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Oblique lineations in orthogneisses and supracrustal rocks: vertical partitioning of strain in a hot crust (eastern Borborema Province, NE Brazil)

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Abstract

Detailed structural work conducted at the eastern area of the Neoproterozoic Brasiliano (=Pan-African) Borborema Province (northeastern Brazil) has shown two orientations of stretching lineations with ESE trend in supracrustal rocks and NE trend in underlying orthogneisses. In the metasedimentary sequence, numerous kinematic indicators showing a top-to-the-northwest sense of shear denote a well-developed non-coaxial deformation. In the orthogneisses, lineations formed dominantly during coaxial deformation, although a component of NE-directed shear is locally observed. The two lineations were produced under similar high-temperature metamorphic conditions and are interpreted as the result of a protracted NW–SE contractional strain regime where (i) subhorizontal non-coaxial shear with superimposed flattening led to an initial phase of NW-directed thrusting, (ii) flattening strains mainly accumulated in the orthogneisses with progressive deformation, leading to a lineation oblique to the transport direction, (iii) the subhorizontal fabric in basement and cover rocks was refolded by overturned folds, and, then (iv) cross-cut by conjugate ENE-striking dextral and NNE-striking sinistral shear zones contemporaneous with NE-trending upright folds. It is proposed that vertical partitioning of strain between basement and cover may explain the presence of oblique lineations in this orogenic belt that did not go through a final stage of extensional collapse.

Keywords: Stretching lineations; Kinematics; Strain partitioning; Flat-lying foliation

1. Introduction

The occurrence of two (or more) directions of lineations in orogenic belts may result from many causes. Perhaps the most common situation is that thrust tectonics is followed by strike-slip shearing, an evolution shown by many collisional belts (Vauchez and Nicolas, 1991). Subhorizontal stretching lineations commonly have distinct orientations due to displacements along thrusts and transcurrent shear zones, respectively, roughly perpendicular and parallel to the orogenic front (e.g. Martelat et al., 2000; Caby and Boessé, 2001; Toteu et al., 2004). Another situation results from strain partitioning during transpressional deformation, where horizontal and vertical lineations can coexist, respectively, in zones of dominant strike-slip and dominant pure shear (Tikoff and Greene, 1997; Goodwin and Tikoff, 2002). In regions characterized by a relatively uniform flat-lying foliation, rotation of a preexisting lineation by later folding (Goscombe and Trouw, 1999; Duebendorfer, 2003) or wrench shearing (Connors et al., 2002) can also explain the occurrence of oblique lineations. Where this possibility can be excluded, tectonic histories that can account for presence of oblique lineations include:

(a) Complex, polycyclic deformation giving rise to lineations of disparate ages and orientations (e.g. Collins et al., 1991; Goscombe et al., 1994);
(b) Polyphase deformation in which successive contractional and extensional strain regimes alternate during a single orogenic cycle. In many mountain belts, this results from extensional collapse during the last stages of orogeny (Malavieille, 1987; Dewey, 1988; Faure, 1995; Gardien et al., 1997), but more complex scenarios

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have also been described, e.g. two thrusting episodes separated by an extensional phase (Roig and Faure, 2000), and two extensional events separated by a contractional one (Tubía, 1994). Oblique lineations are expected in these cases because it is unlikely that displacement occurs exactly along the same slip direction during the successive tectonic events;

(c) Progressive deformation during monocyclic tectonic evolution. In this case, oblique lineations can result from progressive rotation of the stress field (due, for example, to changes in the direction of convergence) or from strain partitioning. Lateral partitioning of strain (Sawyer and Benn, 1993; Connors et al., 2002; Reddy et al., 2003) as well as vertical partitioning of strain at different structural levels (Gilotti and Hull, 1993; Schulmann et al., 1994; Northrup and Burchfiel, 1996; Kisters et al., 2004) have been described. Differences in lineation attitude are attributed either to distinct transport directions or to alternation of coaxial and non-coaxial deformation in adjacent units.

Detailed geological mapping carried out in the eastern portion of the Neoproterozoic Borborema Province, northeastern Brazil (Fig. 1), revealed the occurrence of stretching and/or mineral lineations with distinct orientations in orthogneisses and in metasedimentary rocks. Both groups of rocks are characterized by a dominantly flat-lying foliation developed at high temperature. In this paper, we consider the kinematics associated with these two directions of lineations, and discuss their origin in light of the several possibilities outlined above. Subsequent deformation resulted in overprinting of the flat-lying foliation by steep transcurrent ductile shear zones. It is argued that these events are closely related to a single orogenic episode, the Brasiliano (=Pan-African) orogeny of the Late Neoproterozoic. Finally, the structural evolution of this area is compared with that of Phanerozoic mountain belts, and used to aid the understanding of the deep structure of contemporary and ancient orogens.

2. Geologic setting

The main structural feature of the central domain of Borborema Province is a network of E–W- to ENE–WSW-striking dextral and NNE–SSW- to NE–SW-striking sinistral shear zones (Fig. 1) (Vauchez and Egydio-Silva, 1992; Neves and Vauchez, 1995; Neves and Mariano, 1999; Neves et al., 2000; Silva and Mariano, 2000). Zircon U–Pb and Pb–Pb ages of early- to synkinematic plutons spatially associated with the shear zones constraint their main period of activity to the time span 590–570 Ma (Guimarães and Da Silva Filho, 1998; Almeida et al., 2002a,b; Guimarães et al., 2004; Neves et al., 2004). The shear zones rework an older,

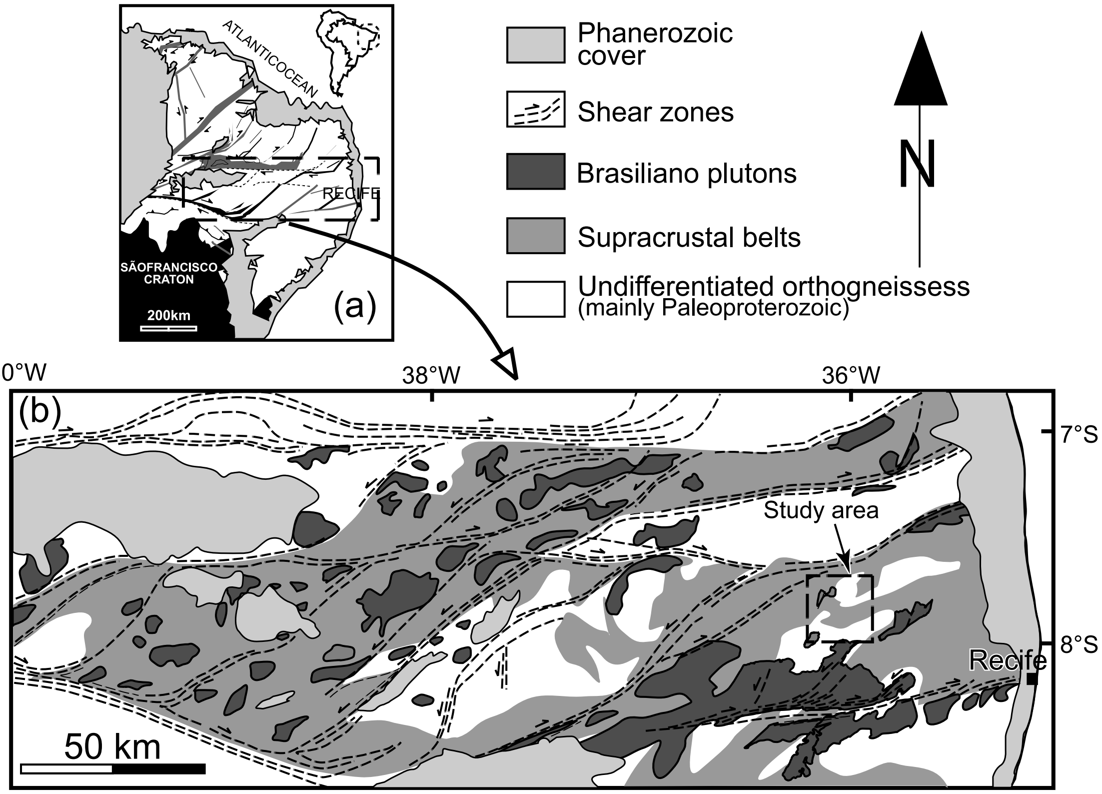

Fig. 1. (a) Location of Borborema Province relative to South America and sketch showing main shear zones. (b) Generalized geologic map of central domain of Borborema Province showing location of the study area in its eastern portion.

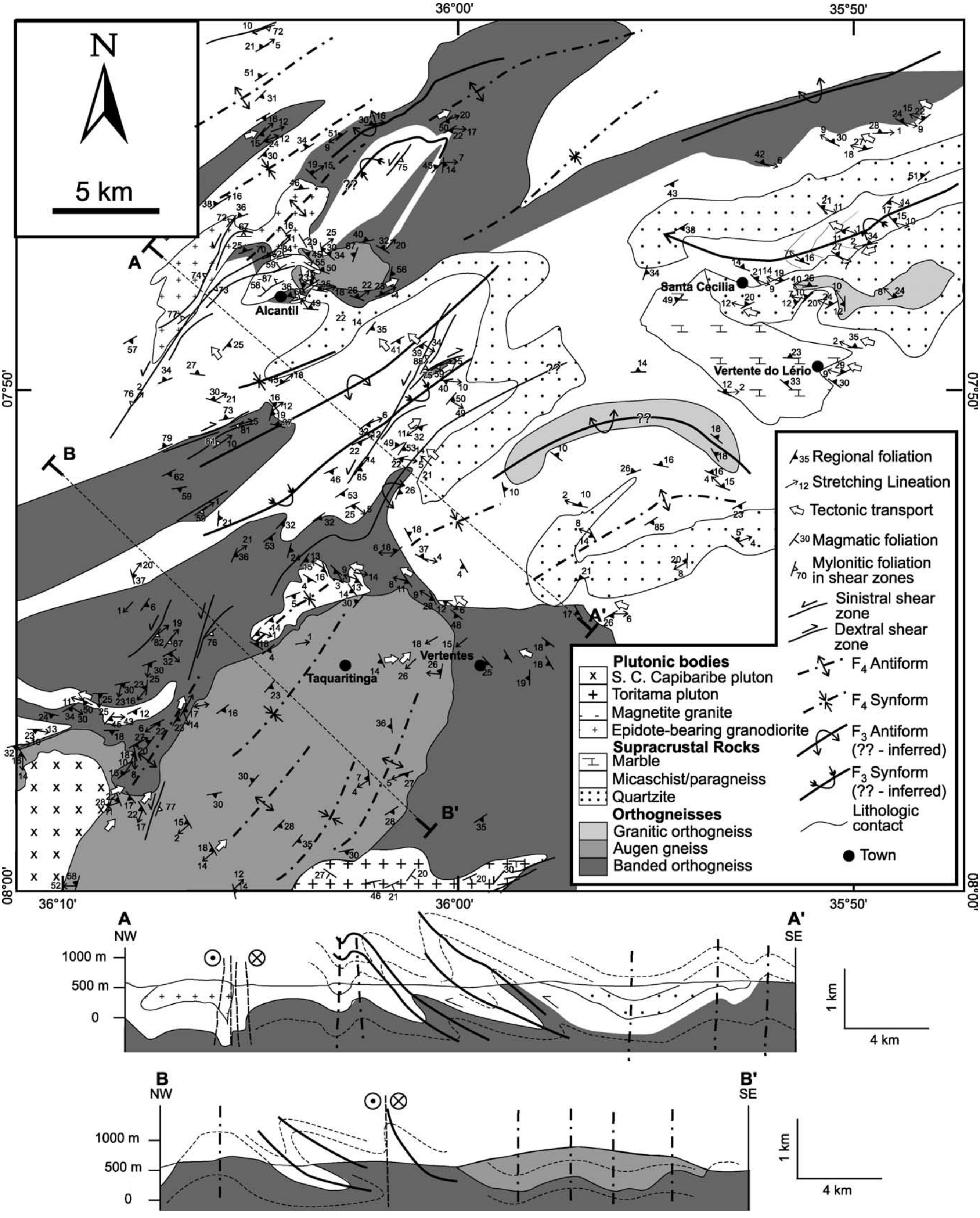

Fig. 2. Geological map of the study area. Two NW–SE cross-sections show large-scale structural features and highlight that the banded orthogneiss is structurally below the supracrustal sequence.

regionally developed, flat-lying foliation present in orthogneisses and supracrustal belts. Most orthogneisses have U–Pb zircon ages in the 2.2–2.0 Ga interval (Santos, 1995; Van Schmus et al., 1995; Brito Neves et al., 2001a,b; Neves et al., 2004). These ages are interpreted as the crystallization ages of their igneous protoliths during the Trans-Amazonian/Eburnean orogeny, which was the main period of crust formation in Borborema Province. Orthogneisses and meta-anorthosites with ages comprised between 1.7 and 1.5 Ga have also been found, and they are interpreted as deformed anorogenic plutons (Accioly et al., 2000; Sá et al., 2002). A third group of orthogneisses is derived dominantly from 0.98 to 0.93 Ga granitoids (Brito Neves et al., 1995, 2001a; Van Schmus et al., 1995; Kozuch et al., 1997; Leite et al., 2000). Some authors interpret these orthogneisses as syntectonic intrusions emplaced during a proposed early Neoproterozoic orogenic event, called Cariris Velhos (Brito Neves et al., 1995). However, other authors argue that the Cariris Velhos event corresponds to a phase of continental rifting, in which case the gneissic fabric would have been developed only during the Brasiliano event (see Brito Neves et al., 2000 and Neves, 2003, respectively, for a review of arguments in favor and against the existence of the Cariris Velhos orogeny). Isotopic and geochronological data for supracrustal rocks are scarce, but they suggest two main periods of deposition, one in the late Mesoproterozoic to early Neoproterozoic and the other in the middle Neoproterozoic (Van Schmus et al., 1995; Kozuch et al., 1997; Bittar et al., 2001; Santos et al., 2002).

3. Geology and structure of the study area

3.1. Orthogneisses and metasedimentary rocks

The study area comprises banded orthogneisses, granitic augen gneisses, metasedimentary rocks and igneous intrusions (Fig. 2). Banded orthogneisses are characterized by alternate bands of dioritic and granitic compositions. The granitic bands are usually a few centimeters thick (Fig. 3a), but locally may be more than 1 m thick. Zircon U–Pb dating from one sample in the southern part of the study area

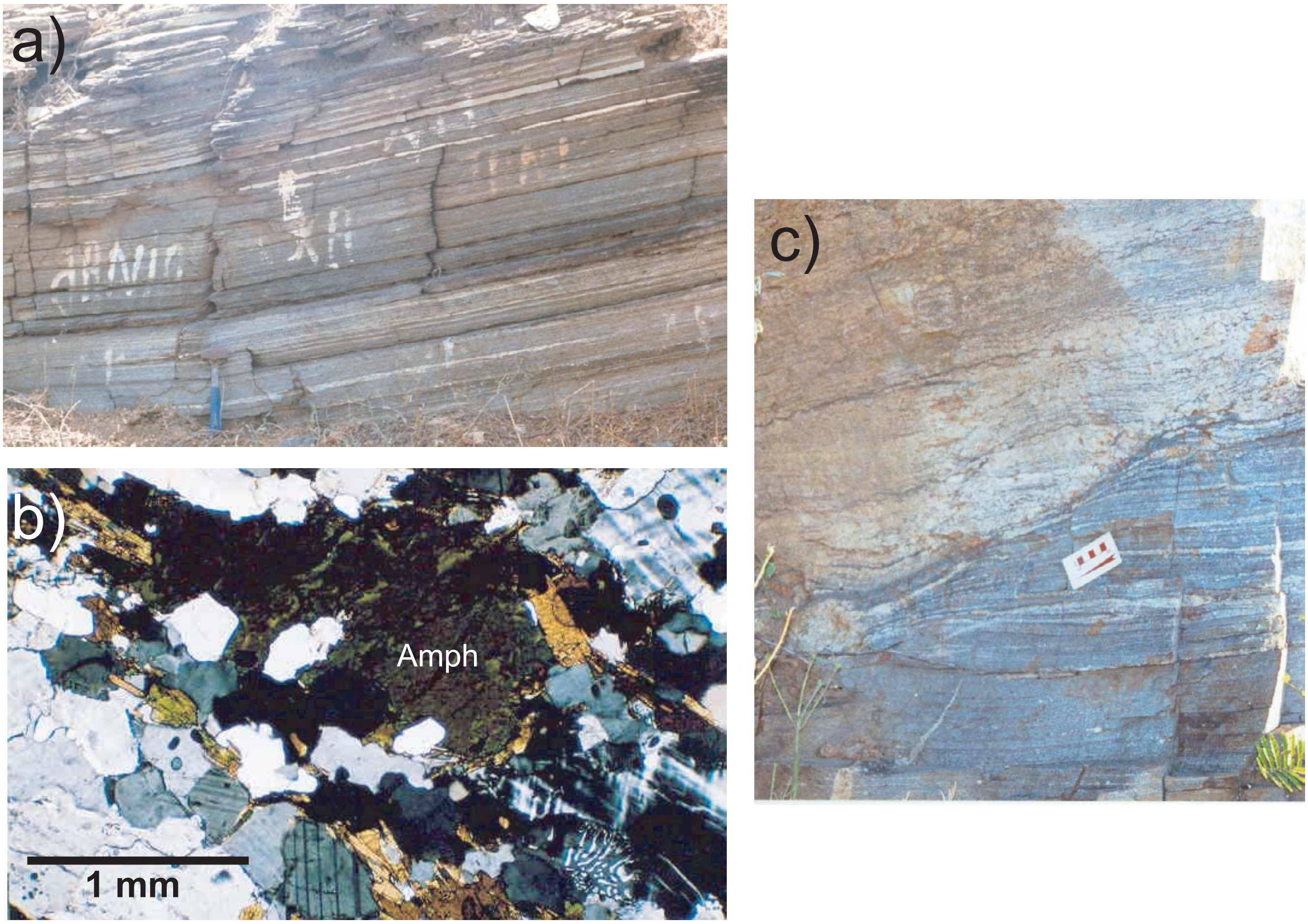

Fig. 3. (a) and (b) Field and microstructural aspects of banded orthogneiss. (a) Characteristic structure consisting of dominantly millimeter- to centimeter-thick mafic bands showing variations in color index (dark to medium shades of gray) alternating with felsic bands (light gray). (b) Photomicrograph showing neoformed amphibole attesting high-T metamorphism. (c) Contact between banded orthogneiss (below) and Taquaritinga orthogneiss crosscut by subhorizontal gneissic foliation.

yielded an age of 1.97 Ga (Sá et al., 2002). The Taquaritinga orthogneiss, an augen gneiss that occupies most of the southwestern part of the study area, yielded a zircon U–Pb age of 1.52 Ga (Sá et al., 2002). Another small augen gneiss, here named Alcantil orthogneiss, occurs in the central northern part of the area (Fig. 2).

The supracrustal sequence consists of a metapelitic–metapsammitic–metacarbonate unit comprising micaschists, pelitic and quartz–feldspathic paragneisses, quartzites and marbles, with smaller lenses of calc–silicate rocks and amphibolites. Santos et al. (2002) report carbon isotope fluctuations in marbles compatible with deposition around 880 Ma. Equigranular, medium-grained, granitic orthogneissic sheets occur intercalated within the metasedimentary sequence; two of these have dimensions large enough to be represented at the scale of the map in Fig. 2.

3.2. Planar fabrics and meso- to macro-scale folds

Orthogneisses and supracrustal rocks have a dominant planar fabric. The banded orthogneiss and the Taquaritinga orthogneiss share a common foliation (Fig. 3c) indicating that the regional fabric in these rocks formed contemporaneously. Coexistence of garnet and amphibole, developing a mosaic microstructure, neoformed amphibole (Fig. 3b), and local anatexis imply high temperatures during deformation of the orthogneisses. Temperature estimates using the amphibole–plagioclase geothermometer ranged from 630 to 760 °C (Neves et al., 2000). In metapelites, the assemblage quartz + plagioclase + biotite + garnet + sillimanite is ubiquitous. Relict kyanite was found in a few places. Neoformed K-feldspar (Fig. 4a) and local anatexis (Fig. 4b) indicate high temperatures during deformation. The mineral assemblages in both units clearly show a high amphibolite metamorphic grade.

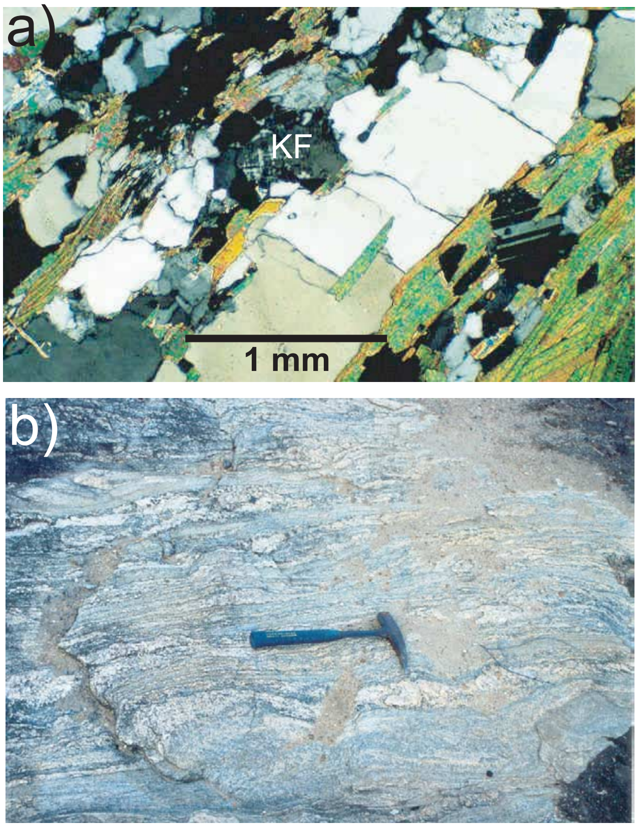

Fig. 4. Field and microstructural aspects of supracrustal rocks. (a) Photomicrograph showing neoformed K-feldspar, attesting high-T metamorphism. (b) Migmatitic biotite paragneiss with stromatitic structure.

Stereographic plots of poles to foliation in the banded orthogneiss and Taquaritinga orthogneiss, and in the supracrustal rocks with intercalated granitic orthogneisses are shown in Fig. 5a. In spite of the obvious influence of later folding, the clear dominance in both cases of gentle- to moderately-dipping foliations reflects a previous subhorizontal fabric. The similarity in foliation orientation and metamorphic grade suggest that the foliation in these two groups of rocks formed during the same tectonic event.

The main foliation was affected by three generations of outcrop- to map-scale folds, namely: (i) early recumbent to inclined folds (Figs. 2 and 6a), (ii) NE-trending upright open to gentle folds (Figs. 2 and 6c) and (iii) NW-trending upright gentle folds that cause inflexions of the axial traces of earlier formed folds. The occurrence of intrafolial and synfoliation folds inside the main foliation attests the existence of previous fold-forming events. Considering that, the above-mentioned folds will be referred to as F_3, F_4 and F_5 folds, respectively. An axial-plane foliation is sometimes associated with F_3 folds (Fig. 6b) but not with the later ones. Locally, pink biotite granite as vein arrays in banded orthogneisses has a subvertical attitude consistent with the filling of tension gashes during development of F_3 folds, demonstrating that this deformation phase occurred at high temperature.

Kilometer-scale transcurrent dextral and sinistral shear zones occur in the western part of the study area, but the strain was generally not high enough to completely obliterate the preexisting fabric. Development of these shear zones was apparently contemporaneous with F_4 folds, characterizing a transpressive regime.

3.3. Plutons

Four plutons, variably deformed by one or more phases of tectonic activity, are found in the study area. The oldest one is an equigranular, epidote-bearing (up to 5% in the mode) amphibole biotite granodiorite (Fig. 2). It locally contains dioritic and amphibolitic enclaves (Fig. 7a), and displays a gentle dipping magmatic foliation that in several places transforms to a gneissic fabric. The flat-lying foliation is clearly crosscut by subvertical shear bands (Fig. 7b), attesting to intrusion prior to the transcurrent deformation. The mineralogical, petrographic and structural characteristics of this pluton are similar to those of 645–635 Ma old, calc-alkalic plutons described in other parts of

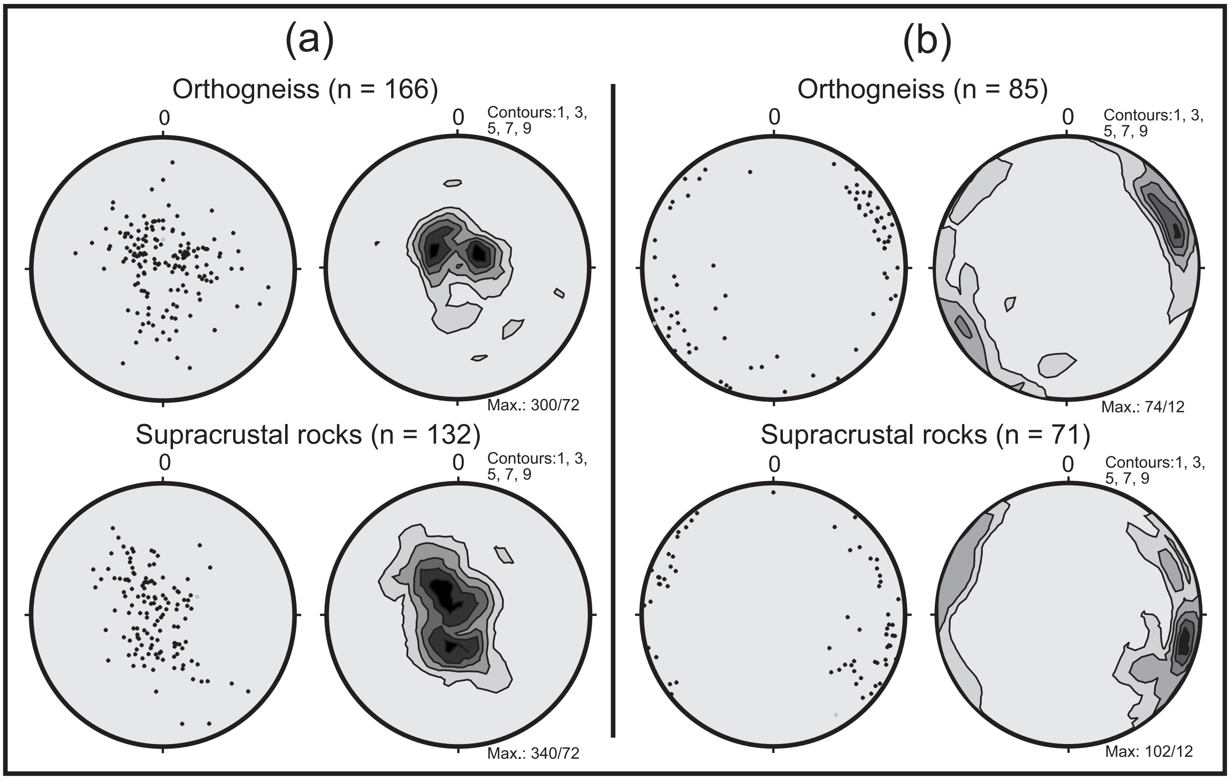

Fig. 5. Scatter and contour plots (lower hemisphere Schmidt projections) of poles to foliation (a) and lineations (b) in banded orthogneiss and Taquaritinga orthogneiss, and in supracrustal rocks and intercalated granitic orthogneiss.

the central domain of Borborema Province (Sial et al., 1998; Almeida and Guimarães, 2002; Brito Neves et al., 2003; Guimarães et al., 2004).

The epidote-bearing granodiorite is intruded by a magnetite leucogranite (Fig. 2). The magnetite leucogranite displays dominantly moderate to steeply dipping magmatic foliation, and locally shows superimposed strike-slip-related solid-state deformation (Fig. 7c), which could suggest intrusion during strike-slip shearing. However, leucosomes of magnetite leucogranite are also found along foliation planes in the Alcantil orthogneiss (Fig. 7d), and this can be interpreted as suggesting intrusion at the waning stages of deformation leading to development of flat-lying fabrics in country rocks, perhaps during the transition from a low-angle to a steep tectonic event.

In the southernmost part of the study area, the Taquaritinga orthogneiss is intruded by the Toritama and Santa Cruz do Capibaribe plutons (Fig. 2). A sinistral shear zone bounds the syenitic Toritama pluton at the south-western side, and the pluton was deformed by strike-slip shearing before fully crystallized. However, its dominant magmatic fabric is characterized by subhorizontal foliations and NW-trending lineations (Neves et al., 2000). Therefore, as in the case of the magnetite leucogranite, emplacement probably occurred during the transition from a low-angle tectonic event to a wrench-dominated one. Preliminary Rb–Sr and ^{40}Ar/^{39}Ar geochronology indicates intrusion around 590 Ma (Guimarães and Da Silva Filho, 1998; Neves et al., 2000). The Santa Cruz do Capibaribe pluton consists of a core of gabbros and gabbronorites/diorites and a border of monzonites. Clear discordant contacts with the Taquaritinga orthogneiss, the apparently isotropic nature in outcrop, and deformation by brittle–ductile shear zones indicate that intrusion was late kinematic with respect to the transcurrent shear zones.

4. Lineations and kinematics

Lineations are defined by alignment of fibrous sillimanite (Fig. 8a) and/or elongated quartz and feldspar grains (Fig. 8b) in supracrustal rocks, and by the dimensional shape-preferred orientation of quartz, plagioclase, biotite and/or amphibole (Fig. 8c and d) in banded and granitic orthogneisses. The deformation fabric of the Taquaritinga orthogneiss is dominantly planar, such that stretching lineations are less common than in the other rock types. High strain coeval with lineation development is indicated by local occurrence of sheath folds (Cobbold and Quinquis, 1980) in metapelites, of oblique folds (Passchier, 1986; also called asymmetric type folds, Holdsworth, 1990) in banded orthogneiss, and by common mylonitic fabrics in the Taquaritinga orthogneiss.

At the outcrop scale, the orientation of lineations is very

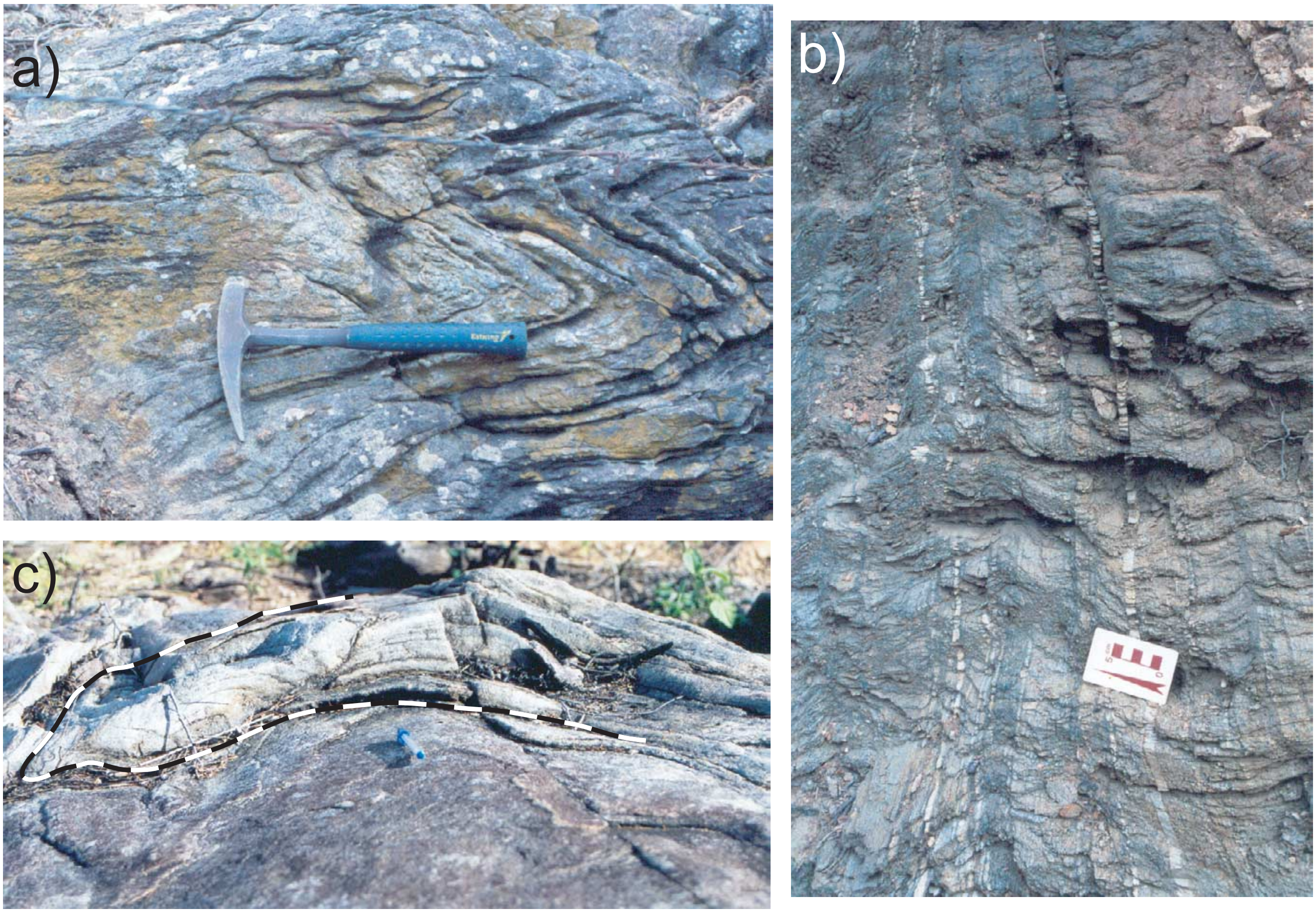

Fig. 6. (a) Recumbent F_3 fold in quartzite. (b) Banded orthogneiss with subvertical banding crosscut by F_3-related subhorizontal cleavage, which is in turn crenulated by upright F_4 folds. View to the northeast. (c) Isoclinal, recumbent F_3 fold (closing to the left) refolded by F_4 upright fold with shallow northeastern-plunging hinge (indicated by pen).

consistent, deviating by less than a few degrees, unless disturbed by later folds. Map-scale distribution and stereographic plots (Figs. 2 and 5b) show gently-plunging ENE- to NE-trending lineations in orthogneisses and ESE-plunging lineations in supracrustal rocks, thus revealing clear obliquity between these two units. Much of the dispersion observed in the stereograms can be explained by reorientation caused by later folding and/or wrench shearing. In particular, inspection of Fig. 2 shows that most NE-trending lineations in metasedimentary rocks occur close to shear zones. However, in some outcrops the banded orthogneiss shows SE-trending lineations, which may reflect an original orientation.

In supracrustal rocks, a number of mesoscopic kinematic indicators in sections normal to the foliation and parallel to the lineation point to non-coaxial deformation with top-to-the-northwest sense of shear (Figs. 2 and 9). The most common are shear bands, σ-type porphyroclasts of K-feldspar (Fig. 9a), asymmetrical boudins of quartz or quartz/feldspar aggregates (Fig. 9b), and rotated and transposed veins (Fig. 9c). In spite of clear evidence for intense non-coaxial flow at mesoscopic scale, mylonitic fabrics and shear criteria are rarely seen at microscopic scale. This suggests that temperatures remained elevated for a long time, allowing grain growth to obliterate syn-shear microscopic fabrics. Unequivocal shear sense criteria were not observed in the granitic orthogneissic sheets intercalated within the metasedimentary sequence. In deformed epidote-bearing granodiorite, asymmetric mafic enclaves (Fig. 7a) and fold asymmetry locally suggest top-to-the-northwest shear sense.

The strong planar fabric and orthorhombic symmetry of feldspar porphyroclasts in the Taquaritinga orthogneiss and symmetric boudins in banded orthogneiss indicate predominantly coaxial deformation. Nevertheless, kinematic shear criteria are also locally found, though much less frequently than in supracrustal rocks. These include foliation curvature (fig. 3 in Neves et al., 2000), asymmetrical porphyroclasts (Fig. 10a), *C*/*S*-fabric (Fig. 10b), and asymmetrical boudins. These kinematic indicators almost invariably indicate a northeasterly displacement direction (Figs. 2 and 10), but a top-to-the-northwest sense of shear, consistent with that of nearby paragneisses and micaschists, was observed in three outcrops of banded orthogneiss in the southern part of the study area (Fig. 2).

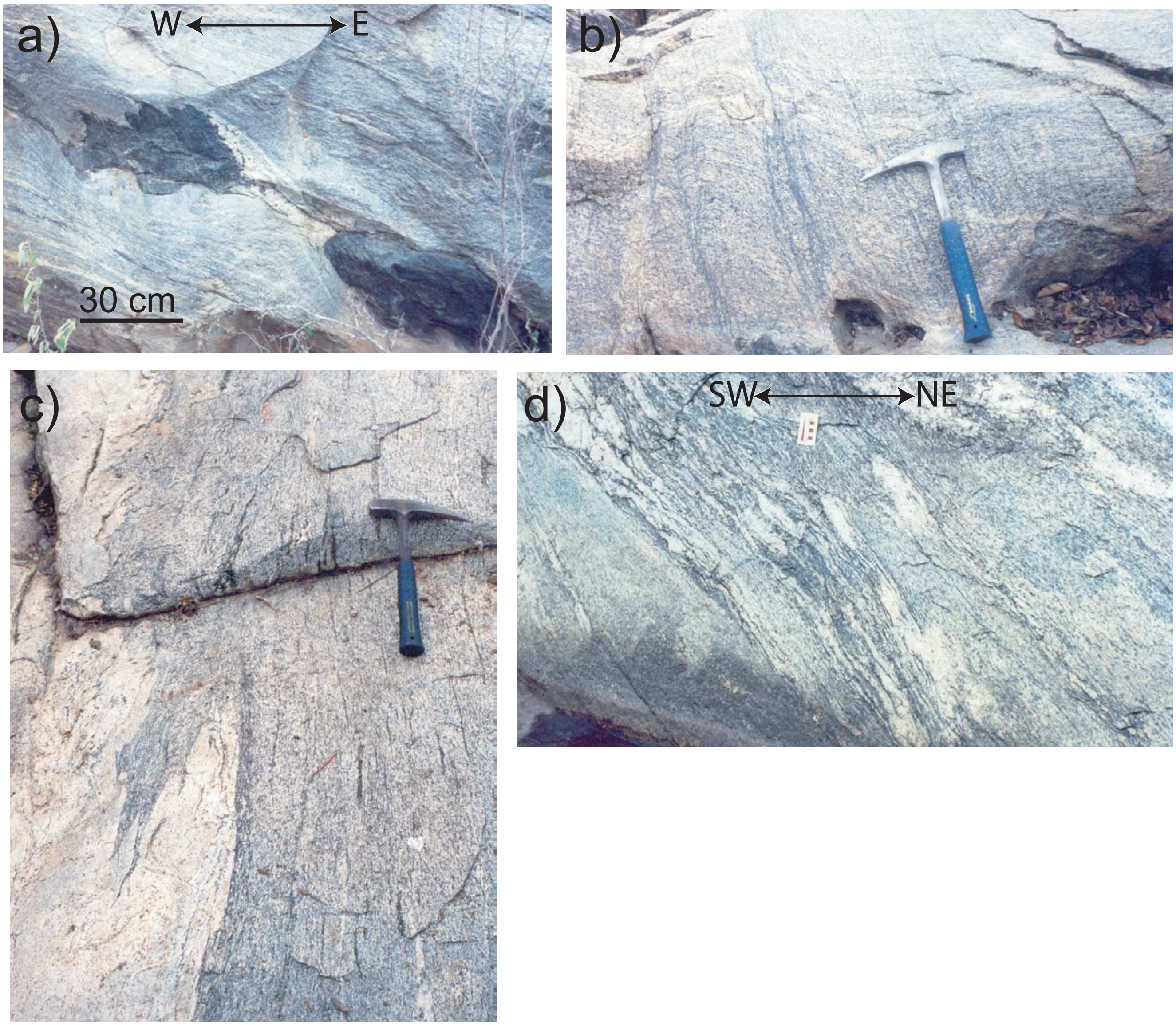

Fig. 7. (a) Epidote-bearing granodiorite with east-dipping gneissic fabric containing asymmetric microgranular enclaves suggesting top-to-the-west shearing. (b) Subhorizontal gneissic fabric in epidote-bearing granodiorite crosscut by steeply dipping mylonitic foliation. Hammer head points to the northeast. (c) Contact magnetite leucogranite/epidote-bearing granodiorite crosscut by subvertical shear bands. Both rocks are deformed by strike-slip shearing, but the strain was not strong enough to obliterate the intrusive nature of the contact. Hammer head points to the northeast. (d) Leucosomes of magnetite leucogranite along moderately, NE-dipping foliation in Alcantil orthogneiss.

5. Discussion

5.1. Relationship between the two directions of lineations

Possible explanations for development of the two directions of lineations in orthogneisses and supracrustal rocks include rotation of a preexisting lineation, polycyclic or polyphasic deformation and strain partitioning during progressive deformation. Although rotation by late folds and shear zones occurred locally, the likelihood of complete reorientation of a previous single lineation seems very unlikely because progressive rotation passing from orthogneisses to supracrustal rocks cannot be detected on the geologic map (Fig. 2). Given that most lineations are gently plunging (Fig. 5b), reorientation would necessarily involve rotation around subvertical axes, which excludes folding as a possible mechanism because folds of all generations have subhorizontal axes. Also, a lack of small-circle distribution in the stereograms of Fig. 5b is inconsistent with reorientation by plunging folds.

The following observations suggest development of foliations and lineations in Taquaritinga orthogneiss, banded orthogneiss and supracrustal rocks during the same tectonic event, rather than as a consequence of polycyclic/polyphasic deformation: (a) the Taquaritinga orthogneiss and the banded orthogneiss share a common

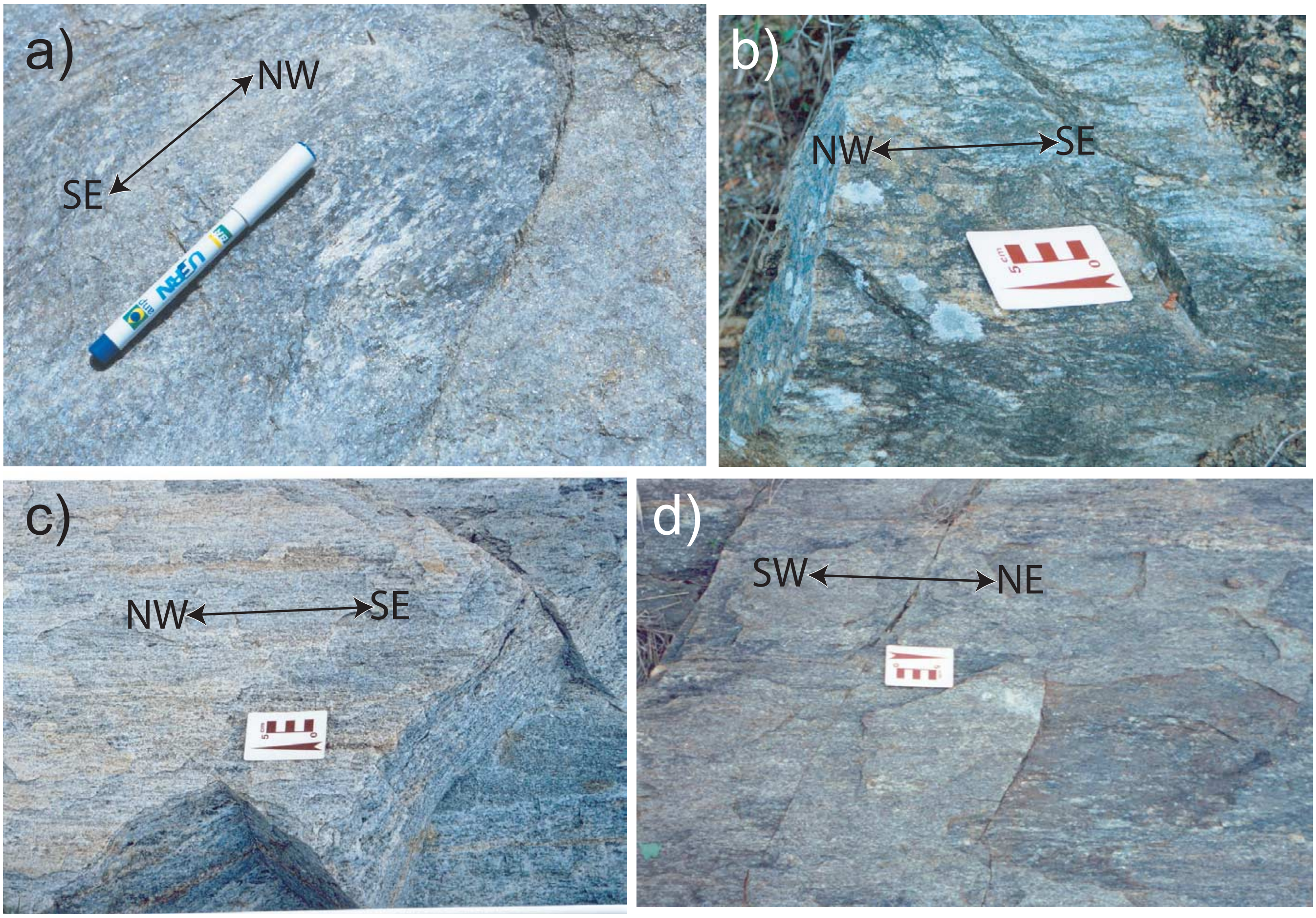

Fig. 8. Subhorizontal foliation planes showing mineral lineations defined by: (a) and (b) elongate sillimanite (a) and stretched quartz (b) in quartzite; (c) stretched quartz, feldspar and biotite in granitic orthogneiss; and (d) stretched plagioclase and amphibole in dioritic orthogneiss.

foliation (Fig. 3c); (b) although exposed contacts between orthogneiss and metasedimentary rocks were not directly observed in the field, in transects a few meters long it can be seen that the foliation maintains the same attitude in both group of rocks; (c) the lineations formed under similar high-temperature metamorphic conditions (Figs. 3 and 4); and (d) absence of overprinting relationships between lineations argues against superposed deformation. Additionally, polyphase deformation in orogenic belts commonly results from extensional collapse following an early period of crustal thickening (e.g. Malavieille, 1987; Lister and Davis, 1989; Rey et al., 2001). In contrast with the universally observed metamorphic break and a major décollement detaching gneisses from cover rocks in this situation, in the present case, a major shear zone does not separate orthogneisses from overlying metasedimentary rocks (although mylonitic fabrics are ubiquitous in the Taquaritinga orthogneiss, the distribution of strain is highly heterogeneous). This indicates that sufficiently high temperatures were reached to smear out rheological heterogeneities resulting from compositional effects, preventing strain localization into a narrow shear zone.

In spite of an absence of strong rheological contrasts between the different rock units, localization of well-developed, non-coaxial shear of consistent sense in the supracrustal sequence (Fig. 9) indicates that kinematic partitioning was important. Strain partitioning has mainly been treated in the context of transpressional deformation. In classical transpression, deformation is laterally and basally confined and occurs between parallel vertical zone boundaries (Sanderson and Marchini, 1984), but the concept can be extended to include the cases of inclined boundaries (Jones et al., 2004) and extension in the horizontal direction (Jones et al., 1997). Strain partitioning during transpression occurs where oblique convergence leads to contemporaneous wrenching and thrusting motions (e.g. Holdsworth and Strachan, 1991; Merle and Gapais, 1997) or to adjacent regions undergoing simple shear and pure shear (e.g. Tikoff and Greene, 1997; Goodwin and Tikoff, 2002; Schulmann et al., 2003). These transpressional models cannot directly be applicable to the present study. The subhorizontal $S>L$ fabric of both orthogneisses and supracrustal rocks requires a component of flattening in the horizontal plane during deformation. This is in contrast with flattening strains in the vertical plane for transpression without strain partitioning (Sanderson and Marchini, 1984), and development of steep

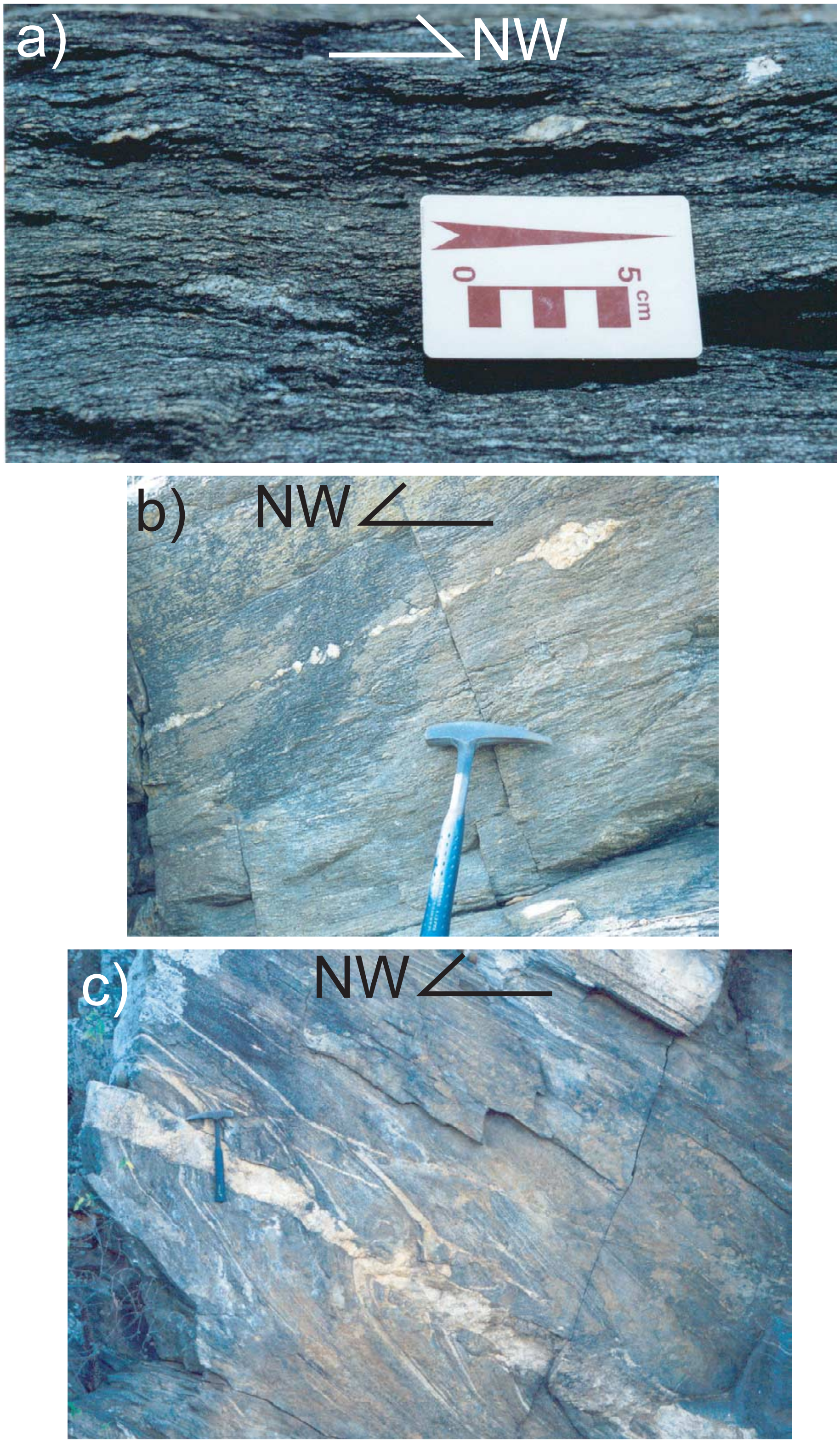

Fig. 9. Examples of kinematic shear criteria in supracrustal rocks indicating top-to-the-northwest displacement. (a) Shear bands and σ-type porphyroclasts of K-feldspar in pelitic paragneiss. (b) Asymmetric boudins of quartz-vein in biotite paragneiss. (c) Rotated and transposed quartz-feldspar veins in biotite paragneiss.

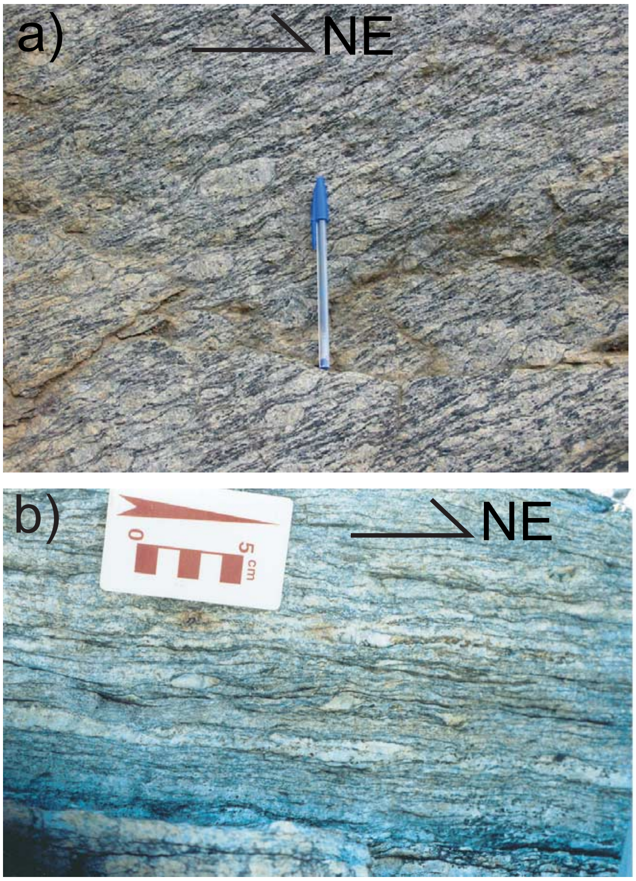

Fig. 10. Examples of kinematic shear criteria in orthogneisses indicating northeastward displacement. (a) Asymmetric K-feldspar porphyroclasts in Taquaritinga orthogneiss. (b) *S–C* fabric in banded orthogneiss.

to vertical foliations, which are present across the whole transpressional domain (e.g. Merle and Gapais, 1997; Tikoff and Greene, 1997) or at least in part of it (e.g. Jones et al., 2004), in cases of transpression with partitioned deformation.

Local occurrence of kyanite in metapelites and the preponderance of thrust geometries, in spite of modifications due to later folding, in the supracrustal succession suggest that the top-to-the-northwest tectonics was associated with thrusting. In thrust settings, a component of pure shear or flattening is common (e.g. Marjoribanks, 1976; Williams et al., 1984; Mukul and Mitra, 1998; Strine and Wojtal, 2004), which probably reflects an increase in gravitational forces related to crustal thickening and a concomitant reduction in strength related to metamorphism. If horizontal extension perpendicular to the transport direction is greater than parallel to it, elongation in this direction may become progressively more important with increased deformation (Tikoff and Fossen, 1999). Occasional kinematic criteria in banded orthogneiss indicate its partial displacement by the top-to-the-northwest tectonics (Fig. 11a). Development of dominant NE-trending lineations in the orthogneisses may thus reflect greater superimposed flattening than in the overlying metasediments during progressive deformation (Fig. 11a). With time, it is therefore anticipated that deformation paths in orthogneisses and supracrustal rocks had progressively diverged, with deformation remaining closer to simple shear in the metasedimentary sequence (Fig. 11b). Gradual partitioning of strain vertically within the crust during progressive deformation is thus regarded as the most likely explanation for production of the oblique lineations.

In addition to important NE–SW extension, a local component of NE-directed shear is also observed in orthogneisses (Fig. 10), which is not expected on theoretical grounds (Tikoff and Fossen, 1999). In like fashion, nearly orthogonal displacement directions occurring at different structural levels have been described in the Scandinavian Caledonides (Northrup and Burchfiel, 1996) and the Pan-African Damara belt of Namibia (Kisters et al., 2004). Although the origin of contrasting kinematics at different crustal levels is not completely understood, it is possible that heterogeneity resulting from differing degrees of softening could locally induce variations in the velocity field and introduce a component of simple shear during overall coaxial ductile flow.

In synthesis, the preferred interpretation for development of two directions of lineations in the study area calls for NW–SE-directed shortening and thickening. This gave rise to an initial phase of top-to-the-northwest thrusting, which was followed with increasing deformation by NE–SW extension in orthogneisses. NE- to ENE-trending F_3 folds that postdate the main phase of metamorphism and affect all units are interpreted as a late increment of this regional strain field, thus indicating continued NW–SE shortening.

5.2. Development of shear zones and late folds

Dextral ENE-striking and sinistral NNE-striking transcurrent shear zones are interpreted as conjugate sets, as elsewhere in the central domain of Borborema Province (Neves and Vauchez, 1995; Neves and Mariano, 1999; Neves et al., 2000). By analogy with conjugate extensional crenulation cleavages (Zheng et al., 2004), the shortening direction is inferred to bisect the obtuse angle between them, such that the shortening direction would have a NW–SE orientation during their development. Therefore, no major rotation of the regional strain field is required between the flat-lying foliation-forming event and the transcurrent regime. The situation is similar, at a smaller scale, to that in central Tibet, where it has recently been shown (Taylor et al., 2003) that conjugate NE-trending sinistral and ESE-trending dextral faults accommodate coeval N–S contraction and E–W extension.

Upright, NE-trending F_4 folds are also consistent with NW–SE shortening, and are thus considered to be contemporaneous with the strike-slip shear zones. This situation occurs in many orogenic belts where localization of non-coaxial deformation into discrete planar zones and of coaxial deformation within intervening low-strain packages

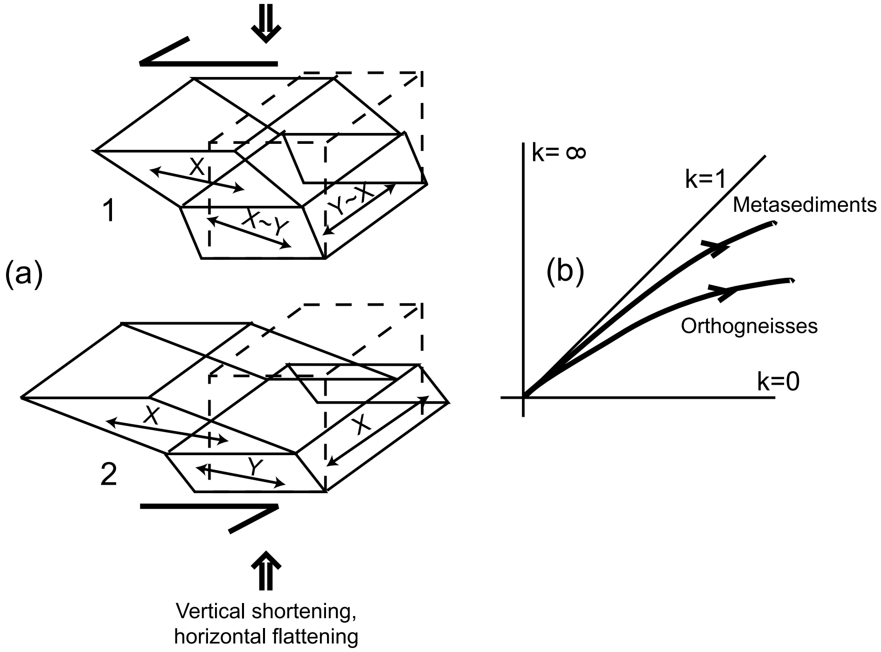

Fig. 11. (a) Schematic diagram depicting two stages in the deformational history leading to development of oblique lineations in orthogneisses and supracrustal rocks. *X* and *Y* stand for approximate orientations and relative magnitudes of major and intermediate strain axes. (1) In the beginning of the deformation process, overall non-coaxial flow with superimposed vertical shortening causes the *X* and *Y* axes in orthogneisses to have about the same size. (2) With increasing deformation, the major strain axis in orthogneisses becomes normal to the transport direction. (b) Hypothetical trajectories in Flinn diagram of deformation paths followed by orthogneisses and supracrustal rocks. See text for discussion.

is observed (e.g. Tikoff and Teyssier, 1994, and references therein). F_5 folds may have resulted from a component of NE–SW shortening during non-plane strain, and thus to be contemporaneous with F_4 folds. Alternatively, it may represent a late deformation event of low intensity developed at high angle to the NW–SE shortening direction.

5.3. Ages of deformation

An upper bound on the development of the flat-lying fabric is placed by the 1.52 Ga age of the Taquaritinga orthogneiss (Sá et al., 2002), which implies that the foliation in this rock and in banded orthogneiss cannot be inherited from the Transamazonian orogeny (≈2.0 Ga). Because no Mesoproterozoic contractional event has been found in Borborema province and the Taquaritinga orthogneiss has geochemical characteristics similar to that of anorogenic granites (Sá et al., 2002), acquisition of the gneissic fabric either occurred during the Cariris Velhos event or the Brasiliano orogeny. Precise isotopic ages are not available for metasedimentary rocks, but preliminary carbon isotope fluctuations in marbles suggest deposition around 880 Ma (Santos et al., 2002), i.e. after cessation of the Cariris Velhos event at ca. 920 Ma (Brito Neves et al., 2000). The flat-lying magmatic to solid-state fabric of the epidote-bearing granodiorite (Fig. 7a), parallel to that in country rocks, and its similarity with 640–630-Ma-old plutons elsewhere in the central domain of Borborema Province (Almeida and Guimarães, 2002; Brito Neves et al., 2003; Guimarães et al., 2004) favor the proposition of a late Neoproterozoic age for the deformation. Taking into consideration these facts and inferences, we tentatively propose that top-to-the-northwest tectonics started around 650 Ma while the transcurrent regime was established around 590 Ma, the latter age being constrained by emplacement of Toritama pluton (Guimarães and Da Silva Filho, 1998; Neves et al., 2000). Ongoing geochronological work will place tighter constraints on these estimates.

6. Tectonic implications and conclusions

Ancient, exhumed regions where mid-crustal levels are now exposed at the surface allow the opportunity to investigate the deeper roots of mountain ranges. Although extrapolation of local kinematic interpretations to the regional scale may be risky, the evolution proposed for the study area can be correlated with those of modern orogenic belts as revealed by field based and seismic studies. These studies indicate that crustal thickening accompanied by temperature increase may (a) cause the middle/lower crust to become too weak to sustain large tectonic loads (Dewey, 1988; Rey et al., 2001; Vanderhaeghe and Teyssier, 2001), and (b) promote decoupling of deformation between basement and cover rocks due to development of orogen-scale décollements that lead to partitioned deformation (Cook and Varsek, 1994; Epard and Escher, 1996).

If convergence slows down or stops after attainment of temperatures high enough to permit ductile spreading of the lower crust, the tectonic history of an orogen will finish with its extensional collapse. Instead, if contractional strains persist for a longer time, extensional collapse may be prevented, and a metamorphic gap at the basement-cover contact does not need to happen. In the study area, refolding of the main foliation by overturned F_3 folds indicates sustained shortening after orthogneisses and supracrustal rocks had acquired a subhorizontal fabric. Furthermore, subsequent development of conjugate transcurrent shear zones and upright folds indicate late increments of contractional strain. This strain regime associated with cooling rates around 5 °C Ma^{-1} (Neves et al., 2000), point to low exhumation rates.

Vertical partitioning of strain during progressive deformation, as proposed here, offers an explanation for the occurrence of oblique lineations in ancient orogens that did not pass by a terminal episode of extensional collapse (e.g. Gilotti and Hull, 1993; Northrup and Burchfiel, 1996). Regions characterized by low/medium-pressure, high temperature metamorphism, no major metamorphic breaks between basement and cover, and slow exhumation rates are common in Proterozoic terrains. Examples include the Pan-African belts of Nigeria (Caby and Boessé, 2001; Ferré et al., 2002) and Cameroon (Toteu et al., 2004), and the Paleoproterozoic Transamazonian orogen in Guyana (Nomade et al., 2002). Based on the results of this study, we propose that some of them may have experienced an evolution where crustal thickening, synconvergence extension in mid/deep crustal levels, and strike-slip shearing occur as successive but partially overlapping events.

Note added in proof

Concerning section 5.3 (Age of deformation), U-Pb geochronological data by LA- ICP-MS became available after the completion of the paper. They attest a late Neoproterozoic age (ca. 630 Ma) for deformation and metamorphism of orthogneisses, supracrustal rocks, and the epidote-bearing granodiorite. However, the age of crystallization of the latter occurred at ca. 2100 Ma.

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