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Laminar flow in shear zones: the Pernambuco Shear Zone, NE-Brazil

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Abstract—The Pernambuco Shear Zone (PSZ) is a 700 km long branch of one of the largest and best-exposed Precambrian strike-slip shear zone systems in the world. The shear zones are part of the eroded record of a large-scale collision zone. Foliation and lineation orientations along the shear zone indicate that local deformation perturbations have produced variable fabric orientations, with up to 40° change in dip and strike. However, the dominant flow pattern is consistently horizontal strike-slip across a vertical shear plane. Well-developed dextral shear sense criteria are observed at most localities, although oblate strain fabrics are common and lineations are frequently absent. Very few small folds were found to refold the shear fabric developed in Late Precambrian granites which intrude along most of the shear zone, but sheath folds are common in mylonitized pre-shear gneisses. This geometrical evidence indicates that steady laminar shear flow took place in the initially isotropic granites, and more irregular, but not turbulent, flow preferentially developed in rocks with a pre-existing fabric. The deformation pattern is similar to many other deep crustal shear zones. Laminar shear flow is thought to be common in granites and coarse-crystalline gneisses deformed in upper-amphibolite to granulite facies conditions. The dramatic weakening of the middle crust produced by syn-shear injection of granites and mafic intrusions into vertical shear zones may cause the predominant movement pattern in collision zones to be strike-slip lateral extrusion, rather than compressional thrusting.

INTRODUCTION

The way that strain is localized in the ductile regime has important implications for the mechanical flow behaviour of the crust, and how heat and fluids are transferred vertically. Shear zones are often directly linked from brittle faults in the upper crust to ductile shear zones in the lower crust, as has been substantiated by deep seismic work (e.g. Allmendinger *et al.* 1983). Many structural studies have been undertaken on Precambrian strike-slip shear zones in greenschist facies rocks in the brittle–plastic transition zone, often because they are important sites of ore deposition, especially of major hydrothermal gold deposits (e.g. Groves & Foster 1991 for references). However, relatively few systematic studies have been made on deeper-level higher-grade zones (e.g. Boullier 1986, Hanmer 1988 and references therein). Northeast-Brazil has an extremely well-exposed, easily-accessed, shear zone system which is believed to be typical of how lower to mid-continental crust behaves during collision coupled with large strike-slip movements. The object of this study is to describe the geometry of the 700 km long Pernambuco Shear Zone (PSZ) and draw some general inferences about deformation patterns produced at this scale.

REGIONAL GEOLOGY

The PSZ forms part of a linked system of strike-slip shear zones in NE-Brazil, which are interpreted to be part of a major crustal collision zone (Santos & Brito Neves 1984, Caby *et al.* 1991). These shear zones extend into Africa totalling 1400 km in length (E–W) (Fig. 1a). The collision zone is bounded to the south by the low grade Sergipano fold belt which was overthrust towards the south and southwest onto the São Francisco Craton (Fig. 1a, Davison & Santos 1989). Published information concerning the PSZ has focused on particular segments of the shear zone (Cobra 1966, Santos 1970, 1971, Siqueira & Mello 1971, Mello 1977, Agrawal 1981,

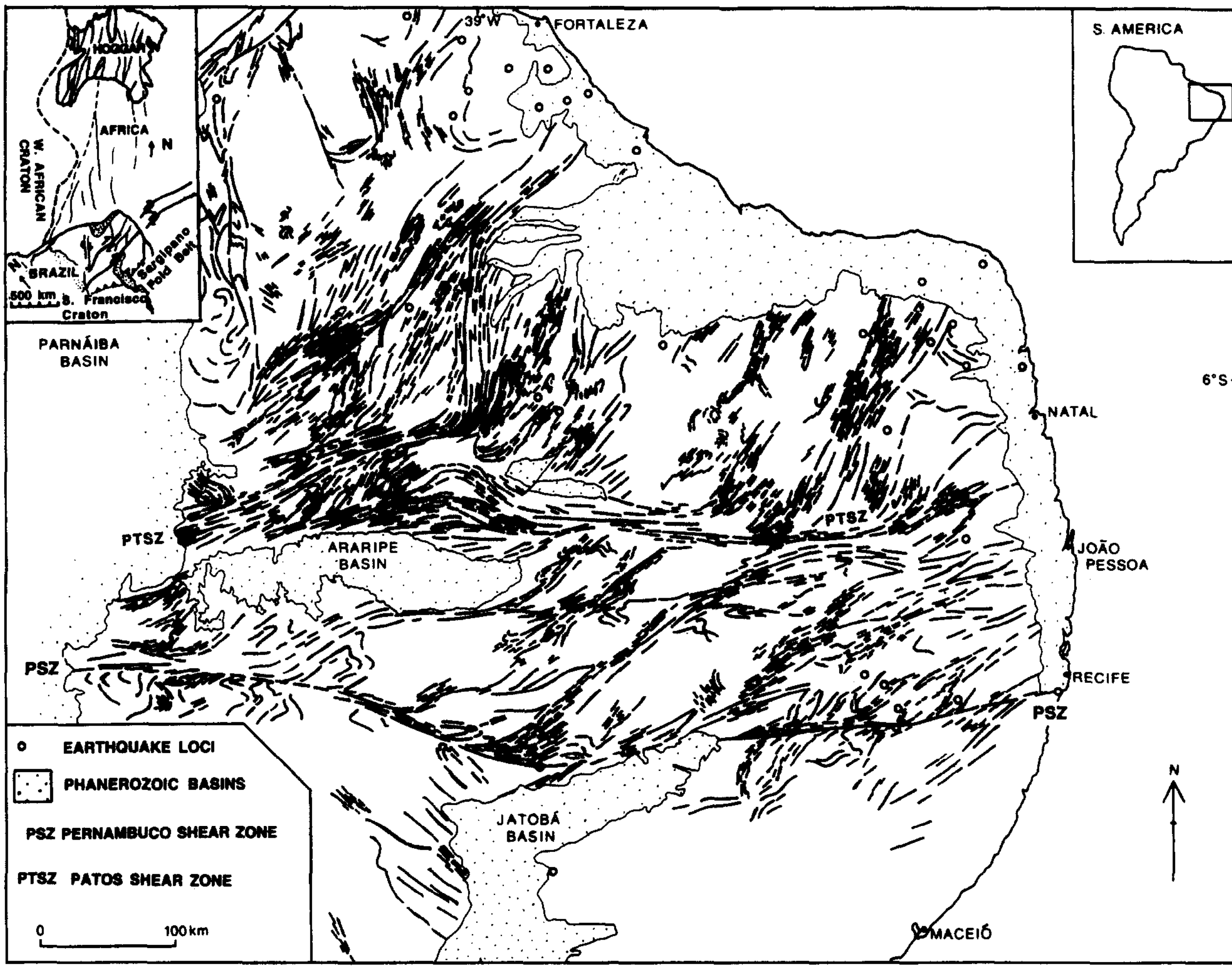


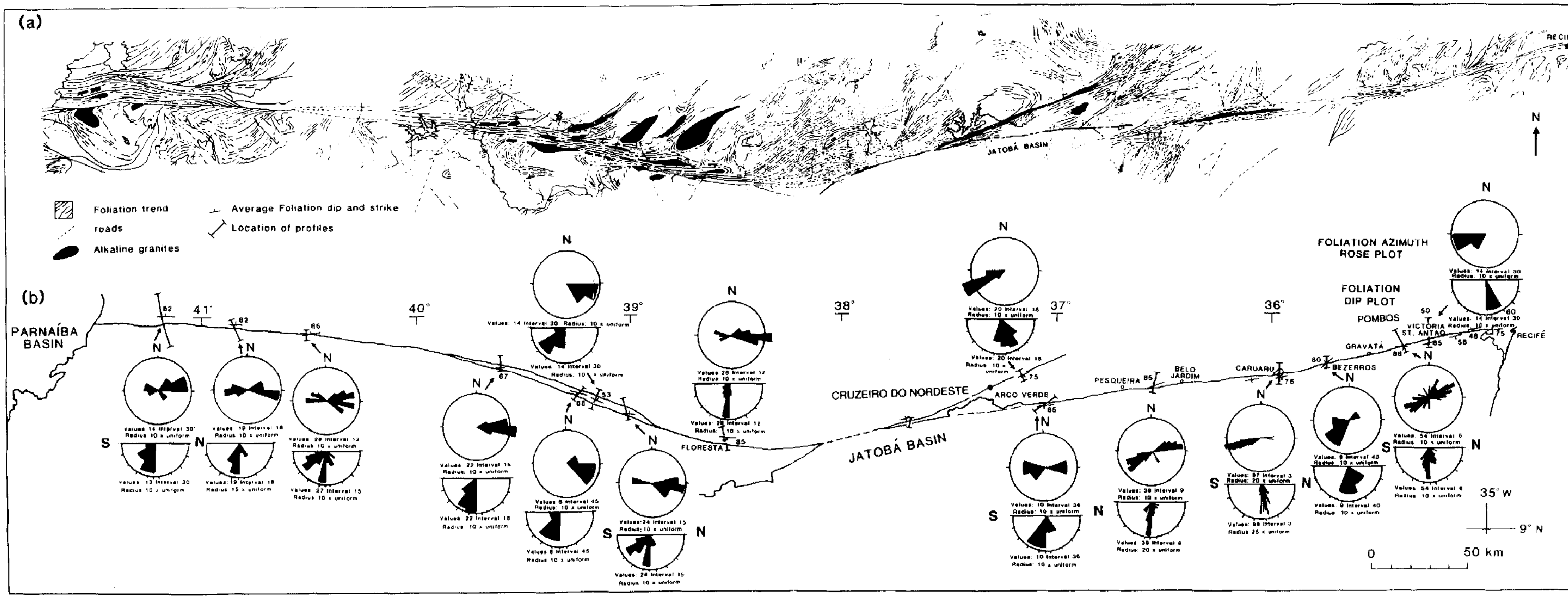
Fig. 1. Map of shear zones in Borborema Province of NE-Brazil interpreted from Radar and Landsat imagery. Closely-spaced structural trend lines indicate zones which are more clearly visible on the remote sensing images. Earthquake epicentres from Assumpção *et al.* (1985) and recent local reports are indicated as open circles. Inset map at top left shows the extension of major lineaments in NE-Brazil and West Africa. Lambert equal area projection (adapted from Schobbenhaus *et al.* 1981, De Wit *et al.* 1988, Caby 1989, and Caby *et al.* 1991).

Vauchez & da Silva 1992). This study looks systematically at the whole length of the exposed shear zone.

The main shear deformation along the PSZ is believed to be of Brasiliano age (510–650 Ma), as inferred from intrusion of syn-tectonic granitoids (Jardim de Sá *et al.* 1988, Sá *et al.* 1991). The Patos Shear Zone, which lies to the north, was active at the same time and here Ar^{40}/Ar^{39} ages from dating of syn-metamorphic mafic intrusives and reworked pre-Brasiliano basement are interpreted as dating movement at 510–560 Ma (Feraud *et al.* 1993). Dextral displacement was transferred from one shear zone to the other via a series of subsidiary NE-trending shear zones (Fig. 1b). Whilst these were previously interpreted to have sinistral displacements (Santos 1971), numerous shear criteria on the Arco Verde–Cruzeiro do Nordeste and Congo subsidiary shear zones indicate that they are dextral (our own observations). Vauchez & da Silva (1992) suggested that the western part of the PSZ may have acted independently of the eastern part, and that the western part terminates in a fanlike structure. However, a continuous lineament can be traced in the field from the western to the eastern branch and at least some of the strike-slip movement must have been transferred from the western to the eastern segment (Figs. 1b and 2).

The linked system of strike-slip shear zones in NE-Brazil seems to have been active since the late Proterozoic, but may have been developed earlier, although no evidence for this has been proved (Jardim de Sá 1984). The PSZ was locally reactivated throughout the early Palaeozoic and Cretaceous periods (Magnavita 1992). It is seismically active along its eastern half with $M_b < 4$ earthquakes, although no focal mechanisms of these earthquakes have been determined (Assumpção *et al.* 1985; Fig. 1b). However, as the Permian sediments of the Parnaibá Basin do not show any significant offset

Fig. 2. (a) Map of foliation trends and syn-shear alkaline granites taken from Landsat images and 1:50,000 CPRM geological maps. Not all syn-shear granites are shown along the eastern half of the shear zone, since they occupy most of the shear zone and would obliterate the foliation pattern on this map. (b) Foliation azimuth and dip variation along the PSZ. Top full circles represent rosette diagrams of azimuth variation with eastern azimuths referring to southern dips, and western azimuths northern dips. Bottom half circles represent dip variations. Data plotted using STEREOPLOT (Mancktelow 1989).


(a)
RECIFE
JATOBÁ BASIN
N
Foliation trend
roads
Alkaline granites
Average Foliation dip and strike
Location of profiles
(b)
PARNAÍBA BASIN
41°
40°
39°
38°
37°
36°
CRUZEIRO DO NORDESTE
ARCO VERDE
JATOBÁ BASIN
FLORESTA
PESQUEIRA
BELO JARDIM
CARUARU
BEZERROS
GRAVATÁ
POMBOS
VICTORIA
ST. ANTAO
RECIFÉ
FOLIATION AZIMUTH ROSE PLOT
FOLIATION DIP PLOT
35° W
9° N
0
50 km

where they are intersected by the PSZ, there is negligible post-Palaeozoic strike-slip movement (Fig. 2). The later brittle reactivations are not pervasive, and are especially limited to the area immediately adjacent to the early Cretaceous Jatobá basin and eastwards to Recife.

The shear zones affected a complex area of Proterozoic and possibly Archaean age sillimanite-bearing gneisses and meta-sediments, which together with voluminous Brasiliano age granitoids make up the Borborema Province in NE-Brazil (Santos & Brito Neves 1984, Caby *et al.* 1991). Approximately 15 km of exhumation has taken place over most of the length of the PSZ since the Brasiliano Orogeny, implying that large crustal thicknesses were developed during continental collision (Caby & Arthaud 1986, Jardim de Sá 1984, 1987, Jardim de Sá *et al.* 1990). The crustal thickening was probably produced by flat-lying folds which have folded the intervening gneiss terrains lying between the strike-slip shear zones. The shortening direction which produced the folds was either directed from north to south or to the southeast (Departamento Nacional da Produção Mineral 1988, Caby & Arthaud 1986). Exhumation was presumably due to isostatic rebound following crustal thickening and occurred at about 500 Ma along the Patos Shear Zone to the north (Féraud *et al.* 1993). Further uplift of approximately 1 km accompanied by erosion took place during the Albian–Oligocene, as Albian marine sediments now lie at approximately 1 km above sea level in the Araripe and Jatobá Basins (Magnavita 1992, Magnavita *et al.* 1994; Fig. 1b). An early Tertiary surface is also preserved at *ca.* 1000 m above sea level west of Natal and Fortaleza suggesting post-Oligocene uplift (R. Caby personal communication 1993).

The country rocks in the western half of the PSZ are mainly flat-lying mica-rich migmatitic quartz–feldspar metasedimentary gneisses and grey orthogneisses, which may have been deformed in a pre-Brasiliano orogenic cycle (Jardim de Sá 1984, Jardim de Sá *et al.* 1988, 1990, Brito Neves 1990, Sá *et al.* 1991), or according to Caby *et al.* (1991), are related to Brasiliano age tectono-metamorphic events. Pre-Brasiliano migmatitic, grey granodioritic gneisses are the main country rock in the eastern half of the shear zone. There are no definite ages on these gneisses, but their foliation is deformed by the PSZ suggesting they formed prior to shearing. These were intruded by numerous granitic plutons during deformation (Fig. 2), especially along the eastern part of the PSZ.

Many of the subsidiary shear zones show consistent movement indicators compatible with a linked dextral strike-slip system throughout NE-Brazil (Fig. 2). The PSZ has a smoothly curving surface trace with many subsidiary dextral shear zones branching off to the north, linking with the Patos Shear Zone (Fig. 2). Our observations suggest that these subsidiary shear zones are predominantly strike-slip, rather than transpressional, as they have horizontal stretching lineations and sub-vertical foliations. This can be explained because of the strong anisotropy which is developed in the shear zones due to shearing and preferential granite intrusion. Shear zones with a strong anisotropy parallel to the shear zone walls may continue to move by strike-slip simple shear even when the principle tectonic stress is at a high angle (>80°) to the shear zone boundary (Weijermars 1992). The principal shortening direction in the Borborema Province was probably oriented approximately east-southeast–west-northwest, which explains the dextral movements on the E–W and NE–SW trending shear zones. However, at least one of the northeast–southwest oriented shear zones is sinistral (Fig. 1, Caby *et al.* 1990), suggesting that the shortening direction may have changed slightly through time during the Brasiliano Orogeny. The main shear zones have a horizontal spacing which rarely exceeds 80 km (perpendicular to shear zone strike). This close spacing of such wide shear zones has led to a linked system across most of NE-Brazil (Fig. 1b).

PT-CONDITIONS DURING DEFORMATION

Metamorphic grade appears to be higher grade along the western part of the PSZ compared to the eastern part. In the western portion, near Salgueiro, horizontal sillimanite lineations are preserved in meta-sedimentary impure quartzites; and amphibole, K-feldspar and quartz *L–S* fabrics are developed in syn-tectonic granitoids. In the granites, quartz is totally mylonitized with no original grains remaining, and a strong crystallographic and shape fabric orientation is present in all samples examined. The K-feldspar crystals, in both the gneisses and the granites, have undergone recrystallization at their borders into smaller grains, and they have a rounded corroded appearance, with new K-feldspar, quartz and biotite recrystallized in the pressure shadows. This suggests metamorphic temperatures above 550°C during deformation (Tullis & Yund 1987). Many granitic bodies were intruded during shearing, and there is evidence for partial melting, with consequent development of migmatitic gneisses. Vauchez & da Silva (1992) estimated *PT*-conditions of 630–700°C and 6 kbar based on metamorphic assemblages found in the western half of the shear zone. This implies a burial depth in the region of 10–20 km (considering the high heat flow during the Brasiliano Orogeny).

The eastern half of the shear zone is mainly intruded by granites which have well-developed mylonitic fabrics with biotite, amphibole, K-feldspar, quartz and plagioclase oriented parallel to the main foliation in the shear zone. The gneissic banding is defined by green amphibole and brown biotite-rich layers and mylonitic quartzo-feldspathic layers, which suggest middle amphibolite facies metamorphic conditions occurred during shearing.

There are a few signs of retro-metamorphism along well defined phyllonite zones and cataclastic zones which reach up to 200 m thick in the PSZ. These have been identified in the Ibimirim, Arco Verde and Pombos areas. The phyllonite zones are generally composed of

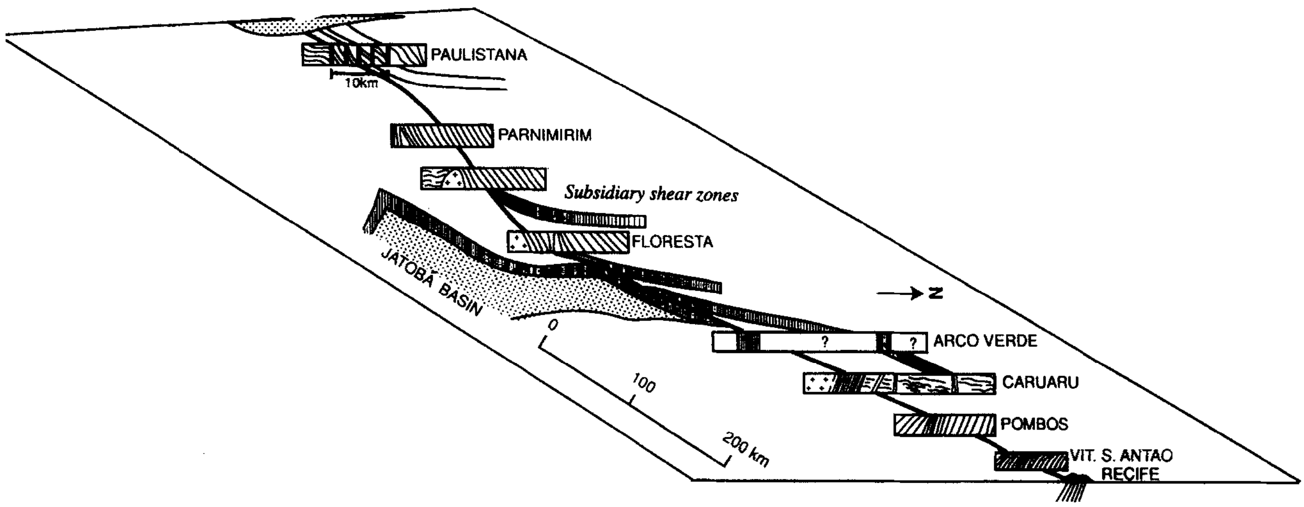


Fig. 3. Schematic diagram showing average foliation dip traverses along the PSZ. Note the less-steep foliation around the bend in the shear zone near Floresta.

epidote, white mica and biotite, and are crenulated with breakage of the micas at fold hinges up to 3 km wide may build up with small displacements (<10 km), if the conditions are suitable (Boullier 1986).

DISPLACEMENT AND WIDTH OF THE PSZ

Displacement across the PSZ is difficult to determine as there are no unequivocal markers that allow correlation across the shear zone. Foliation curvature indicates at least 25 km of dextral movement on the western half of the PSZ (Fig. 2a). Sadowski (1983) made a tentative displacement estimate of 350 km using foliation curvature across the Patos–Pernambuco linked shear system. Strike-slip shear displacement was generally transferred northwards to the Patos Shear Zone, and there is only one shear zone lying along the northern border of the Jatobá basin which branches onto the PSZ from the south (Fig. 1). Hence, displacement generally decreases from west to east along the PSZ. There is a distinct decrease in shear zone width east of the Jatobá basin as much of the displacement on the PSZ is transferred northward onto the Cruzeiro do Nordeste shear zone (Fig. 2a). The width of the Patos Shear Zone also decreases from west to east, implying a similar transfer of movement to subsidiary shear zones branching off northeastwards (Corsini *et al.* 1991; Fig. 1b).

The main deformation zone along the PSZ is marked by steeply-dipping, highly-foliated rocks running parallel to the shear zone. The edge of the shear zone is defined where regional foliation trends start to bend. The PSZ decreases in width from 14 km in the west to approximately 0.5 km in the east (Fig. 2a), indicating that width may decrease with decreasing displacement. However, it must be remembered that mylonite zones

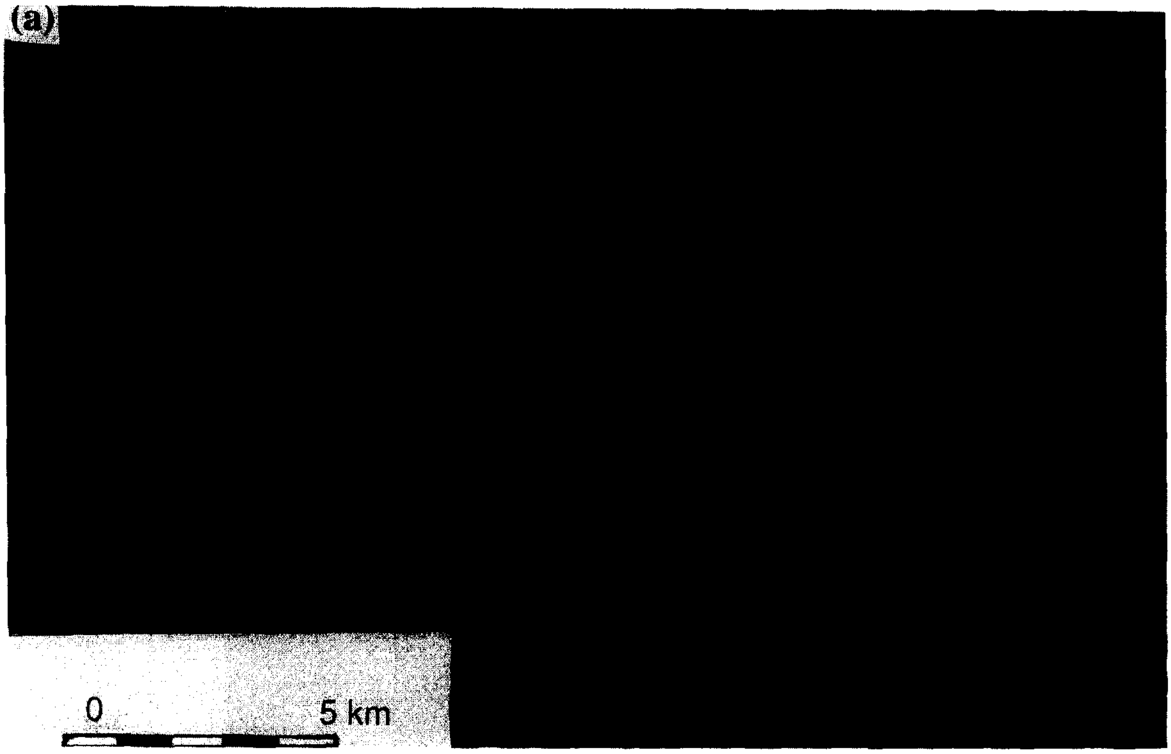
FOLIATION PATTERNS

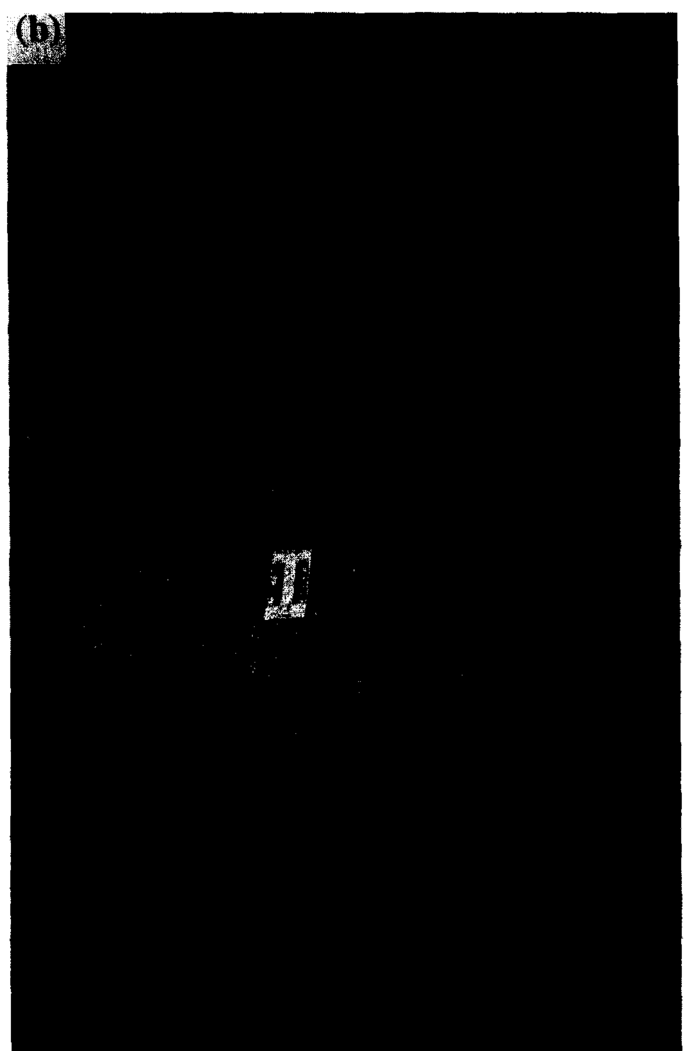
The foliation pattern in the PSZ is apparently simple on a large scale (Fig. 2). In contrast, at outcrop scale, the foliation pattern can be complex due to syn-kinematic magmatic intrusions of different viscosity (Fig. 2b). Over 700 foliation orientations were measured over 400 km of almost continuous N–S traverse mapping (Fig. 2b). These show that the mean foliation dip, averaged over traverses across most of the shear zone, is between vertical and 70°. The variation can reach up to 40° of dip in any one profile, but is generally about 20° (Fig. 2b). The foliation flattens slightly to an average dip of 65° at the bend mapped out at the surface near the Jatobá basin (Fig. 3). Most variations occur in the zones of slightly weaker strain, where lozenges produce deflections up to 40° (cf. Coward 1976). The foliation strike is oriented parallel to the shear zone trend with angular strike variations of up to 40° across any individual traverse through the shear zone (Fig. 2b).

The foliation generally curves smoothly and intensifies into the shear zone over a width varying from 5–10 km (Figs. 2a and 4a). The gneisses which occur along the length of the shear zone appear to have been previously deformed by predominantly horizontal shearing producing recumbent folds of probable Brasiliano age (Caby *et al.* 1991). This older fabric gradually rotates towards the vertical into the PSZ.

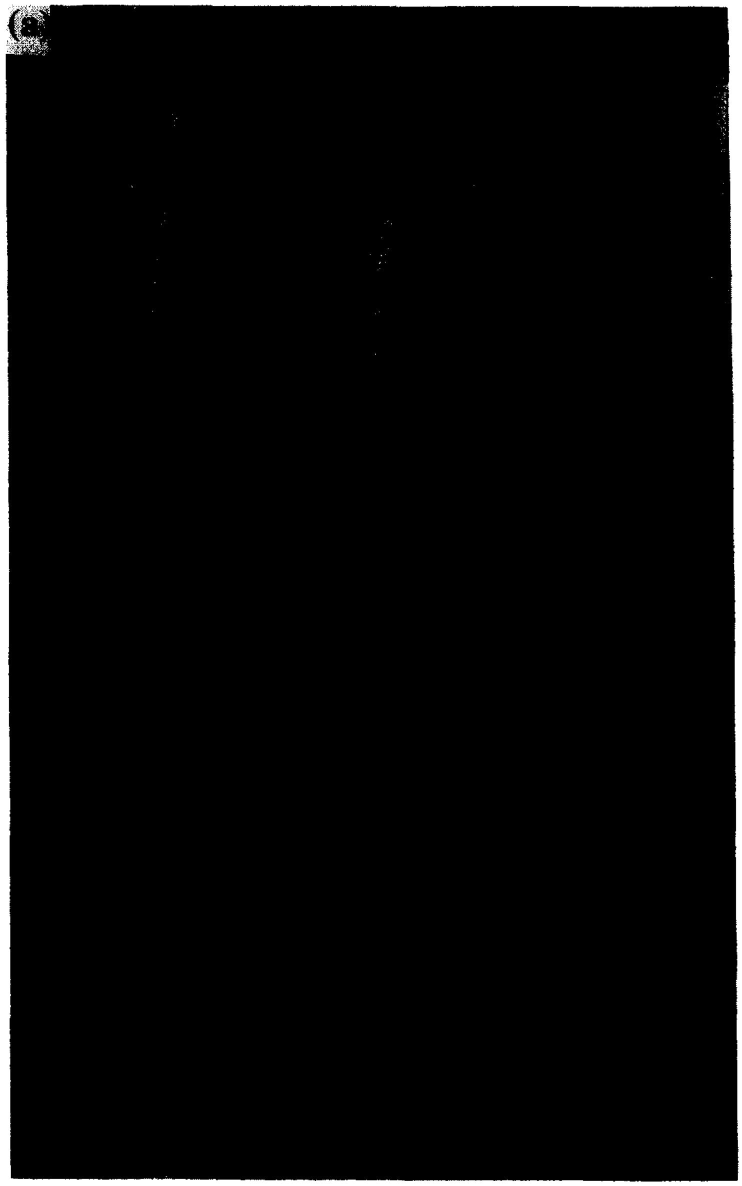
Consistent dextral *C–S* structures are well-developed in the syn-kinematic intrusions, with *C*-bands parallel to

Fig. 4. (a) Aerial photograph showing the foliation behaviour as it swerves into the PSZ. The light banded layer (arrow) is a granitic sill, which has been offset by NW–SE-trending dextral faults. Location of photograph is indicated on Fig. 2(a). (b) Multiple granitic dyke intrusions streaked out to produce a banded appearance. Caruaru road section near Hotel do Sol. (See Fig. 7 for location.)


(a)
0
5 km


(b)

(a)



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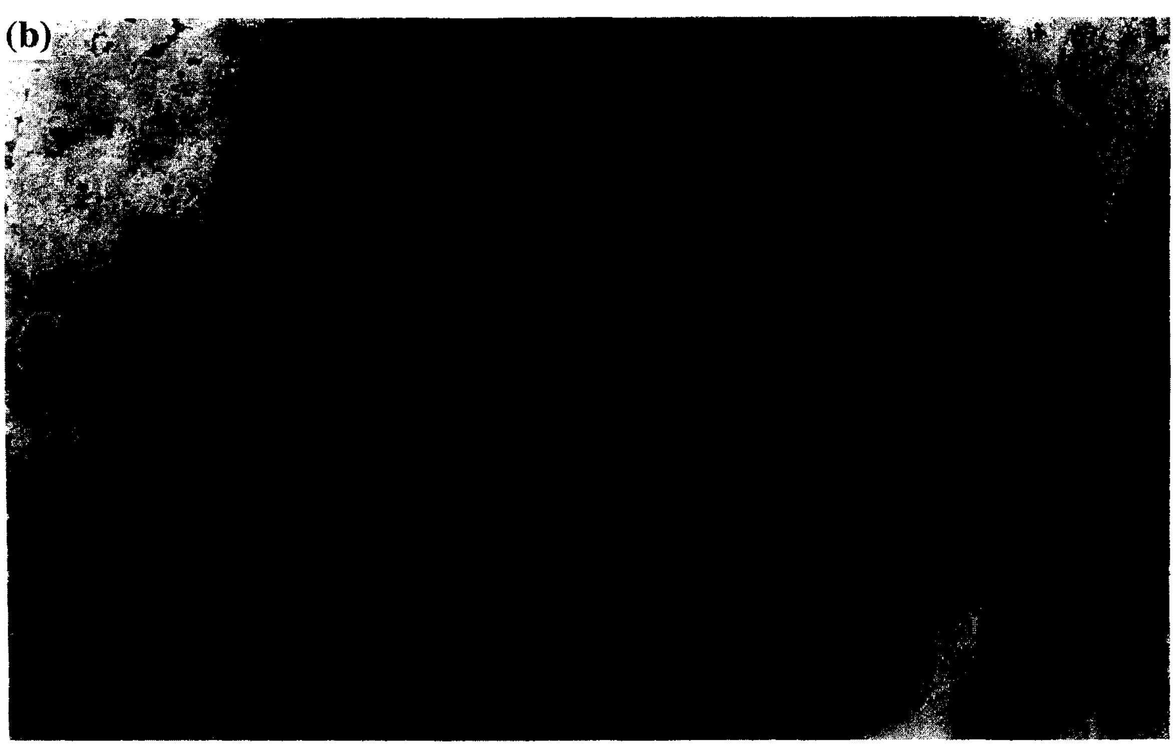

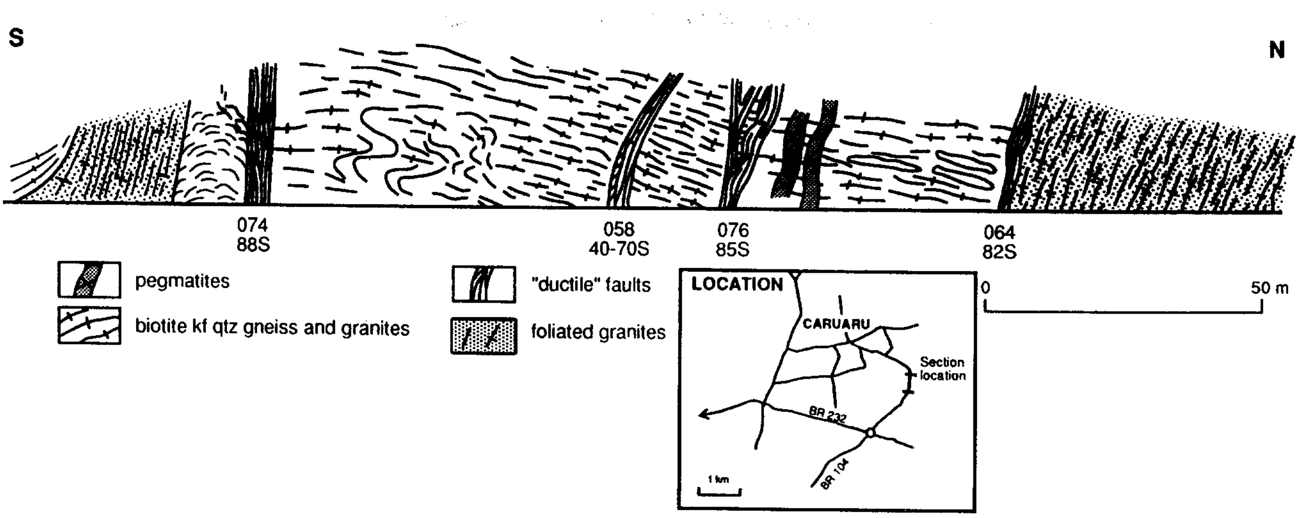

Fig. 6. Detailed cross-section of PSZ east of Caruaru, showing ductile faults cross-cutting flat-lying gneisses. Location marked in inset map.

the trend of the shear zone. *C–S* structure is especially common in K-feldspar porphyritic granites, where instabilities develop with a spacing controlled by the average K-feldspar phenocryst size. As grain size reduces due to mylonitization, *C–S* spacing decreases until it is not observable in hand specimen, although microscopic bands are still present.

Granitic ultramylonitic bands appear as discrete shear zones. These zones transect each other at low angles in the highly-deformed areas (Fig. 5a). There is often a marked reduction in grain size at their boundaries and pre-existing shear fabrics are abruptly truncated without any bending (Figs. 5a and 6).

Oblate finite strains are recorded by K-feldspar porphyroclasts, but localized areas of extremely well-developed prolate ductile stretching lineations also occur (Fig. 5b). This suggests transpressive deformation was dominant in some parts of the shear zone, and simple shear deformation in other parts.

Mylonitic granitic rocks generally occur across the whole shear zone, but ultramylonites (where K-feldspar is totally recrystallized) are restricted to zones less than 300 m thick, and are usually only metres to tens of metres thick (Fig. 7). In several areas no mylonites were observed in 5–6 km long sections across the shear zone. Instead, a very regular granoblastic platy fabric is present in gneisses ('straight gneisses'), which are probably annealed mylonites. The presence or absence of granitic ultramylonites in the shear zone is not thought to be diagnostic of increased amount of displacement. Fine-grained ultramylonite textures have escaped annealing processes, whereas the platy gneisses were probably annealed but underwent the same amount of deformation.

An example of a detailed 400 m long traverse through the well-exposed central part of the PSZ in the Caruaru area is shown in Fig. 7. There are a great many granite dyke intrusions injected into the previously deformed granites (e.g. Fig. 4b), with up to five different types of dykes deformed to varying degrees. Many fine-grained leucogranite veins are injected at high angles to the main foliation in the shear zone, and in places the shear zone consists only of 100% sheeted dyke material. The rock can take on a banded gneiss appearance due to injection of many sub-parallel granite dykes.

There is a distinct absence of folding in the larger granite plutons intruded during the main shearing, except for some larger open folds with 1–2 km wavelength east of Floresta. Where granitic dykes intruded into the shear zone at an angle to the principal shear plane, they were deformed into tight to open folds with axial planes parallel to the main shear foliation, and fold axes generally oriented parallel to the local stretching lineation. Folding in the early grey orthogneisses occurred during shearing and mylonitization and also later after development of the main mylonitic foliation. All of these folds are minor structures with wavelengths less than 5 m, and axial planes lying parallel to the main shear zone boundaries. Fold axes are mainly parallel to the stretching lineation, although plunges of up to 55° have been recorded.

Large retrogressed cataclastic zones of healed silicified breccia reaching up to 200 m in thickness and containing new biotite and white mica, are developed in the Pombos and Arco Verde areas. These zones are probably formed during later uplift when narrow bands of the fault remained active. Rare brittle–ductile fault zones with horizontal white mica lineations or pseudota-

Fig. 5. (a) Minor ductile shear zone along lighter layers (arrowed) transecting mylonite foliation from the cross-section shown in Fig. 7. Although the fabrics are ductile there is a sharp truncation of pre-existing foliation at the shear zone contact. (b) Stretched K-feldspar and quartz defining a strong *L*-fabric on the foliation plane. This structure suggests temperatures above 550°C during deformation. Sample taken from subsidiary shear zone approximately 5 km north of Pombos.

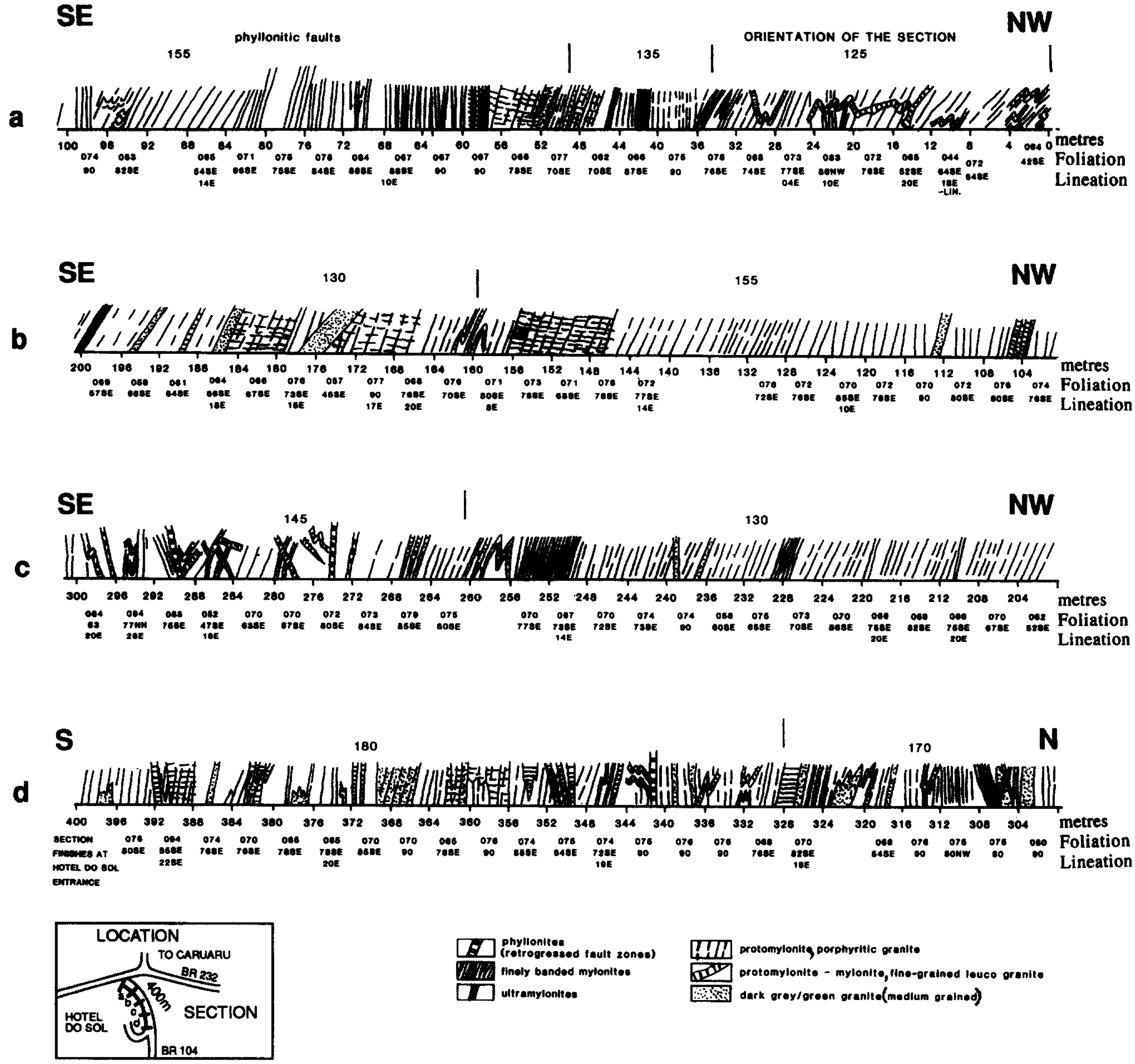

Fig. 7. Detailed structural section across the PSZ, south of Caruaru. The four sections are continuous (see small inset). The numbers underneath the section indicate the dip and strike of the foliation (S) and the pitch of the lineation (L) is also shown at some localities.

chylytes developed on discrete brittle-fault planes, suggesting that strike-slip movement continued during exhumation.

LINEATION PATTERNS

Along the PSZ, lineations in granites and granodioritic gneisses are mainly produced by stretched quartz and feldspar crystals, aligned biotite flakes or amphiboles. Feldspar phenocrysts are deformed homogeneously and replaced by diffuse streaks of small recrystallized grains (Fig. 5b). The lineation is intepreted as marking the main transport and elongation direction in the shear zone. However, in ultramylonitic granitic rocks, lineations are commonly absent. The measured lineations indicate that the dominant movement direction was strike-slip in both ductile and brittle deformation modes (only ductile lineations are plotted on Fig. 8).

Where deformation was ductile, there is an angular variation of approximately 30° in the plunge of the lineations across any single traverse of the shear zone (Fig. 8a). Plunge can be to both east and west in the same profile (Fig. 8a). The average lineation trajectory estimated at each traverse and some intermediate control points has been projected onto a vertical plane through the centre of the shear zone (Fig. 8b). This indicates that there is a slight culmination in the lineation plunge centred over the Jatobá basin, which correlates with the flattening of the foliation in this region. The culmination coincides with a branching of shear zones (Fig. 1). Here a shear zone merges with the PSZ from the south and the Cruzeiro do Nordeste shear zone branches off to the north. The vertical movement associated with shear zone bifurcation, and the bend in the main shear zone,

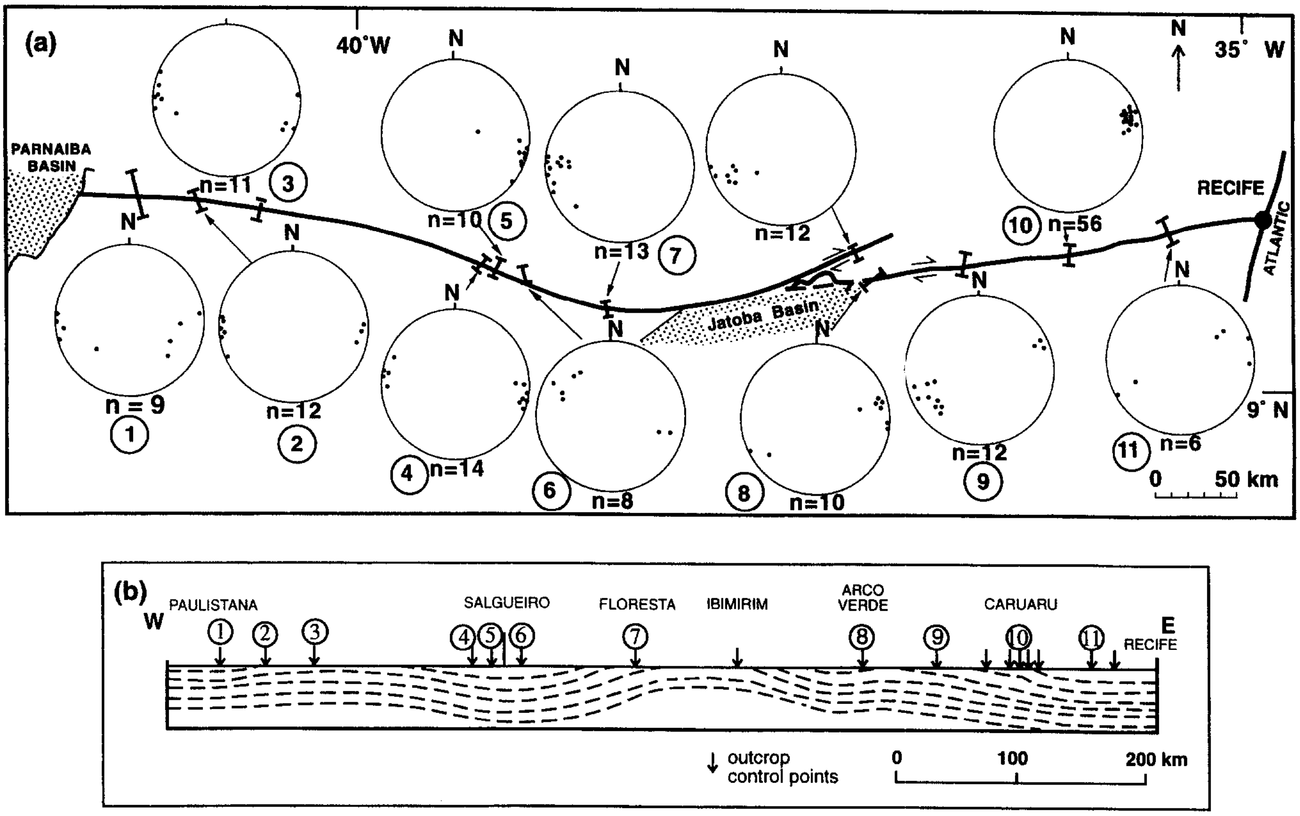

Fig. 8. (a) Lineation pattens along the PSZ, equal area lower hemisphere projections. (b) Simplified compilation of average lineation pitch on a vertical projection plane through the centre of the shear zone.

may have caused a deviation from horizontal simple shear.

RELATIONSHIP BETWEEN MAGMATISM AND SHEARING

There is abundant evidence for intrusion of granitoids during shearing as most are deformed to varying degrees, although some are apparently undeformed. Many different granitoids were intruded during shearing (Brito Neves *et al.* 1982a,b, Ferreira & Sial 1986, Bossière 1987, McMurry *et al.* 1987, Pachecho Neves 1989, Sial 1990). The most voluminous is a K-feldspar-rich porphyry alkaline granite containing dark blue–green amphibole. These alkaline intrusions are mylonitized in places so that they take on a flinty texture which produces spectacular elongate topographic ridges parallel to the shear zone. These alkaline granites appear sporadically along the whole shear zone, but are most voluminous in the eastern half where they occur along the whole length of the shear zone from Ibimirim to Caruaru (Fig. 2a).

Large granitic bodies, or narrow sheeted syn-tectonic intrusions, occupy most of the eastern half of the shear zone. When the latter are dominant, the rock takes on a banded gneiss appearance due to flattening of the sheets (Fig. 4b). Granitic sheet smearing is also very common and produces remarkably continuous bands which typically stretch for up to 100 m along strike but are often only 0.5 cm thick.

The presence of many elongate porphyritic granite plutons (up to 50 km long and 1–5 km wide) along the eastern half of the shear zone is significant (Fig. 2a) as they are not present in the adjacent gneiss terrain. Clearly, the eastern portion of the shear zone formed a preferential site for large granitic sheet-like intrusions. These may have ascended by a dyking mechanism as proposed by Hutton (1992) and Hutton & Ingram (1992), and they have undoubtedly played a major role in weakening the crust during their injection. By enhancing anisotropy they would allow deformation to take place preferentially along these strike-slip shear zones, even when they are at a high angle (80°) to the shortening direction.

RETROGRESSION, FLUID ESCAPE AND FAULTING

Retrogressed phyllonitic fault zones approximately 1 m wide developed parallel to the foliation in the centre of the shear zone. These represent zones of hydrous-fluid transport as they are composed of green-biotite, muscovite, and green-amphibole and quartz. They may represent altered mafic rocks which have preferentially been sheared. They were very rarely observed except at Arco Verde, Caruaru and Pombos (Figs. 6 and 7). The zones are faults, as there appears to be a displacement on them and units are truncated abruptly at their margins, rather than being deflected progressively towards the centre of the zone (Fig. 6). Quartz veins develop in the phyllonites and horizontal slickenlines have been observed on vein surfaces. A phyllonitic mica foliation has developed parallel to the fault zone exhibiting *C–S* fabrics with a dextral transcurrent sense of shear. The amount of movement across these strike-slip zones is unknown. Fluid flow has occurred along the faults to produce the new micas, but there is little evidence of pervasive alteration in the adjacent impermeable rocks. Thin quartz veins (<10 cm thick, 1–2 m long) are developed at many localities, although they are not volumetrically important.

DISCUSSION

Large displacement strike-slip shear zones tend to have smoothly varying anastomosing geometries with constituent shear zones fully-linked together (Hanmer 1988 and references therein). The maximum dihedral angles between shears can reach up to 70° in NE-Brazil, but it is usually less then 30–40° (Fig. 1b). The reason for this large angular variation is not known, but could possibly be due to progressive rotation of the principal shortening direction during the Brasiliano orogeny, or to reactivation of pre-existing weaknesses. There is little evidence for development of large scale transtensional jogs as in brittle strike-slip fault systems, despite the intrusion of large magma volumes.

Constant foliation and lineation orientations have been reported from other shear zones in Brazil. Examples are the Patos Shear Zone (Caby *et al.* 1991, Corsini *et al.* 1991); the granulite facies Atlantic Coast Mobile Belt in S. Bahia (Barbosa 1990); and the granulite facies Além–Paraíba Lineament in Rio de Janeiro State (da Campanha 1981). Smooth flow patterns are common in mid-crustal rocks elsewhere such as the Adrar des Iforas and Hoggar (Boullier 1986) and the Great Slave Lake Shear Zone (Hanmer 1988). There is a notable absence of minor folds in granulite facies shear zones such as the Great Slave Lake Shear Zone (Hanmer 1988), the Atlantic Mobile Belt in S. Bahia, and the Hebei Province in NE-China, suggesting that steady flow patterns occur at high metamorphic grades. The absence of folds and the consistent orientation of the foliation and stretching lineation in the syn-shear granite intrusions in the PSZ indicates that all particle stream lines are parallel and flow took place in a constant direction parallel to the foliation, which is sub-parallel to the shear zone boundaries in the highly-deformed central part of the shear zone. These characteristics strongly suggest that the flow was laminar. The quartz-rich matrix flows around the larger K-feldspar grains in the deformed rocks so that laminar flow does not occur on a very small scale, but must occur on a scale approximately twice the size of the largest crystal in the deforming rock. Laminar flow implies that there must also have been a smooth velocity variation across the shear zone even with the more rapid increase in velocity towards the most highly-deformed zones.

There is a strong similarity between the structures described by Hanmer (1988) in the Great Slave Lake Shear Zone and the PSZ. Both the later lower-grade phyllonitic zones and the brecciated belts are narrow (<200 m in the PSZ) and are superimposed on the wider and higher grade parts of the shear zone. These later zones are interpreted as having been produced during unroofing of the shear zone. The PSZ still continued to be an active strike-slip belt during exhumation. At high metamorphic grades middle-amphibolite to granulite facies shear zones widen due to softening of the wall rocks, whereas at cooler greenschist to lower amphibolite facies, the shear zones are much weaker than the surrounding wall rocks and the active shear zones reduce in width. Hydrous fluid influx along these lower-grade shear zones must dramatically enhance this effect.

CONCLUSIONS

In the central part of the PSZ foliations are sub-vertical and the lineations are sub-horizontal. Refolded shear zone-related foliations in the syn-shear zone granites are very rare. The consistency of the foliation and lineation pattern and absence of folding in these syn-shear zone intrusions indicates that deformation took place by steady laminar flow; where the flow direction in the centre of the shear zone is sub-parallel to the shear zone walls. The formation of a strong foliation which was rotated into parallelism with the shear zone walls must have a strong influence on the flow pattern. A more irregular (but not turbulent) type of flow is common in the earlier gneisses where folds and highly-curved lineation and foliation patterns are observed. Similar simple laminar shear zone patterns have been observed by us in other large shear zones in granulite facies terrains (S. Bahia and Rio de Janeiro State in Brazil, and Hebei Province in NE-China), and we suggest that simple laminar flow patterns are common in the middle and lower part of the crust. The PSZ and subsidiary shear zones are important sites of syn-shear granitoid intrusion and this leads to a dominant laminar shear flow. Magmatic intrusion into vertical strike-slip shear zones must weaken the otherwise strongest middle part of the crust to such an extent that strike-slip deformation may become the dominant movement pattern in zones of continental collision; in such a case even strike-slip faults at a very high angle (80°) to the shortening direction will move as strike-slip zones (cf. Himalayas, Tapponier & Molnar 1976).

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