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First report and significance of the staurolite metabasites associated to a sequence of calc-silicate rocks from the Silgará Formation at the central Santander Massif, Colombia

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Abstract

The Silgará Formation metamorphic rocks have been affected by a Barrovian-type of metamorphism, which has occurred under medium-pressure and high-temperature conditions. Scarce intercalations of metabasites from millimeter up to centimeter scale occur in reaction bands observed in the gradational contact between garnet-bearing pelitic and calc-silicate rocks. In this study, we report for the first time the presence of staurolite metabasites in the Santander Massif (Colombian Andes), which is of particular interest since it is an unusual occurrence, taking into account that staurolite is most commonly regarded as an index mineral in metapelites and is not very well known from other bulk compositions and pressure and temperature conditions. Staurolite metabasites contain plagioclase, hornblende and staurolite, suggesting a history of prograde metamorphism up to amphibolite facies conditions. The origin of staurolite can be associated to aluminium-rich metabasites and, therefore, it is strongly affected by bulk rock chemistry. Taking into account mineral assemblages and geothermobarometric calculations in pelitic rocks, we suggest that the staurolite + hornblende association can be formed at least at 400 to 600 °C and 6 kbar at the peak of prograde metamorphism. Retrograde reactions suggest that these rocks experienced nearly isobaric cooling accompanied by retrograde metamorphism.

Key words: Staurolite, amphibolite, Silgará Formation, metamorphism, central Santander Massif.

Primer reporte y significado de las metabasitas con presencia de estaurolita asociadas a una secuencia de rocas calcosilicatadas en la Formación Silgará de la región central del Macizo de Santander, Colombia

Resumen

Las rocas metamórficas de la Formación Silgará fueron afectadas por un metamorfismo tipo barroviense en condiciones de presión media y alta temperatura. Las intercalaciones de anfibolitas en escala milimétrica a centimétrica son escasas en las bandas de reacción del contacto gradacional entre rocas pelíticas con granate y rocas calcosilicatadas. En el presente trabajo se reporta por primera vez la presencia de metabasitas con estaurolita en el Macizo de Santander (Andes colombianos), lo cual es de particular interés por lo inusual de su ocurrencia y porque la estaurolita comúnmente se considera más como un mineral índice en metapelitas y no se conoce muy bien a partir de otras rocas de diferente composición y condiciones de presión y temperatura. Las metabasitas con estaurolita contienen plagioclasa, hornblende y estaurolita, lo que sugiere una historia que abarca desde el metamorfismo prógrado hasta las condiciones de la facies anfibolita. El origen de la estaurolita puede asociarse a metabasitas ricas en aluminio, por lo cual está fuertemente afectada por el quimismo de la roca. Teniendo en cuenta las paragénesis minerales y los cálculos geotermobarométricos en rocas pelíticas, los autores proponen que la asociación estaurolita + hornblenda puede formarse al menos a 400-600 °C y 6 kbar en el pico de metamorfismo prógrado. Las reacciones retrógradas sugieren que estas rocas experimentaron un enfriamiento casi isobárico acompañado de metamorfismo retrógrado.

Palabras clave: estaurolita, anfibolita, Formación Silgará, metamorfismo, región central del Macizo de Santander.

Introduction

Staurolite occurs almost exclusively as a typical product of regional metamorphism in rocks of pelitic composition; however, it has been recorded as a rare constituent in metamorphic rocks of mafic composition (**Selverstone, *et a1.***, 1984). The occurrence of staurolite in metabasites has been reported by several authors: **Miyashiro** (1973), in metabasites of the Sambagawa metamorphic belt, Japan; **Jan, *et al.*** (1971), in amphibolite of the Timurgara ultramafic complex, Pakistan;

Demange (1976), in epidote amphibolite of the Ovala Sequence, Gabon; **Gibson** (1979), in sheets of interlayered amphibolite and hornblendite in the metamorphosed gabbroic anorthosite of the Upper Seaforth River, Central Fiordland, New Zealand; **Selverstone, *et al.*** (1984), in amphibolites from the Mara Rosa volcano-sedimentary sequence, central Brazil; **Purttscheller & Mogessie** (1984), in garnet amphibolite from Sölden, Ötztal Old Crystalline Basement, Austria; **Helms, *et al.*** (1987), in amphibolites of the Laurel Greece mafic-ultramafic complex, northeastern Georgia Blue Ridge, U.S.A.; **Enami & Zang** (1988), in metabasic eclogites from Jiangsu Province, East China; **Moeen** (1991), in amphibolites in the Vinjamum area of the Nellore granite-greenstone terrain of India; **Soto & Azañón** (1993), in amphibotites from the Beltic Cordillera, Spain; **Kuyumjian** (1998), in ortho-amphibolites from the Chapada region, Goiás, central Brazil; **Tsujimori & Liou** (2004), in epidote-amphibolites from the Early Palaeozoic Oeyama belt, SW Japan; **Faryad & Hoinkes** (2006), in Al-rich metabasites from the Speik Complex in the Eastern Alps. However, the literature contains little reference to staurolite metabasites of igneous origin. In this study, we report and discuss data concerning these unusual staurolite metabasites at the central Santander Massif (CSM) region with the aim of determining whether these rocks resulted from unusual bulk rock composition or from unusual physical conditions.

Geological setting

Several studies have been published on the geology of the Santander Massif since the first work undertaken by **Julivert** (1958), which was followed by those by **Ward, *et al.*** (1969a, 1969b, 1970, 1973). Structural geologic studies have been carried out by **Julivert** (1970), **Forero** (1990) and **Kammer** (1993). **Ward, *et al.*** (1973) divide the pre-Devonian crystalline basement of the Santander Massif into the following three deformed and metamorphosed rocks: Bucaramanga Gneiss Complex, Silgará Formation and Orthogneiss, all of which are cut by Paleozoic–Jurassic intrusive bodies (**Goldsmith, *et al.***, 1971; **Banks, *et al.***, 1985; **Boinet, *et al.***, 1985; **Dörr, *et al.***, 1995; **Restrepo-Pace**, 1995; **Ordoñez**, 2003; **Ordóñez & Mantilla**, 2004) and smaller Cretaceous intrusive bodies. However, **Mantilla, *et al.*** (2009) reported U-Pb ages in zircons of 8.4-9.0±0.2 Ma from riodacite porphyry bodies in the central part of the Santander Massif, which evidences a magmatic phase during the Late Miocene (Tortonian) that took place during the Andean Orogeny. New evidences on this Miocece magmatism have been recently reported by **Mantilla, *et al.*** (2011), who determined U-Pb ages in zircons of 10.9±0.2 Ma (from porphyritic andesite) and 10.1±0.2 Ma (from porphyritic granodiorite). Well-exposed sections of the Silgará Formation crop out at the Santander Massif, which has been recognized as a classic area for the study of rock metamorphism and deformation caused by continental collision during the Caledonian orogeny (**Ríos, *et al.***, 2008a). This metamorphic unit has been studied by **Ríos, *et al.*** (**Ríos**, 1999, 2001, 2005; **Ríos & Takasu**, 1999; **Ríos & García**, 2001; **Castellanos**, 2001; **Ríos, *et al.***, 2003a, 2003b, 2008a, 2008b, 2010; **García, *et al.***, 2005; **Castellanos, *et al.***, 2004, 2008), mostly focusing their research during the last two decades on the estimation of metamorphic conditions, taking into account that the CSM represents a natural laboratory to understand the geotectonic evolution of the northwestern margin of South America. The Lower Paleozoic Silgará Formation at the CSM crops out into two N-S trending strips, locally interrupted by the presence of dykes and sills of orthoamphibolites with banded to gabbroic structures (Figure 1). It is mainly composed by metapelitic rocks with minor intercalated psammitic, semipelitic, metabasic and metacarbonate rocks, which were affected by a metamorphism to upper amphibolite facies regional grade during the Caledonian orogeny, and reveals a very complex tectonic and metamorphic history. **Ríos, *et al.*** (2008b) described in detail the metacarbonate and associated rocks that occur in the contact between marble and pelite layers, displaying a broad spectrum of physical conditions varying from greenschist facies to amphibolite facies; a non-economic mineralization “reaction calcic exoskarn” (except by the exploitation of marble) for the metacarbonate and related rocks that form part of the metamorphic sequence of the Silgará Formation at the CSM has been suggested by these authors based on the composition and texture of the resulting skarn, as well as on the available terminology for these rocks, among other aspects. The rocks of interest in this study correspond to the staurolite metabasites of the Silgará Formation, which were not reported by these authors.

Field sampling and analytical methods

A research team from Universidad Industrial de Santander carried out reconnaissance fieldwork in the Santander Massif, primarily focused on localities presenting amphibolites in the reaction bands observed in the gradational contact between garnet-bearing pelitic and calc-silicates rocks. The team took samples containing reaction bands close to marbles from several outcrops. The metabasites for the study were collected in one outcrop close to the Curpaga marble quarry, and belong to the staurolite-kyanite metamorphic zone. The thin section for microscopic analysis was performed at the Sample Preparation Laboratory of the School of Geology; the mineralogical and petrographic analysis of the sample was performed in a Nikon (Labophot2-POL) transmitted light microscope with trinocular viewing to establish the modal

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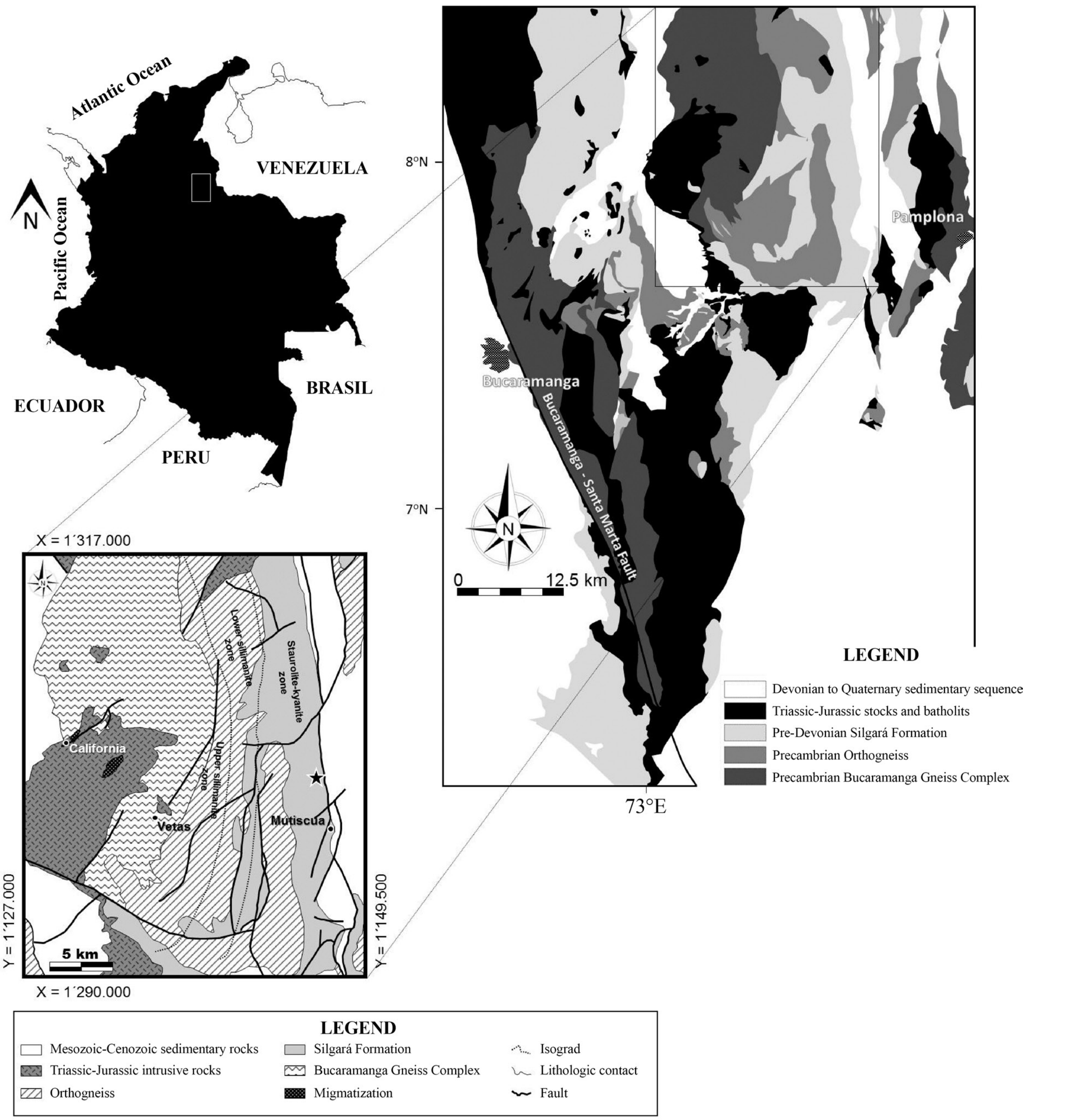

Figure 1. Above, location of the Santander Massif and its corresponding geologic sketch map (modified after **Ward, *et al*.**, 1973), showing the CSM and the distribution of its basement metamorphic and igneous rocks. Below, geologic map of the CSM (modified after **Ward, *et al*.**, 1970), showing the distribution of metamorphic isograds of **García, *et al*.** (2005). The black star indicates the location of the staurolite metabasites.

percentage of mineral constituents and mineral assemblages, with emphasis on textural relationships between mineral phases; photographs were taken with a NIKON AFX-DX microphotographic system at the Research Group in Basic and Applied Geology of the School of Geology. Mineral abbreviations are after **Kretz** (1983). SEM-BSE/EDS imaging and analysis were carried out by environmental scanning electron microscopy (FEI Quanta 650 FEG) to examine textures and cross-cutting relationships in the mineral phases in the staurolite metabasites under the following analytical conditions: magnification = 100-800x, WD = 9,9 mm, HV = 20 kV, signal = Z CONT, detector = BSED.

Field occurrence

Metacarbonate and associated rocks occur as scarce intercalations of variable morphology (with sharp contacts) and thickness, developing discontinuous bands and lenticular bodies within the metamorphic sequence of the Silgará Formation at the CSM. According to **Ríos, *et al.*** (2008b), marbles show a transition into carbonate-silicate rocks, which, in turn, pass into calc-silicate and carbonate-bearing silicate rocks; finally, when carbonate tends to disappear in calc-silicate and carbonate-bearing silicate rocks, they pass into metapelitic and metamafic rocks. These rocks show a very complex mineralogy and appear most commonly as green reaction zones along the contact between marbles or carbonate-silicate rocks and pelitic layers of millimeter to centimeter scale, and their regional proportion is difficult to assess due to exposure limitations. The banding is characterized by the alternation of carbonate-rich layers with pelitic and/or calc-silicate layers. The reaction zones are parallel to the main foliation and in many cases have been folded with it. Gradational contacts between garnet-bearing pelitic and calc-silicate rocks were also observed, which are especially abundant in strongly deformed rocks where calc-silicate zones may have a very irregular shape and variable thickness. The outcrop of interest in this study reveals the occurrence of scarce layers of staurolite metabasites from millimeter up to centimeter scale belonging to the reaction zones that show a gradational contact from garnet-bearing pelitic rocks to marbles, as reported by **Ríos, *et al.*** (2008b). The general features of the staurolite metabasites at field and hand-specimen scale are shown in Figure 2. The outcrop where the staurolite metabasites occurred was found close to a marble quarry characterized by an abrupt topography (Figure 2a). Figure 2b displays the occurrence of interbedded marble (light color) and staurolite metabasite (dark color) bands. A close-up of the staurolite metabasites (dark color)

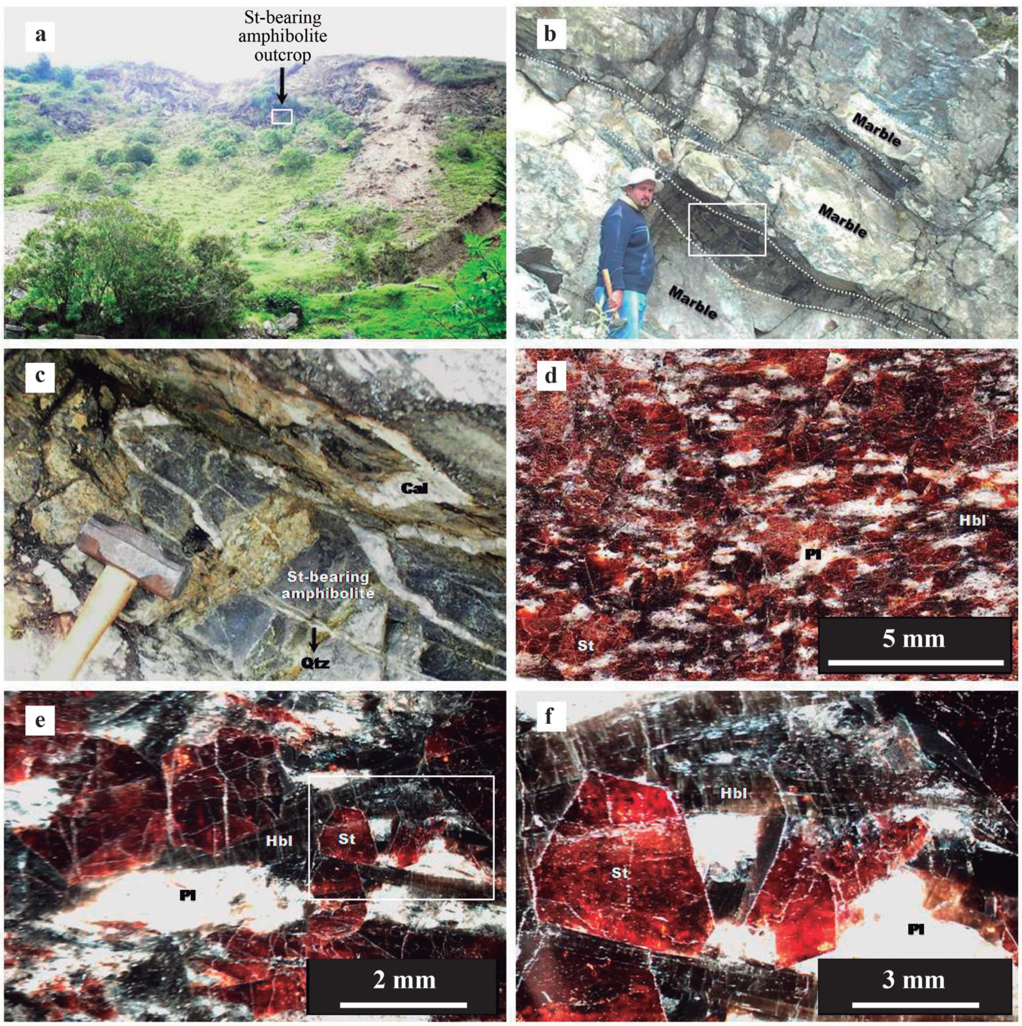

Figure 2. Field and hand-specimen photographs of the staurolite metabasites of the Silgará Formation at the Central Santander Massif

is shown in Figure 2c, where folded calcite veins concordant with the regional foliation quartz veins are observed. Figure 2d shows a hand-specimen of these metabasites, displaying the banding and mineral alignment. The main foliation of the rock is defined by the preferred orientation of staurolite and hornblende. Figures 2e-f illustrate close-ups of the mineral phase relationships and texture features in the staurolite metabasites. The reddish-brown mineral is staurolite, which displays typical elongate and six sided crystals.

Petrography

The contact zone between garnet-staurolite pelitic schists and staurolite metabasites reveals interesting features, which are illustrated in Figure 3. A typical garnet-staurolite pelitic schist with garnet porphyroblasts displaying a sigmoidal pattern of inclusions due to rotation in a matrix, and mainly composed of muscovite, biotite and quartz, is illustrated in Figures 3a-b. Staurolite porphyroblasts in garnet-staurolite pelitic schists commonly display a pattern of inclusions of quartz and ilmenite, which is discordant with the main foliation of the rock defined by biotite flakes (Figures 3c-d). Garnet amphibolites can be found close to the contact zone (Figures 3e-f). Figures 3g-h illustrate the contact between a staurolite-bearing biotite schist in the top and a staurolite metabasite in the bottom. A detail of the occurrence of the staurolite metabasites is shown in Figures 3i-j. Staurolite metabasites are characterized by alternating nematoblastic bands composed of hornblende and staurolite (with penetration twinning) and granoblastic bands composed of quartz and plagioclase (Figures 3k-l).

Staurolite metabasites show an inequigranular texture with staurolite and hornblende randomly distributed developing intergrowth. They are mainly composed by staurolite, hornblende and plagioclase, with minor opaque minerals (ilmenite). Accessory minerals are titanite and rutile, whereas chlorite and sericite are the common secondary minerals. Of special interest is the coexistence of staurolite + hornblende + plagioclase, a mineral association not commonly reported in the literature regarding metabasites. The results of the mineralogical and petrographic analysis of this sample are described below.

Figure 4 illustrates the main petrographical aspects of the staurolite metabasites under study. Staurolite occurs as large and defined lozenge-shaped porphyroblasts randomly oriented. In some cases it shows a simple interpenetrating twin. It can be partly included in hornblende. Hornblende occurs as prismatic (with a diamond-shaped basal cross section) nematoblasts in various orientations, which can be observed as few inclusions in staurolite. Plagioclase shows

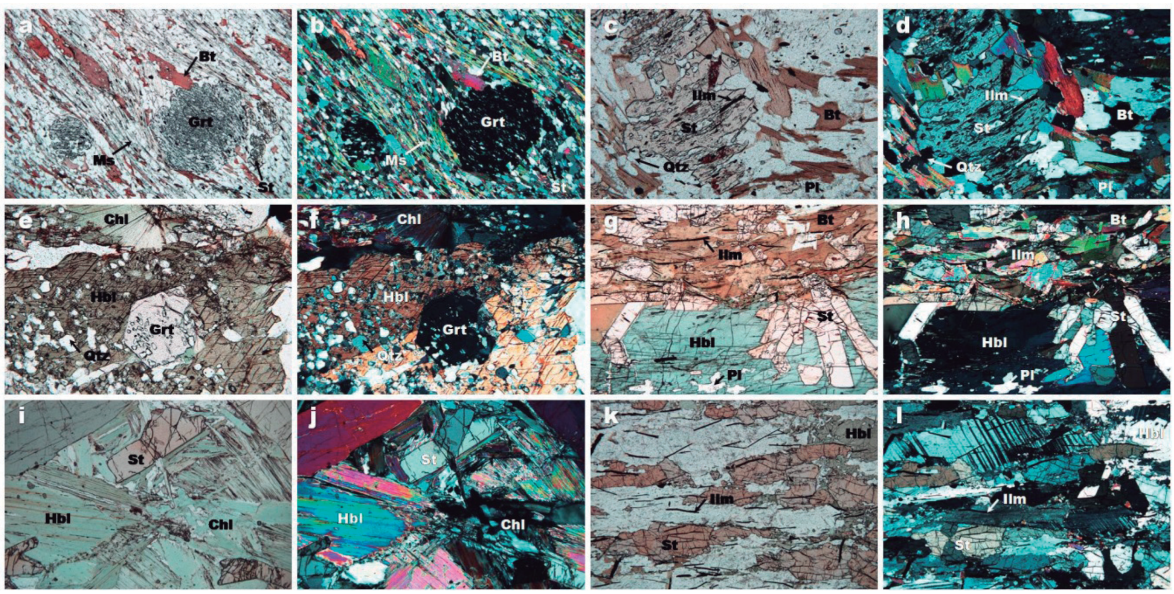

Figure 3. Microtextural relations of metamorphic minerals in the contact zone between garnet-staurolite pelitic schists and staurolite metabasites from the Silgará Formation at the CSM. **a - b**. Sigmoidal pattern of inclusions in garnet porphyroblasts in garnet-staurolite pelitic schist. Note the occurrence of a staurolite around garnet in the right side. **c - d**. Staurolite porphyroblasts with a pattern of inclusions of quartz and ilmenite discordant to the main foliation. Note the granoblastic domains composed of quartz and plagioclase. Garnet is not shown. **e - f**. Garnet amphibolites close to the contact zone. **g - h.** Contact zone between a staurolite-bearing biotite schist and a staurolite metabasite. **i - j.** Occurrence of the staurolite metabasites, with randomly orientation of hornblende, which has been partially replaced by chlorite. **k - l.** Alternating nematoblastic bands of hornblende and staurolite and granoblastic bands of quartz and plagioclase in the staurolite metabasites. Note the orientation not only of these bands but also of the ilmenite laths.

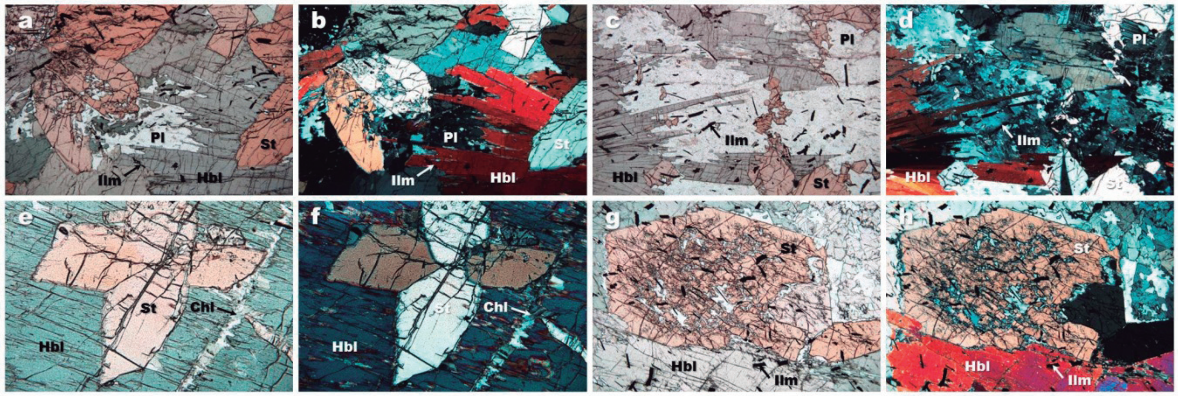

Figure 4. Photomicrographs showing representative textural relationships between staurolite and hornblende and associated mineral phases in staurolite metabasites

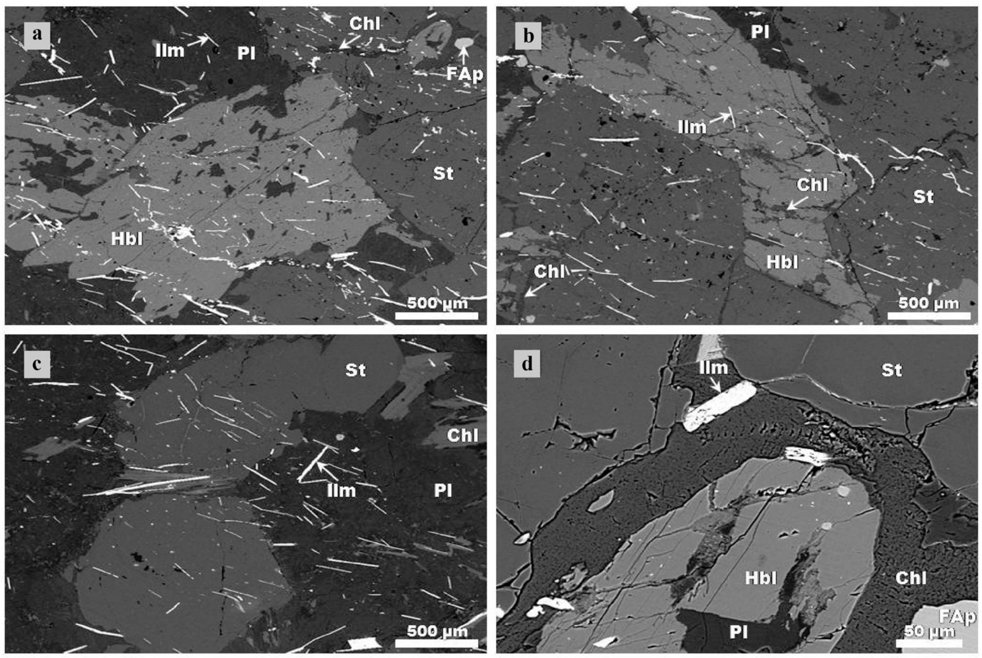

Figure 5. SEM photomicrographs of the staurolite metabasites

a tabular or lath-like shape and may appear cloudy due to incipient alteration to sericite. It occurs as a matrix phase and also as inclusions in hornblende and staurolite. Ilmenite laths, usually randomly oriented locally, tend to develop an oriented trend and are observed as inclusions in staurolite, hornblende and plagioclase. Chlorite occurs as an alteration mineral along irregular fractures in staurolite and hornblende. The staurolite metabasites show interesting textural relationships between staurolite and hornblende. Staurolite displays 90° cruciform twins and included in hornblende with incipient alteration to chlorite. A pseudohexagonal staurolite crystal with an inclusion (quartz)-rich core and inclusion-poor rim is surrounded by large hornblende individuals. Ilmenite laths are randomly distributed. Large staurolite individuals with numerous ilmenite inclusions are closely related to hornblende and plagioclase. Staurolite can be included in honblende, whereas plagioclase sometimes is partly included in staurolite.

Figure 5 reveals some interesting relationships between staurolite and associated mineral phases in the analyzed sample. Figures 5a and 5b display the relationships between staurolite and honblende, showing incipient alteration to chlorite that usually appears along irregular fractures.

Both minerals contain numerous inclusions of ilmenite laths randomly oriented. Staurolite also contains inclusions of hornblende and fluorapatite, whereas plagioclase and quartz are included in hornblende. Figure 5c illustrates numerous ilmenite laths which tend to show an orientation across the matrix. Figure 5d shows a detail of the occurrence of chlorite along an irregular fracture in staurolite, which contains an inclusion of hornblende.

The SEM image in Figure 6 shows the textural relationships between staurolite and honblende, as well as associated mineral phases with semi-quantitative energy dispersive spectrum (EDS) analysis at different points. Energy Dispersive Spectroscopy (EDS) allowed to identify those particular elements and their relative proportions in the mineral phases that constitute the staurolite metabasites. The EDS spectrum of staurolite (1) revealed that it mainly consists of O, Al, Si and Fe elements. The mass ratios of O:Al:Si:Fe were 31.11:27.96:13.29:9.21. The EDS spectrum of hornblende (2) showed that it is mainly composed of O, Si, Fe, Mg and Al elements, with mass ratios of O:Si:Fe:Mg:Al of 30.07:21.22:14.26:8.49:9.26. The EDS analysis of plagioclase (3) indicated the presence of O, Si, Al, Ca and Na elements (mass ratios of O:Si:Al:Ca:Na of 27.94:14.69:6.36:4.10). Very strong Ti, Fe and O peaks (mass ratios of Fe:Ti:O = 39.23:28.17:21.53) were observed in the EDS spectrum of ilmenite (4). The EDS spectrum of fluorapatite (5) revealed the presence of Ca, O, P and minor F elements (mass ratios of Ca:O:P:F = 39.68:21.07:19.46:2.01). The presence of quartz (6) was confirmed in the EDS spectrum, which showed very high intensity peaks for Si and O (mass ratios of Si:O = 48.98:34.27). The EDS analysis of chlorite (7) indicated an alteration of mineral high intensity peaks for O, Si, Mg, Al and low intensity peaks for Fe (mass ratios of O:Si:Mg:Al:Fe = 33.40:13.01:12.91:12.44:11.20). The EDS spectra agreed with literature data (http://www.sfu.ca/~marshall/sem/mineral.htm).

X-rays generated by scanning electron microscopy can be used to produce EDS mapping, which in addition to the BSE image provides a meaningful picture of the elemental distribution of the mineral phases from staurolite metabasites by using X-ray elemental mapping of the selected thin section,

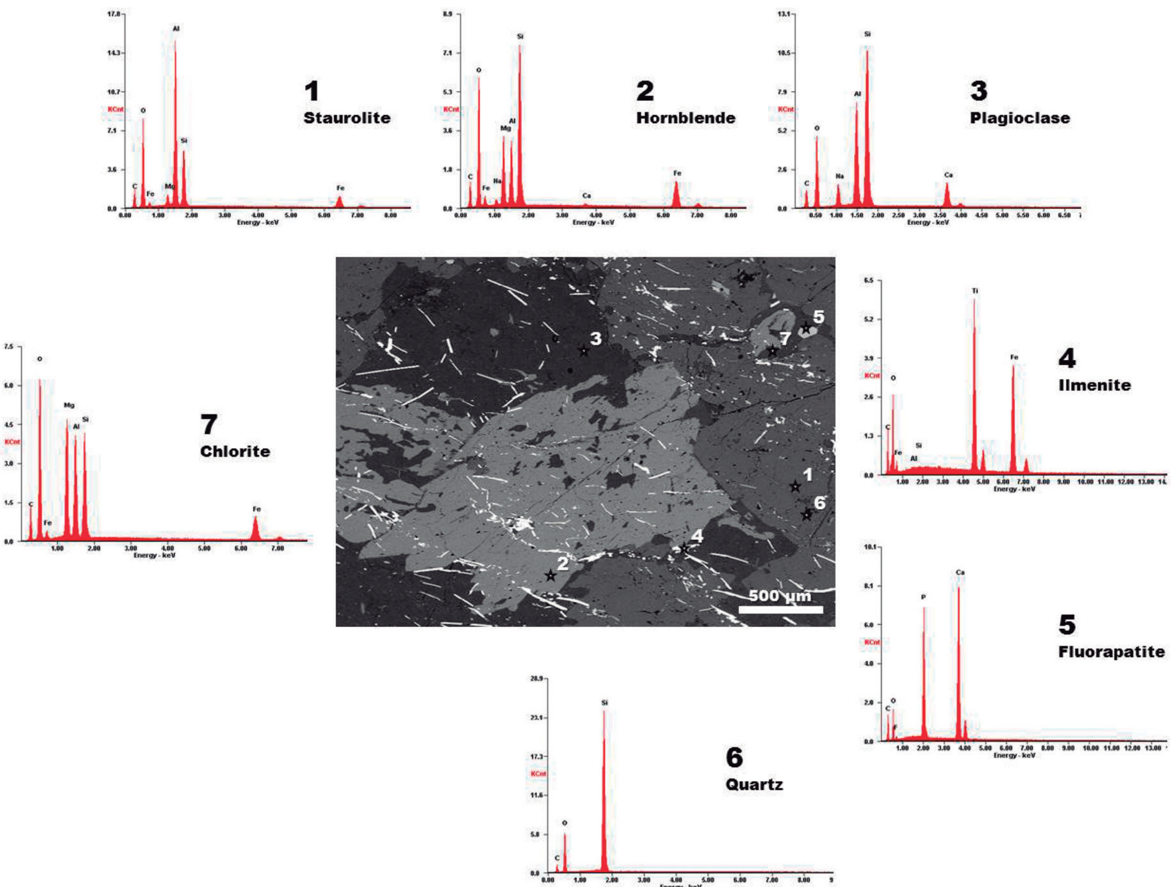

Figure 6. SEM photomicrograph and EDS spectra at the marked stars on the image of the mineral phases in staurolite metabasites. The appearance of C element is attributed to the carbon coating on the sample before SEM analysis

also confirming the abundance of the staurolite-hornblende pair. In Figure 7, the different phases shown on the BSE image (Figure 6) can be identified by elemental mapping, which, however, will only give a qualitative image of the distribution of elements. Figure 7 shows elemental maps corresponding to Si, Al, Mg, Fe Na, K, Ca, Ti and P contents. Note the contrast between Si and Al contents, with staurolite showing the lowest Si content with respect to hornblende and plagioclase. Staurolite shows the highest Al contents followed by plagioclase; hornblende has the lowest Al content. Mg chemical zoning can be observed in hornblende, with Mg content increasing where it is replaced by chlorite. Mg distribution in staurolite is more homogeneous. The Fe content in both staurolite and hornblende is homogeneous. Note the Na and Ca chemical zoning in plagioclase, with Na-rich core and Ca-rich rim. Plagioclase reveals distinct regions of high K content, which can be associated closely with its incipient alteration to sericite. The corresponding maps derived from the X-ray peaks for Ti reveal the compositional identity of Ti oxides (ilmenite), which show a high Ti content. Note the high P regions, which correspond to fluorapatite.

Petrologic significance

Metabasites from the amphibolite facies consist mainly of hornblende, plagioclase and quartz; however, they may also contain combinations of chlorite, garnet, epidote-group minerals, and, more unusually, staurolite, among other mineral phases. Therefore, these mineral assemblages in metabasites can provide tighter constraints on the pressure and temperature conditions of metamorphic terranes that have experienced a very complex tectonic and metamorphic history, such as the Santander Massif. Because of the high variance of most of the mineral assemblages in amphibolites, their phase relationships depend on PT conditions, bulk rock chemistry and fluid composition, with Al content being critical in controlling the occurrence of assemblages involving hornblende with Al-rich minerals, such as staurolite (**Arnold, *et al.***, 2000). However, taking into account that Fe and Mg contents in metabasites are strongly related to the bulk rock chemistry, we consider that they also play a very important role in the formation of staurolite in the Silgará Formation metabasites. It is well known that the Fe/Mg and Na/Ca (to a lesser extent) ratios determine which of the aluminous

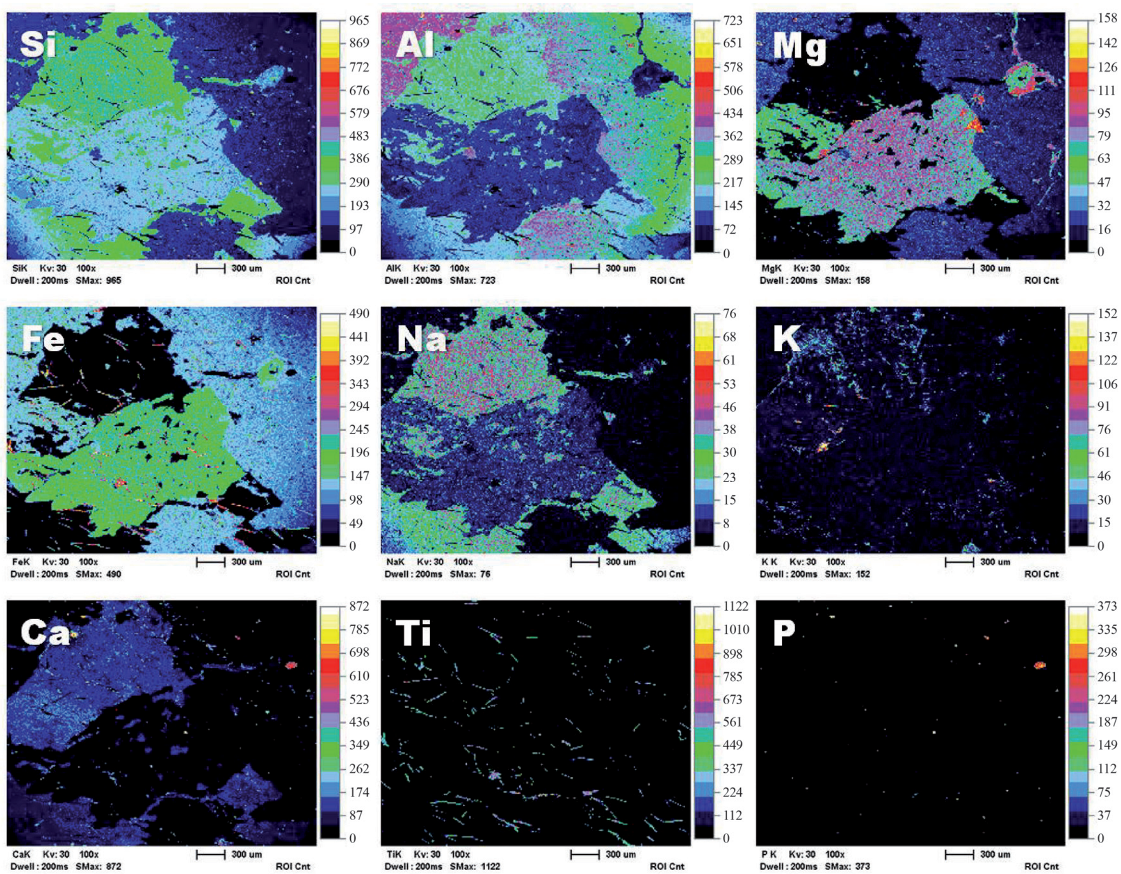

Figure 7. Si, Al, Mg, Fe Na, K, Ca, Ti and P compositional maps of the staurolite metabasites. Light colors show areas of high concentration while dark colors represent areas of low concentration (black is very low concentration).

minerals occur under particular PT conditions. According to the chemical data provided by the EDS spectrum of staurolite, it is Fe-rich with an Fe/Mg ratio of 5.12, which indicates that the staurolite metabasites contain mineral assemblages of Fe-rich metabasites, typically dominated by staurolite-bearing assemblages, thus explaining why their Mg-rich counterparts containing cordierite do not occur in the Silgará Formation metabasites. The development of staurolite metabasites can be attributed to the aluminous and siliceous pelitic rocks in contact with them. On the other hand, the poor K_2O content inhibits the development of K-feldspar producing reactions. Therefore, the Al content in plagioclase and the high Fe content in metabasites promoted the growth of staurolite. A renewed interest in staurolite petrogenesis has led to the report of unusual high-P staurolite assemblages, among which staurolite-hornblende has been reported only in some few studies (**Jan, *et al.***, 1971; **Selverstone, *et a1.***, 1984; **Moeen**, 1991; **Tsujimori & Liou**, 2004). It is well known that amphibolites as a consequence of metasomatic exchange can be observed in the interfase between pelitic and calc-silicate rocks. The textural relations of minerals observed in the staurolite metabasites from the Silgará Formation, which represent an unusual example not only for the CSM but also at world level, reveal equilibrium conditions between staurolite and hornblende at peak PT conditions, characterizing a history of prograde metamorphism that reached the amphibolite facies probably under high-P conditions, similar to what has been reported in the literature. However, according to **Mohammad, *et al.*** (2011), staurolite cannot form in equilibrium with minerals from the amphibolite facies in metabasites. The presence of mineral assemblages with staurolite and hornblende in amphibolites is usually known in metabasites having a mixture of argillaceous or Ca-rich metasediments (**Selverstone, *et al.***, 1983; **Ward**, 1984; **Humphreys**, 1993; **Kuhns, *et al.***, 1994). Textural evidence reveals that staurolite grew subsequently across chlorite and hornblende in the staurolite metabasites of interest in this study, which form part of a sequence of calc-silicate rocks from the Silgará Formation at the CSM that can be interpreted as reaction zones of diffusion metasomatic origin, formed by interaction between original thin limestone layers and adjacent pelitic rocks, which are characterized by the development of narrow, multi-layered, reaction zones with different high-variance mineral assemblages. **Ríos, *et al.*** (2008b) described in detail these metasomatic reaction zones, which are similar to those described by other researchers (**Thompson**, 1975; **López & Soto**, 1999). However, in the staurolite metabasites reported in this work there are scarce mineral phases. Therefore, we consider that they do not have an igneous origin, which has been attributed to a few occurrences of staurolite + hornblende assemblages reported in metabasites derived from mafic rocks (**Purtscheller & Mogessie**, 1984; **Helms, *et al.***, 1987; **Kuyumjian**, 1998). The occurrence of staurolite + hornblende in mafic rocks has been interpreted as a result of either different bulk composition (**Spear**, 1982) or specific PT conditions (**Selverstone, *et al.***, 1984; **Helms, *et al.***, 1987). The textural and phase relationships of minerals from the staurolite metabasites of the Silgará Formation reveal equilibrium between staurolite and hornblende at peak PT conditions (high-P amphibolites facies), which are consistent with data reported in the literature. In this study, we report scarce staurolite inclusions only in the rim of hornblende adjacent to plagioclase, similar to what has been reported by **Gibson** (1978), and chemical zoning of plagioclase (a stable coexisting phase in the rock according to **Selverstone, *et al.***, 1984) with Na-rich core and Ca-rich rim. According to **Arnold, *et al.*** (2000), the X_{Fe} strongly determines which (if any) of the Al-rich minerals occur under particular PT conditions, and where these mineral phases occur in amphibolites, the PTX dependence of their phase relationships is remarkably similar to that in metapelitic rocks. The mineral assemblages occurring in the Silgará Formation staurolite metabasites are characterized by the unusual presence of staurolite + hornblende. In general, the staurolite + hornblende association is characteristic of intermediate- or high-P (~ 5 kbar) and intermediate T (500-650 ^oC) of metamorphism (**Grew & Sandiford**, 1985). **Arnold, *et al.*** (2000) constrained pseudosections for staurolite-bearing assemblages with plagioclase in excess, indicating that in amphibolites with Al-rich staurolite, this mineral can be formed at temperatures higher than 550 °C, and hornblende at temperatures higher than 595 °C. However, a pseudosection constructed by **Faryad & Hoinkes** (2006) revealed that staurolite in such rocks may originate at 570 °C and 0.7-0.8 GPa with plagioclase. Theoretical considerations also suggest a high-P origin of staurolite + hornblende relative to more usual amphibolite-facies assemblages (**Grew & Sandiford**, 1985). However, it is not clear if the high Al content in the bulk rock chemistry is of primary origin or if it is the result of hydrothermal alteration of the rock before amphibolite facies metamorphism (**Faryad & Hoinkes**, 2006). **Froese & Hall** (1983) constructed a reaction grid for quartz-bearing mafic rocks in which the reaction chlorite + garnet + plagioclase = staurolite + hornblende takes place with an increase in pressure conditions. This reaction extends to higher pressure from an invariant point, the existence of which is supported by the assemblage chlorite + garnet + hornblende + gedrite + staurolite proposed by **Spear** (1982), who estimated that this assemblage crystallized at 5-6 kbar, providing, therefore, a minimum pressure for the stability field of staurolite + hornblende proposed by **Froese & Hall** (1983). **Selverstone, *et al.*** (1984) proposed that the reaction would produce staurolite + hornblende in the presence of quartz is plagioclase + chlorite + epidote = hornblende + staurolite ± kyanite ± paragonite (garnet may also be a reactant), which would proceed at a minimum pressure of 6 kbar in mafic rocks of relatively aluminous composition; however, in typical metabasites, pressures required for this reaction would exceed 6 kbar. The formation of staurolite + hornblende appears to involve dehydration, and, therefore, water activity may be an important factor controlling the pressure conditions of formation (**Selverstone, *et al.***, 1984; **Froese & Hall**, 1983). Host rock Fe^{2+}/Mg and Fe^{3+}/Al ratios may also be critical (**Grew & Sandiford**, 1985). Therefore, taking into consideration mineral assemblages and geo-thermobarometric calculations (400-600 °C and 4.0-6.5 kbar) reported by **Castellanos, *et al.*** (2008) in pelitic rocks, we suggest that the staurolite + hornblende association can be interpreted to have formed at least between 400-600 °C and 6 kbar at the peak of prograde metamorphism. On the other hand, there is no doubt that two processes should be considered here: decarbonation of marbles and dehydration of pelitic rocks. Therefore, prograde reactions and CO_2 loss probably occurred in the marble layers within the Silgará Formation metamorphic sequence in response to infiltration of H_2O from dehydration of surrounding pelitic rocks (**Hewitt**, 1973; **Ague**, 2000) or advection-driven infiltration of a H_2O-rich fluid external to the metasedimentary sequence (**Ague**, 2002). We consider an external H_2O-rich fluid that evolved from syn-metamorphic magmas, which can be associated to the emplacement of orthogneiss masses at the lowest structural levels of the Silgará Formation, penetrating mainly along tectonic discontinuities and lithologic contacts. However, it is difficult to establish if cation diffusion dominates with respect to the fluid flow, as in the mechanism of mass transfer suggested by **Thompson** (1975), taking into account that the Silgará Formation metamorphic rocks reveal very important evidence of a fluid circulation with strong influence on the development of hydrothermal veins within calc-silicate reaction zones. Nevertheless, it is very important to undertake future research on the calc-silicate reaction zones to determine in detail their geometry, mineral assemblages and bulk rock chemistry and distinguish between diffusion and flow fluid processes to develop a model for a metasomatic phenomenon. Retrograde reaction textures, including partial replacement of chlorite after staurolite and hornblende along fractures and rims or sericite after plagioclase, suggest that the Silgará Formation experienced nearly isobaric cooling accompanied by retrograde metamorphism, as suggested by rehydration reactions that often do not terminate, with extensive deformation that promoted anisotropy planes in depth and circulation of fluids in the system. The chemical reactions that relate prograde and retrograde mineral assemblages involve transitions between the stability fields of the reactants and those of the products, including a movement from high-PT to low-PT conditions along a nearly isobaric cooling. Taking into account that the staurolite metabasites show lower variance, although without well-developed reaction textures, their mineral assemblages contain important petrogenetic evidences for constraining equilibrium conditions, reaction history and PT conditions to elucidate the tectono-metamorphic evolution of the Silgará Formation at the CSM. Therefore, we suggest performing mineral chemistry and bulk rock analyses of metabasites and associated rocks to contribute to the understanding of the phase relationships of these rocks as a function of PT conditions and bulk rock chemistry.

Conclusions

Staurolite metabasites of the Silgará Formation at the CSM represent a rare amphibolite facies type. On the basis of field and laboratory observations, the staurolite + hornblende assemblage can provide tighter constraints on the PT evolution of this metamorphic unit than is usually possible from metabasites. We suggest that the staurolite + hornblende assemblage is stable in mafic compositions at least at 400-600 °C and 6 kbar at the peak of prograde metamorphism. The fact that the staurolite metabasites occur very closely associated with pelitic and calc-silicate rocks, makes the hypothesis of metamorphism of metasomatised layers at the origin of these metabasites more likely than considering the staurolite-hornblende paragenesis as a result of unusual physical conditions. Retrograde textural reactions suggest that these rocks experienced nearly isobaric cooling accompanied by retrograde metamorphism.

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Conflicts of interest

None declared.

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