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Post-Devonian transpressional reactivation of a Proterozoic ductile shear zone in Ceará, NE Brazil

NIVALDO DESTRO*

Petrobrás Exploration Dept., Aracaju, Brazil 49000

PETER SZATMARI

Petrobrás Research Center, Rio de Janeiro, Brazil 21910

and

EDUARDO A. LADEIRA

Federal University of Minas Gerais, Department of Geology, Belo Horizonte, Brazil 30000

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Abstract—Reactivation of Proterozoic ductile shear zones is often difficult to document because of the lack of conclusive evidence. However, the reactivation of a Proterozoic age ductile shear zone along the northeastern extremity of the Transbrazilian Lineament in northwest Ceará can be well documented by the intense deformation of an early Devonian sandstone body, about 30 km long and 4 km wide. This lineament, which extends across Brazil for more than 2700 km, is well exposed in Ceará as a dextral ductile shear zone with late Proterozoic age subvertical mylonites striking approximately 040°. Post-Devonian reactivation of the shear zone, now by dextral transpression, gave rise to brittle faults that limit the sandstone body. Near the faults, the sandstone beds are steep to subvertical, passing into gently dipping or subhorizontal away from the shear zone. Conjugate Riedel shear fractures within the sandstone body suggest a compressive stress field in which the maximum principal compressive stress (σ_1) trends about 100°, with the intermediate principal stress (σ_2) subvertical. The age of the post-Devonian reactivation in Ceará is uncertain, but structures in mid-Cretaceous sediments of the Parnaíba Basin, and Aptian to early Cenomanian sediments of the offshore Ceará Basin, both situated along the Transbrasilian Lineament, suggest a later mid-Cretaceous age.

INTRODUCTION

THE Transbrazilian Lineament (Schobbenhaus Filho *et al.* 1975) extends over 2700 km from northeastern to southwestern Brazil (Fig. 1), probably passing into Africa to the northeast (Marini *et al.* 1984) and into Paraguay and Argentina to the southwest (Schobbenhaus Filho *et al.* 1975). It is best known in the State of Ceará, NE Brazil, where it transects the well-exposed Precambrian of the Geotectonic Province of Borborema (Almeida *et al.* 1977) (Fig. 1). The so-called Sobral–Pedro II Lineament (Kegel 1961) (Fig. 2) is an important segment of the Transbrasilian Lineament. In Ceará, the lineament is an 040°-trending subvertical zone of mylonitized gneisses and calc-silicate rocks, about 10 km wide, which was formed as a ductile shear zone about 600 Ma ago during the Brasiliano-Panafrican Orogeny. During the deformation cycle, thermal, tectonic, magmatic and metamorphic phenomena affected the Borborema Province, and lasted until Cambrian–Ordovician time (Santos & Brito Neves 1984). Cambro-Ordovician sediments (the Jaibaras Group) occur in a narrow graben along the lineament (Fig. 2). Both the graben and the Precambrian rocks are overlain by generally flat-lying early Devonian sandstones of the Serra Grande Formation (Quadros 1982) which constitute the basal sequence of the Parnaíba Basin (Fig. 2).

Based mainly on field data, we describe here the deformational state of a 30 km long and 4 km wide, very consolidated fluviatile sandstone body. Although it belongs to the early Devonian Serra Grande Formation of the Parnaíba Basin (Fig. 2), it is isolated from the type area, about 50 km southwest of Sobral (Fig. 2), by rock exposures of the Jaibaras Group and the Precambrian basement. The sandstone body is cut by km-scale brittle faults, which were formed by reactivation of suitably oriented splays of the Precambrian ductile shear zone, or by reactivation of some normal faults formed during the extensional event related to the Jaibaras Basin.

No marker allows us to determine the displacement along the reactivated faults, but the direction and the sense of movement can be determined by using field observations, such as deflection of the sandstone bedding planes, and the orientation of conjugate Riedel shear fractures within the sandstone body and small-scale faults dislocating consolidated pebbles in the basal conglomerate. Deflections of the sandstone beds near the major faults appear very clearly on aerial photographs, and support the overall dextral sense of movement during the reactivation.

*Current address: PETROBRÁS/DEXBA/DIREX/NUESP, Av. Antônio Carlos Magalhães, No. 1113-Pituba, 41856-900, Salvador-BA, Brazil.

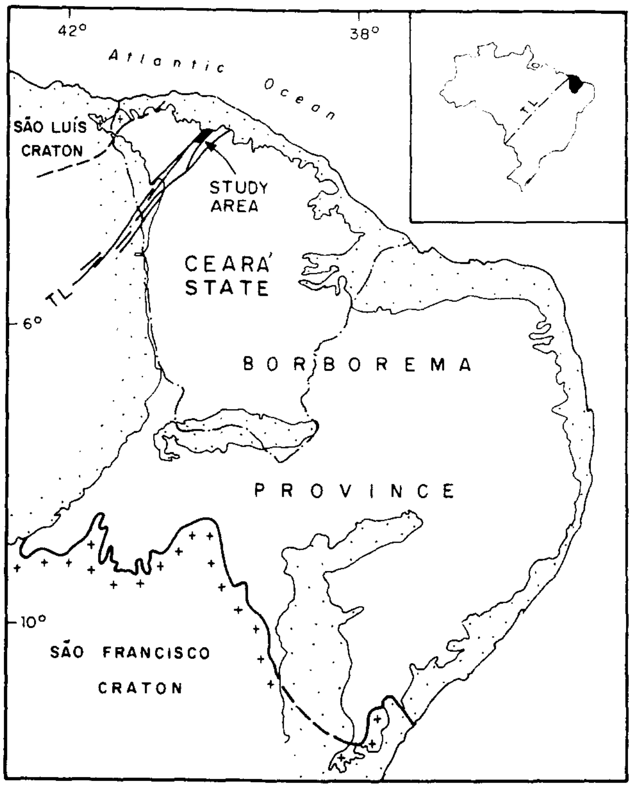

Fig. 1. Location of the study area (small rhomb shape) in northwestern Ceará, within the Borborema Province. Inset map shows location of Ceará State in NE Brazil. Stipple represents the Phanerozoic cover. TL is the Transbrazilian Lineament.

The timing of the deformation is locally constrained as post-Devonian only, but deformed mid-Cretaceous sediments situated in the southwestern portion of the Parnaíba Basin (Fig. 2) are considered to represent post-Cretaceous reactivation of the Transbrasilian Lineament by Northfleet & Neves (1966). Zalán *et al.* (1985) documented a marked wrenching stage, that occurred from late Albian to middle Cenomanian time, during the evolution of the equatorial Atlantic Ocean, in the offshore Ceará Basin (Piauí sub-basin). P. V. Zalán (oral communication 1992) points out that this event also affected the adjacent Acaraú sub-basin (Ceará Basin), and caused transpressional reactivation of the Transbrasilian Lineament. Unpublished (seismic and paleontological) data support a model of reactivation for the portion of the lineament where it is called the Transversal Lineament (Zalán *et al.* 1985). This is represented by deformed sediments from middle–late Aptian to early Cenomanian time, which are unconformably overlain by late Cenomanian to Tertiary flat-lying sediments. According to these data, an early or mid-Cenomanian (mid-Cretaceous) age for the reactivation of the Transbrasilian Lineament is suggested.

GEOLOGIC SETTING

In northwestern Ceará State (NE Brazil), the Borborema Province (Almeida *et al.* 1977) consists of several fault-bounded units (Fig. 2), which are polydeformed,

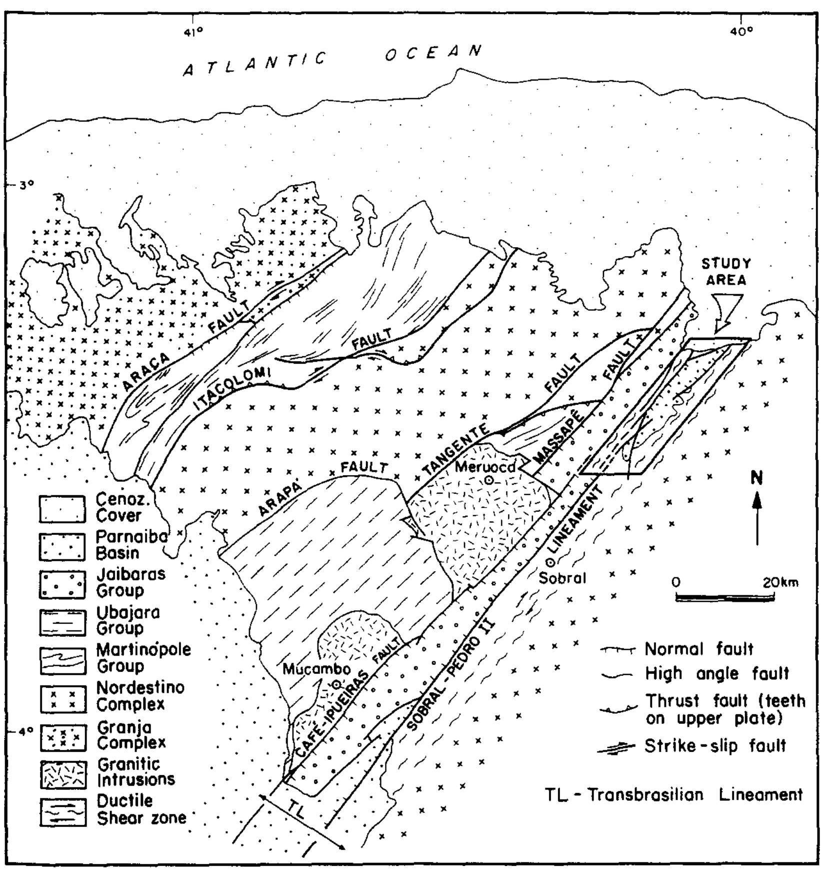

Fig. 2. Geological and structural map of NW Ceará (modified after Costa *et al.* 1979). TL is the Transbrazilian Lineament. The study area (rhomb contour) lies along the Transbrazilian Lineament (Sobral–Pedro II Lineament) northeast from Sobral.

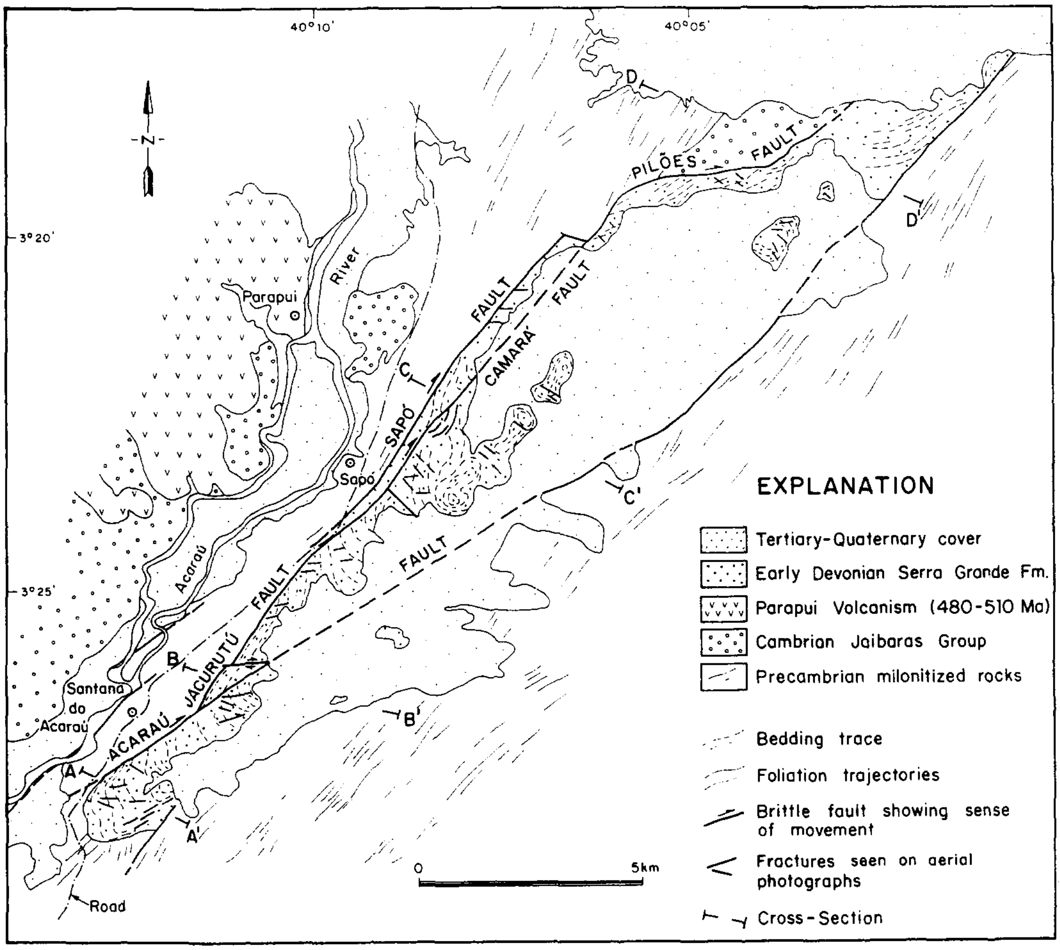

Fig. 3. Geological map of the study area. Note that the trend of the major brittle faults is near to parallel with the ductile mylonitic foliation. Cross-sections are shown in Fig. 5.

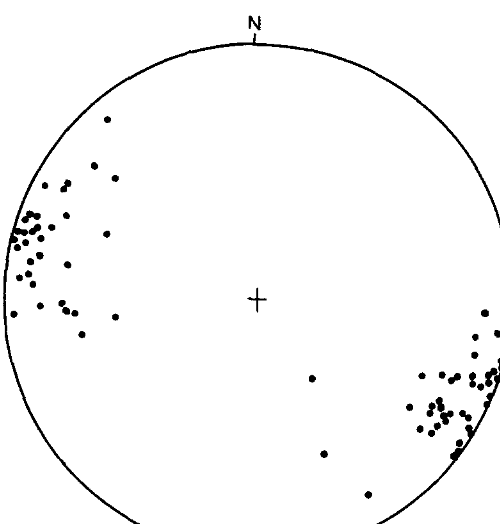

Fig. 4. Equal-area plot of mylonitic foliation poles (*S–C* surfaces) showing NNE to NE strike and steep dip.

and juxtaposed along NE–SW-trending normal, strike-slip and reverse faults, forming a series of horsts and grabens. To the north, the Precambrian is covered by unconsolidated Cenozoic sediments. To the south it disappears underneath the Paleozoic and Mesozoic Series of the Parnaíba Basin. Two major units, the Granja and Nordestino Complexes (Nascimento *et al.* 1981) (Fig. 2), form the structurally higher terranes. The Precambrian exposed in the high terranes is composed mainly of a gneiss–migmatite complex with intercalated quartzites. Those rocks are probably Archean in age (Novais *et al.* 1979), and suffered isotopic re-homogeneization during the Transamazonic deformation cycle (*ca* 2000 Ma; Nascimento *et al.* 1981), and partially during the Brazilian deformation cycle (*ca* 650 Ma; Nascimento *et al.* 1981). Costa *et al.* (1979) identified a granulite facies metamorphism for the Granja Complex, and found almandine–amphibolite facies assemblages for the Nordestino Complex (Fig. 2).

Structurally beneath the higher terranes, are the Martinópole, the Ubajara and Jaibaras Groups (Nascimento *et al.* 1981) (Fig. 2). The first one is composed of phyllites, schists, quartzites and metabasites, and was affected by at least two ductile deformation events. During the younger event, the rocks were metamorphosed to greenschist facies, during the Brazilian Cycle (Costa *et al.* 1979) at 630 Ma, as dated by a Rb–Sr whole-rock method (Nascimento *et al.* 1981).

Unconformably overlying the Martinópole Group, the Ubajara Group represents a complete continental margin tecto-sedimentologic cycle (Brito Neves 1983), which is suggested by clastic and platform-carbonate sedimentation. The rocks of that group were deformed

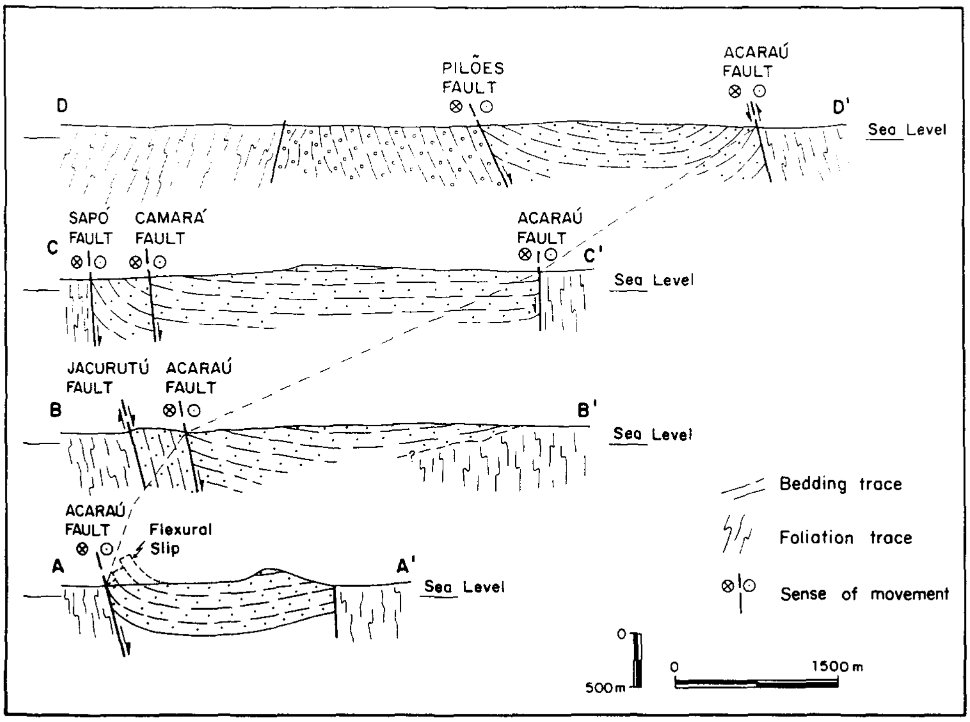

Fig. 5. Cross-sections of the study area. See Fig. 3 for location and key to stratigraphic units. The thin Tertiary–Quaternary cover is not shown. Note that the Acaraú Fault cuts across the whole area, and has dextral normal-slip sense southward (cross-section A–A′) and dextral reverse-slip sense northward (cross-section D–D′), indicating its regional rotational character.

during the emplacement of the Meruoca and Mucambo stock granites (Fig. 2), the latter dated at 580 ± 30 Ma (Novais *et al.* 1979). The Jaibaras Group (Fig. 2) unconformably overlies the previous units in the area. It occupies a series of grabens and half-grabens, whose major normal faults are considered to be formed, partially, by reactivation of Precambrian weakness zones of the Sobral–Pedro II Lineament (Costa *et al.* 1973). The Jaibaras Basin represents an extensional event at the end of the Brazilian deformation cycle, and is represented by clastic sedimentation associated with fissural and extrusive vulcanism, the Parapuí Vulcanism (Brito Neves 1983). K–Ar whole-rock analyses of these volcanic rocks yield predominantly late Cambrian ages of 480–510 Ma (Brito Neves 1983).

STUDY AREA

About 100 km^2 of both deformed sandstone body and adjacent basement rocks have been mapped in detail by Destro (1987) in the region between the southern portion of the NE-trending Acaraú Fault and the northern Pilões Fault (Fig. 3). An essentially homogeneous sequence of very consolidated fluviatile sandstones, including a basal conglomerate, referred to here as the sandstone body, rests with marked angular unconformity on older deformed and indurated early Paleozoic flysch deposits of the Pacujá Formation (Jaibaras Group), and on the mylonites of the ductile shear zone of the Transbrazilian Lineament (Fig. 3). The sandstone body has a marked topographic expression compared with the adjacent basement rocks.

In the northern portion of the studied area (Fig. 3), the sediments of the Jaibaras Group are exposed, or disappear underneath the sandstone body. That fact indicates that the extensional event related to the formation of the Jaibaras Basin (Fig. 2) partially affected the basement on which the sandstone body rests. Thus, the major faults that cut the sandstone body may have been formed not only by the reactivation of the Precambrian ductile shear zone, but also by the reactivation of some normal faults originated during that extensional event. These normal faults are themselves considered to have been formed, partially, by the reactivation of the ductile shear zone (Costa *et al.* 1979).

The ductile shear zones

The lithologies constituting the ductile shear zones are mainly mylonitized gneisses and calc-silicate rocks, which are characterized by a nearly vertical mylonite foliation plane striking 010–050° (Fig. 4), and correspond to *S–C* surfaces of Berthé *et al.* (1979). Criteria for the deduction of the sense of shear described in Simpson & Schmid (1983), such as asymmetric augen (feldspars and mica) structures, asymmetric pressure shadows, and the sense of shear along shear bands are observed in granitic gneiss and calc-silicate rocks in the Precambrian shear zones of the studied area, and indicate an overall dextral sense of shear (Fig. 2).

STRUCTURES AND DEFORMATION OF THE SANDSTONE BODY

Large-scale faults

The sandstone body in the study area is offset by five km-scale subvertical faults (Acaraú, Jacurutú, Sapó, Camará and Pilões) (Figs. 3 and 5) which extend over 30 km and are spread 1–5 km apart, defining fault blocks elongated in the northeast direction. They strike between 020° and 045°, except the Pilões Fault that trends ENE. They are mostly located at the western margin of the sandstone body (Fig. 3), indicating a concentration of deformation across the area studied. They are observed steeply dipping in some outcrops (*ca* 70°) and show up very clearly on aerial photographs, with remarkably straight traces and pronounced topographic fault scarps, where the sandstone body is always several meters higher than the adjacent basement rocks.

Bedding

The pattern of deformation, probably a result of one single event, can be used to divide the area studied into four subareas, labeled A–D (Fig. 6), based on changes in the trends of the major faults and on associated changes in the attitude of the bedding planes. The boundaries between the subareas are also formed, in general, by major faults (Fig. 6).

Field observations of outcrops and observations of the 1:25,000 aerial photographs show that the bedding planes are deflected, generally with marked rotation, into the major subvertical fault planes (Figs. 5 and 6). The deflections are coherent with a dextral sense of movement along those faults, and as it will be seen later, the deformation occurred in a transpressional regime.

In the southern portion of the Acaraú Fault, the sandstone beds form a km-scale gently plunging drag-shaped fold structure which has an asymmetry consistent with horizontal dextral shear across subarea A (Fig. 6). Stereographic plots of bedding poles in subarea A lie along a small-circle near the center of the stereogram, indicating that the drag-shaped fold structure is a result of rotation about an inclined axis plunging nearly 018° towards 020°NE. This suggests that the movement along the Acaraú Fault is oblique with a strong vertical component, indicating that it is a rotational fault (Fig. 5). This is compatible with the pitch of about 65° observed in

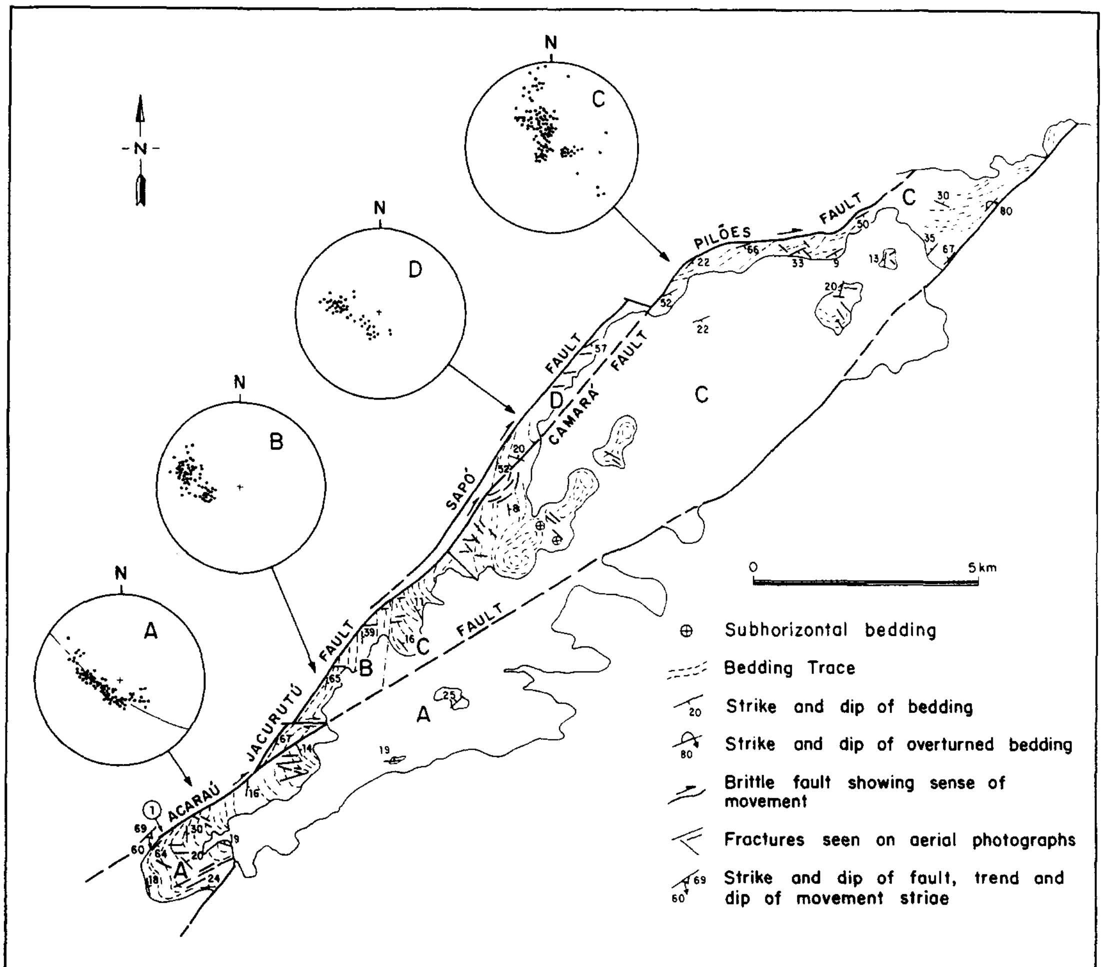

Fig. 6. Structural map of the study area, showing location of subareas and equal-area lower-hemisphere stereograms of bedding poles for each subarea. Stereogram A show best-fit great circle to poles to bedding, which give orientation of the major drag-shaped fold structure of subarea A. The scatter of points in stereogram C is due to the influence of several faults in the structuring of subarea C.

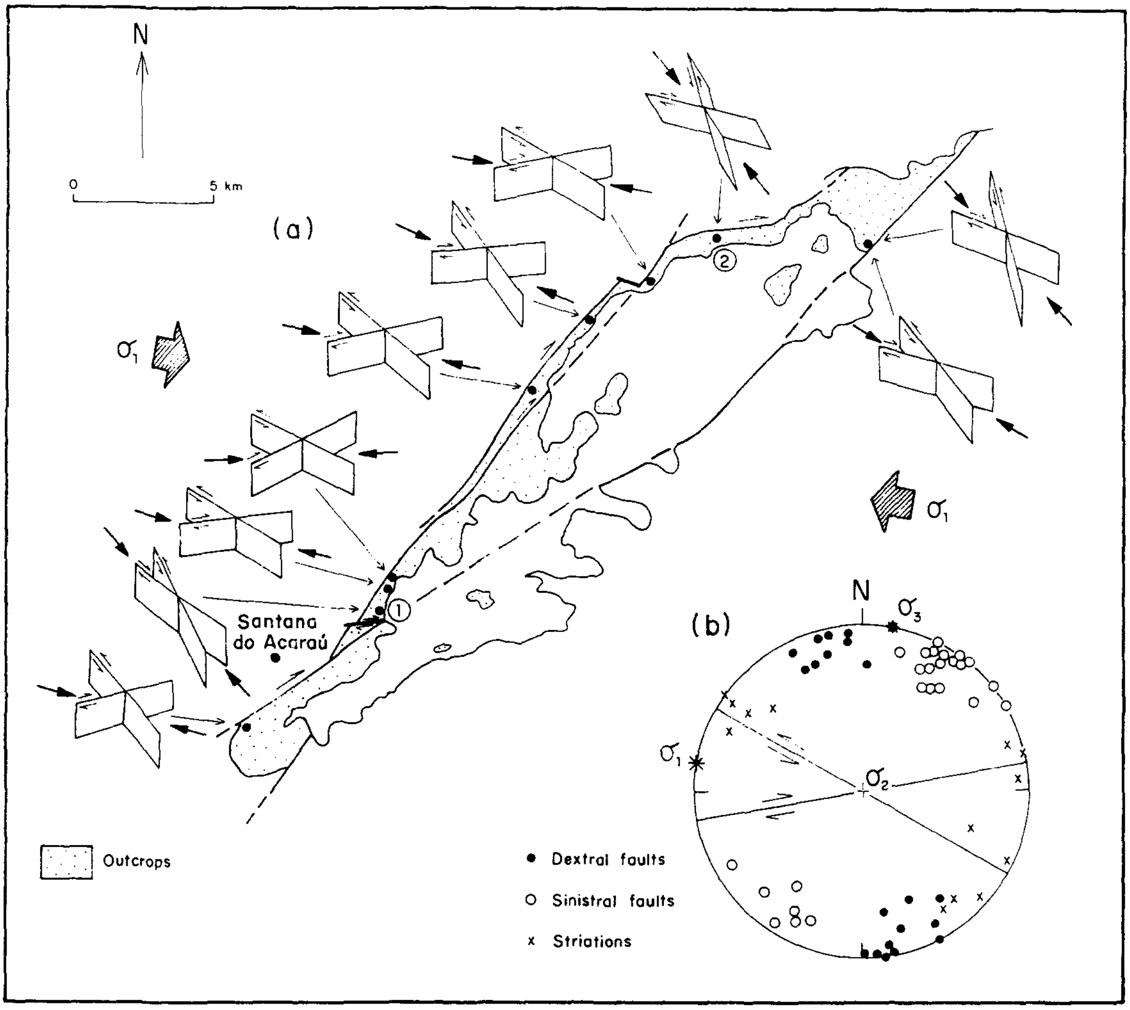

Fig. 8. (a) Structural map of the study area showing major fault trends, sites of measurements of conjugate Riedel shear fractures and localities (numbers in circles) mentioned in text. (b) Lower-hemisphere, equal-area stereographic projection for late faults in the studied area. Plots show poles to faults (dextral and sinistral) and striations.

the movement striae at the Acaraú Fault (locality 1 in Fig. 6). In this locality the Acaraú Fault strikes 040° and dips 70°SE, and present movement striae plunging 60°SSE.

Subareas B, C and D do not contain a fold structure comparable to the NE-plunging drag-fold in subarea A (Fig. 6). Subarea B was very strongly deformed, with the bedding planes near the Jacurutú Fault showing a marked rotation into subparallelism with the subvertical fault plane (cross-section B–B′ in Fig. 5, and Fig. 6). Stereographic plots of bedding poles from subarea B show greater concentration toward the perimeter of the stereogram. Beds are generally steeply dipping (*ca* 60°) southeast; further north, the dips change to the northeast and are less than 45°. Subarea C extends over the largest portion of the sandstone body. The strikes and dips of the beds change with distance from the faults that border them (Fig. 6), producing a scatter in the plot of bedding poles. The deflection of bedding traces near the Pilões Fault also indicates a dextral sense of shear. In subarea D the bedding planes are deflected into the Sapó Fault, similarly indicating a dextral sense of shear (Fig. 6). Near the fault, the beds dip more steeply.

Small-scale faults

Conjugate Riedel shear fractures commonly offset steep strata by up to several cm (Fig. 7c) and reproduce, on a different scale, the pattern of faults and fractures observed within the sandstone body on aerial photographs (Fig. 3). The faults are best observed in subarea B (Fig. 3), where there is one main dextral strike-slip fault with maximum displacement in the order of 100 m (locality 1 in Fig. 8a). In addition, consolidated sandstone pebbles in the basal conglomerate, within a few meters of the adjacent km-scale faults, are commonly fractured, locally with dextral (Fig. 7a) or sinistral (Fig. 7b) dislocation of the pebble fragments, which in Fig. 7(a) are incompletely separated. The Riedel shear fractures represent late-stage deformation when further folding and bedding rotation could not accommodate more shortening. These structures also indicate that the deformation occurred when the sandstone body was extremely consolidated, which was enhanced by silicification during the brittle faulting.

There is a well-defined spatial distribution of dextral and sinistral faults (Fig. 8a) which dip very steeply, and

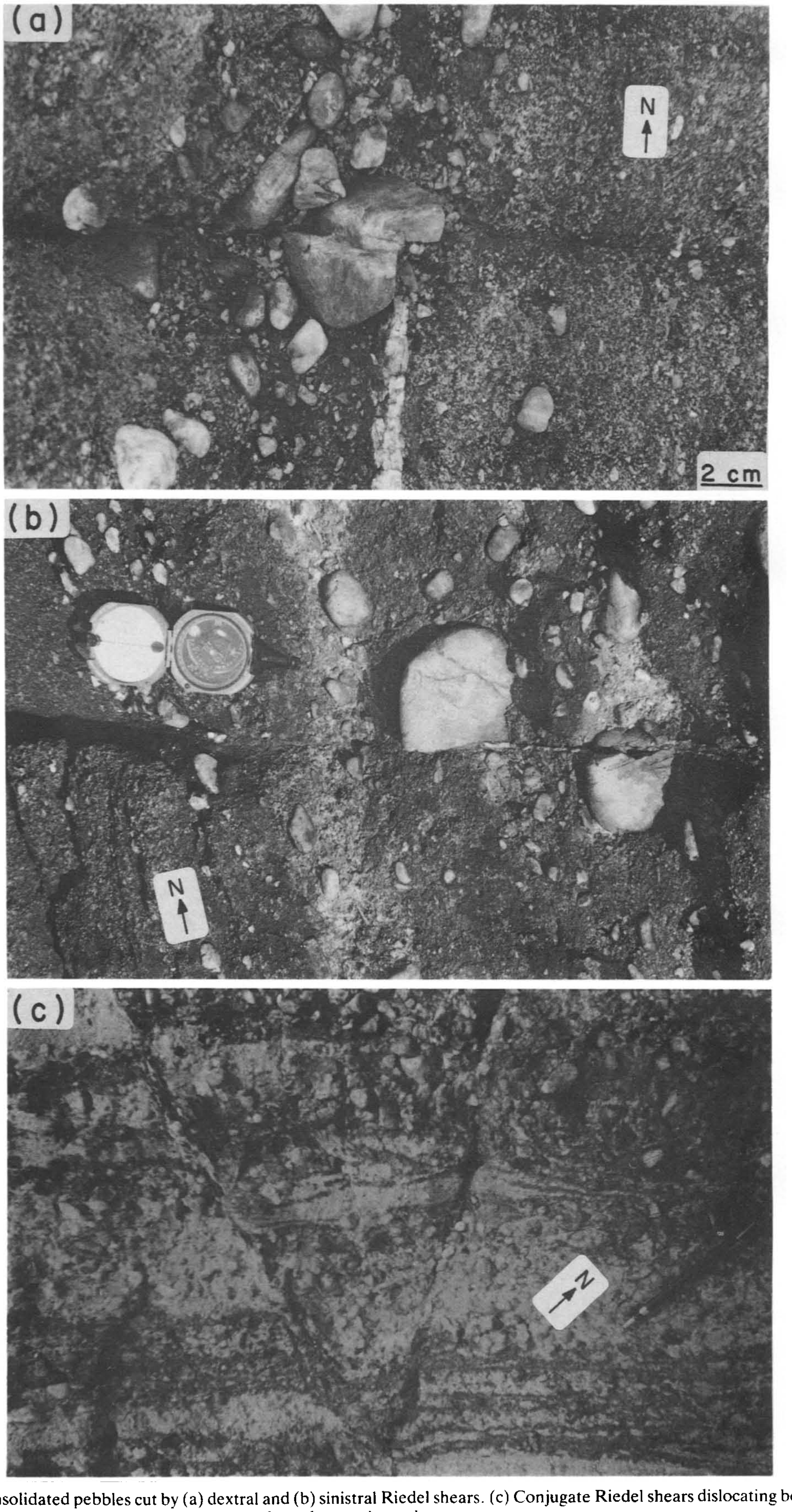

Fig. 7. Consolidated pebbles cut by (a) dextral and (b) sinistral Riedel shears. (c) Conjugate Riedel shears dislocating beds of conglomeratic sandstones.

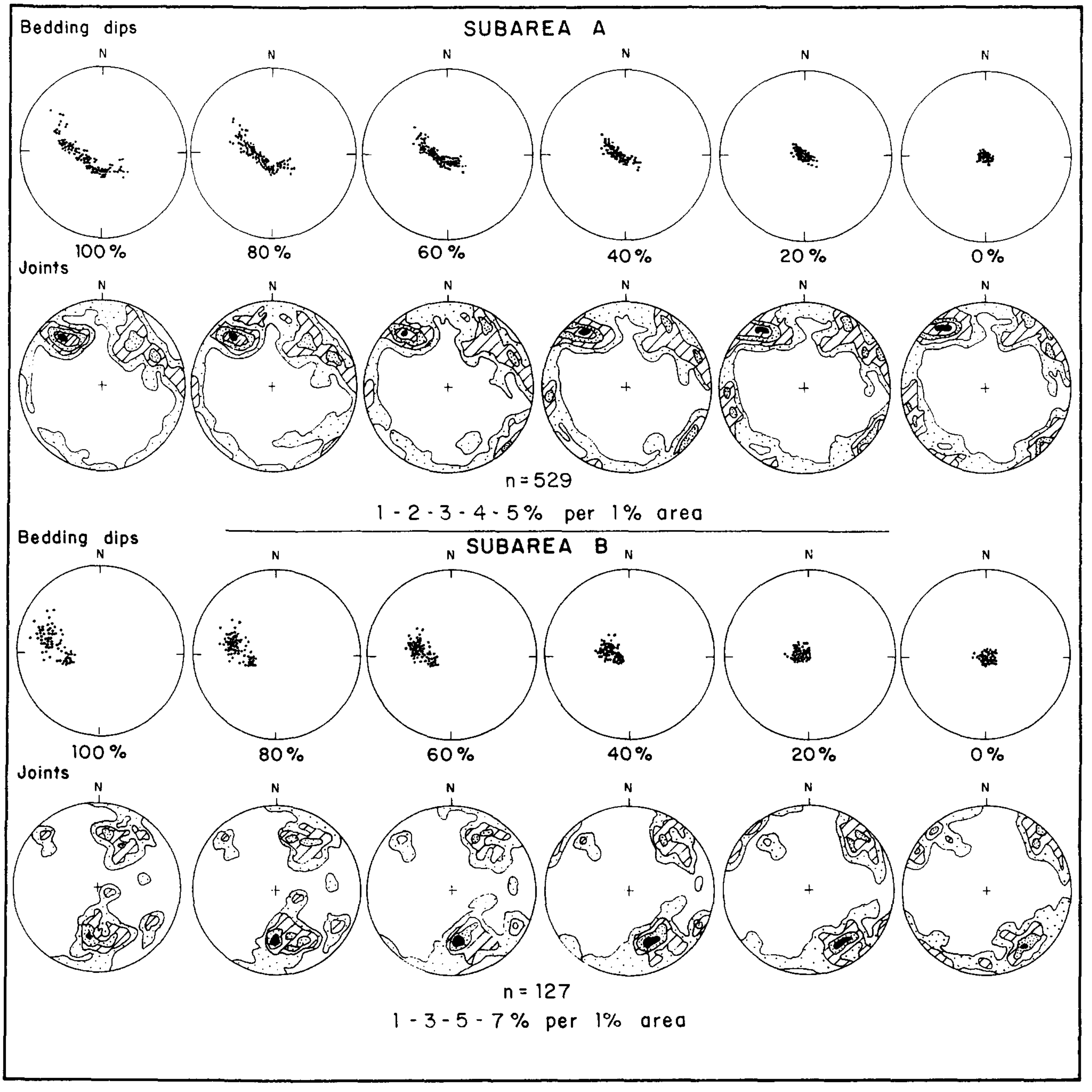

Fig. 9. Equal-area lower-hemisphere stereograms showing dependence of joint distribution (contoured stereograms) on removal of bedding dips in 20% increments, for subareas A, B, C and D. For all subareas the first stereograms (on the left) represent bedding and joints in the present-day deformed state. The subsequent stereograms show bedding and joint dip restorations for each 20% removal of bedding dips. (*Continued overleaf.*)

typically bearing subhorizontal striations, indicating strike-slip displacements (Figs. 8a & b). Sense of shear is indicated along these faults by offset along Riedel shears of both distinctive beds and sandstone pebbles (Figs. 7a–c). The bisectors of modal strike directions of faults (Fig. 8b) gives trends for σ_1 and σ_3 of 280° and 010°, respectively, with steeply plunging σ_2. As the overall orientation of the reactivated Precambrian shear zone is about 040° (Figs. 2 and 8), the angle between the orientation the maximum compressive stress (σ_1) and that deformed zone is *ca* 60°, which is consistent with a transpressional regime, as described in Sanderson & Marchini (1984).

Second-order conjugate Riedel shear fractures occurring near first-order dextral ones (locality 1 in Fig. 8a), and conjugate Riedel shear fractures occurring in the northern portion of the sandstone body along the Pilões Fault (locality 2 in Fig. 8a) show deviation from the overall orientation of these structures (Fig. 8a). It is not clear whether the Pilões Fault is a first-order, synthetic dextral Riedel shear fracture, or a reactivated weakness zone of the Precambrian basement. As these fractures may represent second-order Riedel shear fractures, they are not included in the stereographic projection for the deduction of the principal stresses (Fig. 8b).

Small-scale joints

The style of the joints observed in outcrops is somewhat more complex than the pattern of the small-scale

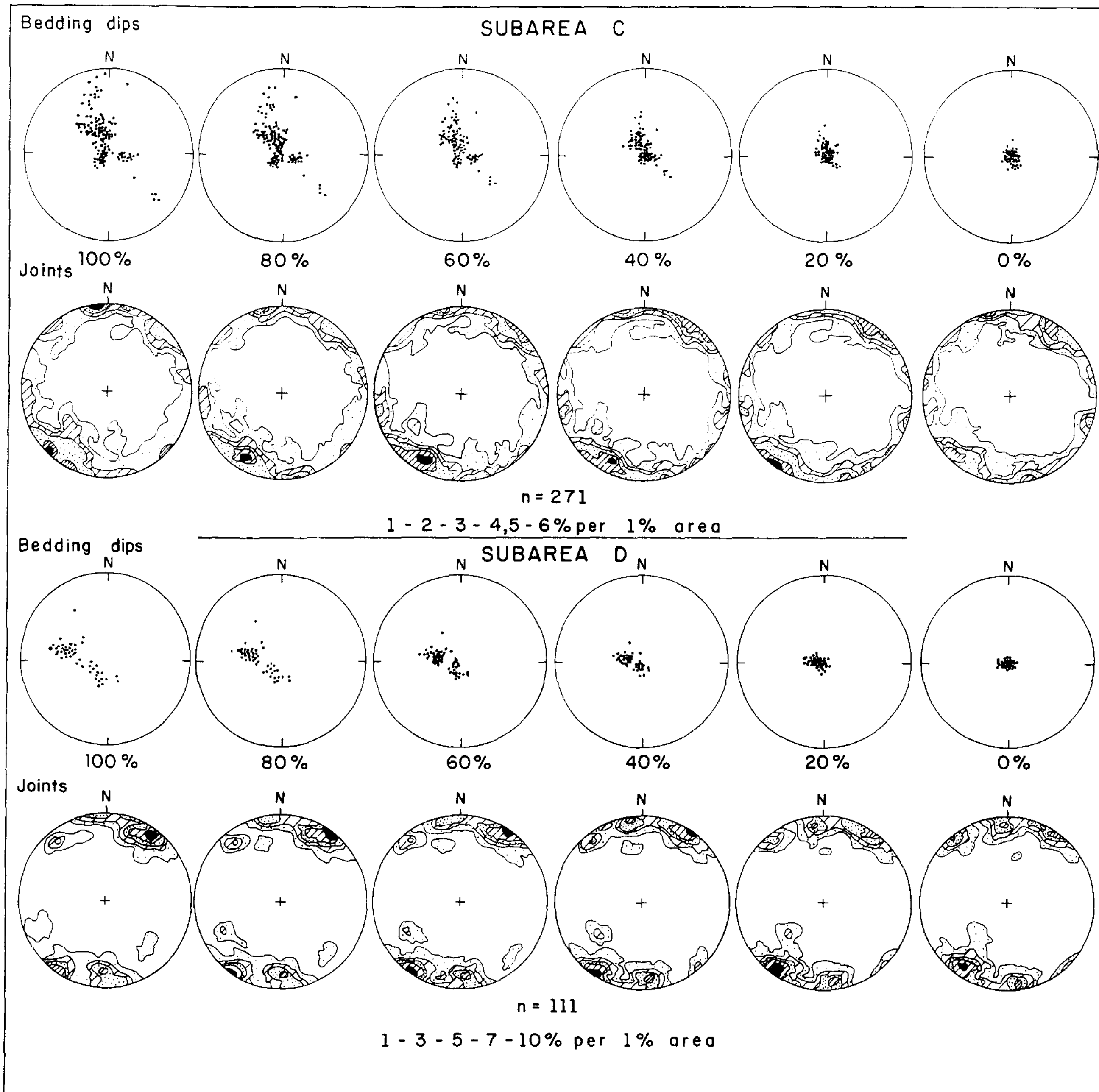

Fig. 9. *Continued.*

faults. Evidence for rotation of joints concomitant with bedding rotation suggests that joints had been forming since the very beginning of the deformation.

The contoured stereograms in Fig. 9 represent joints, and the stereoplots are the correspondent bedding poles for the subareas A, B, C and D. The first stereograms (from left in Fig. 9) show, for the four subareas, the distribution of joints and bedding as they are observed in the field, in the deformed state, i.e. at present-day bedding dips. In the following stereograms and stereoplots we examined the possibility that part of the joints had formed in earlier stages of deformation when the bedding was less steep and were subsequently rotated into their present position. Each reflects the state of joints and bedding after removing, step by step, the bedding dips in 20% increments from present-day (100%). The axes of rotation were defined by the mean value of the strike of bedding for each station. The undeformed state, where bedding is completely horizontal, is represented in Fig. 9 by the last stereograms in the right.

From the stereograms thus obtained, it is difficult to establish in what stage most of joints formed, but some interesting conclusions can be drawn from these procedures.

(a) In subarea A (Fig. 9) the concentration shown in the northwest quadrant of the stereogram of joints corresponds mostly to joints striking NE–SW, subparallel to the Acaraú Fault (Fig. 3). However, other important concentrations are also observed in the northeast quadrant of the stereogram, and represent joints striking NW–SE.

(b) The stereogram of joints in subarea B (Fig. 9) shows two major concentrations, probably representing a conjugate system. In that subarea, beds are steeply dipping, so that if most joints were formed in the first stages of deformation, it may be necessary to eliminate a large amount of bedding dips to restore the original position of such joints.

(c) Stereograms of joints for subareas C and D (Fig. 9) show predominance of steeply dipping joints. The distributions may be roughly compared with the pattern presented by the small-scale faults (Fig. 8b). Subarea C presents a more complex pattern of distribution than subarea D, but its stereoplot of bedding (first in the left in Fig. 9) is also more scattered.

(d) In all cases, the successive removal of the bedding dips did not result in significant dispersion of the contour lines in the stereograms of joints. This may reflect a relatively constant orientation of the principal stresses during the deformation. Furthermore, the contour lines tend to move toward the perimeter of the stereogram, suggesting that most joints formed in a vertical position, typically where the mean principal stress (σ_2) is vertical. This is in agreement with the orientation of the small-scale faults (Fig. 8).

CONCLUSIONS

(1) The analysis of brittle small-scale Riedel shears, allied to the deformation of a monotonous sequence of sandstones, provides evidence for the reactivation of pre-existing weakness zones within the ductile shear zone of the Transbrazilian Lineament.

(2) The orientation of conjugate small-scale Riedel shears indicates that the intermediate principal stress (σ_2) was subvertical, and the maximum and minimum principal stresses (σ_1) and (σ_3), respectively, were subhorizontal. The regional orientation of the maximum principal stress (σ_1) was WNW–ESE.

(3) Steeply dipping beds occur mainly near the major faults, specially where the direction of the faults make higher angles with the deduced direction of the maximum principal stress (σ_1).

(4) The dextral sense of movement deduced along the main faults, which lie along and are subparallel to the Transbrazilian Lineament, together with the pattern of conjugate Riedel shear fractures, indicate that the lineament was reactivated by dextral transpression, with a high angle between the orientation of the shear zone and the maximum principal compressive stress (σ_1). Shortening was accommodated by oblique movement of the major faults and by along-strike rotation of blocks, with very steep bedding dips near the faults.

(5) The timing of reactivation is difficult to constrain, because of the absence of synchronous sedimentation and magmatism in the studied area. However, it may be contemporaneous with: (i) the reactivation of the Transbrazilian Lineament, observed by Northfleet & Neves (1966), in deformed mid-Cretaceous sediments in the southwestern portion of the Parnaiba Basin: and (ii) a marked early or mid-Cenomanian (mid-Cretaceous) wrenching stage, that affected the Transbrasilian Lineament in the offshore Ceará Basin (Acaraú sub-basin) (P. V. Zalán oral communication 1992).

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