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Assessing the tectonic significance of a large-scale transcurrent shear zone system: the Pernambuco lineament, northeastern Brazil

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Abstract

The Pernambuco lineament (Borborema province, northeastern Brazil) is traditionally considered a continuous, 700 km-long dextral, E–W strike-slip shear zone. It is interpreted as a fundamental tectonic element of the Brasiliano/Pan-African orogeny, and proposed to continue into West Africa as the Sanaga or Amadoua faults. Recent structural work reveals that the Pernambuco lineament is segmented into two branches separated by more than 100 km. This study shows that the eastern branch, the East Pernambuco Shear Zone system, consists of two high-temperature (amphibolite facies) and several low-temperature (greenschist facies) mylonitic belts, which are laterally and transversely discontinuous. The main protoliths of the mylonites are magmatic rocks; country rocks proximal to the shear zones are little affected by strike-slip shearing, either at high- or low-*T* conditions. The high-*T* mylonitic belts are located at the southern border of a major granitoid batholith, and the low-*T* belts form a series of overlapping right-stepping shear zones to the south and east of them. These observations strongly indicate that the Pernambuco lineament is not a transcontinental structure, that it was not responsible for significant displacements or for emplacement of large magmatic bodies, and, consequently, that its tectonic role during the Brasiliano event was secondary. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Large-scale intracontinental strike-slip faults and ductile shear zones are prominent structures in modern (e.g. Tapponier and Molnar, 1977) as well as in ancient orogenic belts (e.g. Daly, 1988). Assessing the geometry, length and total displacement of these movement zones is of great tectonic interest since large displacements may be responsible for the juxtaposition of terranes with contrasting histories and for the development of localized zones of extension (which may act as preferential sites for magma emplacement) or compression. In many cases, they have a fundamental tectonic role, as exemplified by the Himalayan and southeastern Asia shear zones, which accommodated hundreds of kilometers of displacement (e.g. Lacassin et al., 1993). However, even in the Himalayan case, some large active faults have modest movements (<100 km) when compared with their length, as exemplified by the 1600 km-long Altyn Tagh fault zone (Wang, 1997). Some large ductile shear zones in high-grade terranes also appear to have been very inefficient from a kinematic point of view. For instance, the Striding–Athabasca shear zone (Canada), in spite of having a length in excess of 500 km and a width up to 20 km, probably did not accommodate major wall-rock displacement (Hanmer et al., 1995). In yet other cases, proposed crustal-scale shear zones have failed to qualify as such when subjected to closer scrutiny (Hanmer et al., 1997; Grujic and Mancktelow, 1998).

Continental-scale transcurrent shear zones are the main structural expression of the Brasiliano (Pan-African) orogeny in the Borborema province of northeastern Brazil (Fig. 1a; Brito Neves, 1983; Caby et al., 1991; Vauchez et al., 1995). Development of the shear zone system was coeval with abundant granitoid magmatism and high-grade metamorphism (Caby et al., 1991; Vauchez et al., 1995; Neves and Mariano, 1997).

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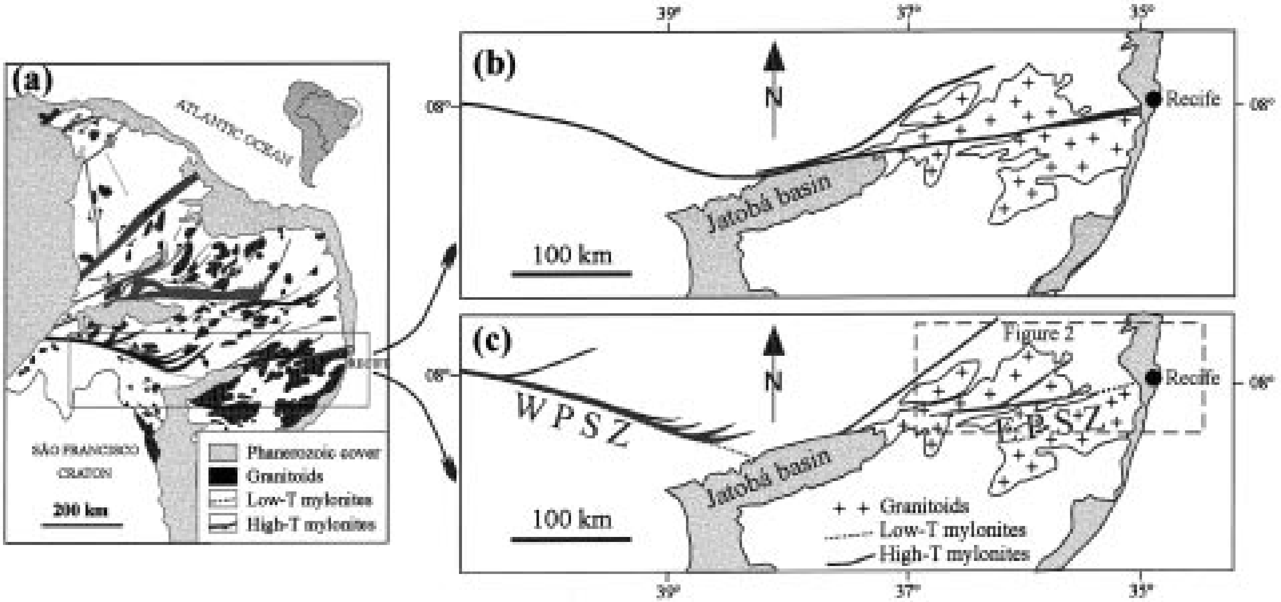

Fig. 1. (a) Generalized geological map of Borborema province showing the main shear zones and Brasiliano granitoids (based on Vauchez et al., 1995). (b) and (c) Contrast between the two views regarding the structure of the Pernambuco lineament. (b) The conventional representation of the Pernambuco lineament as a continuous shear zone (simplified from Brito Neves et al., 1982). (c) The Pernambuco lineament is shown as a discontinuous shear zone system consisting of two branches: the West Pernambuco shear zone (WPSZ) and the East Pernambuco shear zone (EPSZ) (Vauchez and Egydio-Silva, 1992; this work).

^{40}Ar/^{39}Ar hornblende ages on plutons, country rocks and high-*T* mylonites constrain the main activity of shear zones to the time interval 550–590 Ma (Féraud et al., 1993; Monié et al., 1997; Corsini et al., 1998; Neves et al., 1999). The shear zones are clearly seen in aerial photographs and satellite images as linear or curvilinear belts that are referred to in the local geological literature as lineaments. Although Sadowski (1984) estimated displacements of the order of 250–350 km for the main lineaments based on the curvature of the regional foliation towards the shear zones, the real values are difficult to ascertain.

The objective of this paper is to appraise the kinematic significance of the Pernambuco lineament, acknowledged as an important regional structure since the pioneering works on the geology of the Borborema province (Ebert, 1964) and traditionally considered as a continuous 700-km long dextral strike-slip shear zone (Ebert, 1964; Mello, 1977; Davison et al., 1995; Jardim de Sá et al., 1995; Fig. 1b). The Pernambuco lineament has a sinuous shape, with its western (west of the Phanerozoic Jatobá basin) and eastern branches trending roughly N70°W and N70–80°E, respectively. Vauchez and Egydio-Silva (1992) suggested that these two branches are disconnected, forming the West and the East Pernambuco shear zones (WPSZ and EPSZ, respectively; Fig. 1c). They showed that the WPSZ consists of a steep belt of high-*T* mylonites, up to 14 km wide, in which synkinematic melting was coeval with shearing, terminating eastward in a fanlike structure characterized by the development of narrow, NE-trending shear zones (Fig. 1c). East of the virgation, only a narrow zone ($\approx$1km wide) of low-*T* mylonites, continuing up to the Jatobá basin, was observed. Davison et al. (1995) conducted a regional survey on the Pernambuco lineament through the examination of 15 sections across its entire length and challenged the interpretation of Vauchez and Egydio-Silva (1992), maintaining that a continuous lineament could be traced from the eastern to the western branch. However, Davison et al. (1995) recognized a distinct decrease in the shear zone width in the eastward direction. This observation associated with the large spacing of their traverses (from 20 to 50 km) and the similarity of the structural trends observed on their maps and that presented by Vauchez and Egydio-Silva (1992), casts doubt on their claim for the existence of a connection between the two branches of the Pernambuco lineament.

Neves and Vauchez (1995a) and Neves et al. (1996) studied the central portion of the EPSZ, having mapped a 35 km-long segment of the shear zone. In the present work, systematic mapping was undertaken along the entire length of the EPSZ. These studies support the existence of two separated branches of the Pernambuco lineament and reveal that the EPSZ is segmented into several mylonitic belts. In fact, it is more appropriate to describe the EPSZ as a shear zone system because it comprises several high-strain zones of diverse metamorphic grade and scale. A reap-

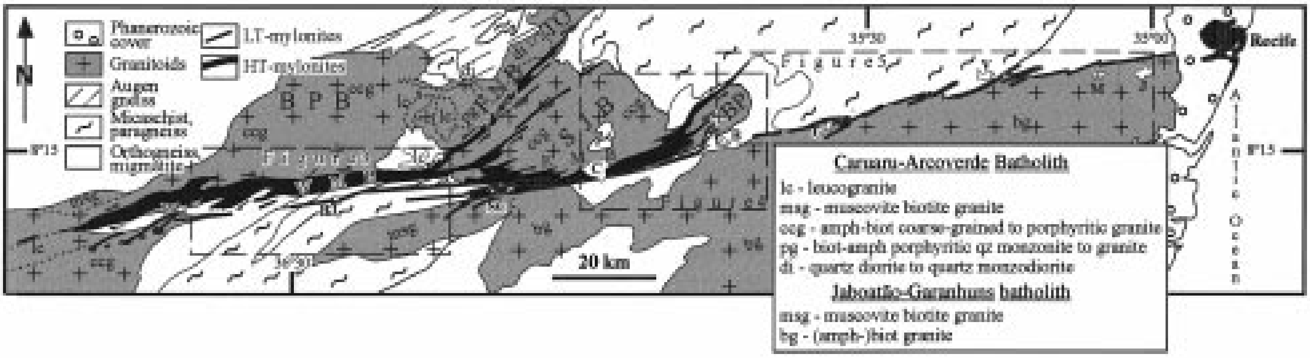

Fig. 2. Generalized geological map of the East Pernambuco shear zone system and its environs (see location on Fig. 1). WMB and EMB—western and eastern high-T mylonitic belts; FNSZ (Fazenda Nova shear zone), FNB (Fazenda Nova batholith), SJB (Serra da Japeganga batholith), BP (Bezerros pluton) and BPB (Belo Jardim–Pesqueira batholith) are the main units of the Caruaru–Arcoverde batholith. TO (Toritama pluton) is a syenite to quartz syenite body outcropping northeast of the Caruaru–Arcoverde batholith. Main towns present in the studied area are, from west to east: P—Pesqueira, BJ—Belo Jardim, SC—São Caetano, C—Caruaru, B—Bezerros, G—Gravatá, V—Vitória, M—Moreno, J—Jaboatão.

praisal of the tectonic significance of the Pernambuco lineament is therefore needed in light of this new information.

2. Geological setting

The geology of the studied area is dominated by granitoids of diverse compositions belonging to the Caruaru–Arcoverde and Jaboatão–Garanhuns batholiths, which occupy most of its northwestern and southeastern portions, respectively (Fig. 2). The Caruaru–Arcoverde batholith has been dated at 630 ± 24 Ma (whole rock Rb–Sr; McMurry et al., 1987) and at 588 ± 12 Ma (zircon U–Pb; Guimarães et al., 1998). The Caruaru–Arcoverde and Jaboatão–Garanhuns batholiths have similar Sm–Nd model ages of 1.8–2.0 Ga (Silva Filho et al., 1997). The country rocks of these large magmatic complexes are: (a) partially migmatized medium-grained gray gneisses (quartz monzodioritic to granodioritic in composition) and granitic gneisses of Paleoproterozoic age (Sá et al., 1997; Silva Filho et al., 1997; Silva Filho, personal communication); (b) micaschists and paragneisses of uncertain age; and, (c) the Taquaritinga orthogneiss (Neves and Féraud, 1996; Neves et al., 1999), an augen gneiss whose protolith is an anorogenic porphyritic granite dated at 1.55 Ga (zircon U–Pb; Sá et al., 1997) (Fig. 2). All these units show a dominantly NE-trending, low- to moderately dipping foliation. The assemblage biotite–garnet ± sillimanite ± cordierite and the local anatexis observed in metasediments indicate that the foliation developed under high temperature metamorphic conditions. Regional cooling to Ar blocking temperatures in amphibole (≈500°C) and biotite (≈300°C) occurred at around 585 and 545 Ma, respectively (Neves and Féraud, 1996; Neves et al., 1999).

The Caruaru–Arcoverde batholith is more than 120 km long and constitutes the largest body of the high-K calc-alkalic association in northeastern Brazil (Neves and Mariano, 1997). It comprises the Fazenda Nova–Serra da Japeganga complex (Neves and Vauchez, 1995b), the Bezerros pluton (Mariano et al., 1996) and the Belo Jardim–Pesqueira batholith (Fig. 2). The typical lithologies present in the batholith are coarse-grained to porphyritic amphibole–biotite granitoids whose compositions span the quartz monzonitic, quartz syenitic, granodioritic and granitic fields. Smaller plutons of leucogranite and muscovite–biotite granite make up the remainder of the batholith.

The Jaboatão–Garanhuns batholith is over 130 km long. It is composed dominantly of medium- to coarse-grained biotite ± amphibole granitic plutons, but a large elongate body of two-mica granite is present in its western portion and small plutons of this composition (not mappable at the scale of Fig. 2) are also found along its northern border and in its interior. Biotite diorites are commonly found in association with the granitoids in both the Caruaru–Arcoverde and Jaboatão–Garanhuns batholiths.

3. The East Pernambuco Shear Zone (EPSZ) system

3.1. Geometry

The EPSZ system is composed of two high-temperature (high-T) and several low-temperature (low-T) mylonitic belts (Fig. 2). Because the mylonites are primarily derived from igneous protoliths, the distinction between low- and high-T belts is based on the preservation (or not) of magmatic mineral phases and on

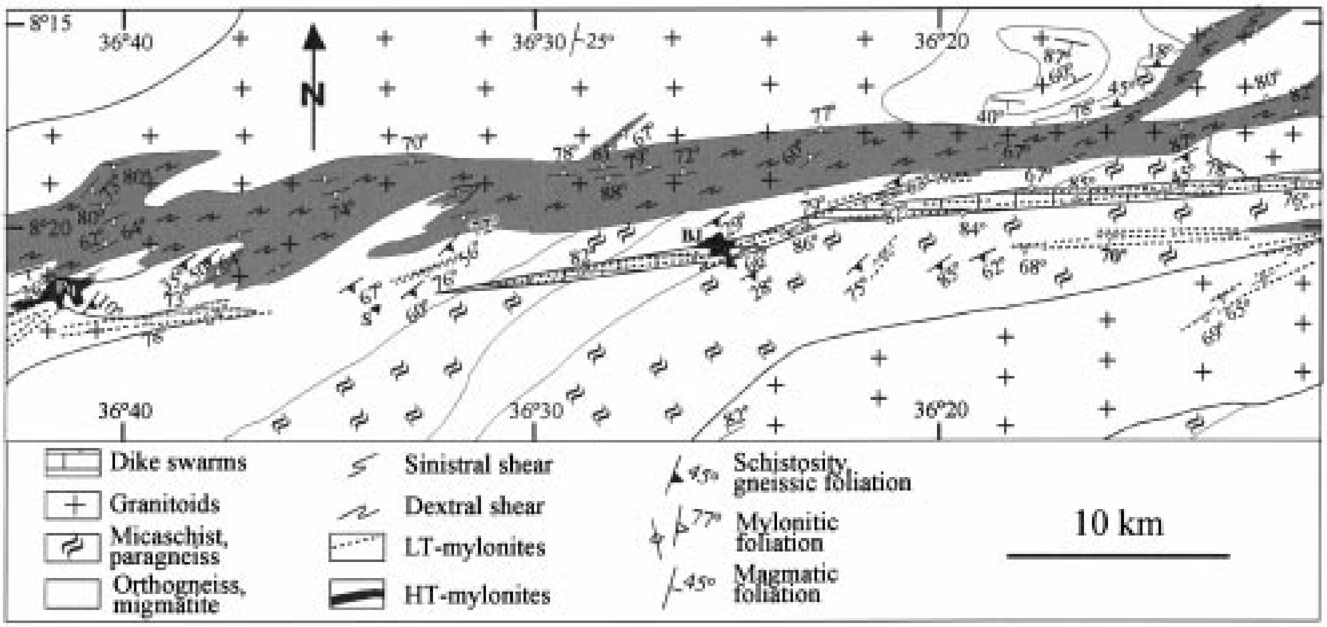

Fig. 3. Geological map of the EPSZ system in the Pesqueira (Pq)–Belo Jardim (BJ) region showing the WMB, its connection with the FNSZ, and its separation from the low-*T* mylonitic belts. S—Sanharó town. See location of the area on Fig. 2.

microstructural criteria, the high-*T* and low-*T* belts displaying characteristics typical of deformation under amphibolite facies and greenschist facies conditions, respectively (see below).

The western and eastern high-*T* mylonitic belts (WMB and EMB) are located in the southern border of the Caruaru–Arcoverde batholith. The WMB attains a maximum width of around 5 km and progressively narrows to the west. Although mylonites have been observed in some outcrops west of the studied area, no continuous belt of high-*T* mylonites can be traced linking the WMB to the high-*T* mylonites of the WPSZ. To the east, the WMB bifurcates and joins the NE-trending, high-*T* sinistral Fazenda Nova shear zone (FNSZ) and other smaller sinistral shear zones that are entirely confined to the interior of the Fazenda Nova–Serra da Japeganga complex (Figs. 2 and 3). The EMB is narrower than the WMB, having a maximum width of 2 km. It also connects with NE-trending, high-*T* sinistral shear zones, one running through the center of the Bezerros pluton and other bounding it to the northwest (Figs. 2 and 4). East of the Caruaru–Arcoverde batholith there is no evidence for strike-slip deformation at temperatures corresponding to amphibolite facies conditions.

The low-*T* mylonitic belts generally are less than 1 km wide, with the westernmost identified belt having a width of only a few tens of meters. West of the studied area low temperature mylonites were not observed. Therefore, the 1 km-wide low-*T* shear zone that marks the southern part of the WPSZ and may be traced up to the Jatobá basin (Fig. 1; Vauchez and Egydio-Silva, 1992) does not continue easternward from the basin.

In the easternmost portion of the studied area the low-*T* mylonitic belts form a geometrical array of right-stepping segments at the northern border of the Jaboatão–Garanhuns batholith (Figs. 2 and 5). These segments, with a ENE–WSW direction, are variable in strike length, but rarely exceed 20 km. The foliation usually dips steeply to the south (65° to subvertical) and the stretching lineation is gently plunging (Fig. 5). These low-*T* mylonitic belts commonly overlap, being separated by slices of country rock not deformed by strike-slip shearing. Therefore, a continuous shear zone does not exist north of the Jaboatão–Garanhuns batholith. Locally, as in the central portion of Fig. 5, it may be seen that foliation in country rocks within the overlapping area of two shear zone segments is almost perpendicular to the mylonitic foliation. These observations indicate that movement was not transferred from one segment to the next. A similar behavior is also observed in the west portion of the studied area, where the low-*T* belts occur as narrow right-step segments trending ENE–WSW to NE–SW (Fig. 2).

Two larger, approximately 50 km long, continuous belts of low-*T* mylonites occur in the central portion of the studied area (Figs. 3 and 4). The eastern one bounds the EMB to its south and ends to the east in a series of NE- to NNE-trending splays (Fig. 4). It is overlapped to the west by the other low-*T* belt (Fig. 3). This latter is separated from the WMB by a 2–3 km-wide strip of country rocks undeformed by strike-slip shearing, and lithological contacts show

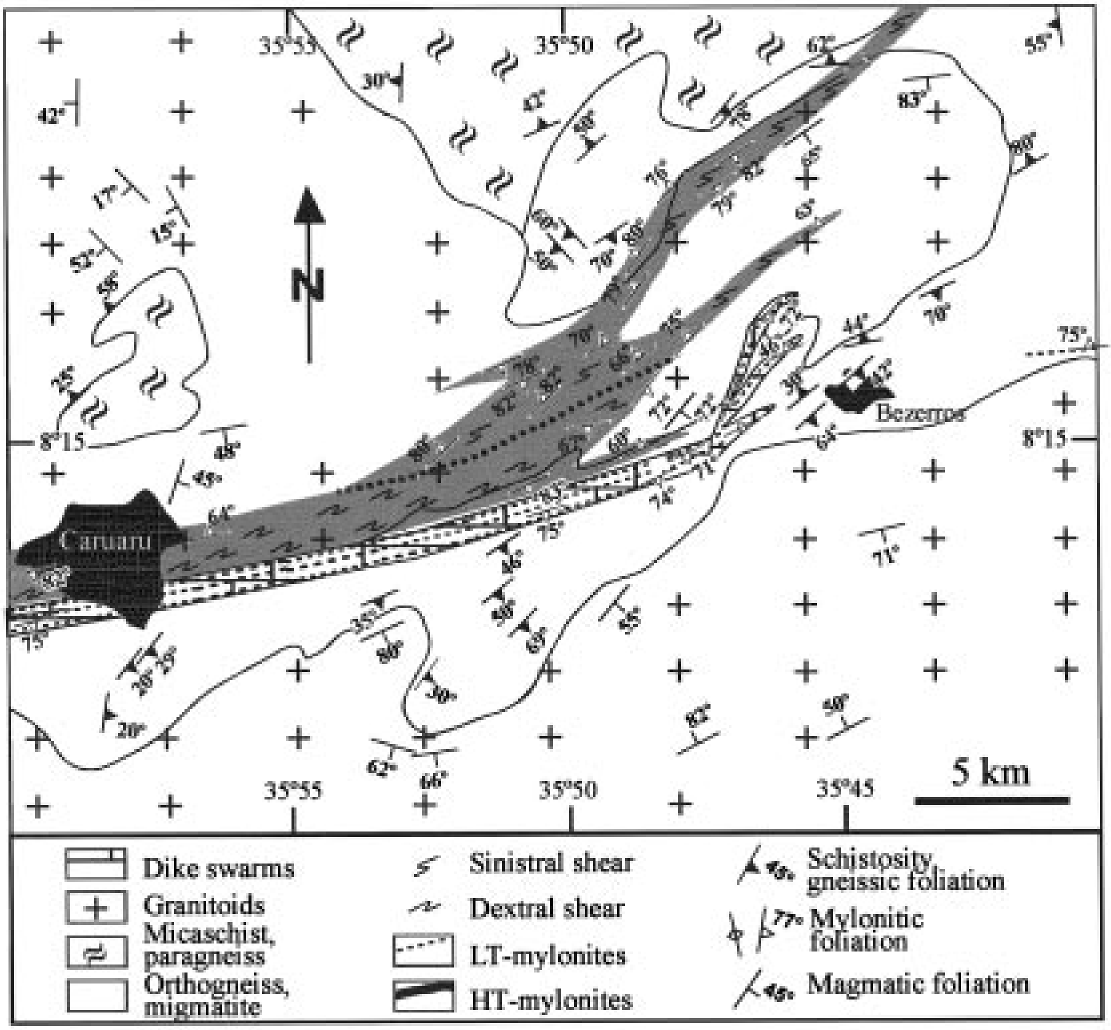

Fig. 4. Geological map of the EPSZ system between the towns of Caruaru and Bezerros, showing the connection of the EMB with sinistral shear zones. The thick dotted line represents the approximate limit between dextral and sinistral shear in mylonites. It is also shown the low-*T* mylonitic belt which terminates in NE-trending splays and partially bounds the EMB. See location of the area on Fig. 2.

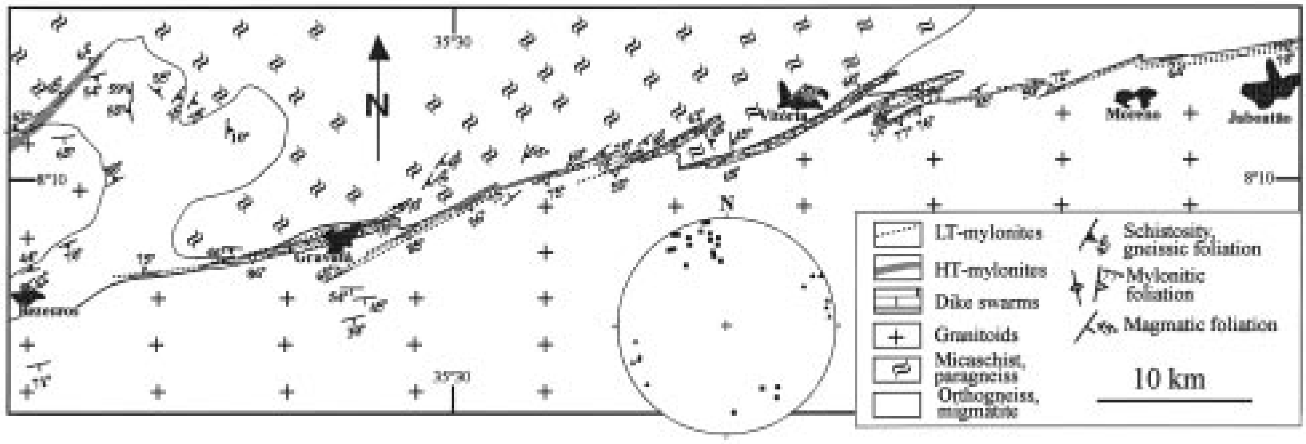

Fig. 5. Geological map of the EPSZ system between the towns of Bezerros and Jaboatão, showing the right-step geometry of the low-*T* mylonitic belts. The stereogram (lower hemisphere Schmidt projection) shows poles to foliation (squares) and stretching lineations (triangles) for the mylonites. See location of the area on Fig. 2.

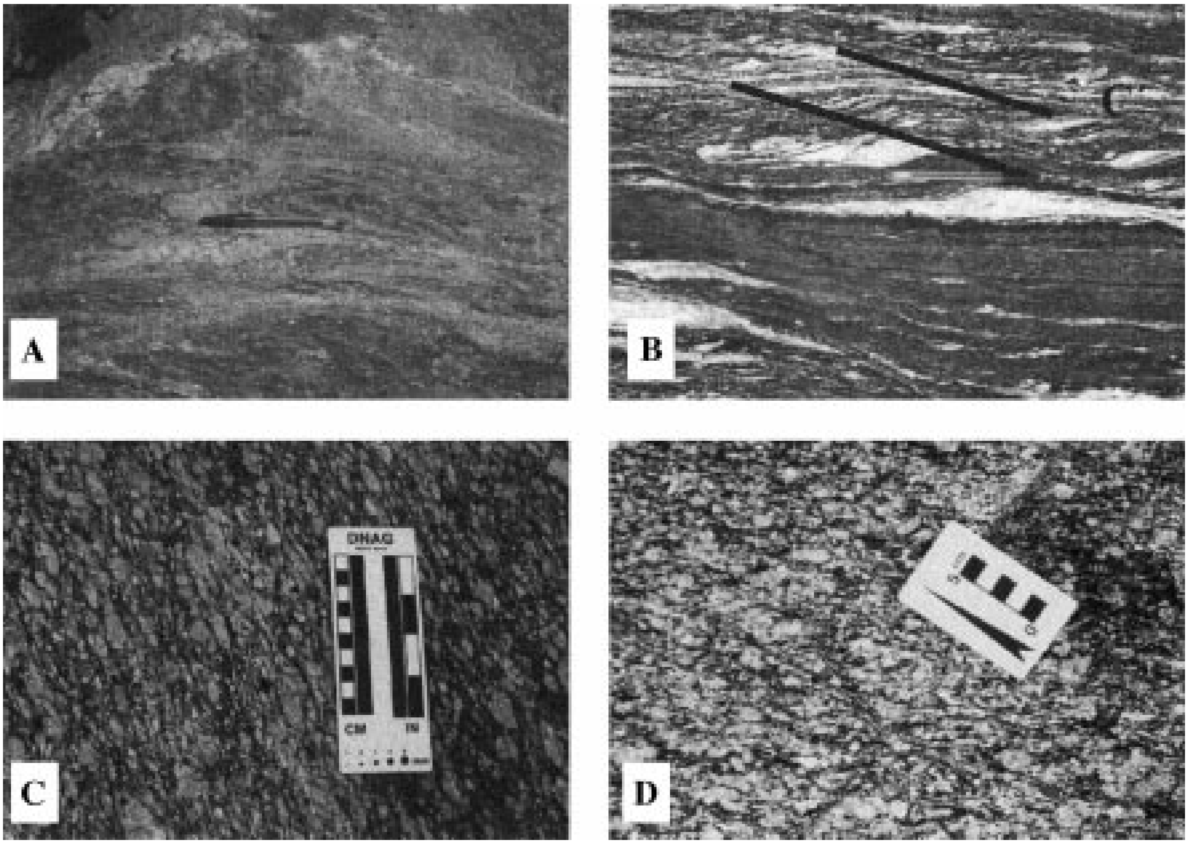

Fig. 6. (a) Moderately deformed migmatite from the EMB. Pen is 15 cm long. (b) Duplex structure developed in a felsic layer in mylonitized migmatite from the WMB, with C'-type shear bands indicating dextral shear. Pen is 15 cm long. Outcrops from which the photographs in (a) and (b) were taken are less than 100 m from the contact with the Caruaru–Arcoverde batholith. (c) *S–C* mylonite produced by shearing at high temperature of amphibole–biotite coarse grained to porphyritic granite. Scale parallel to *C*-planes. (d) Asymmetric tails around some K-feldspar porphyroclasts in mylonitized porphyritic granite indicating dextral shear. Note also the subparallelism of the long axes of most megacrysts, and C'-type shear bands parallel to scale.

very small offsets across it (Fig. 3). The trending of the mylonitic foliation varies along this belt, striking approximately E–W at its eastern and western terminations and ENE–WSW at its central portion. This behavior suggests that the belt may have formed by the coalescence of discontinuous segments.

3.2. Structures and fabrics

3.2.1. High-*T* mylonitic belts

Solid-state strike-slip deformation in the WMB and EMB is essentially confined to the southern border of the Caruaru–Arcoverde batholith. High-*T* mylonitization of country rocks not in direct contact with the batholith was observed only in one place (west of São Caetano; Fig. 2). There, the growth of synkinematic sillimanite in micaschists indicates that temperatures during strike-slip shearing reached upper amphibolite facies. However, in general country rocks show a gently to moderately dipping foliation even when very close to the contact with the batholith (Figs. 3 and 4). Metasedimentary rocks proximal to the shear zones may still preserve pre-shear structures and fabrics, e.g. open to tight folds with NE-trending axes deforming a gently dipping foliation. Even where the country rocks are affected by strike-slip shearing, they are less strained and the mylonitic fabric is less intense than that observed in the granitic mylonites (Figs. 6a and b). These observations are indicative of an abrupt increase in shear strain at the transition from the wall-rock to the Caruaru–Arcoverde batholith.

Contrasting with the above situation, granitoids to the north of the high-*T* mylonitic belts show a progressive increase in strain approaching the shear zones. Granitoids without solid-state deformation grade progressively into protomylonites and then into mylonites. Solid-state deformation is first recorded by elongation of quartz grains, then by the development of spaced shear planes until a pervasive *S–C* fabric dominates (Figs. 6c and d). There is no significant reduction in grain size accompanying this transformation, with the mylonites preserving the coarse-grain size of their protoliths. The ubiquitous *S–C* fabrics (Fig. 6c), C'-type shear band cleavage (Figs. 6b and d) and, less com-

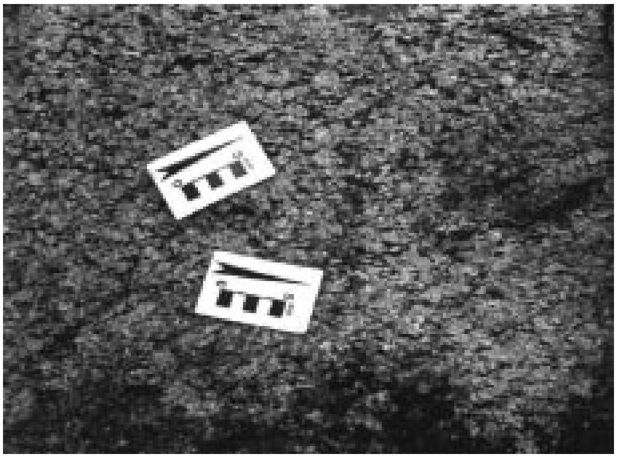

Fig. 7. Conjugate dextral and sinistral *C*-surfaces observed in mylonitized coarse-grained granite at the junction between the WMB and the FNSZ.

Fig. 8. Medium-grained gray granite truncating the foliation of mylonitic coarse-grained granite in the WMB.

monly, K-feldspar porphyroclasts with asymmetric tails (Fig. 6d) clearly indicate a dextral shear sense. Contradictory shear senses are only observed at the junction between the dextral and sinistral shear zones, where conjugate sets of dextral and sinistral shear bands are found (Fig. 7). There is no preference of one set of shear bands to offset the other, indicating that the shear zones formed roughly simultaneously.

Several lines of evidence suggest that development of the WMB and EMB started during crystallization of the Caruaru–Arcoverde batholith. The granitoids usually display a magmatic foliation defined by the preferred orientation of K-feldspar megacrysts, amphibole prisms and biotite flakes. Structural studies of the Fazenda Nova–Serra da Japeganga complex (Neves and Vauchez, 1995a; Neves et al., 1996) and of the Belo Jardim–Pesqueira batholith (Melo et al., 1999) showed that this magmatic fabric is progressively rotated towards the orientation of the mylonitic belts. This indicates that in a late stage of crystallization the magmatic flow was guided by the shear zone kinematics. This is corroborated by the presence of small-scale magmatic shear zones which indicate that the strike-slip regime started before complete crystallization of the magma mush. Additionally, the large majority of K-feldspar porphyroclasts in mylonites derived from coarse-grained to porphyritic granite lie with their longest crystal face subparallel to the foliation plane (Fig. 6d), suggesting that rotation of grains to a stable orientation started in the presence of melt and was enhanced during solid-state deformation. A continuous transition from magmatic to solid-state flow in the high-*T* mylonites is also suggested by: (a) microfractures filled by quartz and feldspar in K-feldspar porphyroclasts, suggesting formation due to stress concentrations at contacts between grains in the sub-magmatic stage (Hibbard, 1980; Bouchez et al., 1992); (b) crystal–plastic deformation and dynamic recrystallization of plagioclase, myrmekite growth along the boundaries of K-feldspar porphyroclasts, and embayed quartz–quartz boundaries, indicating that ductile deformation occurred under high-*T* (Paterson et al., 1989; Passchier and Trouw, 1996, and references therein); (c) stability of biotite and amphibole, indicating amphibolite-grade conditions during ductile deformation.

Reworking of the high-temperature mylonitic belts with decreasing temperature is generally restricted to late, outcrop-scale shear zones and brittle faults. Late equigranular granites intruded into the coarse-grained *S*–*C* mylonites of the WMB, (a) preserve clearly discordant contacts (Fig. 8) which have not been transposed into the foliation, and (b) show microstructural evidence for deformation at greenschist facies conditions. These observations indicate that the deformation was waning as the temperature dropped below ≈500°C. In the EMB, deformation may have continued for an extended period as compared with the WMB because retrogression of amphibole to epidote and sphene is locally observed along foliation planes.

Foliation planes (*S*-surfaces) in the WMB and EMB

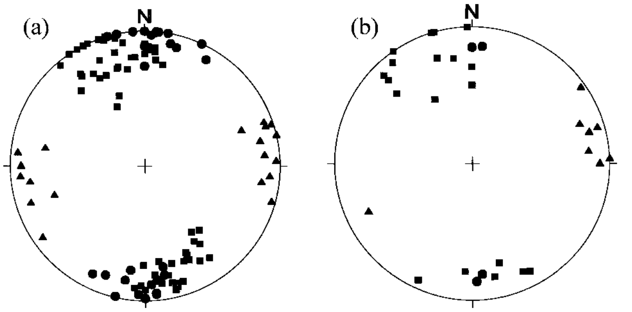

Fig. 9. Stereograms (lower hemisphere Schmidt projection) of poles to *S*-planes (squares), *C*-planes (circles) and stretching lineations (triangles) for the WMB (a) and EMB (b).

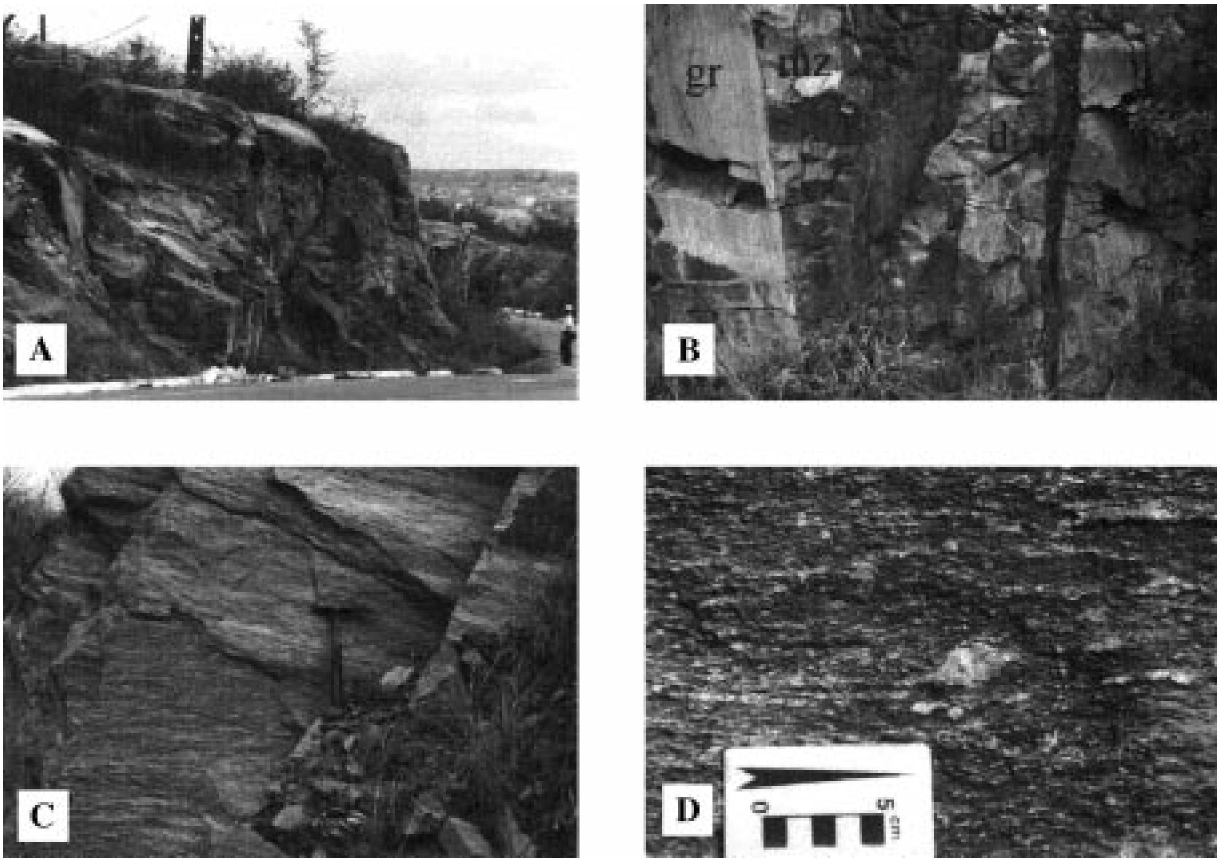

Fig. 10. (a) North facing photograph of dike swarm in a road cut near the town of Caruaru. (b) Detail of (a) in a plane normal to the stretching lineation, showing the various lithological types present in the outcrop and cross-cutting relationships. The dominant rock types are mylonitized leucogranites (gr), porphyritic monzonites (mz) and mafic porphyritic syenite (sy). The porphyritic monzonite is intruded by the mafic porphyritic syenite and also by a dioritic dike (di). Hammer for scale. (c) Stretching lineation plunging gently to ENE in mylonitized porphyritic syenite. Hammer for scale. (d) σ-type porphyroclast indicating dextral shear in low-*T* mylonite derived from medium-grained to slightly porphyritic granite.

typically strike 060°–070° and dip 60°–80° either northwest or southeast (Figs. 3, 4 and 9). The spaced *C*-planes are oriented in a clockwise sense at about 25–30° to the penetrative *S* foliation (Figs. 6 and 9), except in high-strain domains where the two sets of surfaces are parallel. *C*-planes are commonly subvertical, having a dominantly E–W direction (Fig. 9). The deformation fabric is strongly planar. Stretching lineations marked by the elongation of quartz–feldspar aggregates are only locally observed, but in all cases they are subhorizontal, gently plunging either northeast or southwest (Fig. 9). No change in orientation or in strain intensity is observed in the mylonites of the WMB as it decreases in width to the west. Contrary to what is observed for the WMB and EMB, the sinistral FNSZ shows stretching lineations plunging systematically 5–30° northeastwards (Neves and Vauchez, 1995a, b), suggesting possible vertical uplift of the block located northwest of the shear zone.

3.2.2. Low-*T* mylonitic belts

The country rocks surrounding the low-*T* mylonitic belts are only locally affected by shearing, a pattern similar to that observed for the WMB and EMB. The protoliths of the low-*T* mylonites are primarily derived from magmatic rocks intruded as dike swarms (Fig. 10a) or belonging to the Caruaru–Arcoverde and Jaboatão–Garanhuns batholiths. Dikes represent almost the whole volume of rock involved in the low-*T* mylonitic belts in the central portion of the studied area. Individual dikes in dike swarms vary from a few centimeters to some hundreds of meters in width and exhibit a wide range of compositions and deformation conditions. Two-mica leucogranites, equigranular biotite granites, coarse-grained to porphyritic amphibole–biotite granites, mafic and intermediate porphyritic syenites to monzonites, and diorites are the most common lithotypes (Fig. 10b). Most dikes are strongly deformed and different rock types display parallel, straight contacts, except for late aplite dikes. However, cross-cutting relationships are locally observed (Fig. 10b).

In contrast with the high-*T* mylonites, the low-*T* mylonitic belts usually display a well developed stretching lineation (Fig. 10c), although in many places the planar fabric is stronger than the linear one. On the other hand, mesoscopic shear-sense indicators are less common. K-feldspar porphyroclasts in porphyritic syenites are generally not winged, and where they are, the tails are symmetrically developed around the porphyroclasts. The fine grain-size of diorites and most granites hamper the observation of *S–C* fabrics with the naked eye. However, *S–C* fabrics are common in medium-grained granites and σ-type porphyroclasts are occasionally observed (Fig. 10d). Together with microscopic observations (most commonly σ- and δ-type porphyroclasts, asymmetrical shear bands and oblique quartz foliations), these criteria define a dextral shear sense for the low-T mylonitic belts.

The low-T mylonites show a considerable range in texture and microstructure, reflecting the petrographic and compositional variation displayed by their protoliths. There is no evidence that they overprinted higher-temperature fabrics. Ultramylonites are often developed in the finer-grained lithotypes. Fracturing and replacement of feldspars by aggregates of quartz and white mica is common in all rock types. Most low-T granitic and dioritic mylonites and ultramylonites have a banded appearance due to the alternation of feldspar-rich with quartz- or phylosilicate-rich millimetric bands. The metamorphic assemblage quartz–(green)biotite–actinolite–epidote–sphene ± chlorite in deformed mafic to intermediate rocks and amphibole-bearing granites is typical of upper-greenschist facies conditions (400–480°C). In mylonites of the easternmost and westernmost low-T shear zones, chlorite may be abundant, indicating that deformation in these regions occurred, or continued, at somewhat lower temperatures. In these two regions, brittle deformation superimposed on the otherwise macroscopically ductile mylonites and ultramylonites is also evidenced by the local development of cataclasites along narrow, millimetric fault planes and of quartz veining parallel to the foliation as well as in random orientations.

3.3. The WMB and EMB: simple, transpressive or stretching shear zones?

The WMB and EMB display some characteristics typical of simple shear zones, i.e. shear zones formed between rigid blocks by simple shearing (Ramsay and Graham, 1970). First, the rapid transition observed from undeformed or slightly deformed country rocks to strongly foliated granitic mylonites suggests that the country rocks behaved in a rigid fashion during strike-slip deformation. Second, mass balance calculations, showing that gain or loss of elements during mylonitization were not significant (Neves and Vauchez, 1995b), indicate that deformation was close to constant volume. Finally, consistence in orientation of foliations and lineations along the strike of the shear zones, and clear shear sense indicators in the plane normal to the foliation and parallel to the lineation suggest plane-strain, simple shear deformation. Although the last two points exclude the possibility that the WMB and EMB followed a triclinic deformation path, in which case either the quadratic elongation λ_1 or the quadratic elongation λ_3 are not contained in the plane normal to the vorticity vector (Jiang and Williams, 1998), other criteria indicate that they belong to a more general class of monoclinic shear zones (Passchier, 1998) than simple shear.

Evidence of non-simple shear flow during the solid-state evolution of the WMB and EMB is indicated by their association with sinistral shear zones, the $S > L$ tectonic fabric of the mylonites, and the dominance of symmetric tails over asymmetric ones around deformed K-feldspar porphyroclasts. The association of the WMB and EMB with the smaller sinistral shear zones could be interpreted in two ways: either the latter are compatible with the kinematics of the dextral shear zones, or the dextral and sinistral shear zones form conjugate sets. A shear sense opposite to the dominant flow might occur during strike-slip shearing by passive slip of preexisting schistosity planes (Hanmer, 1982). However, this is unlikely to happen in materials not possessing a strong anisotropy, such as granites and gneiss. Therefore, in the present case, shear zones with opposite shear senses must form a conjugate pair (Ramsey and Huber, 1987; Mukhopadhyay and Haimanot, 1989). Conjugate shear zones are common in constrictional settings and, for a ductile material, the direction of bulk shortening bisects the obtuse angle formed by the shear zones (Ramsey and Huber, 1987). The strongly planar fabric of the mylonites and the symmetry of porphyroclasts in the WMB and EMB are consistent with a constrictional setting, which results in an approximately NW–SE orientation of the bulk shortening direction in the present case.

In constant-volume monoclinic shear zones, flattening may be accommodated by stretching normal to the shear direction (transpression; Sanderson and Marchini, 1984; Fossen and Tikoff, 1993; Krantz, 1995) or by stretching parallel to the shear zone boundaries ("lateral escape or extrusion"; Dias and Ribeiro, 1994; Jones et al., 1997). The subhorizontal attitude of the stretching lineation in the WMB and EMB and the occurrence of C'-type shear bands, which are especially well developed in stretching shear zones (Passchier, 1991), favor the second hypothesis. Additionally, stretching is likely to happen due to the expected reduced rheological contrast between the high-T mylonites and their granitic protoliths (Ramsey and Huber, 1987, p. 615). Consequently, the geometry and kinematics of the WMB and EMB indicate that the coaxial component of the flow must have been dominantly accommodated by longitudinal eastward extension and not by vertical extension.

3.4. Amount of displacement

Movement on the broadly synchronous dextral and sinistral shear zones produces compatibility problems when the deformation become large because they tend to lock each other. This limits the amount of displacement that could have occurred across the high-T mylonitic belts, and thus it may be confidently inferred that it was small. Due to the absence of markers that could be used to estimate the amount of displacement, only a crude estimate can be made by considering relationships between thickness and length and displacement in shear zones. Mylonitic zones exhibit an average displacement–thickness ratio of 2 (Hull, 1988). Using this average, maximum displacements of 10 and 4 km are obtained for the WMB and EMB, respectively (assuming constant thickness of 5 and 2 km). Displacement–length ratios for brittle faults usually range from 10^{-2} to 10^{-1} (Cowie and Scholz, 1992). Considering that this relation is also valid for ductile shear zones, a maximum displacement of approximately 11 km is obtained for the combined length of 110 km of the WMB and EMB. It should be noted that these maximum estimates are still an upper limit because the assumption of simple shear.

The small offset of contacts across the largest low-T shear zone (Fig. 3), associated with the fact that movement was not transferred from one segment to the next in the regions where the low-T mylonites display an en échelon geometry (Fig. 5), allow us to infer that displacement of the low-T shear zones was also small. The largest (50 km long) low-T belts are usually less than 1 km wide. The displacement–width ratio applied to these belts results in a maximum displacement below 2 km. Thus, it is unlikely that the combined displacement of all low-T mylonitic belts had exceeded 10 km.

In summary, the total motion of the EPSZ system cannot have been greater than a few tens of kilometers, being probably situated in the range from 10 to 20 km.

4. Discussion

Systematic geologic/structural mapping conducted during this study reveals four main facts: (a) the association of the high-T mylonitic belts with the Caruaru–Arcoverde batholith, and of the low-T mylonitic belts with dike swarms; (b) the restricted reworking of the high-T mylonitic belts at greenschist facies conditions and their spatial separation from the low-T mylonitic belts; (c) the rather limited occurrence of brittle structures along the length of the EPSZ system; (d) the confirmation of the earlier suggestion (Vauchez and Egydio-Silva, 1992) that the Pernambuco lineament does not represent an uninterrupted zone of simple shear flow. The first observation highlights the connection between the presence of igneous bodies or melts in the crust and the process of strain localization that lead to the development of shear zones. The second point suggests that development of the low-T mylonites was not conditioned by the existence of the previous high-T belts and thus that mylonitic belts are not necessarily inherently weak structures, as frequently assumed. The third point suggests that large scale reactivation of the Pernambuco lineament did not occur during the Phanerozoic. Finally, the last observation, together with the geometrical characteristics of the EPSZ system, suggests that the Pernambuco lineament may have had a much less important role during the Brasiliano orogeny than previously thought. These implications are explored in the following sections.

4.1. Strain localization

The lack of high-T mylonites east of the Bezerros pluton (Figs. 2 and 5) and the very high strain gradient observed at the transition from the country rocks into the granitic shear zones imply that development of the WMB and EMB only occurred after the emplacement of the Caruaru–Arcoverde batholith. Several reasons, however, indicate that the strike-slip regime started before crystallization was completed. These include the reorientation of magmatic fabrics toward the direction of the mylonitic belts, the presence of magmatic shear zones, the parallelism of K-feldspar porphyroclasts in mylonites, and microstructural evidence for solid-state deformation close to the granite solidus. The strong differences in rheological properties between solid-state rocks and partially crystallized magma bodies (van der Molen and Paterson, 1979; Rushmer, 1995; Rutter and Neumann, 1995) may have favored strain localization inside the batholith rather than in the country rocks (Neves et al., 1996; Vauchez et al., 1997). Mechanical and thermal factors can have contributed to the continued focusing of solid-state deformation into the granitic rocks of the Caruaru–Arcoverde batholith after its complete crystallization. First, a high degree of preferred orientation inherited from deformation in presence of a melt phase may have provided an anisotropic site more favorable for strain localization than the low- to moderately dipping foliation of the country rocks. Second, large magmatic complexes emplaced in a hot crust may maintain its temperature higher than the country rocks for several millions to some tens of millions years (Davidson et al., 1992; Tommasi et al., 1994, and references therein).

Therefore, a significant rheological contrast between the granitic mylonites and the country rocks, resulting from thermal softening, may have persisted for an extended period of time. Other factors normally invoked for the initial localization of strain in shear zones cannot apply in the present case. For instance, (a) differences in grain size were not significant because the granites are coarse grained than the country rocks and grain-size reduction is not observed in the high-T mylonites, which preserve the grain size of their protoliths; (b) the similar chemical composition of the mylonites and their protoliths (Neves and Vauchez, 1995b) excludes the possibility that mass transfer processes through melt or fluid flow could have been important.

It is also noteworthy that the protoliths of the low-T mylonites are magmatic rocks mainly belonging to dike swarms. A combination of reaction-enhanced softening (replacement of feldspars by quartz and sericite and of amphibole by actinolite, epidote, sphene ± -chlorite) and mechanical softening (resulting from decrease in grain size and development of weak quartz- or phylosilicate-rich millimetric bands) may explain the highly localized deformation inside the dikes as compared with the country rocks. However, this raises the question of how these rocks were emplaced in the first place. The right stepping geometry of the low-T mylonitic belts in the easternmost (Fig. 5) and westernmost (Fig. 2) regions is consistent with their origin as an array of en échelon P-shears. Development of such shears suggests that brittle deformation took place at the beginning of nucleation of the low-T mylonitic belts. This situation is akin to that observed in granitic rocks where outcrop-scale shear zones are localized along pre-existing fractures, veins and aplite dikes (Segall and Simpson, 1986; Christiansen and Pollard, 1997; Tourigny and Tremblay, 1997; Guermani and Pennacchioni, 1998). The more continuous and more east–west oriented low-T mylonitic belts south of the Caruaru–Arcoverde batholith could have formed by the rotation and coalescence of several en échelon segments during progressive deformation.

4.2. Shear zone reactivation

Shear zones are frequently assumed to be inherently weak structures. There is plenty of evidence for their reactivation in subsequent deformation events (Watterson, 1975; Butler et al., 1997, and references therein), and for the occurrence of strain localization as the temperature declines, leading to a concentration of deformation into narrowing belts with time (e.g. Hanmer, 1988; West and Hubbard, 1997). However, the lack of evidence in the eastern portion of the studied area (Fig. 5) for a previous shearing event under high-T conditions, the across-strike separation of the WMB from the low-T mylonitic belts (Figs. 2 and 3), and the very limited reworking of the WMB at low temperature indicate that development of the low-T mylonitic belts of the EPSZ system was largely independent of pre-existent high-T mylonitic belts. This suggests that strain hardening took place when the temperature declined, leading to cessation of deformation in the high-T belts. The reason why this unusual behavior occurred is not fully understood. It might be related to the coarse grain size and the large amount of stiff K-feldspar crystals of the high-T mylonites, which might have impeded the development of the strongly anisotropic banded mylonites that are often observed with increasing deformation in granitic mylonites elsewhere (Gapais, 1989; Schulmann et al., 1996).

The brittle structures locally superimposed on the low-T mylonites may be part of a continuous deformation event, with strike-slip shearing continuing at progressively lower temperatures. In this interpretation, they mark the waning stages of the Brasiliano deformation in the area. However, it is also possible that they formed in a later event. In any case, the localized nature of the brittle deformation argues against the reactivation of large segments of the low-T mylonitic belts after the Brasiliano orogeny (e.g. during the opening of the Atlantic or formation of the Jatobá basin). Equally, lack of continuity between the east and west branches of the Pernambuco lineament indicates that formation of the Jatobá basin was not controlled by its reactivation.

4.3. Tectonic significance of the Pernambuco lineament

The Pernambuco lineament is shown in paleogeographic reconstructions continuing into Africa as the Sanaga (Torquato and Cordani, 1981; Caby, 1989; Villeneuve and Cornée, 1994) or Amadoua (Bertrand and Jardim de Sá, 1990; Castaing et al., 1994) faults of Cameron (fig. 13), in which case it would be comparable to the largest shear zones in the world, with an original total length well over 1000 km. However, (1) the WMB is separated from the western branch of the Pernambuco lineament (the WPSZ) for a distance greater than 100 km, even when restoration of the Cretaceous extension responsible for the development of the Jatobá basin is taken into account, and (2) although the low-T shear zone that marks the southern part of the WPSZ may be traced until the Jatobá basin (Fig. 1; Vauchez and Egydio-Silva, 1992), its continuity is lost easternward from the basin, with low-T mylonites being found only several tens of kilometers away from it. Therefore, a continuous belt of either high- or low-T mylonites cannot be traced extending 700 km from the coast inward. Because the eastern portion of the EPSZ system is represented by discontinuous low-T shear zones, even if some shear

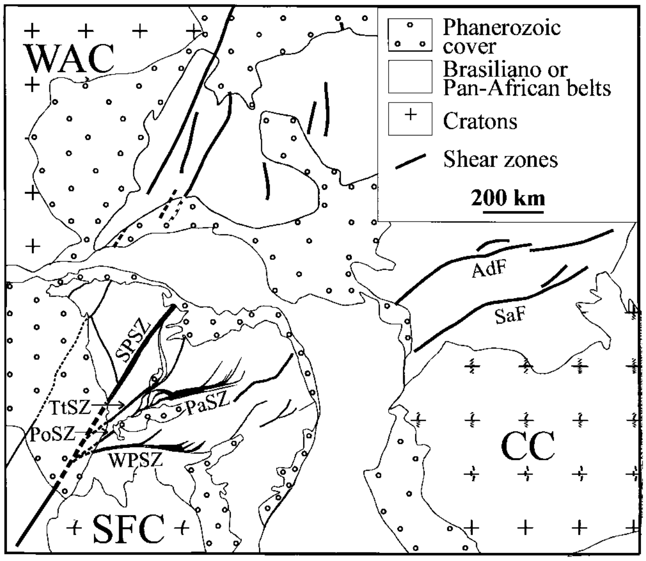

Fig. 11. Schematic map showing the main shear zones of the Borborema Province and West Africa, emphasizing the possible connections of the WPSZ and the Patos (PaSZ), Tatajuba (TtSZ) and Potenji (PoSZ) shear zones with the Senador Pompeu shear zone (SPSZ). The Sanaga (SaF) or Amadoua (AdF) faults are frequently proposed to be a possible extension of the Pernambuco lineament in Africa. CC—Congo craton; SFC—São Francisco craton; WAC—West Africa craton. Brazil rotated approximately 15° counterclockwise relative to its present position.

zone in Africa could be perfectly matched with the Pernambuco lineament, this would have little geodynamic implication as it is unlikely that any significant displacement could have been transferred from the EPSZ system into Africa. Additionally, the same NE–SW structural trend and a similar metamorphic grade is observed in country rocks on both sides of the EPSZ system, and Sm–Nd isotopic studies show that the Caruaru–Arcoverde and the Jaboatão–Garanhuns batholiths have similar Nd-model ages (1.8–2.0 Ga; Silva Filho et al., 1997). These latter observations indicate that the EPSZ system does not separate crustal blocks with distinct characteristics, implying that its displacement was too small to juxtapose terranes with contrasting tectonic histories and that it did not overprint a pre-existing rheological boundary.

From the above, it is clear that the Pernambuco lineament is not a transcontinental strike-slip shear zone. Interpretation of its regional kinematic significance in the context of the Brasiliano orogeny requires an analysis of the other shear zones of the Borborema province. This province may be divided into two domains according to the distribution of its shear zones: a northwestern domain where NE-trending, rectilinear shear zones predominate and an eastern domain characterized by E–W-trending sinuous shear zones (Fig. 1; Vauchez et al., 1995). It has been suggested (Vauchez et al., 1995; Corsini et al., 1996; Tommasi and Vauchez, 1997), and recently confirmed by the analysis of aeromagnetic and gravimetric data (Oliveira, 1998), that these two domains are mechanically linked, with the WPSZ and the Patos, Tatajuba and Potenji shear zones of the eastern domain merging with the Senador Pompeu shear zone (SPSZ) of the northwestern domain (Fig. 11). The SPSZ therefore emerges as a major intracontinental strike-slip shear zone, whereas the WPSZ and the other high-*T* shear zones of the eastern domain represent smaller splays from this main shear zone. Numerical models (Tommasi et al., 1995; Tommasi and Vauchez, 1997; Vauchez et al., 1998) show that stress concentration at the tip of a stiff heterogeneity causes strain localization, originating as a large shear zone, whereas weak heterogeneities promote a perturbation of the strain field, leading to the development of smaller shear zones. These models reproduce nicely the situation in the oriental portion of the Borborema province. Considering the São Francisco craton (Fig. 11) as the stiff heterogeneity, the SPSZ can be interpreted as the master shear zone and the smaller shear zones as ramifications nucleated in weak domains (possible ancient basins).

The separation of the EPSZ system from the WPSZ indicates that these two branches of the Pernambuco lineament may have evolved independently. The high-*T* mylonitic belts of the EPSZ system are small-scale features when compared with the combined SPSZ–WPSZ system. The absence of large shear zones to the south of the EPSZ system associated with its lateral and transversal discontinuities indicates that the intensity of strike-slip deformation was smaller in the easternmost portion of the Borborema province as compared with its central and northwestern portions. The presence of the Caruaru–Arcoverde batholith certainly had an important role in localizing the strain. We suggest that, in its absence, the deformation would have been more uniformly partitioned, preventing the nucleation of the WMB and EMB.

5. Conclusion

The present study indicates that major lineaments observed in aerial and satellite images, and shown as major shear zones on regional geological maps are not necessarily significant from a kinematic point of view, their importance needing to be assessed by field-oriented structural work. Systematic geological mapping conducted on the eastern portion of the Pernambuco lineament confirmed the earlier finding that it is segmented into two branches, the WPSZ and the EPSZ system, and reveals a much more complex picture for the EPSZ system than previously thought. The EPSZ system is characterized by laterally and transversally discontinuous high-T and low-T, dextral mylonitic belts. The high-T, E–W-trending mylonitic belts are associated with high-T, NE-trending sinistral shear zones, and the eastern and western low-T mylonitic belts display a right step geometry. These observations indicate that: (a) the possible amount of displacement along the high-T belts is limited by compatibility problems that arise from the movement on shear zones with opposed shear sense; (b) deformation was not intense enough to promote the connection of the low-T mylonitic belts and the development of a continuous shear zone. Consequently, the Pernambuco lineament can no longer be considered as a fundamental crustal structure responsible for juxtaposition of tectonic terranes or blocks with distinct evolutionary histories. It certainly had a secondary tectonic role during the Brasiliano orogeny in northeastern Brazil.

Other consequences of this study arise from the following observations: (a) country rocks are little affected by strike-slip shearing, either at high- or low-T conditions; (b) low-T mylonitic belts did not overprint the high-T ones; (c) brittle structures are only locally developed. The intimate association of the high- and low-T mylonitic belts with igneous rocks clearly indicates that the presence of magma in the crust played a major role in their nucleation. Cessation of deformation in the high-T mylonitic belts with decreasing temperature shows that granitic mylonitic belts are not necessarily weak structures. Finally, limited post-Brasiliano reactivation of the EPSZ system strongly suggests that it did not exert control on the formation of Phanerozoic interior or coastal basins.

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