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PARAGUAY BELT LITHOSTRATIGRAPHIC AND TECTONIC CHARACTERIZATION: IMPLICATIONS IN THE EVOLUTION OF THE OROGEN (MATO GROSSO-BRAZIL)

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Abstract

The Paraguay Belt is composed by sediments deposited due to extensional events followed by inversion with deformation and magmatism and lastly collision of the Amazonian Craton and Paranapanema Block. The marine sedimentation, with Neoproterozoic ages, should have occurred in a continental shelf region, at about 800-550 Ma, when the closing of many oceans gave place to the amalgamation of the Gondwana supercontinent. Three areas were selected for this study which configuration define the perpendicular profile of the Paraguay Belt and allow the characterization of the main regional structures.

The structural analysis in the sites here reported and surrounding areas allow suggesting that three deformational events are recorded in the rocks of this region. The sedimentary bedding S_0, marked by alternations of dark gray and whitish coloration in the seritic phyllites is folded and the axial plane (Sn) is marked by a cleavage of ardosian. These surfaces are cut by two other deformations, Sn + 1 surface that plunges at high angles to SE as fracture cleavage and Sn + 2 that is orthogonal to the previous deformations and has NW-SE direction with vertical dips, where sometimes occurs quartz veins with high gold content. The Paraguay Belt fan geometry observed in the Sn foliation was developed during the closing of a Brazilian ocean that evolved between the Paranapanema Block and the Amazonian Craton.

Keywords: Paraguay orogeny. Stratigraphy. Tectonic.

1 Introduction

The geologic and structural evolution of the Paraguay Fold Belt is comprised of periods of sedimentation due to extensional kinematic followed by inversion with deformation and magmatism (Almeida, 1984; Alvarenga et al., 2004). The marine sedimentation origin is interpreted being related to a continental shelf region at about 800 Ma, followed by an inversion and collision of the Amazonian Craton and Paranapanema Block. The ages of this tectonic unit are correlated with other orogenies of the Brazilian shield developed in the Neoproterozoic when the closing of many oceans resulted in the amalgamation of the Supercontinent Gondwana (Brito Neves, 2003). This belt forms N-S (southern sector) and W-E trends in the region of Nova Xavantina, Mato Grosso. The rocks crop out along approximately 1,500 km long and 300 km wide (Fig. 1) and are covered by the Phanerozoic sediments of the Paraná, Parecis and Pantanal basins.

Evans (1894) described folded sedimentary rocks in the northern sector of the belt. The Paraguay belt has been subject of several studies focusing different features as whole-rock geochemistry (Alvarenga and Saes, 1992; Alvarenga and Trompette, 1993; Boggiani et al., 1993; Boggiani et al., 1999; Alvarenga et al., 2004, Boggiani and Alvarenga, 2004; Silva et al., 2002; Nogueira et al., 2007; Romero et al., 2012; Bandeira et al., 2012; Babinski et al., 2012), stratigraphy (Silva et al., 2002; Alvarenga et al., 2000; Nogueira and Riccomini, 2006; Babinski et al., 2006), and magmatism (Martinelli, 1998; Martinelli and Batista., 2006). Also, tectonic aspects of the Paraguay Belt have been discussed in Alvarenga and Trompette (1993), Trompette (1994), Tohver et al., (2006), Nogueira et al. (2003) and Barboza et al. (2005).

Geochronological data on the Paraguay Belt suggest Neoproterozoic ages for sedimentation and collision process. As proposed by Cordani et al. (1985), the ages of 660 ± 60 Ma (Ri = 0.7082) obtained by the Rb/Sr method can be interpreted as diagenetic processes. Barros et al. (1982) presented Rb/Sr ages of 484 ± 19 Ma (Ri = 0.743) for phyllites, as well as presented ages of 547 ± 5 (Ri = 0.711) obtained by the same method and interpreted as the end of the orogeny evolution (metamorphism). The crystallization of igneous rocks of the São Vicente granite yielded by the Rb/Sr method indicated ages of 504 ± 12 Ma (Almeida and Mantovani, 1975) being confirmed later by U-Pb method which yielded an age of 504 ± 6 Ma (Pinho, 1990).

The Coxim and Taboco granites indicate cooling ages obtained by K/Ar point out to 453 Ma (Luz et al., 1980). The $^{40}Ar/^{39}Ar$ ages yielded intervals between 541 and 531 Ma, which were interpreted as the cooling age of a metamorphic process for the Cuiabá Group rocks in the Nova Xavantina region (Geraldes et al., 2003, 2007). The radiometric results allowed an advance in understanding the chronology of these events, interpreted as cooling ages (according Geraldes, 2010) as result of the metamorphic event. The rocks formerly known as Mimoso volcanics were for many years attributed to the same magmatic event such as that of the São Vincente Granite due to ages Rb/Sr ages of 480 Ma (Sousa, 1997). The Paraguay Belt rocks are cut by 84-97 Ma mafic dykes according to $^{40}Ar/^{39}Ar$ ages (Gibson et al., 1997; Sousa, 1997).

In a regional profile is possible to distinguish three structural zones: internal, external and platformal structural domains (Alvarenga and Trompette, 1993) (Fig. 1). The first domain consists of strongly folded and metamorphic turbidites and glaciogenic sequences in the green-schist facies, intruded by granite bodies. In the second domain (external zone), glaciogenic rocks occur at the base, carbonates and terrigenous sediments at the top, which are gently folded, but not metamorphosed. These sequences have horizontal extension covering the Amazonia Craton in the platformal domain. The boundary between the internal and external zones is marked by inverse and normal faults.

1.1 The main goals of this work

The main objectives of this research are to distinguish the structural zones, focusing on the geometry characterization of the domains in a perpendicular profile across the Paraguay Belt and to identify the variations in the structural features vergence aiming to check the hypothesis of fan geometry. In order to achieve this aim, three areas of wide outcrop exposure were selected, including the Nobres region, the Guia Synclinal and the exposed areas of the Casa Grande Gold Deposit. These three areas spatially configure a perpendicular profile of the Paraguay Belt and allow to identify the behavior of the main regional structures.

2. Aspects of the Alto Paraguay belt stratigraphy

The sedimentary rocks of Paraguay Belt were deposited in a continental margin basin probably at about 800-550 Ma. The Nova Xavantina region, which is a possible basal sequence of the Paraguay Belt, is constituted by basic and ultrabasic volcanic rocks intercalated with argillites and sandstones called Nova Xavantina volcano sedimentary sequence (Pinho, 1990; Martinelli, 1998).

The stratigraphic units of the Paraguay Belt were initially described by Almeida (1984). These initial stratigraphic studies defined the Cuiabá Group at the base, overlain by the Bauxi and Puga formations, and the Alto Paraguay Group (Araras, Raizama and Diamantino formations) are at the top. Alvarenga (1984) and Nogueira et al. (2003, 2007) included the Guia carbonates in Araras Formation and suggested the Group status for the Araras unit. After this, the Araras Formation was divided into the Guia and Noble formations to separate the calcitic limestones from the dolomites (Alvarenga et al., 2004; Figueiredo et al., 2004, 2006). The Alto Paraguay Group, including the Raizama and

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Diamantino formations, remains without descriptive changes in relation to the initial works.

An important contribution for the geological mapping in the region was carried out by Luz et al. (1980). In this work, the rocks of the internal zone (Cuiabá Group) were divided into nine subunits, from base to top: (1) sericitic phyllites with alternating graphite and metasandstones; (2) feldspathic and greywacke metasandstone, graphite phyllites with alternating calciferous limestone; (3) phyllites, with layers of metaconglomerates and metagreywackes, with alternations of quartzite and lenses of calcitic limestone with hematite at the top; (4) metadiamictites with polymictic clasts and silt-sandy matrix; (5) phyllites, sericitic phyllites with alternations of metasandstone rich in feldspars and metaconglomerates; (6) conglomerate phyllites; (7) diamictites with subordinate sandstones; (8) limestones with dolomite and metapelite lenses on top; and (9) undivided unit (Fig. 2).

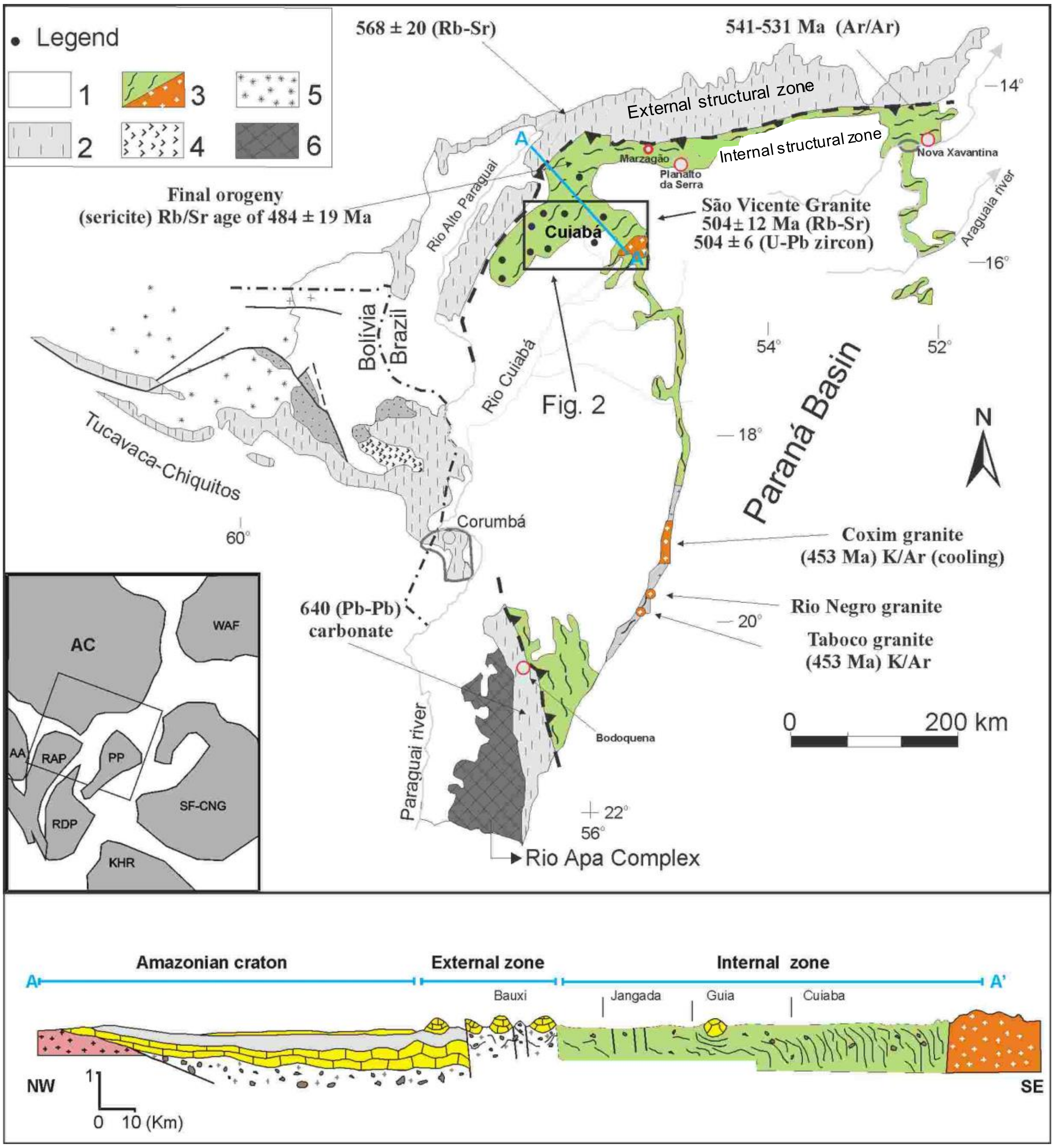

Fig. 1. Regional context of the Paraguay Belt. 1 - Phanerozoic Cover; 2 - Cover of Neoproterozoic / Cambrian Platform; 3 - Metassediments and granites; 4 - Rincon del Tigre Ultramafic Complex; 5 - Metassediments and granitoids from the Sunsás and Rondonian-San Ignácio orogenies; 6 - Gneisses and granitoids from the Rio Apa Complex. Insert (AC= Amazonia Craton; AA = Arequipa-Antofala Craton; RAP = Rio de La Plata Craton; PP = Paranapanema Craton; WAF = West African Craton; SF-CNG - São Francisco-Congo Craton. Paleogeography from Geraldes and Schmitt (2010).

The use of stratigraphic sequence concepts presented by Alvarenga (1984) allowed the identification of the lower unit as similar to subunits 1 and 2 (as proposed by Luz et al., 1980); the intermediate facies represents distal sedimentary facies, intermediate facies including subunits 3 and 5 (according to Luz et al., 1980), and proximal facies (Bauxi and Puga formations) correlated with subunits 4 and 7.

The Carbonatic unit occurs on the cratonic area such as the Araras Group and is correlated with the subunit 8 represented by carbonate rocks of the Guia syncline in the internal zone. Raizama Formation rocks consist of feldspar and clay sandstones and by Diamantino Formation that includes siltstones and argillites as the main lithotypes (both units occur only on the cratonic area). A synthesis of the stratigraphic data of Paraguay belt is presented in Figure 3.

According to Alvarenga and Trompette (1993) and Alvarenga et al. (2004), the rocks of the Cuiabá Group are constituted by phyllites rich in organic matter and metadolomites superimposed by glaciogenic and turbiditic metassediments such as diamictites, conglomerates, sandstones and shales. This sequence slopes toward the cratonic area over the Bauxi and Puga formations. This feature of lateral gradation of the Paraguay Belt was first suggested by Almeida and Mantovani (1975) and others (Alvarenga, 1984; Alvarenga and Trompette, 1992).

The glacial environment deposits are represented by the Bauxi Formation, comprised of diamictites, quartzites and conglomerates, and the Puga Formation, mainly represented by diamictites may be interpreted as lateral gradation of Bauxi Formation (Almeida and Mantovani, 1975). These rocks are correlated with Marinoan glaciation (Nogueira et al., 2003).

Rocks deformation origin is interpreted as a product of gravitational flux and is superimposed by cap carbonates of Araras Group (Alvarenga, 1984; Alvarenga and Trompete, 1993).

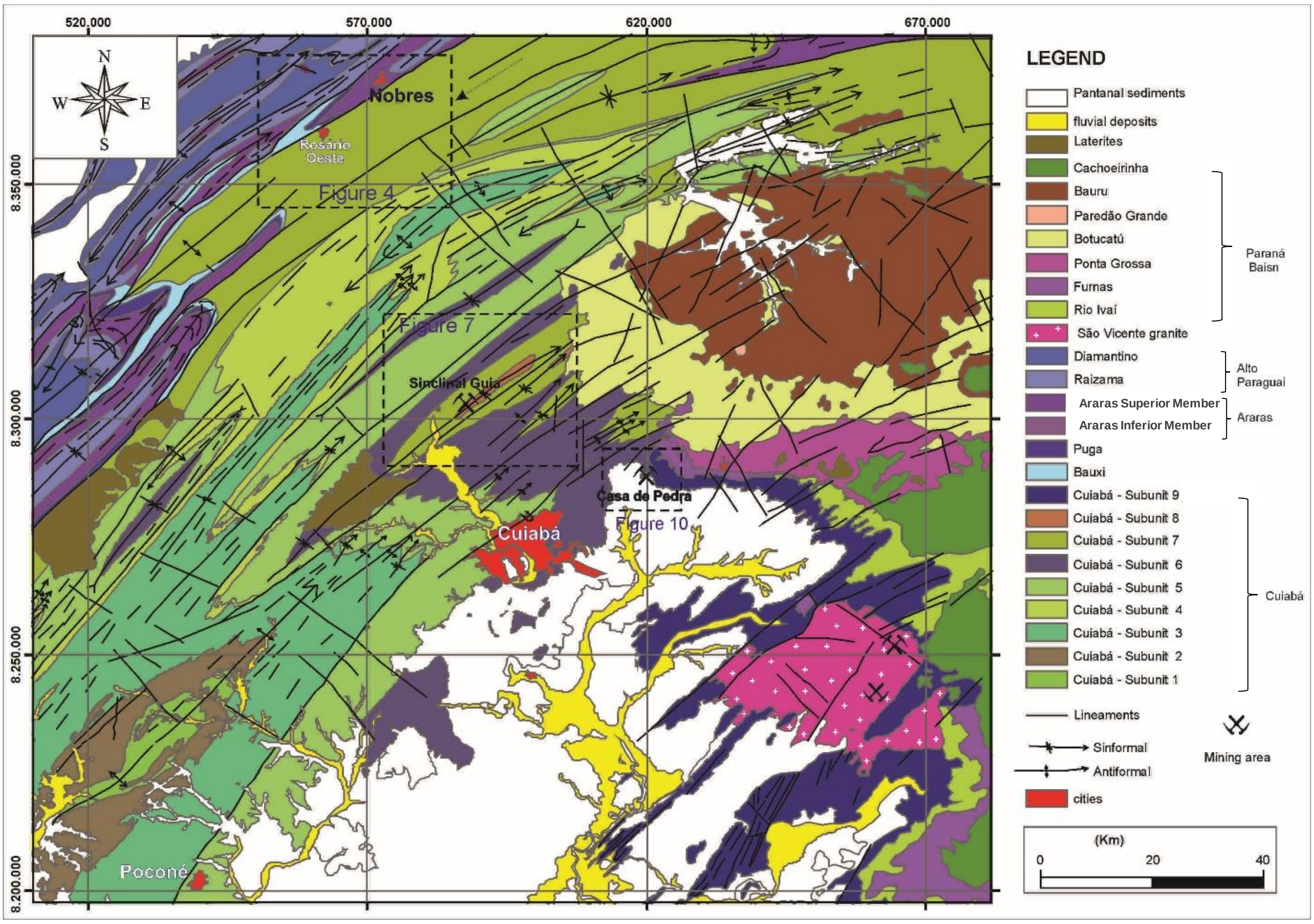

Fig. 2. Geology of the internal zone of the Paraguayan Band in the Cuiabá and Poconé regions (modified from Luz et al., 1980).

The Araras Group rocks were the target of Nogueira et al. (2003) investigation for evidence on pale environmental evolution, according to isotopic ratios of Sr, C and O in stromatolitic structures present in the Araras Group rocks. The results allowed this author to identify four carbonate units: Mirassol d'Oeste (cap carbonate), Guia, Morro do Quilombo and Nobres formations. These formations can be correlated to the Cerradinho, Bocaina, Tamengo and Guaicurus formations (Corumbá Group) in the southern Paraguay Belt, as described by Boggiani et al. (1993). On the other hand, based on the fossil content, Boggiani et al. (1999), suggested that the Corumbá Group is not correlated with the Araras Group. The fossils present in the former suggest mainly Marinoan ages (glaciation) dated by C isotopes (Nogueira et al., 2003) or 590-550 Ma (Ar/Ar ages), as suggested by Geraldes et al. (2003).

The Araras Group rocks include a carbonaceous layer sequence succeeded by transgressive deposits of bituminous and deep-ocean shales (Riccomini et al., 2007). According to these authors, the stratigraphic studies of transgressive deposits exposed in the Guia syncline present negative $\delta^{13}C$, between -2.5‰ and -1‰ and shows a clear correlation with the upper portion of the Guia Formation of the Cáceres region. The $\delta^{13}C$ profile of the Araras Group is comparable to the profiles of other Ediacaran units in the southern part of the Paraguayan belt, western Canada, and the Congo and Kalahari cratons, reinforcing the Ediacaran age assignment for the Araras Group.

Figueiredo et al. (2004) proposed the Serra Azul Formation as a division of the Araras Group. This formation was described in outcrops of the Marzagão district as massive diamictites at the base with a superior sequence of mudstones, siltstones and sandstones at the top (Fig. 3). The origin of this unit may be related to Gaskiers Glaciation (ca. 580 Ma). The aforementioned authors identified a sequence of siltstones and argillites as a possible constituent of the Serra Azul Formation, since they are stratigraphically above the Araras Group and below the conglomerates of the Raizama Formation (Upper Paraguay Group).

3. Materials and methods

The initial stage of this work included the compilation of unpublished geologic maps of the region, as well as the company reports. It also includes a survey of existing cartography of the area in the Universidade Federal do Mato Grosso (UFMT). During the field works, the main method of this study was a lithostructural characterization of the outcrops and mining fronts. The mapping activities occurred in the last 15 years. During these periods, the main lithotypes and geological structures were recognized, always seeking information about the lithology and structural elements registered on the host rocks. Samples collected in the field were described macroscopically and sent to the UFMT laminating laboratory for the preparation of thin and polished sections, and finally described from a petrographic and structural point of view.

The acquired data allows to sketch previous interpretations on the determination of lithology and structural features on different sites of the Internal and External Zones of the Paraguay orogen. The field results obtained in the quarries are also included in this data integration, as well as several points where structural geological surveys were carried out. The lithological and structural data collected in the field were treated in order to elaborate geological maps in a more detailed scale in order to recognize the structural control of the lithologic domains. Based on the results obtained until now it is possible to interpret related aspects to the lithostratigraphy, from the integration of the rock composition data and the geometric relations of the structures.

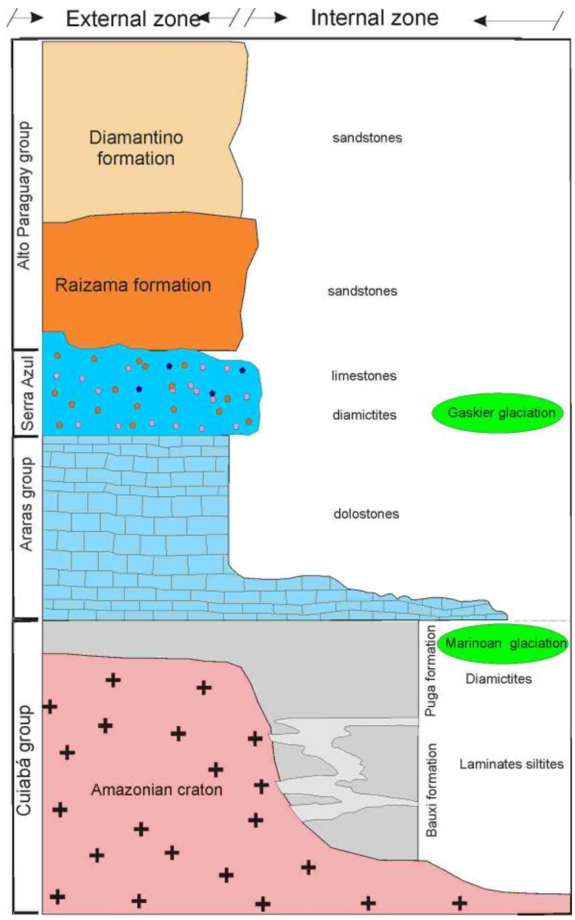

Fig. 3. Stratigraphic column of the Paraguay Belt in the Mato Grosso state (modified from Alvarenga et al., 2000; and Figueiredo et al., 2004, 2006).

4. Results

Below, we present the detailed characterization of three studied areas including petrography (outcrops descriptions), structural and tectonic interpretations.

4.1. The Nobles region

The region of Nobres city is located approximately 150 km north of Cuiabá (MT). Its structural and tectonic aspects in the Paraguay Belt belonged to the external portion, while the gold deposits and other studied sites are in the internal zone. Thus, the wide spatial distribution and structural variety between these two tectonic domains was considered as a criterion to verify the continuity and spatial behavior of these structures. Consequently, several profiles of regional recognition were performed and quarrying fronts were visited in the surroundings of Nobles city.

4.1.1 Local Geology

Near the Nobres city, it is possible to observe practically the whole stratigraphic column of the Paraguay Belt external zone. Figueiredo et al. (2004) described terrines the Serra Azul stratigraphy, where is observed a wide reverse and asymmetrical anticline fold, where several formations outcrop, such as Puga (diamictites), Mirassol d'Oeste (dolomites), Serra Azul (diamictites and argillites), Raizama (sandstones and conglomerates) and Diamantino (siltites and argillites). In this study, several outcrops were visited in the region of Nobres and Rosário d'Oeste, where the Puga, Bauxi, Araras and Raizama formations were observed. The geologic map resulting of detailed work is presented in Figure 4.

The Puga Formation emerges in the vicinity of Acorizal and south of Rosario d'Oeste. These rocks are predominantly reddish-brown to brown-colored diamictites with a silty-clayey matrix clasts-supported, including granites, sandstones and quartzites. The contact between Puga and Bauxi formations is gradational. The Bauxi Formation is represented by yellowish-colored sandstones with medium to fine granulometry, containing several silicified levels.

The Araras Formation was the most studied due to the easy access to the quarries where calcitic and dolomitic limestones outcrops. Calcitic limestones is always present in outcrops of the anticline nuclei. Calcitic limestones are dark gray and well stratified; dolomites are predominant in the flanks and show a light gray to whitish coloration and are massive. Dolomites occur locally with cross-beddings at the sandier levels. Close to the upper contact of the Raizama Formation it is observed dolomites; in this zone intense enrichment in silica is common, probably associated to a transition to the Diamantino Formation. The latter is composed of coarse sandstones to conglomerates, generally exhibiting a reddish-brown coloration.

4.1.2 Structural Aspects

In outcrop scale, the primary sedimentary bedding S_0, S_n foliation, faults and fractures are well preserved. Sedimentary bedding is marked by some compositional differences. For example, in the calcitic limestones and dolomites of the Araras Formation it is possible to identify alternation of pure levels and other silica-enriched layers. In the metasandstone of the Bauxi Formation or Raizama Formation, the bedding is better described based on a sharp contact between levels of different granulometries.

The sedimentary layers are folded and dip between 40º and 50º to SE, rarely to NW (Fig. 5). The folds have as axial plane and tectonic foliation S_n occurs in the form of fracture cleavage. The main orientation is N20E/70SE (Fig. 5). The lithotypes where S_n is recorded are diamictites of Puga Formation, Serra Azul argillites and calcitic limestones of Araras Formation, whereas in dolomites rarely S_n appears, being more common fractures and breccias generated by faults or flexural slip between layers with different competences, similar to those occurring in Guia Synclinal dolomites and the internal zone of Paraguay Belt. In Nobres region, these structures are also common (Fig. 5), mainly in the limestones of Araras Formation, where they are sometimes filled by quartz and calcite, similarly to the filling that occurs in the Guia metalimestone. These NW-SE fractures direction corresponds to the S_{n+2} fracture cleavage.

In diamictites (or tilites) of Puga Formation, the bedding can rarely be distinguished from foliations, as exemplified in Figure 6A, but can be easily distinguished in calcitic limestones. The slope of these folds axis is predominantly to northeast. In Puga Formation tilites, in addition to the micaceous mineral that mark this foliation, the pebbles are also parallel to S_n (Fig. 6B). Other easily visible sedimentary structures are cross-bedding structures (Fig. 6C) and symmetrical wave-formed ripple marks (Fig. 6 D). The folds in S_0 are easily visible in scale of maps as they configure antiforms of kilometric dimensions; in general, they are symmetrical to smoothly asymmetrical, with axial plane near the verticality.

Top-to-bottom movement faults for NW place different lithotypes in contact and is limited laterally by transfer faults with apparent horizontal displacement. These tectonic boundaries bring into contact rocks that show NW vergence, with gently dip and symmetrical features. In spite of the predominance of open and smooth folds in the vicinity of Nobres, asymmetric folds are locally tight and associated with faults. These sites may represent points of greater absorption of deformation reflecting the structures from regional scales.

4.2 The Guia Syncline Region

The Serra da Guia is constituted by a syncline and is located 30 km northwest of Cuiabá in the vicinity of Nossa Senhora da Guia district, Cuiabá municipality. In this locality, a limestone quarry has been operating from the early 1950s (Barboza and Geraldes, 2004). The choice of the Guia syncline as the target site for structural geological surveys in this study had as main criterion the search for the understanding of the structural aspects of the Paraguay Belt outside the auriferous deposits to compare the structural elements that are easily visible in this place due to rocks exposure unchanged in Guia quarry exploratory front.

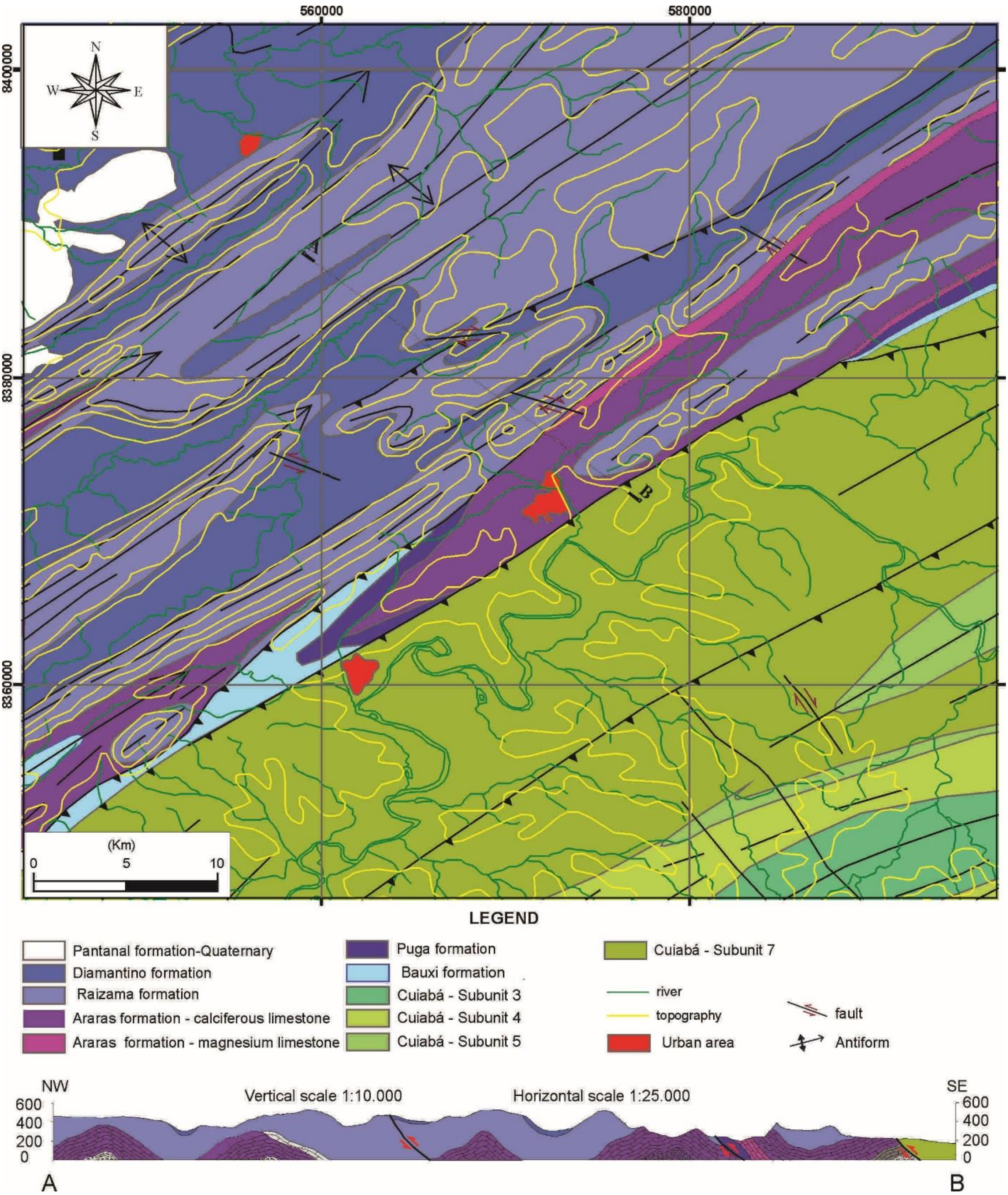

Fig. 4. Geological map of Nobres region. It is important to highlight the reverse faults (thrusting) placing the rocks of the Cuiabá Group (Internal Zone, S-SE) in contact with Puga and Bauxi formations, Araras and Upper Paraguay groups (External Domain, N-NW).

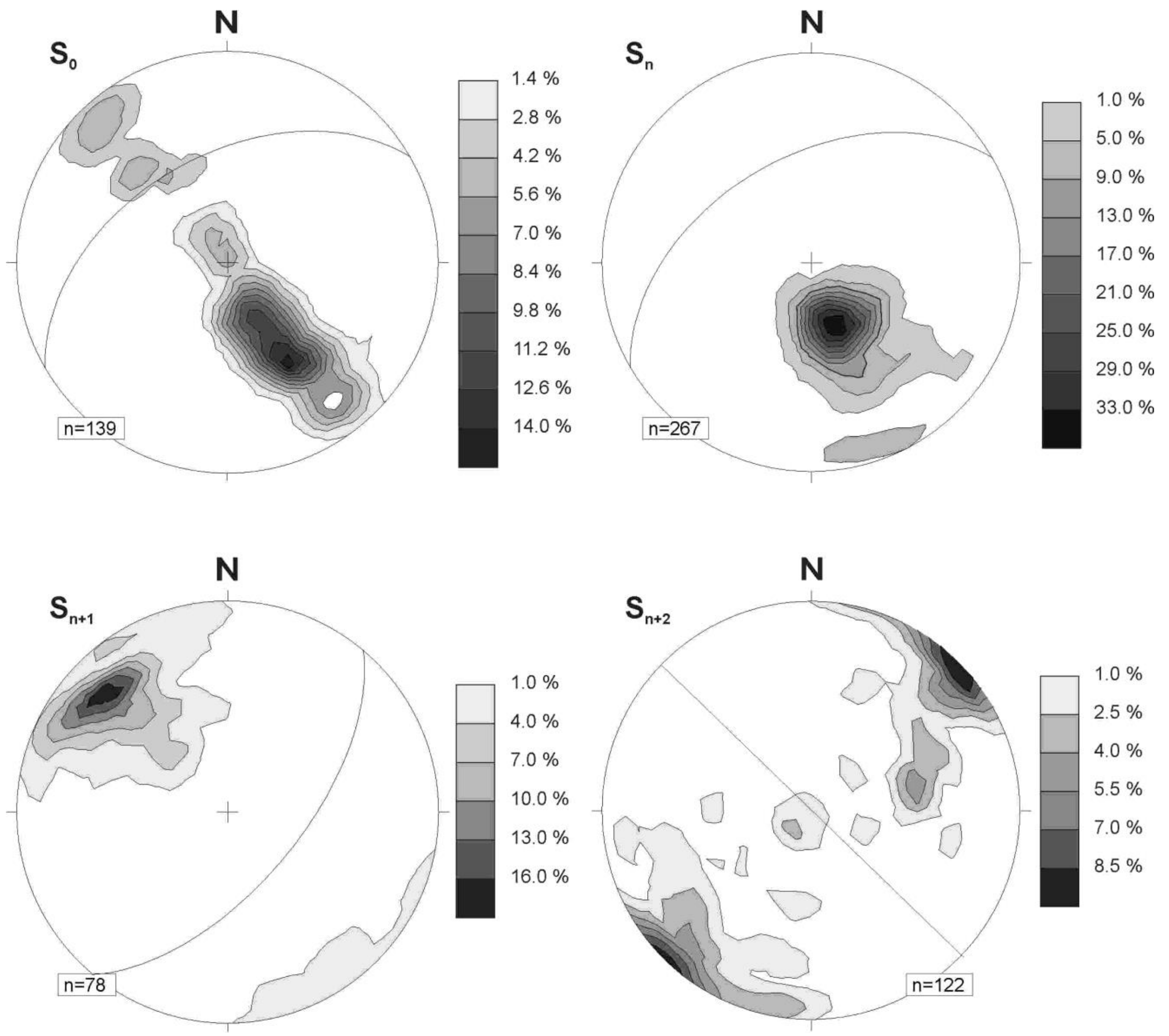

Fig. 5. Diagrams of planar structures found in the Nobres area. Bedding S_0; foliation S_n; $S_{n\ 1}$ fracture cleavage; cleavage spaced S_{n+2}.

4.3 The Guia Syncline Region

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4.3.1 Local Geology

Rocks that appear inside this structure (Fig. 7) are metadiamictites and phyllites of the subunit 7 (Luz et al., 1980), and metalimestones, metadolomites, metasiltites and metagraywacke of the subunit 8. Profiles performed from the base to the top of Serra da Guia allowed the identification of a faciological variation including metadiamictites, phyllites, metalimestones and metadolomites. In the basal portion, metadiamictites arise from a clay-sandy matrix with a coloration ranging from gray, greenish and reddish. The clasts are diverse in nature, but the most common are sandstones, quartzites, granites, limestone and mafic rocks, as well as quartz and feldspars. This rock is in part covered by a thick layer of laterite and soils

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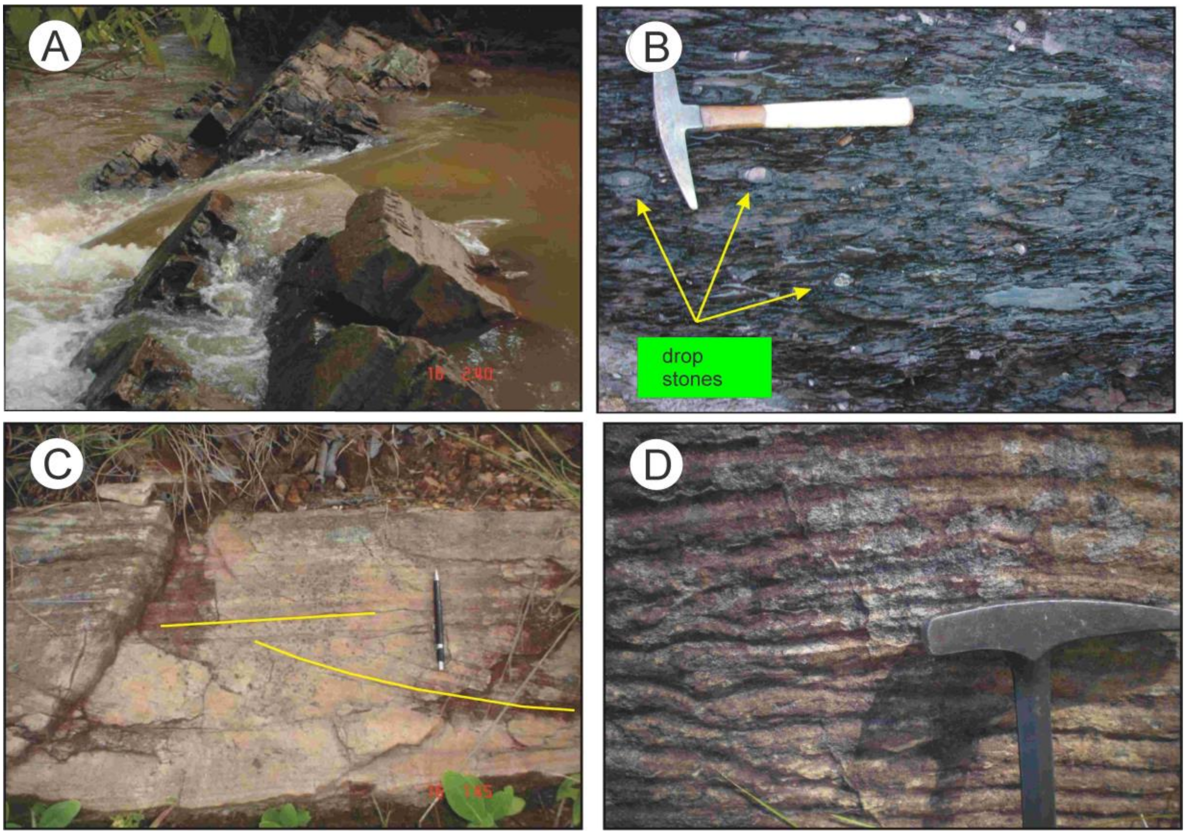

Fig. 6. Photos of rock structures from Nobres region. A - bedding S_0 in limestone with tectonic foliation. (B) Diamictites of Puga Formation (parallel to the hammer). C - Cross stratification of Araras Group. D - Symmetrical wave-formed ripple marks at the top of sandstone strata of Bauxi Formation.

The contact of these metadiamictites with upper calcitic metalimestone is sharp, besides a decrease in the clasts size towards the metalimestones that have a dark gray color. In this metalimestones package of approximately 140 m thickness, there are also alternations of relatively pure limestones with levels marked by the presence of terrigenous materials. Stratigraphically above, the metacalcitic rocks change to massive metadolomites with whitish color. On the metadolomites, in the top of the mountain, metasiltites of gray and yellowish colorations with the metalimestones and metadolomites restricted to the inner part of the syncline.

4.3.2 Structural Aspects

Structures are characterized by asymmetrical and inverse synform of kilometric dimensions that stands out in the devastated relief of the Cuiabá region due to its elevation and the presence of metalimestones in the core. Within this synform, the S0 bedding is easily visualized in the metadolomites related to the presence of alternating layers of terrigenous composition. In the metapelites, beyond composition, there is a change of coloration between thin layers of gray to yellowish color. On the other hand, in the metadiamictites and metadolomites is more difficult to distinguish this feature. On several fronts of the Guia quarry, it is possible to verify that the bedding is folded, and these folds have an axial plane of the foliation Sn that has direction N45ºE and varied dips, as observed in the northwest flank (reverse flank) where, sometimes, layers plunge into NW quadrant (usually at the mountain summit) and then to SE (at the mountain base). On the south flank, S0 direction is maintained but the dip values are shown to be smoother, and the layers always dip to NW. The S0 diagram of Figure 8A clearly shows the bedding folding.

The D_{n+1} phase generated the S_{n+1} foliation (Fig. 8B) marked by fractures in the calcitic metalimestones or as an axial plane of open folds with amplitude of a few meters in length. The average attitude is approximately N40ºE/50ºSE (Fig. 8C). This foliation is visible only in metagraywacke and metadiamictites.

The third phase D_{n+2} is represented by a cleavage spaced in the metalimestones and metagraywacke, but also appears as discrete plane (S_{n+2}) of open metric folds seen in the metasiltites in the internal portion of the synform or as crenulations and kink bands in the metadiamictites in the structure hinge. Its orientation is orthogonal to the other phases of deformation. Regionally, the third phase of deformation has axial plane marked by the presence of veins of quartz rich in gold. In the Guia syncline these fractures are filled by calcite and quartz, and locally contain pyrite of hydrothermal origin.

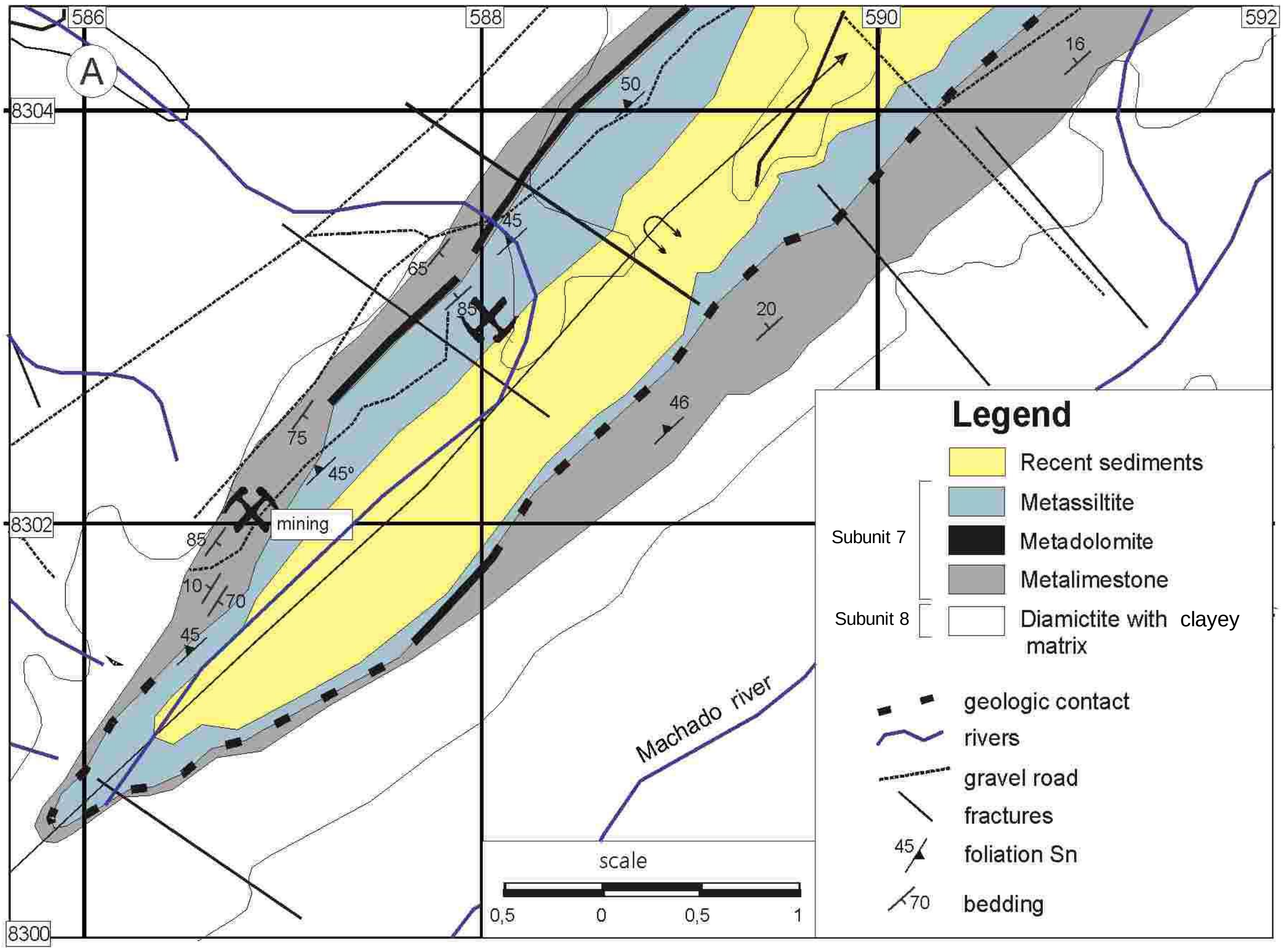

Fig. 7. Geologic map of Guia Syncline (adapted from Barboza et al., 2005).

The foliation S_n shows orientation parallel to the axial plane of the regional folds and is marked by planar micaceous minerals in the most plastic rocks (Fig. 9A) and by cleavage in the metalimestones.

In the metadiamictites, besides the planar organization of the micas, also containing in the foliated drop-stones plans involved in a clay-sandy matrix which also facilitates the identification of S_n in scale of outcrop. The orientation of this foliation (S_n) is N40º-45ºE with a dip between 40º and 60º to NW (Fig. 9B) and the folds axes show a smooth trim between 10º and 15º northeast as observed in the axes of the parasitic folds and the intersection lineage between S_0 and S_n.

In parallel to the S_n planes, there are centimetric to metric displacements which kinematic indicators show normal faults to SE (Fig. 9C and D). These planes, especially when they show block movement, are often filled with quartz and calcite veins In the studied region where the Guia syncline is observed, the contrasts of competence between the rock layers favor the development of folds (Fig. 9E), fractures and breccias formed by flexural slip mechanism (Fig. 9F). For example, in the Guia quarry, the calcitic metalimestones are folded, while the dolomites are fractured. The evidence of flexural slip (8 E and F) is recorded on S_n surface, with relief fractures filled by quartz and calcite veins.

4.4 Casa de Pedra gold deposit area

The Casa de Pedra deposit is located 35 km northeast of Cuiabá (Fig. 10) and rocks are very weathered, which makes it difficult to carry out studies aiming the characterization of the hydrothermal phases and their relations to the gold ore. Despite this, access to the samples from drilling holes, which undoubtedly was essential for the characterization of the metasedimentary units.

4.4.1 Local Geology

In the Casa de Pedra deposit occur rocks from the undivided subunit described in Luz et al. (1980) and that correspond to distal facies unit according to Alvarenga et al. (1990). In general, this subunit is composed of metadiamictites, quartzites, metasandstone, metasiltites and sericitic phyllites. In the open-pit of the Casa de Pedra deposit, the host rocks of the ore are represented mainly by a layer of sericitic phyllites with dark gray levels alternating with whitish levels enclosed by grayish metadiamictites.

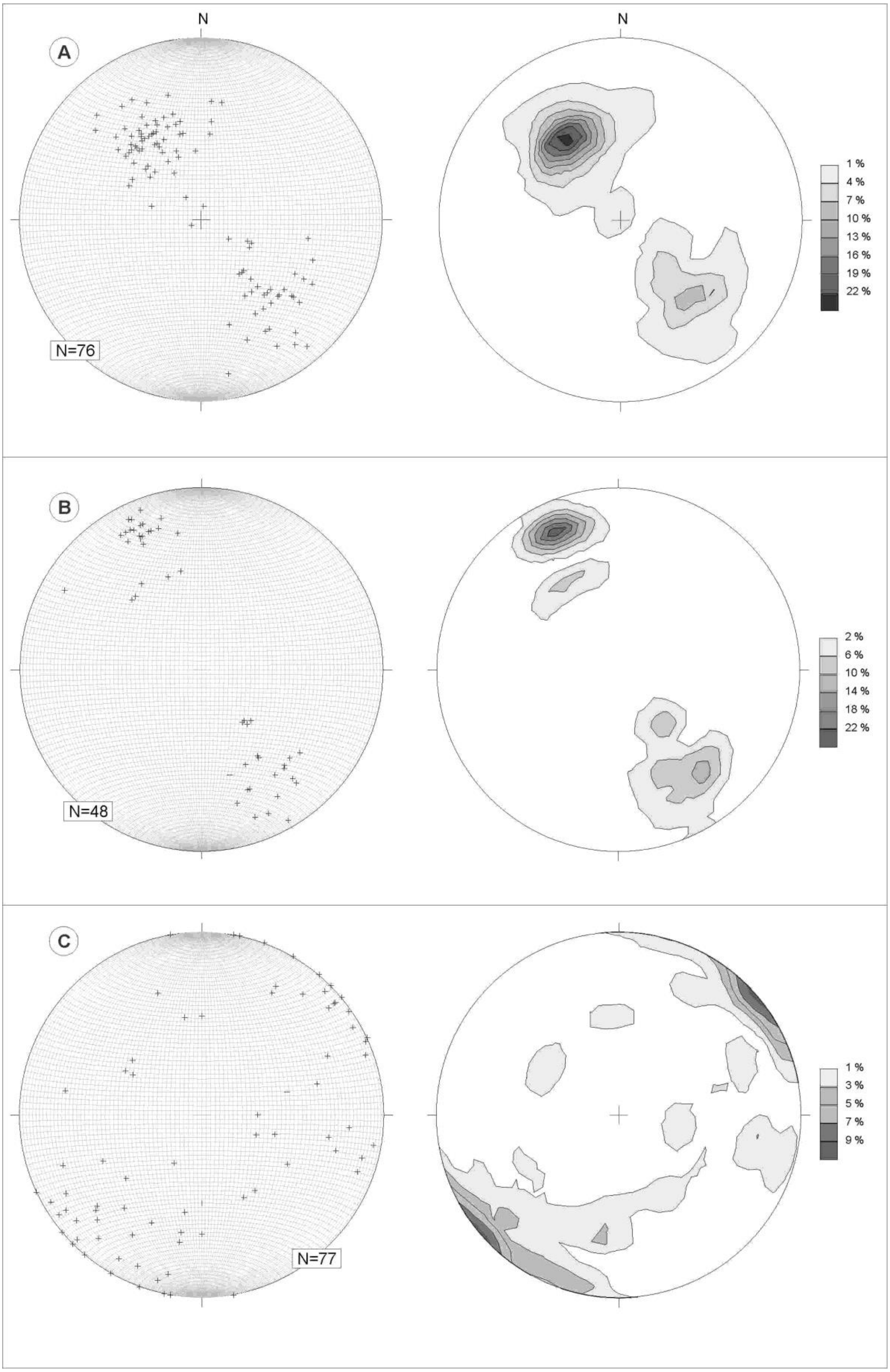

Fig. 8. Planar structures poles diagram measured in the Guia syncline. A - bedding S_0; B - foliation S_n; C - S_{n+1} fracture cleavage.

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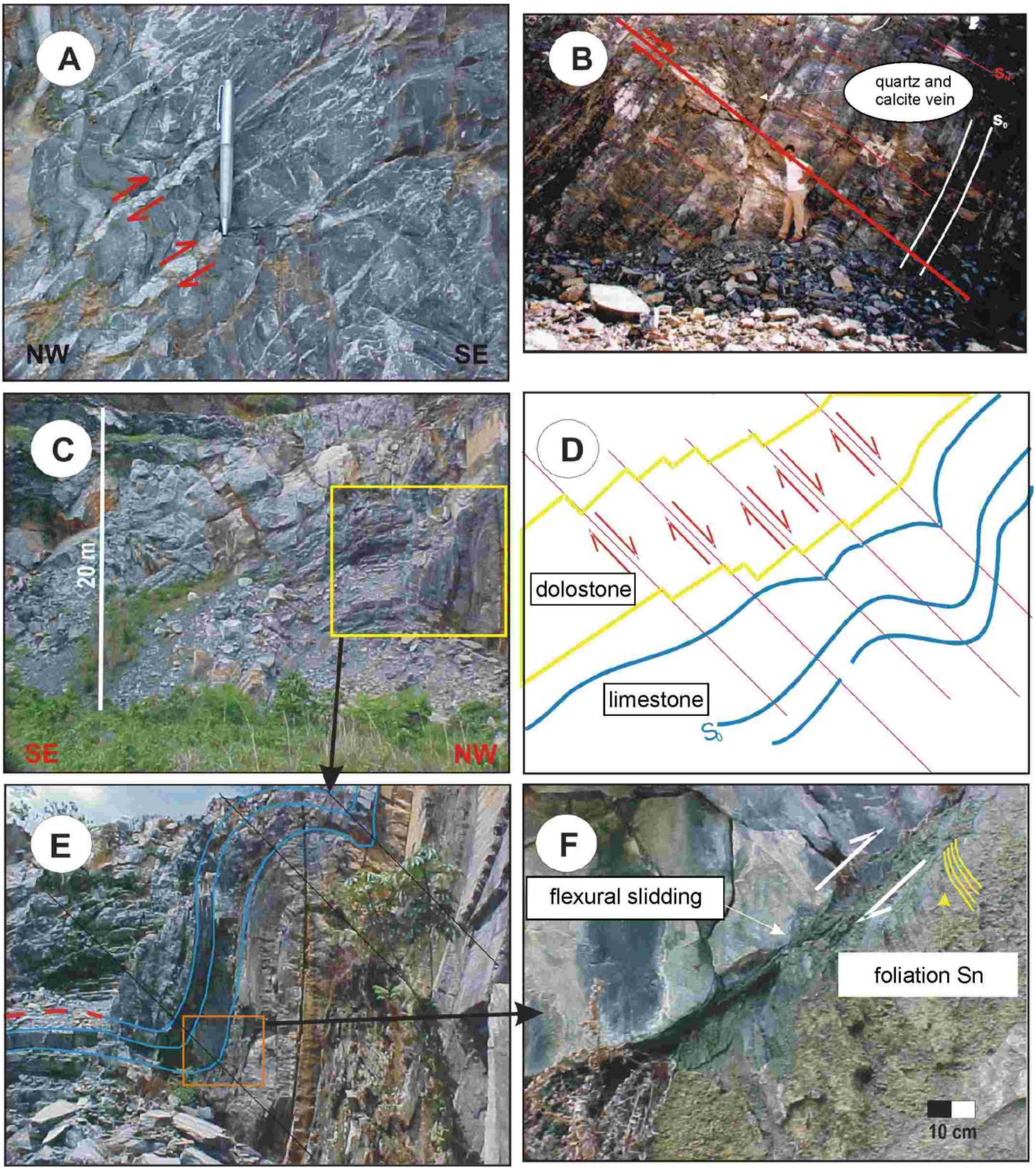

Fig. 9. Outcrops in the Guia Syncline. A and B - bedding cut by S_n foliation with quartz and calcite fillings; C - cava overview; D - interpretation of photo C (note the difference in rock competence between metalimestone and metadolomites); E - detail of C showing parasitic folds in metalimestones; F - flexural slip between layers of metalimestones (lower richer layer) with evidence of flexural slip.

When weathered, the sericitic phyllites, main host-rock of the ore, acquire wine-reddish tones making it similar to metasiltites. The mineral paragenesis associated with ore includes quartz, albite, orthoclase, chlorite, biotite, white mica, carbonates, as well as accessory minerals such as monazites and zircons. Sulfides are mainly represented by pyrite, chalcopyrite, galena and oxide; hematite has also been identified. The carbonate nodules described in host rocks of the Cangas auriferous veins are also present in the Casa de Pedra deposit, and the whole package is in an advanced weathering process.

The contact of the sericitic phyllites with the metadiamictites is gradational. The metadiamictites has sandy matrix where fragments of granites with sandstones, quartzites, granites, limestones and quartz. Although not seen as hosts of ore at the Casa de Pedra gold deposit, reports from a neighboring farm point out that metadiamictites also host veins rich in gold.

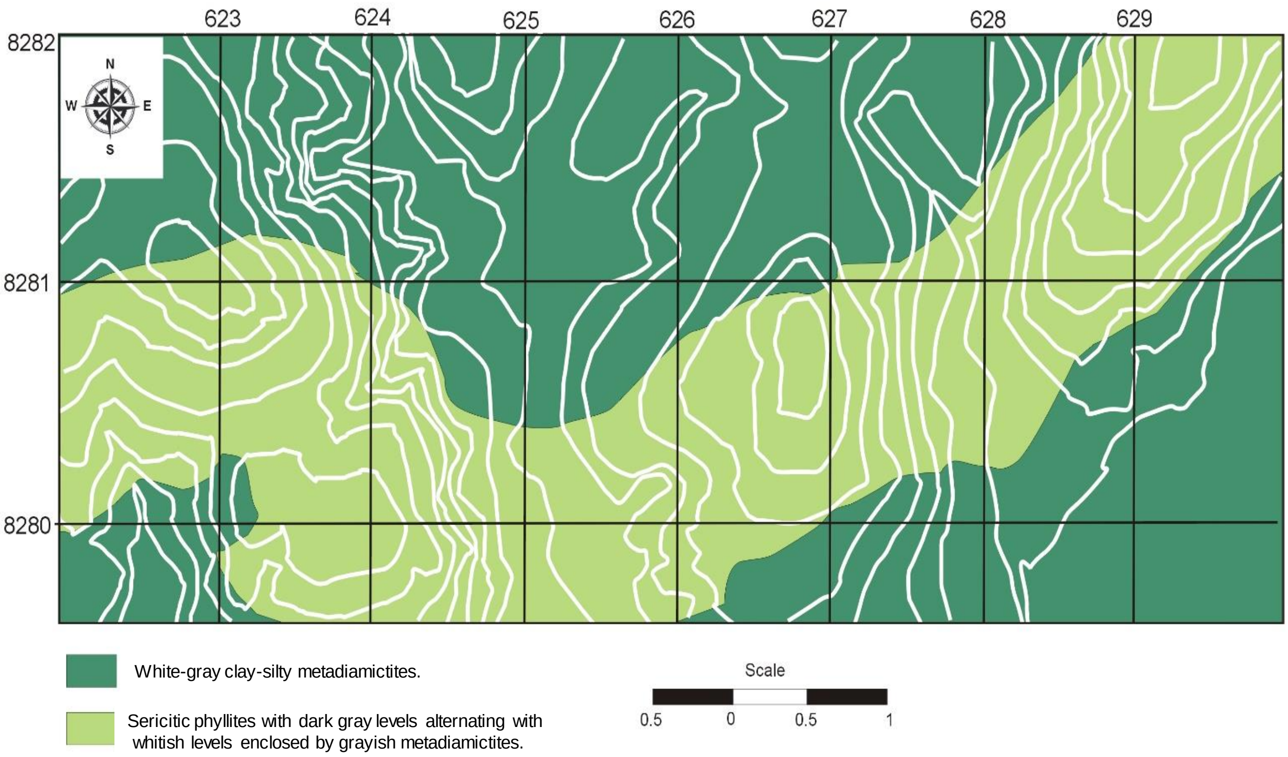

Fig. 10. Geologic map of Casa de Pedra area. The ore is comprised of sericitic phyllites.

4.4.2 Structural Aspects

The folded layers are oriented according to N50ºE with the dip mainly around 50º to NW (Fig. 11A). The axial plane S_n of these folds has directions between N20-50ºE with 25º dip to the northwest quadrant (Fig. 11 B), with the dip values occurring in the metadiamictites and in the phyllites and metasiltites, evidencing that there is a slight inflection in the S_n foliation which varies according to rocks competence. In the metadiamictites, S_n is well marked by the planar micaceous clasts and minerals. The surface S_{n+1} appears in the form of a fracture cleavages spaced in all deposit rocks, but eventually they were observed in crenulation forms. The axial plane fold defined by S_{n+1} has N40ºE direction and plunges around 70º to southeast (Fig. 11C). However, in some rocks, such as happen in diamictites near the open-pit of the Casa de Pedra deposit, it is possible to identify S_{n+2} as kink bands and crenulations.

The main planar structural features observed in the Casa de Pedra deposit includes the bedding S_0, and the foliations S_n, S_{n+1} and S_{n+2} (Fig. 12). The S_0 bedding is visually highlighted by the alternation between dark gray and whitish layers (Fig. 12A), which are folded in NE-SW direction showing vergence for SE. They are low angle folds and can be classified as asymmetrical and inverse. The folds (Fig. 12 B) have an axial plane marked by an intense cleavage (Figure 12 C), which is marked by sericite orientation and other micaceous minerals. The fracture cleavage S_{n+1} (Fig. 12 D) coaxial to S_0 and S_n and S_{n+2} fracture cleavage (Fig. 12 E and F) also occurs in the form of orthogonal kink bands (Fig. 12 G).

The intersection lines between S_n and S_0 are parallel to the folds axis and are orientated 35-40º with smooth dip around 10º. The mineral stretching lineation is visualized only in the diamictites outside the deposit area and is marked by the linear orientation of the flat fragments sub-parallel to the folds axis. Other remarkable structures in the vicinity of the Casa de Pedra deposit are faults, with planes parallel to S_n, which can sometimes be filled by quartz veins.

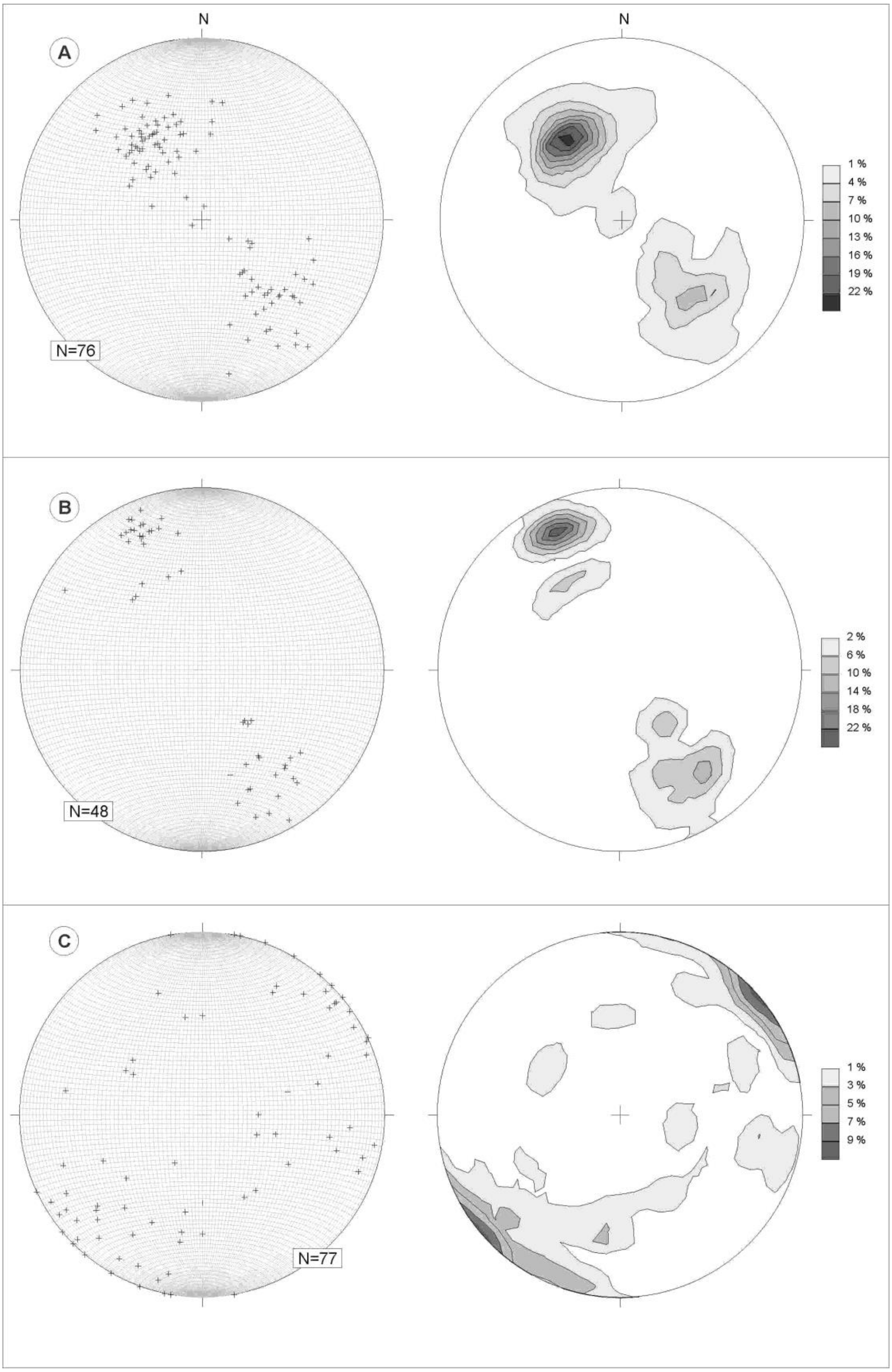

Fig. 11. Diagrams of planar structures found in the Casa de Pedra deposit. A - bedding S_0; B - foliation S_n; C - S_{n+1} fracture cleavage; D - cleavage spaced S_{n+2}.

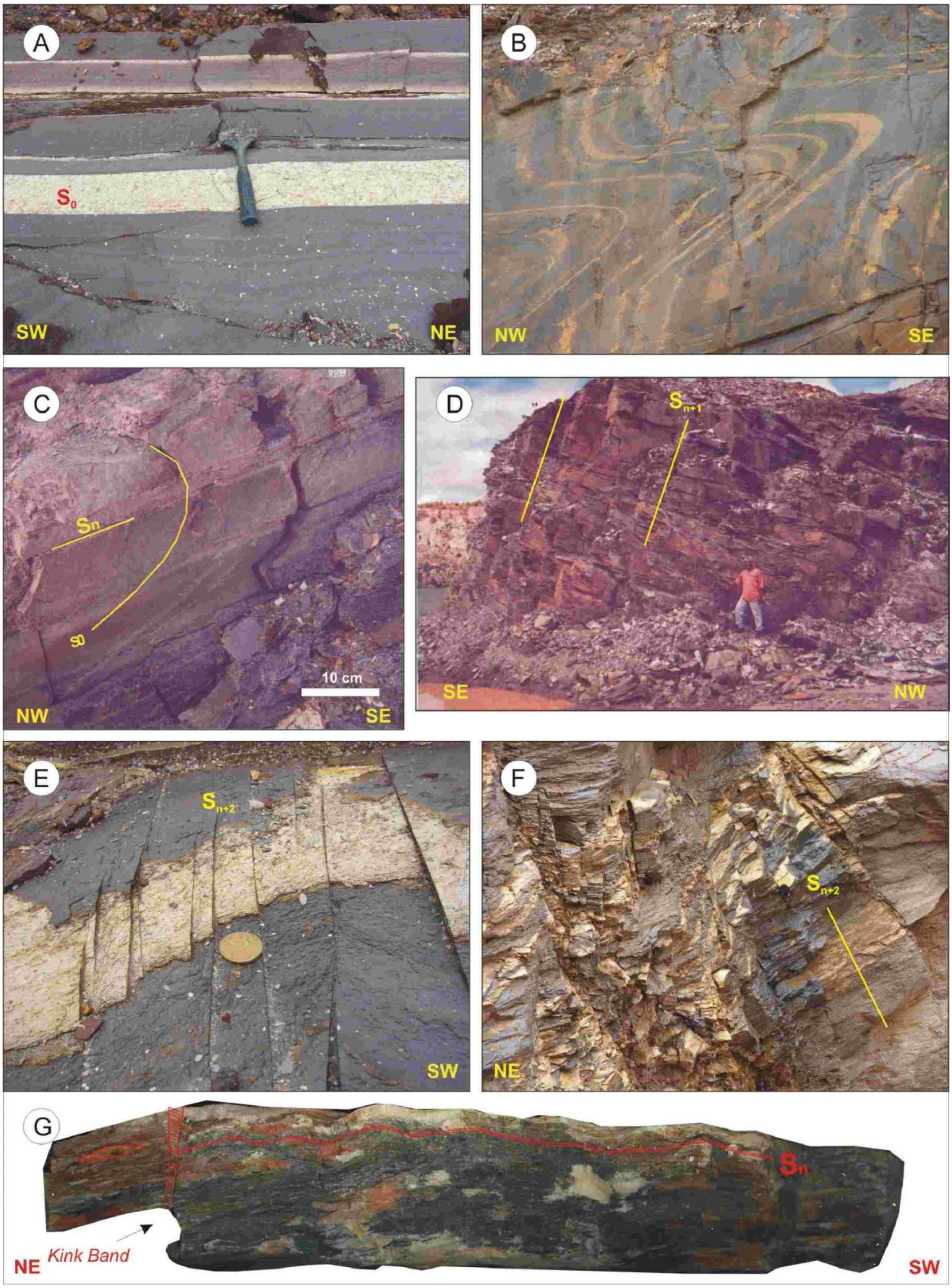

Fig. 12. Outcrops in the pit of the Casa de Pedra deposit. A - Bedding S_0 in plant; B - Bedding seen in section showing low angle folds; C - relationship between folded S_0 and axial plane foliation S_n; D - fracture cleavage S_{n+1}; E and F - fracture cleavage spaced, seen in plan and cut, respectively. G - S_{n+2} as kink bands and crenulations on diamictites.

5. Discussion

The profile along the Paraguay Belt rocks carried out in this investigation allowed to characterize the behavior of the structural features in the Paraguay belt rocks along a profile perpendicular to the strike and different stratigraphic levels. In the NW portion S_0 is folded with predominance of axial plane dipping to SE, passing from 0 to 10º on cratonic area, passing toward SE sequentially to different dips of S_0, with values around 80-90º dipping to NW. At the Nobres deposit area S_0 presents a dip 45º NW, and at Guia synclinal area 75º to NW; and near Casa de Pedra 75º to SE (Fig. 13).

The litho-structural survey made during the development of this study coupled with the descriptions of gold deposits and other sites visited individually suggest that, on a regional scale, continuous phases of deformation affected the rocks of the Cuiabá Group. The first deformation (D_n) has a ductile character and was responsible for the generation of asymmetric folds of regional scale showing vergence to SE in the Cuiabá and Poconé regions, passing gradually to NW towards the external zone, showing fan geometry (Fig. 12). The stretch lineation is marked by the alignment of flattened clasts in the S_n plane and show a gentle slope according to S_n surface. The second phase (D_{n+1}) is ductile and produced open and sometimes asymmetrical folds, with axial planes (S_{n+1}) plunging to SE. The axis of the folds D_{n+1} dip to NE; the folds dimensions vary between one and dozens of meters; cleavages of spaced fractures and kink bands are common.

The third phase (D_{n+2}) is orthogonal to the previous phases, has brittle characteristics and occurs as open folds on kilometric scales and locally as fracture cleavage spaced with plunging to SW and NE. In the gold deposits located in the Internal zone, the best gold contents are found in quartz veins that filled these fractures. Del'Arco et al. (1981) consider the origin of the deformations recorded in the rocks of the Paraguay Belt as a product of a tectonic event involving NW faults in a D_1 phase, followed by the formation of back-thrust to SE, in progressive phases D_2 and D_3.

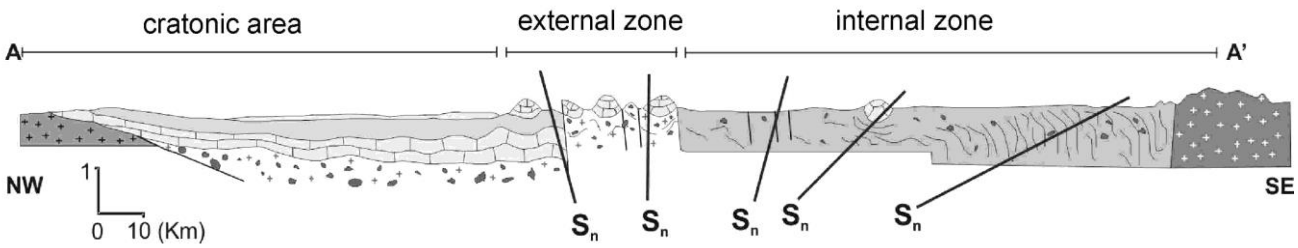

Fig. 13. Regional profile suggesting fan geometry across the Paraguay Belt strike.

Rocks that appear in the region of Nobres include the diamictites (or tilites) of the Puga Formation deposited over sandstones of the Bauxi Formation, calcitic and dolomitic limestones of Araras Formation which top contains silica-rich levels similar to those described by Figueiredo et al. (2004, 2006) as the Serra Azul Formation, covered by sandstones and conglomerates of the Raizama Formation.

In the region of Nobres and Rosario d'Oeste, the external portion of the Paraguay Belt, the folds are generally symmetrical to slightly asymmetrical, but in the outcropping scale some folds have a significant asymmetry. In addition to the S_0 bedding, the tectonic foliations S_n and S_{n+2} were also visualized. The foliation S_n appears as an axial plane of D_n folds and present high (70º) dips for SE near Rosário d'Oeste and verticals in the north of Nobres region.

According to Luz et al. (1980), in the Guia syncline rocks of subunits 7 and 8, the lower subunits portion are comprised of metadiamictites, composed of clay-sandy matrix clasts-supported of diverse nature, including sandstones, quartzites, granites and basic rocks. Towards the stratigraphically superior portion, the observed rocks are metadiamictites with sharp contact with metalimestones. The dominant calcitic metalimestones are dark gray in color, occurring in the form of a layer ca. 140 m thick with impure levels of terrigenous sediments in the middle of the package. Transitionally, calcitic metalimestones pass to massive, light gray to whitish metadolomites. The metadolomites, in turn, evolve from yellow to gray metasiltites.

In Serra da Guia, D_n folds configure as main structure an asymmetric isoclinal and inverted synform that shows SE vergence. The axial plane foliation S_n occurs as cleavage with direction N40º-45ºE, and dips between 40º-60º to NW. The fracture cleavage and folds axial plane presenting metric dimensions and fracture cleavage (S_{n+1}) are oriented according to N40ºE/50ºSE. The foliation S_{n+2} appears as fracture cleavage, crenulations and kink bands orthogonal to the other planes and oriented mainly according to N50ºW/80°SW.

In the region of the Casa de Pedra deposit, the rocks correspond to those described by Luz et al. (1980) as an undivided subunit. The outcropping rocks in the open-pits are mainly sericitic phyllites and rare layers of medium to fine metasandstone. The predominant phyllites, when weathered, show a reddish-wine color becoming similar to

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metasiltites. In the open-pit vicinity, there are diamictites of silt-sandy matrix clasts-supported composed of sandstones, quartzites, granites and basic rocks.

5.1 Implications of the geological evolution of the Orogen

The Paraguay Belt fan geometry observed in the Sn foliation was developed during the closing of a Brazilian ocean that evolved between the Paranapanema Block (Alvarenga et al., 2004; Barboza et al., 2006) and the Amazonian Craton and Rio Apa Block (Tassinari et al., 2000; Geraldes et al., 2001). The tectonic evolution of Paraguay belt occurred in four steps: Extensional (sedimentation); Inversion (thrusting); Collision (metamorphism and magmatism) with Crustal duplication (metamorphism and deformation) (Fig. 14). Tectonic implications such as the geometry of the edges of these tectonic units are directly associated to the configuration of cratonic fragments. The deformation phase Dn is recorded in the rocks of the Internal portion of the Paraguay Belt as regional folds of NE-SW direction with NE plunge. This phase of deformation generated the axial plane foliation Sn that regionally shows clear vergence for NW (dips to SE) in the vicinity of the Amazonian Craton in the region of Rosário d'Oeste, turning almost vertical in Acorizal and smooth dips to NW near Cuiabá, where the folds show vergence for SE.

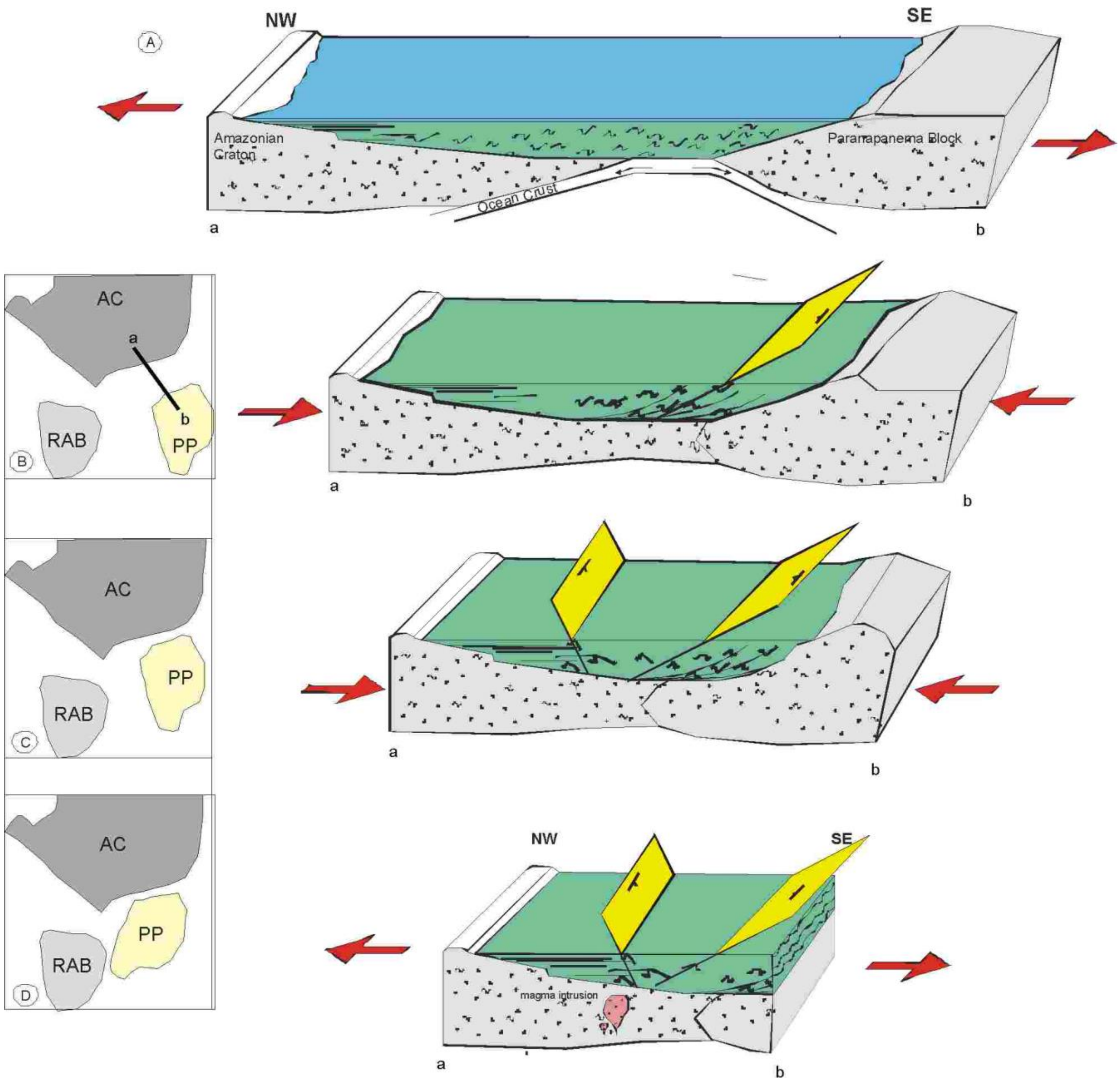

Fig. 14. Tectonic evolution of Paraguay belt in four steps: (A) Extensional (sedimentation) with formation of oceanic crust; (B) Inversion (thrusting); (C) Collision (metamorphism and deformation); (D) Crustal duplication (metamorphism and magmatism). AC = Amazonia Craton; PP= Paranapamenema Block; RAB= Rio de La Plata Block.

The Dn deformation, imprinted in the rocks of the Cuiabá Group the foliation Sn, which probably was developed due to the tension applied by the Block Paranapanema on the sedimentary rocks. Initially Sn foliation had its planar geometry plunging to SE in the region of Cuiabá, later the progressive deformation continued, due to the resistance offered by the crustal fragment and a dip inversion in the most distal portions in relation to the Amazonian Craton and Rio Apa Block where Sn started dipping to NW configuring a fan geometry.

6. Conclusion

The investigation of stratigraphic and tectonic features of the sedimentary rocks along a profile crossing the structures of Paraguay bell allowed to suggest the following conclusions:

- During or even before the break of the supercontinent Rodinia, a separation of tectonic blocks occurred that allowed the installation of a passive margin basin in the S-SE portion of the Amazonian Craton. The geological characteristics of the sediments deposited in this basin suggest that the sedimentation occurred in deep sea-glacial environments with active turbidity current, attested by the presence of metadiamictites and conglomerate metasandstone locally alternated with phyllites and carbonaceous phyllites.

- The constant changes in sea level may have led to the occurrence of turbidity currents as suggested by the presence of chemical sediments alternating with siliciclastic materials, of different grain size and origin present in the subunits. The abrupt alternations between carbonatic rocks, sandstones, diamictites and layers rich in hematite and magnetite suggest an oxidizing environment during the deposition of the sediments, which characteristics reflect abrupt modifications in the depositional environment. The deposition of carbonaceous material was alternated with siltstones and formed centimetric levels with dark gray and light gray layers, probably reflecting the alternation between reducing and oxidizing depositional conditions.

- Above the carbonatic rocks ascribed as end of Marinoan glaciation are observed deposits represented by an alternation of phyllites, metadiamictites, metaconglomerates, metasandstone, being possible to identify light gray to greenish gray colors and fine to very fine granulation. In the middle of this package the presence of phyllites or diamictites with graphite matrix is common. The metadiamictites and phyllites are predominante, present similar matrix with alternations of quartz and micaceous levels. The difference between these rocks is in the addition of clasts in the metadiamictites, which are quartzite, metasandstone and granitic rocks. These rocks may be related to the Gawkier glaciation.

- Metamorphism and deformation show ages slightly above 500 Ma, since the rocks of the Cuiabá Group were intruded by the late-tectonic São Vicente Granite with 504 ± 6 Ma. In this way, during the deformational process, Sn features are folded with predominance of Sn dips (parallel to S_0) for SE (in the External area), passing to 25º to 30º for SE (in central area), passing sequentially to dips around 45º NW at Guia synclinal, 75º for NW in the Internal area, near Nobres. Initially Sn had its planar geometry plunging to SE, later the progressive deformation promoted, due to the resistance offered by the cratonic fragments, an inversion of the dip in the most distant portions in relation to the Amazonian Craton and Rio Apa Block where Sn started to dive to NW by configuring a fan geometry.

- The fan geometry of the Sn foliation was developed during the closing of a Brazilian ocean that evolved into the clash between the Paranapanema Block and the Amazonian Craton and Rio Apa Block. Tectonic implications such as the geometry of the edges of these tectonic units and aspects related to rheology are directly associated to the configuration of this foliation. The deformation phase Dn is recorded in the rocks of the inner portion of the Paraguay belt as regional folds of NE-SW direction with NE strike. This phase of deformation generated the axial plane foliation Sn that regionally shows clear vergence for NW in the vicinity of the Amazonian Craton in the region of Rosário Oeste, passing to the verticality near Acorizal and smooth dips to NW near Cuiabá, where the folds show vergence for SE. The Dn deformation imprinted on the rocks of the Cuiabá Group the foliation Sn which probably developed due to the tension applied by the Block Paranapanema on the Amazonian Craton and Rio Apa Block.

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