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Structural evolution of Au, Ag and Pb lode occurrences of Serrita and Parnamirim, Pernambuco, Brazil

Evolução estrutural de ocorrências de lodo Au, Ag e Pb em Serrida e Parnamirim, Pernambuco, Brasil

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ABSTRACT: Structural and microstructural studies have been carried out to assess the structural evolution of Au, Ag and Pb lode occurrences that spread among Serrita and Parnamirim municipalities, Pernambuco, Brazil. These occurrences are hosted in metassediments, correlated to the Salgueiro Group, and granodiorites from Serrita Suite, in the Piancó-Alto Brígida Domain, southwestern Zona Transversal, Borborema Province. The metassediments underwent four deformation phases that switched from compressional to strike-slip tectonics. The first two phases developed a low-angle fabric and the third and fourth ones produced folds with NE-SW/ENE-WSW plane-axial crenulation cleavages and regional shear zones, respectively. In the metassediments, the veins grew by E-W and N-S/NNW-SSE branched fractures, associated with rapid propagation and dilatation. These veins underwent new mineral crystallization phases concomitant with deformation and mineralization, which mark the transition from the ruptile-ductile to the ruptile regime. The granodiorite hosted-veins show incipient deformation, as do theirs hosts. We conclude that the veins, in both host-rocks, formed by the same stress field attributed to the end of fourth phase, under a NW-SE maximum compressive tensor. The differences between the veins resulted from a fracture refraction in function of rheological contrasts in the host-rocks. This refraction induced the development of E-W/ESE-WNW and N-S/NNW-SSE shear fractures in the less competent lithology, the metassediments, and NW-SE tensile fractures in the more competent one, the granodiorite.

KEYWORDS: quartz veins; structural geology; Zona Transversal.

RESUMO: *Um levantamento estrutural e microestrutural foi realizado para analisar a evolução das ocorrências filoneanas de Au, Ag e Pb, localizadas entre as cidades de Serrita e Parnamirim, PE. Essas ocorrências ocorrem encaixadas em metassedimentos, correlacionados ao Grupo Salgueiro, e em granodioritos associados à Suíte Serrita, no Domínio Piancó-Alto Brígida, sudoeste da Zona Transversal, Província Borborema. Foram identificadas quatro fases de deformação nos metassedimentos, que registram a mudança de uma tectônica compressiva para direcional. As duas primeiras geraram uma trama de baixo ângulo, enquanto a terceira e a quarta fases formaram dobras, com clivagem de crenulação NE-SW/ESE-WSW, e zonas de cisalhamento regionais, respectivamente. Nos metassedimentos, os veios formaram-se a partir de fraturas anastomosadas de direção E-W e N-S/NNW-SSE, cuja propagação e dilatação ocorreram em curtos intervalos de tempo. Após sua cristalização, os veios foram submetidos a novas etapas de cristalização mineral concomitante a processos de deformação e mineralização, os quais marcam a transição do regime rúptil-dúctil para o rúptil. Os veios nos granitoides exibem deformação incipiente e similar à rocha encaixante. Concluiu-se que, nas duas encaixantes, os veios se formaram sob o mesmo campo de tensão, durante o final da quarta fase, sob um tensor de compressão máxima de direção NW-SE. As diferenças resultariam de um processo de refração de fraturas em função do contraste reológico das encaixantes. Essa refração induziu a formação de fraturas de cisalhamento direcionais com direções E-W/ESE-WNW e N-S/NNW-SSE na litologia menos competente, o metassedimento, e fraturas de tração de direção NW-SE na litologia mais competente, o granodiorito.*

PALAVRAS-CHAVE: *veios de quartzo; geologia estrutural; Zona Transversal.*

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INTRODUCTION

A series of lode occurrences have been described in the Serrita and Parnamirim municipalities, Pernambuco State, northeastern Brazil. The first records were reported by the Brazilian Geological Survey (CPRM) on Serrita region in the early 80's (Torres & Santos 1983, Torres *et al.* 1986). The authors identified schist-hosted veins with variable Au, Ag and Pb contents. Other studies also described granitic-hosted mineralized veins near Serrita (Mont'Alverne *et al.* 1995, Beurlen *et al.* 1997) and schist related occurrences on the north of Parnamirim.

A majority of the studies on the area are products of mineral research or digging registration (Torres & Santos 1983, Torres *et al.* 1986, Dantas & Viera Filho 1990, Mont'Alverne *et al.* 1995), and only one addresses the ore genesis (Beurlen *et al.* 1997).

These studies emphasize the textural and petrological features of the veins and though they present detailed morphological and orientation data, the structural evolution of the veins and theirs hosts are not well understood. The Parnamirim occurrences remain not studied until now.

The objective of this study was to provide a structural model depicting the evolution of the ore-veins, based on detailed macro- and microstructural data collected in diggings and adjacent areas, as well as integrating trench data presented by the Serrita Project (Torres & Santos 1983, Torres *et al.* 1986).

REGIONAL GEOLOGICAL SETTING

The Borborema Province is a geotectonic unit, consolidated during the Brasiliano/Pan-African Cycle (0,6 – 0,5 Ga). This unit is a compound of Paleoproterozoic basement inliers, including minor Arquean rocks, separated by Meso- and Neoproterozoic supracrustal belts. The entire province underwent intense magmatism during its evolution (Brito Neves 1975, Almeida *et al.* 1977, Santos & Medeiros 1999).

The studied area is located in the southwestern Zona Transversal Domain, central part of the Borborema Province (Fig. 1). This domain is made up of NE-SW-striking crustal segments that show distinct petrotectonic associations, metamorphism, plutonism and geochronological signatures (Brito Neves 1975, Brito Neves *et al.* 1995, Santos & Medeiros 1999, Neves 2003).

The Zona Transversal Domain is characterized by the development of flat-lying foliation, which is penetrative in basement and supracrustal units. According Neves *et al.* (2006), this structure formed contemporaneously with the metamorphic peak of Zona Transversal, during Early Ediacaran (630 – 610 Ma). This metamorphic fabric was partially overprinted by a network of E-W/ESE-WNW-striking dextral and NE-SW/NNE-SSW-striking sinistral transcurrent shear zones (Vauchez *et al.* 1995, Medeiros 2004, Archanjo *et al.*, 2008). These shear zones were activated during the Ediacaran (590 – 580 Ma), constrained by U/Pb and Pb-Pb ages of shear zones-related plutons

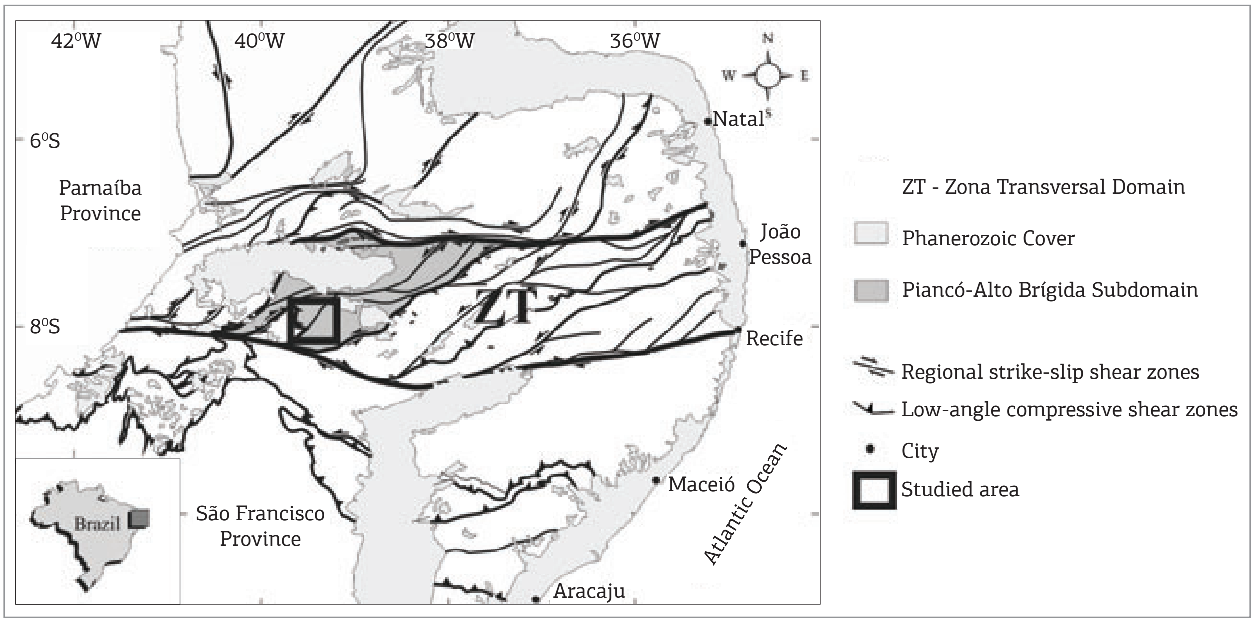

Figure 1. Geotectonic sketch of Borborema Province and Zona Transversal Subdomain highlighting the localization of the studied area. Modified from Medeiros (2004).

(Guimarães & Silva Filho 1998, Neves 2003), and recorded activity until 512 Ma, according to ($^{40}Ar/^{39}Ar$) plateau-ages of muscovite from the Coxixola shear zone (Hollanda *et al.* 2010).

The Salgueiro-Cachoeirinha belt, also called Piancó-Alto Brígida Subdomain, is comprised of Paleoproterozoic mygmatitic-gneiss basement rocks, Meso- and Neoproterozoic low- to medium-grade metamorphic supracrustal rocks, and plutonic bodies with Brasiliano ages (Silva Filho 1984, Brito Neves *et al.* 1995, Caby *et al.* 2009) (Figs. 1 and 2).

The supracrustal rocks were originally split into the Salgueiro and Cachoeirinha groups (Barbosa 1970; Silva Filho 1984). Silva Filho (1984), based on Rb/Sr and K/Ar data, has ascribed them respectively meso- and neoproterozoic ages and differentiated from the metamorphic, deformational and metalogenetic points of view. The first unit is composed of mica-schist with subordinate quartzite and metavulcanic intercalations. A metarhyodacitic sheet interlayered in biotite schist near Salgueiro City, Pernambuco, has provided a Tonian age (962 Ma) to the group (Brito & Cruz 2011). The Cachoeirinha Group has similar lithological content but shows a lower metamorphic grade than the Salgueiro Group. U/Pb ages in Cachoeirinha rhyolites have furnished Criogenian to Ediacarian (650 – 625 Ma) depositional ages to the unit. Many alternative stratigraphic models have been proposed for this domain, as exemplified by Campos Neto (1994), Brito Neves *et al.* (1995) and Bittar (1998).

The Neoproterozoic plutonism is one of the most important features in the Salgueiro-Cachoeirinha belt. It shows great diversity and was classified as calc-alkaline (Conceição type), high-K calc-alkaline (Itaporanga type), trondhjemitic (Serrita type), peralkaline (Catingueira type) and shoshonitic (Serra dos Cavalos type) suites (Ferreira *et al.* 2004, Medeiros 2004). In the studied area, plutonic stocks correlated to Serrita Trondhjemitic Suite are intrusive in schists and phyllites correlated to the Salgueiro Group (Sial *et al.* 1981, Neves 1986) (Fig. 2). These bodies exhibit rounded to NE-axis-ellipsoid shapes and were affected by discrete ruptile-ductile strike-slip shear zones suggesting a pre- to sin-kinematic emplacement. They comprise meta- to peraluminous biotite leucogranodiorites with trondhjemitic affinity (Neves 1986).

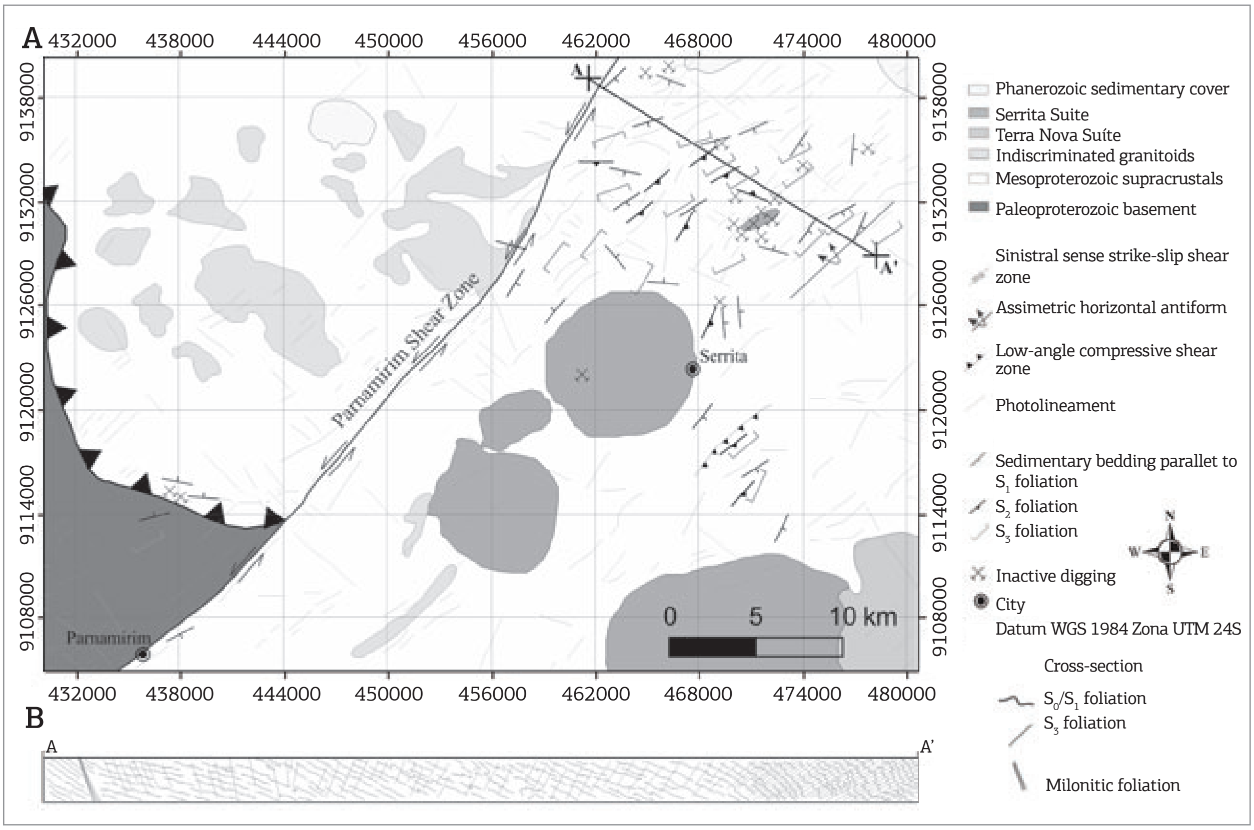

Figure 2. (A) Geological map of the studied area. Modified from Brazilian Geological Map (1:1.000.000), charts: Jaguaribe (SB-24) (Angelim *et al.* 2004) and Aracaju (SC-24) (Kosin *et al.* 2004); (B) Interpretative geological cross-section (out of scale) of the A-A' segment highlighted in figure (A).

THE SERRITA LODE OCCURRENCES

According to Torres *et al.* (1986), Mont'Alverne *et al.* (1995) and Beurlen *et al.* (1997), the Serrita lode veins are hosted by Salgueiro supracrustal rocks and leucogranodiorites of the Serrita pluton and Barra Verde stock, both correlated to the Serrita Suite. Locally, the supracrustal rocks are comprised of phyllites and micaschists, which show a well-defined compositional banding composed of millimetric to centimetric micaceous and quartz-feldspatic layering. This rhythmic feature has been interpreted as a sedimentary bedding (Fig. 3A).

Previous works (Torres & Santos 1983; Torres *et al.* 1986; Dantas & Vieira Filho 1990) pointed out that the ore in supracrustal rocks is associated with three arrays of subvertical veins. The first one consists of highly fractured ENE-ESE-striking veins, hosting the highest Au, Ag and Pb contents. The second and third arrays are later and comprise ENE-striking and N-S/NNW-SSE-striking veins, which are less fractured and present lower metal contents. The granodiorite hosted-veins have a NW-SE strike unimodal direction, are less deformed, and generally show minor thickness and lengths (Beurlen *et al.* 1997).

Fluid inclusion studies have shown that the mineralization on supracrustal-hosted veins was closely related to vein deformation while, in granodiorites, it was associated with vein crystallization (Beurlen *et al.* 1997). Despite this difference, Beurlen *et al.* have defined the presence of aqueous-carbonic fluids trapped under immiscibility conditions during the ore genesis in both host-rocks. These fluids have a mean salinity of 6.9% $NaCl_{eq}$ and entrapment conditions varying between 290° and 310°C and 1.3 to 1.8 kbar. Such features are similar to mesothermal orogenic gold deposits (Groves *et al.* 1998).

METHODOLOGY

In this study, we collected structural (ductile and ruptile) data at 91 stations, in which 18 comprise inactive diggings hosted in supracrustals rocks and granodiorites at northeastern Serrita and northern Parnamirim – both located in Pernambuco State. Sixteen stations (6 diggings) were selected and a systematic fracture (vein, fault and joint) measurement was carried out by inventory method. The statistic data treatment was performed using StereoNet 3.06 and Georient 9.4.4 softwares.

A detailed macroscopic description of all observed veins was accomplished for supracrustal rocks and granodiorites. This structural data set was supplemented with morphological, chemical and orientation data obtained from prospecting trenches and presented in Torres *et al.* (1986).

Thin sections were made from 22 ore-vein samples (13 oriented). These samples were used to describe the veins microstructures and determine possible crystallization and deformation mechanisms.

The ore-veins lack macroscopic and microscopic kinematic indicators, such as displaced layers, fibrous or elongated crystals etc. This fact ruled out a classical kinematic analysis. Hancock (1995) described a similar situation on joint studies and suggested the use of many criteria, which taken in together could help to trace the genetic nature of these structures. In this context, structural and mineralogical features were used for better understanding of the Au-vein development.

The ductile deformation

Four ductile deformation phases have been identified in the supracrustal rocks (D1 to D4). The first phase (D1) is characterized by the development of S1 foliation and V1 quartz veins, both parallelized to sedimentary bedding (S0) (Figs. 3A and B). The S1 foliation is the most prominent structure in the supracrustal rocks and presents NE-SW directions with gentle dips to the SE and NW (Fig. 4A). It corresponds to a continuous cleavage or schistosity defined by lepidoblastic micas, chlorite and hematite, stretched quartz and elongated plagioclase.

The second phase has been identified based on centimetric- to decametric-mesoscopic folds (D2). These folds are tight to isoclinal, show reclined to plunging inclined geometries and present an axial foliation (S2) (Fig. 3B). This foliation shows almost the same attitude as S1 (Fig. 4B) and occasionally exhibits *lit-par-lit* emplaced quartz veins (V2).

The third phase (D3) is marked by a penetrative crenulation cleavage (S3) that represents the axial surface of upright- to horizontal inclined folds (d3). These folds exhibit NE-SW/ESE-WNW fold-hinges and show distinct structural style at the NW and SE portion of the studied area (Fig. 2B). The northwestern part is comprised of gentle to open folds with steep axial surfaces (Fig. 3C), while at southeastern end, they correspond to tight- to isoclinal-folds presenting gentle axial-surfaces dips and vergence to SE (Fig. 3D). These fold geometries suggest a NW-SE shortening and a southeastward increase on the deformation gradient.

The last phase (D4) corresponds to development of a regional strike-slip shear zones. In the studied area, the Parnamirim strike-slip shear zone is the main representative structure of this phase (Fig. 2). It consists of a NE-SW-striking structure showing steep milonitic foliation and sinistral-sense kinematic indicators.

The deformation phases record the transition from a low-angle compressive ductile (D1 – D2) to a strike-slip tectonic (D4). According to literature, the low-angle fabric at the Zona Transversal domain formed at 640 – 610 Ma (Medeiros 2004, Neves 2003, Neves *et al.* 2006). The regional strike-slip shear zones of D4 phase are interpreted as the result of a NW-SE/NNW-SSE compressive event that took place at 590 – 570 Ma (Guimarães & Silva Filho 1998, Archanjo *et al.* 2008). As noted by Vauchez *et al.* (1995) and Neves and Mariano (1999), the regional strike-slip shear zones commonly mark the transition between high-temperature ductile and low-temperature ruptile-ductile deformation.

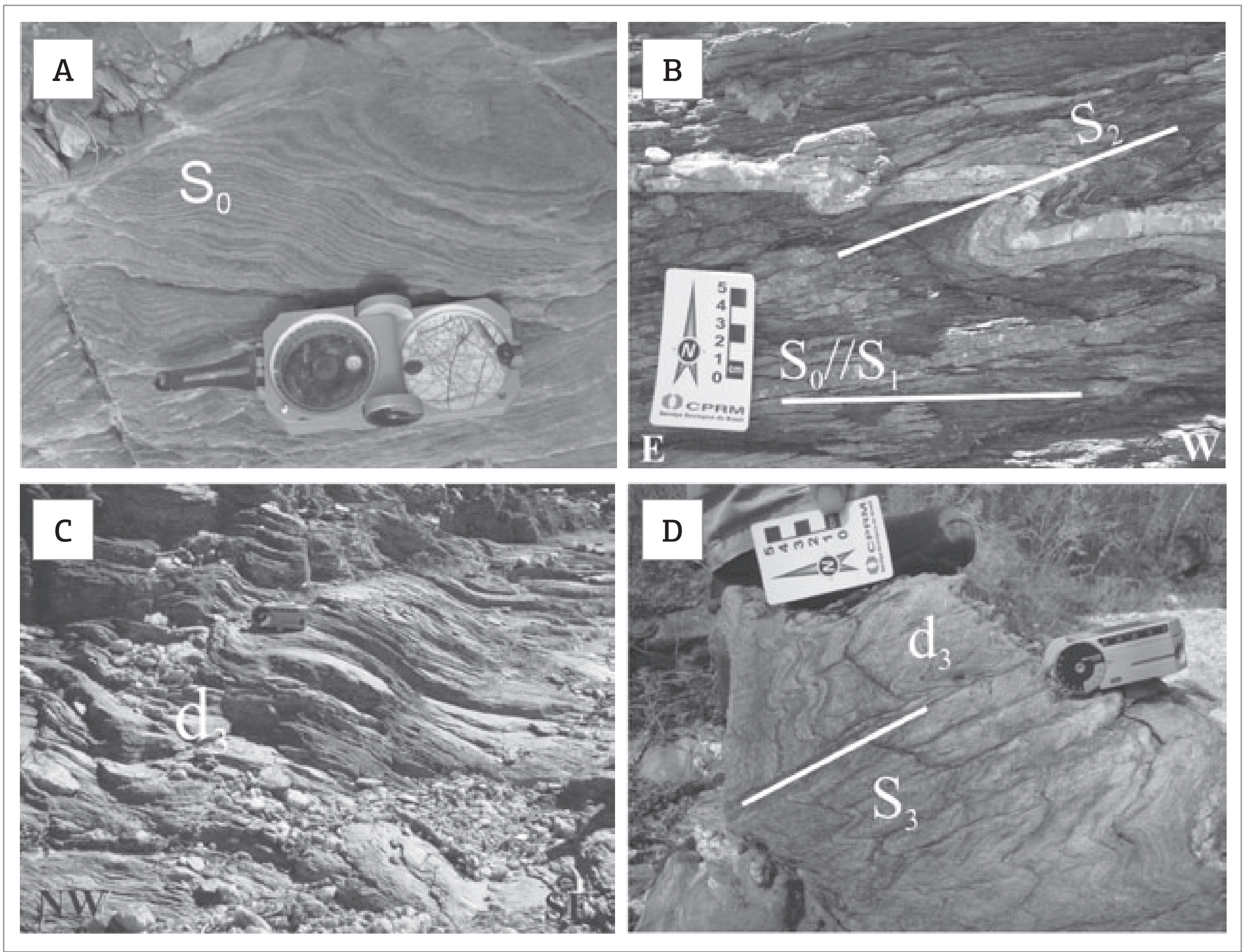

Figure 3. (A) Sedimentary bedding defined by milimetric to centimetric interlayered metapelitc and metapsamitic levels; (B) Relationship between d_2-fold and S_1 and S_2 foliations; (C) A d3-fold exhibits open geometry and NW-steeply dipping axial surface (S_3); (D) Tight-assymetric d_3-folds showing low angle axial surface (S_3) with southeastward vergence.

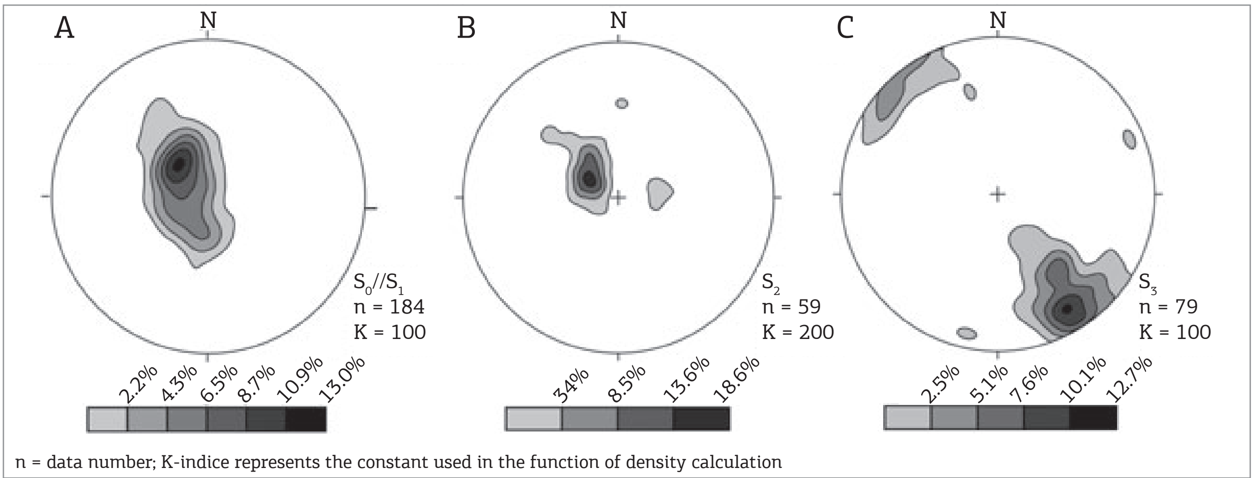

Figure 4. Pole contour diagrams for S_1 (A), S_2 (B) and S_3 (C) foliations.

The Serrita pluton and Barra Verde stock present an isotropic fabric. Microscopically, these rocks record an incipient deformation represented by quartz undulose extinction and subgrains and plagioclase deformation twins. These bodies developed a shear boundary foliation near the contacts. The presence of ruptile-ductile shear zones at Serrita pluton suggests an emplacement pre- to sin-D4.

The ruptile and ruptile-ductile deformation

The subvertical veins which are discordant of low-angle fabric and locally S3-concordant were called V3 veins. This section presents the main features of this group as it covers the ore-related veins.

METASSEDIMENT-HOSTED VEINS

The metassediment-hosted-V3 veins comprise white-milk quartz veins, which may also show sulfides, carbonates, iron oxides, limonite, clay minerals and box-works in ore-related bodies. Veins are generally steeply dipping, showing more than 80% of the veins with dips higher than 70°.

The V3-veins' azimuths are represented in rose diagrams at Fig. 5. The barren veins are characterized by two main azimuth distributions, a NE-SW major trend and a secondary NNE-SSW trend (Fig. 5A). These veins exhibit milimetric to centimetric widths and are commonly axial to d3 open folds.

Figs. 5B to D illustrate the ore-vein azimuth distribution. Figs. 5B (extracted from Torres *et al.* 1986) and C strike represent the lode occurrences northeast of Serrita, Pernambuco. The data indicate the presence of two main arrays defined by E-W/ESE-WNW and N-S/NNW-SSE trends. Figure 5D shows the northern Parnamirim's occurrences, which define a main ENE-WSW-strike array. In both cases, the ore-veins keep their dips despite the ductile fabric attitude.

The ore-veins form tabular bodies and commonly exhibit branches and host-rock xenoliths, which give them an arborescent pattern in cross-sections. The E-W array presents widths ranging from 0.1 up to 1.4 m at NE-Serrita

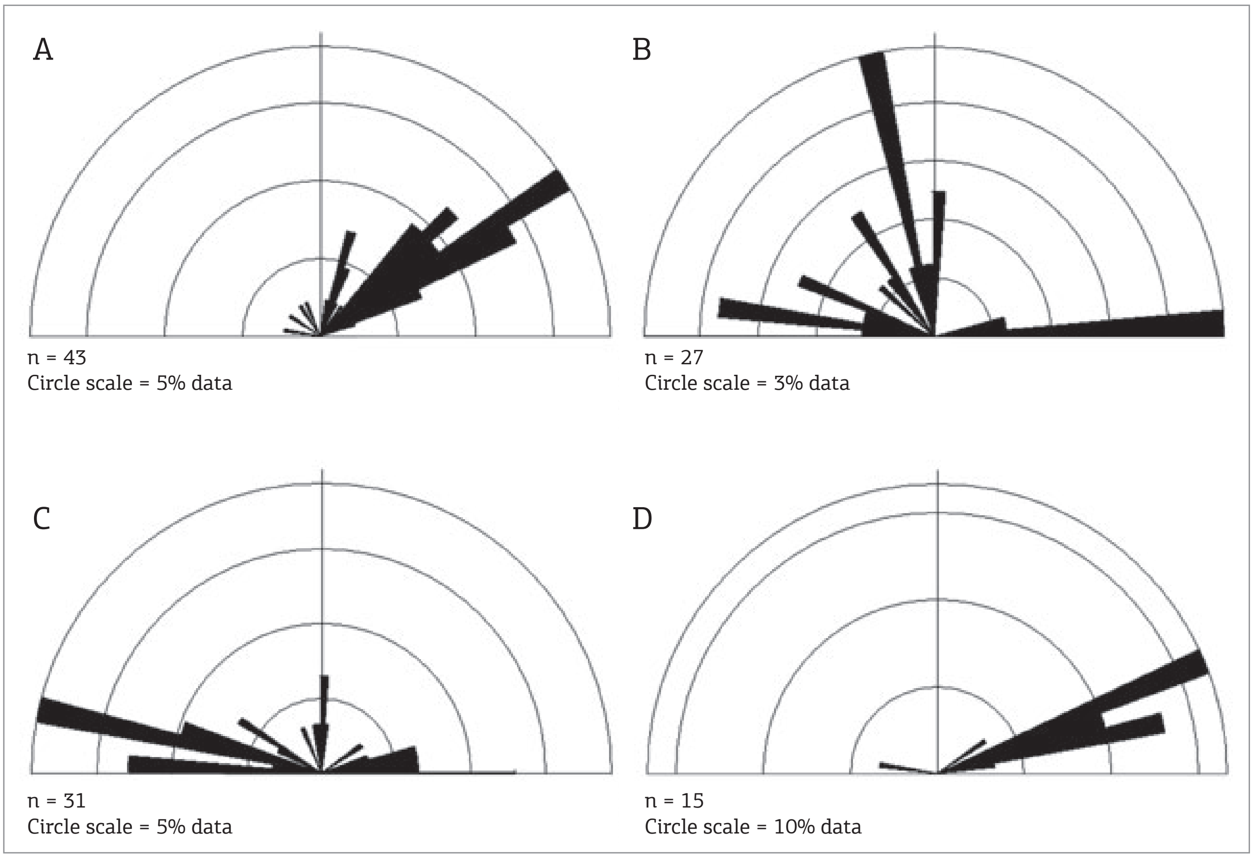

Figure 5. Rose diagrams of V_3-veins. All diagrams present sector angle equal to 5°. (A) Barren V_3-veins; (B) Ore-veins graphically extracted from Torres *et al.* (1986); (C) Ore-quartz veins from northeastern Serrita (Pernambuco) diggings; (D) Ore-quartz veins associated with Parnamirim (Pernambuco) occurrences.

and 0.01 up to 0.90 m at N-Parnamirim. The N-S array contains relatively thicker veins, reaching up to 3.8 m width. Both arrays show hectometric lengths.

The veins show massive texture, commonly presenting open-fill textures as cavities partially filled by euhedral quartz and also secondary boxwork cavities. Microscopically, the veins are dominated by a blocky texture defined by medium- to coarse-grained quartz crystals.

The most important feature of these veins is their internal deformation. The internal deformation is highly heterogeneous and defines low and high strained zones. These zones have a quite irregular distribution within the veins and also exhibit different structural styles. Macroscopically, the internal deformation of the vein is characterized by various types of fractures (here called fractures I and II) and breccias (mosaic and crackle). The fractures I are filled by sulfides or their alteration product (*e.g.* limonite) (Fig. 6A) while the fractures II are barren and frequently covered by a thin black, reddish or yellowish film. The fractures are mainly strike-parallel in respect to the veins although secondary directions are also found in highly strained zones.

Different styles of breccias were found in veins and they were classified according to Woodcock and Mort (2008). The mosaic breccias present a typical jigsaw pattern and were differentiated according to the nature of the fragments and cement. The first one, here called mosaic breccia (I), presents subangular fragments defining a large triangular texture (Figs. 6B e C). The cement is mainly composed of quartz, galena, pyrite and secondary minerals (*e.g.* limonite). The second type (mosaic breccia II) is represented by breccias showing a cockade texture, in which galena fragments are surrounded by a crustiform cement made of microcrystalline quartz and covellite (Fig. 6D). The cackle breccias constitute the third type and exhibit a subangular matrix and fragments and lack cement

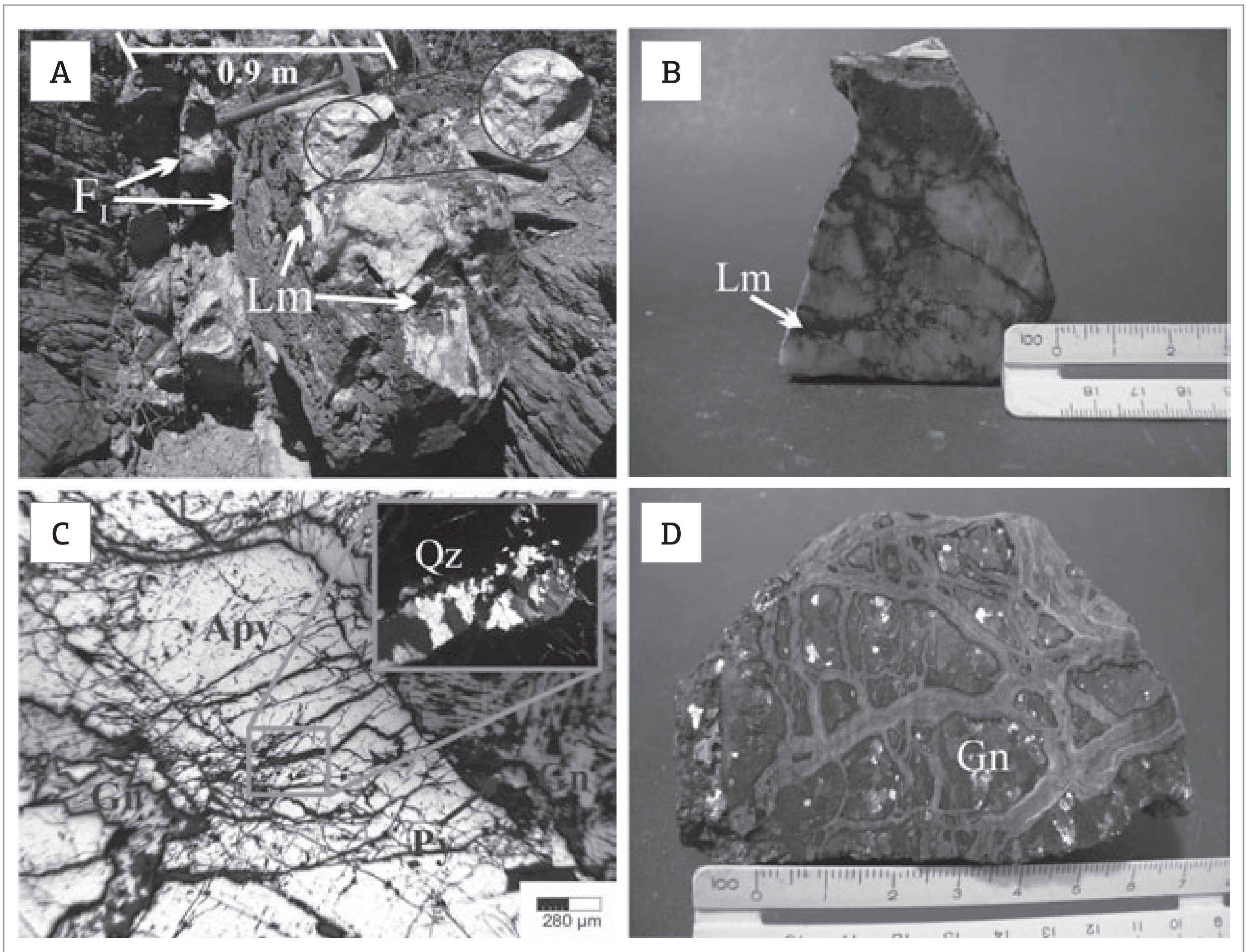

Figure 6. Internal deformation structures of the ore-veins. (A) Limonite(Lm)-filled fracture array is parallelized to vein walls. The detail exhibits crackle breccias; (B) Mosaic breccia (I) presenting quartz subangulous fragments surrounded by a hematite-limonite cement; (C) Mosaic breccia (I) photomicrography showing fractured arsenopyrite crystals (Apy) filled with galena (Gn), pyrita (Py) and quartz (Qz). The detail presents quartz grains with enlogated blocky texture; (D) Mosaic breccia (II) exhibits cockade texture defined by subrounded massive galena fragments (Gn) and crustiform cement.

(Fig. 6A). The matrix and fragments are normally surrounded by a thin black, yellowish or reddish film.

Microstructures also indicate inhomogeneous deformation. Low deformed areas are characterized by quartz undulose extinction, centimetric scale deformation bands, subgrains and newgrains. The grains show straight to serrated boundaries, suggesting an incipient bulging recrystallization. This recrystallization also occurs as anastomosed intra- or intergranular strips, here called recrystallization bands. These bands usually make low angles (~ 20°) with the walls of the vein.

Highly strained zones occur as narrow zones approximately parallel to the walls of the vein or encompassing the entire vein. These areas present abundant anastomosed recrystallization bands, indicating the predominance of bulging recrystallization although bigger recrystallized grains can also be found (Figs. 7A and B). The presence of carbonate and sericite within these bands has indicated

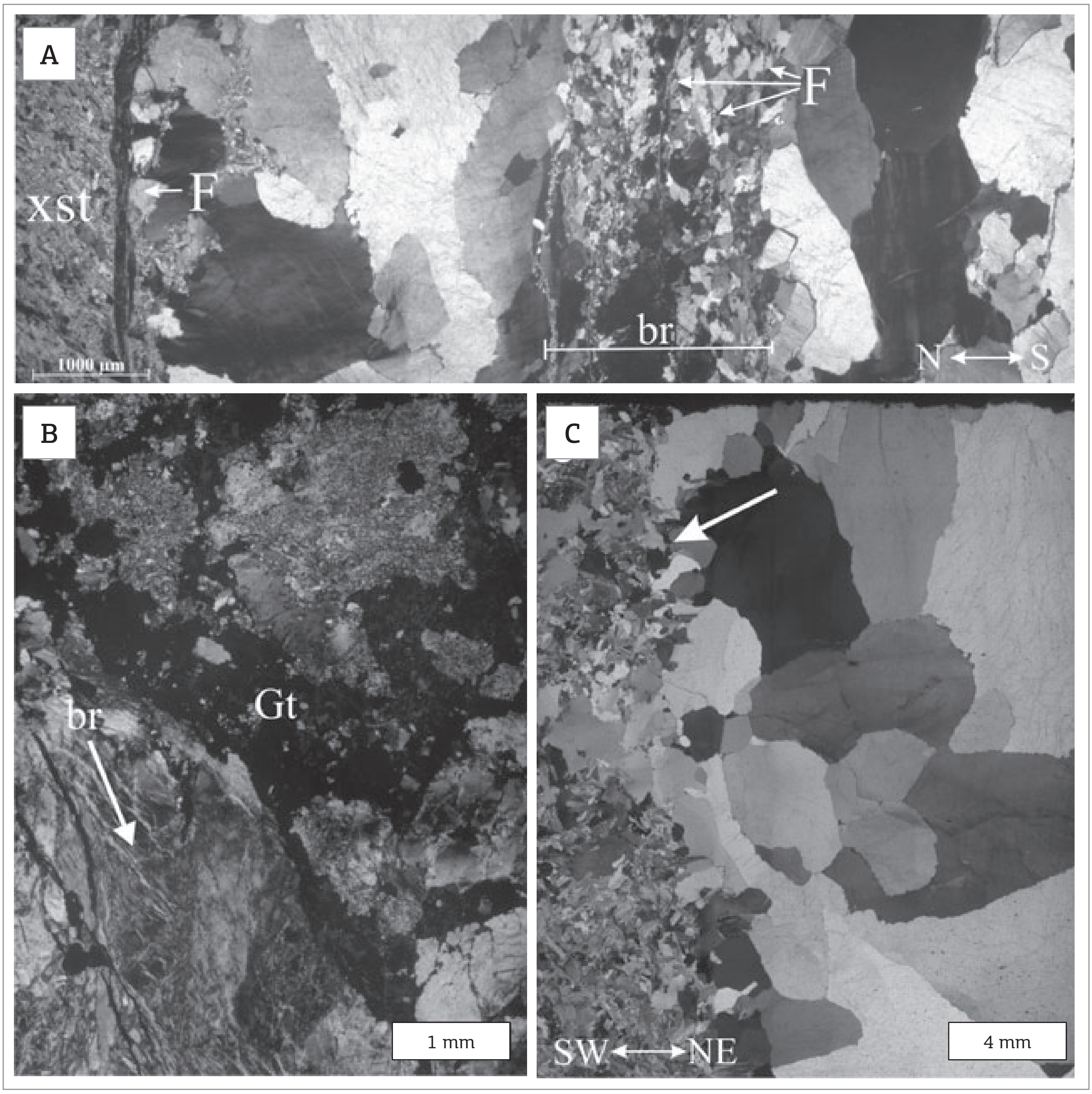

Figure 7. Microstructural aspects of the ore-veins (crossed polarized light). (A) Milimetric limonite filled fractures (F) surrounded by a zone of quartz recrystallization (br) associated with muscovite and carbonate. A second fracture developed near the vein-schist (xst) contact; (B) Goethite (Gt)-filled mosaic breccia (I) showing intense recrystallization. The recrystallization bands (br) present an anastomosed pattern; (C) Granodiorite-hosted vein with irregular walls (arrow) and incipient deformation.

that deformation took place concomitantly with the fluid activity. The crosscut relationships suggest that crystal-plastic deformation was prior to the brecciation and fracturing of the veins.

GRANODIORITE-HOSTED VEINS

The granodiorite-hosted veins form two groups according to their mineralogy. The first group occurs predominantly at the Serrita pluton and is comprised of quartz-feldspathic veins which occasionally show pegmatitic texture. The ambiguous cross-cut relationship among these veins and aplite/pegmatite dikes has suggested their contemporaneity. These veins exhibit steep dip angles, centimetric widths and lengths reaching up to several decimeters. They can present abrupt direction changes and are commonly associated with milimetric width ruptile-ductile shear zones.

The second group represents veins essentially composed of quartz. In this group, some veins present distinct amounts of carbonate, sericite, sulphides and gold (here called ore-veins). These veins usually form swarms and present a NW-SE unimodal direction with subvertical dip angles (Fig. 8). They are tabular, show milimetric to centimetric width and centimetric to metric lengths. The alteration selvage and open-fill cavities partially filled with euhedral quartz are their most noticeable features.

The deformation of the veins is restricted to fault planes that nucleated along their walls. Microscopically, the ore-veins show irregular walls (Fig. 7C) surrounded by a muscovite fringe. The quartz displays blocky texture and incipient deformation aspects, such as undulose extinction, subgrains and new grains. The grain boundaries between new and subgrains are usually straight, interlobate and rarely serrated. Some muscovite grains exhibit kink bands.

DISCUSSION

Metassediment-hosted veins

The main texture in the metassediment-hosted veins is that of quartz blocky grains. Oliver and Bons (2001) have interpreted this feature as a product of ongoing nucleation due the supersaturation of the vein-forming mineral, chaotic fracturing or dynamic recrystallization. The first hypothesis seems more reliable in this case as the recrystallization and fracturing have an irregular intensity and present a scattered distribution within the veins. Thus, the ongoing nucleation probably occurred in function of a silica supersaturation in the fluid. In general, this process is associated with abrupt fluid pressure drops triggered by fault-related fractures, or by a sudden arrest of mobile hydrofractures (Bons 2001, Oliver & Bons 2001). The texture also indicates that the opening rate of the fracture exceeded the quartz growth rate; otherwise, it should have formed fibrous or elongated blocky crystals (Passchier & Trouw 2005). The anastomosed pattern of the veins also points out high fracture propagation rates (Trepmann 2002).

The quartz crystal-plastic deformation indicates deformation temperatures between 280 and 400°C, similar to those interpreted for the ore formation (Beurlen *et al.* 1997). The presence of phyllossilicates and carbonates in recrystallization bands suggests dissolution and precipitation mechanisms and points to a fluid-assisted deformation.

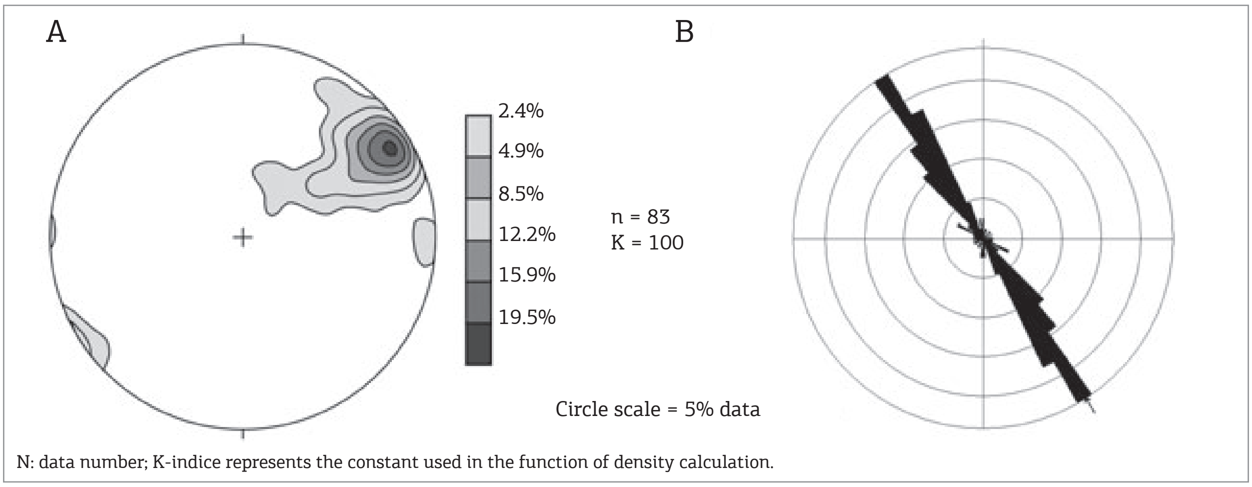

Figure 8. Ore-veins attitudes from Barra Verde stock. (A) Pole contour stereographic diagram (K = 100); (B) Rose diagram showing sector angle equal to 5°.

The brecciation and fracturing within the veins record a multiphase fragile deformation. The parallelism between fractures and the walls of the vein suggests that lodes accommodated part of the strain, acting as preexistent flaws zones.

The mosaic breccias (I and II) and fractures (I) formed important flow conduits for metalliferous fluids. The mosaic breccias (I) and (II) show different contents of fragments and cements, which indicates distinct opening rates and physicochemical conditions of cementation.

According to Dong *et al.* (1997) and Hagemann *et al.* (1992), the cockade texture and microcrystalline quartz (mosaic breccia II) are typical of the epithermal systems and probably reflect the evolution of the fracturing process in shallower crustal levels. The crackle breccias postdate the fluid activity, and could represent a late deformational event.

The subvertical pattern of the veins let us infer that they formed under a paleostress field with principal minimum subhorizontal stress (σ3). This fact indicates a strike-slip or an extensional tectonic regime. Taking into account that the ore-veins exhibit dihedral angles between 60° and 80° (E-W/ESE-WNW and N-S/NNW-SSE) and record a multiphase deformational history, it is feasible to suggest that the veins are genetic related to shear fractures formed in a strike-slip regime. Although the conjugate angles are higher than those expected for hybrid or shear fractures (Hancock 1985, Peacock & Sanderson 1992), these changes are expected on faults formed at the base of the seismogenic zone due the increase of confining pressure (Watterson 1999). We also suggest that the veins developed during the last stages of the fourth deformation phase (D4) in a ruptile-ductile regime.

CONCLUSION

Based on discussed evidences, we purpose an evolution model for the ore-veins, characterized by multiphase fracturing and crystal-plastic deformation cycles, partially coupled with hydrothermal mineralizing activity. Figs. 9A and B present the branched- and anastomosed-fractures nucleation phase, which formed abundant host-rock xenoliths and triggered the quartz precipitation.

Afterwards, the crystallization of the veins constituted important zones for strain accommodation, which are characterized by heterogeneous distribution and intensity. The presence of quartz bulging recrystallization (Fig. 9C) associated with sericite and carbonate suggests a fluid-assisted deformation under a ruptile-ductile regime.

This period was followed by fracturing phases marked by the presence of mosaic breccias (I) and fractures (I) with predominantly quartz, pyrite and galena cements (Fig. 9D). The relationship between the ruptile deformation and the

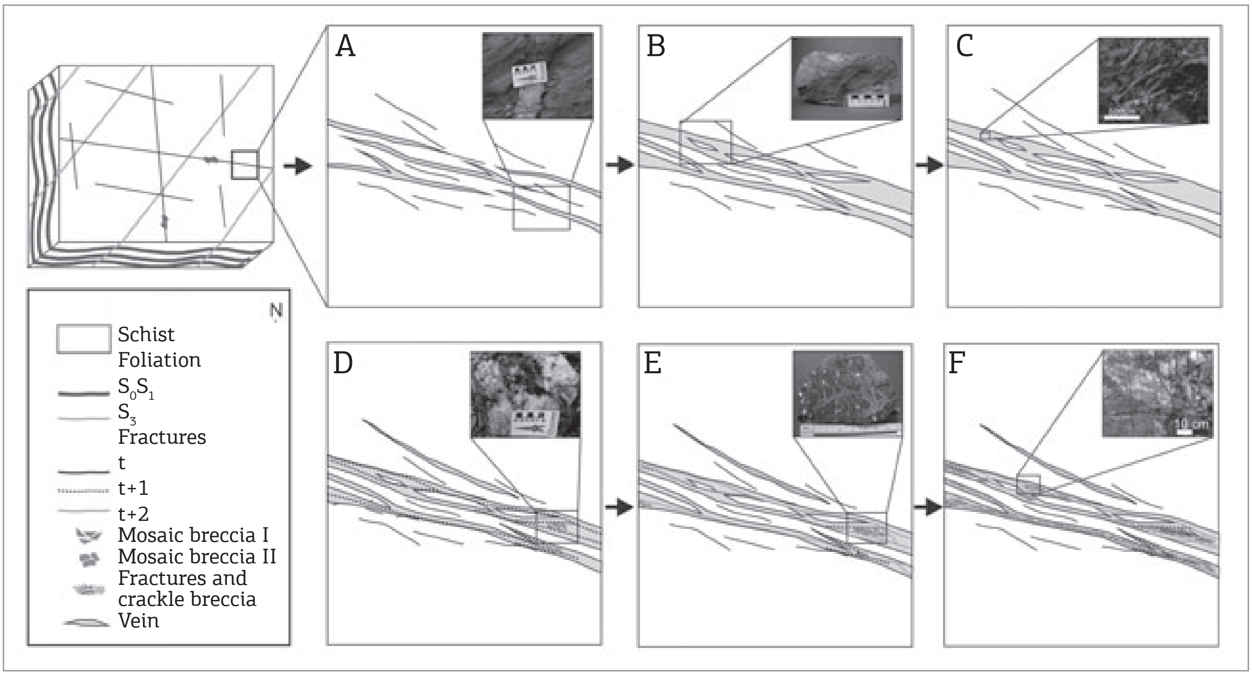

Figure 9. Evolution model of metassediment-hosted veins. The abbreviation (t + n) refers to successive time intervals that fractures formed. The pictures represent the typical features of each stage. (A) and (B) Anastomosed fractures propagation producing xenolith-rich veins lacking internal deformation; (C) Quartz cristal-plastic deformation; (D) Mosaic breccias I; (E) Mosaic breccias II; (F) Barren fractures and crackle breccias.

ore is evidenced by the gold-pyrite association and also by free gold grains infilling healed fractures. The morphological and mineralogical differences related to mosaic breccia (II) indicate a distinct physicochemical environment and suggest the deformation proceeded in progressively shallower crustal levels (Fig. 9E).

The last deformational phases of the vein correspond to the development of fractures (II) and crackle breccias (Fig. 9F) in oxidizing states, lacking fluid activity. It was not possible to establish if these structures were related to a recent deformational event.

The granodiorite-hosted veins (Barra Verde stock) show distinct features when compared with the metassediment-hosted veins. They are substantially thinner, shorter and present an unimodal azimuth distribuition. The microstructures indicate an incipient deformation that is similar to their host-rocks. These characteristics point to a distinct evolution for granodiorite-hosted veins.

Taking into account that both metassediment- and granodiorite-hosted veins formed from a similar fluid (Beurlen *et al.* 1997), we propose two hypothesis of vein formation. The first hypothesis considers that the granodiorite-hosted veins postdate the metassediment-hosted veins and grew under a different paleostress field. In the latter, the veins formed by the same stress field but would present a distinct evolution in function of their host-rock rheology.

The second hypothesis suggests fracture refraction (Hancock 1985, Peacock & Sanderson 1992), which occurs when a perpendicular stress is applied against rocks that show contrasting mechanic behavior. According to these authors, the less competent lithologies (*e.g.* schists) tend to develop shear fractures while extension fractures occur in more competent rocks (*e.g.* granitoids). This hypothesis is favored as the metassediments and granodiorites have undergone a NW-SE-compressive stress regime. Moreover, the inexistence of metassediment-hosted veins showing similar features as those in the granodiorites favors the second hypothesis.

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