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ARTICLE

Superposition of structures in the interference zone between the southern Brasília belt and the central Ribeira belt in the region SW of Itajubá (MG), SE Brazil

Superposição de estruturas na Zona de Interferência entre as faixas Brasília Meridional e Ribeira Central na região SW de Itajubá (MG), SE do Brasil

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ABSTRACT: The study area is localized in the Socorro nappe, part of the southern Brasília belt, with a minor part in the Embu terrane, part of the central Ribeira belt. Three phases of deformation were detected, Dn-1, Dn and Dn+1. Sn-1 seems to be generally transposed into Sn, but in the northwestern part it is well preserved, dipping about 60º to W and SW, with a stretching and/or mineral lineation plunging down dip. The main foliation in most of the area is Sn, dipping about 70º to SSE. Dn folds are tight to isoclinal, with axes that plunge about 40º to SW. Quartz-feldspathic segregation veins are folded by Dn. The structures related to Dn-1 and Dn are cut and modified by four important shear zones ascribed to deformation phase Dn+1. Two samples of a granite that is elongated along the Caxambu shear zone, and also cut by it, were dated. One yielded a crystallization age of 575 ± 5 Ma, and the other one, from the shear zone, an age of 567 ± 8 Ma, interpreted either as representing the age of movement along the Caxambu shear zone, or as metamorphic growth.

KEYWORDS: structural geology; geochronology; Socorro-Guaxupé nappe; Embu terrane.

RESUMO: *A área de estudo está localizada na nappe Socorro, faixa Brasília Meridional, e no terreno Embu, faixa Ribeira central. Foram detectadas três fases de deformação, Dn-1, Dn e Dn+1. Na maior parte da área estudada, Sn-1 só ocorre preservado em charneiras de dobras, estando geralmente transposto por Sn. No entanto, na parte noroeste, Sn-1 está bem preservado e representa a foliação principal que mergulha cerca de 60º para W e SW. Associadas a essa foliação, ocorrem localmente lineações de estiramento/mineral down dip. A foliação principal na maior parte da área é Sn. Ela mergulha cerca de 70º para SSE e raramente para NW. As dobras Dn variam de apertadas a isoclinais com eixos que mergulham cerca de 40º para SW. Veios de segregação quartzo-feldspáticos são dobrados por Dn. As estruturas relacionadas à Dn-1 e Dn são afetadas por quatro zonas de cisalhamento atribuídas à fase deformacional Dn+1, zonas de cisalhamento São Bento do Sapucaí, Caxambu, Campos do Jordão e Buquira. Duas amostras de um corpo granítico alongado e em parte afetado pela zona de cisalhamento Caxambu foram datadas. Uma rendeu a idade de cristalização de 575 ± 5 Ma, e a outra, retirada de uma parte do granito afetada pela zona de cisalhamento, idade de 567 ± 8 Ma, interpretada como a idade do cisalhamento, ou como o crescimento metamórfico tardio relacionado à Dn.*

PALAVRAS-CHAVE: *geologia estrutural; geocronologia; nappe Socorro-Guaxupé; terreno Embu.*

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INTRODUCTION

In southeast Brazil, the Brasília belt runs roughly NW to SE. It is the result of the convergence and final collision of the Paranapanema and São Francisco cratons during the late Neoproterozoic (Campos Neto & Caby 2000, Trouw *et al.* 2000, 2013, Vinagre *et al.* 2014a) (Fig. 1). An interference zone occurs along the contact of the southern Brasília belt with the central part of the Ribeira belt, which was produced by the collision of the São Francisco paleocontinent with the Rio Negro Magmatic arc (Heilbron *et al.* 2004, 2008, 2013).

This interference zone has been systematically investigated from the lithological, structural and geochronological points of view (Trouw *et al.* 2000, 2013, Peternel *et al.* 2005, Campos Neto *et al.* 2011). In the region focused in this article, the interference zone is recorded in two major geotectonic units, where both structures and metamorphism are

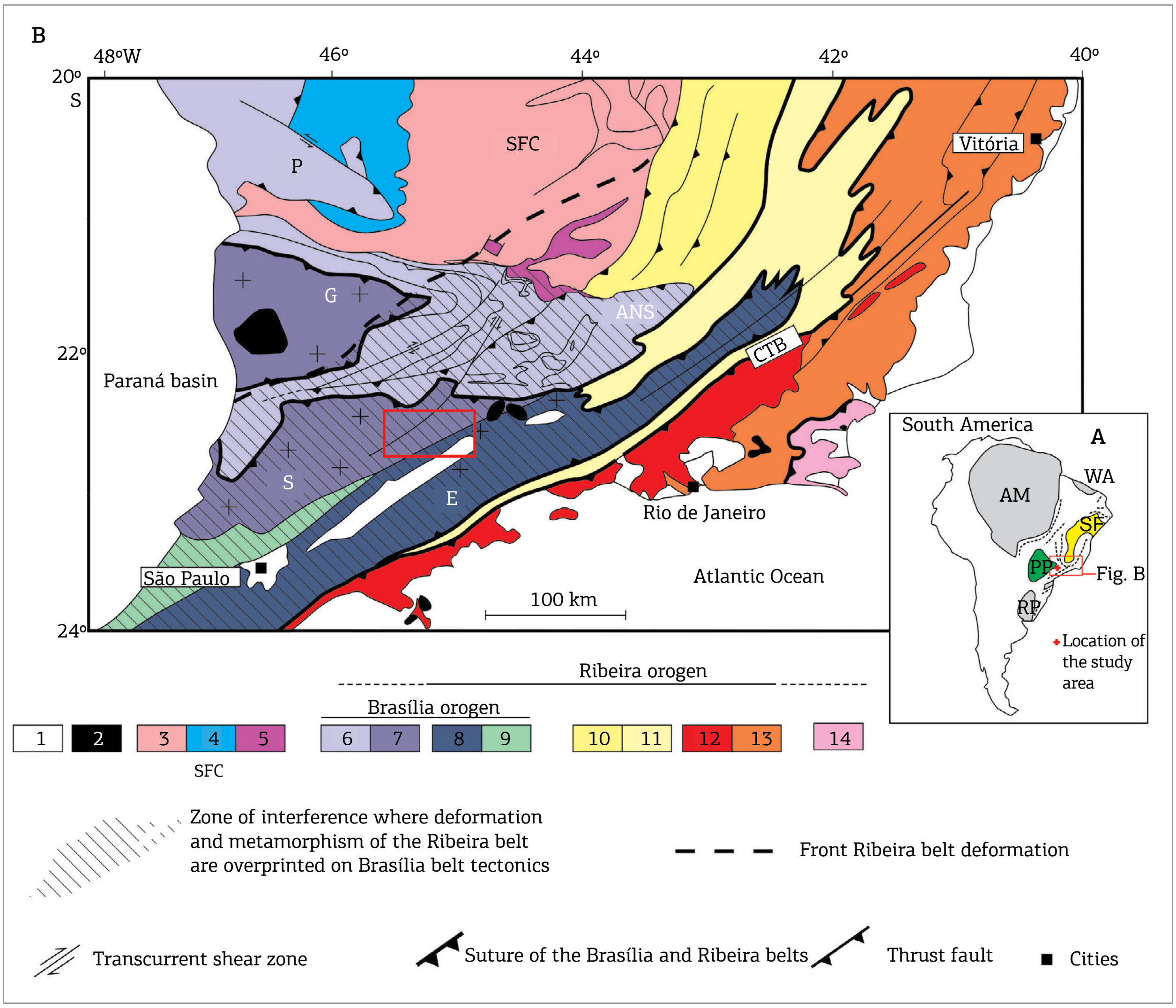

Figure 1. (A) Tectonic setting within South America: PP) Paranapanema craton; SF) São Francisco craton; AM) Amazonas craton; RP) Rio da Prata craton; WA) West African Craton. The red square marks the outline of Fig 1B. (B) Simplified tectonic map of the region after Trouw *et al.* (2013). The red rectangle marks the studied area. 1) Cenozoic basins; 2) alkaline intrusives of Cretaceous to Cenozoic age; São Francisco Craton and foreland (3–5); 3 basement; 4) (meta)sedimentary cover (Bambuí Group); 5 allochthonous and para-autochthonous metasedimentary rocks; Brasília orogen (6-9); 6) Andrelândia nappe system (ANS) and Passos nappe (P); 7) Socorro (S)-Guaxupé (G) nappe; 8) Embu (E)–Paraíba do Sul (PS) terrane; 9) Apiaí terrane; Ribeira orogen (10–14); 10 external domain; 11) Juiz de Fora domain; 12) Rio Negro arc (Oriental terrane); 13) Occidental terrane; 14) Cabo Frio terrane. The zone of superposition between the southern Brasília and the central Ribeira orogens is marked by the shaded area limited to the north by a traced line that marks the front of the Ribeira orogen.

superposed: the Socorro-Guaxupé nappe, integrating the southern Brasília belt (Campos Neto 2000, Campos Neto *et al.* 2004, 2007, 2011) and the Embu terrane (Hasui 1975, Heilbron *et al.* 2004, 2008), part of the central Ribeira belt (Fig. 1). The contact between these units was interpreted as a major shear zone — the Buquira-Jundiovira shear zone — separating the two belts (Campos Neto & Caby 1999, 2000, Campos Neto *et al.* 2011). An alternate interpretation considers the contact between the units as gradational, with the shear zone of only minor importance (Trouw *et al.* 2013, Vinagre *et al.* 2014a). According to this interpretation, both units are part of the Paranapanema block (Mantovani & Brito Neves 2005), considered as the upper plate of the collision that led to the construction of the southern Brasília belt, in the time span of 630 to 605 Ma (Campos Neto & Caby 1999, 2000, Trouw *et al.* 2000). The superposition of structures and metamorphism related to collision in the central Ribeira belt, also affecting both units, took place shortly afterwards between 590 and 560 Ma (Heilbron *et al.* 2004, 2008).

The aims of this paper are to describe the structures related to these two collisions in the region considered to present geochronological data, which constrain the age of some of these structures, and to discuss their meaning in the geotectonic evolution.

GEOLOGICAL CONTEXT

Along the southwestern border of the São Francisco craton, the Ediacaran southern Brasília belt is characterized by a thick pile of nappes, the Andrelândia nappe system (ANS) (Campos Neto 2000), composed of metasedimentary rocks of the Neoproterozoic Andrelândia megasequence (Paciullo *et al.* 2000), interleaved with slices of Paleoproterozoic to Archean basement orthogneisses (Fig. 1). The sense of shear varies in southward direction from top to SE, to E, and finally to NE (Trouw *et al.* 2000, Valeriano *et al.* 2004, 2008). The system was thrust onto the underlying São Francisco craton with parautochthonous metasedimentary rocks along the contact. The metamorphism grades from low-greenschist facies on the craton margin to high-pressure granulite facies in the uppermost nappe of the system (Ribeiro *et al.* 1995).

On top of the ANS lies the Socorro-Guaxupé nappe, interpreted as the active margin of the Paranapanema paleocontinent, mainly composed of deformed igneous rocks, described as the root of a magmatic arc (Campos Neto & Caby 1999, 2000, Trouw *et al.* 2000, 2013, Vinagre *et al.* 2014a). The metamorphism in the Socorro-Guaxupe nappe decreases from high- to medium-pressure granulite facies along its lower contact to medium pressure low amphibolite facies in the upper part. At the base of the nappe, pressures in the order of 12 kbar and temperatures of about 850ºC were obtained by Del Lama *et al.* (2000) and Campos Neto & Caby (2000). In the main body of the nappe, pressures of about 7 kbar and temperatures up to 900ºC were reported (Oliveira & Ruberti 1979, Vasconcellos *et al.* 1991, Negri 2002, Campos Neto *etal.* 2004, 2011, Negri & Oliveira 2005).

The southern part of the Brasília belt is interpreted as the result of a major continental collision between the Paranapanema paleocontinent (upper plate) and the São Francisco paleocontinent (lower plate), in the time span 630–605 Ma (Campos Neto *et al.* 2004, 2007, 201 1, Valeriano *et al.* 2004, 2008, Trouw *et al.* 2000, 2013). According to Trouw *et al.* (2013), the suture of this collision would be located along the contact of the ANS and the Socorro-Guaxupé nappe, or below the system, according to Campos Neto *et al.* (2011).

The ENE–WSW trending central Ribeira belt apparently truncates the southern Brasília belt at high angles (Fig. 1). It is also a collisional belt with its suture defined as the central tectonic boundary (Almeida *et al.* 1998, Almeida 2000), reactivated as a subvertical transcurrent dextral shear zone (Fig. 1). South of this shear zone, the Rio Negro magmatic arc (part of the Oriental terrane of Heilbron *et al.* 2004, 20 08, 2013) crops out (Tupinambá *et al.* 2012, Heilbron *et al.* 2004, 2008, 2013), representing the upper plate, whereas to the north of it, the lower plate is sliced up in several tectonic domains (the Occidental terrane), including the Embu terrane, with structures indicative of thrusting toward N and NW. The age of this collision is estimated at 590–560 Ma (Heilbron & Machado 2003, Heilbron *et al.* 2004, 2008).

An elongated zone along the contact of the two belts (Fig. 1) is interpreted as the zone of interference or superposition (Trouw *et al.* 2000, 2013, Peternel*et al.* 2005, Zuquim *et al.* 2011), where metamorphism and structures related to both belts can be recognized.

Socorro-Guaxupé Nappe

This nappe is composed of two lobes, the Guaxupé lobe in the north, and the Socorro lobe in the south, separated by an antiformal structure of the underlying ANS (Fig. 1). To the west, both lobes are covered by the Phanerozoic rocks of the Parana Basin. The nappe is essentially composed of metagranitoids, varying from mafic to felsic, with a large proportion of intermediate compositions (Campos Neto 2000), intrusive in ortho and paragneisses. The ages of these granitoids are mainly confined in the time span of 690–625, and, based on their chemical composition, they were interpreted as the root of a magmatic arc (Campos Neto & Caby 1999, 2000, Cam pos Neto *et al.* 2004, 2007, 2011, Trouw *et al.* 2000, 2013, Hackspacher *et al.* 2003, Vinagre *et al.* 2014a, 2014b) installed in the active margin of the Paranapanema paleocontinent and preceding the collision that led to formation of the southern Brasília belt. The metamorphism decreases both in temperature and pressure from bottom to top in the nappe, from granulite facies in the lower part to lower amphibolite facies in the upper part (Trouw *et al.* 2013).

The Guaxupé lobe contains a weak to strong metamorphic foliation describing a shallow synform, typical of a nappe, with subvertical E-W striking axial plane and axis plunging about ten degrees to the west. In the Socorro lobe, the foliation dips steeply to S and SE, and a possible former nappe structure can only be inferred. Few penetrative stretching lineations, recognized in the Guaxupé lobe, plunge to SW, W or NW, consistent with the well defined nappe transport to the E in the underlying ANS, varying from ESE in the Passos nappe, to the north, to E in the central part of the ANS, to NE in the southern part of the ANS (Trouw *et al.* 1984, Peternel *et al.* 2005). The main structure in the Socorro lobe is a moderate to steep SE dipping foliation, locally accompanied by a down dip or oblique stretching lineation, with shear sense indicators showing reverse shear with a dextral component. The intensity of the foliation and the lineation increases along well defined map scale shear zones, with mylonites reaching thicknesses of up to a few kilometers. These shear zones tend to evolve from oblique reverse movement with a dextral component to transcurrent, subvertical dextral shear zones with ENE-WSW trend (Almeida *et al.* 1981, Campanha 1981, Campos Neto & Caby 2000, Campos Neto 2000, Heilbron *et al.* 2004, Almeida 2000, Morales *et al.* 2005, Trouw *et al.* 2013).

Embu Complex

A NE-SW elongated lens (Fig. 1), bounded by major shear zones, was originally defined as the Embu complex (Hasui 1975). Later the terrane nomenclature was adopted for this lens, which contains mainly metasedimentary rocks, few orthoderived basement lenses and various granitic intrusions (Janasi *et al.* 2003). To the north, the complex is separated from the Socorro-Guaxupé nappe by the Caucaia-Rio Jaguari-Buquira shear zones. To the south, the Cubatão shear zone forms the limit between this complex and the adjacent Oriental terrane (Heilbron *et al.* 2004). The arguments to justify the terrane nomenclature (Janasi & Ulbrich 1991, Janasi *et al.* 2003) were the contrasting metasedimentary composition — with respect to the Socorro-Guaxupé nappe —, the peraluminous character of most of the granitic intrusions, in contrast to the metaluminous composition of most of the granitoids in the nappe, the presence of basement in the terrane, and reported igneous and metamorphic ages of about 790 Ma (Vlach 2001, Cordani *et al.* 2002), discrepant from ages in the adjacent terranes or nappes.

The metasedimentary rocks are mainly biotite schists locally with garnet, sillimanite and/or staurolite, and biotite gneisses, with quartzite, calcsilicate and few marble intercalations (Fernandes *et al.* 1990). Some amphibolites and ultramafic lenses are also present. A Paleoproterozoic orthoderived basement occurs locally as mappable lenses, and more or less deformed granitic intrusions with ages concentrated around 590 Ma are common (Janasi *et al.* 2003, Heilbron *et al.* 2004, 2008, Alves *et al.* 2013).

A recent reinterpretation (Trouw *et al.* 2013) questions the importance of the Jaguari-Buquira shear zone as a terrane boundary and advocates a more gradual transition between the Socorro-Guaxupé nappe and the Embu complex, calling attention to the presence of arc-related metaluminous batholiths in the complex. In this interpretation, the complex would be an extension of the Socorro-Guaxupé nappe and hence, tectonically related to the collision of the southern Brasília belt, including it in the zone of interference.

STRUCTURES OF THE STUDIED AREA

The study area is located mostly in the Socorro nappe, with a minor part in the Embu complex. It is essentially composed of amphibolite facies metasedimentary rocks, schists and gneisses, apart from metagranitoids. Although subdivided in two geotectonic units — the Socorro-Guaxupé nappe and the Embu terrane (Figs. 1, 2 and 3) —, the structures are not different in both units. Two sedimentary basins are also present in the area, one, filled with the Pico do Itapeva formation (Teixeira *et al.* 2004), is late synorogenic, with rocks showing a well developed cleavage, verticalized bedding and low grade metamorphism, and the other one, the Taubaté basin, is not deformed and Cenozoic in age.

The observed structures are foliations, lineations, folds and mylonitic shear zones. On the basis of the superposition criteria (Ramsay 1967), they can be subdivided in three groups ascribed to three broad deformation phases, labeled Dn-1, Dn and Dn+1.

The main foliation in the area, Sn, dips moderately to steeply to the SSE and is ascribed to Dn. It is locally parallel to the axial plane of tight to isoclinal folds that fold an earlier foliation, Sn-1, formed by Dn-1(Fig. 2). In other places, Sn is folded in open to gentle folds ascribed to Dn+1, with Sn+1 defined as axial planes, rarely developed as a new penetrative foliation. Shear zones locally cut Sn, developing a distinct mylonitic foliation, also labeled Sn+1. The gradual intensification of Sn to a mylonitic foliation, merging one into the other, is also present. Hence, either the shear zones were formed both during Dn and during Dn+1, or all shear

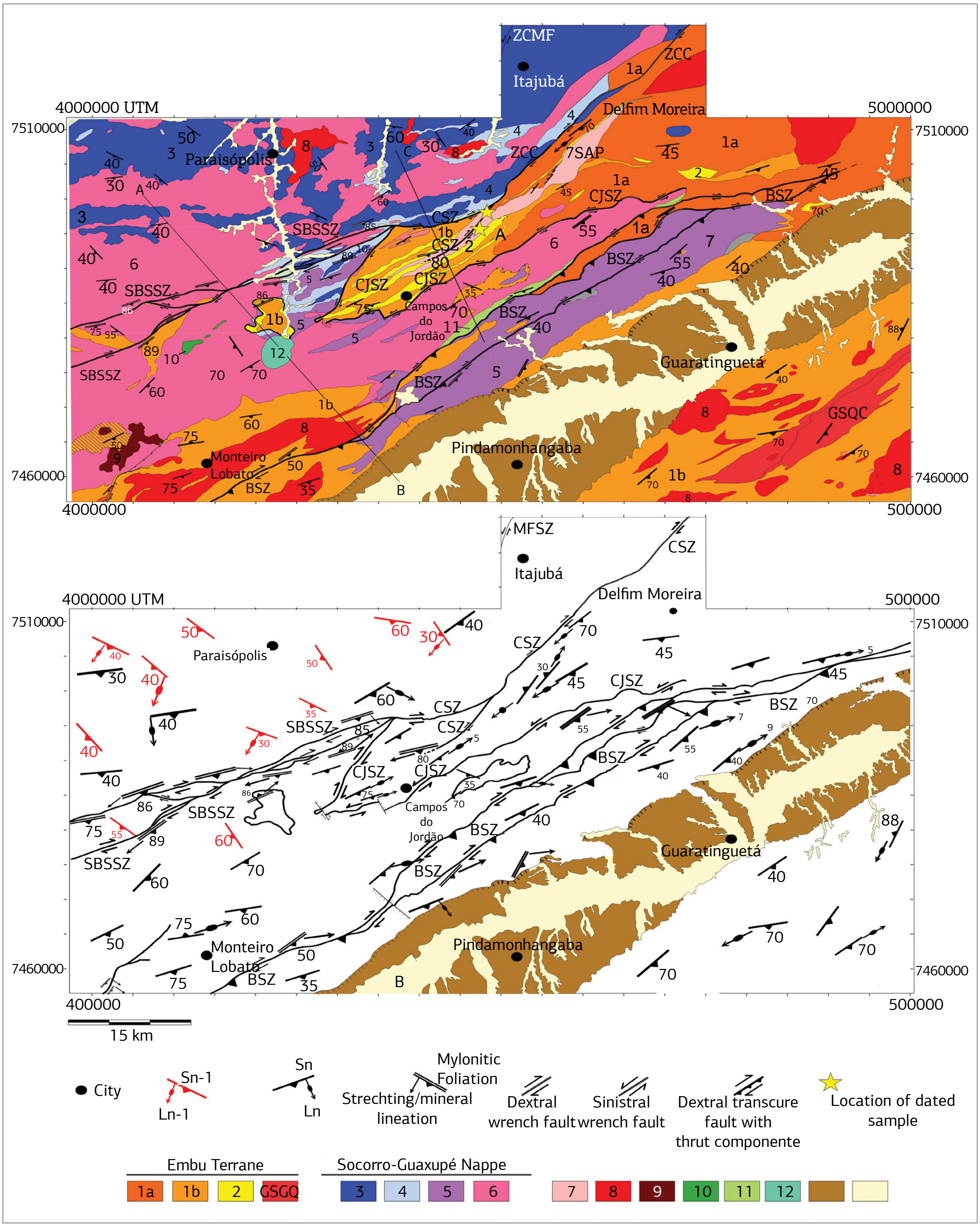

Figure 2. Geologic and structural map of the studied area: 1a) gneiss of the Embu terrane, containing cordierite where marked with oblique stripes; 1b) schist of the Embu terrane; 2) quartzite of the Embu terrane; 3) SQCG: Serra do Quebra Cangalha granite; 4) Ortho- and paraderived gneisses of the Socorro nappe; 5) schist and paragneiss with sillimanite and garnet of the Socorro nappe; 6) ortho and paragneisses of the Pedra do Baú complex; 7) Serra da Água Limpa batholith; 8) SAP: Serra do Alto da Pedra granite (S-type); 9) undifferentiated granites; 10) São Francisco Xavier charnoquite; 11) isotropic norite; 12) Pico do Itapeva formation; 13) Ponte Nova alkaline plug (Cretaceous); 14) Taubaté basin (Cenozoic); 15) quaternary deposits; yellow stars, U-Pb age dating in zircon; SBSSZ: São Bento do Sapucaí shear zone; BSZ: Buquira shear zone; CJSZ: Campos do Jordão shear zone; CSZ: Caxambu shear zone; MFSZ: Maria da Fé shear zone.

zones were formed during Dn+1, but some were generated locally on the preexisting Sn foliation.

Dn-1

In most parts of the area, Sn-1 is only preserved in fold hinges and seems to be generally transposed into Sn. However, in the northwestern part of the area, the main foliation is dipping about 60º to W, SW (average 210/33) (Fig. 4A), consistent with the probable original attitude of the Socorro-Guaxupé nappe, now better preserved in the Guaxupé lobe. This foliation is interpreted as a remnant of Sn-1 that escaped from transposition by Dn. At several places, a stretching and/or mineral lineation is present on the Sn-1 plane, plunging about down dip (224/32) (Fig. 4B). Although no reliable shear sense indicators were detected in these structures, the orientation is consistent with top to the northeast movement, as was well established in the underlying ANS (Trouw *et al.* 2000). Physically, Sn-1 is defined by the preferred orientation of micas, sillimanite and quartzo-feldspathic segregations, probably related to local anatexis (Fig. 5A). Especially in more micaceous lithotypes, the Sn-1 foliation is often well preserved in fold hinges, visible both in outcrop (Fig. 5B) and in thin sections (Figs. 5C and 5D).

Dn

As already stated, the main foliation in most of the area is Sn. It dips about 70º to SSE (calculated average attitude 145/69) and rarely to NW (Fig. 4C). Depending on the lithotype, the foliation can be classified as continuous in schists and orthogneisses (Fig. 6A), or spaced in banded paragneisses. Where continuous, it is defined essentially by preferred orientation of tabular mica crystals (Figs. 6B and 6C). The spaced foliation is composed of micaceous domains separating up to millimetric quartzo-feldspathic microlithons (Fig. 6D).

Sn is parallel to the axial planes of Dn folds, folding Sn-1 that is apparently parallel to bedding (S0) and locally to quartzo-feldspathic segregation veins (Figs. 7A, 7B and 7C). Dn folds are tight to isoclinal, with axes that plunge about 40º to SW. They vary in size from millimeter to map scale.

Sn commonly contains a stretching or mineral lineation — Ln —, plunging down dip or oblique to SE to ESE (Fig. 7D). It may be defined by the preferred orientation of acicular sillimanite crystals in schists or by elongated quartz in quartzites or quartz veins. The average attitude is 120/57 (Fig. 4D).

The attitude of Sn and Ln is consistent with the interpretation that Dn represents a phase of NW–SE shortening, with vergence towards NW.

The cleavage present in metasediments of the Pico do Itapeva formation is parallel to Sn in its basement, dipping about 60º to SE or SSE. No vestiges of an older deformation were observed in this formation that is, therefore, interpreted as deposited between Dn-1 and Dn. Apparently, Dn tilted S0 to an upright position and generated a penetrative cleavage, Sn. The deformed conglomerates reveal an oblate deformation ellipsoid, compatible with NW–SE shortening during Dn.

Dn+1

The structures related to Dn-1 and Dn are cut and modified by four important shear zones at map scale within the area considered (Fig. 2), ascribed to deformation phase Dn+1. These shear zones are: the São Bento do Sapucaí shear zone (SBSSZ), the Caxambu shear zone (CSZ), the Campos do Jordão shear zone (CJSZ) and the Buquira shear zone (BSZ). They are described in detail ahead.

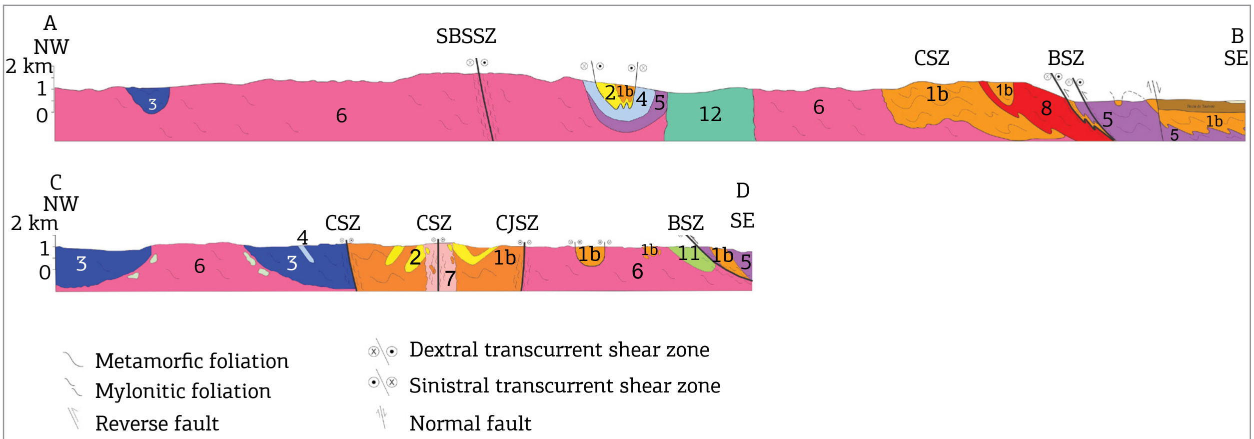

Figure 3. Geological sections as marked on Fig. 2, with the mapped units as on Fig. 2.

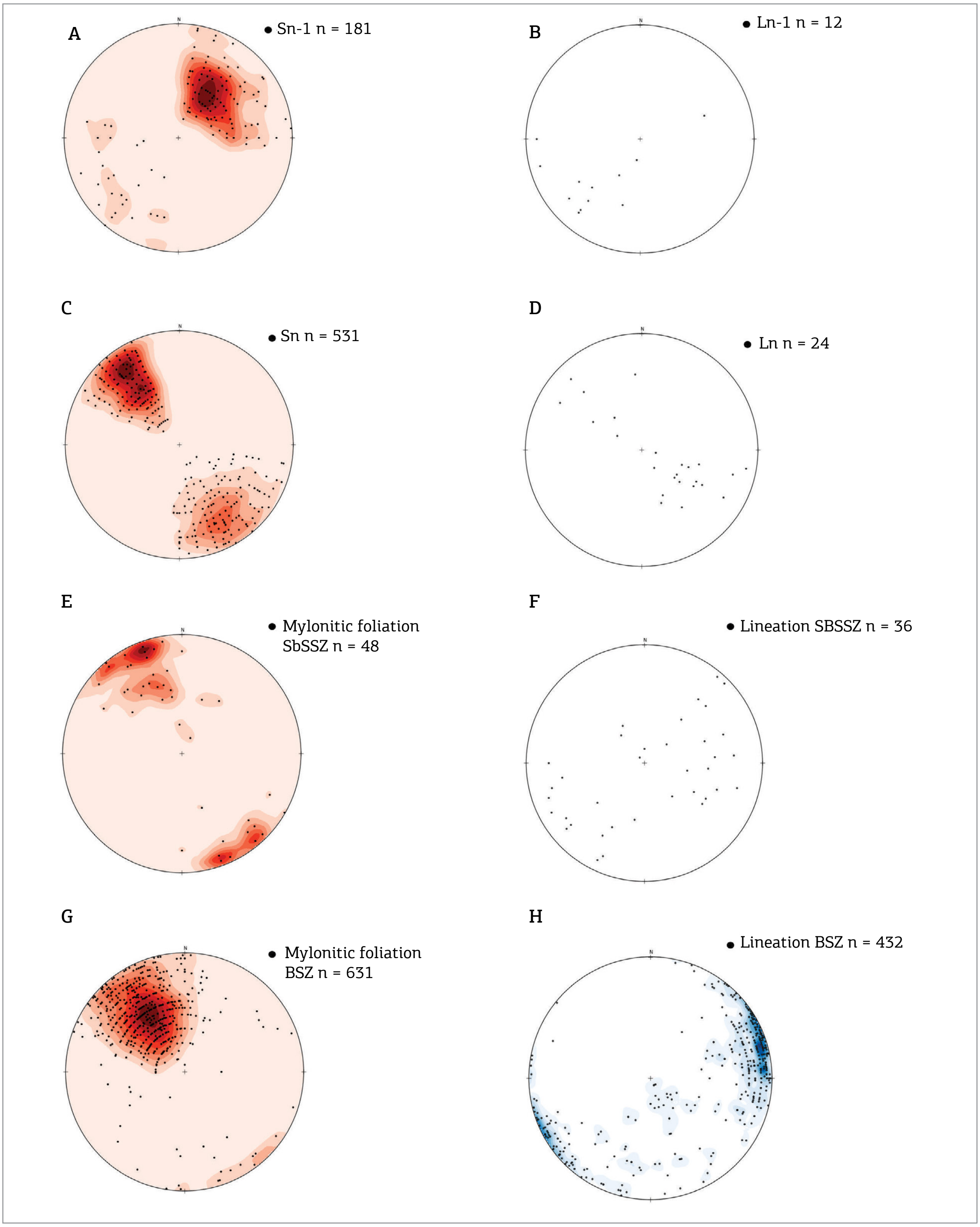

Figure 4. (A) Stereogram of poles to Sn-1 foliation, showing predominant dip to W/SW and a minor amount dipping E/NE (n = 181); B) stereogram showing attitude of Ln-1 lineations, plunging mainly to SW (n = 12); C) stereogram of poles to Sn foliation, showing a main concentration of dips to SE (n = 531); D) stereogram of stretching lineation Ln, plunging mainly to SE (n = 24); E) stereogram of poles to Sn+1 mylonitic foliation from the São Bento do Sapucaí shear zone (n = 48), showing a subvertical attitude varying to steep dips either to SE or to NW; F) stereogram of attitude of stretching lineation Ln+1 on the mylonitic foliation of the São Bento do Sapucaí shear zone (n=36); G) stereogram of poles to the mylonitic foliation, Sn+1, from the Buquira shear zone (n = 631), showing predominance of moderate dips to SE; H) stereogram of the attitudes of stretching lineation Ln+1 from the Buquira shear zone (n = 432).

São Bento do Sapucaí shear zone

This shear zone crops out in the northern part of the area (Fig. 2). It is an anastomosing shear zone with several duplications and branches; the strike is mainly ENE–WSW, varying locally to E–W and NE–SW. The zone is situated in the Socorro nappe (Fig. 2) and cuts mainly rocks of the Serra da Água Limpa batholith (Vinagre *et al.* 2014a, 2014b) and its host rocks. The thickness of the zone varies from few tens of meters to several hundreds of meters. Toward the NE, the shear zone merges into the Caxambu shear zone (Trouw *et al.* 2007).

The mylonitic foliation, Sn+1, either cuts the Sn foliation at a small angle, or shows a gradational transition toward it. The attitude is subvertical to steeply dipping to SE (average 158/83) (Fig. 4E). The mylonites have fine grained texture with ribbons of well recrystallized quartz, indicating medium temperature conditions (transition greenschist facies to amphibolite facies) during formation (Trouw *et al.* 2010).

A conspicuous stretching lineation on Sn+1 is well developed in most outcrops and plunges usually at low angles either to NE or SW (averages 65/14 and 230/14) (Fig. 4F), but higher values, up to 55° to SE, were also locally observed.

The orientation of the mylonitic foliation and lineation, together with several shear sense indicators (σ, δ, C'shear bands, asymmetric folds) (Fig. 8A and 8B), point to dextral transcurrent movement with a minor up-dip oblique component. The amount of lateral dislocation (slip) is hard to estimate, but the fact that the batholith crops out at both sides of the shear zone suggests that the slip is not more than a few kilometers.

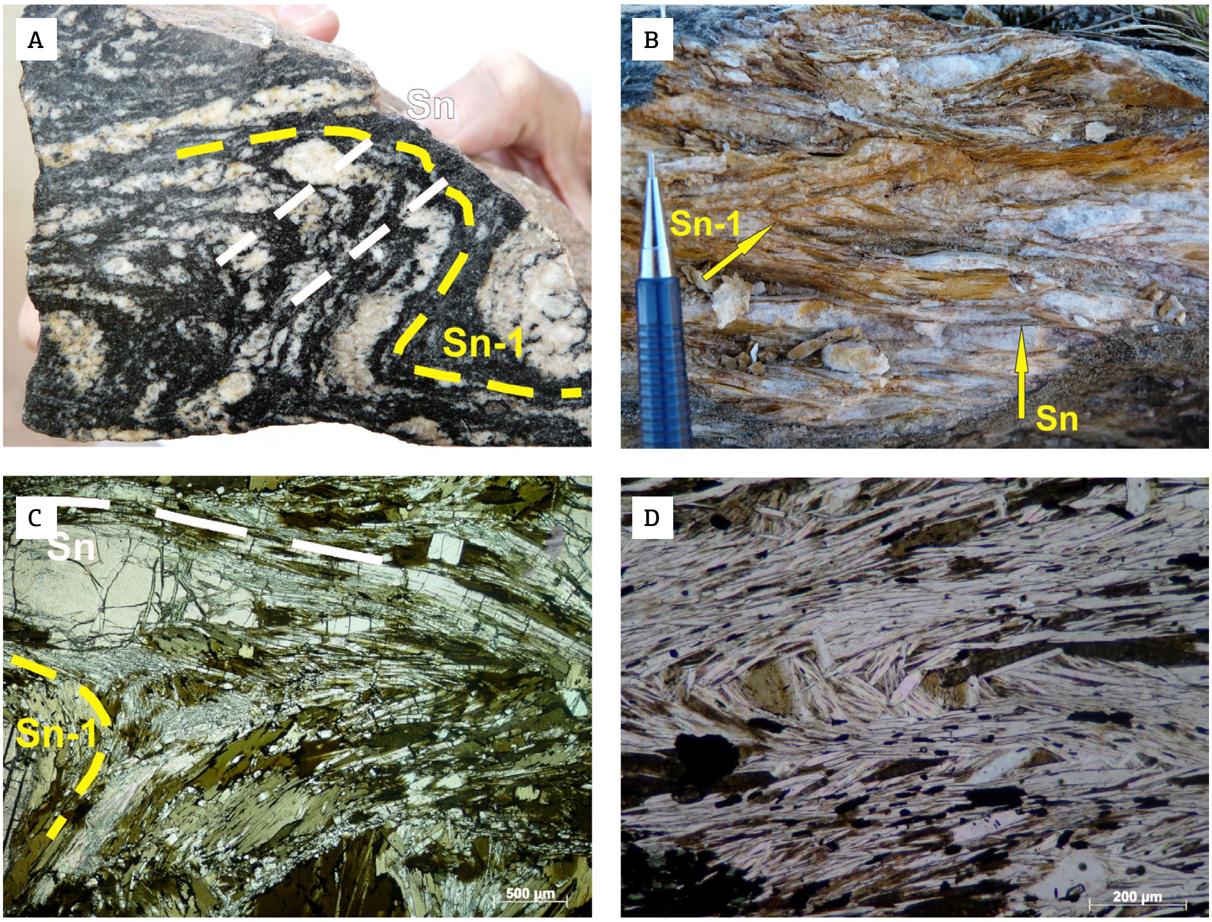

Figure 5. (A) Orthogneiss of Socorro nappe with leucosomatic (probably anatectic) veins parallel to foliation Sn-1, both folded by Dn, with Sn paralel to the axial plane; (B) outcrop of quartzite intercalated with schist (Embu terrane) showing Sn-1 tightly folded and partially transposed by Dn; (C) biotite sillimanite schist of Socorro nappe, showing Sn-1 tightly folded and partially transposed (note the polygonal arcs) by Dn with development of Sn (horizontal) along the axial plane; (D) schist of the Embu terrane with foliation Sn-1 preserved in tight fold hinges with polygonal arcs and partially transposed by Dn, with development of Sn (horizontal) along the axial plane.

Caxambu shear zone

This shear zone is located in the northeastern part of the area. It strikes NE–SW and continues to the NE, where it was studied in detail (Trouw *et al.* 2007). It is about 100 km-long and 2.5 km-wide, and it dies out some 40 km NE of the city of Caxambu. Toward the SW, it merges into the SBSSZ. The attitude of the mylonitic foliation is subvertical to steeply SE dipping. The mylonitic foliation contains microstructures indicative of medium grade temperatures during mylonitization, like the SBSSZ. A conspicuous stretching lineation plunges either shallowly to NE or to SW. Numerous kinematic indicators, like mica fish, oblique foliation, S-C-C' structure and asymmetric folds (Fig. 8C and 8D) (Trouw *et al.* 2007) show a dextral transcurrent movement with maximum dislocation estimated at about 20 km in the central part (Trouw *et al.* 2007).

This shear zone is of special interest in this paper, because constraints on its age were determined by geochronology as described ahead.

Campos do Jordão shear zone

Close to the city of Campos do Jordão, an indentation structure was recognized, where metasedimentary rocks of the Embu complex are indented into orthogneisses of the Socorro nappe (Fig. 2). This elongated NE-SW structure is about 34 km-long and 9 km-wide; it is surrounded by a steep mylonitic shear zone (CJSZ) with contrasting sense of shear, dextral on the NW side and sinistral on the SE side, compatible with the idea of indentation. In the frontal part, the mylonitic foliation dips steeply to NE with down-dip stretching lineations and shear sense indicators revealing reverse movement. Along the limbs of the indentation, the

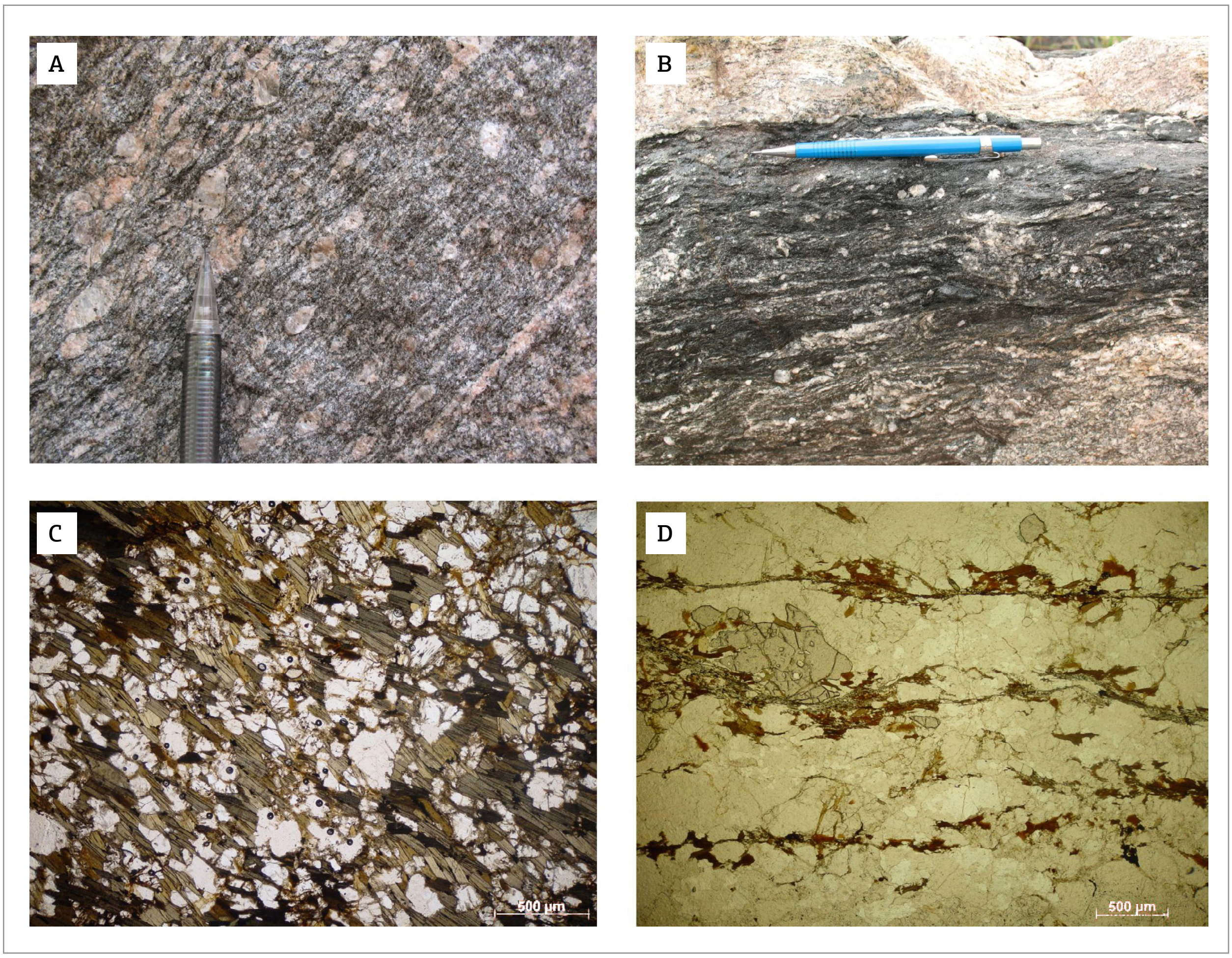

Figure 6. (A) Tectonic foliation Sn in the Serra da Água Limpa batholith; (B) foliation Sn in schist of the Embu terrane; (C) photomicrograph of continuous Sn in schist of the Socorro nappe; (D) photomicrograph of Sn in banded paragneiss of the Socorro nappe, defined by preferred orientation of biotite, quartz and feldspar. This foliation is spaced with intercalation of biotite-rich domains and quartz-feldspar-rich ones.

stretching lineation is sub-horizontal, and reliable shear sense indicators (Figs. 9A, 9B, 9C and 9D) confirm the contrasting sense of shear. The physical characteristics of the mylonitic foliation are similar to the ones described before for the SBSSZ and CSZ and the sense of movement of the indentation structure is top to the SW, compatible with the kinematic picture of Dn+1 (Fig. 10). An alternative interpretation of this structure is that it represents a nappe with a top-to-SW shear zone at its base that was folded into a synformal shape (similar to the pattern in section A-B, in Fig. 3) and modified by later shear.

Buquira shear zone

This shear zone is of particular interest because it is considered, in the literature (Campos Neto 2000, Campos Neto *et al.* 2004, 2007, 2011), as marking the limit between the southern Brasília belt and the central Ribeira belt. As such, it should be some kind of suture. Trouw *et al.* (2013) questioned this interpretation, mainly based on the map (Fig. 2) that shows lithotypes of the Embu terrane on both sides of the shear zone. In addition, detrital zircon from samples on either side of the shear zone show very similar age distribution patterns (Trouw *et al.* 2013, Duffles 2013, Duffles *et al.* 2016). These authors proposed that the transition between the Socorro nappe and the Embu terrane is gradational and that the terrane is part of the same upper plate (Paranapanema) as the Socorro nappe.

The shear zone, in the area considered here (Fig. 2), has similar characteristics, as the ones already described. It is also anastomosing with various branches, NE–SW oriented and

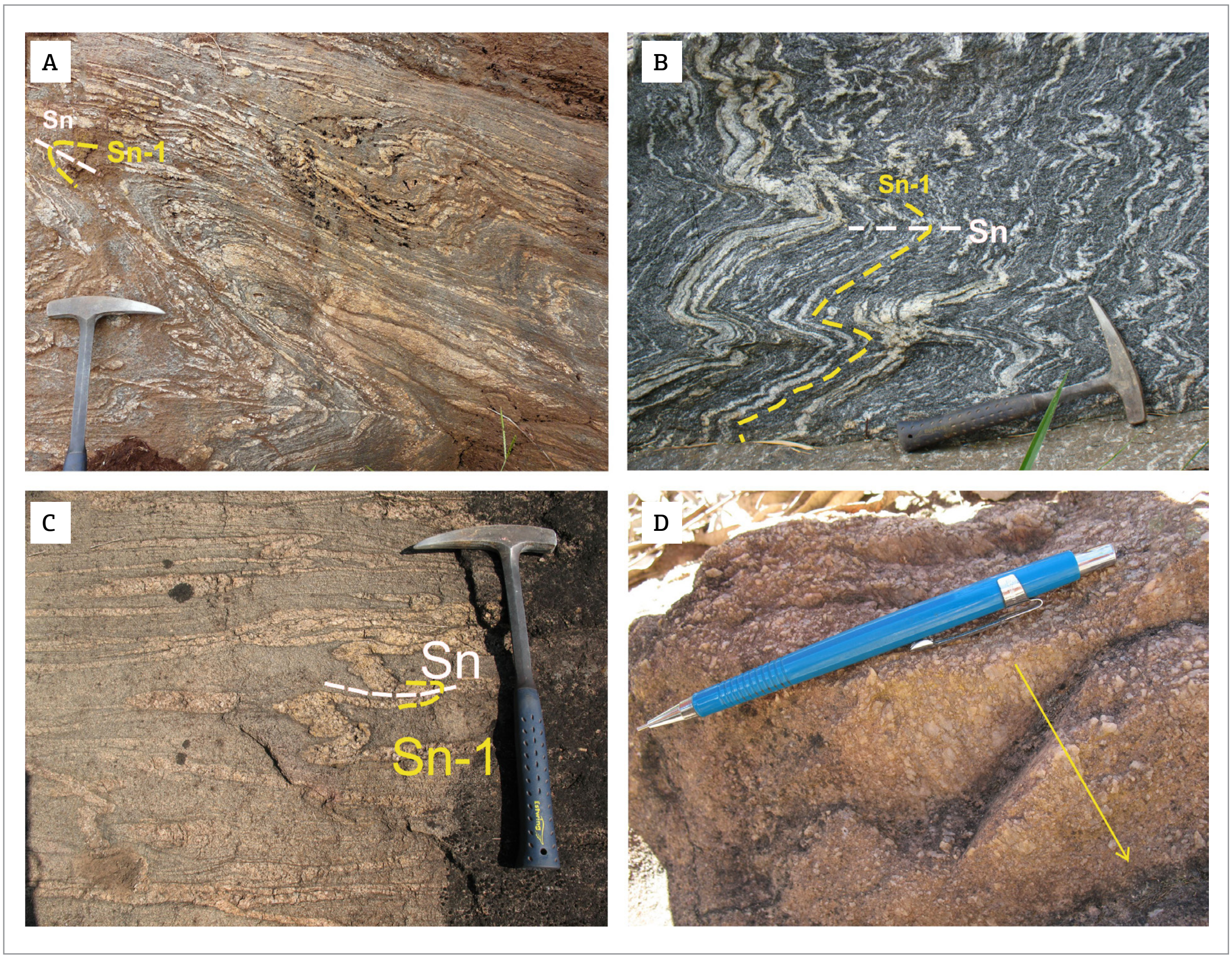

Figure 7. (A) Orthogneiss of the Socorro nappe with quartz-feldspathic veins, probably generated by anatexis, parallel to Sn-1, both folded by Dn, with Sn parallel to the axial plane, dipping to SE; (B) orthogneiss of the Socorro nappe with quartz-feldspathic veins parallel to Sn-1, both folded by Dn, with Sn developed along the axial planes of folds; (C) orthogneiss of the Socorro nappe with leucosomes parallel to Sn-1, folded by Dn with Sn parallel to the axial plane; (D) stretching lineation Ln plunging steeply to SE, within the Sn foliation (dipping ~60º to SE) in coarse grained quartzite of the Embu terrane.

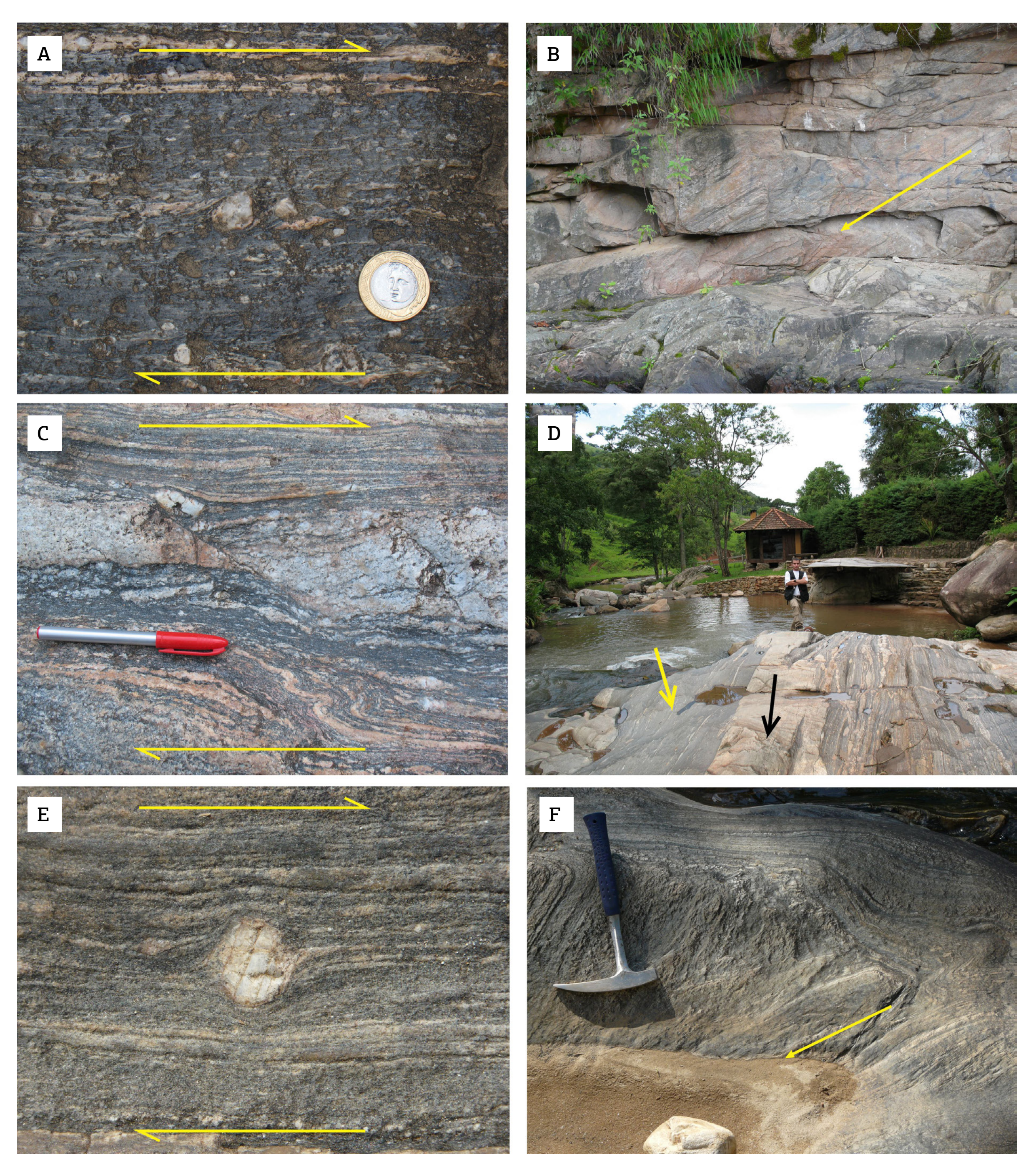

Figure 8. (A) Orthogneiss of the Serra da Água Limpa batholith (Socorro nappe) mylonitised by the São Bento do Sapucaí shear zone, with Sn+1 approximately vertical striking NE-SW. The photo shows a horizontal surface with a delta-type kinematic indicator revealing dextral movement; (B) at the same outcrop as shown in (A) the stretching lineation Ln+1 plunges shallowly to SW within the subvertical NE–SW striking Sn+1 plane; (C) paragneiss of the Embu terrane mylonitized by the Caxambu shear zone. The photo shows a horizontal surface with kinematic indicators, like C'shear bands and asymmetric folds indicating dextral transcurrent movement; (D) same outcrop as figure (C), the black arrow points to a granitic body about 1.5 m in diameter, intruded into metasedimentary host rock, both mylonitized by the Caxambu shear zone; (E) orthogneiss present both in the Socorro nappe and in the Embu terrane, mylonitized by the Buquira shear zone, with the subvertical mylonitic foliation (Sn+1) striking NE–SW. The photo shows a delta type shear sense indicator with dextral movement; (F) this photo of the same outcrop as (E) shows the Sn+1 stretching lineation, contained in Sn+1 plunging with low angle to SW.

up to a few kilometers wide. A major difference is that it is dipping on average only moderately to the SE (145/38) (Fig. 4G), although locally it is still steep to subvertical. The stretching lineations are more variable as compared to the other shear zones described before, either of low plunge, subparallel to the strike, or oblique, plunging E to SE (Figs. 4E, 4H, 8E and 8F), with shear sense top to W or NW. The microstructures related to the mylonitic foliation are again indicative of medium temperatures. A rough estimate of the horizontal dislocation is again in the order of maximum a few tens of kilometers, mainly based on the fact that the same lithotypes occur on both sides.

An important detail of this shear zone is that it limits the Pico de Itapeva metasedimentary basin, clearly affecting it along its southern boundary. Hence, it should be at least in part, younger than the sedimentation, estimated at 600–540 Ma (Teixeira *et al.* 2004) and probably contemporaneous with the low-grade metamorphism in the basin.

The last ductile deformation phase, Dn+1, generated also locally gentle folding of the main foliation Sn. This folding is often accompanied by gentle crenulations in mica-rich parts of the metasedimentary rocks, both in the Socorro Nappe and in the Embu terrane. These folds and crenulations have steep N–S trending axial planes and also N–S trending axes (Fig. 11), compatible with the interpretation that Dn+1 reflects essentially E–W shortening, also coherent with the orientation and kinematics of the shear zones.

GEOCHRONOLOGY

Two samples were selected for geochronological investigation with the objective to constrain the age of the last ductile deformation phase. The method used was U-Pb in zircon by laser ablation (LA-ICP-MS, Thermo Finnigan Neptune multicollector) at the Geochronological Laboratory of the

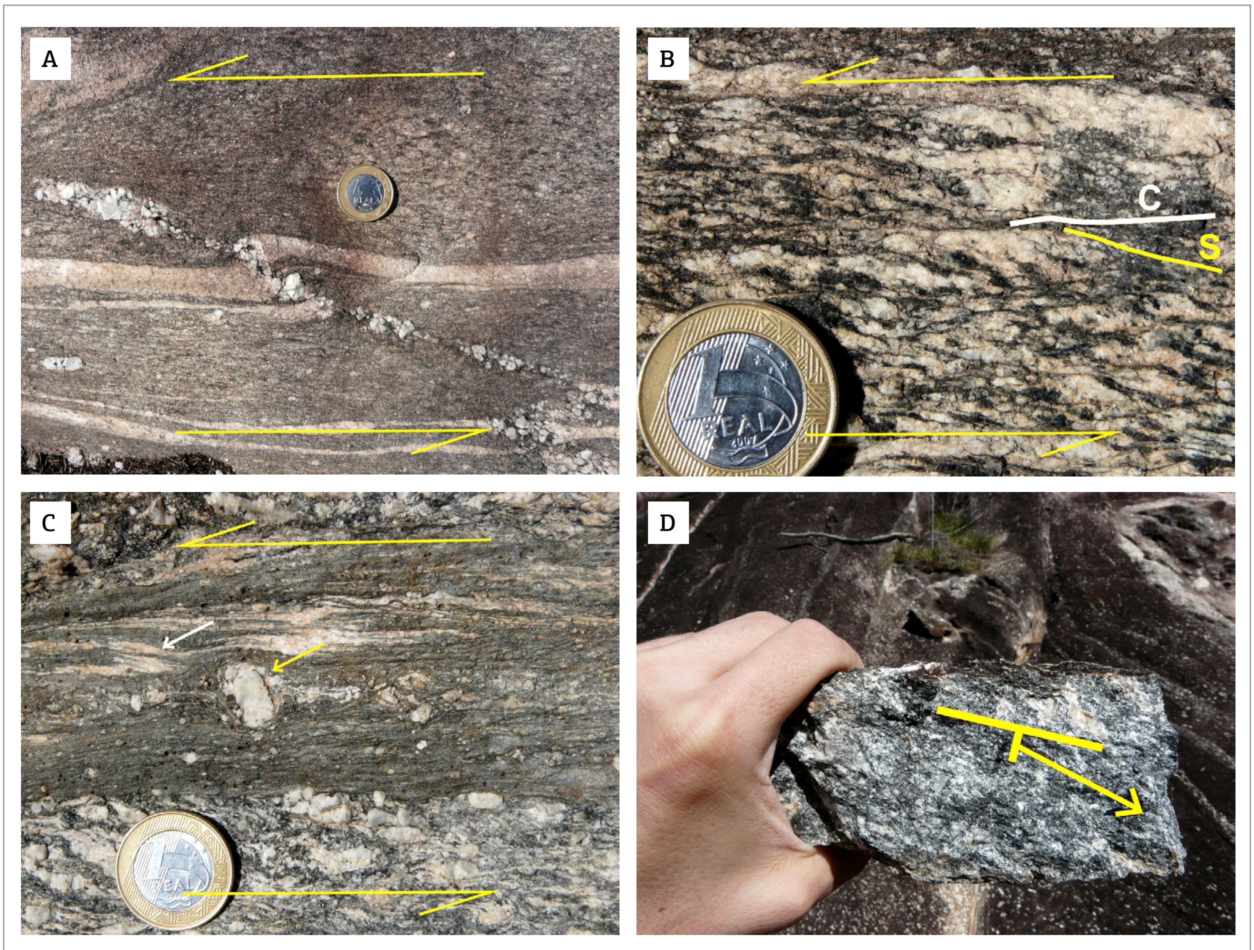

Figure 9. All photos of this figure were taken at outcrops of the Serra da Água Limpa batholith, mylonitised by the Campos do Jordão shear zone around the Campos do Jordão indentation. (A) Fault, synthetic to the sinistral movement; (B) horizontal surface with S/C type structure indicating sinistral movement; (C) similar as (B), kinematic indicators (orange arrow points to fish; yellow arrow to sigma structure) showing sinistral movement; (D) Ln+1 stretching lineation within Sn+1 plunging with low angle to NE.

University of Brasília (UnB), which operates according to the method explained by Bernhard *et al.* (2009). Both samples are from the same granite, the Serra do Alto da Pedra granite (Fig. 2), one from a site away from the Caxambu shear zone and the other one from a part of the granite affected by the shear zone, with a mylonitic fabric.

The granite forms a lenticular body on the map with its long axis oriented NE–SW, parallel to the regional trend of Sn (Fig. 2) foliation that is present within the granite. It was described (Vinagre 2010) as leucocratic deformed S-type monzo- and syeno-granite, with equigranular xenomorphic texture of fine to medium grain size. The mineralogical composition is microcline, plagioclase, quartz and biotite with accessory white mica, garnet, allanite, rutile, zircon, apatite, sphene and opaque minerals. The granite is surrounded by metasedimentary rocks of the Embu terrane and is situated in the Campos do Jordão indentation.

The sample away from the Caxambu shear zone (VAC 212) shows the penetrative Sn foliation that should be younger or contemporaneous with the crystallization of the granite. The other sample (ZCC) (Fig. 8D) was taken from a metric sized vein, with composition similar to the granite, which was interpreted as cogenetic, affected by the Caxambu shear zone in the vicinity of the city of Wenceslau Braz, Minas Gerais.

Sample Vac 212

The zircon crystals are slightly yellowish, with few inclusions and moderately fractured. The habit is predominantly prismatic (2:1), but granular shapes are also present. The prismatic grains have pyramidal terminations.

The sample yielded a Concordia age of 575 ± 5 Ma (Fig. 12), mainly obtained in cores of grains, interpreted as the crystallization age of the granite.

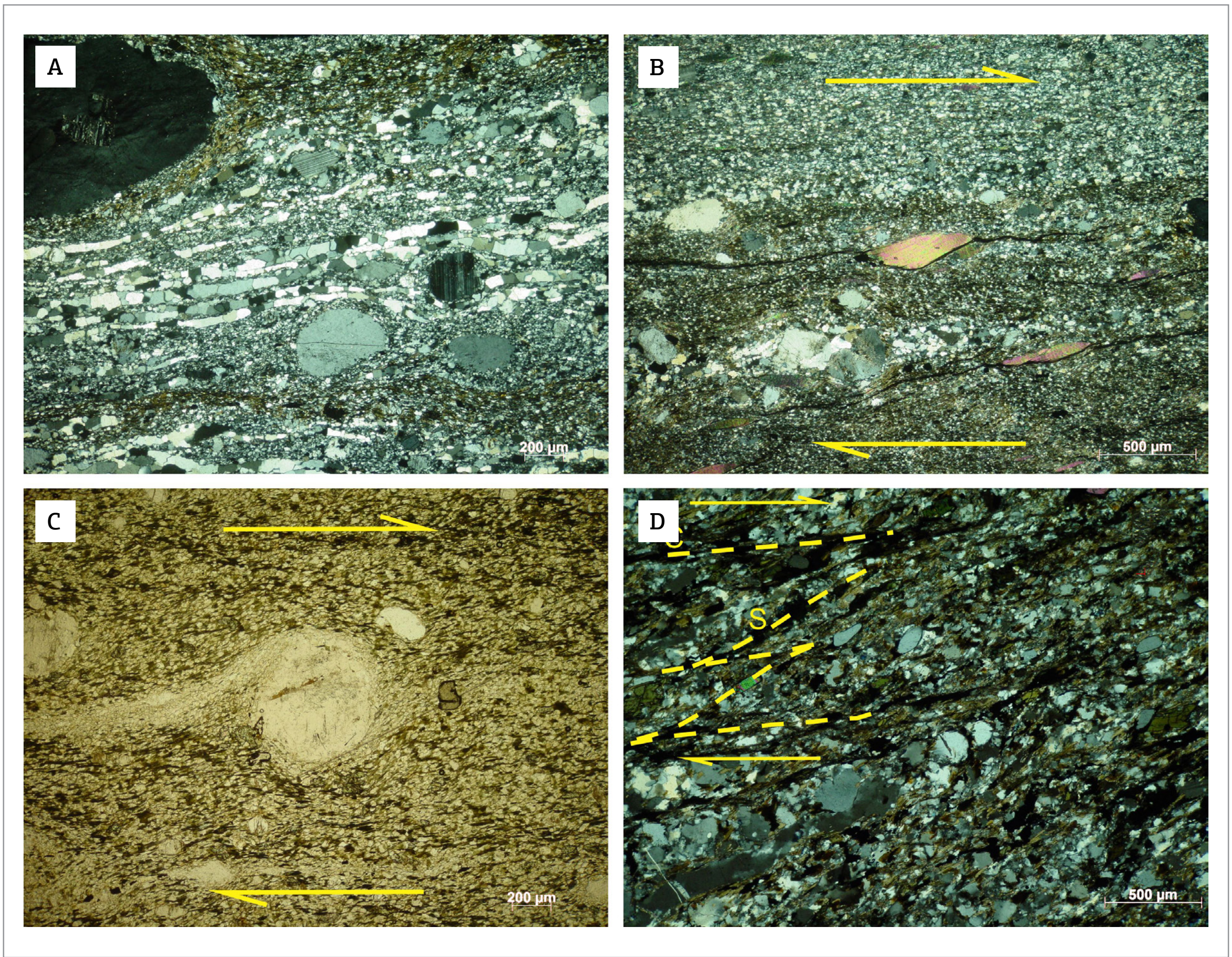

Figure 10. (A) Photomicrograph of the SALB (Socorro nappe) mylonitized by the SBSSZ with feldspar porphyroclasts. The fine grained mylonite shows ribbons of polygonized quartz indicating moderate temperature during its formation; (B) as in (A), showing mica fish indicating dextral sense of shear; (C) as in (A), showing delta-type shear sense indicator demonstrating dextral movement; (D) microscopic aspect of a paragneiss of the Embu terrane mylonitised by the Caxambu shear zone with dextral S/C type kinematic indicator.

Sample ZCC

Few zircon crystals were obtained from this sample. They are colorless to slightly yellowish with a moderate number of inclusions and considerably fractured. The shapes vary from prismatic with pyramidal terminations (2:1) to granular (1:1).

The sample yielded a Concordia age of 567 ± 8 Ma (Figs. 12, 13 and 14), in rims of grains. The cores did not produce good enough data to calculate a reliable age.

Interpretation of the ages obtained

The age obtained from sample VAC 212, interpreted as the crystallization age of the granite, 575 ± 5 Ma, probably also dates the peak of the regional metamorphism related to deformation phase Dn. The Th-U values (Table 1) are predominantly higher than 0.1, indicating igneous growth related to the crystallization of the granite. Since the granite is an S-type granite, it seems reasonable to suppose that it was generated by partial melting of supracrustal rocks as a consequence of high-grade metamorphism. The granite is strongly elongated along the Sn plane and bears a penetrative although not strong Sn fabric, hence the granite probably intruded during Dn, with its shape molded by the Dn stress field. Solid-state ductile deformation after its crystallization, still related to Dn, induced the penetrative Sn fabric. The age is consistent with published ages for the peak of regional metamorphism in the central Ribeira belt, associated with genesis of syncolisional granites, constrained in the range 590–560 Ma (Machado *et al.* 1996, Mendes *et al.* 2006, Heilbron *et al.* 2004, 2008).

The other age, 567 ± 8 Ma, obtained from sample ZCC, close and within error with relation to the first one, is less reliable because it only represents three analyses; it reflects the age of metamorphic rims with Th/U ratios below 0.1 (Table 2) and can be interpreted in several ways. First of all, it could represent the age of movement along the Caxambu

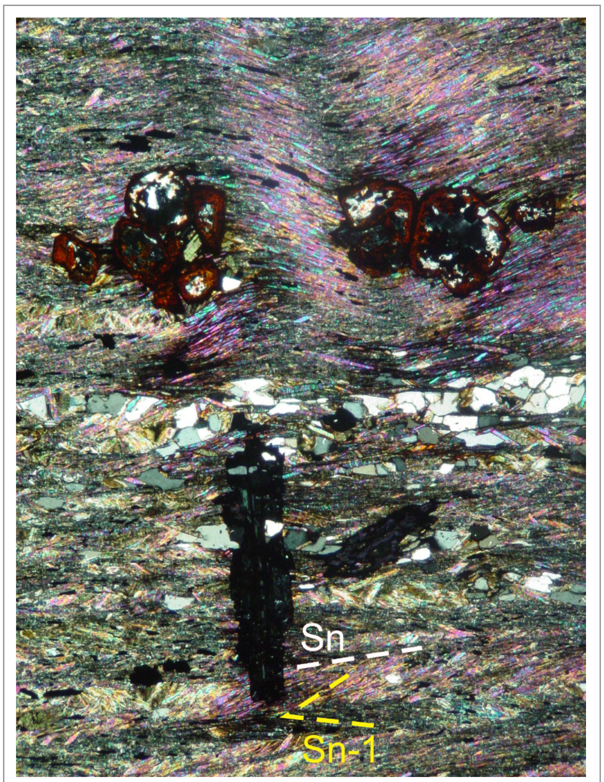

Figure 11. Photomicrograph of schist from the Embu terrane, showing the Sn-1 foliation folded in tight crenulations with polygonal arcs. Sn, axial planar with respect to the crenulations is in turn gently crenulated itself by Dn+1, with subvertical axial plane, trending N-S in the area considered.

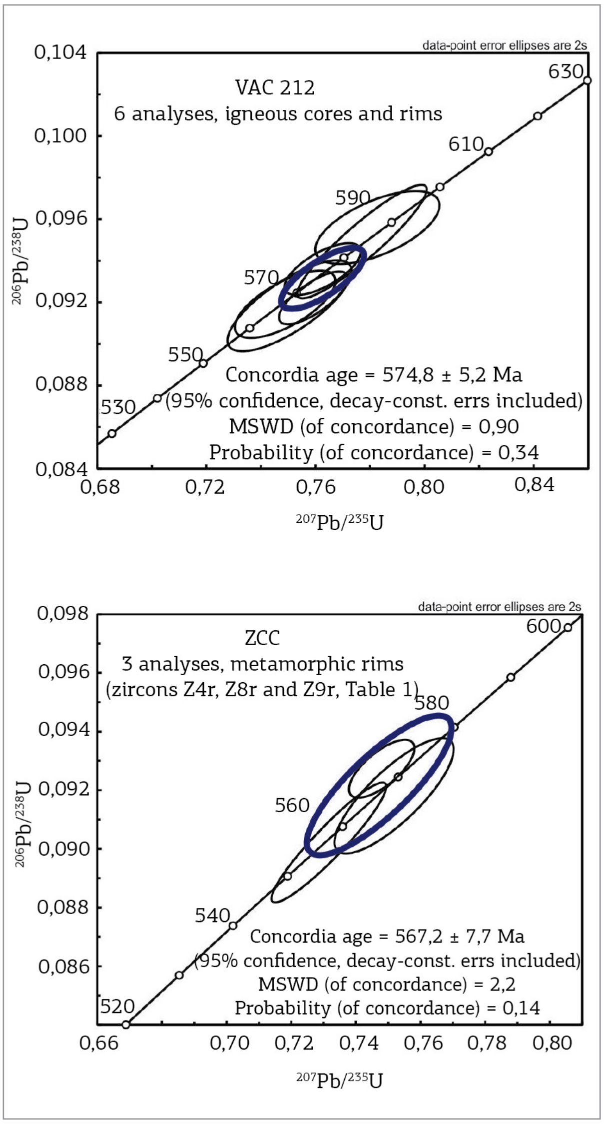

Figure 12. Concordia diagrams showing the results of the geochronological U-Pb analyses (LA-ICP-MS) in zircon. Sample VAC 212 yielded a crystallisation age of 575 ± 5 Ma and sample ZCC a metamorphic age of 567 ± 8 Ma.

shear zone, since it was taken from a vein interpreted as cogenetic to the granite, affected by this shear zone. The fact that the mylonite within this shear zone was probably formed at medium temperature (Trouw *et al.* 2007, Trouw 2008), insufficient for the growth of zircon, argues against this, but since shear zones usually mobilize considerable amounts of fluids, the possibility cannot be discarded. A second possibility is that the metamorphic growth of the rims still reflects a late stage of the main metamorphism related to Dn. The closeness in age would favor this interpretation. A combination of both hypotheses is also possible, interpreting the Dn+1 phase as continuous with Dn, representing a late stage of it, with rotation of the stress field (Heilbron *et al.* 2004, 2008). In any case, the shear zones (Dn+1) should have a maximum age of 567 ± 8 Ma.

DISCUSSION AND CONCLUSIONS

The mapping and structural analysis of the area considered revealed structures grouped in three main deformation phases: Dn-1, Dn and Dn+1, within the Socorro nappe and in the Embu terrane.

Dn-1 produced SW dipping Sn-1 planes with down dip stretching lineations, consistent with top to the NE thrusting, characteristic of the southern Brasília belt (Campos Neto 2000, Campos Neto *et al.* 2004, 2007, 2011, Trouw *et al.* 2000, 2013). This thrusting is interpreted as the result of collision between the Paranapanema and São Francisco paleocontinents in the time interval of 630 to 605 Ma for the region considered, dated by the peak of relatively high-pressure metamorphism (M1) (Campos Neto *et al.* 2007, 2011, Trouw 2008, Trouw *et al.* 2013, Vinagre *et al.* 2014a).

Dn generated folding of Sn-1 planes on micro to macro scales and a new penetrative foliation dipping steeply to moderately towards SE, associated with a down dip stretching lineation. Shear sense indicators show up-dip sense of shear and the general kinematics of this phase reflect NW–SE shortening related to collision in the central Ribeira belt (Heilbron *et al.* 2004, 2008) of the agglutinated

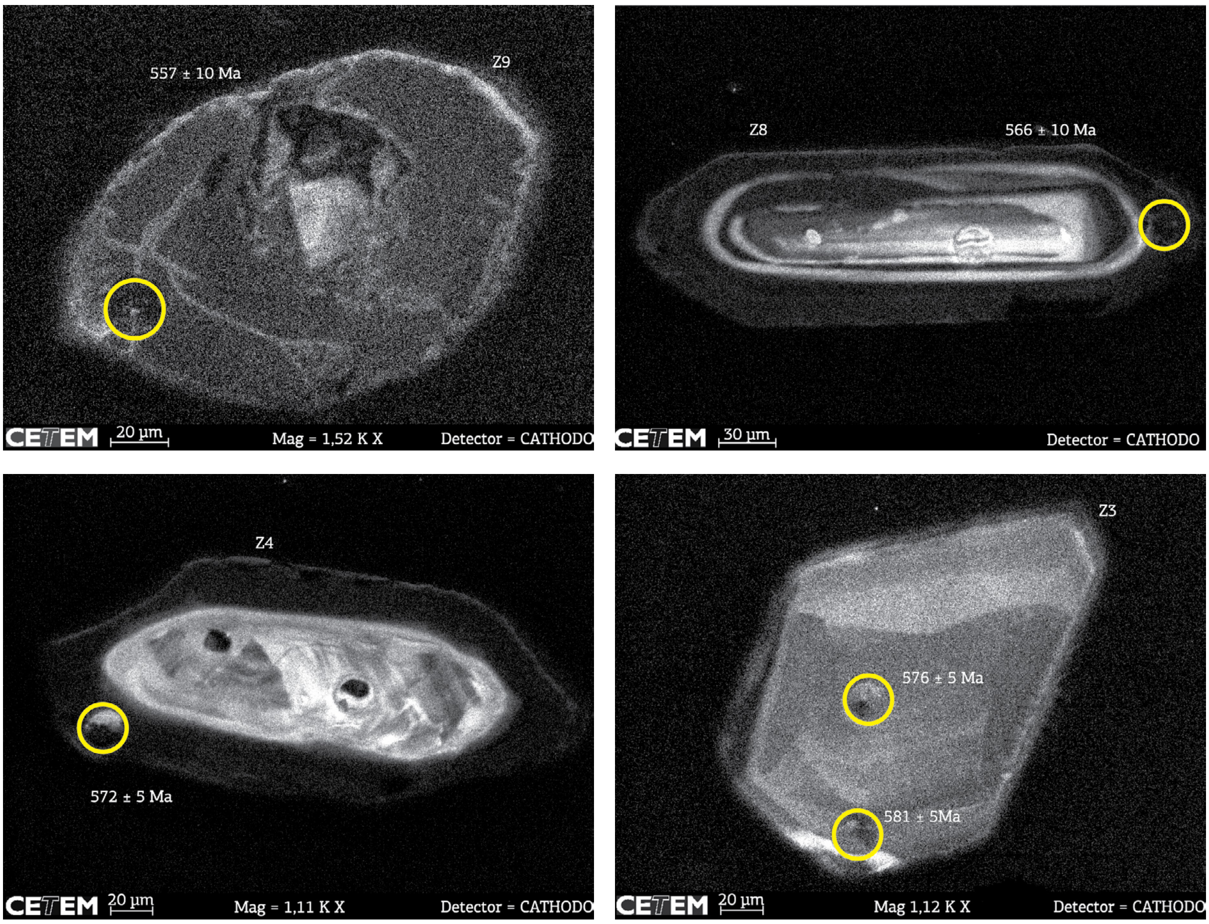

Figure 13. Sample ZCC. Cathodoluminescence images of analyzed zircon grains. Circles in zircon crystals represent analyzed areas; Z refers to the number of the grain (Table 1); the ratio used in this figure is Pb^{206}/U^{238}.

Paranapanema and São Francisco paleocontinents as lower plate, with the Rio Negro arc/Oriental terrane as upper plate. The age of this collision and hence this phase, associated with the peak of the second metamorphism (M2), is consistent with the ages obtained in this paper as 575 ± 5 Ma by U-Pb (LA-ICP-MS) in cores of zircon grains from an S-type granite, syntectonic to Dn. The published age interval for this tectonic event is 590–560 Ma (Machado *et al.* 1996, Heilbron *et al.* 2004, 2008, Zuquim *et al.* 2011).

Structures ascribed to a third phase, Dn+1, are regional shear zones, mainly steep and NE–SW striking, with dextral movement, associated with sub-horizontal stretching lineations, revealing transcurrent movements compatible with E–W shortening. Gentle folding with steep N–S trending

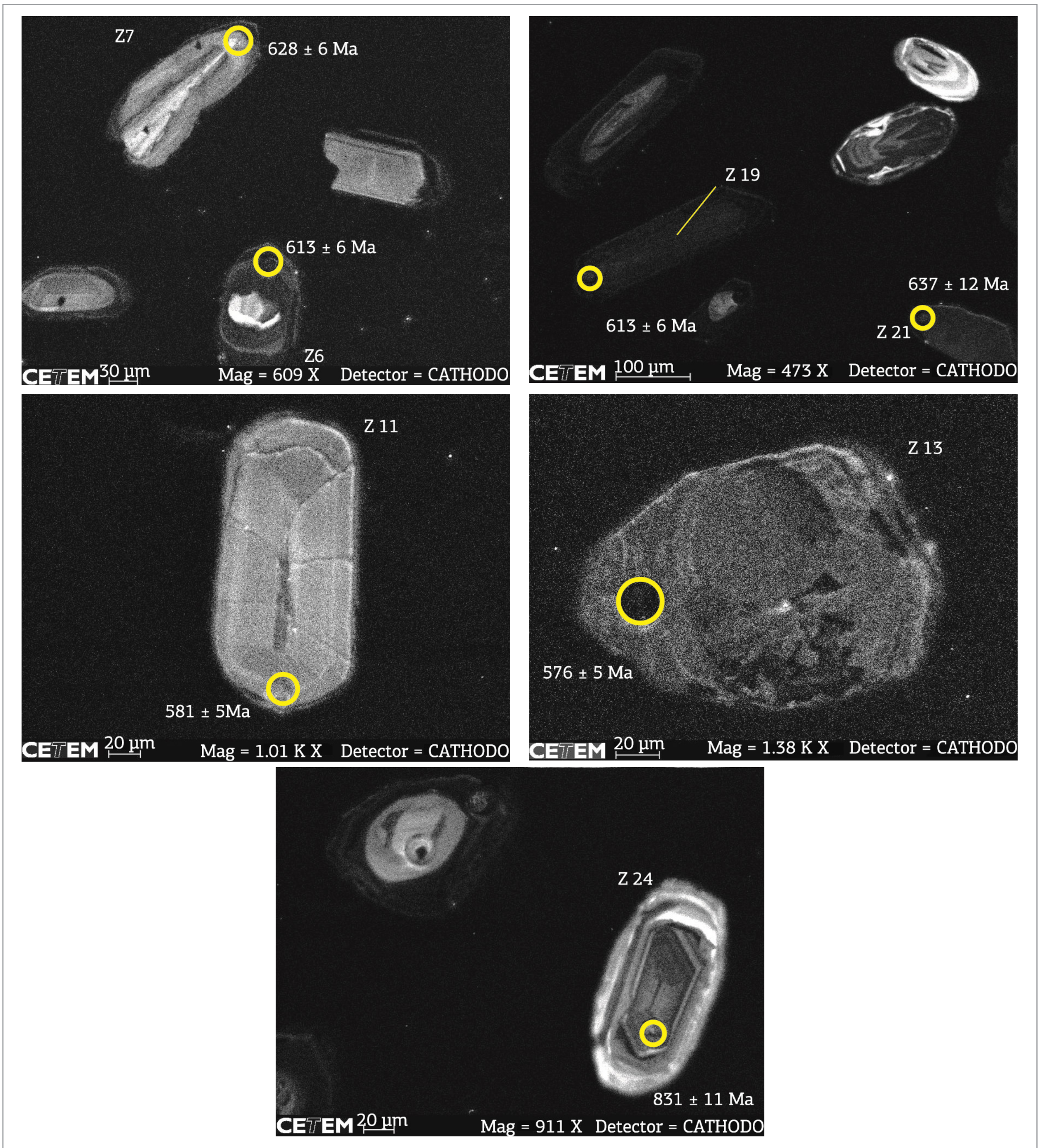

Figure 14. Sample ZCC. Cathodoluminescense images of analyzed zircon grains. Circles in zircon crystals represent analyzed areas; Z refers to the number of the grain (Table 1); the ratio used in this figure is Pb^{206}/U^{238}.

Table 1. U-Pb analytical results of zircons from samples VAC 212.

Analyses r-rim	^{206}Pb (%)	Th U	^{206}Pb ^{204}Pb (%)	^{207}Pb ^{206}Pb (%)	1s (%)	^{207}Pb ^{235}U (%)	1s (%)	^{206}Pb ^{238}U (%)	1s (%)	^{207}Pb ^{206}Pb	1s	^{207}Pb ^{235}U	1s	^{206}Pb ^{238}U	1s	Rho	Conc (%)
Z26	0,06	0,17	29.030	0,05925	1,5	0,7504	2,5	0,09185	1,9	576,4	33,1	568,4	10,8	566,5	10,5	0,76	98,28
Z4	0,17	0,29	12.152	0,05908	2,5	0,7488	2,0	0,09192	1,4	570,0	52,8	567,5	8,7	566,9	7,8	0,69	99,45
Z3	0,04	0,17	46.388	0,05970	1,8	0,7592	1,4	0,09223	1,1	592,7	37,9	573,5	6,0	568,7	6,1	0,75	95,95
Z16	0,07	0,47	24.120	0,05908	1,0	0,7625	1,5	0,09360	1,1	570,1	22,5	575,5	6,6	576,8	6,0	0,68	101,18
Z11	0,04	0,17	43.577	0,05937	3,4	0,7770	2,5	0,09493	2,3	580,5	72,7	583,8	11,0	584,6	13,1	0,92	100,71
Z22	0,11	0,30	16.677	0,05937	1,8	0,7826	2,4	0,09561	1,5	580,6	40,2	587,0	10,6	588,6	8,4	0,61	101,38
Z1	0,04	0,01	49.586	0,06022	1,3	0,7947	1,1	0,09571	0,8	611,5	28,6	593,8	4,9	589,2	4,2	0,57	96,36
Z25	0,06	0,15	31.284	0,06037	1,6	0,7971	1,3	0,09577	0,9	616,8	33,9	595,2	5,9	589,6	5,1	0,66	95,58
Z24	0,03	0,06	36.811	0,05991	1,6	0,7946	1,2	0,09619	1,0	600,4	33,7	593,8	5,4	592,0	5,7	0,82	98,60
Z7r	0,04	0,20	44.962	0,06013	0,7	0,8130	1,7	0,09806	1,5	608,3	14,3	604,1	7,5	603,0	8,7	0,93	99,13
Z8r	0,05	0,03	38.880	0,06035	1,4	0,8172	1,1	0,09822	0,9	616,0	30,4	606,5	5,1	604,0	5,1	0,79	98,04
Z14	0,32	0,08	5.545	0,06091	0,9	0,8270	1,3	0,09848	0,9	635,9	18,6	611,9	5,8	605,5	5,3	0,69	95,21
Z19	0,15	0,17	12.113	0,06098	2,1	0,8509	3,1	0,10120	2,3	638,7	44,1	625,2	14,3	621,4	13,5	0,73	97,30
Z2	0,03	0,06	68.634	0,06068	1,1	0,8495	1,5	0,10153	1,1	628,0	23,2	624,4	7,2	623,4	6,5	0,66	99,26
Z12	0,01	0,01	211.853	0,06022	0,6	0,8697	1,0	0,10474	0,9	611,5	12,6	635,4	4,9	642,1	5,3	0,77	105,00
Z20	0,05	0,28	29.607	0,11981	0,7	5,9716	2,1	0,36150	2,0	1953,3	12,6	1971,7	18,4	1989,3	34,2	0,91	101,84
Z5	0,01	0,27	127.524	0,13647	1,8	7,3103	1,4	0,38851	1,2	2182,8	31,5	2150,1	12,2	2115,9	21,8	0,81	96,94
Z18	0,02	0,20	75.778	0,22493	0,6	18,5474	1,5	0,59803	1,3	3016,4	9,6	3018,6	14,0	3021,9	31,9	0,88	100,18
Z21	0,00	0,19	552.840	0,28774	1,8	27,1168	1,3	0,68350	1,2	3405,4	27,8	3387,7	12,9	3357,8	31,9	0,88	98,60

Table 2. U-Pb analytical results of zircons from samples of the Caxambu Shear Zone (ZCC).

Analyses r-rim	^{206}Pb (%)	Th U	^{206}Pb ^{204}Pb (%)	^{207}Pb ^{206}Pb (%)	1s (%)	^{207}Pb ^{235}U (%)	1s (%)	^{206}Pb ^{238}U (%)	1s (%)	^{207}Pb ^{206}Pb	1s	^{207}Pb ^{235}U	1s	^{206}Pb ^{238}U	1s	Rho	Conc (%)
Z9r	0,03	0,00	41.560	0,05880	2,7	0,7315	2,0	0,09023	1,8	559,7	58,0	557,5	8,5	556,9	9,8	0,93	99,50
Z8r	0,04	0,01	46.859	0,05938	2,7	0,7518	2,0	0,09182	1,7	581,1	56,7	569,3	8,7	566,3	9,5	0,81	97,45
Z4r	0,01	0,03	150.654	0,05849	0,7	0,7479	1,1	0,09274	0,9	548,0	15,1	567,0	4,8	571,7	4,8	0,71	104,33
Z3	0,04	0,08	29.448	0,06007	1,6	0,7745	1,3	0,09350	0,9	606,2	33,2	582,3	5,6	576,2	5,0	0,66	95,05
Z3r	0,05	0,05	35.285	0,06012	1,5	0,7814	1,2	0,09427	0,9	607,9	31,9	586,3	5,4	580,7	4,8	0,63	95,54
Z6r	0,02	0,00	65.434	0,05953	0,8	0,8182	1,3	0,09969	1,1	586,5	16,9	607,1	6,0	612,6	6,2	0,74	104,45
Z19r	0,02	0,04	107.974	0,05992	0,9	0,8246	1,4	0,09981	1,1	600,7	18,4	610,6	6,2	613,3	6,2	0,71	102,10
Z11r	0,08	0,04	23.426	0,06031	1,8	0,8381	3,3	0,10079	2,8	614,7	38,6	618,1	15,3	619,0	16,4	0,82	100,71
Z7r	0,14	0,03	12.988	0,05985	1,4	0,8447	1,7	0,10237	1,0	598,0	29,7	621,8	8,0	628,3	6,1	0,51	105,07
Z21r	0,01	0,04	145.324	0,06014	0,7	0,8614	2,1	0,10389	2,0	608,5	15,5	630,9	10,0	637,2	12,1	0,95	104,72
Z13r	0,04	0,01	47.072	0,06255	6,4	0,9768	4,6	0,11326	4,4	693,0	130,3	692,0	23,0	691,7	28,6	0,94	99,82
Z24	0,04	0,20	136.938	0,06625	0,8	1,2568	1,6	0,13759	1,4	814,2	17,5	826,4	9,2	831,0	10,9	0,84	102,06

axial planes and an indentation structure, the Campos do Jordão indentation, confirm this kinematic pattern. A tentative age of 567 ± 8 Ma for this last phase was obtained in metamorphic rims of zircon grains from a sample affected by one of these shear zones. However, this age should be considered as a maximum age, since the metamorphic conditions during mylonitization were probably not high enough to enable zircon growth and the rims could well be related to late stages of M2.

The results show that structures of both the southern Brasília belt and the central Ribeira belt are present in the Socorro nappe and in the Embu terrane within the studied area, which was, therefore, ascribed to the zone of superposition of both belts (Trouw *et al.* 2000, 2013, Peternel *et al.* 2005). The older structures (Sn-1) are better preserved in the northwestern part and the younger structures (Sn and Sn+1) are better developed in the southeastern part, but both are present in the entire area.

A first point of discussion is how these three deformation phases relate to up to four deformation phases described in the central part of the southern Brasília belt (e.g. Valeriano *et al.* 2004, 2008, Seer 1999), away from the zone of superposition, and to the four phases described in the central Ribeira belt, also in areas outside the zone of superposition (Heilbron *et al.* 2004, 2008). One point to consider is that deformation phases are usually better preserved in low-grade rocks, especially phyllites, abundant in the area described by Valeriano *et al.* (2004, 2008) and Seer (1999). In higher-grade rocks, mainly gneisses, as described in this paper, early phases are easily obliterated by transposition and mineral growth. Another point is that several deformation phases may be related to a single bulk flow pattern as seems to be the case in the Passos nappe (Valeriano *et al.* 2004, 2008) and also in the Luminarias nappe (Ribeiro *et al.* 1995). Anyway, the concept of deformation phase should not be used with excessive rigidity and should be judged in association with the concept of bulk tectonic transport.

A second point of discussion is the meaning of Dn+1. While Dn-1 and Dn both reflect more or less frontal collisions, Dn+1 has a more transcurrent character. The regional shortening direction changed from NW–SE to E–W either as the consequence of the morphology of colliding blocks or caused by the final contraction of west Gondwana in response to the last agglutination related to the Buzios orogeny (530–500; Schmitt *et al.* 2004) and to the final contraction between the Amazonia paleocontinent and the remainder of west Gondwana. Although the shear zones are treated as a "deformation phase" they could in fact represent prolonged and/or repeated movements during a protracted time span (567–500 Ma), related to final contractions within west Gondwana. In the present study, we dispose of the following data: at 587 ± 9 Ma the stress field was still producing NW–SE shortening as testified by the sinistral almost N–S trending Maria da Fé shear zone (Zuquim *et al.* 2011). This stress field is also compatible with the 573 Ma age obtained by Peternel (2005) for the Pedra Branca granite, interpreted as syntectonic to Dn, and with the 575 ± 5 Ma age for the Serra do Alto da Pedra granite, also syn-Dn, reported in this paper. After this, the stress field could have rotated to a more E–W position, but exactly when is still an open question. We know that the metasedimentary rocks of the Pico de Itapeva basin were deformed along the Buquira shear zone. The sedimentation of these rocks was estimated as confined to the interval 570–540 Ma (Teixeira & Petri 2001), but there are some doubts about this time interval (Peternel, personal communication), and not necessarily all deformation along the Buquira shear zone has to be younger than the sedimentation.

The Buquira shear zone is of special significance, considered in the literature as a kilometer-thick mylonitic shear zone, separating the southern Brasília belt from the central Ribeira belt (Campos Neto *et al.* 2004, 2007, 2011). Our mapping shows the zone as an anastomosing moderately SE dipping shear zone with branches rarely thicker than one kilometer (Kussama 2012). Although most stretching lineations tend to be of low rake, a complete transition to down-dip attitudes indicates the progressive evolution from up-dip to transcurrent movement, translated as a gradual transition from Dn to Dn+1. Typical rock units of the Embu terrane occur on either side and age distribution patterns of detrital zircon grains taken from samples on either side do not show significant difference (Trouw *et al.* 2013, Duffles 2013, Duffles *et al.* 2016). Hence, this shear zone is interpreted as of local importance and not as a terrane boundary (Trouw *et al.* 2013). This interpretation correlates with the interpretation that the Embu terrane is actually part of the Socorro nappe, as indicated by the presence of several metaluminous deformed calc-alkaline granitoids with ages in the range 680–625 Ma (Trouw *et al.* 2013, Alves *et al.* 2013, Vinagre *et al.* 2014a).

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REFERENCES

Almeida F.F.M., Hasui Y., Neves B.B.B., Fuck R.A. 1981. Brazilian structural provinces: an introduction. Earth-Science Reviews, **17**(1-2):1-29.

Almeida J.C.H. 2000. *Zonas de cisalhamento dúctéis de alto grau do Médio Vale* ***do Rio Paraíba do Sul***. PhD Thesis, Instituto de Geociências, Universidade Estadual Paulista, Rio Claro, 190 p.

Almeida J.C.H., Tupinambá M., Heilbron M., Trouw R. 1998. Geometric and kinematic analysis at the Central Tectonic Boundary of the Ribeira belt, Southeastern Brazil. In: SBG-MG, Congresso Brasileiro Geologia, 39, Belo Horizonte, Anais..., p.32.

Alves A., Janasi V., Campos Neto M.C., Heaman L., Simonetti A. 2013. U-Pb Geochronology of the granite magmatism in the Embu Terrane: Implications for the Evolution of the Central Ribeira Belt, SE Brazil. *Precambrian Research*, **230**:1-12.

Bernhard M.B., Pimentel M.M., Massimo M. Dantas E.L. 2009. High Spatial Resolution Analysis of Pb and U Isotopes For Geochronology by Laser Ablation Multi-Collector Inductively Coupled Plasma Mass Spectrometry (La-Mc-Icp-Ms). *Anais da Academia Brasileira de Ciências*, **81**(1):99-114.

Campanha G.A. 1981. O Lineamento de Além Paraíba Na Área de Três Rios. *Revista Brasileira de Geociências*, **11**:159-171.

Campos Neto M.C. 2000. Orogenic systems from southwestern Gondwana, an approach to Brasiliano-pan African Cycle and orogenic collage in southeastern Brazil. ***In***: Cordani U.G., Milani E.J., Thomaz Filho A., Campos D.A. (eds.) *Tectonic Evolution of South America*. 31st International Geological Congress. Rio de Janeiro, Brazil, p. 335-365.

Campos Neto M.C., Basei M., Vlach S.R.F., Caby R., Szabó G.A.J., Vasconcelos P. 2004. Migração de orógenos e superposição de orogêneses: um esboço da colagem Brasiliana no sul do Cráton do São Francisco, SE -Brasil. ***Geologia USP*** *- Série Científica*, **4**(1):13-40.

Campos Neto M.C., Basei M.A.S., Janasi V.A., Moraes R. 2011. Orogen Migration and Tectonic Setting of the Andrelândia Nappe System: an Ediacaran Western Gondwana Collage, South of São Francisco Craton. *Journal of South American Earth Sciences*, **32**(4):393-406.

Campos Neto M.C. & Caby R. 1999. Tectonic constrain on Neoproterozoic hig-pressure metamorphism and nappe system south of São Francisco craton, southeast Brazil. *Precambrian Research*, **97**(1-2):3-26.

Campos Neto M.C. & Caby R. 2000. Lower crust extrusion and terrane accretion in the Neoproterozoic nappes of southeast Brazil. *Tectonics*, **19**(4):669-687.

Campos Neto M.C., Janasi V., Basei M., Siga Jr. O. 2007. Sistema de nappes Andrelândia, setor oriental: litoestratigrafia e posição estratigráfica. *Revista Brasileira de Geociências*, **37**(4Suppl):47-60.

Cordani U.G., Coutinho J.M.V., Nutman A.P. 2002. Geochronological constraints on the evolution of the Embu Complex. *Journal of South American Earth Sciences*, **14**(8):903-910.

Del Lama E.A., Zanardo A., Oliveira M.A.F., Morales N. 2000. Exhumation of high-pressure granulites of the Guaxupé Complex, Southeastern Brazil. *Geological Journal*, **35**(3-4):231-249.

Duffles P. 2013. *Petrografia, geoquímica e geocronologia do Complexo Embu e rochas intrusivas associadas, folhas Lorena e Delfim Moreira (1:50.000), estados de SP e MG*. PhD Thesis, Instituto de Geociências, Universidade Federal do Rio de Janeiro, Rio de Janeiro.

Duffles P.A., Trouw R.A.J., Mendes J.C., Gerdes A., Vinagre R. 2016. U-Pb age of Detricial Zircon from the Embu Sequence, Ribeira Belt, SE Brazil. *Precambrian Research*, **278**:69-86.

Fernandes A.J., Campos Neto M.C., Figueiredo M.C.H. 1990. O Complexo Embú no leste do Estado de São Paulo: limites e evolução geológica. In: SBG, Congresso Brasileiro de Geologia, Natal, Anais..., Vol VI, p.2755 - 2763.

Hackspacher P.C., Fetter A.H., Ebert H.D., Janasi V.A., Dantas E.L., Oliveira M.A.F., Braga I.F., Negri F.A. 2003. Magmatismo há 660-640 Ma no Domínio Socorro: registros de convergência pré-colisional na aglutinação do Gondwana Ocidental. *Geologia USP. Série Científica*, **3**:85-96.

Hasui Y. 1975. Evolução polifásica do Pré-Cambriano a oeste de São Paulo. ***Boletim IG***, **6**:95-103.

Heilbron M. & Machado N. 2003. Timing of Terrane Accretion in the Neoproterozoic - Eopaleozoic Ribeira Belt (SE Brazil). *Precambrian Research*, **125**(1-2):87-112.

Heilbron M., Pedrosa-Soares A.C., Campos Neto M., Silva L.C., Trouw R.A.J., Janasi V.C. 2004. A Província Mantiqueira. ***In***: Mantesso-Neto V., Bartorelli A., Carneiro C.D.R., Brito Neves B.B. (eds.) *O desvendar de um continente*: a moderna geologia da América do Sul e o legado da obra de Fernando Flávio Marques de Almeida, p. 203-234.

Heilbron M., Tupinambá M., Valeriano C.M., Armstrong, R., Siva, L.G.E., Melo R.S., Simonetti A., Soares A.C.P., Machado, N. 2013. The Serra da Bolívia Complex: The Record of a New Neoproterozoic Arc-Related Unit at Ribeira Belt. *Precambrian Research*, **238**:158-175.

Heilbron M., Valeriano C.M., Tassinari C.C.G., Almeida J.C.H., Tupinambá M., Siga Jr. O., Trouw R.A.J. 2008. Correlation of Neoproterozoic terranes between the Ribeira Belt, SE Brazil and its African counterpart: comparative tectonic evolution and open questions. ***In***: Pankhurst R.J., Trouw R.A.J., Brito-Neves B.B., de Wit M. (eds.) *West Gondwana pre-Cenozoic Correlations across the South Atlantic Region*. Journal Geological Society London, Special Publication 294, p. 211-232.

Janasi V., Alves A., Vlach S.R.F., Leite R.J. 2003. Granitos peraluminosos da porção central da Faixa Ribeira, Estado de São Paulo: Sucessivos eventos de reciclagem da crosta continental no Neoproterozóico. *Geologia* ***USP*** *- Serie Cientifica*, **3**(1):13-24.

Janasi V.A. & Ulbrich H.H.G.J. 1991. Late Proterozoic granitoid magmatism in the state of São Paulo, southeastern Brazil. *Precambrian Research*, **51**(1-4):351-374.

Kussama H. 2012. *A zona de cisalhamento Buquira entre Monteiro Lobato e Piquete, SP e sua relação com as Faixas Brasília e Ribeira*. MS Thesis, Instituto de Geociências, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 68 p.

Machado N., Valladares C., Heilbron M., Valeriano C. 1996. U–Pb geochronology of the central Ribeira Belt (Brazil) and implications for the evolution of the Brazilian Orogeny. *Precambrian Research*, **79**(3-4):347-361.

Mantovani M.S.M. & Brito Neves B.B. 2005. Geophysical boundaries of Paranapanema Proterozoic blocks: its importance for the Rhodinia to Gondwana evolutionary theories. *Gondwana Research*, **8**:303-315.

Mendes J.C., Ávila C.A., Pereira R.M., Heilbron M.P.L., Moura C.A.V. 2006. ^{207}Pb/^{206}Pb-ages of zircons from syn-collisional I-type porphyritic granites of the central Ribeira belt, SE Brazil. *Gondwana Research*, **9**(3):326-336.

Morales N., Hasui Y., Zanardo A. 2005. Evolução tectônica do Cinturão de Cisalhamento do Campo do Meio baseada nos indicadores de sentido de cisalhamento. ***In***: Simpósio Nacional de Estudos Tectônicos, 10. International Symposium on Tectonics, 4. Curitiba. Resumos Expandidos... Curitiba: SBG/PR, p. 432-435.

Negri F.A. 2002. *Petrologia das rochas charnockitograníticas e encaixantes de alto grau associadas na região de São Francisco Xavier, SP*. PhD Thesis, Instituto de Geociências e Ciências Exatas, Universidade Estadual Paulista "Júlio de Mesquita Filho", Rio Claro, SP.

Negri F.A. & Oliveira M.A.F. 2005. Geoquímica e Geotermometria dos Granulitos Máficos Associados às Rochas Supracrustais da Extremidade Meridional do Domínio Socorro, Região de São Francisco Xavier, SP. *Revista Brasileira de Geociências*, **35**(4):591-602.

Oliveira, M.A.F., Ruberti, E. 1979. Granada-cordierita gnaisses do complexo granulítico-migmatítico de São José do Rio Pardo, Caconde, SP: indicações sobre pressão e temperatura de formação. *Boletim de Mineralogia*, **6**:15-29.

Paciullo F.V.P., Ribeiro A., Andreis R.R., Trouw R.A.J. 2000. The Andrelândia Basin, a Neoproterozoic intraplate continental margin, southern Brasília belt, Brazil. *Revista Brasileira de Geociências*, **30**:200-202.

Peternel R. 2005. *A zona de superposição entre as Faixas Brasília e Ribeira na região entre Caxambu e Pedralva, sul de Minas Gerais*. PhD Thesis, Instituto de Geociências, Universidade Federal do Rio de Janeiro, Rio de Janeiro.

Peternel R., Trouw R., Schmitt, R. 2005. Interferência entre duas faixas móveis neoproterozóicas: o caso das faixas Brasília e Ribeira, no sudeste do Brasil. ***Revista Brasileira de Geociências***, **35**(353):297-310.

Ramsay J.G. 1967. *Folding and Fracturing of Rocks*. New York, McGrawHill.

Ribeiro A., Trouw R.A.J., Andreis R.R., Paciullo F.V.P., Valença J.G. 1995. Evolução das Bacias Proterozóicas e o Termo-Tectonismo Brasiliano na Margem Sul do Cráton do São Francisco. Revista Brasileira de Geociências, **25**(4):235-248.

Schmitt, R.S., Trouw, R.A.J., Van Schmus, W.R., Pimentel, M.M. 2004. Late amalgamation in the central part of Western Gondwana: new geochronological data and the characterization of a Cambrian collisional orogeny in the Ribeira belt (SE Brazil).

Precambrian Research, **133**(1):29-61.

Seer H.J. 1999. ***Evolução Tec****tônica dos Grupos Araxá, Ibiá e Canastra na sinforma de Araxá, Araxá, Minas Gerais*. PhD Thesis, Instituto de Geociências, Universidade de Brasília, 267 p.

Teixeira A.L. & Petri S. 2001. Estratigrafia e Correlações da Bacia de Pouso Alegre, Transição Neoproterozóico-Cambriano, Minas Gerais, Brazil. *Revista do Instituto Geológico*, **22**:5-26.

Teixeira A.L., Gaucher C., Paim P.S.G., Fonseca M.M., Parente C.V., Silva Filho W.F., Almeida A.R. 2004. Bacias do Estágio da Transição da Plataforma Sul-Americana. ***In***: Mantesso-Neto V., Bartorelli A., Carneiro C.D.R., Brito-Neves B.B.B. (orgs.) *Geologia do Continente Sul-Americano*. Evolução da Obra de Fernando Flávio Marques de Almeida. São Paulo, Beca, p. 487-536.

Trouw C.C. 2008. *Mapeamento da Folha Virgínia-MG, Geocronologia U-Pb (SHRIMP) em zircão e interpretação geotectônica*. PhD Thesis, Instituto de Geociências, Universidade Federal do Rio de Janeiro, Rio de Janeiro.

Trouw C.C., Medeiros F.F.F., Trouw R.A.J. 2007. Evolução tectônica da Zona de Cisalhamento Caxambu, MG. *Revista Brasileira de Geociências*, **37**(4):767-777.

Trouw R.A.J., Ribeiro A., Paciullo F.V.P., Heilbron M. 1984. Os Grupos São João dei Rei, Carrancas e Andrelândia interpretados como continuação dos Grupos Araxá e Canastra . ***In***: Congresso Brasileiro de Geologia, 33, Rio de Janeiro, 2, p. 3227-3240.

Trouw R.A.J., Heilbron M., Ribeiro A., Paciullo F.V.P., Valeriano C.M., Almeida J.C.H., Tupinambá M., Andreis R.R. 2000. The central segment of the Ribeira belt. ***In***: Cordani U.G., Milani E.J., Thomaz Filho A., Campos D.A. (eds.) *Tectonic Evolution of South America*. 31st International Geological Congress, Rio de Janeiro, Brazil, p. 287-310.

Trouw R.A.J, Passchier C.W., Wiersma D.J. 2010. Atlas of mylonites – and related microstructures. Berlin, Springer-verlag.

Trouw R.A.J., Peternel R., Ribeiro A., Heilbron M., Vinagre R., Duffles P., Trouw C.C., Fontainha M., Kussama H.H. 2013. A new interpretation for the interference zone between the Southern Brasília Belt and the Central Ribeira Belt, SE Brazil. *Journal of South American Earth Sciences*, **48**:43-57.

Tupinambá M., Heilbron M., Valeriano C., Porto Júnior R., De Dios F.B., Machado N., Silva L.G., Almeida J.C.H. 2012. Juvenile contribution of the Neoproterozoic Rio Negro Magmatic Arc (Ribeira Belt, Brazil): Implications for Western Gondwana amalgamation. *Gondwana Research*, **21**(2-3):422-438.

Valeriano C.M., Machado N., Simonetti A., Valladares, C., Seer H.J., Simões L.S.A. 2004. U-Pb geochronology of the southern Brasilia belt (SE-Brazil): sedimentary provenance, Neoproterozoic orogeny and assembly of West Gondwana. *Precambrian Research*, **130**(1-4):27-55.

Valeriano C.M., Pimentel M., Heilbron M., Trouw R.A.J., Almeida J.C. 2008. Tectonic evolution of the Brasília Belt, Central Brazil, and early assembly of Gondwana. ***In***: Pankhurst R.J., Trouw R.A.J., Brito Neves B.B., de Wit M.J. (eds.) *West Gondwana*: Pre-Cenozoic Correlations across the South Atlantic Region. Geological Society of London, Special Publications, 294, p. 197-210.

Vasconcellos A.C.B., Harris N.B.W., Tindle A.G. 1991. The relationship between metamorphism and tectonics: evidence from the Socorro-Guaxupé Thrust Nappe, southeastem Brazil. ***In***: Tulsku P., Laajaki K. (eds.) *Metamorphism, deformation and structure of the crust*. Oulu, The University of Oulu, p. 86.

Vinagre R. 2010. Geologia, Geoquímica e Geocronologia da Folha Campos do Jordão 1:50.000, Divisa dos Estados de Minas Gerais e São Paulo. MS Dissertation, Instituto de Geociências, Universidade Federal do Rio de Janeiro, Rio de Janeiro.

Vinagre R., Trouw R.A.J., Mendes J.C., Duffles P., Peternel R., Matos G. 2014a. New Evidence of a Magmatic Arc in the Southern Brasília Belt, Brazil: The Serra da Água Limpa Batholith (Socorro-Guaxupé Nappe). *Journal of South American Earth Science*, **54**:120-139.

Vinagre R, Trouw RAJ, Mendes JC, Ludka I. 2014b. Química mineral e geotermobarometria do Batólito Serra da Água Limpa, Nappe Socorro-Guaxupé, Faixa Brasília Meridional, Sudeste do Brasil. *Brazilian Journal of Geology*, **44**(3):387-414.

Vlach S.R.F. 2001. Microprobe monazite constraints for an early (ca. 790 Ma) Brasiliano orogeny: The Embú Terrane, Southeastern Brazil. *In*: Sernageomin, Simposio Sudamericano en Geología Isotópica, 3, Pucón. Extended Abstracts..., Pucón, p. 265-268, CD-ROM.

Zuquim M.P.S., Trouw R.A.J., Trouw C.C., Tohver E. 2011. Structural evolution and U-Pb SHRIMP zircon ages of the Neoproterozoic Maria da Fé shear zone, central Ribeira belt - SE Brazil. *Journal of South American Earth Sciences*, **31**(2-3):199-213.