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Ductile duplexing at a bend of a continental-scale strike-slip shear zone: example from NE Brazil

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Abstract—During the Pan-African orogeny, the Borborema Province in NE Brazil developed a continental-scale shear-zone system that comprises NE- and EW-trending ductile strike-slip shear zones. Remote sensing and structural mapping has revealed a pattern of arcuate anastomosing strike-slip shear zones separating sigmoidal lenses of less deformed material, located at the western end of the EW-trending Patos shear zone, which is one of the largest shear zones of the Province. This structure of imbricate shear zones was initiated under high-temperature deformation conditions. It is interpreted as a ductile strike-slip duplex and may represent a kinematic pattern for strain accommodation in response to a bend of a ductile mega-shear zone.

INTRODUCTION

The concept of duplexes was first applied to structural geology to designate a special kind of imbricate fault system associated with thrust tectonics (Dahlstrom 1970, Boyer & Elliot 1982). A duplex involves a set of imbricate faults that transfer the displacement from a floor thrust to a roof thrust. The imbricate faults usually curve asymptotically towards the two bounding-faults of the thrust, and delineate lens-shaped imbricate units. Duplexes tend to develop in areas of complex kinematics, for instance at a flat–ramp–flat transition due to a change in gliding horizons. Extensional duplex structures have also been described for rifted basin margins, where listric normal fault arrays with flat–ramp footwalls are responsible for imbricate faulting (Gibbs 1984). Finally, the development of strike-slip duplexes associated with transcurrent tectonics was suggested by Woodcock & Fischer (1986). Examples of outcrop- to regional-scale strike-slip duplexes, which appear to have formed to accommodate the jog between en échelon faults (Woodcock & Fischer 1986, Swanson 1988, 1990), are abundant in rocks deformed in the brittle field or at the transition between the brittle and ductile fields. Whatever their tectonic environment, the development of duplex structures appears as an accommodation process for local perturbations of the kinematic field. In this paper, we present evidence suggesting that duplexing occurred under high-temperature ductile conditions, at a bend of a continental-scale transcurrent shear zone.

GEOLOGICAL SETTING

During the Late Proterozoic Brasiliano orogeny, a complex network of continental-scale ductile strike-slip shear zones developed in the Borborema Province of NE Brazil (Fig. 1). These shear zones are typically several hundreds of kilometres long and ten to a few tens of kilometres wide, forming a kinematically consistent system over more than 200,000 km^2 (Mello 1977, Santos & Brito Neves 1984, Caby *et al.* 1991). Many of these Precambrian ductile shear zones suffered reactivations in the brittle regime during the Cretaceous time (Magnavita 1992, Destro *et al.* 1994, Françolin *et al.* 1994). Considering the continuity of the Borborema shear zone system over a huge area, the continental composition of the crust in which the shear zones were formed, the existence of a long pre-kinematic history dominated by the development of extensional basins around 1.8 and 1.0 Ga (Sá *et al.* 1991, Van Schmus *et al.* 1993) and the long-lasting magmatic history, Vauchez *et al.* (in press) suggested that the Borborema shear zone system was formed within a continental plate. The rock units exposed within the Borborema province and involved in the shear zones can be subdivided into three. (1) A Pre-Brasiliano basement, Archean–Lower Proterozoic in age (De Souza *et al.* 1993), which is mostly composed of supracrustal formations intruded by plutonic rocks now converted into high-grade gneisses, some migmatitic, and comprising lenses of mafic rocks and amphibolites. (2) Neo-Proterozoic metasedimentary units including a lower platform-type sequence older than 1.8 Ga with

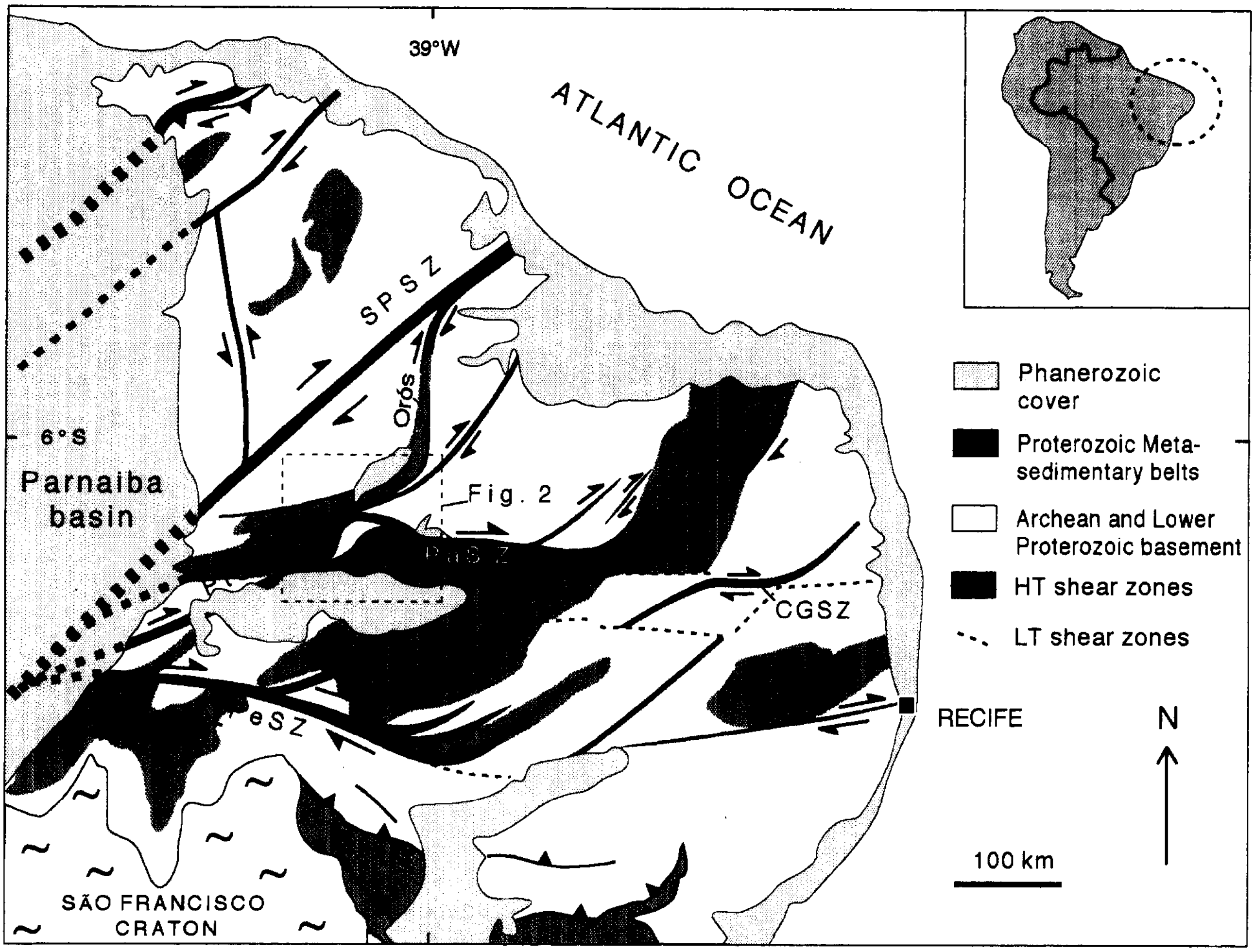

Fig. 1. Location of the ductile strike-slip duplex in the shear zones system of the Borborema Province, NE Brazil. CGSZ, Campina Grande shear zone; PaSZ, Patos shear zone; PeSZ, Pernambuco shear zone; PtSZ, Potengi shear zone; SPSZ, Senador Pompeu shear zone.

quartzites, pelites, marbles and calc-silicates suggestive of local evaporitic conditions and a younger, unconformable pelitic unit possibly younger than 1 Ga (Caby *et al.* in press). (3) Syn- to late-kinematic brasiliano granitic intrusions (Archanjo 1993) which were emplaced between 650 and 550 Ma.

Two domains displaying contrasting tectonic characteristics may be considered (Fig. 1): (i) a northwestern domain where dextral ductile strike-slip shear zones are NE-trending and continuous over hundreds of kilometres (Caby & Arthaud 1986), and (ii) a central and southeastern domain characterized by EW-trending dextral ductile strike-slip shear zones that display a more sinuous shape and are often connected to N–NE-trending metasedimentary belts (Sá *et al.* 1991, Corsini *et al.* 1992, Vauchez & Da Silva 1992, Davison *et al.* 1995).

In the entire system, the main deformation is coeval with low pressure, high temperature peak metamorphism. Local partial melting and emplacement of syn- to late-kinematic granites were partly controlled by the shear zones.

Recent $^{40}Ar/^{39}Ar$ analyses were performed on single grains of amphibole, biotite and muscovite from rocks (reworked pre-Brasiliano basement, Proterozoic metasediments and Brasiliano intrusives) sampled in the whole area. Ages recorded within the Patos and Campina Grande shear zones and the Seridó belt range from 560 to 490 Ma (Figueiredo *et al.* 1992, Féraud *et al.* 1993). In the Seridó belt, the syn-kinematic pluton of Acarí (Jardim de Sá *et al.* 1986, Archanjo 1993) yield U–Pb on zircon ages of 555±5 Ga (Legrand *et al.* 1991) and 579±7 Ga (Letterier *et al.* 1994). These dates, beyond the confirmation of the Brasiliano age of the main tectono-thermal event, provide good evidence that deformation and metamorphism were coeval in the different branches of the system. Thermochronology (Dodson 1973) also suggests a high thermal gradient over the whole area and a relatively low rate of cooling during the shear-zone related deformation at high temperature, followed by fast cooling and exhumation.

CONNECTION OF THE WESTERN AND EASTERN DOMAINS

Although the western and eastern domains display different deformation patterns, their mechanical continuity is suggested by the connection of the EW-trending Patos shear zone that belongs to the eastern domain,

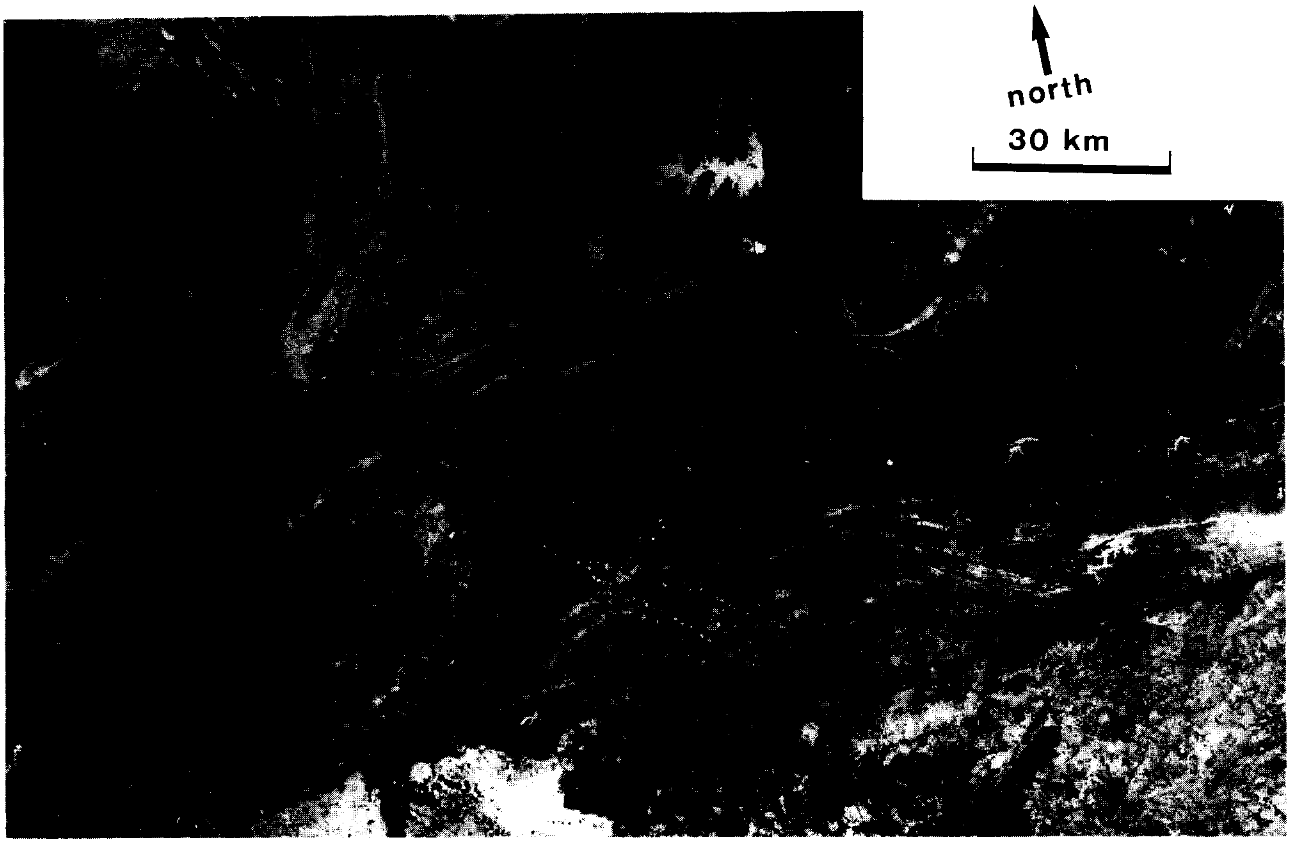

Fig. 2. Mosaic of Landsat images showing the imbricate shear zones and less deformed unit developed at the junction between the EW-trending Patos shear zone and the NE-trending Potengi shear zone. Outline shown in Fig. 1.

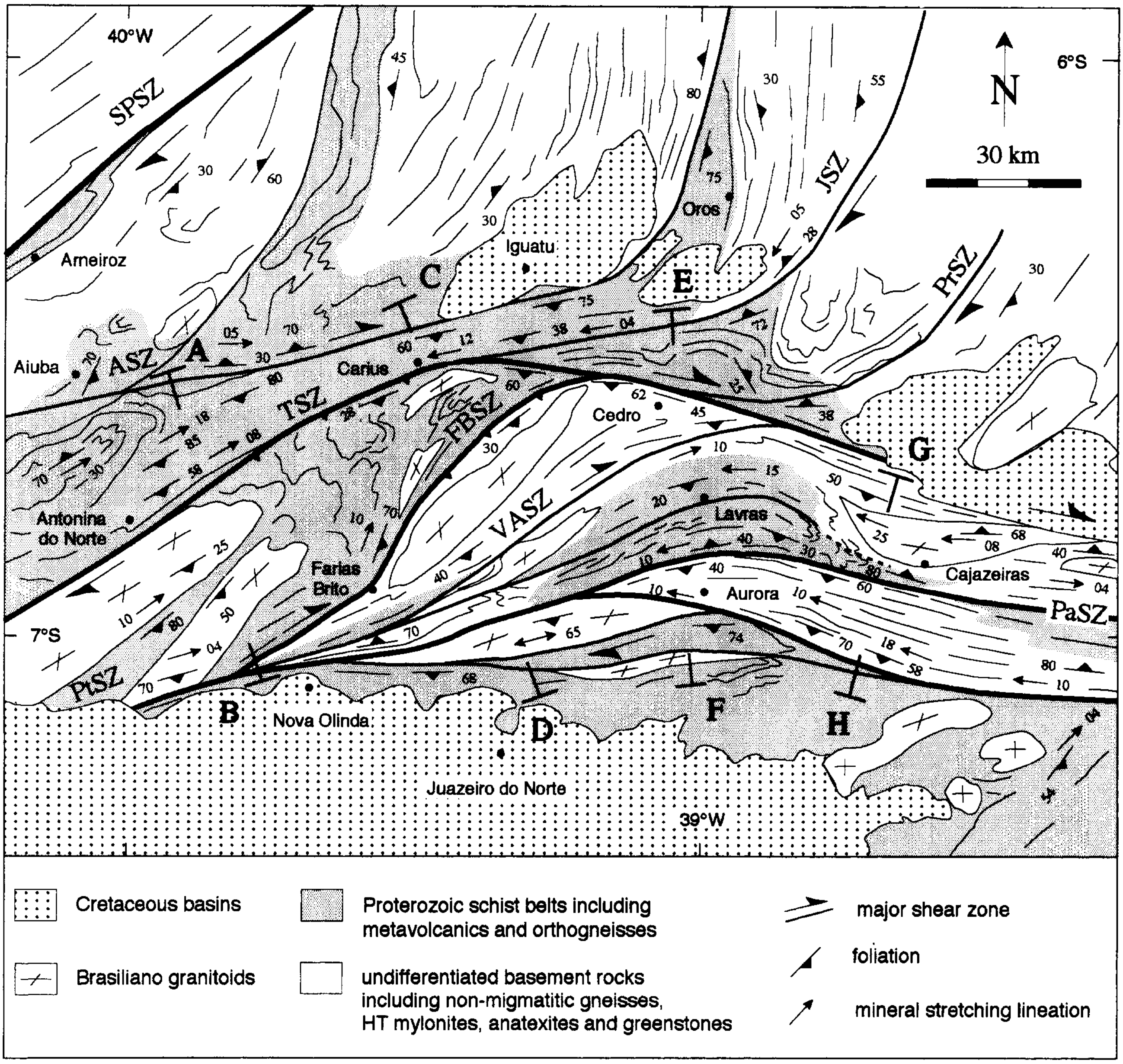

Fig. 3. Geologic sketch map of the duplex; compare with Fig. 2. ASZ, Aiuba shear zone; FBSZ, Farias Brito shear zone; JSZ, Jaguaribe shear zone; PaSZ, Patos shear zone; PtSZ, Potengi shear zone; PrSZ, Portalegre shear zone; SPSZ, Senador Pompeu shear zone; TSZ, Tatajuba shear zone; VASZ, Varzea Alegre shear zone. Minor molassic, Mesozoic basins and related extensional faults have been omitted. A–B, C–D, E–F and G–H indicate lines of sections in Fig. 4.

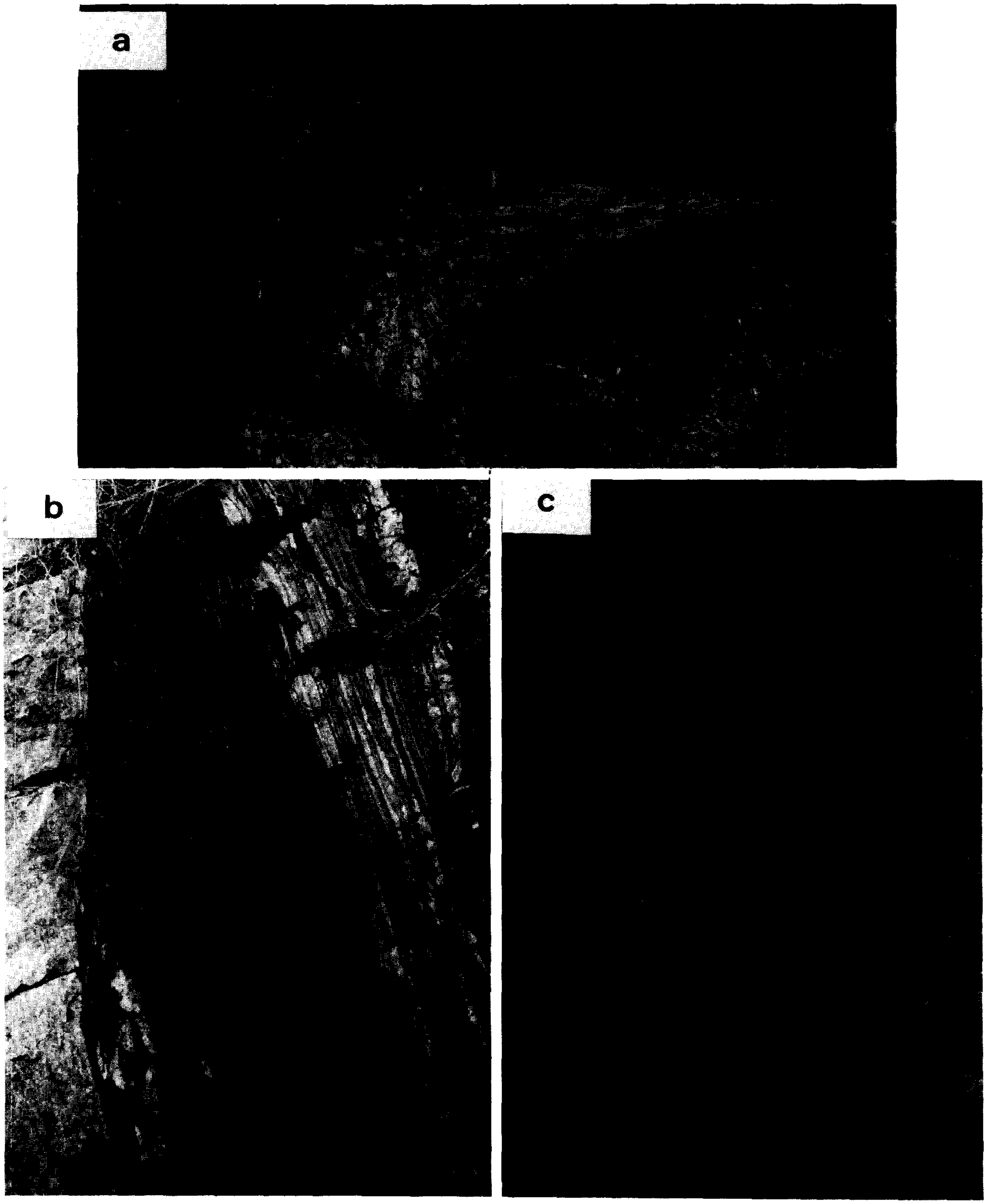

Fig. 5. (a) Metaconglomeratic layer in the vicinity of Lavras with recumbent cleavage showing a strong elongation of quartzitic and hematitic pebbles. The hematitic pebbles display a pencil-shape with an average ratio of 1:4:40 (bedding is vertical). (b) Mylonitic zone north of Lavras. Three rock types can be recognized: (1) mylonitic gneiss with boudined leucosome veins on the right; (2) dark biotite-rich mylonitic schists with dispersed plagioclase-rich boudins and clasts in the center; and (3) a cross-cutting granodiorite vein of assumed Brasiliano age with protomylonitic fabric (area of view is vertical). (c) Migmatitic orthogneiss at Aurora showing the development of steep transtensional shear bands injected by leucocratic veinlets. This cuts at high angle the previous foliation bearing southeast horizontal lineation (area of view is horizontal).

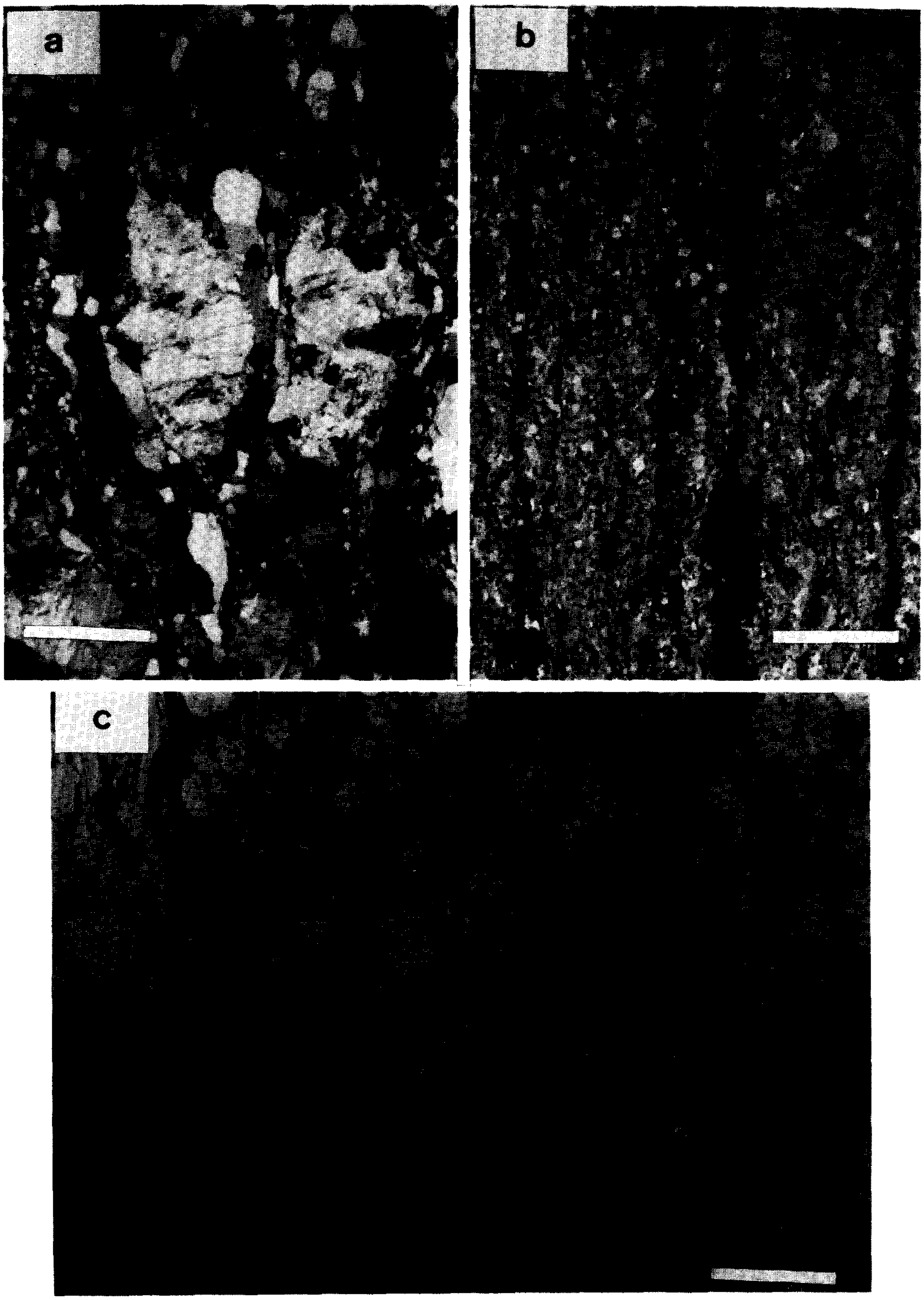

Fig. 6. (a) Coarse-grained mylonite with large feldspar porphyroclasts and elongate quartz ribbons. (b) Mylonitic granodiorite gneiss. Amphiboles (dark) form elongate polycrystalline clasts whereas plagioclases form asymmetric augen. (c) Relatively fine grained mylonite displaying asymmetric feldspar porphyroclasts with finely recrystallized tails in a quartz-rich matrix. Scale bar is 3 mm, with crossed nicols for all micrographs.

with the NE-trending Potengi shear zone that belongs to the western domain. The Patos shear zone (Fig. 1), up to 30 km wide, extends over 400 km (Amaro *et al.* 1991, Corsini 1995). It is delineated by a steep belt of high-grade, mylonitic and migmatitic gneisses that consistently display a sub-horizontal mineral stretching lineation. Mylonitization occurred at high temperature and was coeval with the percolation of syn-kinematic mobilizates through most rock types. This resulted in the development of coarse-grained mylonites, frequently migmatitic. Lower amphibolite to greenschist facies mylonites and ultramylonites are restricted to narrow belts, especially along the southern boundary of the Patos shear zone where a continuous belt, some hundreds of metres to a few kilometres wide, sharply delimits the high-temperature mylonites from the Salgueiro–Cachoeirinha low-grade metamorphic domain. Eastward, the Patos shear zone merges into the NE-trending Seridó sedimentary belt (Corsini *et al.* 1991) where the deformation is characterized by NNE-trending folds with a fan-like foliation associated with stretching, and ductile strike-slip shear zones parallel to the strike of the belt (Jardim de Sá 1984, Archanjo & Bouchez 1991). Corsini *et al.* (1991), on the grounds of remote-sensing, structural, geophysical, metamorphic and geochronological data, suggested that the Patos shear zone and the Seridó transpression belt are in structural continuity, and that most of the strain was transferred from the shear zone into the belt.

Westward, the Patos shear zone progressively curves southwestward and then connects with the Potengi NE-trending shear zone. The transition of the dominant structural trend from E–W to NE–SW is underlined by an arcuate array of anastomozing shear zones up to 50 km wide and 150 km long. This structure, clearly visible on satellite images (Fig. 2), is geometrically similar to duplexes and horses developed in thrust tectonics; its northern and southern boundaries are underlined by mylonite belts that are similar to roof and floor thrusts. Imbricate units are made of several lenses of unmylonitized material (metasediments, basement gneisses or igneous bodies) wrapped around by kilometre-wide sigmoidal shear zones that link the southern and northern boundaries (Fig. 3). Eastward, all shear zones merge together to form the Patos shear zone. Subsidiary NE-trending shear zones (e.g. Portalegre and Jaguaribe shear zones) splay off from the duplex and the NS-trending Orós metasedimentary belt is in structural continuity with the Tatajuba shear zone.

In the NE- and EW-trending rectilinear branches of the system, the mylonitic foliation is consistently steeply dipping, whereas, at the bend, low- and high-angle mylonitic foliations coexist, suggesting a complex deformation regime. In the arcuate shear zones, the dip of the foliation decreases gradually from south to north (Fig. 4). The systematic southward dip of the shear zones (Fig. 3) clearly outlines the asymmetry of the system. Moreover, the inward dipping geometry of the imbricate shear zones suggests that they converge at depth into a single shear zone (Fig. 4) and globally define a positive asymmetric flower structure (Sylvester & Smith 1976, Harding 1985).

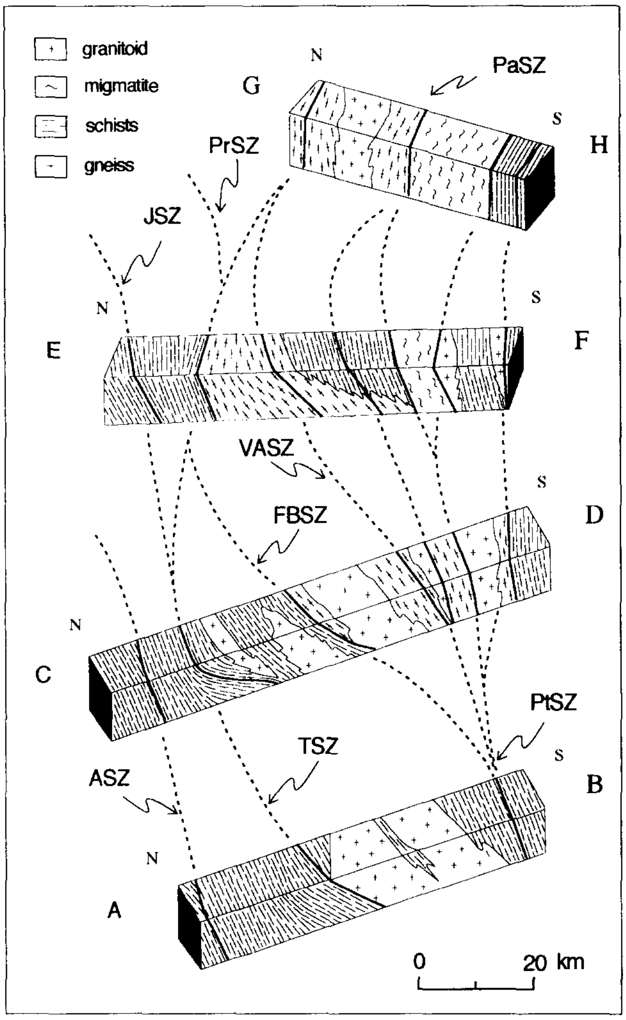

Fig. 4. Schematic block diagram of the duplex (see location of profiles on Fig. 3). ASZ, Aiuba shear zone; FBSZ, Farias Brito shear zone; JSZ, Jaguaribe shear zone; PaSZ, Patos shear zone; PtSZ, Potengi shear zone; PrSZ, Portalegre shear zone; TSZ, Tatajuba shear zone; VASZ, Varzea Alegre shear zone.

DEFORMATION WITHIN THE DUPLEX

Shear zones

Shear zones within and around the duplex correspond to relatively narrow zones of intense mylonitization, which reach up to a few kilometres thick, bounded by domains in which a clear deformation gradient makes the transition to less deformed adjacent domains. Around the duplex, the mylonitic foliation dips steeply toward the southeast and consistently bears a sub-horizontal mineral stretching lineation (Fig. 3) marked by elongated aggregates of quartz and feldspar in orthogneisses and by pressure shadows over syn-kinematic garnet and alignment of mica flakes in the pelitic metasediments. Various kinematic criteria including S/C fabric, asymmetric recrystallized tails over porphyroclast and sigmoidal lenses have been observed in the different branches of the system. They suggest that all the shear zones have the same dextral sense of shear over the entire system independently of their trend. Within the duplex (e.g. the Farias Brito shear zone), the dip of the foliation decreases gradually from south to north and locally places the high-grade gneisses of the basement on top of the metasedimentary sequences (Fig. 4). Although the lineation remains sub-horizontal whatever the dip of the foliation, this abnormal superposition suggests a component of northwest-directed thrusting.

Various types of mylonites to ultramylonites are exposed in the shear zones (Fig. 5b), reflecting deformation under decreasing temperature conditions. Coarse-grained mylonites display: (1) polycrystalline ribbons of large quartz grains with a tabular shape and linear boundaries (Fig. 6a), that sometimes involve a foliation marked by aligned micas, amphiboles or small plagioclase grains (Fig. 6b); (2) K-feldspar porphyroclasts with core and mantle structure due to replacement of K-feldspar by plagioclase and quartz aggregates; (3) plagioclase porphyroclasts with undulose extinction and some subgrain boundaries, that respectively suggest extensive grain-boundary migration of quartz, breakdown of K-feldspar and incipient dislocation creep in plagioclase. All these processes are indicative of mylonitization under high-temperature conditions.

Finer-grained mylonites containing a high amount of matrix (up to 50%) and ultramylonites have been deformed under retrograde conditions down to greenschist facies metamorphism. They display feldspar clasts with dynamically recrystallized tails (Fig. 6c) embedded in a quartz–mica matrix rich in pale-brown to green biotite and white mica, plagioclase clasts with asymmetric pressure shadows in which elongate quartz grains have recrystallized, and well-defined oblique quartz grain-shape fabric in quartz ribbons. These low-temperature fabrics result from re-working of high-temperature mylonites and suggest that the shear zones initiated during the peak of metamorphism and remained active during cooling. However, with decreasing temperature, the deformation was localized in narrower shear zones, up to a few hundred of metres thick.

The lenses

In the lenses between the shear zones, the rocks also display penetrative structures. The ductile deformation is less intense than in the mylonite but still pervasive and characterized by a nearly horizontal planar and linear fabric. The origin of this fabric is not known: it is in perfect continuity with the mylonitic fabric in the shear zone, yet the flat-lying foliation is preserved away from the main shear zones, both in the basement and in the Proterozoic cover throughout the Borborema Province. Locally, the low angle foliation observed in the reworked basement around Aurora (Fig. 3), in the lenses within the duplex, clearly pre-dates the shear zone development. In the imbricated units, both the stratification and the main foliation have been folded by N-verging asymmetric folds. These folds display, at different scales, a new axial-plane cleavage and usually sub-horizontal axes. Metasediments are mostly preserved in synforms separated by basement antiforms (Fig. 4). At the scale of an individual lens, folds display an en échelon pattern consistent with dextral shearing. A mineral-stretching lineation parallel to the fold axis was consistently recorded in all rock types. Locally at Lavras (Fig. 3), in metaconglomerates, stretching results in a severe elongation of pebbles (Fig. 5a). Strain within the imbricate units is thus characterized by a direction of principal extension and shortening respectively parallel and perpendicular to the shear zones that bound the lenses, suggesting a transpressional deformational regime.

Structural continuity, coherent kinematics and similar deformation conditions in the entire system suggest that transcurrent and compressive deformation are contemporaneous and indicative of transpressive tectonics.

DEFORMATION CONDITIONS

Microstructures and metamorphic mineral assemblages suggest that the mylonitization was initiated under high-temperature, low-pressure metamorphic conditions. The highest grade is recorded at the more eastern part of the duplex along the Patos shear zone. South of Aurora, shearing of orthogneisses from the reworked basement was synchronous with the emplacement of anatectic mobilizates (Fig. 5c). Metapelites sampled south of Cajazeiras (Fig. 3) display the mineral assemblage: Ti-rich biotite, plagioclase, garnet and sillimanite with prograde Fe–Zn spinel. Biotite–garnet rims suggest temperature around 700°C for $P = 5\text{–}6$ Kb during shearing. In the duplex area in the vicinity of Lavras, non-anatectic metapelites of the Proterozoic cover display the mineral assemblage: quartz, biotite, plagioclase, andalusite including garnet, cordierite and late muscovite, suggesting lower temperatures. Less severe metamorphic conditions were reached northwest of the duplex in the southwestern part of the Orós belt. The mineral assemblage, two micas, andalusite, staurolite and garnet, around Orós, implies temperature around 550°C for $P < 4$ Kb. Northwest of the FBSZ, regional metamorphic conditions culminated in lower greenschist facies conditions. Metapelites contain syn-S_1 tiny white mica, albite and later green biotite. Secondary chlorite crystallized in the regional crenulation cleavage is well developed close to dextral shear zones parallel to the western part of the Orós belt.

In conclusion, there is no change between the regional metamorphic conditions and those having occurred within the shear belts. However, retrograde greenschist facies conditions affected the mylonitic belts to varying degrees, with the activation of C planes underlined by chlorite superimposed onto two-mica mylonitic fabrics. It is significant that high-temperature protomylonitic to mylonitic fabrics affecting many shear-zone related granitoids did not register any low-temperature conditions, therefore arguing for their Brasiliano age.

DISCUSSION AND CONCLUSION

The deformation pattern observed at the junction of the Patos shear zone with the Potengi shear zone is very similar to duplexes formed at ramp–flat transitions in thrust tectonics, where duplexing results in arcuate structures that are convex upward in cross-section and result from stacking of lenticular units or 'horses'. The Potengi and Tatajuba shear zones show geometric and kinematic similarities with floor and roof thrusts respectively, whereas the Farias Brito and Varzea Alegre sigmoidal shear zones are analogous to subsidiary shear zones that limit horses in thrust tectonics. This similarity may suggest that the system of imbricated shear zones surrounding lenses of less deformed material may represent a case of duplexing due to a perturbation of the kinematic field, associated with a change in flow direction from NE–SW to EW (Fig. 7). The Potengi and Patos shear zones are in structural continuity and therefore are likely to represent two branches of the same curved shear zone that accommodated respectively a northeastward and an eastward flow; the duplex formed in the connection area.

Strikingly, there is no structural complication south of the duplex. However, if the southern domain really were displaced along the southern boundary of the Patos–Potengi shear zone system, it would have been subjected to a local compression due to the necessity for the rocks to accommodate the curvature of the flow direction from one branch of the system to the other. On the contrary, all structural complications are developed north or northwest of the southern boundary of the system. This suggests that the northwestern and northern domains moved relative to a southern, more rigid, domain. The structural system had to accommodate a relatively abrupt transition from dominant northeastward motion along the Potengi shear zone to a dominant eastward motion along the Patos shear zone, and the solution should satisfy kinematic compatibility. The change in flow direction occurs over a relatively short distance (*ca* 100 km) and in this case, duplexing, i.e. partitioning of the deformation in several shear zones, each accommodating a moderate component of curvature, undoubtedly represents an easier process in terms of kinematic compatibility (Fig. 7). Folding within the lenses together with a subsidiary thrust component of movement within the transcurrent shear zones that bound the imbricate units suggests that a transpressional deformation regime prevailed in the duplex. Transpression may also account for the change in dip of the shear zones from high angle in the internal part to low angle in the external part of the bend.

Duplexes formed in relation to strike-slip tectonics differ from those formed in thrust belts, in that the mechanism in the former is independent of the existence of any décollement level or overburden load. Instead of transferring slip from a lower to a higher level, strike-slip duplexes develop to accommodate local perturbation of the strain field. Nevertheless, the existence of an inherited foliation that entails an anisotropic mechanical behaviour of the rocks may considerably influence the geometry of the duplex (Fig. 8). The transition from high- to low-angle mylonitic foliation, and the accommodation of a subsidiary thrust component on the flat-lying shear zones, may have been favoured by the low-angle fabric that pre-dates the shear zones. Moreover, changing of the flow direction was certainly allowed by the low strength of crustal material due to high-temperature conditions and partial melting during deformation. Such curvatures are common in the Borborema shear zone system; they systematically formed in relation to high-temperature mylonitization, and have escaped from the low-temperature reactivation of the shear zones (Vauchez & Da Silva 1992).

It remains more difficult to account for the bending of the movement zone. The NE-trending shear zones of the western part of the Borborema Province probably represent the main movement zones of the system. Their development may be related either to an oblique collision at the northwestern margin of the continent or to a perturbation of the first-order strain field by the termination of the São Francisco craton. The huge E–W trending strike-slip shear zones that splay off the NE-trending shear zones may have been formed because of the existence of large-scale crustal heterogeneities, such as ancient basins which were easier to deform (Vauchez

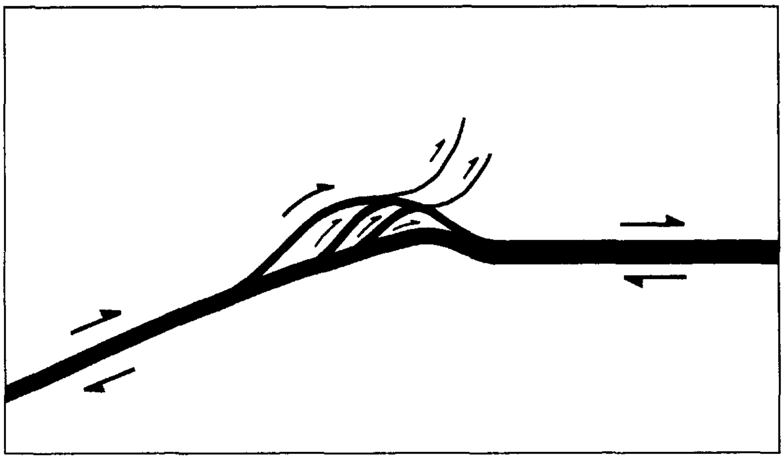

Fig. 7. Schematic planar model of the duplex structure developed at a bend.

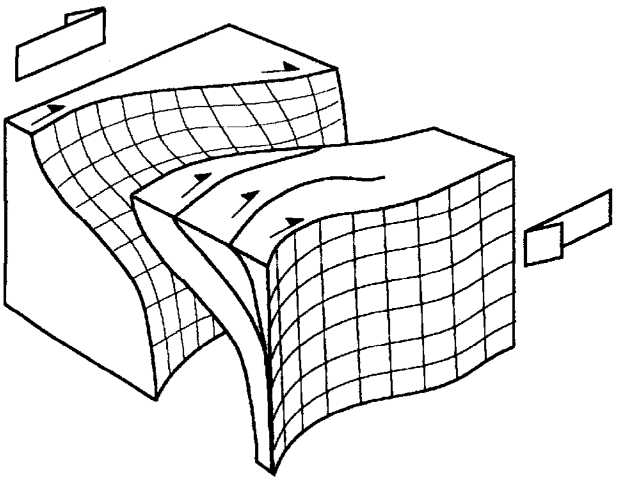

Fig. 8. Interpreted structure of the strike-slip duplex in three dimensions.

& Tommasi 1993). Another possibility is that the Patos shear zone already existed, and so represents an ancient transcurrent shear zone formed during the opening of intracontinental basins. In this case, the connection of the two branches of the system results from the intersection of a later-formed shear zone propagating northeastward, with a pre-existing E–W trending shear zone.

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