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ARTICLE

The thrust contact between the Canastra and Vazante groups in the Southern Brasília Belt: structural evolution, white mica crystallinity and implications for the Brasiliano orogeny

O contato do empurrão dos grupos Canastra e Vazante na Faixa Brasília Meridional: evolução estrutural, cristalinidade de mica branca e implicações para a Orogenia Brasiliana

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ABSTRACT: Two regional thrust-sheets of Neoproterozoic metasedimentary rocks occur in the Southern Brasília Belt, northwest Minas Gerais. The lower one comprises the Vazante Group, that is formed in the studied area, from base to top, by the Serra do Garrote (metapelites interlayered with carbonaceous phyllite), Serra do Poço Verde (beige to pink stromatolitic metadolomite with interlayered greenish slates), Morro do Calcário (gray stromatolitic metadolomite interlayered with gray slates) and Serra da Lapa (phyllite with dolarenitic lenses interlayered with slates) formations. The upper thrust sheet consists of the Canastra Group (Paracatu formation): laminated sericite phyllites and carbonaceous phyllites interlayered with quartzite. The Braziliano orogeny resulted in four phases of contractional deformation, associated with low-grade metamorphism. The first two (D_1 and D_2) are ductile, while the third and fourth ones (D_3 and D_4) are brittle-ductile. D_1 developed a slaty S_1 cleavage subparallel to the primary layering, with shallow to steep dips to NW. D_2 developed a crenulation cleavage (S_2) that dips moderately to NW and is associated with tight to isoclinal folds. D_3 and D_4 phases developed crenulations and open folds and kink bands. S_3 dips steeply to NW, while S_4 has moderate to steep dips to NE and SW. White mica crystallinity (Kübler index) measurements in metapelites indicate that both the Canastra and Vazante groups reached anchizone/epizone conditions, and metamorphic discontinuities along thrusts indicate that the peak of metamorphism is pre or syn-thrusting.

KEYWORDS: Neoproterozoic, Zinc-Lead, X-Ray Diffraction, Thrust-fold Belt.

RESUMO: *O contato do empurrão dos grupos Canastra e Vazante na Faixa Brasília Meridional: evolução estrutural, cristalinidade de mica branca e implicações para a orogenia brasiliana. Duas escamas de cavalgamentos regionais de rochas metassedimentares neoproterozoicas ocorrem na Faixa Brasília Meridional, em Minas Gerais. A inferior compreende o Grupo Vazante, que na área de estudos é formado da base para o topo, pelas formações Serra do Garrote (metasiltitos e filitos carbonosos intercalados), Serra do Poço Verde (metadolomitos estromatolíticos bege a rosados com intercalações de ardósias e margas esverdeadas), Morro do Calcário (metadolomitos estromatolíticos cinza com intercalações de ardósias cinza) e Serra da Lapa (metarritmitos carbonosos com lentes de dolarenitos). A escama superior é composta do Grupo Canastra (formação Paracatu): sericita filitos laminados e filitos carbonosos com intercalações de quartzitos. A deformação resultou em quatro fases de deformação compressivas, contemporâneas ao metamorfismo de baixo grau. D_1 e D_2 são de caráter dúctil, enquanto D_3 e D_4 são de regime rúptil-dúctil. D_1 foi responsável pela clivagem ardosiana S_1 subparalela ao acamamento sedimentar, com mergulhos baixos a altos para NW. D_2 desenvolveu clivagem de crenulação (S_2) que mergulha moderadamente para NW e está associada a dobras apertadas a isoclinais. D_3 e D_4 desenvolveram crenulações espaçadas e dobras abertas com kinks associadas. S_3 apresenta eixos para NW, e S_4 eixos para NE e SW, ambas com caimento moderados a altos. Medições por cristalinidade de mica branca (índice de Kübler) sugerem que os grupos Canastra e Vazante alcançaram condições de anquizona/epizona, e descontinuidades metamórficas ao longo dos planos de cavalgamento indicam que o pico metamórfico é anterior ou contemporâneo à tectônica de cavalgamento.*

PALAVRAS-CHAVE: *Neoproterozoico, Chumbo-zinco, Difração de raios X, Cinturão de dobramentos e cavalgamentos.*

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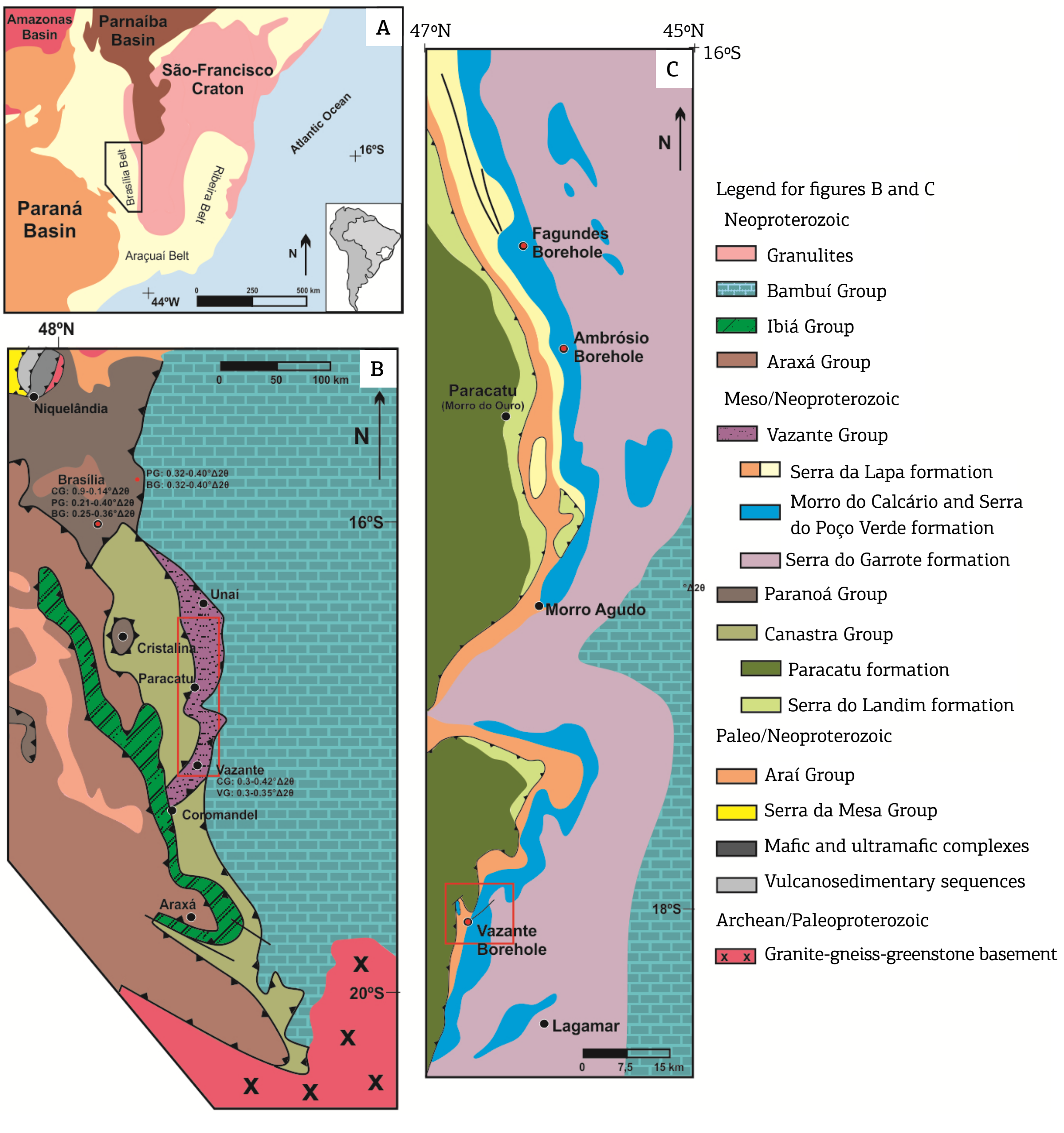
INTRODUCTION

Since the discovery of zinc deposits within the Vazante Group metasedimentary rocks, in the early 20th century, several structural and petrological studies have been carried out in this external portion of the Southern Brasília Belt (Figs. 1A and 1B), located in northwest Minas Gerais State (Dardenne 2000, Valeriano *et al.* 2004, 2008).

The Vazante Mine — with presently total assets of 40–60 Mt to 20% Zn — is the world's largest deposit of hydrothermal nonsulfide zinc (willemite), and it is operated by Votorantim Metais (Baia 2013). The zinc ores are associated with a steeply dipping fault of NE–SW strike direction, the Vazante Fault, and are hosted in the metadolomitic rocks of the Vazante Group, which are in contact with the metapelitic rocks of the Canastra Group.



GC: Canastra Group; BG: Bambuí Group; PG: Paranoá Group; VG: Vazante Group (Dardenne 2000).

Figure 1. Geological location of the study area. (A) Tectonic provinces of the South American platform (Dardenne 2000) with the Brasília Belt in black; (B) Southern Brasília Belt with location of the Paracatu–Vazante zone, of the study area (red rectangle) and of samples analyzed by Campos *et al.* (2015) in red circles; (C) geological map of the Vazante Group (Monteiro *et al.* 2006), with location of the boreholes in Vazante, Ambrósio and Fagundes areas (red dots).

The Vazante deposit (Fig. 1C) is part of an important belt of mineral deposits hosted by low-grade metasedimentary rocks of the external Brasília Belt, which also includes the Morro Agudo, Ambrósio and Fagundes lead and phosphate deposits, and the Morro do Ouro gold mine (Pinho 1990, Monteiro 2002, Monteiro *et al.* 2006, Diniz-Oliveira 2013, Slezak *et al.* 2014)

In this region (Fig. 1), the main geological feature is the thrust contact between the phyllites and quartzites of the Canastra Group and the underlying metapelites and dolomitic rocks of the Vazante Group (Dardenne 2000). Over the years, many proposals on the hierarchy of the deformation phases in the Southern Brasília Belt have been discussed (Campos Neto 1984a, Pinho *et al.* 1989, 1990, Pinho 1990, Pereira 1992, Pinho & Dardenne 1993, Rostirolla *et al.* 2002), and will be detailed further in this work. In addition, new knowledge (Campos *et al.* 2015) related to the metamorphic conditions was accepted by recent studies of X-ray diffraction (XRD) in the rocks from the Canastra Group, located in Distrito Federal and Goiás state (Fig. 1B).

Despite those studies, there still are many uncertainties about the geological history of stratigraphic and tectonic evolution of the host metasedimentary basin of the mineralization, especially the Canastra and Vazante groups. This study aimed to characterize in more detail the petrography and structural evolution of the important contact zone between the Canastra and Vazante groups surrounding the Vazante mine area. An area of 400 km^2 was mapped at the scale of 1:100,000 in conjunction with structural analysis and petrographic characterization, with the objective to compare the tectonic evolution of these two important lithostratigraphic units (Carvalho 2013, 2015, Carvalho *et al.* 2014, 2015, González *et al.* 2014).

White mica crystallinity determinations by XRD (Yang & Hesse 1991, Verdecchia *et al.* 2011) were carried out in metapelites (slates and phyllites) in order to better characterize the degree of regional metamorphism, and whether any of the mapped thrust surfaces constitute important metamorphic discontinuities.

GEOLOGICAL SETTING

The Brasília Belt (Fig. 1B) is one of the most important geotectonic domains of Central Brazil and it is a thrust-fault complex of Neoproterozoic passive margin metasedimentary successions that were thrusted eastward against the western margin of the São Francisco Craton (Dardenne 2000, Valeriano *et al.* 2004, 2008), during the Brasiliano Neoproterozoic orogenic collage of the Gondwana supercontinent (Almeida 1967, Almeida & Hasui 1984, Neves *et al.* 1990), with the convergence of the Amazon, São Francisco and Paranapanema paleocontinental blocks (Almeida 1977, 1981, Neves *et al.* 1999, Dardenne 2000, Valeriano *et al.* 2004, 2008).

The Brasília Belt consists of (Figs. 1A and 1B): a granite-greenstone-gneiss basement (Freitas-Silva 1996); the Goiás Magmatic Arc; the Goiás Massif; the Northern Brasília Belt (NE orientation), formed by Araí, Serra da Mesa and Paranoá groups and the Palmeirópolis, Juscelândia and Indaianópolis volcano-sedimentary sequences (Valeriano *et al.* 2004); and the Southern Brasília Belt (NW orientation), whose allochthones portion consists of tectonic stacking of stratigraphic terranes related to Araxá, Ibiá (Fernandes *et al.* 2014), Canastra, Vazante and Bambuí groups.

The Southern Brasília Belt shows a general increase in deformation and metamorphism from the cratonic zone to west, ranging from anchimetamorphic sediments in the former area to granulite facies rocks in the uppermost allochthons.

Studies dealing with the tectonic evolution of the Southern Brasília Belt in the Passos Nappe segment, south of the study area, indicate an inverted metamorphic zonation caused by a deflection of isotherms in a subduction zone setting and continuous non-coaxial shear expulsion of high-pressure rocks towards shallow crustal levels (Simões 1995), on top of the external thrust-fold belt of low-metamorphic grade. Biotite-bearing phyllites and schists occur along the base of the Passos Nappe, whereas the metapelitic rocks of the underlying thrust-fold belt are slates and phyllites of lower-metamorphic grade indicated by quartz-chlorite-white mica assemblages (Simões 1995, Valeriano *et al.* 2000).

The metamorphic peak in the upper Passos Nappe is pre or syn D_2 and occurred about 630 Ma (Seer & Dardenne 2000), followed by a retrogressive metamorphic event during nappe exhumation at ~610 Ma (Valeriano *et al.* 2004). The youngest K-Ar cooling on white mica around 600 Ma in the Passos Nappe, and around 590 Ma in the external thrust-fold domain (Valeriano *et al.* 2000), provides a time limit for the thrust stacking in the Southern Brasília Belt.

The deformational evolution of the Brasília Belt is consensually polyphased, involving early sin-metamorphic low-angle nappe emplacement followed by later folding and faulting at shallower crustal levels.

Deformational evolution of the Araxá and Passos upper metamorphic nappes (Valeriano 1992, Simões 1995, Seer & Dardenne 2000) involves early D_1 sub-horizontal isoclinal folding, transitioning into D_2 tight to isoclinal folds, associated with tectonic transport to ESE direction, overprinted by D_3 and D_4 normal folding and crenulation, associated with sub-vertical faulting. Metamorphic mineral associations indicate a late-D_2 retrogressive event associated by those authors as related to nappe exhumation.

In the underlying low-metamorphic grade thrust-fold belt, geometric models for the deformational evolution of Ibiá, Canastra and Vazante groups vary among several previous studies, but generally with a similar overall history involving early thrusting and late folding and faulting. Campos Neto (1984a) distinguished between seven phases of deformation in the Canastra and Vazante group rocks, north of the study area: the first two are ductile and related to the orogenic paroxysmal period with SW folding; the following three are also ductile, but related to a late period, respectively, of thrust-sheets parallel to the principal structures, NW and NE folding; and the last two are brittle-ductile, involving E–W folding and transverse faulting. Pinho *et al.* (1989, 1990), Pereira (1992) and Pinho and Dardenne (1993) defined only two deformation phases in the Canastra Group near Coromandel town, south of the study area: a first one of regional character related to shear zones and thrust belts that were responsible for the formation of the main penetrative foliation parallel to subparallel to primary layering; and a second one limited to kink bands, tension gashes and crenulations.

Two previous studies were performed around the Vazante Fault, within the study area of Vazante Group rocks. Pinho (1990) differentiated between four phases of deformation: the first two related with heterogeneous, brittle-ductile simple shear zones in progressive ductile regime; a third compressional phase characterized by reverse faults in ductile-brittle regime; and a last, extensional phase. Rostirolla *et al.* (2002), however, reported five deformation phases: the first two formed by heterogeneous brittle-ductile simple shear in a progressive ductile regime, the third one producing a ductile-brittle sinistral transcurrent pattern, and the last two developed under an extensional regime, with development of tension gashes.

Both the Canastra and Vazante groups were deposited in the context of the Meso to Neoproterozoic passive margin basin along the southwestern margin of the São Francisco Craton, during the break-up of the São Francisco–Congo craton by west-directed subduction and consumption at 900–950 Ma (Neves *et al.* 1996). The main structural deformation and metamorphic grade occurred at 650–610 Ma, during the Brasiliano orogeny (Pimentel & Fuck 1992).

XRD studies by Campos *et al.* (2015) have shown that the rocks of the Canastra Group located in Distrito Federal and Goiás state (Fig. 1B) are composed of quartz and muscovite with Kübler Index (KI) Full Width Half Maximum (FWHM) values ranging from 0.09 to 0.14°Δ2θ for fractions of less than 2 μm, and from 0.30 to 0.37°Δ2θ for fractions of less than 0.2 μm. These values, although not corrected according to the methods proposed by Warr & Rice (1994), indicate epizone metamorphism, while underlying rocks from the Bambuí and Paranoá groups exhibit Kübler index values within the transition between diagenesis-anchizone and anchizone-epizone. There is no metamorphic data available from the Vazante Group, but, as for the Canastra Group, it is considered to be of very low-metamorphic grade.

Canastra Group

The Canastra Group succession is regarded as a regressive megacycle that grades from continental shelf facies dominated by currents, and shallow platform facies dominated by storms. The Canastra Group consists of alternations of quartzite and carbonaceous phyllite with lateral and vertical gradations (Pinho & Dardenne 1993) and subordinate carbonate facies. It is divided, from base to top, into the following formations (Freitas-Silva 1991, 1996, Campos Neto 1984b, Dardenne 2000): Serra do Landim (greenish calc-phyllite and calc-schist); Paracatu (carbonaceous phyllite rich in organic matter and pyrite interlayered with white quartzite); and Chapada dos Pilões (regular intercalations of phyllite rich in organic matter and pyrite and quartzite on base and top).

U-Pb ages of detrital zircons from quartzites of the Canastra Group indicate a cratonic (Paleoproterozoic to Archean) provenance with subordinate Mesoproterozoic (possibly anorogenic) zircons of 1.2 to 1.5 Ga (Valeriano *et al.* 2004, Rodrigues 2008). Nd model ages of metapelitic rocks from this unit between 1.90 Ga and 2.34 Ga also support cratonic sources (Pimentel *et al.* 2001, 2011).

Vazante Group

The Vazante Group (Dardenne 2000, Valeriano *et al.* 2004, Babinski *et al.* 2005) extends about 250 km in the N–S direction, and is predominantly composed of carbonate rocks interlayered with metapelitic rocks. It is regarded as shallow platform facies dominated by tidal currents, represented, from base to top, by the following formations: Retiro/Santo Antônio do Bonito Formation — basal unit of white quartzite and conglomerates interlayered with pelitic levels; Rocinha Formation — rhythmic sandstones and slates; Lagamar Formation — psammo-pelitic carbonate unit with alternating conglomerates, quartzite, metasiltstone and slates; Serra do Garrote Formation — dark to greenish gray carbonaceous slates, sometimes rhythmic, interlayered with quartzite; Serra do Poço Verde Formation — gray to pink metadolomite interlayered with greenish metapelite and marble, subdivided into Morro do Pinheiro and Pamplona members; Morro do Calcário Formation — stromatolitic metadolomite associated with oolitic and oncolytic limestones; and Serra da Lapa Formation — consisting of carbonaceous phyllite with metasiltstones, metadolomite lenses and minor quartzite levels.

The Vazante Group age of sedimentation is dated between 1.35 and 0.95 Ga based on its stromatolite associations (Dardenne 2005, Dardenne *et al.* 2005), 1.1–1.0 Ga according to Re–Os ages (Azmy *et al.* 2008), and detrital zircon U-Pb ages (Rodrigues 2008, Rodrigues *et al.* 2012), indicating a sedimentation age younger than 935±14 Ma.

METHODS

Field and petrographic studies

The field studies involved detailed geological mapping of an area of 400 km^2 with characterization of the lithostratigraphic units of the thrust-contact between the Canastra and Vazante groups, and the geometry and superposition of deformational phases. This characterization was associated with petrographic examination of thin sections of selected samples of both units.

White mica crystallinity studies by X-ray diffraction analysis

Whole-rock white mica crystallinity by XRD analyses were carried out in the Centro de Investigaciones de Minerales Arcillosos (CIMAr) of the Universidad Nacional del Comahue, Argentina, for the measurement of KI of metapelites of the Canastra and Vazante groups.

Whole rock and clay minerals were identified using a Rigaku DMAX-2D diffractometer, employing Cu radiation, with a step size of 0.05°2θ and scanning speed of 0.01°/min, at 40 kV and 20 mA. The preparations of the total rocks were scanned from 3° a 65°2θ, and the clay minerals (< 2 μm) were scanned from 40°2θ a 2°2θ. Clay-size fraction (< 2 μm) samples for XRD analysis were prepared following the recommendations of Moore and Reynolds (1997). A < 2 μm fraction, assumed to be representative of the neo-formed and transformed phases and conventionally used for main crystallographic index measurements, was separated from 10 metapelite samples. Clay-mineral composition was established by the comparison of orientated aggregates that were air-dried (AD), ethylene-glycol solvated (EG; 24 hours), and heated at 500°C (H500; 4 hours).

The XRD reflections were evaluated with the Rigaku software. Quantitative analyzes of the clays were performed following the mineral intensity factor method described by Moore and Reynolds (1997). For quantitative estimation of phyllosilicate, the NEWMOD III program was used. The KI (Kübler 1968, Kish 1991) was measured in the white mica (001 crystallographic plane) reflection by the FWHM parameter of program, in AD oriented clay mineral aggregates.

Crystallinity Index Standard (CIS) and KI values (Warr & Rice 1994) were established from the regression equations (1.0316x + 0.0781, R 2: 0.9945) for the diffractometers employed.

The interpretation of KI for diagenesis and metamorphism is using the following boundaries for 0.25 and 0.42°Δ2θ: more than 0.42° is diagenetic zone; between 0.25° and 0.42° the anchizone; and below 0.25° the epizone (Campos *et al.* 2015).

RESULTS

Lithostratigraphic units

The geologic map of the study area (Fig. 2) shows that the Canastra and Vazante Group rocks are in thrust contact, and therefore represent two tectonic terranes with distinct lithological and deformational characteristics. The Canastra Group, within the studied area, is represented only by the Paracatu formation quartzites and phyllites, thrusted over the carbonatic-pelitic rocks of the Vazante Group, represented by four units (from base to top): Serra do Garrote, Serra do Poço Verde, Morro do Calcário and Serra da Lapa formations (Figs. 2 and 3).

Canastra group

The local apparent thickness of the Canastra Group is 800 m, of which 600 m are quartz-sericite phyllite interlayered with carbonaceous quartzite and 200 m are laminated slates (Fig. 3).

The quartz-sericite phyllite is a fine grained carbonaceous rock of gray color, with millimeter-thick quartzite lenses. The mineralogy consists of quartz, plagioclase, K-feldspar, white mica, chlorite and anhedral opaque minerals, and detrital zircon and tourmaline (Fig. 4A).

Pure or impure quartzites displays white color, medium to coarse grained quartz and subordinate plagioclase, white mica, chlorite and opaque minerals (pyrite and magnetite). Metamorphic textures show evidence of dynamic recrystallization (Figs. 4B and 4C) locally with polygonal grains.

The laminated slates exhibit very fine to fine grain size, with green and gray or purple color with some carbonaceous material, containing fine to medium-grained impure muscovitic quartzite lenses.

Vazante group

The local apparent thickness of the Vazante Group (Fig. 3) is 3,400 m, represented by the Serra do Garrote formation

(1,000 m), Serra do Poço Verde formation (800 m), Morro do Calcário formation (700 m) and Serra da Lapa formation (900 m). These units are briefly described ahead, from bottom to top.

Serra do Garrote formation

This unit is predominantly composed of black carbonaceous laminated slates of fine to medium grain size with quartz, feldspar (submillimeter plagioclase with sericitization and chloritization), white mica and anhedral opaque minerals. The metamorphic texture is lepidoblastic, and primary layering is still locally preserved as differences in grain size and composition, with two distinct lithofacies: laminated metasiltstones and laminated metamudstone, containing millimeter- to centimeter-thick levels of metasandstones and metasiltstones.

Serra do Poço Verde Formation

The Serra do Poço Verde formation consists of a metadolomitic sequence formed by: stromatolitic intensely recrystallized gray metadolomites; beige to pink metadolomites with barite nodules interlayered with greenish metapelites, locally with mudcracks, and stromatolitic beige metadolomites. The lamination is locally preserved as microbial/algal mats (Figs. 4D and 4E) and bird's eyes, oncolytic marble, metasandstone lenses and intraclastic breccia intercalations occur in all of these rocks.

Morro do Calcário formation

The metadolomites of the Morro do Calcário formation display bluish-gray colors and coarse grain size, with silicification features represented by chert. Algal mat structure is locally preserved, which reveals the primary layering of the rock. They are interpreted as dolostone with carbonate cementation or boundstones involving aggregation of ooids and peloids (Fig. 4F).

The gray slate intercalations have bluish-gray color, slaty texture with presence of impure fine metasandstones lenses. The particle size is fine with angular and rounded clasts, locally tectonically stretched. Mineralogy is given by sub-milimetric quartz, white mica (sericite) and chlorite, as well as anhedral opaque minerals.

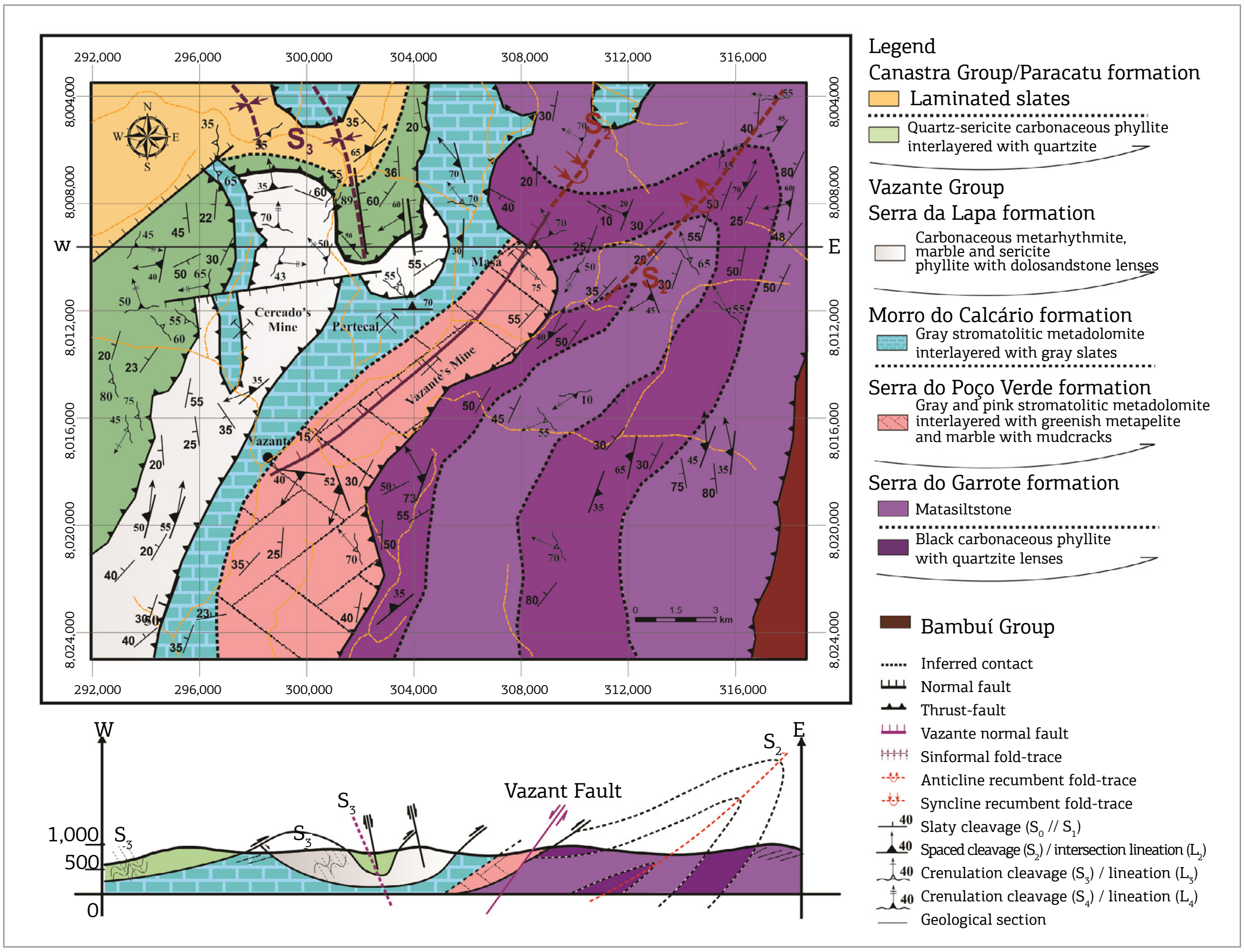
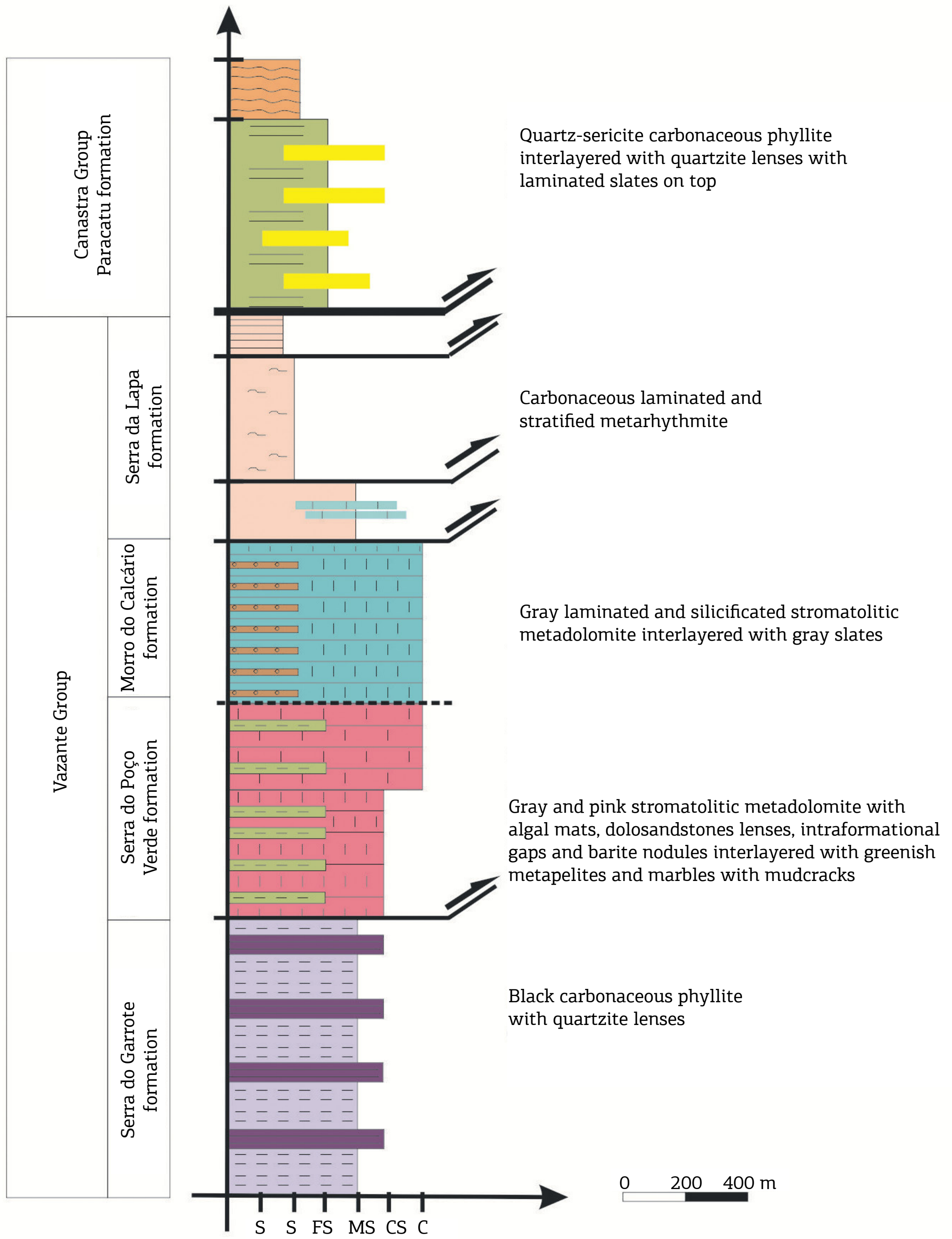


Figure 2. (A) Lithostratigraphic units and their structural relationship in the studied area; (B) geological section A–B from Carvalho *et al.* (2014).

Serra da Lapa formation

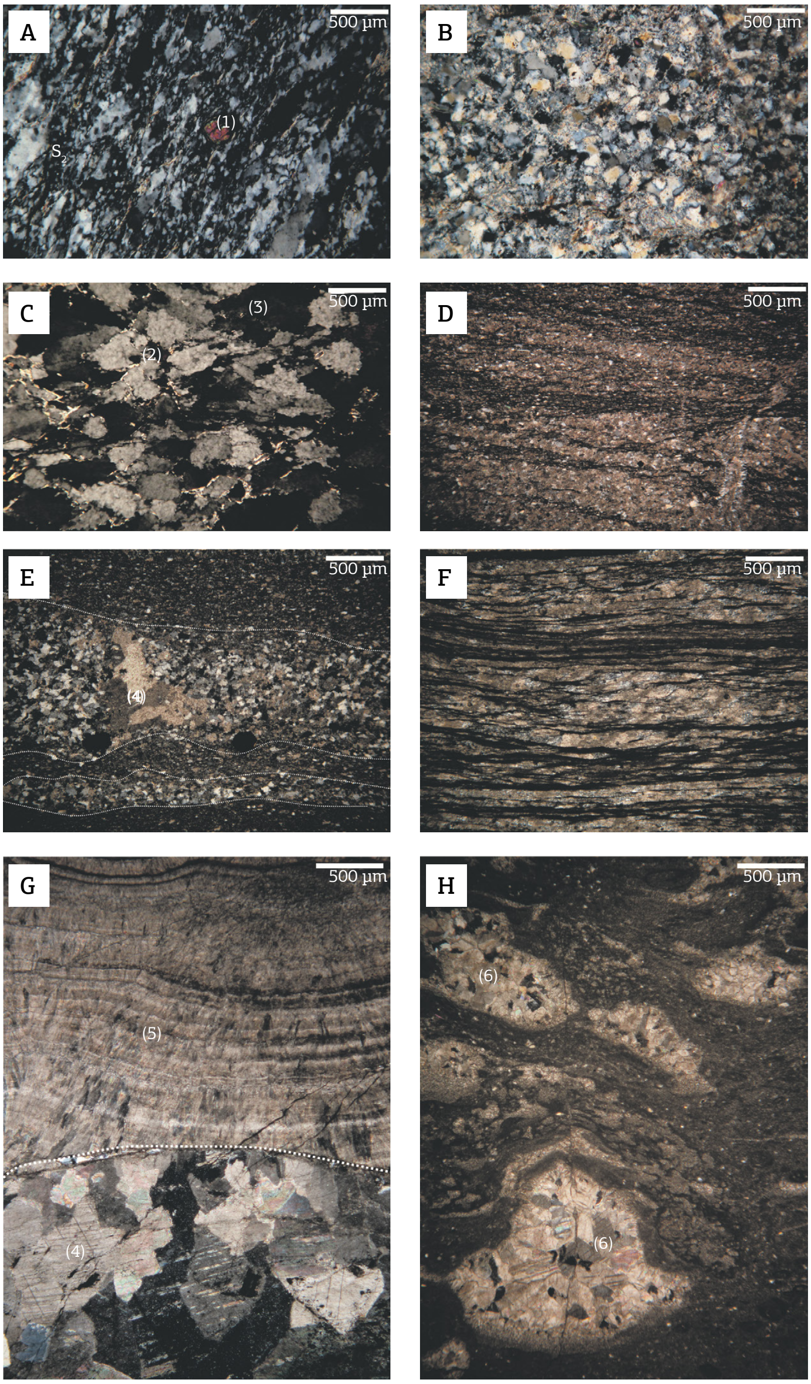
The top unit of the local Vazante group is the Serra da Lapa formation, represented by metarhythmites and sericite phyllites with carbonaceous quartzite lenses.

Three lithofacies were described by Carvalho (2013) in the Barrocão Synform area (Fig. 5): marble with millimetric to centimetric levels of fine to medium quartzite and milimetric levels of metapelite (Fig. 4G), sericite phyllite



S: slate; FS: fine-grained metasandstone; MS: medium-grained metasandstone; CS: coarse-grained metasandstone; C: carbonatic rock.

Figure 3. Lithostratigraphic column of the studied lithological units (modified from Carvalho *et al.* 2014).



1: zircon grain; 2: iron oxide; 3: quartz grain with serrated outline; 4: carbonate; 5: preserved lamination; 6: lithic fragments.

Figure 4. Petrographic features of Canastra and Vazante Group rocks (Carvalho 2013, Carvalho *et al*. 2014): (A) quartz-sericite carbonaceous phyllite with D_2 crystal orientation with quartz, white mica, plagioclase and opaque minerals grains, as well as zircon. The quartz grains present oblique extinction and serrated edges; (B) impure quartzite consisting of quartz, white mica and opaque minerals; (C) quartzite composed by quartz and white mica. Some iron oxide material is observed; (D) black carbonaceous laminated phyllite with primary layering (S_0) separating layers with distinct grain size and some layers with algal mats growth; (E) dolosandstone lenses in black carbonaceous laminated phyllite, with contact between preserved lamination and granular carbonate domain; (F) stromatolitic metadolomite with lithic fragments formed by quartz, white mica, plagioclase, carbonate and opaque minerals; (G) greenish marble with primary layering (S_0) separating layers with distinct grain size. It is possible to determine grains of quartz, white mica, carbonate and opaque minerals; (H) black carbonaceous laminated phyllite showing S_2 foliation.

(Fig. 4H), and carbonaceous metapelites with metasiltstone lenses (Fig. 4D).

Deformational evolution of the Canastra and Vazante groups

The dominant structural style of the external zones of the Southern Brasília Belt is characterized by complex structures related to regional ductile tectonics developed under low-grade metamorphism, generated by thrust-faults with general eastward tectonic transport direction. In the study area, one of these major thrust zones resulted in the juxtaposition of the Canastra Group rocks over those of the Vazante Group. The existence of this thrust is supported in the present work by detailed mapping of the Barrocão Synform area (Fig. 2), where the basal contact of Canastra Group rocks truncates underlying contacts within Vazante Group rocks.

Based on geometric style, orientation and superimposition of folds and associated (or absence of) foliations and lineations, four deformation phases were recognized (Figs. 6 and 7), two pre- or syn-metamorphic phases with development of penetrative foliations, and two post-metamorphic phases with the development of crenulation cleavages superimposed over the previous two.

The structural analysis allows for the differentiation of four phases of superimposed contractional deformation: D_1 and D_2 occurred in the ductile regime with penetrative foliations associated with folding during the emplacement of a low-angle Nappe system with the development of a thrust fault, while D_3 and D_4 are brittle-ductile with crenulation cleavages associated with post-metamorphic peak shortening. In most cases, the thrusting accompanied the original sedimentary layering between Canastra and Vazante units with the development of cleavages with stretching lineation showing the same eastern direction as the thrust.

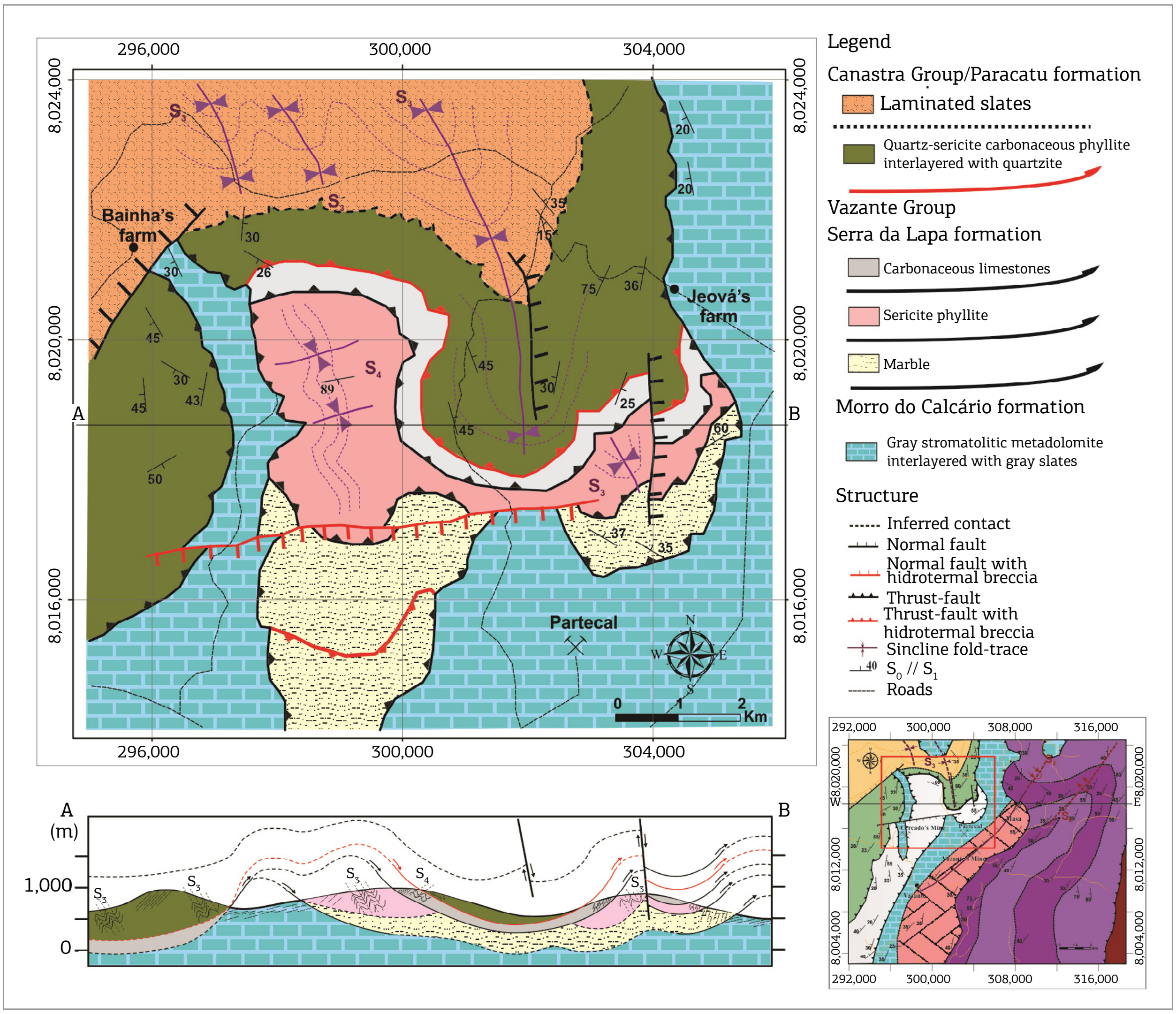


Figure 5. (A) Geological map; and (B) section of the Barrocão synform area (modified from Carvalho 2013).

The four documented deformation phases in the studied area (Fig. 7) are a S_1 slaty cleavage, which is difficult to differentiate from the primary bedding (S_0); a S_2 crenulation cleavage, with associated L_2 intersection and stretching

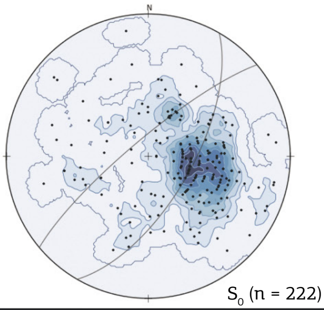
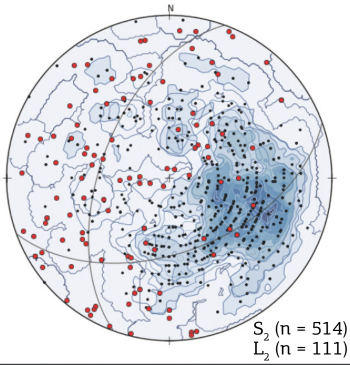
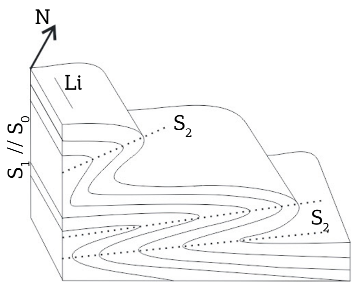
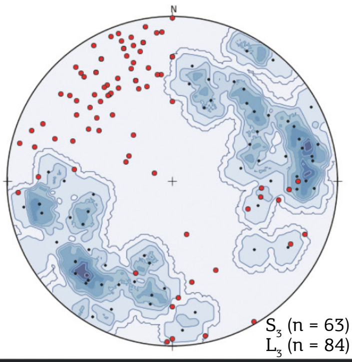
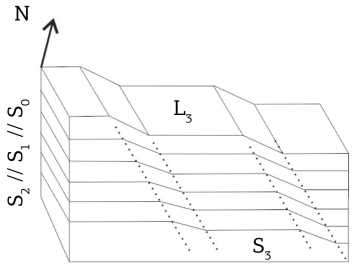
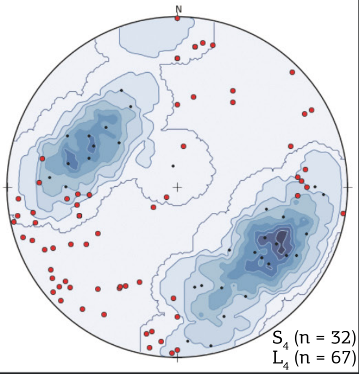
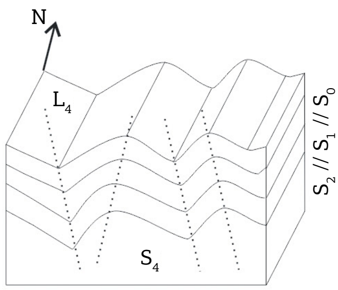
Deformational phases	Structure	Structure descriptions	Equal Area projections lower hemisphere	Diagrams
D_1	S_1 // S_0	Slaty cleavage generally observed parallel to the primary layering		. . . . . .
D_2	S_2 and L_2 (S_2 // S_1 // S_0) (S_2 oblique to S_1 // S_0)	Crenulation cleavage related to tight folds and isoclinal folds with two diferent lienations, one of intersection and other of stretching. This cleavage is, sometimes, sub-parallel or highly oblique to S_1 // S_2		
D_3	S_3 and L_3	Crenulation cleavage and lineation with open folds and kink bands		
D_4	S_4 and L_4	Crenulation cleavage and lineation with open folds		

Figure 6. Comparative geometric characteristics of the observed deformational phases. Stereographic projections are equal-area using the lower hemisphere, with contours of poles to S_1 // S_0, S_2, S_3 and S_4 (black dots) and red circles representing either L_2, L_3 or L_4 lineations, as indicated in each diagram.

lineation, both associated with tight to isoclinal folds with low-angle axial planes; D_3 and D_4 involved the formation of gentle to open folds with kink bands and crenulations, characteristically without the development of axial plane penetrative foliations; and fractures and quartz veins are observed with the same direction of the D_3 and D_4 fold axial planes.

Figure 7. Common structural features of Vazante and Canastra Group rocks (Carvalho 2013, Carvalho *et al.* 2014): (A) carbonaceous metarhythmite from the Serra da Lapa formation with D_2 isoclinal fold affecting S_1–S_0, superimposed by D_3 kink band; (B) photomicrograph (crossed polars) of Canastra Group slate showing D_2 isoclinal folds affecting S_1–S_0, superimposed by D_3 or D_4 gentle crenulation; (C) photomicrograph (crossed polars) of Canastra Group slate showing D_2 isoclinal folds affecting S_1–S_0; (D) photomicrograph (crossed polars) with D_3 or D_4 folds on S_2 oblique to S_1 // S_0; (E) photomicrograph (crossed polars) of grey slates from Morro do Calcário formation with quartz vein filling a fault displacing S_1 // S_0; (F) Canastra Group quartzite outcrop with D_4 folds superimposed on D_2 folds; (G) and (H) carbonaceous metapelite from the Serra da Lapa formation with D_3 kinks on S_2 // S_1 // S_0.

- D_1: the first (D_1) deformation phase is essentially observed as a penetrative slaty cleavage (S_1), marked by the preferential orientation of phyllosilicates. As described by previous studies related to the Brasília Belt units, the S_1 cleavage in the study area is only clearly identified in S_2 fold hinges, where S_1 parallel to the primary layering (S_0) is cross-cut by the S_2 foliation (Figs. 7A, 7B and 7C). The S_1 (// S_0) foliation generally dips gently to WNW direction with maximum attitude of 290/22, and with a secondary concentration that dips to the opposite direction (Fig. 6). No lineation was noticed associated with S_1 foliation, possibly due to the strong overprint by the D_2 main deformation phase;
- D_2: the second (D_2) deformation phase was responsible for the development of intense tight to isoclinal folding and the main penetrative axial planar S_2 foliation, and associated stretching and intersection (S_2 x S_1 // S_0) L_2 lineations. The S_2 foliation predominantly dips moderately to NW (Fig. 6). Under the microscope, S_2 is generally observed as a crenulation cleavage near D_2 fold hinge zones or as an oblique foliation with respect to S_0 //S_1 in fold limbs. In thin sections (Figs. 7B, 7C and 7D), the S_2 foliation is conspicuous in almost all rock types, except in the metadolomites, and is defined by preferred orientation of phyllosilicates, quartz, and platy opaque grains (Figs. 7D and 7E). D_2 deformation is commonly associated with undulose extinction of quartz grains, and dynamic recrystallization textures with polycrystalline quartz with irregular serrate boundaries. Sericite and chlorite recrystallization and growth were also observed. An intersection (L_2) lineation, representing the axes of D_2 folds, shows a large dispersal of orientation, but with predominant low to intermediate plunges to the NW. An L_2 stretching lineation follows the same range of orientation (Figs. 7A, 7F, 7G and 7H);
- D_3 and D_4 deformation phases: they are responsible for the development of open folding, generally without the development of any pervasive axial plane foliation. These structures heterogeneously overprinted the previous D_1 and D_2 structures (Figs. 7D, 7E, 7F and 7G). D_3 and D_4 folds are both characteristically concentric, frequently with angular style, associated with small scale kink bands. D_3 and D_4 are only differentiated by orientation, since many outcrops display the overprint of both fold generation. D_3 folds have gently plunging axes (and L_3 crenulation lineation) with NW–SE direction. D_4 folds and crenulations also show gently plunging axes (and L_4 crenulation lineation), but with predominant NE–SW orientation. Folds of both deformation phases display steep to sub-vertical axial planes (Figs. 7D, 7E, 7F and 7G). Fractures, tabular quartz veins and tension gashes are verified with the same direction of the D_3 and D_4 folds axial planes, locally closely spaced. Some normal faults were also observed with the same direction of the D_3 axial planes, generally dipping 60º–75º to NE, SE or SW.

Although the Vazante Fault was not studied here, this structure is important because it hosts the largest silicate zinc-lead deposit in the world, related to tectonic-hydrothermal activity near the contact between lower Pamplona and upper Morro do Pinheiro members, metadolomites of the Serra do Poço Verde formation, Vazante Group (Dardenne 2000, Appold & Monteiro 2009). It dips ~60–70º NW with N40–50E strike, parallel to regional geologic contacts. The Vazante fault is considered as an extensional structure by most authors, but with still unclear relationships with the timing of orogeny (Pinho 1990, Diniz-Oliveira 2013, Slezak *et al.* 2014).

One of the main D_3 structures in the studied area, named in this work as the Barrocão synform (Fig. 5), is a sub-vertical synformal fold with NW-trending axis that occurs in approximately 30 km^2 of the total mapped area. The orientation of this structure, which also folds several thrust surfaces, is coincident with the average orientation of D_3 crenulation lineation (Fig. 6), and is related to post-thrusting shortening.

White mica crystallinity studies by X-ray diffraction analysis

Ten samples (Tab. 1) from three drill holes in Vazante, Paracatu and Fagundes (Minas Gerais) areas (Fig. 1C) were collected for white mica crystallinity studies by XRD analysis (Gonzalez *et al.* 2014), aiming to detect a difference in metamorphic grade between the Canastra and Vazante thrust-sheets.

Eight samples from the Vazante Group consist of carbonaceous phyllites from the Serra da Lapa (three samples) and Serra do Garrote (three samples) formations and two samples of metadolomites from the Morro do Calcário formation. Two slate samples from the Serra do Landim formation, Canastra Group, were also analyzed.

The white mica crystallinity results (Tab. 1 and Fig. 8) show that in all samples the dominant phyllosilicate is illite, with subordinate chlorite. Percentages of illite and chlorite in the samples vary, respectively, from 60 to 100% and from 4 to 40%. The whole-rock results confirm the presence of abundant quartz and traces of plagioclase, K-feldspar and carbonate, as observed in thin sections.

The FWHM KI for white mica varies from 0.15 to 0.21 Δ°2θ, and the KI_{CIS} varies from 0.23 to 0.29 Δ°2θ (Fig. 9). Values between 0.23 and 0.29 Δ°2θ suggest temperatures between 250 and 300°C. In an average continental geothermal gradient of 30°C/km, they would result in calculated depths of about 10 km. The measured KI results indicate a very low-grade metamorphism, in high anchizone to lower epizone conditions.

Only one episode of clay mineral growth in the rocks analyzed from Canastra and Vazante groups were reported by the white mica crystallinity data, which is coincident, respectively, with the phyllosilicates crystallization on the S_2 foliation.

DISCUSSION

Four phases of superimposed compressive deformation are geometrically characterized in the study area. The first two (D_1 and D_2) occurred in the ductile regime with the development of penetrative foliations associated with folds generated during the development of low-angle thrust-faults that affected the Canastra Group rocks. This contractional event, related to the peak activity of the Brasiliano orogeny, was also responsible for the low-grade metamorphism that originated phyllites and slates with growth of sericite and chlorite, also with quartz recrystallization. The third and fourth (D_3 and D_4) phases occurred under brittle-ductile regimes, with heterogeneous deformation involving folds, associated crenulations and kink bands, locally with faults and fractures

Table 1. X-Ray diffraction results for analyzed samples from the Vazante and Canastra groups.

Sample	Group / formation	Kübler Index (KI_{CIS}, Δ°2θ)		Clay minerals	
		KI FWHM (< 2 μm)	KI_{CIS} FWHM (< 2 μm)	White mica (%)	Chlorite (%)
1	VG / SLF	0.16	0.24	90	10
2	VG / SLF	0.15	0.23	95	5
3	VG / SLF	0.16	0.24	84	16
4	VG / MCF	0.18	0.26	95	5
5	VG / MCF	0.21	0.29	100	-
6	VG / SGF	0.17	0.25	96	4
7	VG / SGF	0.17	0.25	96	4
8	VG / SGF	0.17	0.25	75	35
9	CG	0.21	0.29	60	40
10	CG	0.16	0.24	75	35

VG: Vazante Group; CG: Canastra Group; SLF: Serra da Lapa formation; MCF: Morro do Calcário formation; SGF: Serra do Garrote formation; KI: Kübler index; FWHM: full width half maximum.

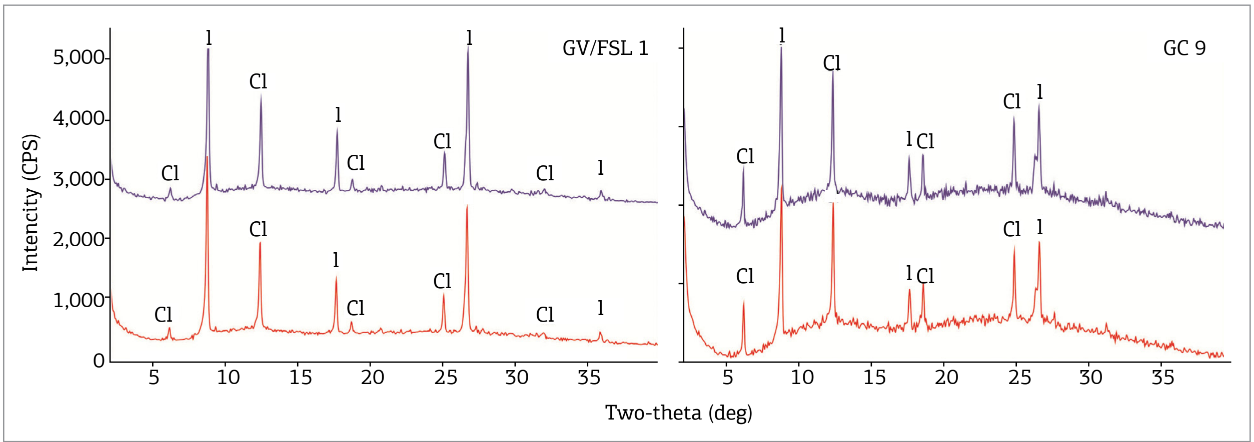


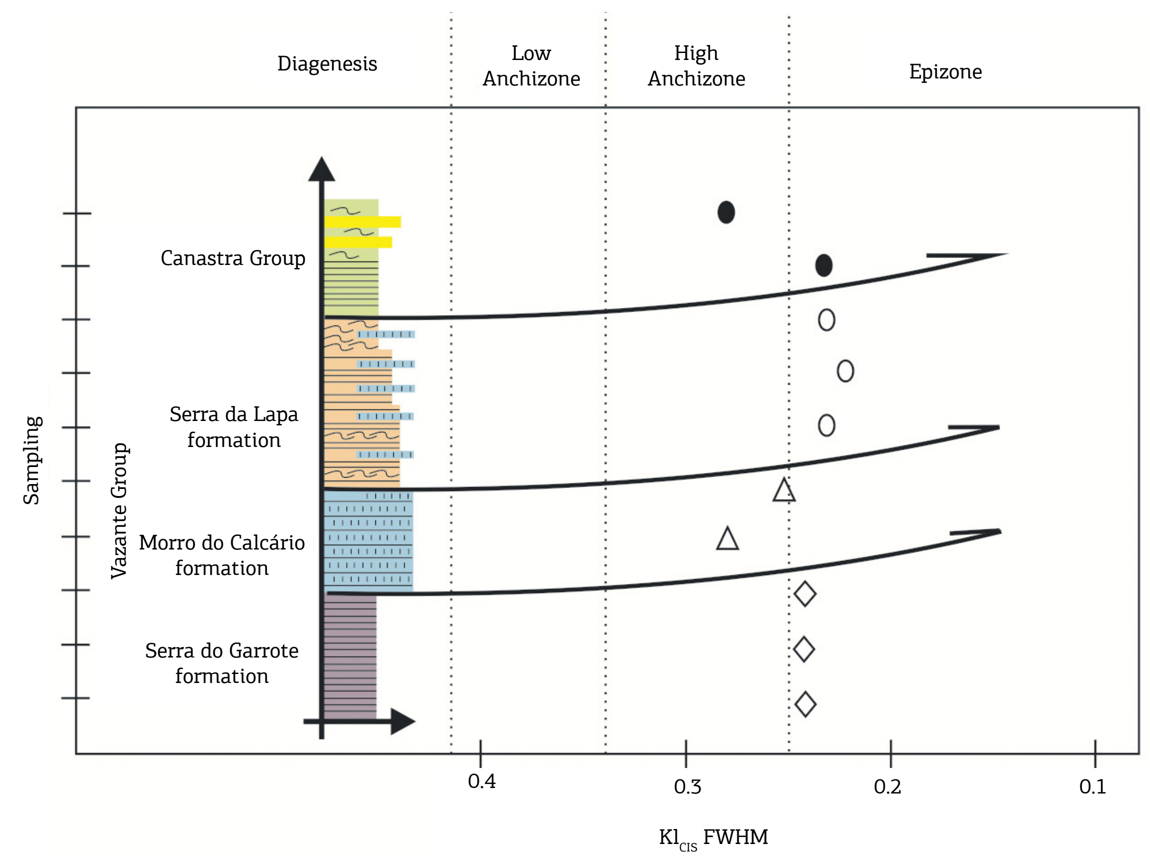
Figure 8. Representative white mica crystallinity studies by X-ray diffraction (XRD) diagrams of Vazante/Canastra Group samples showing illite (I) and chlorite (Cl) peaks. Normal in red and glycollated in blue.

along axial planes. No mineral growth was observed associated with D_3 and D_4 structures, an indication that a shortening took place after the metamorphic peak.

Tentative correlation of the four deformation phases defined in this work can be made with those of previous studies of Vazante and Canastra groups, as follows (Tab. 2): D_1 and D_2 correspond to the regional compressional shear zones and thrust-faults responsible for the main structures in the belt (penetrative cleavage parallel and sub-parallel to the primary layering), as defined by Pereira (1992) and Pinho and Dardenne (1993), and to the heterogeneous brittle-ductile simple shear in progressive ductile regime of Pinho (1990) and Rostirolla *et al.* (2002). D_3 and D_4 may be correlated with the pure shear brittle-ductile regime with kink bands, tension gashes and crenulation cleavages of Pereira *et al.* (1994) and of Pinho and Dardenne (1993), and with the sinistral brittle-ductile directional and brittle extensional phases of Rostirolla *et al.* (2002).

A broader evolutionary model can be proposed from comparison of these local evolutionary schemes with similar studies in other segments of the Southern Brasília Belt, south of the study area. As proposed by Valeriano (1992), Simões (1995) and Seer and Dardenne (2000), all four deformation phases are compatible with a broad E–W orogenic compression, but in progressively shallower environments. D_1 and D_2 phases are related to thrust tectonics resulting in folds and thrusts with movement towards the São Francisco Craton. In the southern most segments of the Brasília Belt, the aforementioned authors relate D_3 folds with WNW-trending sinistral transcurrent shear zones which displaced the main thrust surfaces. D_4 folds, with predominantly NS-oriented axes, are related to final E–W shortening in a pure shear regime.

White mica crystallinity data show only one episode of clay mineral growth in the rocks analyzed from Canastra and Vazante groups, which are related to the second phase of deformation (D_2), contemporary with the regional



KI: Kübler index; FWHM: full width half maximum.

Figure 9. Kübler index diagram showing similar metamorphic grade between the Canastra and Vazante groups in the studied area. Metamorphic discontinuities along thrust planes in the Vazante Group rocks indicate that thrusting post-dated metamorphic peak.

metamorphic peak (Rostirolla *et al.* 2002), which was also responsible for the development of penetrative S_2 cleavage in lower epizone conditions.

Campos *et al.* (2015) recently measured KI values of samples from the Canastra, Paranoá and Bambuí groups in the Distrito Federal and adjoining areas in Goiás state. Although those values are in KI FWHM without correction, as indicated by Warr and Rice (1994) standardization's parameters, they conclude that the Canastra Group rocks reached epizone conditions, while the Paranoá and Bambuí samples, from underlying thrust sheet, reached only anchizone conditions. These results are consistent with the new results in this work, with both the Canastra and Vazante thrust sheet having reached high anchizone to epizone conditions, especially in the rocks above the thrust-fault contact.

As represented in Figure 9, a similar metamorphic degree is observed between the Canastra and the Vazante groups in the studied area. However, metamorphic discontinuities along thrust planes within the Vazante Group rocks suggest that metamorphism pre-dated thrusting, which is compatible with observations in other areas of the Southern Brasília Belt (Simões 1995, Valeriano *et al.* 2000).

CONCLUSIONS

In this work, we present a geological and structural map of an area of approximately 400 km^2 that shows that the psammo-pelitic metasedimentary rocks of the Canastra Group and pelitic-carbonatic metasedimentary rocks of the Vazante Group are separated by a regional thrust-fault, supported by detailed mapping of Barrocão synform area, where the Canastra Group thrust fault truncates contacts between Vazante Group strata in the footwall. The deformation in the Canastra Group rocks was more intense than in the Vazante Group rocks, with generally tighter main phase (D_2) folds in a similar style with thicker hinges and thinner limbs. Furthermore, metapelites of the Canastra Group are phyllites, in contrast with slates from the underlying Vazante Group.

Four deformation phases were defined in the study area. The first one (D_1) occurred in a ductile contractional regime and is represented by a slaty cleavage generally subparallel to bedding. The second phase of deformation (D_2) is also of ductile contractional nature and is represented by a crenulation cleavage associated with tight to isoclinal folds. The orientation of the L_2 stretching lineation, plunging predominantly to NW, supports tectonic transport to SE during D_2.

Table 2. Comparison between deformation phases in this work and selected previous works. Here is presented a correlation based in the description of each structural geometry literature data.

<table>
<tr><th>Pinho (1990)</th><th>Pinho et al. (1989, 1990)
Pereira (1992)
Pinho & Dardenne (1993)</th><th>Rostirolla et al. (2002)</th><th>This work</th></tr>
<tr><td rowspan="2">D_1 + D_2
Compressive NW–SE regime with the Vazante fault reactivation</td><td rowspan="2">D_1
Thrust-faults and shear zones with late E asymmetric folding</td><td>D_1
Slaty cleavage (S_1) sub-parallel to primary layering (S_0), with tight and isoclinal folds</td><td>D_1
Slaty cleavage (S_1) sub-parallel to primary layering (S_0)</td></tr>
<tr><td>D_2
Spaced cleavage (S_2) oblique to S_1</td><td>D_2
Spaced cleavage (S_2) oblique or sub-parallel to primary layering (S_0) with tight and isoclinal folds</td></tr>
<tr><td rowspan="2">D_3
Final compression with brittle-ductile deformation and inverse movement of pre-existing faults</td><td rowspan="2">D_2
Kink bands, tension gashes and fractures</td><td rowspan="2">D_3
Vazante fault zone related with a sinistral transcurrent system and the development of a crenulation cleavage (S_3) associated with kink bands</td><td>D_3
NW–SE crenulation cleavage with NW lineation</td></tr>
<tr><td>D_4
NE–SW crenulation cleavage down-dip to S_2</td></tr>
<tr><td rowspan="2">D_4
Extensional regime</td><td rowspan="2">-</td><td>D_4
NE normal fault</td><td rowspan="2">-</td></tr>
<tr><td>D_5
Two joints systems: N40–60W and EW</td></tr>
</table>

The third and fourth phases of deformation (D_3 and D_4) are related to post-thrust stacking and developed gentle to open folds and associated kink bands and crenulations, but without the development of penetrative foliations. The third phase of deformation was responsible for the Barrocão Synform, an expressive map-scale structure mapped in this work.

XRD data on white mica crystallinity indicate that rocks below and above the thrust-fault contact between the Canastra and Vazante groups reached similar anchizone/epizone conditions, typical of lower greenschist facies. The Canastra Group rocks show only one episode of clay mineral growth related to chlorite crystallization on the S_2 foliation in syn-thrusting regime. In the Vazante Group, metamorphic discontinuities along thrust planes indicate that the peak of metamorphism probably pre-dated thrusting.

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