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The evolution of quartz veins during the tectonometamorphic development of the Brusque Metamorphic Complex, Brazil

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A R T I C L E I N F O

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A B S T R A C T

Microstructural analysis and characterization of quartz veins hosted in rocks from the Brusque Metamorphic Complex in the region of Brusque, State of Santa Catarina, have been performed to establish the relations between fluid regimes, tectonic styles and deformation/recrystallization mechanisms. The analysis was based on observations of structural overprinting, spatial structural relations, the origin of the quartz veins and microtectonics studies. Five types of veins were identified: meter-long veins parallel to the regional foliation (V1-veins); massive, meterwide veins present in thermal aureoles (V2-veins); millimeter-wide, erratic veins, also present in thermal aureoles (V3-veins); tabular, undeformed and NW striking (V4-veins); millimeter-wide erratic veins restricted to brittle reactivation of strike-slip shear zones (V5-veins). The regional foliation, developed under garnet zone metamorphic conditions, was more effective in vein production when compared to the steeply dipping mylonitic foliation corridors developed under chlorite zone conditions. Pressure solution was the main deformation mechanism during the regional foliation development. However, granoblastic and decussate textures in hornfels reveal an influence of grain boundary area reduction mechanism. The granoblastic texture in hornfels would have inhibited fluid circulation during dehydration reactions, increasing fluid pressure and promoting massive (V2-veins) and erratic hydraulic fracture-related (V3) veins. In dextral NEtrending strike-slip shear zones, tabular quartz veins (V4-veins) are parallel to tension gashes. Reactivation of strike-slip shear zones under brittle conditions has produced local brecciated millimeter-wide quartz veins (V5-veins). This study underscores the important role of fluids during orogenic evolution near the brittle-plastic transition of the crust, and demonstrates how combined vein and microtextural analysis can reveal the tectonometamorphic history of lowgrade metamorphic rocks.

1. Introduction

The study of microstructures in metamorphic rocks constitutes a powerful tool to understand deformation and recrystallization mechanisms and to estimate temperature and pressure conditions (Van der Pluijm and Marshak, 2004; Vernon, 2004; Passchier and Trouw, 2005). Deformation mechanisms are controlled by temperature, deformation rate and fluid behavior (Knipe, 1989; Hirth and Tullis, 1992; Blenkinsop, 2000; Stipp et al., 2002; Passchier and Trouw, 2005).

In particular, fluids may control recrystallization mechanisms enhancing metamorphic reactions and change the mechanical properties of rocks (Carter et al., 1990; Yardley and Bottrell, 1992; Yardley, 2009; Jamtveit and Austrheim, 2010; Fiori and Wandresen, 2014; Hobbs and Ord, 2014), while the state of stress in rocks influences fluids distribution and transfer of chemical components (Daines and Kohlstedt, 1997; De Meer et al., 2002; Bons et al., 2012).

Systematic geologic mapping performed under the undergraduate geologic mapping program of the UFPR has revealed an abundance of quartz veins in metapelitic schists of the Brusque Metamorphic Complex of the Dom Feliciano orogenic system, and that they formed repeatedly during the tectonic evolution of this complex.

In this contribution we explore the different generations of quartz veins in the Brusque Metamorphic Complex. The microstructural observations of the metasediments, allowed the association with the different vein generations and tectonic/magmatic processes during the Brasiliano evolution of this part of the Mantiqueira Province.

1.1. Microstructural background

To better understand the different recrystallization regimes that

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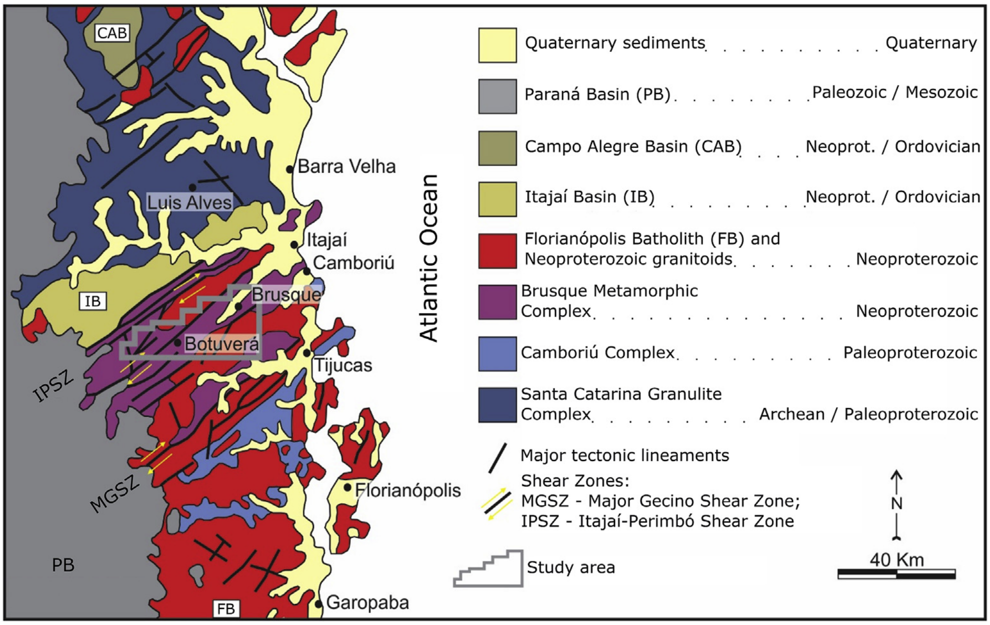


Fig. 1. Geological map of the Eastern Santa Catarina state (After Hartmann and Fernandes, 2000).

control the mechanical behavior of the crust, Hirth and Tullis (1992) and Stipp et al. (2002) compared microstructures preserved in naturally deformed rocks to those produced during laboratory experiment. Those authors recognized **bulging** (**BLG**), **subgrain rotation** (**SGR**) and **grain boundary migration** (**GBM**) recrystallization regimes, replacing each other in that order with increasing temperature, decreasing strain rate and amount of intergranular liquid present during the deformation (Drury and Urai, 1990; Hirth and Tullis, 1992; Stipp et al., 2002; Passchier and Trouw, 2005).

According to Stipp et al. (2002), **BLG recrystallization** coincides with regime 1 and the regime 2 lower temperature of Hirth and Tullis (1992). At low temperatures, the grain boundary may bulge into the crystal with high dislocation density and form small independent new grains (Passchier and Trouw, 2005). Old grains show finely serrated grain boundaries and undulose extinction, and at low temperatures some of the old grains are fractured (Stipp et al., 2002; Passchier and Trouw, 2005).

The **SGR recrystallization** corresponds to regime 2 of Hirth and Tullis (1992). Movement of dislocations into subgrain boundaries causes a progressive rotation of the subgrains, leading to the formation of a new grain. In regime 2 new grains occur predominantly by progressive misorientation of subgrain or subgrain rotation, producing a distinctive core and mantle texture. This mechanism generally occurs at higher temperatures than **BLG recrystallization. SGR** can be inferred from the coexistence of new grains with subgrains of similar size within the older grains. The old grains tend to be elongated or ribbon-shaped, and different from the angular or only moderately elongated old grains found in the zone of **BLG**. Other diagnostic microstructure **of SGR** consists of internal deformation features such as undulatory extinction and deformation lamellae (Blenkinsop, 2000; Stipp et al., 2002; Passchier and Trouw, 2005).

At relatively high temperature, **GBM recrystallization** is characterized by new grains larger than the coexisting subgrains, absence of highly flattened original grains, and high rate of recrystallization. This corresponds to regime 3 of Hirth and Tullis (1992). Grain boundaries are lobate and grain size is variable. At very high temperature, no undulose extinction or subgrains occur and grains have highly loboid or amoeboid boundaries (Stipp et al., 2002; Passchier and Trouw, 2005).

Pressure solution is an important deformation mechanism in rocks that contain an intergranular fluid. According to De Boer (1977), the pressure solution process in quartz is enhanced by increasing the temperature, but it is hardly affected by the composition of the intergranular fluid. This mechanism shows evidence for material removal, transport and precipitation without fracturing or intracrystalline deformation. Typical cases to illustrate the microstructures of material removal are distinctive types of grain contacts and stylolites. Microstructures indicating precipitation include veins, overgrowths and pressure shadows (Knipe, 1989; Blenkinsop, 2000; Passchier and Trouw, 2005).

The shapes of the veins can be divided into two main classes: (a) Strain shadow or strain fringes around rigid crystals; and (b) General veins with variable shapes, unrelated to competent objects, and disposed along mesoscopic structures (fractures, faults and foliations). Veins are opening fractures filled by minerals, and can be classified into extension veins that open perpendicular to the maximum compressive stress direction (σ1), and hybrid veins that form by opening oblique to the walls. Veins can occur as isolated structures, as en echelon gashes in zones of shear, and in fault damage zones, and in breccias where they show more irregular shapes and erratic orientations.

1.2. Geologic setting

The **Mantiqueira Province** (Almeida et al., 1981) comprises a Neoproterozoic orogenic province interpreted to have formed during the closure of Adamastor Ocean and collision of several tectonic plates. It is located along the Atlantic coast, from the southern Bahia State of Brazil to Uruguay, and is composed of Neoproterozoic Araçuaí, Ribeira and Dom Feliciano orogenic systems (Brito Neves and Cordani, 1991; Soares et al., 2000; Heilbron et al., 2004; Silva et al., 2005; Basei et al., 2010; Brito Neves and Fuck, 2013; Bento dos Santos et al., 2015). The Dom Feliciano belt (Fig. 1) is situated in the southern domain of the Mantiqueira Province (Fragoso Cesar, 1980; Basei, 1985; Basei et al., 2000) and is generally interpreted to have developed during successive episodes of subduction and collision during the amalgamation of the Rio de La Plata, Luís Alves and Kalahari blocks (Basei et al., 2000, 2005), although alternative models calling for less subduction and more continental orogeny have recently been put forward (Meira et al., 2015; Konopásek et al., 2019).

The **Brusque Metamorphic Complex** (**BMC**) (Silva, 1991; Caldasso et al., 1995; Philipp et al., 2004; Basei et al., 2011) is located in the northeastern Santa Catarina state (Fig. 1) and is limited to the north by the Itajaí basin trough the Itajaí-Perimbó strike-slip shear zone (Silva, 1991) and to the south by the Major Gercino strike-slip shear zone (Bitencourt et al., 1989; Passarelli et al., 2010; Passarelli et al., 2011). The complex is composed of schists, phyllites, quartzites, marbles, metamarls and metabasites/metaultrabasites. U–Pb zircon ages of 834.7 ± 8.7 Ma (IDTIMS) and 843 ± 12 Ma (SHRIMP) obtained from rift-related leucogranites were attributed to rifting responsible for the basin formation (Basei et al., 2008).

A low angle schistosity, referred to as S_2 by previous workers (e.g., Basei et al., 2011), is the main ductile structure in the Brusque supracrustal rocks, and has been associated with thrusting (Basei, 1985; Caldasso et al., 1995; Philipp et al., 2004; Basei et al., 2011). NE-trending strike-slip shear zones with a new internal foliation (previously called S_3) and related folds affect and transpose the low angle schistosity (Caldasso et al., 1995; Philipp et al., 2004). Where the shear strain is high, the transposed schistosity is completely obliterated and all foliations become parallel. In these rocks, metamorphic conditions vary from garnet zone to chlorite zone. However, in thermal aureoles related to Neoproterozoic granites, temperatures may have reached the pyroxene hornfels facies (Basei, 1985; Silva, 1991; Caldasso et al., 1995; Philipp et al., 2004; Basei et al., 2011).

Neoproterozoic granites intruded the rocks of the BMC at different times. The emplacement of early granites commonly is parallel to the general trend of the main schistosity of the country rocks (Philipp et al., 2004; Tickyj et al., 2004). The later orogenic granites are massive to weakly foliated and thought to be coeval with the strike-slip tectonics (Basei, 2000; Philipp et al., 2004; Basei et al., 2011). The most important suites of this second magmatic episode are the São João Batista, Valsungana and Nova Trento suites whose ages range from 620 Ma to 570 Ma (Basei, 2000; Silva et al., 2003; Basei et al., 2011).

2. Petrography of the Brusque Metamorphic Complex

The studied rocks from the BMC are metapelitic schists, phyllites, quartzites and marbles (Fig. 2). The schists are composed of muscovite, chlorite, quartz, biotite and garnet (Fig. 3a and b). These rocks show lepidoblastic texture and granoblastic texture in quart-rich parts. Garnet porphyroblasts may have helicitic or straight inclusions and, locally, asymmetric strain shadows occur. Garnet may show partial or complete alteration to chlorite.

In quartz-micaschists, phyllosilicates do not exhibit evidence of intracrystalline deformation. However, micas display strong preferred orientation and rectilinear faces parallel to the foliation. Very narrow films of opaque minerals along the regional schistosity are also observed. These features (Beach, 1979; Bell and Cuff, 1989) permit us to suggest that pressure solution was an effective deformation mechanism.

Hornfelsed schists display reddish biotite, andalusite and subordinately staurolite without any strong preferred orientation. The matrix is made of muscovite and quartz. Locally there are chlorite-quartz-sericite phyllites with lepidoblastic texture. Quartz grains are in general elongated, show straight grain boundaries, weak undulose extinction or subgrains and, less commonly, new grains.

Quartzites outcrop locally in meter-to decimeter-wide layers conformable to the regional schistosity. These rocks may present granoblastic to granolepidoblastic textures, and muscovite and biotite as subordinated minerals. In rocks deformed in the strike-slip corridors (Figs. 2 and 3c and d), the very fine grain-size of new grains and the serrated boundaries suggest bulging as the main recrystallization mechanism.

Marbles and metamarls occur in the BMC as layers intercalated with the quartz-micaschists. These rocks show a granoblastic texture and in levels of carbonate, mica and quartz, a granolepidoblastic texture is observed. Veins of calcite or quartz may be both concordant and discordant to the foliation.

3. Tectonic structures of the Brusque Metamorphic Complex

3.1. Regional foliation

The regional foliation has low-angle dip and is folded and steepened by strike slip shear zones. It is characterized by a penetrative schistosity

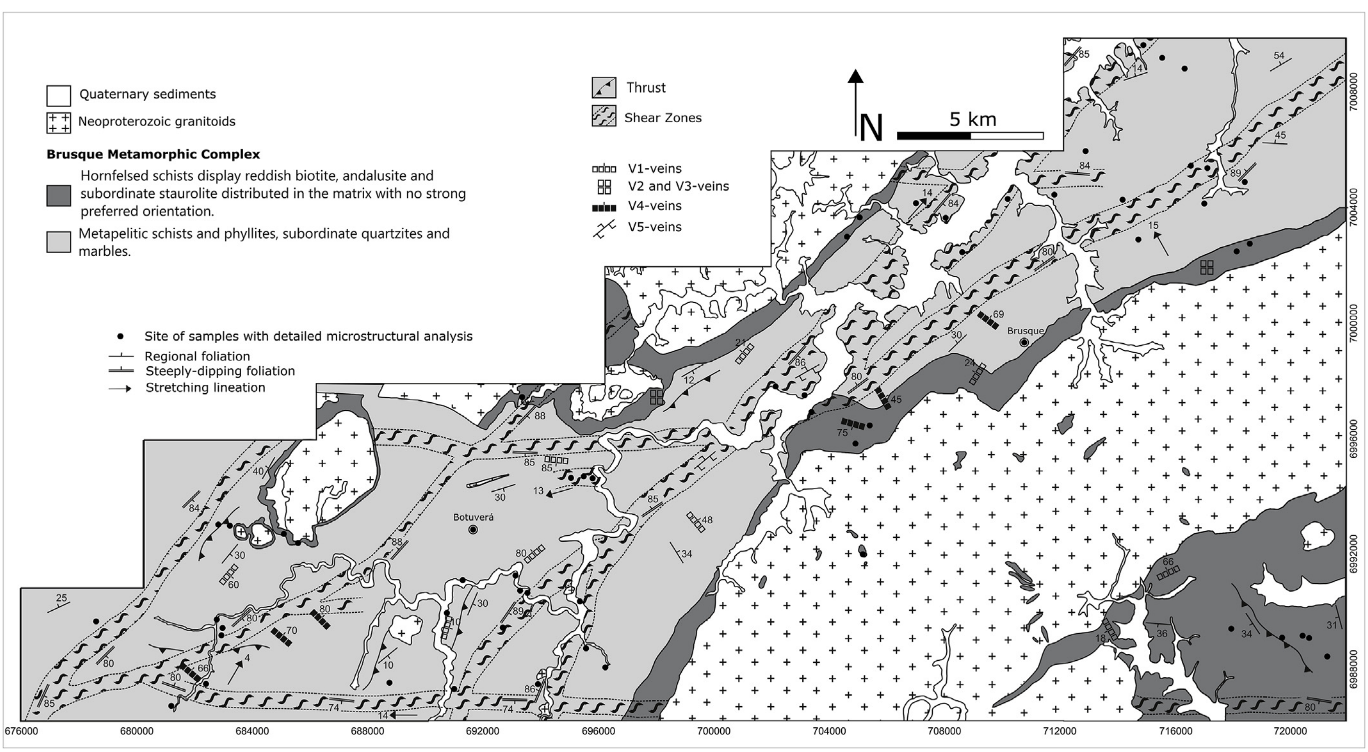


Fig. 2. Litho-structural map of Brusque region showing the trend of the foliation, the location of the main outcrops of quartz veins and described thin sections.

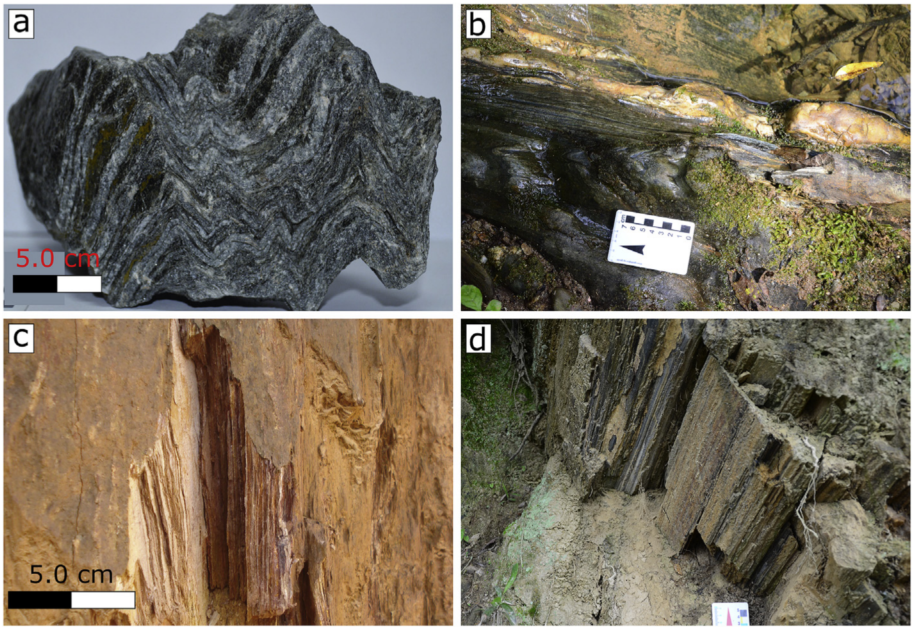


Fig. 3. The main foliations of the Brusque Metamorphic Complex. a) Regional foliation in quartz-muscovite schist, characterized by the preferred orientation of micas, setting up a penetrative schistosity. The schistosity was deflected and deformed by folding. According to dip isogon classification these folds are Class 1C folds; b) Gently dipping mylonite formed by shear-related plastic grain-size reduction. These rocks are composed of sericite, chlorite and quartz with micas displaying a strong preferred orientation; c) Steeply-dipping mylonitic foliation (NE-SW trending); d) Steeply-dipping mylonitic foliation (E-W trending).

defined by chlorite, biotite, muscovite and quartz (Fig. 3a). In some places gently-dipping mylonites formed by shear-related plastic grain-size reduction (Fig. 3b) occur laterally and can be associated with the main foliation. This foliation, called the regional or penetrative schistosity in this work, is correlated with the S2 foliation described by other authors (Caldasso et al., 1995; Philipp et al., 2004; Basei et al., 2011).

A penetrative schistosity in schists and phyllites is characterized by a disjunctive cleavage defined by millimeter-scale microlithons. The **cleavage domain** (**M**) is usually rich in mica whereas the **microlitons** (QF domains) are made of quartz (Fig. 4a and b). Micas display strong preferred orientation, straight grain boundaries and no evidence of intracrystalline deformation. Fine dark seams composed of very fine-grained opaque minerals occur along the foliation (Fig. 4b). The microlitons consist of anhedral quartz grains with weak wavy extinction and lobate margins. The rectilinear shapes of the faces parallel to the schistosity, strong preferred orientation of micas and the presence of the strain shadow or strain fringes (Fig. 4c) suggest that pressure solution controlled the fabric formation. Garnet porphyroblasts, when present, shows quartz and opaque helicitic inclusions, suggesting syntectonic growth under greenschist facies - garnet zone conditions.

Locally, microlithons show a partially preserved previous foliation (S_1). In these cases, the foliation is a crenulation cleavage. This earlier foliation (S_1) is rarely preserved because of the transposition due to the thrust tectonics and associated regional schistosity.

In the gently dipping mylonites, intracrystalline deformation and dynamic recrystallization contribute to develop the main foliation as a transposition foliation whose mylonite aspect is revealed by S–C, C–C' and asymmetric mica fish features. Wavy extinction, deformation bands and subgrains characterize the intracrystalline deformation of quartz.

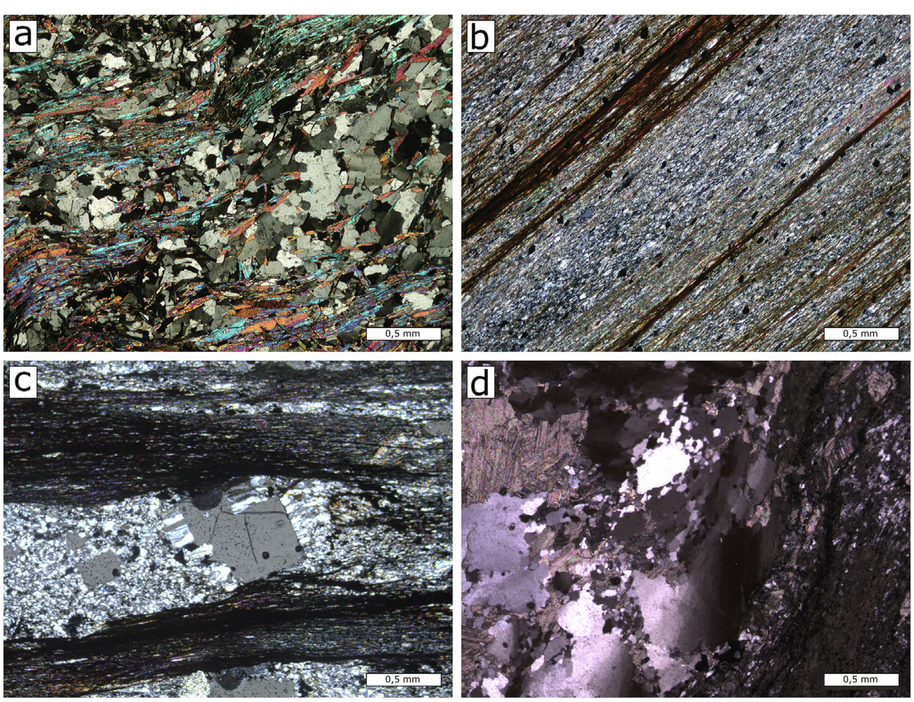


Fig. 4. Crossed polarized light photomicrographs of rocks from the Brusque Metamorphic Complex. a) Disjunctive foliation in quartz-mica schist. Note the rectilinear shapes of the faces parallel to the schistosity and the strong preferred orientation of micas; b) Disjunctive cleavage in quartz-mica phyllite, defined by mica-rich layers and quartz-mica layers. Note the fine dark seams along the foliation indicating pressure solution; c) Strain fringes made of fibrous quartz observed around opaque crystal; d) Intracrystalline deformation of quartz (wavy extinction and subgrains) and the formation of new grains by subgrain rotation.

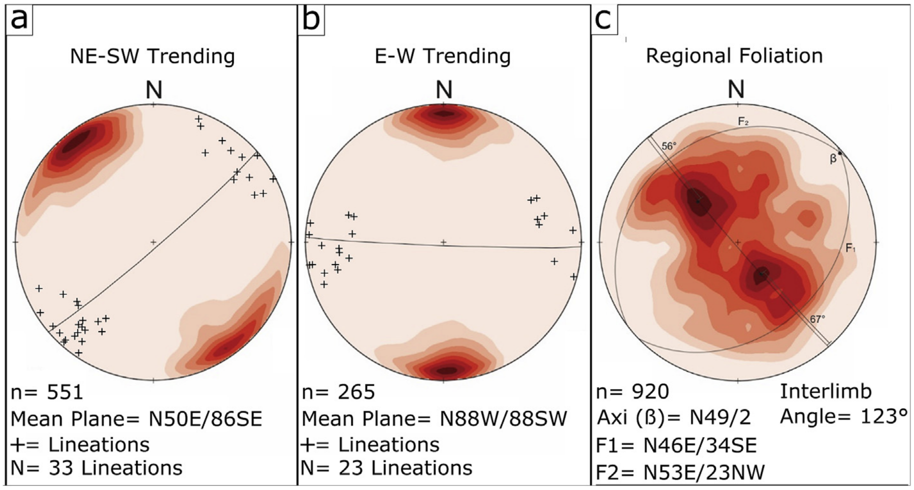


Fig. 5. Stereogram showing contoured structural data of rocks from Brusque Metamorphic Complex. a) Poles to steeply-dipping foliation (NE-SW trending) with crenulation and stretching lineations in the strike-slip shear zones; b) Poles to the steeply-dipping foliation with crenulation and stretching lineations (E-W trending); c) Poles to the regional foliation away from the shear zones with attitudes of average of planes and axes.

The dynamic recrystallization was controlled mainly by subgrain rotation (Fig. 4d).

Microstructures present in these grains of quartz are temperature-dependent and result from different deformation/recrystallization mechanisms as demonstrated by Hirth and Tullis (1992), Stipp et al. (2002) and Faleiros et al. (2010). Bulging generally operates at 250–400 °C, under greenschist facies (Stipp et al., 2002). As demonstrated in this paper, the somewhat higher deformation temperatures characterizing the garnet zone would rather invoke subgrain rotation recrystallization (Fig. 4d).

3.2. Shear zone foliation and lineation

Several zones of steeply-dipping mylonitic foliation have been mapped in the study area (Figs. 2, 3c and 3d). These up to 2 km wide zones define a NE trending anastomosing shear zone network, and the associated subhorizontal stretching lineation suggests strike-slip movement. Crenulation lineations can also be seen in these rocks. Stereographic projections (Fig. 5) show the poles of foliation from the strike-slip zones (Fig. 5a and b), indicating maximum concentrations around N50E/86SW and a secondary concentration at N88W/88SW. One of this NE strike-slip shear zones, named Itajaí-Mirim, is of regional importance and control the location of the Itajaí-Mirim River. Similar NW-SE trending structural corridors have been described previously (Caldasso et al., 1995; Philipp et al., 2004; Basei et al., 2011).

Where the strain is less intense, the regional schistosity was deflected and deformed by folding and shearing (Fig. 3a). The poles of the regional foliation are distributed along a great circle (Fig. 5c), indicating a cylindrical fold with an average axis of N49E/02. In the field these folds exhibit isogons of convergent dip to the internal arc, characterizing Class 1C folds according to Ramsay's (1967) dip isogon classification. These folds probably evolved to Class 2 folds within the shear zones. Anastomosing shear zones (Fig. 2) of combined shearing and shortening commonly occur in orogenic belts, as described by several authors (Sanderson and Marchini, 1983; Gapais et al., 1987; Bell and Johnson, 1992; Fossen et al., 1994; Tikoff and Greene, 1997; Fossen and Tikoff, 1998; Bell, 2010).

The steeply dipping mylonitic foliation (Figs. 2, 3c and 3d) is a transposition foliation defined by the preferred orientation of recrystallized white mica, quartz and chlorite. Serrated grain boundaries in quartz are common, suggesting bulging recrystallization (Fig. 6a). Fine-grained mica having asymmetric fish shapes also defines the mylonite foliation. Mica can show trails of very fine new grains along the foliation, indicative of basal plane slip. Narrow films (black seams) of fine-grained opaque minerals along the mylonite foliation are locally found, indicating that pressure solution is present in these strike-slip shear zones.

The presence of recrystallized chlorite in the mylonitic foliation (Fig. 6b) indicates greenschist facies – chlorite zone conditions during the ductile strike-slip tectonics, which agrees well with the low temperature dynamic recrystallization mechanisms identified in quartz (bulging). S–C foliations, mica fish (Fig. 6c) and rotated porphyroclasts together indicate dextral shear sense in the Itajaí-Mirim shear zone.

Brittle shear zones have been recognized along the NE strike-slip shear zones in the study area. Apparently, these steep fine-grained mylonite zones acted as planes of weakness during this subsequent reactivation (White et al., 1986). Even though the NE strike-slip shear zones are reactivated, the faults and hydrothermal breccias appear to be limited in length, and there is no evidence of reactivation of the entire length of the shear zone.

3.3. Contact aureoles

Hornfels domains formed during contact metamorphism and reach 3 km in with around the granitic bodies (Fig. 2). The foliations, developed before the Valsungana Granite emplacement, are frequently preserved within the aureoles. However, the porphyroblasts can be observed to be randomly oriented, similarly to the textures described by Philipp et al. (2004) to the SE.

The metapelitic schists located within the thermal aureole are constituted by muscovite + quartz + biotite ± garnet ± staurolite ± andalusite. Porphyroblasts of andalusite (Fig. 6d) and staurolite do not show preferred orientation, and have inclusions continuously linked to the regional foliation. In hornfels, porphyroblasts and quartz crystals are undeformed (Fig. 6d). Straight quartz grain boundaries give rise to triple junctions and a polygonal granoblastic texture (Fig. 6d). This texture developed by grain boundary area reduction under static recrystallization conditions during thermal metamorphism.

4. Quartz veins population of the Brusque Metamorphic Complex

The quartz veins are divided into five sets, V_1–V_5 (Table 1), and each vein set was characterized in detail in terms of orientation (azimuth, dip) and geometric relations with other veins and structural elements (foliations, fold). Here we discuss the timing of their emplacement relative to the established structural history in the BMC.

A very regular and constant population of regional foliation-parallel veins is developed throughout the studied area (Fig. 7a and b). These veins, labelled V_1-veins, are widespread and generally concordant to the regional schistosity. The majority of V_1-veins consist of tabular quartz veins. Length of the veins commonly ranges from 5 cm to 4 m, exceptionally up to several meters and show thicknesses from 1 mm to

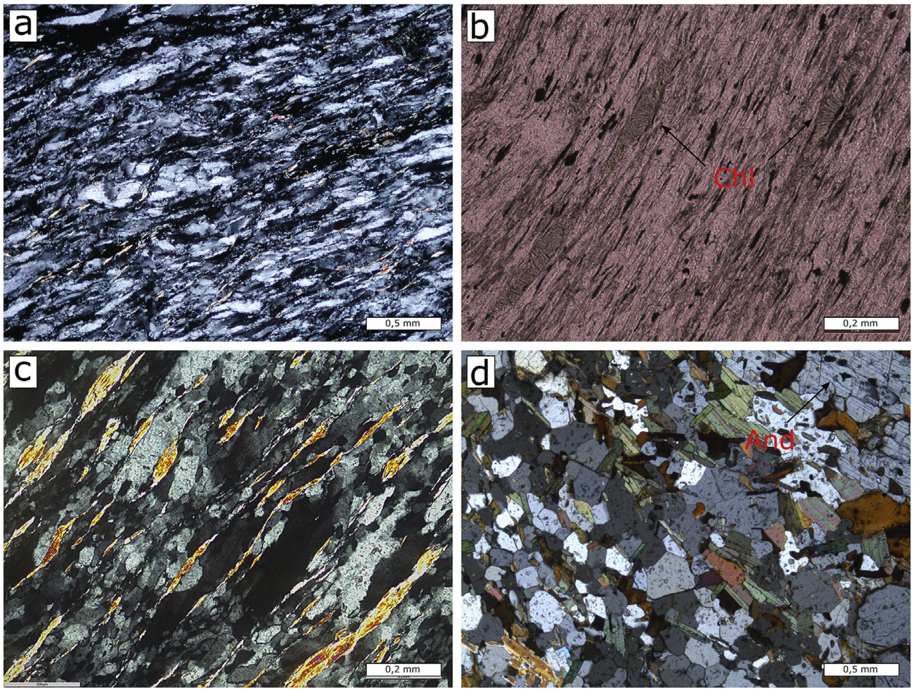


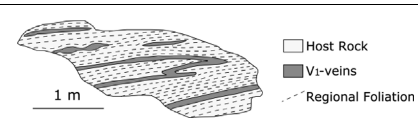
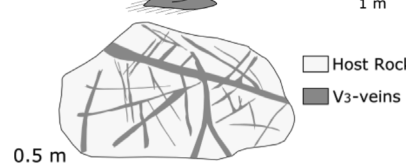
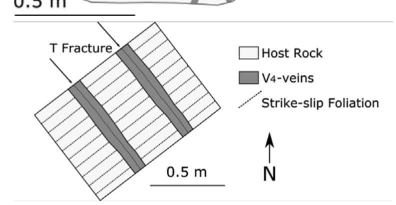
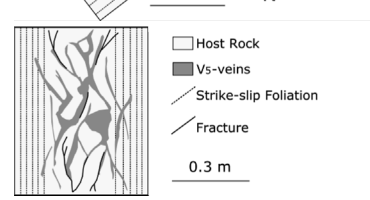
Fig. 6. Photomicrographs of rocks from the Brusque Metamorphic Complex. a) Quartzite mylonite showing continuous foliation marked by the preferred orientation and stretching of grains. Serrated grain boundaries in quartz suggest bulging mechanism; b) Chlorite occur as mica neoblasts marked by the preferred orientation along the mylonitic foliation; c) Mylonitic quartzite with mica fish indicate dextral shear sense in the Itajaí-Mirim shear zone; d) Granoblastic biotite-muscovite-quartz hornfels showing porphyroblasts of andalusite.

20 cm.

Many of the V_1-veins are boudinaged and folded (Fig. 7a and b) within the regional schistosity, which indicates plastic deformation, probably when the surrounding rock was deformed by progressive simple-shear within the regional foliation. Sometimes, in thin sections, the V_1-veins may develop into deformation fringes made of fibrous quartz observed around both opaque crystals (Fig. 4c) and garnet porphyroblasts. The asymmetric distribution of these fringes confirms the rotational tectonics (shear deformation) during the development of the reginal foliation.

The V_1-veins microstructures became progressively involved in the regional foliation. As the deformation proceeded, the new grains continued to develop until the vein was completely recrystallized into an aggregate of granular grains (Fig. 8a). Low-grade deformation produced

Table 1
Quartz veins characterized in terms of directional data and geometric relationship with other veins and structural elements.

Class	Description	Vein sets
V1-veins	Usually tabular, widespread and generally concordant to the regional schistosity. Boudins and folds are common in these veins. Length from 5 cm to 4 m and, exceptionally, up to several meters. Thickness from 1 mm to 20 cm.	
V2-veins	Veins consist of meter-wide massive blocks of quartz in hornfelsed schists.	
V3-veins	Centimeter- to millimeter-wide tabular quartz veins in erratic or conjugate arrays in hornfels.	
V4-veins	Undeformed, mainly vertical (> 80°) veins resulting from strike-slip shear zone striking to N55W. Length ranges from 2 to 10 m. Thickness between 5 and 20 cm.	
V5-veins	Irregular, approximately millimeter-wide quartz veins surrounding clasts in breccia.	

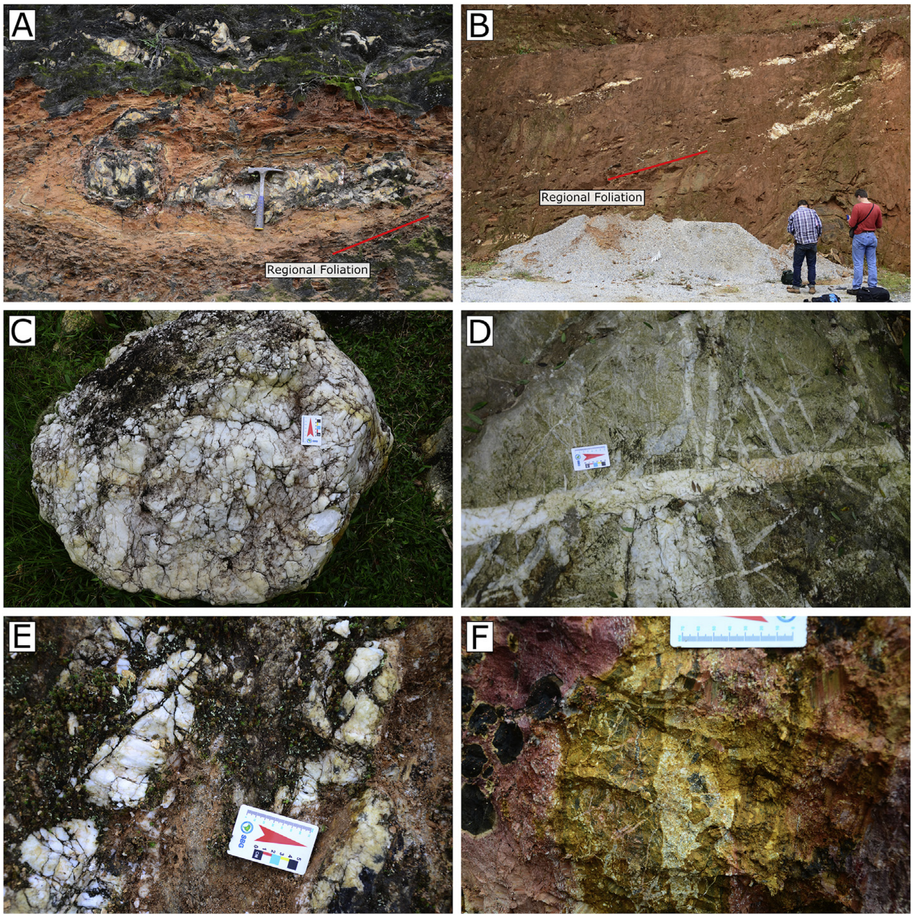


Fig. 7. Quartz veins hosted in rocks of the Brusque Metamorphic Complex. a) Folded quartz vein within the regional surface (V1-veins); b) regional foliation-parallel veins develops throughout the studied area (V1-veins); c) Massive quartz vein blocks occurring in hornfelsed schists (V2-veins); d) Tabular quartz veins distributed in erratic or conjugate arrays (V3-veins); e) Tabular quartz veins striking N55W (V4-veins). These veins crosscut the later quartz veins near the N50E shear zones; f) Erratic quartz veins formed during brittle reactivation of the strike-slip shear zones (V5-veins).

structures such as bulging grain boundaries, wavy extinction, deformation bands and subgrains (Fig. 8b). Together, these features indicate that V_1-veins were generated during the episode of deformation that formed the regional foliation in the BMC.

Sites of contact metamorphism host two different sets veins, V_2 and V_3-veins. The V_2-veins consist of meter-wide massive quartz veins outcrop (Fig. 7c) normally weathered out of the softer hornfelsed schists and would be related to dehydration reactions and fluid migration. The massive quartz V_2-veins are crosscut by centimeter-to millimeter-wide tabular quartz veins disposed in erratic or conjugate arrays (Fig. 7d). The erratic array of V_3-veins gives support to a hydraulic origin, as expected in response to the increasing fluid pressure during dehydration reactions.

Veins originated during the strike-slip shear zones are very rare in the study area. However, close to the NE-trending shear zones, quartz veins are mainly vertical ($> 80°$) and strike N55W (Fig. 7e). The lengths of these veins, named V_4-veins, range from 2 to 10 m and their thickness from 5 to 20 cm (Fig. 7e). The V_4-veins are undeformed, and generally crosscut the V_1-veins that are conformable to the regional foliation. They frequently show well-preserved fibrous crystal growth morphologies, which potentially allow us to determine the opening direction of individual veins as being perpendicular to the rock walls.

Finally, the brittle deformation, related to reactivation of the NE-trending shear zones, produced a sequence of hydrothermal breccias that are filled with millimeter-wide irregularly shaped quartz veins (Fig. 7f). These veins, labelled V_5-veins, form a matrix between clasts in a breccia and were formed during extensive fracturing, without significant preferred orientation.

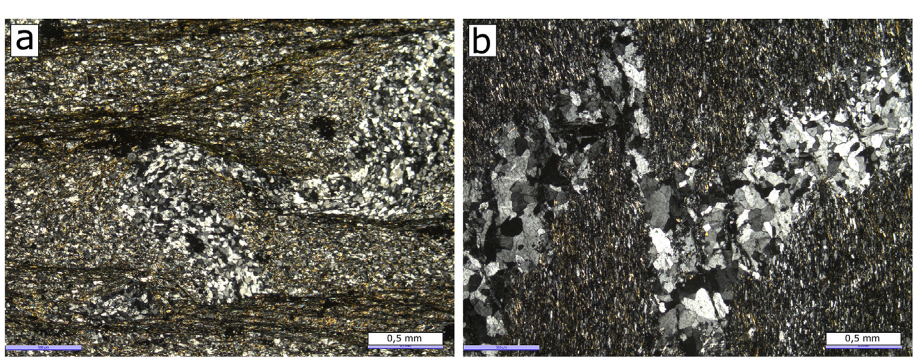


Fig. 8. Microstructures of hots grains in the V_1-veins from the Brusque Metamorphic Complex. a) The vein is completely recrystallized into an aggregate of granular new grains; b) Bulging grain boundaries, wavy extinction, subgrains and new grains indicate low-grade deformation of vein quartz.

5. Discussion

The microstructural data show differences in microstructures of metasedimentary rocks from the Brusque Metamorphic Complex when thrust or strike slip tectonics are considered. This behavior could reflect different deformation/recrystallization mechanisms in each structural system and their variation according to metamorphic conditions.

Microstructural evidence shows that **pressure solution** was the main active deformation process during the development of the regional schistosity. This conclusion is supported by the widespread occurrence of V_1-veins. A number of studies have shown that pressure solution plays an important role during the development of thrust systems, causing the formation of abundant quartz veins in the deformed rocks (Burkhard and Kerrich, 1988; Meneghini et al., 2012; Chandonais and Onasch, 2014). When the fluid pressure is high, the lithostatic pressure can be overcome so that circulation and migration are enhanced. Overpressure is a well-known explanation for the origin of many nappes and thrusts (Hubbert and Rubey, 1959; Fyfe and Kerrich, 1985; Fiori and Wandresen, 2014), and may explain why quartz-veins parallel to the regional schistosity are so abundant in the schists of the Brusque Metamorphic Complex.

In this work, we propose that the occurrence of veins in hornfels is controlled by dehydration reactions during thermal metamorphism, a less common situation according to Yardley (2009). In hornfelsed schists, the granoblastic or decussate textures result from grain boundary area reduction accompanied by dehydration reactions and increasing fluid pressure. The presence of centimeter-wide veins (V_3-veins) crosscutting meter-wide veins (V_2-veins) indicates a cyclic process within the same episode. Examples of veins associated with thermal metamorphism, similar to those from the Brusque Metamorphic Complex, have been shown elsewhere (Davies and Ferry, 1993; Cesare, 1994; Dutrow and Norton, 1995; Barros et al., 2001).

Quartz veins in hornfelsed schists of hornblende to pyroxene hornfels facies would have formed by dehydration reactions, increase in fluid pressure and hydraulic fracturing. These conditions could explain the erratic occurrence of the V_3-veins. During thermal metamorphism of a previously hydrated mineral assemblage, veining is normally ubiquitous. Veins associated with contact metamorphism are present in the Brusque Metamorphic Complex, but are not widespread. This is explained by the previous fluid migration during the development of the regional schistosity under garnet zone conditions.

Most veins are parallel to the regional foliation (V_1-veins), but a few veins (V_4-veins) cut across this foliation and occur adjacent to the NE-trending strike-slip shear zones. The V_4-veins appear to have originated as extension fractures. These extension fractures and veins are commonly found near faults and within fault zones at a range of scales, and are formed perpendicular to the minimum principal stress σ_3 (Robert et al., 1995; Blenkinsop, 2008; Bons et al., 2012; Fiori and Wandresen, 2014).

The V_4-veins are mainly vertical and strike NW, supporting the interpretation as extension veins developed during NE-SW opening along the strike-slip shear zones. The scarce formation of veins along the strike-slip shear zones could be explained by the low temperatures (chlorite zone) and by the fact that the more effective fluid migration seems to have occurred during thrusting and under greenschist facies - garnet zone conditions. Moreover, microstructural evidences suggest that pressure solution played a subordinate role during the development of the steeply-dipping mylonitic foliation.

6. Conclusions

Analysis of the relationship between deformation and vein distribution (fluid transfer) in metasedimentary rocks of the Brusque Metamorphic Complex allows us to draw the following conclusions:

(1) The main deformation, associated with crustal thickening (related to thrusting), was accommodated by extensive **pressure solution** involving both quartz and micas. This deformation resulted in the development of quartz veins (V_1-veins) oriented parallel to the regional foliation during regional metamorphism;
(2) The exclusive presence of some sets of veins within contact aureole supports the inference of a genetic relationship between granite intrusions and veins (V_2 and V_3-veins). It is likely that these veins were formed by dehydration reactions, increase in fluid pressure and hydraulic fracturing during thermal metamorphism;
(3) The transcurrent shear zones forming an anastomosing network with predominantly NE-trending elements and subordinate E-W trending elements combine shearing and shortening during the evolution of the orogenic belt. This deformation was accommodated mainly by bulging recrystallization together with subordinate pressure solution during the development of the mylonitic foliation;
(4) The last important indicator of fluid flow in the metasedimentary rocks of the Brusque Metamorphic Complex is the V_5-veins that occur as brecciated veins within reactivated shear zones.

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