Anais da Academia Brasileira de Ciências (2006) 78(2): 373-389
(Annals of the Brazilian Academy of Sciences)
ISSN 0001-3765
www.scielo.br/aabc

Kinematics and geometry of structures in the southern limb of the Paraíba do Sul divergent structural fan, SE Brazil: a true transtensional shear

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Manuscript received on April 4, 2004; accepted for publication on November 22, 2005;
presented by WILSON TEIXEIRA

ABSTRACT

Shear zones geometry in the Paraíba do Sul belt, southeastern Brazil, delineates a NE-trending fan-like structure. Shear zones dip towards SE in the northern limb, and towards NW in the southern one. This geometry has been interpreted either due to transpression or to late folding of flat-lying thrust surfaces. Stretching lineation plunges to ENE-ESE in the northern limb and towards NNE-NE in the southern one. Structural data in the southern limb of the divergent fan suggest a two stage kinematic evolution in high-temperature conditions: an earlier stage with top-to-SSW/SW sinistral thrusting and orogenic-parallel tangential motion, and a later stage with top-down to NNE/NE transtensional deformation. We propose a heterogeneous deformation model to explain the observed shear reversal, and suggest that the imposed transpressional displacement gradient may change during progressive deformation due to transient rheological inhomogeneities in bulk pure shear strain. In the earlier stage, the partially molten material could easily accommodate the imposed strain rates, giving rise firstly to the SW-directed shearing. As the thermal disturbance tended to vanish and the convergence increased, the NNE-directed transtensional shearing developed. We propose that the transtensional deformation characterized in this paper could be related to extrusion processes during regional transpressional strain.

Key words: transtensional deformation, extrusion, transpression, divergent fan.

INTRODUCTION

Extensional shear zones are a common structural feature in modern and ancient convergent zones (Coward et al. 1987, Malavieille 1993, Platt 1993). Such features have been described in the Caledonides (Marten and Dewey 1998, Fossen 2000, Stra-

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chan et al. 2001), in the Himalaya (Herren 1987, Pêcher 1991), in the Andes (Dalmayrac and Molnar 1981), in the western Cordillera (Crittenden et al. 1980, Wernicke 1981, Davis 1983, Spencer 1984), in the Alps (Selverstone 1988, Ratschbacher et al. 1989), and elsewhere.

Field and theoretical work has demonstrated the natural tendency of the thickened continental crust to be extended. Glazner and Bartley (1985) suggested that a balance between radioactive decay and denudation rates of a continental crust duplicated by thrusting may cause strong softening which enhances post-thrusting extension. Moreover, the lower strength of the continental crust in relation to mantle material suggests that thickened continental lithosphere is weaker than normal thickness continental and oceanic lithospheres (Brace and Kohlstedt 1980, Kuznir and Park 1987), and hence it will be able to flow under its own weight (Molnar and Lyon-Caen 1988). So, if we consider the strong preexistent anisotropy due to structural discontinuities formed during convergence, and the rheological controls that lower the strength of duplicated continental crust (Teyssier and Vanderhaeghe 2001), the orogenic belts are suitable sites for extensional flow regimes (Norton 1986). This was generically called extensional collapse of orogens (Dewey 1988).

Although theoretical work predicts extension and collapse of an overthickened crust, some doubts still remain about the existence of a unique interpretation of the relation between extensional and compressional tectonics (see Doglioni 1996). Based on structural and/or geochronological evidence, extensional motion in the Higher Himalayas has been considered coeval with thrusting at lower topographic levels (Royden and Burchfiel 1987, Inger 1998, Dézes et al. 1999). In the Caledonides, Harz et al. (2001) proposed the same structural relationship. In the Alps, Ratschbacher et al. (1991 a,b) and Mancktelow (1992) suggested that crustal extension was related to orthogonal contraction and orogen-parallel motion. These relationships may lead to the motion of crustal fragments linked by extensional and compressional structures, in what is called tectonic extrusion (see references cited above).

In the Late Precambrian orogen of southeastern Brazil (Mantiqueira Province) (Almeida and Hasui 1984), extensional structures were recently described in some of its branches, such as the NS-trending Araçuaí belt (I. Endo, unpublished data, H. Nalini, unpublished data; and Alkmin et al. 2002), and NE-trending Paraiba do Sul belt (Dehler et al. 2000, Dehler and Machado 2002). Machado et al. (2001) suggested that E-directed Neoproterozoic extension affected both of these branches.

In this paper we discuss the extensional kinematics of a regional, high-grade ductile shear zone in the Paraiba do Sul belt, Central Mantiqueira Province. Previous work of the southern limb of the fan-structure (Trouw 1995, J.C.H. Almeida, unpublished data) suggests that apparent extension in the RSSZ is a geometric consequence of the folding of an earlier NW-directed thrust. Based on the structural relations, and mechanical and metamorphic evidence, we suggest that the transtensional strain reflect true crustal extension, and that this kinematic regime is related to oblique extrusion during regional transpression of a partially molten, deep seated continental crust.

Regional Structure of the Paraíba do Sul Belt in the Central Mantiqueira Province (SSE of the São Francisco Craton)

The Paraíba do Sul belt (PSB) is a NE-trending deformed zone metamorphosed in the amphibolite to granulite facies, exposed S-SE of the São Francisco Craton (SFC) (Ebert 1968, 1971) (Fig. 1). The regional structure of the belt is characterized by an array of NE-trending ductile shear-zones, parallel to the southeastern Atlantic coast of Brazil, called the Central Mantiqueira Province (*sensu* Almeida and Hasui 1984).

At the southern edge of the SFC supracrustal rocks of the Andrelândia domain (Fig. 1) crop out. Their earliest ductile structures are fold and thrust nappes transported eastwards (Trouw et al. 1998). These authors also suggested that emplacement of high-pressure granulites and eclogites in this

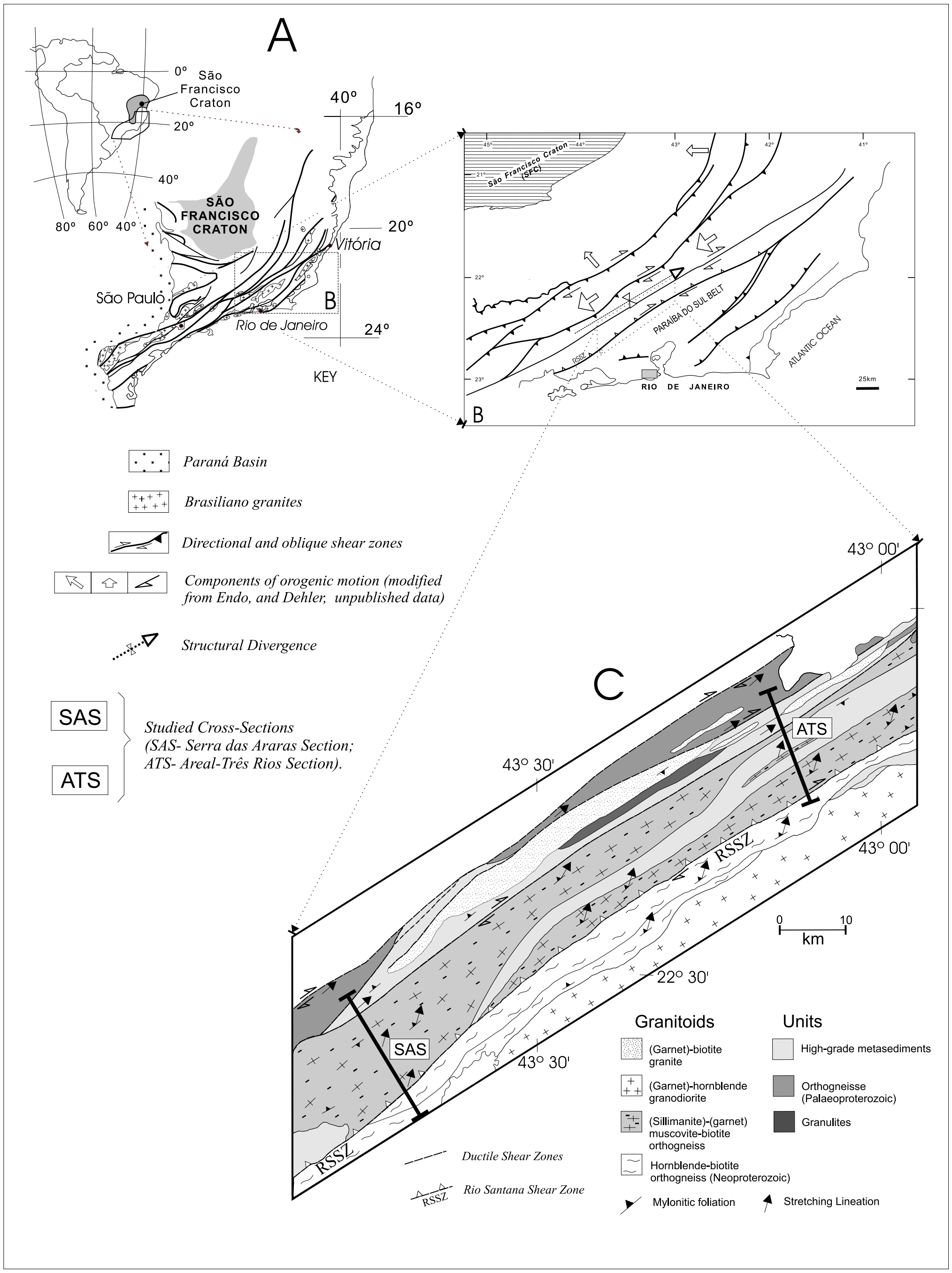

Fig. 1 – Map of the Mantiqueira Province (A), regional shear zone pattern in the Paraíba do Sul Belt, southeastern São Francisco Craton (B), and the southern limb of the regional fan-like structure (C). The tectonic situation and the regional lithostructural map of the southern limb of the divergence is also shown in b and c respectively. See text for further discussion (modified from N.M. Dehler, unpublished data).

domain occurred during top-to-E ductile shearing. Eastward movement of crustal slices in this region are believed to be associated with the tectonic evolution of the southern Brasília thrust belt, at the southwestern limit of the SFC (Trouw et al. 2000).

According to Ebert (1971) the tectonic evolution of the Brasilia belt predates the tectonic history of the PSB belt. The earlier structures associated with the structural history of the PSB are represented by NW-directed ductile thrusts (Ebert 1968). Upright folds and dextral transpressive shear zones overprint the NW-directed thrusts in the PSB (Trouw et al. 2000). The regional geometry of shear zones in the PSB is fan-like (Ebert 1968), the structure dipping towards southeast and northwest in a regional NS cross-section through of the belt (Fig. 1B). This geometry is interpreted as either a late deformational feature due to folding during transpression of older NW-vergent thrusts (Heilbron et al. 1991, J.C.H. Almeida, unpublished data), or a mega-flower structure resulting from dextral transpressional strain (Machado and Endo 1993).

Towards the S-SE the mylonitic foliation becomes steeper, and large NE-trending ductile shear zones deformed the cover and basement units (Heilbron et al. 1995). Stretching lineation trends to ESE-ENE, and shear sense indicators suggest top-to-WNW thrusting and dextral motion (Machado and Endo 1993, Ebert and Hasui 1998). This is the characteristic style of deformation in the PSB (Trouw et al. 2000). Ductile flow occured under high-grade metamorphic conditions (amphibolite to granulite facies – J.C.H. Almeida, unpublished data), coeval with crustal anatexis and the thermal peak at around 580 Ma (Machado et al. 1996).

Farther to the SE regional strain increased, and large sub-vertical mylonitic shear belts occur. Stretching lineation is sub-horizontal or slightly plunging, and the kinematic indicators in the PBS rocks suggest that dextral rotation occurred during ductile transpression (Dayan and Keller 1989, Ebert et al. 1993, Corrêa Neto et al. 1993). Folding of an earlier sub-horizontal foliation with gently plunging axes and sub-vertical axial surfaces, both sub-parallel to the regional trend, also suggest shortening perpendicular to the regional shear zone walls (Rosier 1957) and transpressional strain. These structures are found elsewhere in the belt and commonly control the emplacement of granitic plutons (A.R. Nummer, unpublished data). U/Pb geochronological data from two syn-tectonic granitic bodies suggest that dextral sub-horizontal shearing was active at about 540 Ma (Machado et al. 1996).

Towards the south of the vertical shear belt described above, the mylonitic foliation dips towards NW in a relatively narrow and straight corridor (Fig. 1B and 1C). The mylonitic foliation flattens southwestwards and southeastwards, and the oblique stretching lineation plunges to the NNE-NE (Trouw 1995). Inferred sense of shear is controversial, with both oblique normal motion (Trouw 1995) or southward thrusting being described (Machado 1983, Dehler and Machado 2002, N.M. Dehler, unpublished data).

Two regional cross-sections in the southern limb of the structural divergent fan fan (Serra das Araras Section – SAS, and Areal-Três Rios Section – ATS) were studied in detail to establish the geometry and the kinematics of the structures (Fig. 2). Our kinematic data and interpretations presented in this paper are incompatible with the previous models proposed for the southern limb of the divergent fan. We propose a kinematic model that envisages tectonic extrusion in order to explain the transtensional shearing in an overall transpressional environment.

Geometric and Kinematic Analysis of Structures

Structural analysis was carried out delimiting homogeneous domains with respect to a specific chosen structural element (Turner and Weiss 1963), which in this study was the mylonitic foliation. In the SAS the geometry of the main foliation and shear zones is a homocline (Fig. 2). In the ATS, however, the homocline structure (Structural Domain I in figure 2) passes northwestwards into a sub-horizontal folded domain (Structural Domain II). Farther towards the northwest the foliation becomes subvertical and strain increases (Structural Domain III, not considered in this work, but discussed by domain Dayan and Keller (1989). Kinematic data were collected in sections parallel to the stretching lineation and orthogonal to the mylonitic foliation (XZ plane of finite strain) (see review in Passchier and Trouw 1996).

Based on geometric criteria, it has been proposed that the moderately NW-dipping mylonitic foliation was overprinted by upright folds and subvertical shear zones in the southern limb of the structural divergent fan (Machado 1983, J.C.H. Almeida, unpublished data). Hence, subhorizontal to moderately dipping shear zones, like the RSSZ, were deformed by late transpression-related structures. We use the geometrical approach in our discussion, but we believe that other conceptual aspects should be considerated in order to fully interpret the tectonic meaning of the described superposition relations (e.g. kinematics, strain partitioning, rheology, etc.), and we discuss here some of these aspects.

Kinematics and Geometry of the Earlier Structures

Earlier structures in the cross-sections are represented by NW-dipping and subhorizontal shear zones and related structures like mylonitic foliation, stretching lineation, intrafolial folds, shear-bands and asymmetrical boudins. In the lower structural levels of both cross-sections, outcrops occur with NW-dipping mylonitic and protomylonitic rocks derived from heterogeneous granitoids, locally with a well-developed banded fabric. These mylonites represent a ductile shear zone (Rio Santana Shear Zone – RSSZ – R. Machado, unpublished data) that placed high-grade metasediments and S-type orthogneiss in the hanging-wall, in contact with a plutonic complex with subordinate metasediments in the footwall. The regional foliation in the southern limb of the divergent fan is sub-parallel in the RSSZ in both cross-sections.

In the RSSZ, banding is well maraked by flattened and boudinaged "layers" of coarse to medium-grained granite, granodiorite and diorite. Gneissic banding and lamination are locally developed in zones of high strain. The mylonitic foliation is associated with the development of tails of recrystallized feldspar and S-C fabrics, together with flattening and boudinage of the layering and minerals, suggesting solid-state deformation of granitoid rocks (Paterson et al. 1989). The solid-state mylonitic foliation dips gently to moderately to the NW in the shear zone, and the stretching lineation measured on the plane of the foliation, plunges to the NNE (Figs. 3 a, b, c, d and e).

Microtectonic studies in the RSSZ suggest that ductile shearing occurred under high-temperature conditions (J.C.H. Almeida, unpublished data, N.M. Dehler, unpublished data). Field relations also suggest the presence of granitic melts during high-temperature, solid-state ductile strain (N.M. Dehler, unpublished data). Sillimanite and feldspar dynamic recrystallization, plus intense grain boundary migration features and "chess-board" extinction pattern in quartz (Kruhl 1996), all suggest deformation at high-temperature conditions (Passchier and Trouw 1996).

At the SAS, syn-tectonic leucogranitic bodies occur injected sub-parallel to the solid-state foliation (sub-parallel to the regional C foliation in the cross-section) in the RSSZ, or at a low to high angle to it, associated with syn-magmatic C' and R' shear-zones (Fig. 4a, c and d). Locally folded or boudinaged veins and sheets are observed, depending on the orientation of the intrusion in relation to the incremental deformation axes (see double arrow in Fig. 4e). In this case, asymmetric structures may result. Dehler and Machado (2002) described leucogranitic bodies with distinct degrees of solid-state deformation without an obvious change in orientation (parallel to the C' or C surfaces), suggesting that syn-tectonic melt segregation occurred (Paterson et al. 1989) (Fig. 4a). The contacts between the leucogranitic bodies and host mylonitic to protomylonitic granitoids may be relatively straight or lobate, suggesting that some bodies were intruded into a host that was still partially plastic. A protracted

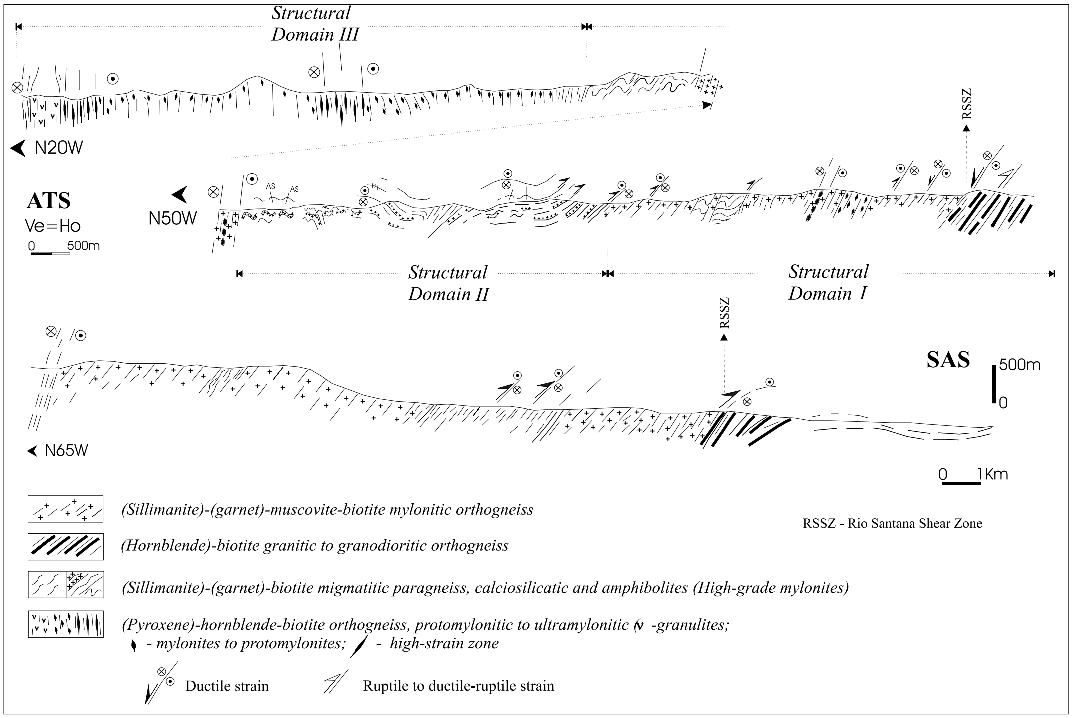

Fig. 2 – Lithostructural cross-sections studied in this paper. ATS – Areal-Três Rios section; SAS – Serra das Araras section. Stereographic plots shown in figure 3 follow the structural domains and major structures defined in the sections.

history of syn-tectonic intrusion during cooling was suggested by Dehler and Machado (2002). The observed relationships indicate that ductile deformation in the RSSZ occurred under high-temperature conditions and in the presence of granitic melts.

The planar structure throughout the SAS is relatively homogeneous (homocline structure), dipping to NW (see Figs. 2 and 3 a), parallel to the RSSZ fabric at the lower structural level of the cross-section (Fig. 2). In the ATS, however, the geometry of the mylonitic foliation defines two structural domains (Figs. 2, 3 c and e). As in the SAS, a S-type orthogneiss occurs in the hanging-wall of the basal shear zone (Figs. 1c and 2). This heterogeneous granitic pluton is correlated to the Serra das Araras batholith that occurs in a similar structural position along the SAS (Barbosa and Sad 1981). Magmatic fabrics are strongly overprinted by high-temperature solid-state strain, the rocks developed a gneissic banding and lamination, and stretching and recrystallization of feldspar, quartz and sillimanite, as well as calc-silicate enclaves, occurred.

Primary magmatic structures are hard to observe in the S-type orthogneiss in both sections, due to the strong solid-state high-temperature overprint. In thin sections intense recrystalization also obliterates primary magmatic features. Ductile deformation near the *solidus* of wet crustal granites may be inferred by syntectonic recrystalization of coarse grained sillimanite. Mesoscopic evidence of a magmatic stage could be inferred from the relative homogeneity of the orthogneiss outcrops, from the presence of euhedral centimetric to decimetric feldspar in strongly banded and laminated rocks, and from the rheological relationships between syntectonic garnet-muscovite bearing leucogranitic dykes and the host orthogneiss (Paterson et al. 1989). Additionaly, the widespread presence of

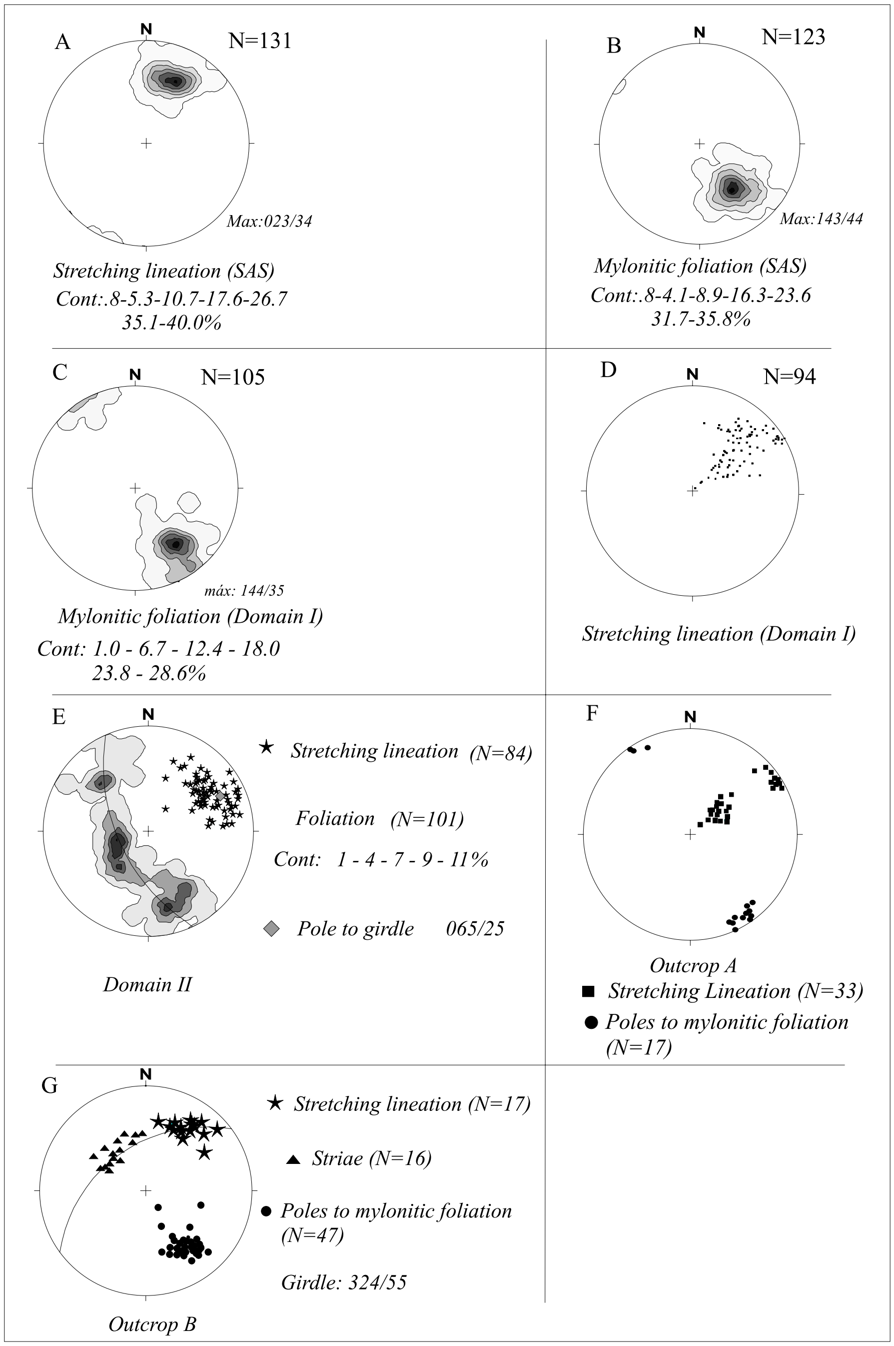

Fig. 3 – Stereographic plots (lower hemisphere projections) of the structural elements measured in the cross-sections. 3a and 3b – foliation and lineation of the SAS; 3c and 3d – foliation and lineation in Structural domain I of the ATS; 3e – Structural domain II of the ATS; 3f – outcrop of a high-grade shear zone with two mineral lineations (Dom I of the ATS); 3g – outcrop of RSSZ. See text for further explanation and discussion.

deformed metasedimentary enclaves and the segregation of granitic melts during boudinage, suggest high degree of partial melting and syntectonic melt-segregation, respectively.

Stretching lineation in the SAS and in structural domain I of the ATS trends NNE. In domain II of the ATS, the lineation trends NE subparallel to the axes of upright folds which deform the sub-horizontal shear zones (Figs. 3 d and e). Lineation is defined by alignment of coarse grained minerals such as sillimanite, feldspar, quartz and their aggregates. Aligned elliptical calc-silicate enclaves also define the stretching lineation. Aligned minerals are frequently boudinaged suggesting that this alignment was a direction of maximum finite stretching.

In the SAS cross-section, shear sense indicators observed in sections sub-parallel to the XZ plane of the finite strain ellipsoid, such as S-C-C' relationships, asymmetrical porphyroclasts and pull-apart structures (Figs. 4a and e) all suggest top-to-SSW/SW sense of shear during high-temperature solid-state deformation, coeval with the intrusion/ segregation of leucogranite bodies in low-angle shear zones (Fig. 4a). Top-to-SSW/SW sense of shear implies a sinistral component of motion in the NE-trending shear planes, reverse to the overall dextral motion described in the PSB. Boudinage and pinch-and-swell of layers and foliation suggest shortening sub-perpendicular to the foliation (Price and Cosgrove 1990). Conjugate shear-bands are locally present, and granite bodies are also controlled by these structures.

Antithetic ductile top-down-to-NE extensional shear-zones may deform the solid-state fabric in the SAS and also control the emplacement of granitic bodies (Figs. 4c and e). In some places, decametric ductile extensional shear zones overprint the mylonitic foliation. However, these structures can also show relations that are compatible with the geometry of R'-C-C' systems during the main SW-directed ductile strain (see Fig. 4c, on the same outcrop). Moreover, these shear zones may also control the emplacement of leucogranite bodies (see detail in Figs. 4c and e). On the other hand, an S-C composite foliation may also suggest top-down-to-NE within the main mylonitic foliation in sections sub-parallel to the stretching lineation (Fig. 4f), in agreement with previous studies of the kinematics of the RSSZ (see Trouw 1995). Hence, our data suggest that normal motion may be slightly younger or contemporaneous with the SSW-directed ductile shearing. In the RSSZ within the ATS section (lower levels of structural domain I), the deformational fabric (mylonitic foliation and stretching lineation) is subparallel to the same primery fabrics as in SAS. SC fabrics, however, suggest ductile top-down-to-NNE sense of motion, as described by Trouw (1995). Although the same ductile fabric can be seen in the overlying S-type orthogneiss (structural domain I), shear-sense indicators are ambiguous due to the overprinting of strong flattening strain and S-tectonite development.

A subhorizontal mylonitic foliation occurs in the upper structural levels of the northern section (structural domain II of the ATS). In this region, folds with axes parallel to the extension lineation (extension-parallel folds) deform the flat-lying shear zones. In this domain, foliation is sub-parallel to the sub-horizontal compositional banding given by interlayering of sillimanite-garnet migmatitic paragneiss, calc-silicate rocks, amphibolite and porphyritic granites. Stretching lineation of coarse grained boudinaged sillimanite and feldspar crystals in flat-lying folded shear zones, plunges gently to the NE (see Fig. 3e). Shear-sense indicators such as S-C composite foliation, asymmetric boudins and pressure shadows around centimetric garnets are consistent with top-to-SW ductile shearing in sub-horizontal planes, sub-parallel to the orogenic trend and to the fold axes (see also Dehler and Machado 2002). These data are consistent with the SW-directed motion shown to occur in the SAS.

Kinematics and Geometry of the Late Structures

Structures superposed on the main ductile fabric occur in both cross-sections. In the SAS, a late structure is represented by sub-horizontal leucogranitic

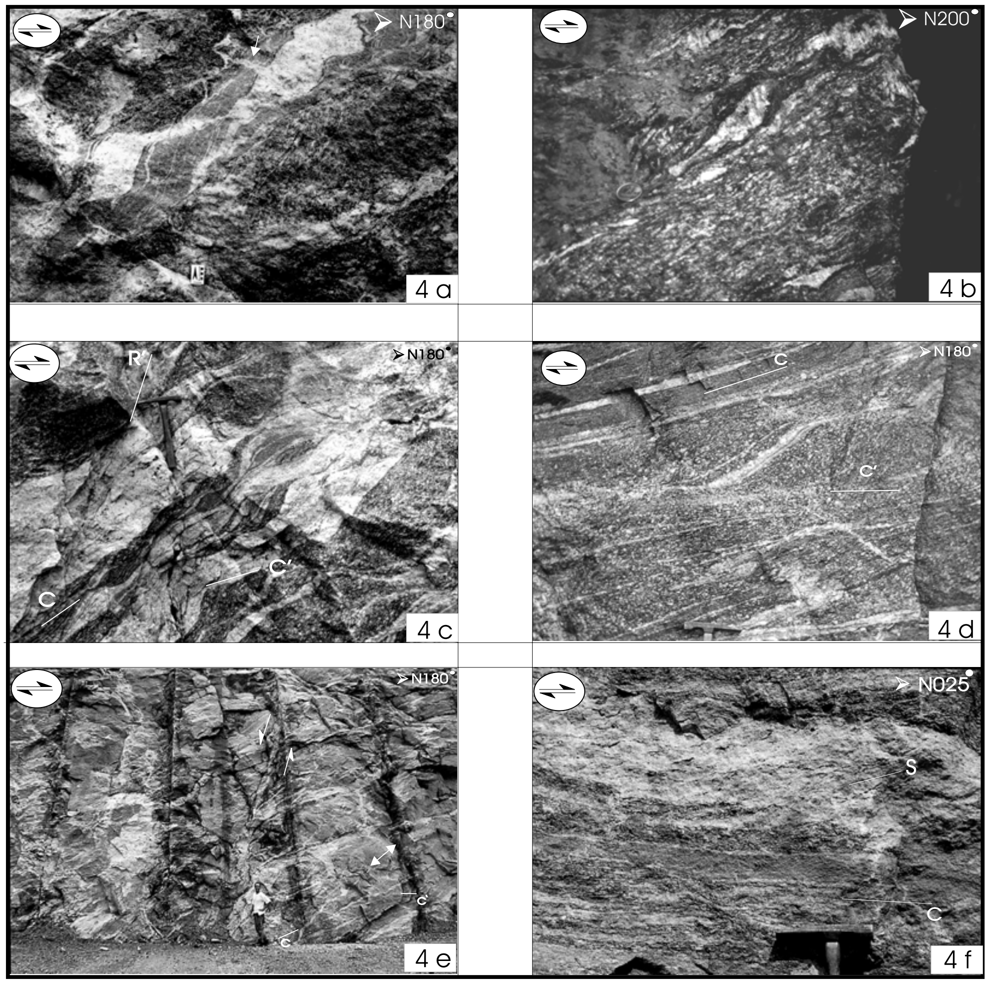

Fig. 4 – Kinematic indicators in the southern limb of the structural divergent fan (always in sections subparallel to the XZ plane of the finite strain elipsoid): (a) asymmetrical boudins and pinch-and-swell structures. Note the granite apophysis cutting the host granite – white arrow; (b) asymmetrical centimetric porphyroclast in high-grade, coarse-grained mylonites of the SAS; (c) asymmetrical pull-apart structure. Note the development of synthectic (C') and antithectic (R') shear band foliation and the association with leucogranite; (d) C' extensional shear-bands developed in orthogneisse mylonite of the RSSZ. All described structures suggest top-to-SSW sense of shear; (e) Decametric ductile extensional (top-down to NNE) shear band deforming the earlier SSW-directed fabric of the RSSZ (see also fig. 4c); (f) SC fabric deforming granite sheets in mylonitic orthogneiss. The asymmetry suggests top-down-to NE sense of shear.

dykes that show abrupt contacts and xenoliths of the host S-type orthogneiss. They can be controlled by ductile to ductile-brittle SE-directed thrust surfaces. Sub-horizontal ductile thrusts also occur in the ATS. In the RSSZ, in the northern section, along the contact zone between the banded mylonites and the S-type ortogneisses, a discrete mineral lineation is present, defined by mica and quartz, with striae-like structures (Fig. 3g), essentially restricted to the mylonitic foliation surfaces. Kinematics deduced from striae-step relationships suggest top-to-SE thrusting.

Mylonitic foliation is steeper in the uppermost part of the SAS and in structural domain I of the ATS, where strong flattening strain and S-tectonites occur. In this place the stretching lineation is poorly developed. In some strongly flattened shear zones, however, two mineral lineations are present (Fig. 3f): one defined by the alignment of coarse-grained sillimanite and feldspar, oblique to the foliation trend and plunging to NNE, and the second resulting from the sub-horizontal alignment of fine-grained mica, quartz and sillimanite. In these zones, shear-sense indicators suggest dextral shearing, and chocolate-tablet boudinage suggests stretching in horizontal and vertical directions (and hence transpressional strains – see also Dayan and Keller 1989).

Towards the upper structural levels of the ATS folded high-temperature mylonitic metasediments occur, interlayered with garnet-sillimanite bearing porphyritic granitoid sheets and subordinate orthogneiss. This folded domain defines structural domain II of the ATS (see discussion in Dehler and Machado 2002 – Fig. 2). Extension-parallel folds can be open to tight, and axial-surface foliation may be developed in the hinge zone. In sections normal to the hinge lines, folds may be cylindrical and may show strong thickening of the hinge zones. The axial surfaces are sub-parallel to the regional shear zone walls, with steep dips towards NW and subordinately towards SE (see stereographic projection in Fig. 3e). As described by Machado (1983) and Dehler and Machado (2002), folding may also be associated to SE-directed ductile thrusting, with the development of transpressional shear zones developed in strongly stretched and disrupted limbs.

DISCUSSION

Geometric Overprint Relationships and Transtensional Shearing in the RSSZ

The geometric overprinting relationships described in this paper have been previously described (e.g. Rosier 1957, Campanha 1981, Machado 1983, Heilbron et al. 1995, among many others). Extension-parallel folds, transpressional ductile shear belts and SE-directed thrusts deform NW-dipping and flat-lying high-temperature mylonitic foliation in the southern limb of the fan-like structure. Previous work suggests top-to NNE shearing in the earlier structures (Trouw 1995). However, our kinematic data suggest that the earlier movement was SSW/SW-directed.

This conclusion would lead to a new interpretation of the movement history of the RSSZ, because it is inconsistent with the folded thrust model proposed by Heilbron et al. (1991), in order to explain the oblique kinematics in the RSSZ (Fig. 5). It follows that the transtensional deformation observed in the RSSZ may be interpreted as a true crustal extensional deformation. Although geochronological data are lacking, structural relationships presented in this paper suggest that oblique extensional motion in this structure may be younger than previously interpreted.

Kinematic models proposed for the tectonic evolution of the belt, NW-directed thrusts followed by dextral transpression (Ebert et al. 1993, J.C.H. Almeida, unpublished data), or dextral transpression (Machado and Endo 1993, Ebert and Hasui 1998), do not fully explain either the earlier horizontal sinistral component observed in the southern limb of the divergent fan, or the transtensional motion of the RSSZ. Dehler (N.M. Dehler, unpublished data) suggested a tectonic extrusion model during regional oblique convergence in the PSB, in order to explain these major structural features of the regional fan-like structure (Fig. 5).

Extrusion Kinematics and a Model for Extensional Shearing in the RSSZ

Dehler and Machado (2002) suggested that the top-to-SSW ductile shearing in the PBS resulted from the oblique extrusion of the deep crust during oblique convergence. Assuming a reference frame fixed in the São Francisco Craton, and an E-W convergence direction (Wernick et al. 1981), the characterized lateral motion of the belt was dextral in relation to the stationary reference frame (see Figs. 6A and A_1). Hence, the proposed extrusion

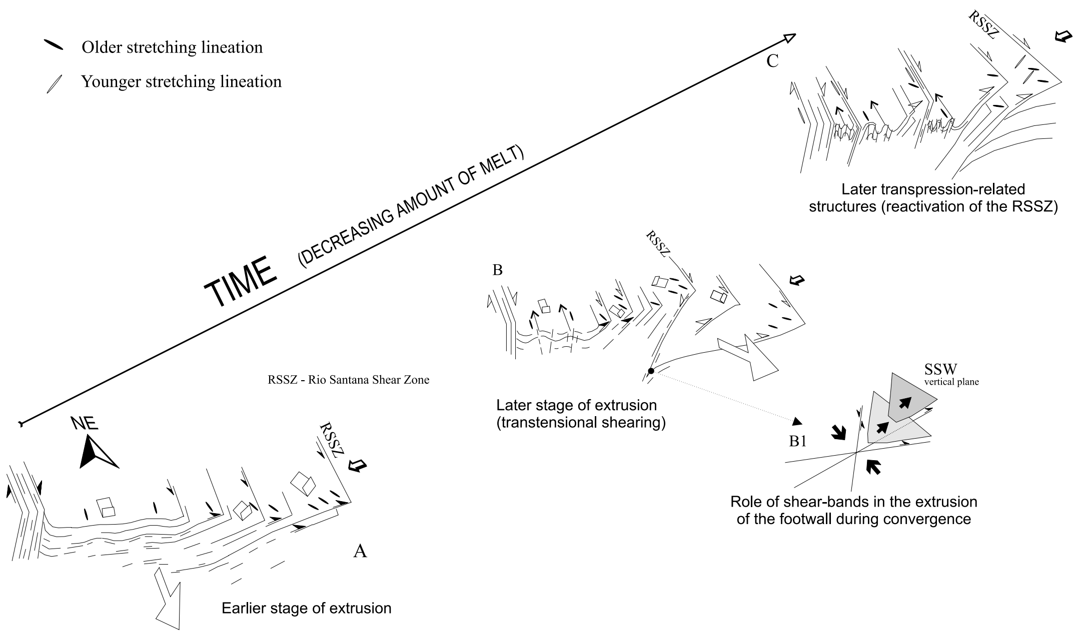

Fig. 5 – Cartoon showing the tectonic model for the southern limb of the structural divergent fan, and the extensional motion in the RSSZ: (a) Initial kinematic stage with high-temperature, transient melt-assisted SSW-directed motion (earlier extrusion stage); (b) Transtensional shearing nucleated in order to maintain strain compatibilities between obliquely moving, heterogeneously deforming and partially molten crustal slices (later extrusion stage). A sketch showing the interpreted role of the late shear bands on the extrusion of the footwall is also shown (b_1); (c) Thrusts, folds and ductile dextral shear zones resulting from progressive increase of finite transpressional strain (after N.M. Dehler, unpublished data). See text for further discussion.

model would explain the SW-directed orogenic parallel motion within the dextral kinematic picture interpreted for the PSB (see also Vauchez et al. 1994). The presented extrusion model, however, does not explain the transtensional strain. In our opinion, a model for a transtensional deformation along the RSSZ must also take into account not only the oblique extrusion of crustal fragments, but also the absence, until now, of recognized and widespread late-convergence extensional structures in the belt, the parallelism of the stretching lineation during the top-to SSW and NNE shearing, and the established geometric relations among different structures.

The structural data suggest that the NE-directed extensional motion in the RSSZ may reactivate or overprint the earlier top-to-SSW fabric. Stretching lineation and mylonitic foliation may be either parallel, or ductile extensional shear bands may cut the earlier formed foliation/shear zones (Fig. 4). Microstructural data suggest that the same minerals (sillimanite and feldspar) are aligned in the stretching direction in outcrops with the two kinematics, and that deformation in both stages occurred in the presence of melt. Thus, there is evidence that both shear movements occurred near anatectic conditions.

Using a simple bi-dimensional approach to the problem of shear sense reversals along the same stretching direction, it is suggested that the shift between the SSW- (sinistral thrusting) and NNE-directed motion (dextral transtension) may result only from the change in the sense of shear of the horizontal component parallel to the orogenic trend (Figs. 5a and 6b and b_1). Dehler (N.M. Dehler, unpublished data) used simple kinematic models suggesting that oblique convergence can be partitioned between a shear zone parallel component, responsible for the translation of a rock mass parallel to the margin, and an orthogonal or subduction component (Beck 1991, McCaffrey 1992 – see also Jiang et al. 2001) (showed in Figure $6a_1$). In these homogeneous models, however, the reverse slip would not occur.

Such bi-dimensional modeling suggests that the SSW-directed shearing would be associated to a horizontal sinistral component (transient extrusion component), reverse to the imposed dextral component (present in the NNE-directed extension). In our opinion, departures from the model and shear reversals are related to heterogeneous deformation (see also Hippertt and Tohver 1999). Hence, reverse shearing in the RSSZ (kinematics of the earlier structures) would be only possible if an increase in the longitudinal strain rate occurs, in relation to the externally applied deformational field (Figs. 6a and b). The tectonic situation may be due to transient changes in the rheological properties of deforming crust due to syn-tectonic intrusion/partial melting (strong strain softening – Hollister and Crawford 1986, Vigneresse et al. 1996), and heterogeneous longitudinal/oblique stretching coeval with orthogonal shortening and convergence (Means 1990). Dextral shearing would occur when the unstable and heterogeneous condition vanish and finite shortening strain increases (Figs. 5b and 6c).

Therefore, it is suggested that strong strain softening enhances oblique/lateral flow of hot crust during convergence, giving rise to a SSW/SW-directed tangential orogenic-parallel component of motion (stage A in Fig. 5). This would be responsible for the sinistral inverse shearing in the RSSZ , during the earlier stage of the extrusion (compare Figs. 6 a and b). On the other hand, the major ductile shear zone and rheological boundary at the base of the S-type orthogneiss shows evidence of dextral extensional motion, without change in the lineation trend (the same shear direction). We suggest here that the change of shear sense was also related to a change in the rheological conditions at hangingwall block. It is suggested that extensional motion in this structure would be coeval with a period of increasing relative strain hardening by cooling in the hangingwall, but still in the high-temperature realm. As strain softening decreases due to progressive crystalization of granitic melts in the partially molten hangingwall, the ability to accummulate the imposed strain rates decreases. Thus, the displacement of the hangingwall relative to the footwall also decreases (Figs. 5b and 6c). This process would lead, at a later stage, to the shear reversal in the RSSZ and to the relative collapse of the core of the divergent fan-like structure. At this time, the rocks in the footwall are obliquely extruded towards SSW, and are uplifted in relation to the hangingwall. One should notice that all stages would occurred during orogenic oblique convergence.

The proposed model envisage a heterogeneous behavior in order to explain the complex kinematic pattern in the RSSZ. Additionaly to the evolving rheological properties of deforming crust as responsible for the shear reversal in the RSSZ, a buttressing effect in this region would also lead to lock the reverse unstable component of motion (the SSW/SW-directed motion – see Figs. 5 and 6). This might also be possible in order to explain the shear reversal in the RSSZ. On the other hand, field data suggest that top-to SSW/SW movement occurred in the presence of leucogranitic melts. Thus, partially molten material would have been able to extrude laterally and vertically more easily, giving rise initially to sinistral thrusting and southwestward tangential motion in response to pure shear strain in deeper levels.

As discussed above, hardening by cooling would change relative longitudinal strain rates in different rheological domains, because a partially molten material would accommodate more easily the deformation (Grujic and Mancktelow 1998). At this time, extensional motion along the earlier foliation planes and extensional ductile shear zones could have been nucleated in order to maintain material compatibility between the oblique mov-

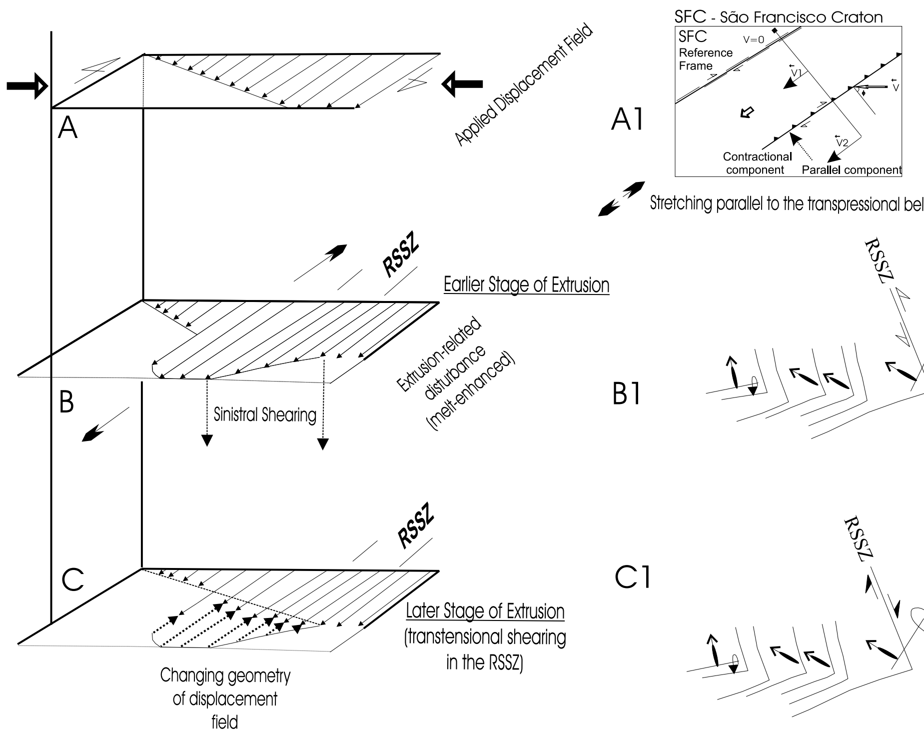

Fig. 6 – Simplified drawing showing in two dimensions (left column) the applied displacement field, and the inferred changes in the mechanical state interpreted as resulted from the extrusion tectonics. (a) regional transpressional displacement field imposed on the Paraíba do Sul Belt, resulted from the situation shown in a1; (b) Extrusion-related disturbance and extrusion of the partially molten hangingwall. Note the development of a horizontal sinistral component in the RSSZ (b_1); (c) Decrease in the relative displacement of the hangingwall, and nucleation of transtensional motion in the RSSZ and extrusion of the footwall (b) (c_1). See text for a full explanation.

ing slices during extrusion and oblique convergence. The finite structure resembles a triangle zone in cross-sections typical of extrusion tectonics (see Harz et al. 2001) (Figs. $5b_1$ and 6 b). The footwall obliquely extrudes toward the SSW and was uplifted during transpression and parallel motion (see inlet in Fig. 5b).

Ductile fabrics related to SSW-SW-directed shearing and to extensional motion in the RSSZ (late extrusion stage) are geometrically overprinted by extension-parallel folds, transpressional ductile shear zones and SE-directed ductile to ductile-brittle thrusts related to the later stages of transpressional deformation (Figs. 5c and 6c). This late stage also occurred in amphibolite facies conditions and in the presence of a lesser extent of melt, and may be related to the same regional transpressional deformation field.

CONCLUSIONS

Structural data from two cross-sections in the southern limb of a regional fan-like structure in the Paraíba do Sul belt suggest a two-stage kinematic evolution under high-temperature conditions: in the earlier stage top-to-SSW/SW thrust shearing; in the later stage, top-down to NNE/NE. In the first stage, the hot crust under transpression extrudes towarded obliquely towards SSW. The horizontal component of this movement in the shear zone was sinistral, reverse to the dextral component of late transtensional motion in the RSSZ. Changes in the rheological properties of rocks in the hanging wall led to decrease longitudinal strain rate during progressive deformation, and also transtensional shearing at the footwall of the hot crustal pile. At this stage, dextral transtensional motion reactivated the RSSZ.

Top-to-NNE transtensional shearing developed still at high grade conditions and in the presence of granitic melt. This transtensional movement have occurred along the same stretching lineation and under similar metamorphic conditions as regards to first stage. Extensional kinematics linked to southwestward motion in melt-lubricated thrusts formed triangle-like structures and accommodated oblique extrusion of the footwall. Later structures related to regional dextral transpression deform the earlier extrusion-related structures, and may be related to the same convergent-deformation field as in the earlier stage.

Finally, we propose that the transtensional deformation characterized in this paper not is related to a classical post-orogenic collapse setting. On the contrary, the transtensional strain appears to be genetically related to the regional transpressional strain.

ACKNOWLEDGMENTS

This work was supported by Companhia de Pesquisa de Recursos Minerais – CPRM and Fundação de Amparo à Pesquisa do Estado de São Paulo – FAPESP (Grant 1998/0912-8). RM gratefully acknowledges Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) research fellowships (30.0423/ 82-9). The final english version was carefully reviewed by Dr. Marcus Waring di Valderano and by Wilson Marson.

RESUMO

A geometria das zonas de cisalhamento no Cinturão Paraíba do Sul no Rio de Janeiro, sudeste do Brasil, delineia uma estrutura-em-leque com direção NE. Estas zonas de cisalhamento mergulham para SE no flanco norte, e para NW no flanco sul da estrutura. Esta geometria tem sido interpretada de duas formas: (a) implantação de um regime transpressivo ou (b) dobramento tardio de superfícies de empurrão originalmente sub-horizontais. A lineação de estiramento mineral mostra caimento para ENE-ESE, no flanco norte, e para NNE-NE, no flanco sul, onde ocorre a Zona de Cisalhamento do Rio Santana. No flanco sul da divergência-em-leque, os dados estruturais sugerem uma evolução tectônica em dois estágios, sob condições de alta temperatura: um estágio precoce, envolvendo empurrões oblíquos sinistrais e movimentos tangenciais paralelos ao orógeno com cinemática de topo para SSW-SW, e um estágio tardio, envolvendo deformação transtrativa destral, com movimento de topo para NNE-NE. Propõe-se aqui um modelo de deformação heterogênea para explicar esta inversão cinemática. Neste modelo, durante a deformação progressiva, o gradiente do campo de movimento transpressivo pode variar de duas maneiras: (a) por mudanças transitórias na reologia da crosta ou (b) por mudanças no componente de cisalhamento puro. No estágio precoce, o material parcialmente fundido acomoda mais facilmente as deformações impostas, ocorre cisalhamento dúctil com movimento de topo para SSW-SW. À medida que ocorre o decréscimo do distúrbio termal e aumenta a razão de convergência, instala-se um regime de deformação cisalhante transtrativa com movimento de topo para NNE. Sugere-se que esta deformação transtrativa esteja relacionada a uma tectônica de extrusão associada à deformação transpressiva regional.

Palavras-chave: deformação transtracional, extrusão, transpressão, divergência em leque.

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