Pergamon

Journal of South American Earth Sciences, Vol. 8, Nos 3/4, pp. 247-266, 1995

0895-9811/95 $9.50 + 0.00

0895-9811(95)00012-7

The Borborema shear zone system, NE Brazil

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(Received May 1994; Revisions Accepted December 1994)

Abstract—The Neoproterozoic evolution of the Borborema Province is characterized by the development of a continental-scale network of transcurrent shear zones. These shear zones form a kinematically consistent system over more than 200,000 km^2. This shear zone system is coeval with a high-temperature, medium- to low-pressure metamorphism, partial melting of the crust, and synkinematic magmatism involving both crustal- and mantle-derived magmas. Preliminary geochronological data suggests that the deformation in the shear zones probably began around 570-600 Ma and continued under decreasing temperature to around 500 Ma. The Borborema shear zone system is subdivided in two domains, a western domain in which rectilinear NE-trending dextral strike-slip shear zones dominate, and an eastern domain characterized by sinuous, discontinuous EW-trending shear zones that terminate in NE-trending metasedimentary belts. The sinuous pattern of the EW-trending shear zones may be due to pre-existing lithospheric heterogeneities: basins or domains where crustal accretion occurred at different ages. Finally, it is suggested that the Borborema shear zone system developed within a heterogeneous continental plate to accommodate the deformation imposed by plate tectonic processes (oblique collision?) active at the margin.

Resumo— A evolução Neoproterozóica da Província da Borborema é caracterizada pelo desenvolvimento de uma malha de zonas de cisalhamento em escala continental. Esta zonas de cisalhamento formam um sistema cinematicamente consistente por mais de 200.000 km^2. A zona de cisalhamento estudada desenvolveu-se durante metamorfismo de alta temperatura e pressão média a baixa, fusão parcial da crosta e magmatismo sincinemático com magmas derivados tanto da crosta quanto do manto. Dados geo-cronológicas preliminares sugerem que a deformação nas zonas de cisalhamento teve início por volta de 570-600 Ma, e continou sob condições de temperatura decrescente até cerca de 500 Ma. O sistema de cisalhamento Borborema é subdividido em dois domínios: o domínio ocidental onde predominam zonas de cisalhameanto destrais com direção NE, e o domínio oriental caracterizado por zonas de cisalhamento sinuosas e descontínuas, com direção E-W, que terminam nos cinturões de metassedimentos de direção NE. O padrão sinuoso das zonas de cisalhamento E-W pode está relacionado a heterogeneidades litosféricas préexistentes: bacias ou domínios onde acresção crustal ocorreu em períodos diversos. Finalmente, é sugerido que o sistema de cisalhamento Borborema desenvolveu-se dentro de uma placa continental heterogenea para acomodar a deformação imposta por processo de tectônica de placao (colisão oblíqua) em margem continental ativa.

INTRODUCTION

DEFORMATION OF CONTINENTS SUBJECTED TO COLLISION is frequently accommodated by continental scale shear zones (Tapponnier and Molnar, 1976). When the deformed continental domain is large, a number of shear zones may occur and form a network, which minimizes the volume of deformed rocks necessary to accommodate the imposed strain rate. In recent orogens, the displacement field associated with a fault network is frequently difficult to unravel because of the shallow level of exposure. Indeed, the mechanical behavior of the brittle crust is extremely complex, and it remains difficult to discriminate major from subsidiary tectonic features.

The Neoproterozoic Pan-African/Brasiliano orogeny is known to have produced huge, frequently transcontinental systems of fault zones. Erosion of old orogens usually allows one to observe deep crustal levels over very large areas that cover the entire tectonic system. Through kinematic analysis of mylonites formed in these shear zones, an image of the displacement field associated with the fault system in the ductile crust may be obtained.

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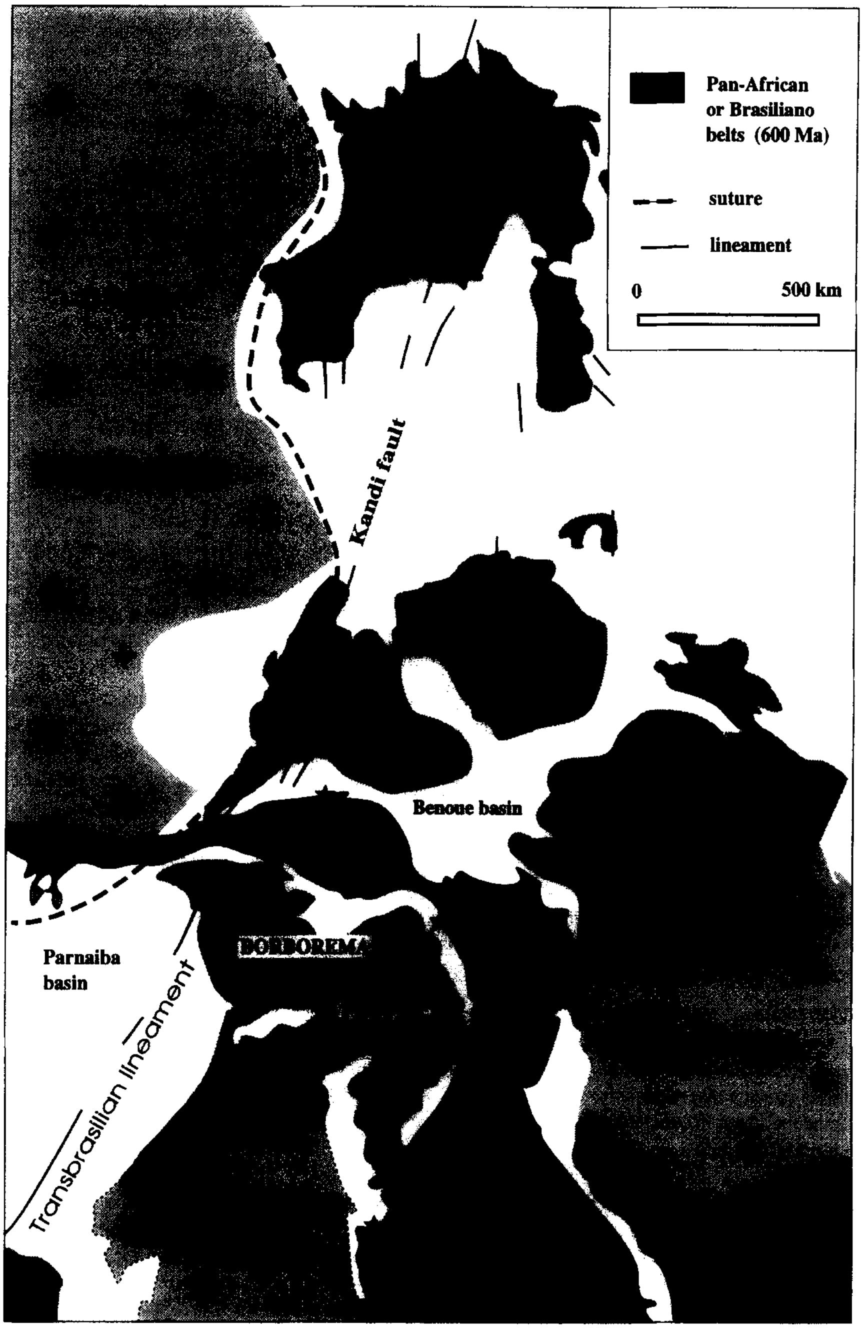


Fig. 1. Relationships between northeast Brazil and Africa before the opening of the South Atlantic Ocean. The main shear zones of the Borborema Province may represent a prolongation of major lineaments in Africa (after Caby *et al.*, 1991).

Northeast Brazil is certainly one of the best places to study a continental-scale, strike-slip fault network. In this area, the Brasiliano orogeny resulted in the development of shear zones several hundreds of kilometers long and typically from ten to several tens of kilometers wide, that form a mechanically coherent array over more than 200,000 km^2.

This paper is essentially descriptive; it intends to present the state of knowledge on this shear zone system. Kinematics of the shear zones, metamorphic conditions of the deformation, relationships between the shear zones and the magmatic history and finally the large-scale tectonic interpretation of the shear zone network are successively addressed.

SHEAR ZONES IN THE BORBOREMA PROVINCE

The general reconstruction of the position of continents before the opening of the South Atlantic Ocean (Figure 1), shows huge continental-scale lineaments that run between and around the cratonic masses of Brazil and Africa. The cratons have been stable since Early Proterozoic time, and largely escaped subsequent orogenies. The Borborema Province lies precisely in between the West-African, the Amazon, and the Congo-São Francisco cratons. This area has a special geodynamic significance since EW-trending lineaments, more than 1000 kilometers-long from NE-Brazil to Cameroon, merge into NE-trending lineaments that run about 3000 kilometers from central Brazil to Hoggar (Figure 1).

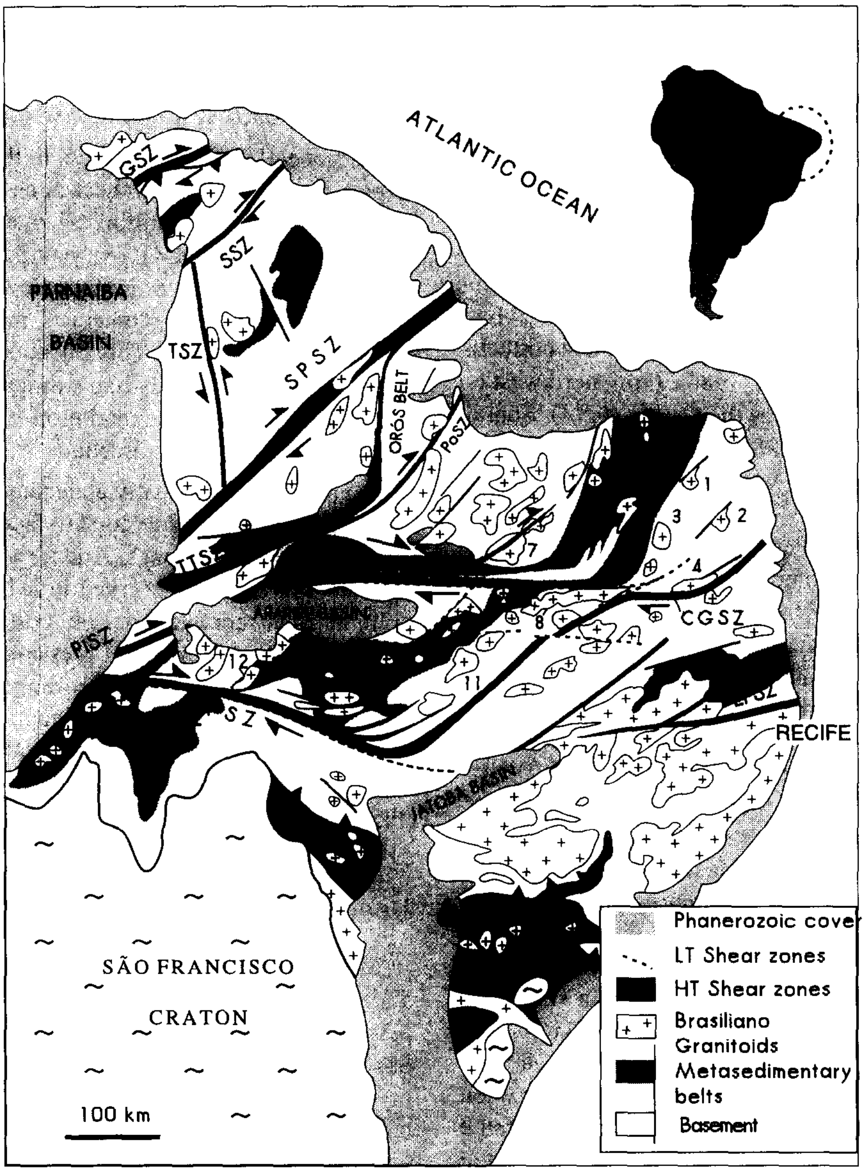


Fig. 2. Schematic map showing the Borborema shear zone system and Brasiliano granites. CGSZ: Campina Grande shear zone; EPSZ: East Pernambuco shear zone; FNSZ: Fazenda Nova shear zone; GSZ: Granja shear zone; PaSZ: Patos shear zone; PiSZ: Potengi shear zone; PoSZ: Portalegre shear zone; SPSZ: Senador Pompeu shear zone; SSZ: Sobral shear zone; TSZ: Tauá shear zone; TTSZ: Tatajuba shear zone. Numbers represent plutons referred to in the text: 1: Barcelona; 2: Gameleiras; 3: Picuí; 4: Pocinhos; 5: Acari; 6: São Rafael; 7: Pombal; 8: Teixeira; 9: Emas; 10: Itaporanga; 11: Triunfo; 12: Terra Nova; 13: Fazenda Nova.

Huge ductile faults in the Borborema Province were first recognized more than 20 years ago (Ebert, 1970; Santos and Brito Neves, 1984). The shear zone network was already outlined on regional-scale geological maps (e.g., on the 1:2,500,000 map of Brazil or on the 1:1,000,000 map of the Borborema Province by Brito Neves, 1983). However the organization of the shear zones in a tectonic system, mechanically coherent over the entire province (i.e., over more than 200,000 km^2) has been recognized only recently (Vauchez *et al.*, 1991; Vauchez *et al.*, 1992).

A more accurate picture of the shear zone system was gained from remote sensing (e.g., Amaro *et al.*, 1991), especially using satellite (both Spot and Landsat TM) and radar images. In both kinds of images, shear zones are marked by a strong linear pattern that contrasts with the sinuous fabric, or the lack of clear fabric, in the surrounding domains. Field observations have shown that this linear pattern is related to the existence of a vertical foliation, usually mylonitic, and alternating layers of different rock types parallel to the shear zone. Two types of shear zone boundaries have been observed: continuous, with the foliation splaying off from the fault zone to connect without any discontinuity with the fabric of the bordering domain, or discrete, where the fabrics of the shear zone and of the bordering domain respectively are oblique and totally disconnected. In several shear zones (Patos shear zone, West Pernambuco shear zone, e.g., see Fig. 20), the two types of boundary coexist. However, it should be noted that some of the sharpest contacts correspond to Mesozoic or even Quaternary reactivation of the ductile fault zones. Remote sensing allows us to evaluate the width of the lineaments, which typically range from 1 km for subsidiary faults, up to 10 km for the West Pernambuco and the Senador-Pompeu SZ and 25 km for the Patos SZ. In the field, these wide lineaments comprise not only mylonites, but also migmatites, syn- to late-kinematic plutons and dikes, lenses of unmylonitized material, etc.; they may therefore be regarded as movement zones, i.e., wide zones in which the offset was accommodated by a heterogeneous non-coaxial deformation.

The Borborema shear zone system (Fig. 2) may be conveniently subdivided into a western and an eastern domain. The western domain (mainly Ceará state) is characterized by rectilinear, NE-trending movement zones which postdate nappe emplacement in central and northern Ceará state (Caby and Arthaud, 1986). From northwest to southeast this domain involves the Granja (GSZ), Sobral (SSZ), Senador-Pompeu (SPSZ), Tatajuba (TTSZ), and Potengi (PiSZ) shear zones, with the latter two connected with the eastern domain. The eastern domain, which spreads over the Paraíba, Pernambuco and Rio Grande do Norte States, displays a complex structural system consisting of: 1) two major EW-trending composite movement zones separated by a distance of about 200 km: the Patos-Campina Grande system and the Pernambuco system, 2) NE-trending transpressional belts: the Seridó and the Cachoeirinha belts in which folding was coeval with the development of strike-parallel shear zones, and 3) NE-trending subsidiary shear zones displaying evidence of early dextral motions and of late sinistral motions between the PaSZ and the Pernambuco shear zones (PeSZ). The EW-trending shear zones are not continuous, and do not offset the NE-trending belts as was previously thought. They are formed by disconnected segments, whose termination is marked by a progressive change in structural trend from EW to NE-SW. This progressive transition suggests that the shear zone and the transpressional belt were in mechanical continuity. A similar interlinkage between shear zone and transpression belt is observed in both the Patos-Campina Grande and Pernambuco systems and will be described in more detail further on.

Despite the contrast in geometric pattern between the western and eastern domains, the tectonic fabric in the shear zones and the synkinematic metamorphic evolution remain similar over the entire shear zone system and will be presented first.

Shear Zone Fabric

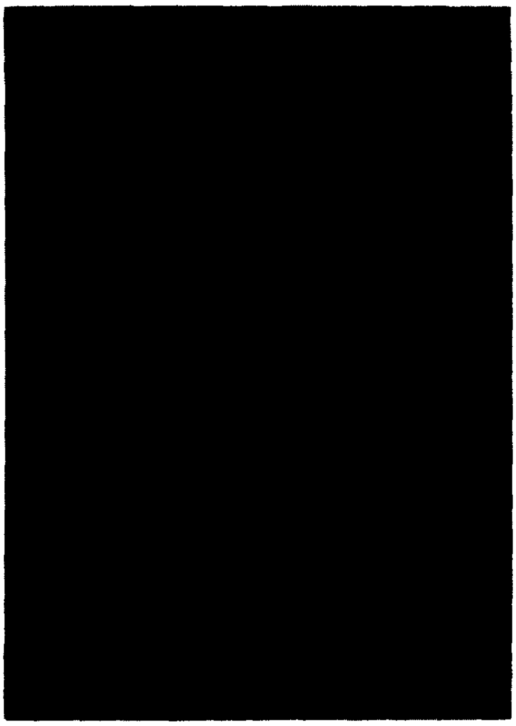
All major shear zones in the Borborema Province are marked in the field by well-developed mylonite belts in which high-temperature (HT) to low-temperature (LT) protomylonites and mylonites coexist. HT-mylonites have been derived from various kinds of pre-existing rocks: gneisses and granitoids from the Archean to Lower Proterozoic basement (Fig. 3), metasediments and metavolcanics from the Proterozoic sedimentary sequence and pre- to syn-kinematic intrusive rocks. They usually display a subvertical foliation bearing a well-developed subhorizontal mineral-stretching lineation. However, in some places a transition from a high-angle to a low-angle mylonitic foliation, consistently bearing a subhorizontal lineation, may be observed. Two different situations have been observed: the trend of the foliation either remains constant (i.e., EW), as observed on the northern boundary of the Patos SZ, south of the city of Pombal (Archanjo *et al.*,1994) or rotate northeastward as observed at the eastern tip of the West Pernambuco SZ (Vauchez and Egydio-Silva, 1992).

Evidence of stretching parallel to the lineation is widespread throughout all the shear zones, especially boudinage and extensional faulting of layers or dikes of more competent rocks (Fig. 4), recrystallization tails on feldspars, elongated enclaves in mylonitized magmatic rocks, stretched pebbles in conglomerates, and pressure-shadows on synkinematic garnet. This lineation is usually defined by metamorphic minerals like sillimanite (both prismatic and fibrolite), amphibole, and biotite, which have grown parallel to the stretching direction.

Shear criteria are usually abundant and consistent over a large area, allowing us to satisfactorily constrain the kinematics of shear zones. A large variety of kinematic indicators have been observed in HT and LT-mylonites: asymmetrical recrystallized tails on feldspar porphyroclasts (Fig. 3), asymmetrical pressure shadows on garnet or staurolite porphyroclasts, rolling structures (Fig. 5), asymmetrical lenses and boudinage (Fig. 6), SC-structures, centimeter- to meter-scale shear bands, and an assymmetry in the lattice-preferred orientation of quartz (Fig. 7).

Metamorphic Conditions of Mylonitization

Most mylonites in the major shear zones developed during the main high-temperature metamorphism, and display evidence of late to post-kinematic annealing. The observed microstructure is therefore different from the mylonitic microstructure at the time of deformation. High-temperature mylonites are quite similar to migmatitic gneisses (Fig. 8), but they have retained evidence of mylonitization: at the mesoscale, they display a well-defined mineral-stretching lineation, with intense deformation of minerals less sensitive to annealing (like feldspars or magmatic pyroxenes, for instance), and frequent shear indicators that suggest a non-coaxial deformation. In thin-section (Fig. 9), coarse-grained mylonites have a microstructure suggesting extensive grain-boundary migration in minerals sensitive to annealing, especially micas and quartz that frequently involve a foliation marked by aligned micas or small plagioclase grains (Fig. 10). Replacement of K-feldspar porphyroclasts by plagioclase and quartz (frequently through myrmekitization) resulting in a core and mantle structure is usual. In some cases, an extensive replacement may occur and K-feldspar may only exist as relicts. Plagioclase grains display evidence of incipient plastic deformation such as undulose extinction and mechanical twins. Quartz frequently appears as tabular grains within elongated ribbons that wrap up more resistant minerals like feldspar or garnet porphyroclasts (Fig. 9). Although almost free of internal microstructure, quartz in these HT mylonites may have retained a good crystallographic preferred orientation suggesting a dominant prismatic slip system (e.g., Vauchez and Egydio-Silva, 1992; Fig. 7).



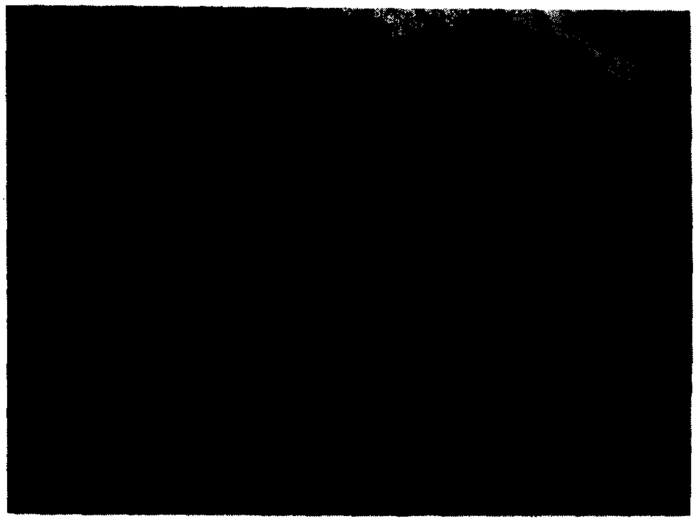


Fig. 3. (*Left*) Mylonitic augengneiss with discrete mobilizates. The foliation is crosscut at a small angle by moderately to undeformed veins of leucogranite. Note the clear asymmetry of feldspar clasts consistent with dextral shear (Patos SZ, WNW of Patos, horizontal surface). Hammer is 30 cm long. Fig. 4. (*Right*) Mafic mylonite with felsic bands of dispersed boudins of gabbro. A random, igneous texture is preserved. Mylonite displays a syn-kinematic metamorphic assemblage with green hornblende, biotite and plagioclase. (Patos SZ near Catingueira, looking east). Hammer is 30 cm.

Fig. 5. (*Left*) Rolling structure developed over a K-feldspar clast indicative of dextral shear sense (Patos SZ, south of Pombal).
Fig. 6. (*Right*) Asymmetric lens in a migmatitic mylonite. This figure results from boudinage in a simple shear regime. The obliquity of the mylonitic foliation within and outside the lens, along with the asymmetrical shape suggests a dextral shear sense (West Pernambuco SZ, south of Floresta). Coin diameter = 1.5 cm.

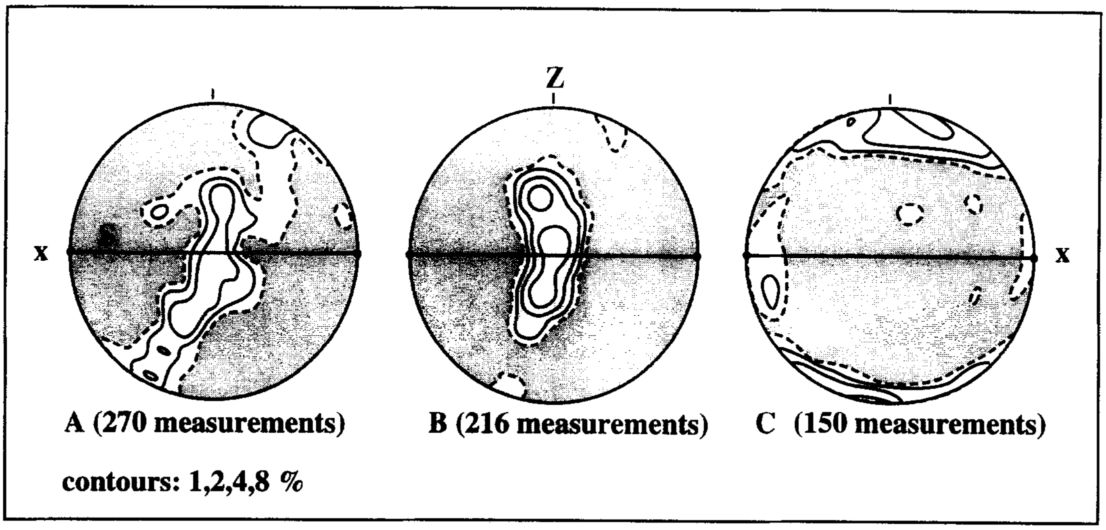


Fig. 7. Quartz crystallographic fabric in mylonites from the WPSZ showing an asymmetry in agreement with a dextral sense of shear (after Vauchez and Egydio-Silva, 1992). A and B suggest activation of a prismatic-<a> slip-system, and thus deformation under high-temperature conditions, whereas C suggests a dominant, low-temperature, basal-<a> slip-system.

The highest metamorphic conditions of mylonitization have been found in the Granja SZ (presented in detail further on in this paper). There, in mafic granulites displaying coronas, symplectites of secondary clinopyroxene and plagioclase have crystallized between orthopyroxene and garnet, in pressure shadows on garnet (Fig. 11) and within shear bands. This strongly suggests that cooling reactions typical of granulite facies metamorphism occurred coeval with the earliest stages of the shearing of the granulite belt. HT mylonites have been also found within the western Pernambuco SZ, where mylonitization was coeval with partial melting (Vauchez and Egydio-Silva, 1992). Mylonites derived from metasediments contain synkinematic prismatic sillimanite, centimeter-scale garnet (Fe/(Fe+Mg)=0.80 to 0.83), intergrowth of fibrolite and biotite, and decimeter- to meter-scale lenses of granitic neosome (see section on the Western Pernambuco shear zone). From preliminary P-T estimates from microprobe analyses, along with the absence of muscovite and the presence of melt in these mylonitic metasediments, (Vauchez and Egydio-Silva, 1992) suggested synkinematic metamorphic conditions around 700°C and 600-700 MPa. In the same area, leucocratic mylonites containing prismatic sillimanite and muscovite suggest a continuation of the deformation under slightly lower temperatures. Similar temperature conditions of mylonitization, but probably at slightly lower pressures prevailed in the Patos SZ, where synkinematic metamorphic crystallization (garnet, biotite, fibrolite and prismatic sillimanite, ± cordierite), the absence of muscovite and partial melting in HT mylonites suggest an early deformation in the shear zone under metamorphic conditions in the range 650-720°C and 550-600 MPa.

Coeval shearing and partial melting of rocks is illustrated in many places. Boudinage of migmatites (Fig. 12), melt collecting in small-scale shear zones (Fig. 13), asymmetric foliation of migmatites around preserved lenses usually more mafic in composition, asymmetric lenses of neosome (Fig. 14), emplacement of neosome veinlets par-

Fig. 8. Migmatite/mylonite displaying a vertical migmatitic banding parallel to relicts of mylonitic foliation preserving kinematic indicators (Fig. 5 is from the same outcrop). Hammer is 30 cm.

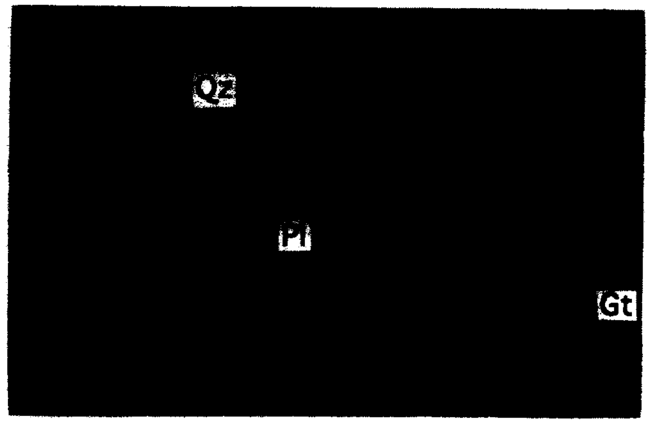
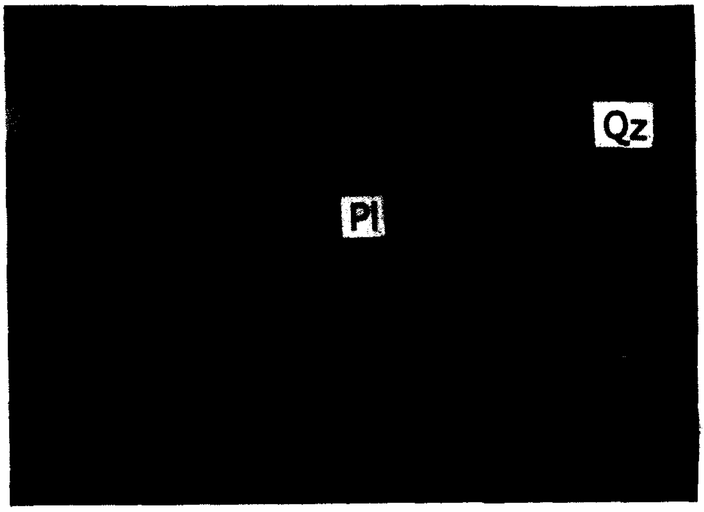
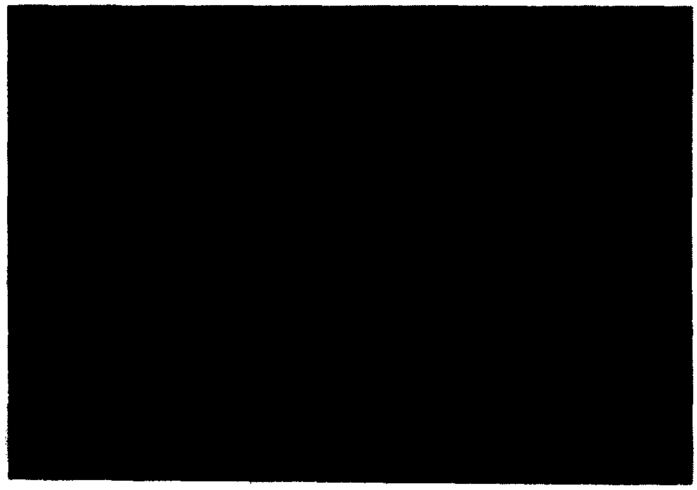
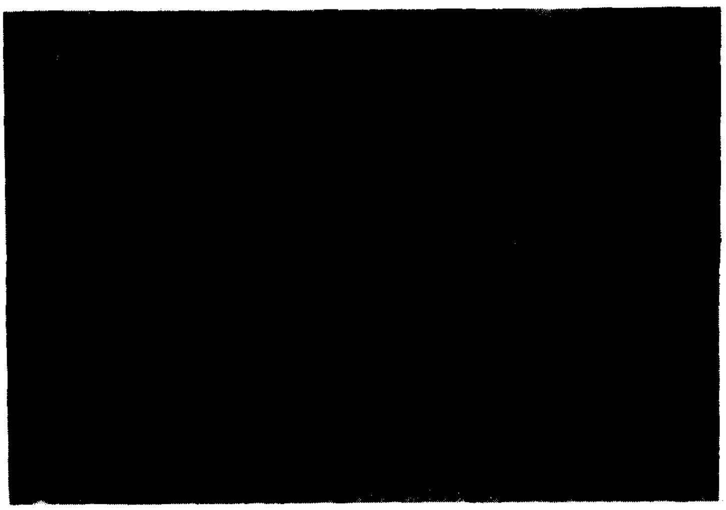


Fig. 9. Typical HT mylonite from the WPSZ, showing plagioclase (Pl) and garnet (Gt) porphyroclasts wrapped up by quartz ribbons (Qz). Dimensions: 1.2x0.8 cm.







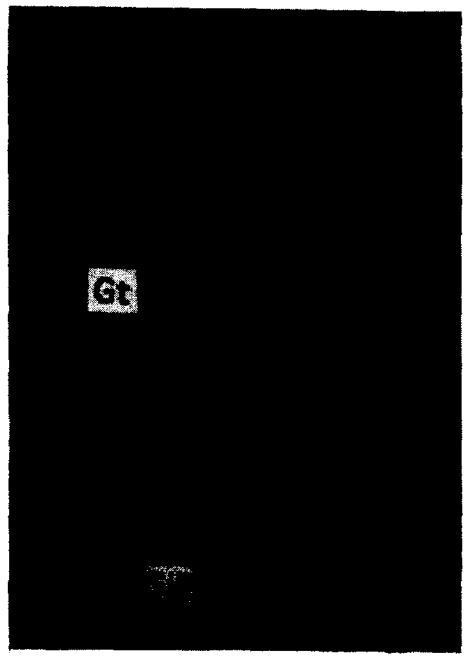


Fig. 10. (*Top Left*) Detail of a quartz ribbon from the mylonite of Fig. 8. Large tabular quartz grains involve small, sometime asymmetric grains of plagioclase. Pattern suggests that the mylonite was annealed at high T long enough for extensive grain boundary migration to occur. 5x3 mm. **Fig. 11.** (*Left Center*) Asymmetric pressure shadows contain symplectites of secondary clinopyroxene and plagioclase, formed around garnet (Ga) in Granja pyrigarnite. 1x1.7 mm. **Fig. 12.** (*Bottom Left*) Boudinage of a more mafic layer in migmatite. Gaps between the boudins are filled with neosome, suggesting that the neosome was still molten when boudinage occurred. Patos SZ at the junction with the Seridó belt. Diam. of the black circle is 5 cm. **Fig. 13.** (*Top Right*) Leucocratic melt collected in small-scale dextral shear zones formed in migmatites. Suggests that the shear zone formed in a partially melted rock. Eastern termination of the WPSZ, in the horse-tail like structure. Migmatitic foliation trends NE-SW and the shear zones EW. Coin diameter = 1.5cm. **Fig. 14.** (*Center Right*) Asymmetric lenses of neogranite in mylonitic metasediments at the eastern termination of the WPSZ. Granite in the lenses is almost free of deformation. The more mafic matrix contains synkinematic garnet and prismatic sillimanite. Coin diameter = 1.5 cm. **Fig. 15.** (*Bottom Right*) Ultramylonite containing more than 70% of fine-grained matrix rich in tiny brownish biotite, in which spherical clasts of garnet (Ga) and broken prisms of sillimanite (Sill) are included. Northern termination of the Orós belt. Dimensions: 3x5 mm.

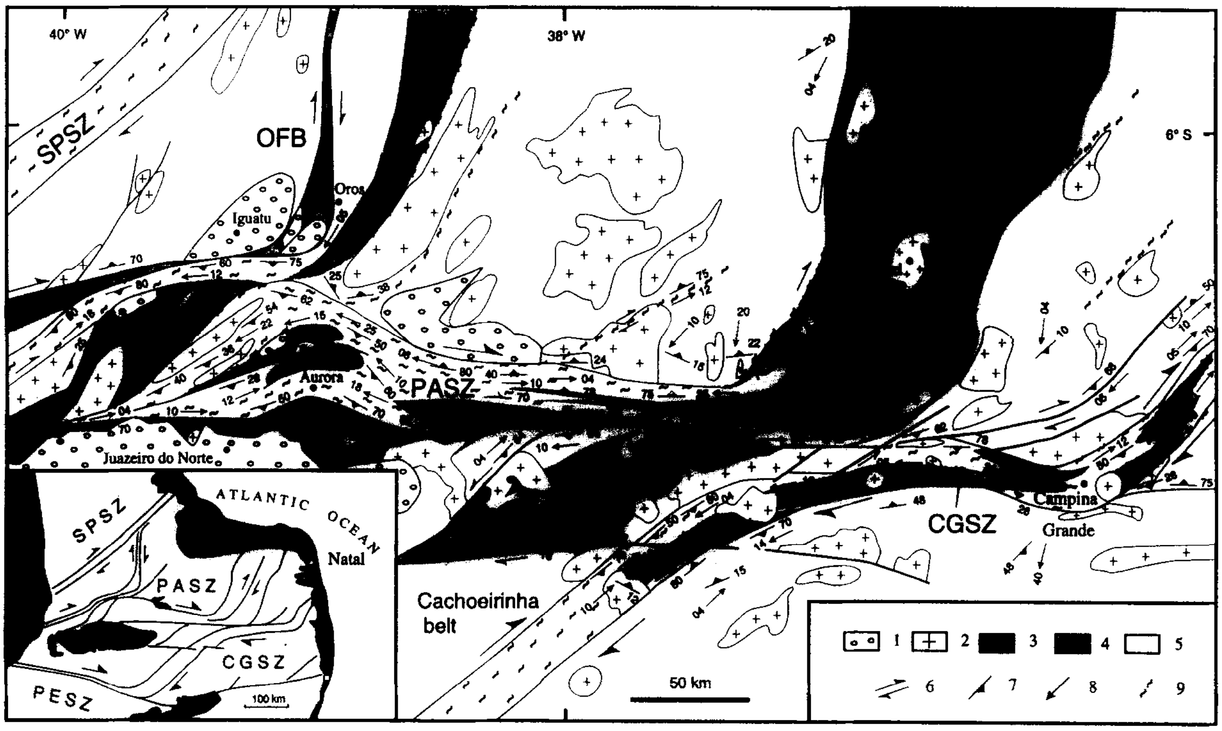


Fig. 16. Schematic structural map of the Patos-Seridó-Campina Grande system. Abbreviations are the same as in Fig. 2. 1: Post-Proterozoic sediments; 2: Brasiliano granites; 3: Migmatites and in-situ granites; 4: Metasediments; 5: Basement; 6: Motion of strike-slip shear zone; 7: Foliation; 8: Mineral stretching lineation; 9: HT-Mylonites.

allel to the foliation, may be very commonly observed in the main shear zones of the system, and also in subsidiary HT-shear zones within the metasedimentary belts. Frequently the transition between the HT-mylonites and the migmatites is progressive (Fig. 8): relicts of mylonitic fabric become more uncommon, the mineral-stretching lineation vanishes, the migmatitic foliation, which is subvertical and relatively coherent close to the mylonites, progressively becomes nebulitic.

Continuous, or cyclic, mylonitization under decreasing temperature is supported by temperature estimates from the biotite-garnet exchange reaction, which yields intermediate values in the 500-600°C range (e.g., Vauchez and Egydio-Silva, 1992), and by the occurrence of mylonites displaying a microstructure typical from medium- (MT) to low-temperature conditions.

These rocks are restricted to narrow zones developed within or at the boundary of the HT mylonite belts, and thus suggest further localization of the deformation with decreasing temperature. They are fine-grained mylonites to ultramylonites that display a mylonitic fabric and frequently contain inherited sigmoidal feldspar, garnet, muscovite and even clasts of sillimanite (Fig. 15). Synkinematic biotite and garnet, when present, display a relatively small crystal size, and biotite is usually light-brown to greenish. Depending on the temperature of deformation, feldspars have undergone dynamic recrystallization through nucleation and growth, pressure-solution or brittle deformation. In MT mylonites, quartz displays evidence of plastic deformation, and has a strong crystallographic preferred orientation that suggests either simultaneous activation of the basal, rhombic, and prismatic slip systems or a dominant basal slip system (Fig. 7). LT mylonites contain muscovite, chlorite, epidote, minute green-biotite grains; feldspar is largely retrogressed, and quartz is very fine-grained and does not show any crystallographic fabric.

THE EASTERN DOMAIN

The Patos-Seridó-Campina Grande System

The Patos-Seridó-Campina Grande system (Corsini *et al.*, 1991; Vauchez *et al.*, 1991; Corsini *et al.*, 1992) is certainly the most complex, and thus most interesting shear zone system of the Borborema Province (Fig. 16). The Patos shear zone runs E-W over 300 km and is between 20 and 30 km-wide. It separates the Rio Piranhas domain, mostly composed of early Proterozoic HT-metamorphic and magmatic rocks from the low-temperature metasediments of the Cachoeirinha (or Piancó-Alta Brígida) belt. Most of the shear zone is composed of subvertical HT mylonites, except for a strip of migmatites 3 to 5 km-wide and a kilometer-wide layer of annealed quartzite, both in the central part of the shear zone, and a 1 to 2 km-wide zone of LT mylonites that marks the northern limit of the Cachoeirinha belt. The kinematics of the Patos SZ associated with both the HT and LT mylonites is consistent with a dextral strike-slip fault, however in a very few places structure indicating sinistral shear sense has been observed.

Westward, the Patos SZ is connected with the Tatajuba (TTSZ) and Potengi (PiSZ) NE-trending transcurrent shear zones that both display evidence of dextral motion. The transition of the dominant displacement direction

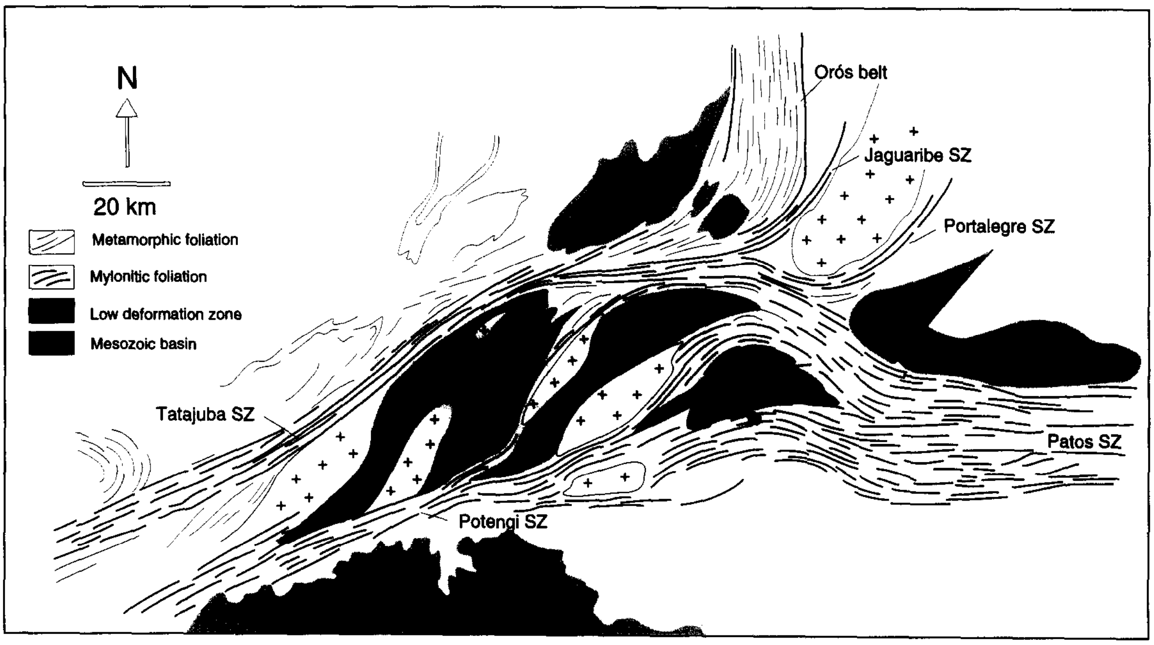


Fig. 17. Hand-drawing from satellite images of the connection between the EW-trending Patos shear zone and the NE-trending Tatajuba and Potengi shear zones.

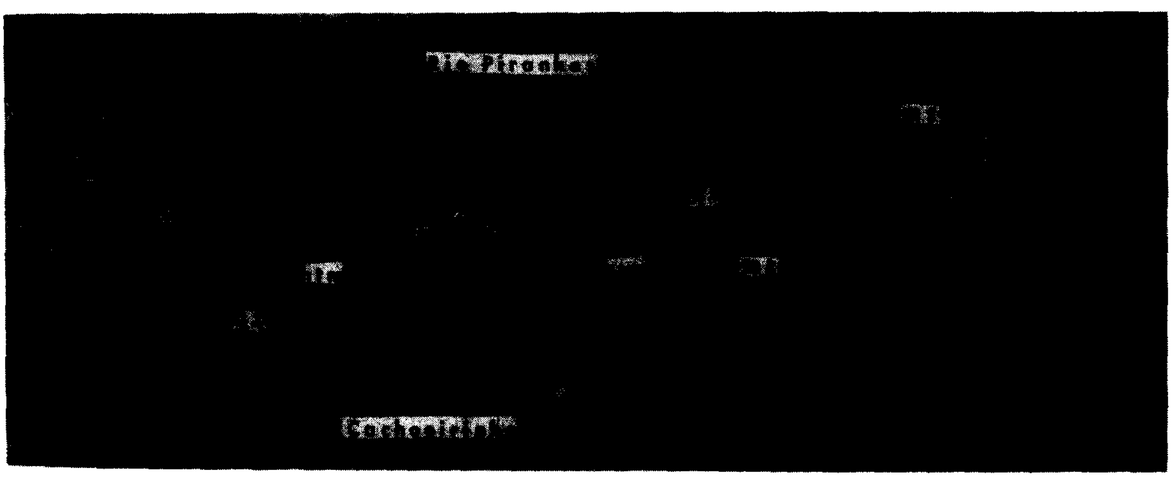


Fig. 18. Landsat image showing the connection area between the Patos shear zone and the Seridó belt. htm: high temperature mylonites; ms: metasediments; qz: quartzite; Cg: Catinguera granite; Tg: Teixeira granite. Scale-bar is 25 km.

from EW to NE-SW is accommodated over a 100 km-long arcuate strike-slip duplex structure (Corsini *et al.*, submitted). In this area, several lenses of unmylonitized materials (metasediments, basement gneisses or igneous bodies) are wrapped up by kilometer-wide arcuate shear zones. This structure (Fig. 17), clearly visible on satellite images, is geometrically similar to horses and duplexes developed in thrust and transcurrent tectonics (Woodcock, 1986), and is thus certainly related to the same kind of tectonic process: the accommodation of a complex kinematic field due to a transfer of deformation between two shear zones. This connection of the EW-trending Patos SZ with NE-trending dextral transcurrent faults is also particularly interesting because it demonstrates that there is no discontinuity between the eastern and western domains of the Borborema shear zone system. The EW-trending branch splays off from the NE-trending branches, and it will be suggested later that a similar pattern may occur at the western tip of the West Pernambuco SZ.

Eastward, the Patos SZ is connected with the Seridó belt. Satellite images (Fig. 18), as well as field evidence support a structural continuity between the shear zone and the belt (Corsini *et al.*, 1991; Amaro *et al.*, 1991). The tectonic fabric progressively rotates from EW to NE-SW. The mylonitic fabric is replaced by a migmatitic fabric in the curvature, then grades continuously into the fabric developed in the metasedimentary belt. An intersection of the Seridó belt by the Patos SZ, and therefore a late development of the PaSZ relative to the deformation in the Seridó belt, may be ruled out on the grounds of structural, geophysical, metamorphic and geochronologic arguments combined.

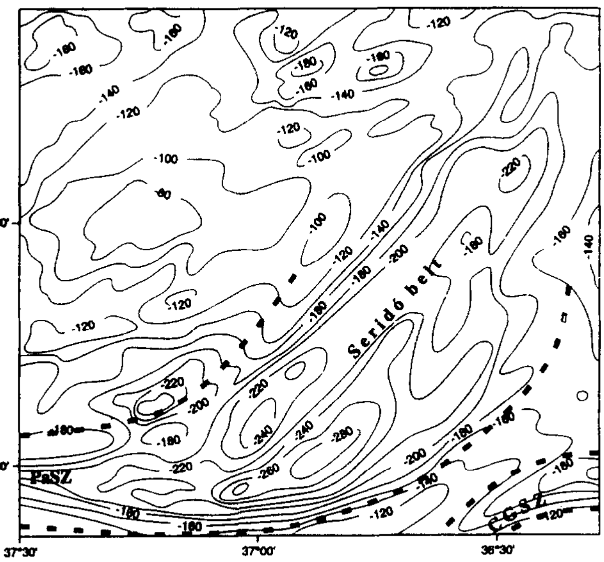


Fig. 19. Aeromagnetic map of the area where the Patos shear zone merges into the Seridó belt (Moreira *et al.*, 1989). A negative anomaly underlines the virgation of the structural trend: it trends EW on the SW corner of the map, and progressively curves to a NE trend. In the SE corner, another anomaly underlines the curvature of the Campina Grande shear zone.

At the southern tip of the belt, massive quartzite (Equador quartzite) and mica-schists, clearly visible on satellite images and aerial photographs, underline the curvature of the structural fabric; their trend is progressively bent from NE-SW to EW, and they penetrate into the Patos SZ where the quartzite is boudinaged. In the PaSZ, more than 8 kilometers of HT mylonites are exposed north of the strip of metasedimentary rocks. If the shear zone transected the Seridó belt, the quartzite would be disrupted and an offset of the quartzite would occur; this is clearly not the case. A structural continuity is also suggested by the progressive curvature of the aeromagnetic anomalies (Moreira *et al.*, 1989) that follow the rotation of the tectonic fabric without any discontinuity (Fig. 19). Synkinematic metamorphic conditions are similar in both the PaSZ and the Seridó belt; the deformation was contemporaneous with HT metamorphism and partial melting.

The southern boundary of the PaSZ is marked by a kilometer-wide belt of lower-temperature mylonites to ultramylonites reworking the HT mylonites. Mylonitization in this late shear zone usually occurred under greenschist facies conditions, but in the vicinity of granite bodies, as for instance, the Catinguera pluton, synkinematic garnet, sillimanite and staurolite may be observed in mylonites from metasediments, suggesting that the thermal aureole of the granite was deformed during this late episode.

East of the junction between the PaSZ and the Seridó belt, HT mylonites are lacking or reduced to a narrow zone that does not exceed a few hundred meters. In this area, migmatites from the basement are cross-cut by several NE-trending medium- to low-temperature shear zones, one of which limits the Teixeira batholith. Farther east another zone of EW-trending HT mylonites, the Campina Grande shear zone (CGSZ), occurs. It is more than 10 km-wide and contains mylonites to ultramylonites suggesting deformation coeval with partial melting. The characteristics of the CGSZ are very similar to those of the Patos SZ, and $^{40}Ar/^{39}Ar$ measurements performed on mylonites from these two shear zones yield cooling ages in the same range (Féraud, 1993). Approaching the Patos SZ westward, the Campina Grande SZ curves to a NE-SW trend (Fig. 16), then extends southwestward toward the Pernambuco SZ to which it probably connects. Eastward, the CGSZ crosscuts the southern boundary of the Pocinhos granite, then splits in two branches. The southern branch extends eastward up to the city of Campina Grande where it is interrupted by a post-tectonic granite, and the northern branch rotates to a NE trend and follows the eastern boundary of the Pocinhos granite (Figure 16). It is remarkable that the fabric of the mylonites in the EW- and NE-trending branches differs although the protolith is similar. In the EW-trending branch, kinematic indicators are abundant and consistently indicate a dextral sense of shear. This is in agreement with a deformation regime dominated by simple shear. In the NE-trending branch, reliable kinematic indicators are scarce and inconsistent (with the exception of a few narrow mylonitic zones, more deformed than the surrounding rocks, which may be regarded as dextral shear zones). Recrystallized tails over K-feldspar porphyroclasts are usually symmetrical or display a faint asymmetry suggesting either a dextral or a sinistral sense of shear. Shear bands are commonly observed in the mylonitized granite; they form a set of conjugate dextral and sinistral C-surfaces symmetrically intersecting the foliation, without any dominance of one type on the other. A balanced development of dextral and sinistral shear sense indicators in the same rock, along with the frequent absence of asymmetry, suggest a significant component of pure shear despite a well-developed stretching lineation. Such a variation in deformation regime is consistent with the change in orientation of the mylonitic fabric. A deformation mostly accommodated by simple shear in the EW-trending branch would result in a transpressional deformation in the NE-trending branch in which strain partitioning into alternating zones dominated by pure or simple shear may occur.

Recent geochronological data (Figueiredo, 1992; Féraud *et al.*, 1993) strongly support a similar tectonothermal evolution for the PaSZ, the Seridó belt and the CGSZ. $^{40}Ar/^{39}Ar$ plateau ages in the range 534-544 Ma were obtained on amphiboles from samples collected in the Patos and Campina Grande shear zones. This result is consistent with U-Pb dating on zircon from synkinematic diorite and granite in the Seridó belt, which yield ages of 570 Ma and 550 Ma respectively, (Leterrier, 1994). Muscovite and biotite pairs from the three domains were analyzed and yield $^{40}Ar/^{39}Ar$ plateau ages around 500 Ma suggesting a slow cooling rate immediately after the peak metamorphism, then a rapid cooling below ca. 300°C around 500 Ma (Féraud *et al.*, 1993).

In summary, the Patos-Seridó-Campina Grande system presents a complex kinematic field: from west to east, the Patos shear zone splays off from the NE-trending shear zones of the western domain through a transcurrent duplex that accommodates the rotation of the flow direction. The

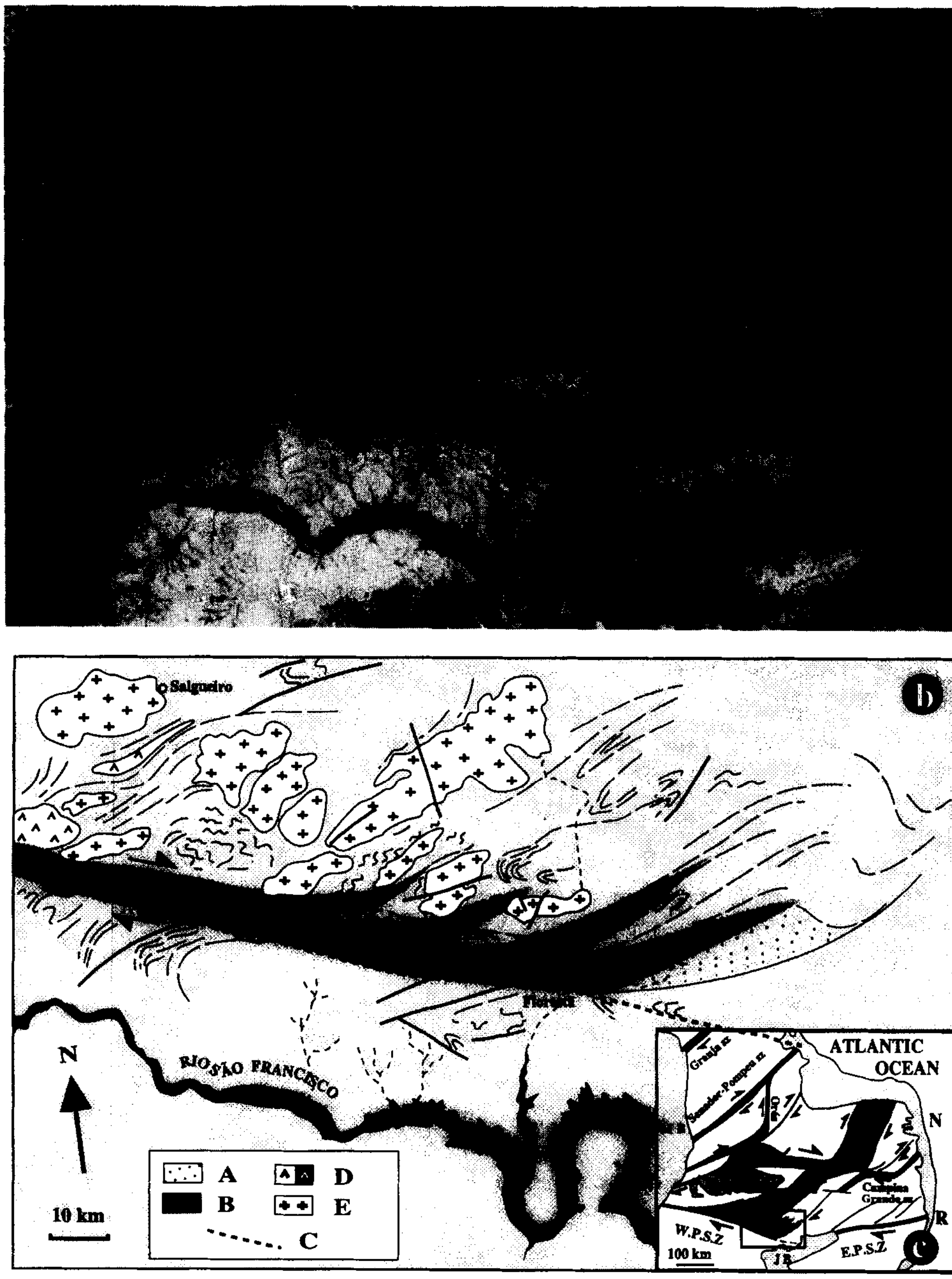


Fig. 20. Landsat image (a) and geologic interpretation (b) showing the easterly termination of the WPSZ. Westward the shear zone is marked by a strip 10 km-wide, of strongly foliated rocks (in between arrows). Eastward, the foliation is involved in a huge horse-tail and rotates to a NE trend. South of Floresta, a leucocratic formation (stippled on b) is squeezed and mylonitized in the southern boundary of the shear zone, then follows the virgation NE. This image clearly shows that the HT-mylonites exposed north of the leucocratic mylonite do not crosscut the leucocratic formation in the virgation. It also illustrates the coexistence of continuous type and discrete-type shear zone boundaries respectively at the northern and southern edges of the shear zone. (A: Leucocratic formation; B: HT mylonites; C: Low-temperature shear zone; D: Peralkaline granitoids; E: Undifferentiated granites).

PaSZ then runs eastward over more than 300 km and merges into the Seridó metasedimentary belt in which most of the strain is transferred. The system then continues eastward through an en-échelon disposition with the Campina Grande shear zone, which itself curves at both ends to a NE-SW trend.

The Pernambuco System

In previous works, the so-called Pernambuco lineament was regarded as a single fault, continuous over almost 600 km from the Parnaíba Basin to the coastal plain close to Recife. Recent detailed studies (Vauchez and Egydio-Silva, 1992; Neves and Vauchez) have shown that the lineament is in fact composed of two distinct segments, the West- and East-Pernambuco shear zones (WPSZ and EPSZ respectively), which may represent a system of relay faults. Although less complex, the Pernambuco system shows many similarities to the Patos-Seridó-Campina Grande system.

The Western Branch

The western tip of the WPSZ is buried under the Parnaíba Basin, and therefore its relationship with the NE-trending system of the western Borborema remain unknown. Eastward, the WPSZ has been surveyed over ca. 200 km (CPRM unpublished maps, Vauchez and Egydio-Silva, 1992).

It is also clearly visible on satellite images and aerial photographs where it appears as a 10 km-wide strip of strongly foliated rocks (Fig. 20). The rocks in the shear zone are typical HT mylonites derived from various protoliths: gneisses and igneous rocks from the basement, metasediments (quartzite, micaschists, marble and leucocratic gneisses), pre-kinematic syenites (e.g. the Terra Nova batholith), and various types of synkinematic dikes and elongated plutons that have only recorded part of the deformation history. Mylonitization under high temperature conditions is especially supported by the occurrence of partial melting, and crystallization of prismatic sillimanite, both synkinematic (Vauchez and Egydio-Silva, 1992).

Several subsidiary NE-trending shear zones splay off the northern boundary of the WPSZ and penetrate the Cachoeirinha belt in conformity with the regional metamorphic foliation. The WPSZ terminates eastward in the vicinity of the city of Floresta. Over a distance of more than 50 km, the HT-mylonitic foliation progressively curves to a NE-SW trend, and forms a compressional horse-tail that links the WPSZ to the foliation of the Salgueiro schists of the southern part of the Cachoeirinha belt. The bending of the foliation-trend is accompanied by a rotation of the orientation of the folds affecting the foliation. The northern boundary of the shear zone is outlined by several elongated EW-trending domes in which the basement is sometimes exposed. These domes are wrapped up by zones of HT mylonites that anastomose at the tip of the domes. Northward, the fold axes rotate, following the curvature of the foliation, and are finally NE-SW further north from the shear zone. This change in fold trend associated with the horse-tail-like geometry of the foliation is in agreement with the compressional nature of the horse-tail.

As for the Patos shear zone, considering the distribution of rock units, an eastward termination of the WPSZ is unavoidable. South of the city of Floresta, the southern boundary of the WPSZ is underlined by HT mylonites derived from Al-rich quartzite and leucocratic gneisses. This formation is perfectly visible on satellite images and aerial photographs, where it appears white (Fig. 20). Northward, HT mylonites from various protoliths are exposed over ca. 8 km. Eastward, the orientation of the foliation is rotated to NE-SW while the thickness of the leucocratic formation increases. In the NE-trending branch, this formation is largely exposed and is no longer mylonitic. The continuity of the leucrocratic formation was confirmed by aerial photographs which preclude the possiblity that the mylonites of the WPSZ crosscut and continue eastward.

The southern limit of the WPSZ is characterized by a zone of greenschist-facies mylonites a few hundred meters-wide that reworked HT mylonites. Several peralkalic granite bodies emplaced within the HT mylonites are also slightly mylonitized at low temperature. Eastward, the LT shear zone does not follow the curvature of the HT mylonites, but instead continues with an EW trend and is finally buried under the Jatobá basin.

The Eastern Branch

The East Pernambuco shear zone (EPSZ) and the Fazenda Nova SZ (FNSZ) are described in more detail in a companion paper (Neves and Vauchez, this issue). We will only present here a summary of the main features that characterize these fault zones. The East Pernambuco shear zone extends over 200 km westward from the coast. It is marked by a mylonite zone (ca. 2 km-wide) that increases in width to reach a maximum in the area of the city of Caruaru where it connects with the NE-trending Fazenda Nova SZ. Further westward, the width of the EPSZ decreases rapidly and finally vanishes. Mylonites in the EPSZ have been extensively reworked under greenschist facies metamorphic conditions.

Some relicts of HT mylonites, however, subsist locally and suggest that the fault was initiated at much higher temperature. This conclusion is also supported by the dragging of the magmatic foliation in the granite exposed north of the EPSZ. Shear sense indicators are common and consistently indicate a dextral motion in both the HT and LT mylonites.

The FNSZ is a km-wide sinistral HT shear zone that merges into the EPSZ. In the connection area the strain field is complex and in several places evidence of pure shear (conjugate shear bands, symmetrical recrystallized tails over K-feldspar porphyroclasts) have been observed. The FNSZ extends northeastward over about 45 km, limiting or cross-cutting several magmatic bodies, then progressively vanishes into metasediments of the country rock. The fault zone comprises HT mylonites almost free of retrogression that allow deciphering of the early stages of the evolution of the shear zone and its relationships with magma emplacement.

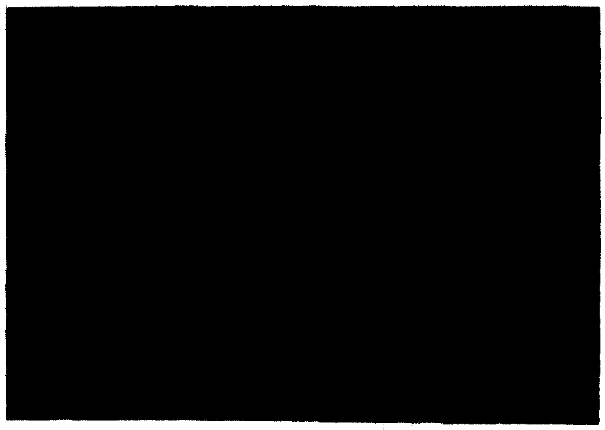
There is no apparent structural discontinuity between the FNSZ and EPSZ, and this, together with field and petrographic arguments, strongly suggest that they shared the same tectonothermal evolution. Neves and Vauchez (this issue), suggest that nucleation of both the EPSZ and the FNSZ was triggered by the existence of a local rheological instability associated with the still incompletely solidified magmatic stocks. This would explain the limited extension of these faults and their longitudinal change in width. In this model, the EPSZ-FNSZ system represents a local structure due to the presence of a large magma chamber in the crust.

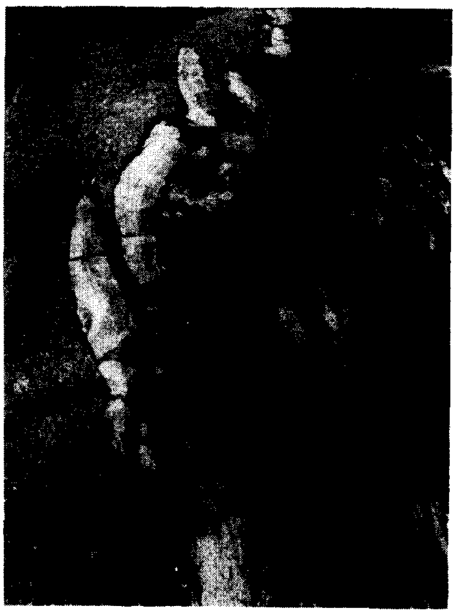
NE-Trending Shear Zones in the Eastern Domain

The NE-trending ductile strike-slip faults, although they appear subsidiary relative to the main EW-trending shear zones, raise interesting questions that have not yet been solved. North of the Patos-Seridó-Campina Grande system, all NE-trending shear zones display good evidence of dextral shear sense (e.g. Hackspacker and Legrand, 1989; Corsini *et al.*, 1992; Archanjo *et al.*, 1994). Mylonitization in these shear zones occurred under high-temperature conditions, similar to those inferred for mylonitization in the EW-trending faults.

Moreover, most NE-trending shear zones splay off from the main EW-trending shear zones and there is no cross-cutting relationship, suggesting that this pattern accommodated a progressive change in transport direction from EW to NE-SW (Corsini *et al.*, 1991; Vauchez *et al.*, 1992). Frequently NE-trending shear zones are discontinuous; they terminate in compressional fan-like structures through which the mylonitic foliation is connected with the regional metamorphic foliation, or they delineate an en-échelon system (e.g., Archanjo and Bouchez, 1991; Archanjo *et al.*, 1994). In several cases, they developed at the boundary of a granitic pluton in which evidence of strike-slip faulting was recorded in the magmatic stage (Archanjo *et al.*, 1992; Archanjo *et al.*, 1994).

The situation is more complex south of the Patos-Seridó-Campina Grande system. Numerous subsidiary dextral transcurrent shear zones branch off to the North-east from the West Pernambuco SZ, and are thought to connect with the Patos and Campina Grande SZ (Caby *et al.*, 1991; Vauchez *et al.*, 1991; Vauchez *et al.*, 1992). However, many NE-trending mylonite zones (e.g., Fazenda Nova SZ, Congo SZ, Cabaceiras-Boa Vista SZ, Itaporanga SZ) display kinematic indicators in agreement with sinistral strike-slip faulting (Figs. 21 and 22). Usually these mylonites have been formed under moderate- to low-temperature conditions, probably synchronously with the LT reactivation of the Patos and West Pernambuco shear zones. However, in some cases, higher synkinematic metamorphic conditions have prevailed, as for instance in the Fazenda Nova SZ (Neves and Vauchez, 1995) and although these conditions may reflect the residual temperature of the batholith and not necessarily the regional metamorphic conditions, an early development of some NE-trending sinistral shear zones cannot yet be ruled out.





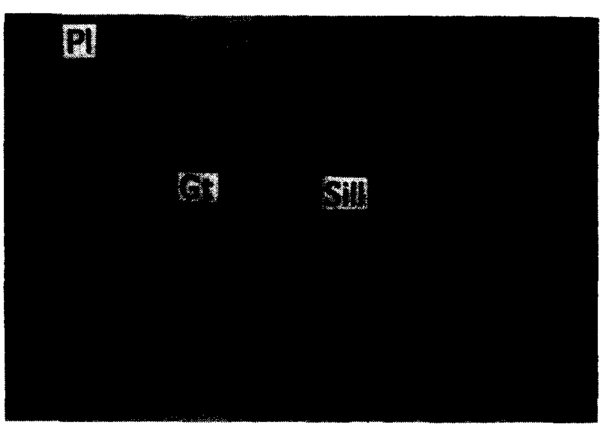


Fig. 21. (*Top Photo*) Small-scale LT shear zone in an undeformed porphyric granite close to the main, higher temperature Fazenda Nova shear zone. Rotation of the foliation and asymmetrical tails over K-feldspar porphyroclasts suggest a sinistral shear sense. The black circle is 5 cm in diameter.

Fig. 22. (*Top Center*) Asymmetric tails around K-feldspar porphyroclast and shear bands suggesting sinistral shear sense in a porphyric facies of the Teixeira batholith. The pencil is 15 cm long.

Fig. 23. (*Bottom Center*) Slightly deformed porphyritic granodiorite dike emplaced during dextral shear within the Senador Pompeu SZ. Note the small-scale duplexes affecting the aplitic vein and the isoclinally folded leucosome veins formed in garnet-biotite-plagioclase metagreywacke (dark) to the right (SSE of Quixeramobim). Scale bar = 25 cm.

Fig. 24. (*Bottom Photo*) Deformed prismatic sillimanite (Sill) around garnet (Ga) in the Granja kinzigites. Plane light, area of view 3x5 cm.

THE WESTERN DOMAIN

The kinematic pattern in the western domain (mostly Ceará State) is less complex than in the eastern Borborema Province. Transcurrent shear zones in Ceará state are mostly NE-SW trending (Granja, Sobral, Senador-Pompeu, Tatajuba and Potengi SZ) and display shear criteria indicating dextral sense of shear. The Tauá shear zone, the westernmost ductile fault of the Borborema Province, however, departs from this simple picture; it trends NNW-SSE and kinematic indicators in the shear zone are in agreement with a sinistral sense of shear. All shear zones but the Sobral SZ are underlined by HT mylonites and display evidence of LT reworking.

The Granja Shear Zone

The Granja shear zone (Gama *et al.*, 1990) was superimposed on a Transamazonian (Gaudette 1993, personal communication) belt of lower crustal, granulite-facies metasediments and associated syn-metamorphic intrusives (Fig. 23). All rock units trend NE-SW, nearly parallel to the shear zone. Except for some lenses of charnockites, mafic norites and calc-silicate boudins, all rocks display a secondary steep protomylonitic HT foliation which is axial-planar to the ENE-trending folds parallel to the belt. This foliation is mostly marked by platten-quartz frequently involving sigmoidal plagioclase clasts, and by plastically deformed orthopyroxene, sillimanite (Fig. 24), plagioclases, and synkinematic secondary biotite. Brittle deformation of many minerals such as pyroxenes and sillimanite took place along late shear bands. In mafic granulites with a coronitic texture, symplectites of secondary clinopyroxene + plagioclase crystallized between orthopyroxene and garnet, in pressure shadows over garnets (Fig. 11) or in C-S surfaces. This strongly suggests that cooling reactions typical for granulitic terrains occurred in relation to transcurrent shearing of the granulite belt. Shear criteria, mainly asymmetric crystallization of biotite in pressure shadows over garnets, consistently suggest a dextral sense of shear.

A 2 Ga U/Pb zircon age, obtained on a leucocratic vein (Gaudette 1993, personal communication), suggests that the primary, coarse-grain granulitic assemblage is the result of a pre-Brasiliano metamorphism. $^{40}Ar/^{39}Ar$ plateau ages of 575 Ma recently obtained on pargasite (Monié, 1993, pers. comm.) may record cooling at temperatures ca. 500-550°C. Since all observed metamorphic reactions are consistent only with cooling and depressurization, we infer that this granulitic terrain most probably was metamorphosed under granulite facies conditions during the Transamazonian orogeny, remained deeply buried and hot (T >550°C) in the lower crust and was only exhumed during the development of the Borborema shear zone system.

Protracted deformation under decreasing P-T conditions is evidenced by mylonite zones, a few meters-thick, that display much lower temperature assemblages. These LT mylonites are characterized by a porphyroclastic to cataclastic microstructure and a high amount of matrix rich in pale brown biotite, epidote, and occasional white mica.

The Sobral Shear Zone

This lineament limits the northwesterly Jaibaras molassic graben from the southeasterly nappe complex of central Ceará (Caby and Arthaud, 1986). Southwest of Sobral, the shear zone is marked by an up to 1.5 km-wide belt of steeply dipping ultramylonites bearing an horizontal stretching lineation. Ultramylonites from various kinds of protoliths display a fine-grained mosaic microstructure, and contain variable amounts of minute green biotite and white mica. Lenses and cigar-shaped pseudoboudins of coarse-grained gneisses and pegmatites are wrapped in the ultramylonites, the mylonitic fabric of which, approaching the lenses, is deformed into sheath folds. Mica-rich ultramylonites display C-S surfaces always consistent with dextral movement. In summary, mylonitization within the Sobral shear zone, which is considered as a possible extension of the Kandi-4°50' lineament of west Africa, occurred under relatively low-temperature conditions. No evidence of earlier high-temperature shearing has been yet reported. It is therefore impossible to ascertain whether this shear zone was already active early in the history of the Borborema shear zone system or developed late during a low-temperature reactivation of the system.

The Senador Pompeu Shear Zone (SPSZ)

This NE-trending, straight shear zone marks the southeastern boundary of the nappe complex of central Ceará (Caby and Arthaud, 1986). On satellite images, the SPSZ forms a lineament 350 km-long and 10-15 km-wide. Northeastward, it merges with the Orós belt whose trend rotates from NS to NE-SW, then is buried under the coastal plain. Southward, the SPSZ merges with the Tauá shear zone, then, approaching the Cococi molassic graben, is concealed by superimposed brittle deformation.

The SPSZ, as deduced from satellite images, involves various rock types: HT mylonites, migmatites and HT-metamorphic rocks, that consistently display evidence of dextral transcurrent shearing. In the central part of the SPSZ, the Mombaçá granulite belt covers most of the width of the lineament. Granulite-facies assemblages developed during a poorly known early tectonic event coeval with emplacement of sheets and veins of charnockites and norite. Dextral strike-slip faulting began under decreasing P-T conditions and reworked the granulites at still high temperatures. Recent $^{40}Ar/^{39}Ar$ dating yields ages of cooling under the blocking temperatures of ca. 573 and 568 Ma respectively for amphibole and biotite from the reworked granulite (Monié 1994 pers. comm.). This retrograde evolution is well illustrated in the vicinity of the city of Senador Pompeu, where a mylonitic tonalite displays extremely deformed mafic enclaves up to several meters long, with highly prolate axial ratios up to 1:15:300, and a syn-kinematic mineral assemblage involving acicular green hornblende and green clinopyroxene, green biotite, plagioclase, quartz, minor microcline and titanite suggesting deformation under HT (late-magmatic?) conditions. At the eastern margin of the pluton, granitic to tonalitic dikes were injected within the shear zone and crosscut the HT-mylonitic foliation; after solidification, these dikes have been sheared under moderate temperature conditions.

Southward, numerous straight shear zones, usually a few meters thick, containing porphyroclast-poor ultramylonites enriched in very fine-grained secondary green biotite and/or white mica, Na-plagioclase, epidote and opaques, suggest a reactivation of the SPSZ under greenschist facies conditions. In the vicinity of the Cococi molassic graben, brittle deformation associated with steeply dipping extensional faults extensively reworked the LT mylonites.

The Orós Belt

Although the Orós belt cannot be considered as a shear zone, its characteristics are worth taking into account in a tectonic model of the Borborema shear zone system. This sinuous belt more than 500 km-long (Fig. 2) comprises a continuous Lower Proterozoic unit of quartzites overlain by metapelites, and voluminous masses of metaporphyries and sub-alkalic orthogneisses dated around 1.7 Ga (Sá *et al.*, 1991; Sá, 1992). This belt separates the easterly polycyclic pre-Brasiliano basement of the Rio Piranhas domain from a westerly migmatitic, low-angle foliation domain; its width regularly decreases northward from ca. 40 km down to a few kilometers. The boundaries of the belt are underlined, on both sides, by a continuous narrow shear zone formed under retrogressive LT-conditions (Sá *et al.*, 1991).

The Orós belt is characterized by significant changes in strain pattern and metamorphic conditions along its trend. In the southern domain, where the belt connects with the Tatajuba shear zone, the regional deformation is expressed by a steep S_1 cleavage axial-plane of gently plunging, open to tight folds, and is coeval with greenschist-facies metamorphism (tiny white mica, chlorite, chloritoid, albite and garnet). The lack of primary biotite suggests low-T, medium-P (400-600 MPa?) conditions. Further northward, higher temperature conditions prevailed and the occurrence of kyanite included in andalusite (close to the city of Iguatu) also supports medium-P conditions. In this southern domain, a subhorizontal stretching lineation defined by stretched quartz and feldspar porphyrocrysts with elongate pressure shadows is frequently observed and a constrictional strain is suggested by shape ratio of feldspar porphyroclasts systems in the range 1:3:100 to 150. However, shear sense indicators are scarce, except approaching the boundaries of the belt, and strain estimates suggest a dominantly coaxial deformation (Sá, 1992).

In the northernmost domain, the width of the Orós belt is reduced to a few kilometers and its trend is bent to northeast, paralleling the Senador-Pompeu shear zone. Synkinematic granulite-facies conditions have prevailed: metapelites contain prismatic sillimanite, garnet (alm 60-pyr up to 37 in cores), quartz, K-feldspar, plagioclase, Mg-cordierite (X Mg=0.780), rutile and graphite, and quartzites contain sillimanite + K-feldspar. Preliminary estimates of P-T conditions give temperatures higher than 700° C and pressures around 600-800 MPa. Granulites suffered a pervasive HT mylonitization under decreasing temperatures. Similarly to the Granja granulites, the protomylonitic to mylonitic foliation is axial-plane of tight folds with horizontal axes, that deform the compositional layering and garnetiferous leucosomes. Kinematic indicators, mainly asymmetric biotite tails, are consistent with a dextral shear sense. Mylonitic deformation at decreasing P-T conditions is evidenced by numerous zones of ultramylonite, a few centimeters thick, parallel to the HT-mylonitic foliation. In these zones, the mylonites contain a high volume of fine-grained matrix made up of brown biotite and minor fibrolite, and a small amount of clasts (sub-spherical garnet with preserved prograde sillimanite inclusions, plagioclase, sphene and broken prismatic sillimanite) free of significant retrogression and displaying rolling structures (or ∂-type tails).

In summary, the Orós belt illustrates the case of a metasedimentary/metavolcanic fold belt that progressively becomes a narrow belt, deeply mylonitized under high metamorphic conditions, and finally merges with a major NE-trending shear zone. It is interesting to note that the stretching lineation is parallel to the trend of the belt whether the deformation is dominated by coaxial or non-coaxial strain.

The Tauá Shear Zone

The Tauá shear zone (TSZ) extends over 300 km in a NNW-SSE direction and comprises a mylonitic belt 4 to 6 km-wide. Mylonites mostly derive from stromatitic migmatites, pre-kinematic intrusives and, to a lesser extent, from paragneisses, mica-schists and amphibolites. The deformation is heterogeneous: domains of high and low strain alternate at the outcrop scale. Lenses of material almost free of mylonitization may reach more than 1 km in width. The mylonitic foliation is generally steeply dipping to vertical and bears a subhorizontal stretching lineation. A linear fabric is locally better developed than the planar fabric, specially in amphibolites and granites. Evidence of stretching is widespread, especially as asymmetric boudinage and pull-apart of layers or dikes of more competent material. S-C structures and asymmetric tails over K-feldspar porphyroclasts are common in granitoids. All shear criteria consistently indicate a sinistral shear sense (Neves, 1991).

Deformation under amphibolite facies conditions in the TSZ is suggested by the stability of magmatic hornblende and biotite in mylonitized granitoids, and the preservation of regional metamorphism assemblages: plagioclase-K-feldspar-quartz-garnet in micaschists and paragneisses and plagioclase-hornblende-clinopyroxene-quartz-garnet in amphibolites. Continuing deformation under decreasing temperature conditions was localized in narrow bands.

Synkinematic magmatism was recorded by the Pedra Lisa biotite-amphibole-bearing granite (Neves, 1991), a sheet-like body at least 50 km-long and up to several hundred meters-wide. This granite (calc-alkaline or high-

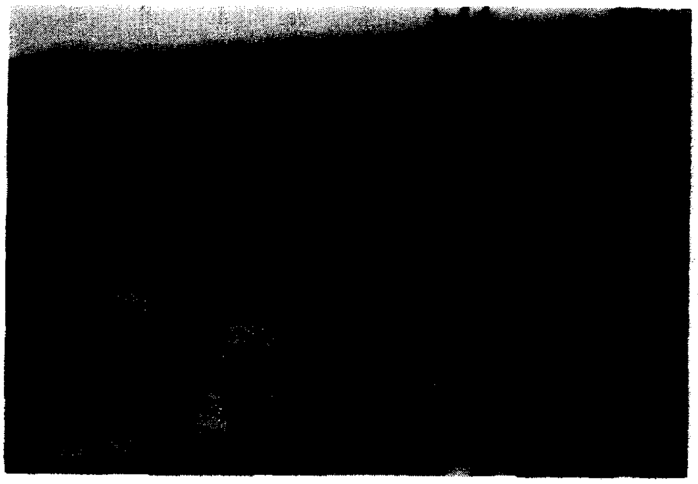


Fig. 25. Mylonitic tonalite within the Senador-Pompeu shear zone (1 km ENE of Senador-Pompeu city) containing plagioclase, quartz, minor microcline and amphibole, secondary biotite and highly stretched mafic enclaves with shape ratio as large as 1:15:300.

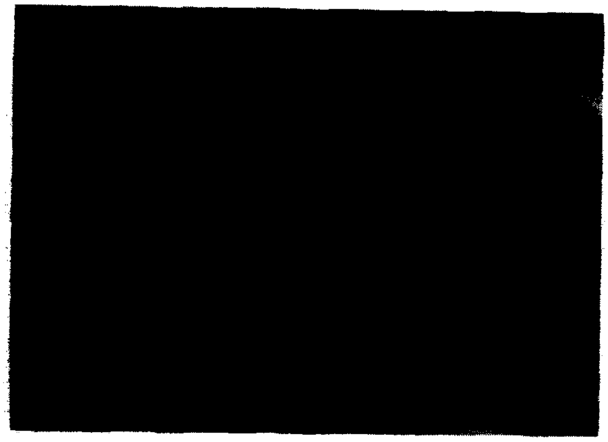


Fig. 26. Alternating mylonitized dikes of porphyric granite, diorite and aplite in the Fazenda Nova shear zone, illustrating synkinematic intrusions. Diorite contains K-feldspar xenocrysts, suggesting mechanical incorporation that likely began at the magmatic stage. Hammer length=30 cm.

potassium calc-alkaline according to its mineralogy) is restricted to the HT-mylonitic belt in which it was intruded; it contains xenoliths of mylonitized country rock and was itself deformed in the solid-state.

SHEAR ZONES AND MAGMATISM

Many granitoids in the Borborema Province of NE Brazil are spatially associated with strike-slip shear zones. Sial and co-workers (Sial, 1986, 1993; Sial and Ferreira, 1990; Ferreira and Sial, 1986; McMurry *et al.*, 1987; Mariano and Sial, 1990; 1993) have recognized four groups of granitoids: calc-alkaline (Conceição type), high-potassium calc-alkaline (Itaporanga type), with trondhjemitic affinities, and shoshonitic to peralkaline (this group also including syenitoids). There are, however, only limited data available on the relationship between shear zones and magmatism.

Detailed tectonic studies of granites, including field work, remote sensing and analysis of anisotropy of magnetic susceptibility (Archanjo *et al.*, 1992a, 1992b, 1994; Archanjo, 1993; Olivier and Archanjo, 1994; Jardim de Sá, 1993; Neves and Vauchez, 1996, this issue) have been mostly performed in the Seridó belt and, to a lesser extent, in the Cachoeirinha belt. Most studied plutons (Emas and São Rafael Conceição-type plutons; Gameleiras, Barcelona and Fazenda Nova Itaporanga-type plutons; Triunfo syenite, Picuí alkaline granite), independently of their petrologic nature, display a nearly horizontal magmatic foliation parallel to the solid-state foliation of the country-rock. According to Archanjo (1993), the magmatic lineation dominantly trends NS in the São Rafael and Picuí plutons, EW in the Triunfo pluton and NE-SW in all the others. The magmatic fabric of the São Rafael, Picuí and Triunfo plutons does not show any evidence of transcurrent motion during their emplacement. The Emas pluton displays EW-trending narrow magmatic shear zones developed lately during magma crystallization. In the Gameleiras, Barcelona and Fazenda Nova batholiths, which have been locally mylonitized post-solidus, the magmatic foliation tends to become vertical approaching the solid-state shear zones.

The Acarí, Itaporanga-type pluton, which was emplaced in the central part of the Seridó belt, displays a steeply dipping magmatic foliation bearing a subhorizontal magmatic lineation over the entire massif. This was parallel to the solid-state mylonitic fabric in the shear zone developed along its eastern boundary (Jardim de Sá *et al.*, 1986; Archanjo, 1993; Jardim de Sá, 1993).

In the Cachoeirinha belt, the Terra Nova peralkaline batholith, belonging to the "syenitoids line" defined by Ferreira and Sial (1986) and Sial and Ferreira (1988), was mylonitized at high temperature in the northern part of the West Pernambuco SZ (Vauchez and Egydio-Silva, 1992; Silva Filho *et al.*, 1993). On the other hand, several small bodies of peralkaline granites (e.g., Serra do Bendó, Serra de Ouricuri, Serrote do Falcão) were emplaced along the southern boundary of the West Pernambuco SZ in the HT mylonites (Sial and Ferreira, 1988). Subsequently, these magmatic stocks underwent an incipient solid-state deformation under low temperature conditions (Vauchez and Egydio-Silva, 1992). In agreement with Sial and Ferreira (1988), two generations of peralkaline magmas, one pre-kinematic and the other late-kinematic, may be distinguished by their relationships with the deformation in the Pernambuco SZ.

Numerous magmatic bodies, less deformed than the surrounding mylonites, may be observed in shear zones. This is, for instance, the case in the Tauá SZ with the Pedra Lisa granite, or in the West Pernambuco SZ (south of Parnamirim) where the HT mylonites have been intruded by a large granitic body that subsequently underwent local mylonitization. Several shear zones (e.g., Senador Pompeu, Patos, Fazenda Nova, Pernambuco), involve dike complexes consisting of variably mylonitized to undeformed dikes parallel to the mylonitic foliation (Fig. 26; Arthaud and Caby, 1993; Neves and Vauchez, this issue). Individual dikes range in width from a few centimeters to tens of meters; they are felsic to mafic in composition. Dikes of mafic rocks may belong to the high-potassium calc-alkaline association (diorites, e.g., Neves and Vauchez, this issue) but they are more commonly of shoshonitic, peralkaline or ultrapotassic affinity (Ferreira and Sial, 1986; Silva Filho and Guimarães, 1990; Neves, unpublished data). The felsic dikes cover a wide compositional range, from monzonites to leucogranites. The shear zones have clearly represented an easier path for the ascent of this voluminous synkinematic magmatism; this may be related to a transtensional deformation regime developed either over the entire shear zone or locally in relation with local pull-apart formed at bends in the shear zones.

There is, therefore, good evidence that part of the magmatism is coeval with the functioning of the shear zones, and the varied petrologic nature of the synkinematic magmatism suggests that the shear zones have favored upward migration of melt from different lithospheric levels, including the upper mantle. This strongly supports that at least the main shear zones of the Borborema shear zone system represent lithospheric faults rooted in the mantle (Vauchez and Nicolas, 1991).

A control of transcurrent faulting on magma emplacement is less obvious for a set of plutons (Gameleira, Barcelona, Pombal; Fig. 2) bounded by a shear zone in which they have been locally mylonitized. Although over most of the massif the magmatic foliation is dominantly gently dipping, it tends to become parallel to the mylonitic foliation approaching the shear zone. The main magmatic fabric formed while these plutons were still molten and was locally controlled by NE-trending dextral shear zones. Their intrusion was assigned to the progressive infilling of tectonic "cavities" in local extensional sites related to strike-slip movement in fault zones (fault bends, fault stepover zones, or fault zone termination) by Archanjo (1993) and Olivier and Archanjo (1994). However, the magmatic foliation in these plutons is dominantly gently dipping and parallel to the flat-lying metamorphic foliation in the country rock. Moreover, none of these plutons displays evidence of magmatic sheeting and this suggests that extensional models are inadequate (Paterson and Fowler, 1993). Deformation in shear zones outlasted pluton crystallization but there is no evidence that it began before their emplacement. For instance, xenoliths of mylonitized country rocks have never been reported in these plutons.

Neves and Vauchez (this issue), from the study of a magmatic complex comprising shoshonitic to high-potassium calc-alkaline plutons, show that the deformation of the still molten magmas in shear zones postdated an early evolution of the magma chamber. They proposed an alternative interpretation of the spatial relationships between plutons and shear zones, in which strain localization resulting in the nucleation of several shear zones in the Borborema Province may have been triggered by the existence of local rheological instabilities associated with preexisting magma chambers in the crust.

Finally, some granites (e.g., Picuí or São Rafael) do not display any influence of the shear zones on the kinematics of their emplacement. They probably were emplaced during a tectonic evolution dominated by the development of a nearly horizontal foliation and a NS to NE-SW stretching lineation under HT-LP conditions that allowed crustal and upper mantle partial melting; this tectonics is still poorly understood and may be related to a period of crustal extension predating the activation of the shear zone system.

In conclusion, an overview of the relationships between magmatism and transcurrent faulting demonstrates that the magmatic activity began before the activation of the shear zone system. The earliest intrusions may represent a calc-alkaline to high-potassium calc-alkaline magmatism resulting from melting of the lower crust; their emplacement may be related with an episode of crustal extension. Transcurrent faulting was initiated before most plutons were solidified. Some shear zones may have nucleated on magma chambers, then propagated both horizontally and downwards and, reaching a stage of maturity, have finally represented an easy channel for new batches of magmas, including mantle-derived magmas, to rise up into the crust.

DISCUSSION AND CONCLUSIONS

The recent studies performed on the shear zones have resulted in a wealth of new data, and considerably improved our understanding of the tectonic evolution of the Borborema shear zone system. The most striking result is certainly that the shear zones are organized in a mechanically coherent system over more than 200,000 km^2 (Vauchez *et al.*, 1991, 1992; Tommasi, *et al.*, in press) and that they certainly represent transcurrent faults rooted in the upper mantle. The Borborema shear zone system therefore appears as one of the largest lithospheric transcurrent shear zone systems in the world, and very good exposure conditions, allowing observations from the scale of satellite images to the scale of hand-samples, turn the Borborema Province in one of the best natural laboratories.

The Borborema shear zone system (Fig. 27) is subdivided into a western domain where NE-trending, rectilinear strike-slip faults predominate and an eastern domain characterized by EW-trending sinuous transcurrent shear zones. In both the NE- and EW-trending main shear zones the mylonitization: 1) began around 600-570 Ma under high-temperature conditions; 2) was coeval with partial melting at shallow crustal levels (sometime less than 20 km deep) and abundant magmatism (in part mantle-derived); and 3) accommodated a dextral shear sense. The two domains were certainly in mechanical continuity as suggested by the connection of the Patos SZ with the Tatajuba and Potengi SZ where a change in flow direction from NE-SW to EW is accommodated through a strike-slip duplex, and by the numerous NE-trending dextral transcurrent shear zones that branch off from the main EW-trending shear zones.

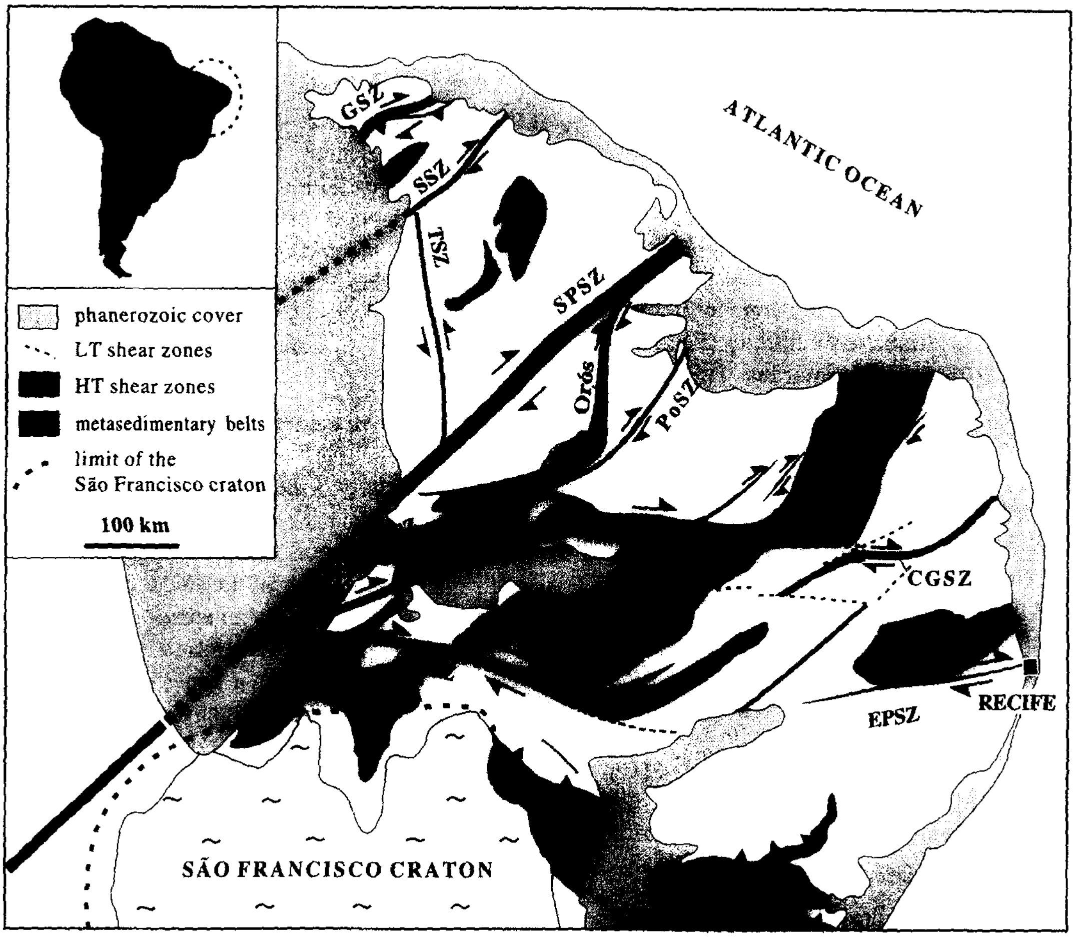


Fig. 27. Schematic map showing possible relationships between NE- and EW-trending high-temperature shear zones and the shear zone system with the São Francisco craton. Abbreviations as in Figure 2. See discussion in text.

Preliminary estimates of synkinematic PT-conditions suggest that mylonitization began under slightly higher pressure conditions in the western than in the eastern domain, a difference that may reflect a larger crustal thickening in the western domain. Indeed, in the eastern domain no evidence of crustal thickening has been found; HT-LP conditions (650-700°C at 12-14 km) prevailed, and Ar^{40}/Ar^{39} analyses point to a cooling rate as low as 3-4°C/Ma (Féraud, *et al.*, 1993).

Reliable geochronological data provide an insight into the thermotectonic evolution of the Borborema Province. The deformation within the shear zones (Senador-Pompeu, Patos and Campina Grande) and the Seridó metasedimentary belt probably began before 570 Ma under high temperature conditions responsible for partial melting of the crust. Subsequently the deformation occurred under decreasing temperature conditions. In the western domain, the cooling temperature was probably high (Monié, 1994, pers. comm.). In the eastern domain, after the peak metamorphism, the cooling rate was probably slow at the beginning, and then, around 500 Ma, began rising. This evolution may be explained by a faster exhumation rate in the west than in the eastern domain, probably related to a larger crustal thickening. The change in cooling rate suggested for the eastern domain may record the time of the final stress relaxation in this area, and thus the end of the Low Temperature functioning of the shear zone system.

Shear zones in the eastern domain are sinuous and terminate in N- to NE-trending transpression zones developed either on a metasedimentary belt (the Orós belt for Tatajuba SZ, the Seridó belt for the Patos SZ) or on a major limit between two different domains as is the case for the West Pernambuco and Campina Grande SZ. The change in structural trend is progressive, the structural and metamorphic characteristics are similar on both sides of the connection zone, suggesting a mechanical continuity and a progressive rotation of the flow direction. Accommodation of the kinematic pattern in zones of curvature was probably allowed by high-temperature synkinematic conditions and partial melting that should have substantially lowered the strength of the continental crust (Vauchez and Egydio-Silva, 1992). The origin of the sinuous pattern of the EW-trending shear zones in the eastern domain is far from totally understood. It may, however, be related to the existence of continent-scale heterogeneities in the deformed lithosphere. Numerical modeling (Tommasi, *et al*, in press), based on the Tatajuba-Orós and Patos-Seridó systems, has shown that the existence of a thermal anomaly associated with a pre-existing basin elongated in a NS to NE-SW direction, may result in a perturbation of the strain field very similar to the natural case. Recent geochemical data (Brito Neves *et al.*, 1993; Van Schmus *et al.*, 1993) strongly suggest a highly heterogeneous lithosphere resulting from possible extensional tectonics and associated crustal accretion at ca. 1.0 Ga. According to these authors, the crust of the central Borborema Province may be regarded as the juxtaposition of crustal domains either comprising an old basement (lower Proterozoic to Archean?) or formed of rocks accreted around 1.0 Ga. Such a "mosaic-structure" may account for a lateral heterogeneity of the rheological properties of the crust that may have favored the development of the complex tectonic pattern observed in the Borborema Province.

Many questions however remain to be answered, among which we may mention:

- The amount of displacement accommodated by the shear zones. The lack of markers precludes any direct estimate, and available methods to compute the shear strain are not valid in such shear zones where the deformation was strong enough to result in a complete transformation of the initial fabric into a laminar flow fabric.
- The tectonic significance of the low-temperature shear zone, and especially the offset they may have accommodated.
- The relationships between the low-temperature Cachoeirinha belt, south of the Patos SZ, the HT mylonites in the shear zone, and HT-metamorphic rocks in the Rio Piranhas domain north of the PaSZ. A large temperature contrast between these domains is observed, which is difficult to account for in the absence of evidence of major vertical motions.
- The relations between the development of the shear zone system and the deformation responsible for the flat-lying foliation bearing a NE-trending lineation that is recorded both in the country rock and the plutons of the eastern domain. The available data set suggests that the low-angle foliation slightly predates the shear zones, and that a continuity between the two deformation regimes is likely. Of course, in this case, the tectonic regime responsible for the development of the low-angle foliation becomes a major outstanding issue. We speculate that it may be related to a homogeneous continental lithosphere extension, a model that may account not only for the deformation, but also for the HT/LP metamorphism and the voluminous magmatism of the eastern domain. Moreover, a rapid transition from extension to transcurrent faulting is possible through a permutation of the Y and Z principal strain axes.

Further work is needed to fully understand the geodynamics responsible for the development of the Borborema shear zone system. However, considering: 1) the continuity of the Borborema shear zone system over a huge area, 2) the continental composition of the crust in which the shear zones were formed, 3) the lack of possible suture zone, 4) the lack of evidence for HP-metamorphism and crustal thickening in all of the Borborema Province southeast of the Senador Pompeu SZ, 5) the existence of a long pre-kinematic history dominated by the development of extensional basins (around 1.8 and 1.0 Ga; Sá, 1992; Van Schmus *et al.*, 1993), and 6) the long lasting magmatic history, we suggest that the Borborema shear zone system represents an intra-continental fault network developed to accommodate the deformation of an already existing continent.

In this model, the NE-trending transcurrent faults of Ceará may represent either trench-link, strike-slip faults developed on the continental margin during an oblique convergence (Vauchez *et al.*, 1992) or, more probably, shear zones initiated to accommodate lateral escape of the northwestern domain induced by the termination of the São Francisco craton (Tommasi, *et al.*, in press; Vauchez *et al.*, in press). In both cases, EW-trending shear zones of the eastern domain may be regarded as second order faults that have been initiated and propagated to accommodate the perturbation of the kinematic field occasioned by the existence of large lithospheric heterogeneities.

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