systematic strike variation: in the NE sector (Diagram 1, Fig. 9b) strikes N65E preferentially, N54E in the middle (Diagram 2, Fig. 9b), and then strikes N10E in the SW part (Diagram 3, Fig. 9b). The lineation exhibits dip directions of N55E with shallow plunges in the NE sector, N45E and S57W trends in the middle with intermediate to steep plunges, and plunge at intermediate to steep angles toward S20W in the SW sector.

The strike of the main mylonitic foliation of the SEB is preferentially N50E, with high-angle, NW dip (Diagram 4, Fig. 9b). The stretching lineation is defined by quartz ribbons and elongated feldspar porphyroclasts and by the alignment of biotite and muscovite flakes. The lineation dips S50W, with intermediate to low plunge (max. 20).

The variations of stretching lineation plunge in the MGSZ may reflect along-strike variations in finite strain or strain partitioning, revealing, in a no continuous manner, the record of a progressive transition from early stages of thrust to transpressional tectonics (Passarelli et al. 2010).

The mylonites of MGSZ derived mainly from granitoids which undergone dominant processes of grain-size reduction by dynamic re-crystallization of quartz, fracturing of plagioclase and K-feldspar during deformation. The mylonitization in greenschist facies conditions promoted the neoformation of sericite, chlorite, biotite, albite, clinozoisite/zoisite and epidote. The granitoid bodies that occur between the NWB and the SEB are elongated (Fig. 9b), and their borders are sheared, but they are usually only weakly deformed or megascopically isotropic in the cores. The presence of a range between magmatic and high-temperature solid-state microstructures where additionally sub-magmatic microstructures were characterized and the apparent rotation of the magmatic structures into the direction of the mylonitic belts indicate that during and after crystallization of the plutons, the shear zone controlled the ascent and emplacement of magma in a dextral transpressional tectonic regime (Passarelli et al. 2010).

The flat-lying magmatic/submagmatic and high-temperature solid-state microstructures (Diagram 5, Fig. 9), e.g., chessboard subgrain patterns in quartz, bent plagioclases and kinked biotites (see Fig. 11; Passarelli et al. 2010) is possibly a record of an early control of the intrusion by the initial stages of an oblique/thrust shear zone, which placed the Granite Belt over the Schist Belt. The shear zone evolved to a transpressive one only during the later stages after the peak of dynamic metamorphism, as observed in several shear zones of the southern Brazil and Uruguay. In addition, flat-lying low-temperature deformation microstructures are locally preserved on the SW sector of the NWB (Diagram 3, Fig. 9).

Correlations between the major southern Brazilian and Uruguayan shear zones have already been discussed by a number of authors (Basei 1990; Passarelli et al. 1993; Fernandes and Koester 1999; Basei et al. 2000; Bitencourt and Nardi 2000; Bossi and Gaucher 2004; Oyhantçabal et al. 2009a; Passarelli et al. 2010) based on the strong suggestion of geometrical and geophysical continuities (Mantovani et al. 1989). Together with the Cordilheira (RS) and Sierra Ballena (UY) Shear Zones, the MGSZ is considered part of a lithospheric-scale system of discontinuities that separates geochemical and isotopically distinct terranes (Basei et al. 2008). It is important to stress out that the Cordilheira Shear Zone is in the literature referred as Dorsal do Canguçu Shear Zone (e.g. Frantz et al. 2003; Philipp and Machado 2005). This interpretation is not accepted here and considered instead as two distinct and independent shear zones, parallel to one another. The Cordilheira, as mentioned before, belongs to the suture that separates two distinct terranes (Basei et al. 2000; Passarelli et al. 2006), whereas Dorsal do Canguçu is a shear zone that occurs inside the Pelotas Batolith (Fig. 1), as characterized by Jost et al. (1984) and Sadowski and Motidome (1987).

The N65W-trending principal compressional stress in the MGSZ in Santa Catarina (Passarelli et al. 1993, 1997) guaranteed a significant component of pure shear deformation as also observed in the transpressional sinistral phase of the SBSZ in Uruguay (Oyhantçabal et al. 2009a, b) and in the Cordilheira Shear Zone in RS (Basei et al. 2008) during a single episode.

Ages of main deformation and cooling episodes

The evolution of the DFB is related with both a tangential tectonic regime and a transcurrent one in the Neoproterozoic terranes of southern Brazil (Frantz and Botelho 2000). The first one is related to continent–continent collision (Basei and Hawkesworth 1993; Nardi and Frantz 1995; Basei et al. 2000; Philipp and Machado 2005). The tangential regime, defined by low-angle planar structures, could represent the timing of continental collision and is identified in Rio Grande do Sul under amphibolite facies metamorphic conditions (Fernandes et al. 1992) and in the MGSZ in Santa Catarina (Bitencourt and Nardi 1993; Passarelli et al. 2010). After peak metamorphic conditions were reached, N–S sinistral and NE dextral transcurrent shearing began (Basei 1990; Fernandes et al. 1992; Bitencourt and Nardi 1993), under low-grade metamorphic conditions.

Preciozzi et al. (1993) outlined the evolution for the Dom Feliciano Belt in Uruguay characterized by four major events. The first one would be represented by low- to high-grade metamorphism of the supracrustal Lavalleja Group responsible for the origin of orthogneisses and migmatites. Shear zones with associated granitoids of *ca.* 650 Ma represent the second event. The third event is characterized by late-wrenching and post-orogenic granitoids with ages ranging from 630 to 550 Ma. This event also generated a highly strained zone involving imbricated units. Finally, the fourth event generated late thrust and post-wrenching granitoids.

In Santa Catarina, Major Gercino region, the transpressional phase of the MGSZ is constrained by the emplacement of the meta- to peraluminous calc-alkaline elongated granites of the Central Granitoids (FGA and RGA). The U–Pb zircon ages for this syn-transpressional magmatism range from 610 to 615 Ma and are interpreted as the interval of formation of both granitic associations (Passarelli et al. 2010).

In Porto Belo area, the early high-K, calc-alkaline granitic magmatism of *ca.* 650-630 Ma (Bitencourt and Nardi 2000) was mainly controlled by flat-lying shear zones. In the same period, in the Cordilheira Shear Zone (Rio Grande do Sul State), the emplacement of granitic intrusions from 658 to 625 Ma (Frantz et al. 2003) was controlled by a transpressional deformation in a steep dipping shear zone. The period of 625–617 Ma represents a transition from a transpressional to a transtractive period. The emplacement of the late- and post-tectonic granite suites occurred later between 615 and 580 Ma, with a peak at approximately 600 Ma (Babinski et al. 1997) defined by shoshonitic magmatism (Bitencourt and Nardi 2000). The transtensional period is characterized by the emplacement of granites with U–Pb ages around 605 Ma (Frantz et al. 2003) followed by younger alkaline magmatism.

Additionally, Philipp and Machado (2005) pointed out that the magmatism of the Pelotas Batholith corresponding to the age of tangential deformation supplied an interval of 630–610 Ma and rocks with ages between 570 and 600 Ma may correspond to the development of high-angle ductile shear zones.

In the Aiguá Batholith, Uruguay, the 614 ± 3 Ma syntectonic intrusions associated with the SBSZ (Oyhantçabal et al. 2007) support a similar time interval for the transpressional episode observed in the MGSZ, in SC state. Two main transpressional episodes can be separated from an extensional one with an age of *ca.* 590 Ma (Oyhantçabal et al. 2009a, b): (1) an early, associated with the nucleation of conjugate shear zones and (2) a late event, associated with sinistral reactivation of the NS-trending shear zones. The age of the second transpressional episode is constrained by the ^{40}Ar/^{39}Ar cooling age of muscovite from quartz mylonite (586 ± 2 Ma; Oyhantçabal et al. 2009a) similar to U–Pb ages ranging from 570 to 580 Ma obtained for the alkaline felsic magmatism from Uruguay to southern Brazil (Siga et al. 1997; Leite et al. 1998; Hartmann et al. 2002; Chemale et al. 2003).

In Uruguay, U–Pb SHRIMP zircon ages of 564 ± 7 Ma (syntectonic Maldonado granite, Oyhantçabal et al., 2009b) and zircon U–Pb age of 551 ± 4 Ma (sintectonic alkaline magmatism associated with mylonitic porphyries, Oyhantçabal et al. 2010 this volume) are interpreted to represent late movements along the SBSZ.

K/Ar ages on biotites and muscovites of *ca.* 570 Ma from mylonites of MGSZ, northern belt (Fig. 9b) are indistinguishable from the K/Ar ages of the Central Granites and represent the time of cooling through the 300–350°C interval (McDougall and Harrison 1999) after the regional thermal peak. One muscovite sample from a mylonite in the southern belt is probably younger (*ca.* 540 Ma), suggesting that the movements along the two shear zones may have occurred at different times (Passarelli et al. 2010).

In the Rio Grande do Sul state, analogous biotite K–Ar ages around 570 Ma were obtained in syn-transcurrent granitoids of the Cordilheira Shear Zone (Koester et al. 1997) and mica Ar–Ar and biotite K–Ar dating on mylonites of ductile shear zones in the eastern Pelotas Batholith, ranging from 540 to 530 Ma, are interpreted as result of a reactivation of faults related to a late thermal-tectonic event probably responsible for the installation of the Camaquã Basin (Philipp and Machado 2005). K–Ar ages of *ca.* 530 Ma obtained from biotite, which are similar to those obtained in the ZCMG, were also associated with ductile–brittle to brittle structures (open normal folds, normal and reverse faults and fractures) in Uruguay (Mallmann et al. 2004).

Additionally, ages around 570 Ma can also be found in the late stages of the Florianópolis Batholith magmatism (Basei et al. 2000; Silva et al. 2005b). Similar Rb–Sr whole-rock ages are also found for parts of the Pelotas Batholith (Soliani 1986; Philipp and Machado 2005). Late-tectonic granite bodies within the Aiguá Batholith (Uruguay) yielded U–Pb zircon ages up to 570 Ma (Preciozzi et al. 2001).

Shear zone reactivations in the southern portion of the Mantiqueira Province characterized in the Devonian (359 and 377 Ma) can be associated with an exhumation event related to block tectonics correlated the Paraná Basin evolution (Hackspacher and Tello Sáenz 2006; Passarelli et al. 2010), and in the Triassic (206 and 230 Ma) in mylonites of the northern branch of the Major Gercino Shear Zone, in this case probably associated with a thermal pulse connected to an early phase of the opening of the South Atlantic Ocean.

Discussion

As a consequence of the collision of crustal masses that led to the formation of Western Gondwana, in all south-eastern Brazilian and Uruguayan portions, major shear zones developed with lateral movements that accommodated most of the energy associated with the collisions. This scenario, built during the Ediacaran-Cambrian transition, is registered along the totality of the Mantiqueira Province as a result of the juxtaposition of the São Francisco, Kalahari, Paranapanema and Rio de La Plata cratons (Fig. 10).

The lateral escape tectonics combined with a vertical component was responsible for the juxtaposition of terranes from distinct structural levels. The oblique movement between most of the tectonic blocks determined the transpressional character of the main suture zones. During the late stages of the Western Gondwana formation, distensional structures were installed later to the principal compression (Fig. 11).

In the southeastern and central portions of the Ribeira Belt, structural features characteristic of the two types of deformation (Ebert and Hasui 1998) are recognized: transcurrency (non-coaxial deformation—directional structures of predominantly dextral and sinistral movement) and shortening perpendicular to the shear zones (coaxial deformation). This attests for that a large part of the Ribeira Belt underwent dextral transpression generated by oblique collision between different terranes in the E–W direction, accommodated by means of the deformation partitioning in NW–SE-trending compressive and NE–SW-trending transcurrent structures along this belt (Fig. 11). The transpressional deformational character is also characterized in the Dom Feliciano Belt, mainly represented by the orogen-parallel Major Gercino—Sierra Ballena Shear System (Fig. 11).

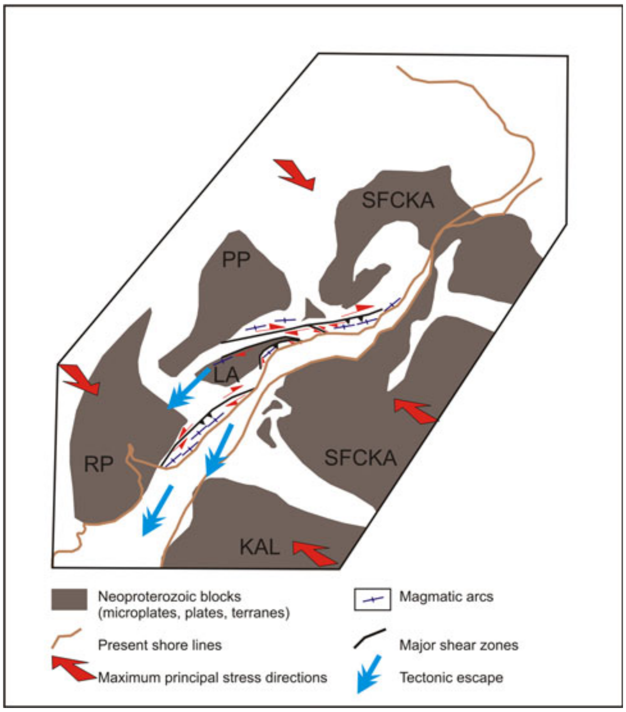

Fig. 10 Sketch diagram for the paleogeographic scenery of the closure of the Brasiliano-Panafrican Cycle, showing the main collisional segments (plates, microplates, terranes). Neoproterozoic blocks (plates, microplates, microcontinents, terranes): *SFCKA* São Francisco–Congo–Kasai–Angola, *PP* Paranapanema, *KAL* Kalahari, *RP* Rio de La Plata, *LA* Luis Alves. The maximum principal stress directions and tectonic escape are shown (Simplified and modified from Almeida et al. 2000)

The partitioning of deformation, common in tectonic limits, has already been reported in the Mantiqueira Province (Ebert and Hasui 1998; Hackspacher and Godoy 1999; Egydio-Silva et al. 2005 and others) and it is caused mainly by collision of the irregular continental margins, besides for processes of oblique convergence. The most of the natural orogens accommodates transpressional deformation, with orogen-parallel tectonic transport in response to oblique convergence (Jezek et al. 2002). In the

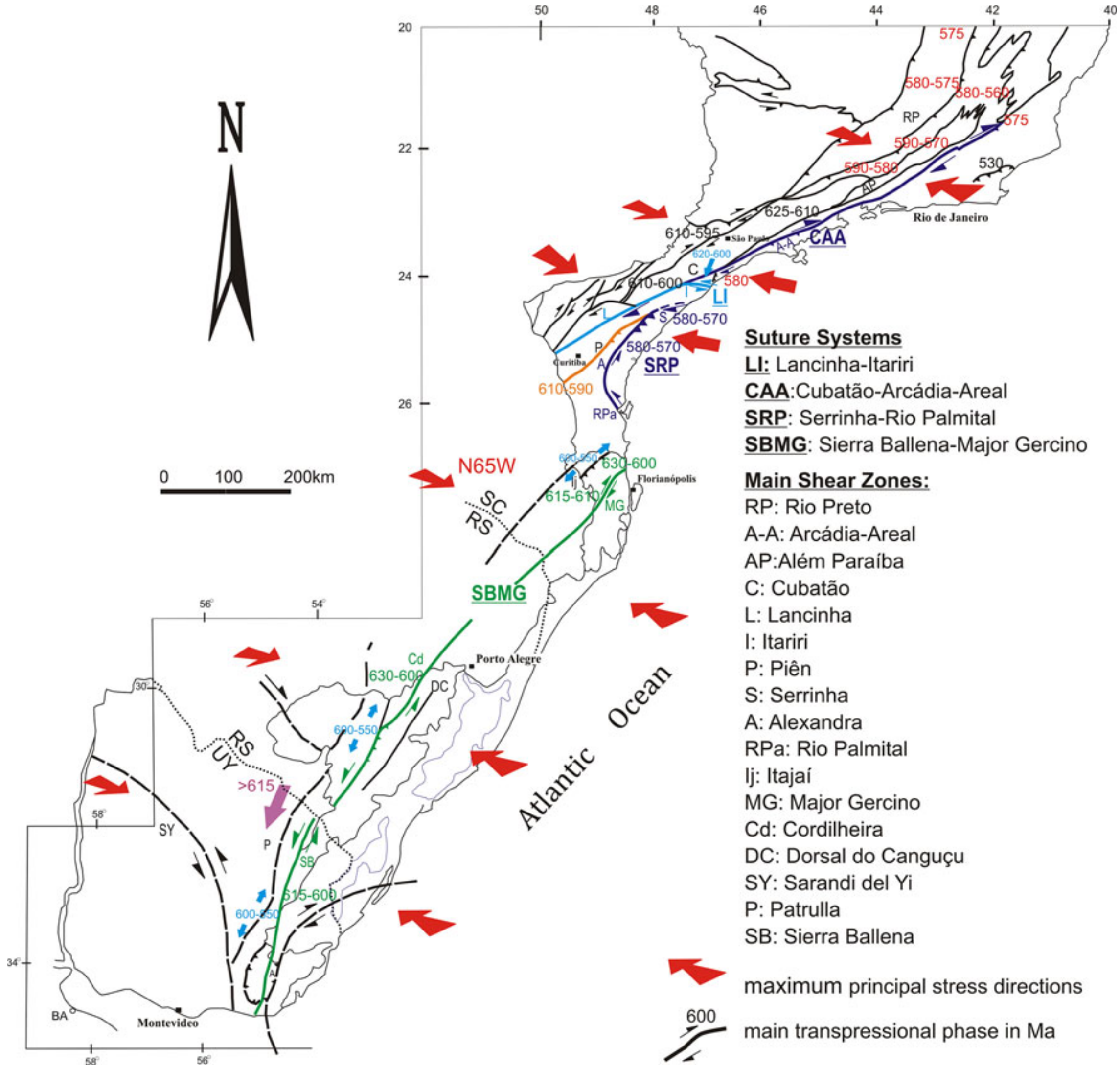

Fig. 11 General outline of the Mantiqueira Province (Brazil–Uruguay) showing the main shear zones with the main transpressional phase in Ma and the maximum compressional stress directions

transpressive shear zones (Harland 1971), the concept of strain partitioning is characterized into zones of simple shear deformation and domains of pure shear (Tikoff and Teyssier 1994).

In Fig. 11, the principal compression directions of the transpressional systems are represented (Egydio-Silva and Mainprice 1999; Hackspacher and Godoy 1999; Campanha and Brito Neves 2004; Faleiros and Campanha 2004; Hippertt et al. 2001; Oyhantçabal et al. 2009a, b, Passarelli et al. 2004b), as well as the ages of these processes. The syn-collisional and transpressional phase is older in the Dom Feliciano Belt when compared to that of the Ribeira Belt, confirming the diachronic character of the evolution of these orogenic belts, as brought into attention by several authors (Brito Neves and Cordani 1991; Brito Neves et al. 1999; Almeida et al. 2000).

In the Dom Feliciano Belt, the transpressional event in the Major Gercino – Sierra Ballena System occurred between approximately 630 and 600 Ma (Babinski et al. 1996; Basei et al. 2000; Bitencourt and Nardi 2000; Philipp et al. 2003; Chemale et al. 2003; Oyhantçabal et al. 2009a, 2009b; Passarelli et al. 2010), with a reasonable concentration of syn-kinematic granitic activity at *ca*. 615 Ma. Older granitic magmatism (*ca*. 650-630 Ma) controlled by low-angle shear zones is recorded locally in the Porto Belo region in Santa Catarina (Bitencourt and Nardi 2000; Chemale et al. 2003) and in the Quitéria Granite (Rio Grande do Sul), which could record the beginning of the transpressional phase (Frantz et al. 2003) of this shear system in Rio Grande do Sul. The N65W-trending principal compressional component led to dextral and sinistral movements in this shear system in association with a strong coaxial component. Therefore, the Sierra Ballena Shear Zone sinistral and the Major Gercino Shear Zone dextral movements were generated simultaneously, as a local response, as a function of the attitude of these lineaments in relation to the principal compressional stress. This process is repeated in several lineaments, mainly those of the south-Brazilian portion. In Uruguay (Sierra Ballena Shear Zone), as in the Itariri Shear Zone, a *ca*. N20E-trending compressional component is recorded associated with movements prior to the main transpressional phase (Oyhantçabal et al. 2009a, b).

In the Ribeira Belt, the transpressional deformation was not simultaneous in the major shear zones. In its northern and central portion, the interval between 590 and 560 Ma is defined by U–Pb dating of titanite and monazite for the WNW thrust and zircon U–Pb dating of syn-kinematic granites (Heilbron et al. 1995; Machado et al. 1996; Heilbron and Machado 2003; Silva et al. 2003; Mendes et al. 2006; Vauchez et al. 2007), with high concentration between 580 and 570 Ma. This period is associated with the juxtaposition of the Andrelândia, Juiz de Fora and Paraíba do Sul terranes (Figs. 1, 11) to the SE border of the São Francisco Craton.

In the central-southern portion of the Ribeira Belt, north of the Cubatão-Arcádia-Areal suture zone, the transpressional phase defined mainly by the generation of compressive tectonic-associated granites occurred between *ca*. 625 and 595 Ma (Ebert et al. 1996; Hackspacher and Godoy 1999; Hackspacher et al. 2004b; Passarelli et al. 2004a, 2008), with a conspicuous peak at *ca*. 610 Ma. This period is associated with the juxtaposition of the Socorro-Guaxupé Nappe, the Apiaí and Embu Terranes and the Curitiba Microplate (Figs. 1, 11) to the eastern border of the Paranapanema Craton. A N20E–N40E principal compression was responsible for the sinistral movement of the Itariri Shear Zone during the juxtaposition of the Embu and Curitiba/Registro terranes (Passarelli et al. 2004b) in a period that must be better defined (between 620 and 600 Ma). The relationship between this compressional movement and the general compression between E–W and N65W, observed in practically all the Ribeira Belt, needs to be further investigated. This previous NE compressional direction is recorded only in the Sierra Ballena Shear Zone in Uruguay (Oyhantçabal et al. 2009a, b). South of the Cubatão Shear Zone, the transpressional phase resulting from the collision between the Luis Alves and Curitiba microplates was probably concomitant with the period reported above, having as lower limit the age of the Piên magmatic arc and post-tectonic granites, between 610 and 590 Ma (Harara et al. 1997; Basei et al. 2000).

The juxtaposition of the Coastal terrane to the other terranes was later, between 580 and 570 Ma (Heilbron et al. 1995; Machado et al. 1996, Pedrosa-Soares and Wiedmann-Leonardos 2000; Passarelli 2001; Passarelli et al. 2004a, b, 2008) through the Cubatão-Arcádia-Areal Suture Zone in the northern portion and the Serrinha-Rio Palmital Suture Zone in the southern portion. This juxtaposition reactivated the Lancinha-Itariri suture, leading to a sinistral movement in the Itariri ramification (E–W) and a dextral movement in the Lancinha-Cubatão ramification (N60E). Along with this compressional movement, a tectonic wedge was formed, limited by the transcurrent to transpressional faulting, with micro-thrusting verging westwards inside the Mongaguá Terrane (Figs. 1, 11). The Serrinha-Rio Palmital Shear System in the northern portion developed through a frontal ramp varying to oblique and lateral ramps of dextral movement, under amphibolite facies metamorphic conditions (Passarelli et al. 2007). In its southern portion the Palmital and Alexandra, transcurrent shear zones are characterized by sinistral kinematics with oblique component marked by coexisting strike-slip and down-dip lineations (Cury et al. 2008).

Additionally, from the compilation of all geochronological data obtained by the U–Pb, K–Ar/Ar–Ar methods applied to minerals and fine fractions and fission-track dating of apatites and respective closure temperatures, a slow cooling and uplift of the terranes is suggested by the biotite K–Ar ages. The K–Ar results for the fine fractions indicate latter brittle reactivation of the shear zones in Devonian times, possibly associated with the stabilization phase with low exhumation of tectonic blocks of the Mantiqueira Province, and in the Triassic times, reflecting the initial removal of heat from beneath Pangea and the beginning of fragmentation of Gondwana.

The diachronism regarding the Mantiqueira Province Shear Zones is associated with distinct pulses of approximation of the São Francisco–Congo, Kalahari and Rio de la Plata cratons and minor continental fragments that occurred along a period of *ca*. 60 Ma, from the initial collision phase until the lateral escape phase predominantly defined by the major transcurrent shear zones.

Conclusions

Continental collisions are processes closely related to the formation of supercontinents. The main mechanisms that accommodate crustal shortening are subduction, thrusting and folding, as well as lateral mass transport (Molnar and Tapponnier 1975; Tapponnier et al.1982; Peltzer and Tapponnier 1988; Aitchison and Davis 2004). Most part of the plate limits presents a markedly oblique relative velocity vector at the borders, and the accommodation of these oblique movements usually involves types of plate-boundary related strike-slip faults with very characteristic kinematic roles in the convergent plate limits (Woodcock

1986). In a continental collision process, the variation in the tectonic regime (thrust tectonics and transcurrent tectonics), as well as the sense of shear of the transcurrent/transpressional zones, reflects the kinematics accommodation, where the perimeter and shape of the rigid blocks play an important role, as can be observed along the whole Mantiqueira Province.

The Ribeira and Dom Feliciano orogens, respectively, central and southern segments of the Mantiqueira Province, evolved during the formation of Western Gondwana in Neoproterozoic Brasiliano/Panafrican orogenic cycle. These old orogens resulted from the closing of the Adamastor Ocean caused by the convergence of cratons, microplates and minor terranes.

In the Ribeira and Dom Feliciano belts, the tectonic escape regime took place by means of extensive NE-trending ductile transpressive shear zones, juxtaposing different crustal levels parallel to the craton limits (Dantas et al. 2000; Hackspacher et al. 2004b).

In the central and southern Ribeira Belt, the escape tectonics took place at ca. 580 Ma (Hackspacher and Godoy 1999; Silva et al. 2005a, b) where dextral orogen-parallel wrench faulting dominated (Vauchez et al. 2007). These wrench faulting favoured the formation of NE-trending pull-apart basins (Jacobs and Thomas 2004) that were filled by continental sediments.

The escape-related shear zones are exposed for *ca.* 3,000 km along predominantly dextral transpressional zones in its northern portion and dextral and sinistral transpressional zones in its southern portion. The kinematics of the major shear zones detailed here, with concavity mainly toward ESE, led to simultaneous movements of opposite directions at their terminations (sinistral to the south and dextral to the north), resulting from collisions between microplates and cratons through a predominantly westward continuous compression. North of the Itariri Shear Zone there is regularity in the dextral movement of the shear zones.

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