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Exploring the relationships between shear zones and granites: field and microstructural data for contrasting case studies of the Borborema Province (NE Brazil)

Explorando as relações entre zonas de cisalhamento e granitos: dados de campo e microestruturais em estudos de caso contrastantes da Província Borborema, (NE do Brasil)

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Abstract

We discuss meso- and microstructural features of granites closely related to strike-slip shear zones in the Borborema Province, NE Brazil. The Riacho do Icó stock is an *en-cornue* intrusion aged at ca. 607 Ma. Magmatic fabric is recorded in the core of the granite, whilst increasing deformation is marked by the development of mylonitic fabrics towards the Afogados da Ingazeira shear zone, including magmatic foliation and lineation rotation. Early recrystallization of quartz and K-feldspar crystals is widespread as a fabric with well-developed granoblastic polygonal textures and lobate subgrain boundaries, heterogeneously deformed lenses and ameboid quartz ribbons, typical of igneous rocks submitted to deformation in deep crustal levels. On the other hand, the Espinho Branco-Santa Luzia leucogranitic belt is hosted along the Patos Lineament, aged between the ca. 575 – 565 Ma interval. These rocks show discordant relationships with the host migmatites and the main deformational fabric is characterized by a dominant magmatic foliation that is locally overprinted by structures that are typical of solid-state flow. Quartz melt pockets and interstitial quartz grains filling fractures in feldspar clasts are common. Such characteristics are compatible with granites that were injected in the continental crust along planar anisotropies (*i.e.,* shear zones) formed during the late-stage partial melting events that originated the migmatites of the area. The case studies are proxies in the understanding of different episodes of magma emplacement along shear zones in this part of West Gondwana.

Keywords: Granitic magma emplacement; Shear zones; Microstructures; Borborema Province.

Resumo

Apresentamos dados meso e microestruturais de granitos associados a zonas de cisalhamento na Província Borborema, Nordeste do Brasil. O *stock* Riacho do Icó representa uma intrusão *en-cornue* datada em ca. 607 Ma. A trama magmática é bem representada no núcleo da intrusão, enquanto o incremento da deformação é marcado pelo desenvolvimento de estrutura milonítica em direção à zona de cisalhamento Afogados da Ingazeira, acompanhado de rotação da foliação e lineação. Recristalização precoce de cristais de quartzo e K-feldspato é abundante ao longo de tramas poligonais limites de grãos e subgrãos retilíneos, lentes deformadas de forma heterogênea e grãos fitados de quartzo, típicos de rochas ígneas submetidas a níveis crustais profundos. Por outro lado, o cinturão leucogranítico Espinho Branco-Santa Luzia é hospedado pelo lineamento Patos, como idades variando entre ca. 575 – 565 Ma. Essas rochas apresentam relações discordantes com os migmatitos, e a principal trama deformacional é caracterizada por foliação magmática, localmente obliterada por estruturas típicas de fluxo no estado sólido. Mobilizados de fusão parcial compostos de quartzo intersticial preenchendo fraturas nos clastos de feldspato são comuns. Tais características são compatíveis com granitos injetados na crosta continental por meio de anisotropias planares (*i.e.*, zonas de cisalhamento) formadas durante os últimos estágios de fusão parcial que originaram os migmatitos da área. Os casos de estudo apresentados representam modelos para o entendimento dos diferentes episódios de alojamento de magmas associados a zonas de cisalhamento nessa parte do Gondwana Ocidental.

Palavras-chave: Alojamento de magmas graníticos; Zonas de cisalhamento; Microestruturas; Província Borborema.

INTRODUCTION

Granites are major products of long-term magmatic differentiation and are key elements to understand the evolution of the Earth´s Lithosphere. These rocks are reliable markers of crustal growth and recycling, providing clues on complex thermodynamic processes that are inherent to a number of tectonic settings (Chappell and White, 2001; Kemp et al., 2007; Moyen and Laurent, 2018). In general, granites are the result of buoyant magma that is mostly generated during plate convergence, involving a combination of processes such as melting, assimilation, storage and hybridization (MASH) zones, which occur below island- and continental arcs. In collisional settings, they are the products of upper crust melting (*e.g.*, Hawkesworth and Kemp, 2006). Since seminal works that addressed the space problem for granitic magma emplacement in the crust (*e.g.*, Hutton et al., 1990 and references therein), crustal discontinuities are considered the main physical conduits for magma migration and final storage. However, events of granitic magma migration and emplacement are still complex, due to the variability of its composition, viscosity and plumbing characteristics, besides the interaction with the host rocks (Brown, 2013).

Flow processes in magma chambers can be successfully tracked by means of detailed fabric analysis of the magmatic suites (enclaves + host rocks). The main mechanisms of fabric development in crystallizing granites comprise viscous and solid-state flow (Paterson et al., 1989; Vernon, 2004) at decreasing melt fractions. In the first case, numerical modelling shows that the orientation of mineral phases is acquired through the rotation of ellipsoidal particles in a liquid, *i.e.*, melt (Jeffery, 1922). The oriented grains define a shape-preferred orientation (SPO) usually consistent with the magmatic flow plane. However, these models do not take into account the interactions between adjacent particles during shear flow, which lead to imbrication or tiling of crystals in the magma (Blumenfeld and Bouchez, 1988; Tikoff and Teyssier, 1994); such interactions may disturb the flow and and can result in monoclinic fabrics with local solid-state strain accumulated at grain boundaries (Vigneresse and Tikoff, 1999).

Alternatively, solid-state deformation may develop fabric orientations through crystal plastic behaviour during dislocation creep in syntectonic granites (Hutton, 1988). In these cases, the fabric shows marked crystallographic preferred orientations (CPOs), i.e., the alignment of specific crystallographic planes and axes with the shear plane and direction as the results of dislocation creep along those intracrystalline planes and axes. CPOs may be used to retrieve shear sense in deformed granites. It follows that detailed fabric analysis and is a powerful tool to establish the interaction between magmatism, metamorphism and shearing during a liquid to solid state transition at progressively decreasing temperature associated with the emplacement and crystallization of plutonic bodies (Zibra et al., 2010).

In the Neoproterozoic orogenic belts of South America, several crustal domains that were fertile in granitic production have been long recognized, being interpreted as the record of subduction and collision episodes related to the Brasiliano Orogeny during the assembly of Western Gondwana (Brito Neves et al., 2014). Within this large orogenic system, the Borborema Province in NE Brazil presents several examples of granitic batholiths and plutons, in which magma emplacement mechanisms are closely related to the development of deep-seated shear zones (Santos and Medeiros, 1999; Weinberg et al., 2004; Archanjo et al., 2008). Among them, large arrays of strike-slip shear zones concentrate most of the plutonic activity in the region, being characterized by high- and low temperature mylonites and migmatites that are linked to Pan-African structures in paleogeographic reconstructions (Vauchez et al., 1995; Brito Neves et al., 2000). For instance, Viegas et al. (2014) have shown that during the final stages of the Brasiliano Orogeny (*i.e.,* 566 ± 6 Ma), crustal melting resulted in large migmatitic domains along the Patos Lineament.

Such processes have critical regional implications, since these conditions present a fair estimation for final metamorphic peak, timing of magma migration and emplacement and possibly mark terrane assembly episodes (*e.g.*, Santos et al., 2017a). In addition, considering a broader scenario, the final configuration of granitic distribution in the province is interpreted as the result of collision and extrusion tectonics recorded along the major shear zones (Ganade de Araujo et al., 2014).

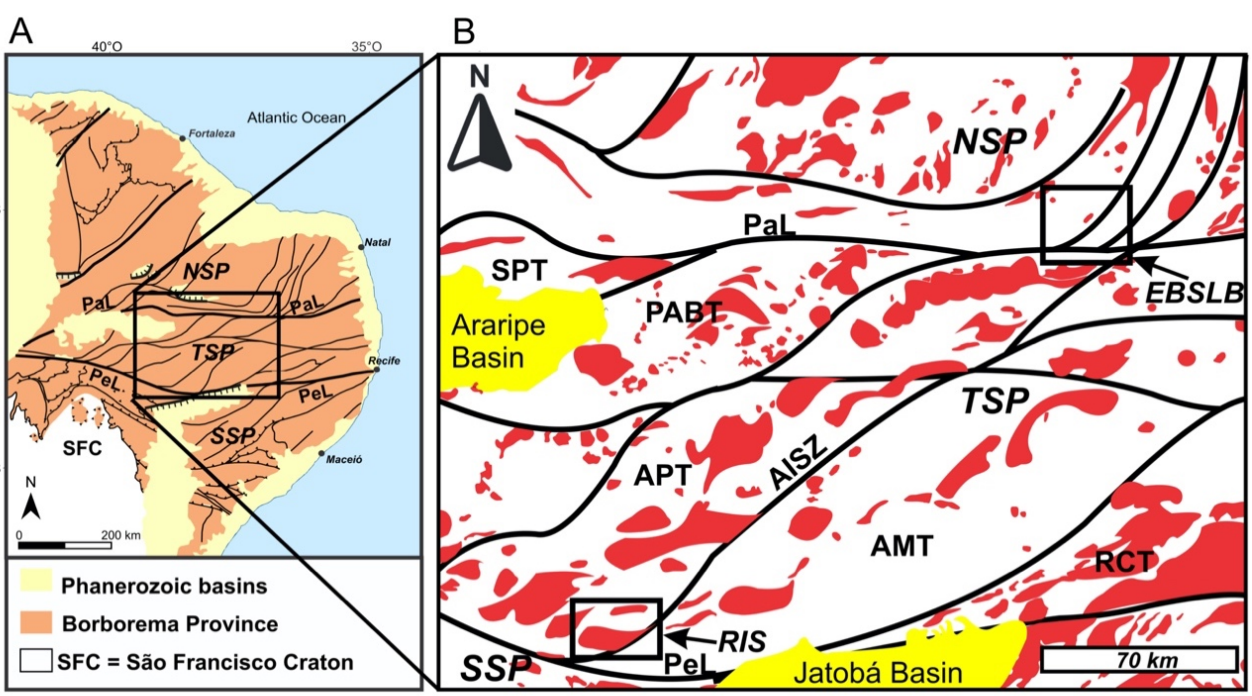
In this contribution, we present field and microstructural data of granitoid plutons emplaced in association with ductile shear zones of the Borborema Province. Based on field structural mapping and the microstructural characterization of the intrusions in two key-areas, *i.e.,* on the SW tail of the Afogados da Ingazeira shear zone and the central region of the Patos Lineament, we report the development of both magmatic and solid-state fabrics during progressive cooling and syn-magmatic shearing of the granitoids. Such data is fundamental in the discussion about the relationships between pluton emplacement mechanisms and deformation in a broader scenario, aiming to contribute with the understanding of the feedbacks between magmatism and orogenic processes that operated in the province during the Neoproterozoic.

GEOLOGICAL SETTING

The Borborema Province (Figure 1A) corresponds to one of the major Neoproterozoic orogenic belts of South America defined by Almeida et al. (1981). Prior to the opening of the Atlantic Ocean, the province has had crustal continuity into the Oubanguides, Central Africa and Dahomeyides belts through Togo, Benin, Nigeria and Cameroon (Caxito et al., 2020a and references therein). In a simplified way, the overall configuration of this province includes Archean and Paleoproterozoic gneissic-migmatitic domains (*e.g.*, Santos et al., 2015; Ferreira et al., 2020) that are bounded or interleaved with Neoproterozoic supracrustal sequences (*e.g.*, Neves et al., 2017; Santos et al., 2019) and granitic domains that represent remnants of accretion episodes during the assembly of West Gondwana (Figure 1B; Brito Neves et al., 2000; 2014; Caxito et al., 2020b).

One of this province's remarkable features is the dense network of shear zones including the E-W Patos and Pernambuco, dividing the province in Northern, Transversal and Southern subprovinces (Figure 1A; Van Schmus et al., 1995). Granitic domains are widespread in the province and represent one of the major tectonic markers of the Brasiliano Orogeny, largely studied for decades (*e.g.,* Almeida et al., 1967; Sial, 1987; Santos and Medeiros, 1999, among others). Most of these have been proven to be closely associated with strike-slip shear zones, especially the ones aged 590 – 470 Ma, marking the transition between subduction-related to collisional magmatism (Guimarães et al., 2004; Ganade de Araujo et al., 2014). The intrusions addressed in this work crop out in two different regions of the province, characterized by a complex network of NE-SW and E-W shear zones that host several granitoid intrusions (Figure 1B).

The Riacho do Icó stock (Figure 2) is located within the Transversal Subprovince that comprises a mosaic of crustal domains interpreted as tectono-stratigraphic terranes separated by NE-SW thrust and strike-slip shear zones (*i.e.,* Rio Capibaribe, Alto Moxotó, Alto Pajeú, Piancó-Alto Brigída, São Pedro; Santos and Medeiros, 1999). See Neves (2015) for a different interpretation of these domains. This stock is part of the Lagoa das Pedras metaplutonic complex that represents a long-lived (1.0 – 0.6 Ga) record of crustal growth within the Alto Pajeú Terrane (Santos, 1995; Santos et al., 2017b; Lages and Dantas, 2016). The related rocks are intrusive in *ca.* 858 – 806 Ma metavolcanosedimentary rocks of the São Caetano Complex (Guimarães et al., 2012; Santos et al., 2019). Early Neoproterozoic rocks are related to the Cariris Velhos Orogeny (960 – 920 Ma), being grouped with the cumulatic/ophiolitic Serrote das Pedras Pretas Suite, as well as a series of arc-related calc-alkaline metagranites, orthogneisses and metavolcanic rocks (Kozuch, 2003; Santos et al., 2010). Younger bodies related to this complex include Ediacaran granites representing the record of the Brasiliano Orogeny in the area, including the ca. 607 ± 3 Ma Riacho do Icó stock, recently interpreted as the result of oceanic slab melting (Santos et al., 2020).



RIS: Riacho do Icó stock; EBSLB: Espinho Branco-Santa Luzia leucogranitic belt. Subprovinces: SSP: Southern; TSP: Transversal; NSP: Northern. Terranes: RCT: Rio Capibaribe; AMT: Alto Moxotó, APT: Alto Pajeú; PAB: Piancó-Alto Brígida; SP: São Pedro. Main shear zones: PeL: Pernambuco; AISZ: Afogados da Ingazeira; PaL: Patos.

Figure 1. (A) Simplified tectonic framework of the Borborema Province with the main subprovinces outlined; (B) Geological map of part of the central Borborema Province showing the major shear zones and granitic rocks. The rectangles outlined in figure B represent the studied cases in this paper.

The second granitoid suite is located along the connection of the Patos shear zone with the Seridó metasedimentary belt, and consists of E-W to NE-SW elongated bodies of leucogranites that are spatially associated with the Espinho Branco and Santa Luzia migmatites (Archanjo et al., 2013; Viegas et al., 2013). These leucogranites are characterized by mostly metric-sized stocks, locally reaching few km in diameter, that intrude the partially molten rocks. Previous studies have associated these leucogranites with the large volumes of anatexis and granitoid magmatism that occurs within the Patos-Seridó shear system (Viegas et al., 2013). In the Patos shear zone, the leucogranites intrude the metatexites and diatexites of the Espinho Branco migmatite and are mostly associated with the late stages of magma transfer along the shear zone. On the other hand, the leucogranites of the Seridó belt are interpreted as the products of magmatic differentiation within the magma chamber that fed the Santa Luzia anatexite (Archanjo et al., 2013). Zircon U-Pb geochronological data of these plutons have constrained their age of crystallization within the interval of ~575 – 565 Ma (Archanjo et al., 2013; Viegas et al., 2014), thus in a different timing as compared with the Riacho do Icó stock.

RESULTS

Mesoscopic characteristics of the Riacho do Icó stock

The granodioritic to monzogranitic Riacho do Icó stock presents a 60 km^2 *en-cornue* shape along the E-W and NE-SW regional trend of the Afogados da Ingazeira shear zone (Figure 2). On its central portion, it shows equigranular, medium- to coarse-grained texture (Figure 3A) and may exhibit porphyritic facies. The primary mesoscopic features include magmatic foliations

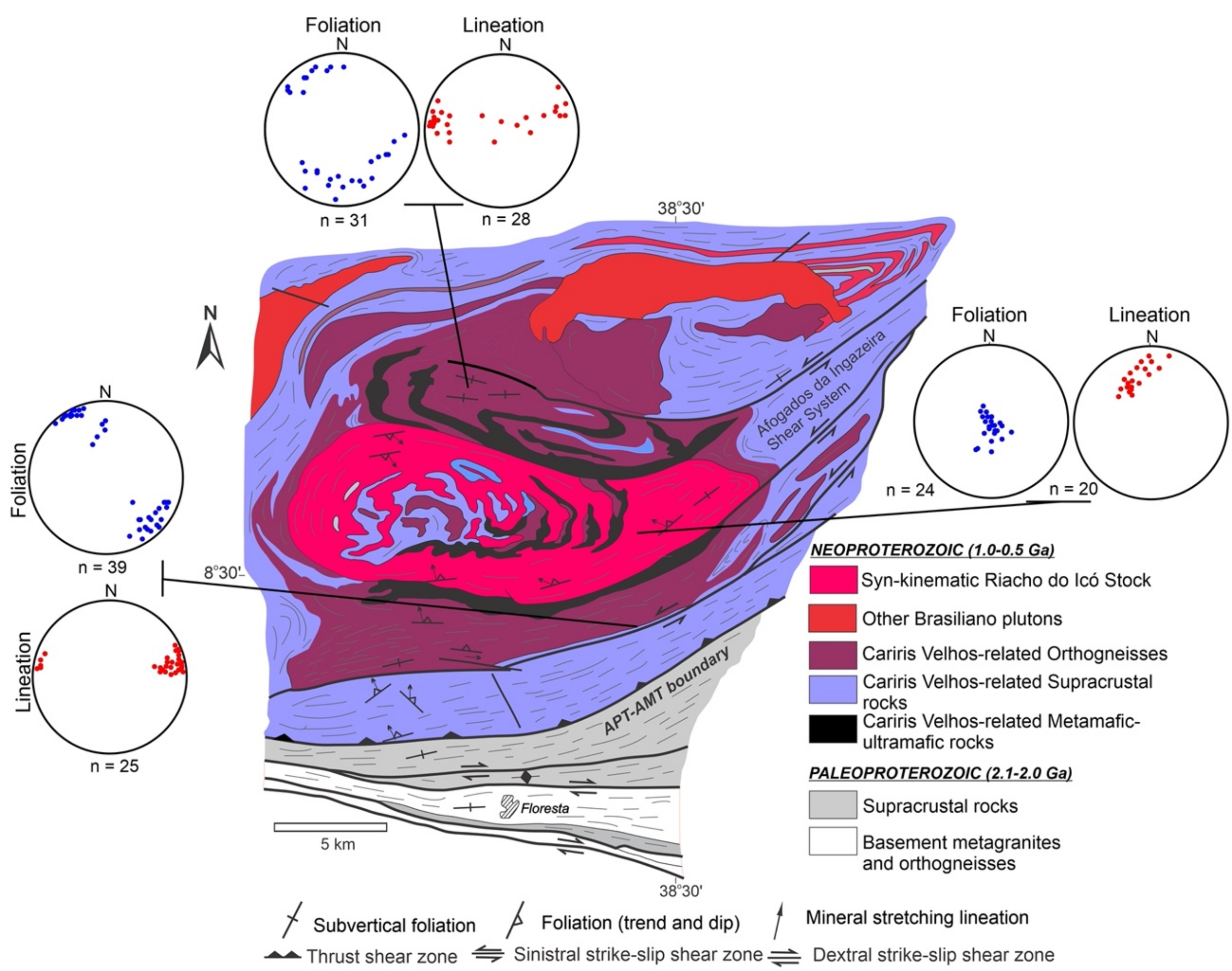


Figure 2. Geological map of the Riacho do Icó stock and its host rocks. The blue circles and red circles on the presented stereograms mark the kinematic variations in the planar and linear fabrics in the inner portions of the intrusion and the marginal zones.

marked by the dimensional orientation of k-feldspar crystals and amphibole clots as well as widespread oval to ellipsoidal dioritic to quartz-dioritic enclaves interpreted as autholiths. Xenoliths are widespread where the magmatic fabric dominates, including those of the heavily foliated muscovite-schists (Figure 3B) and irregularly shaped muscovite-bearing mylonites (Figure 3C).

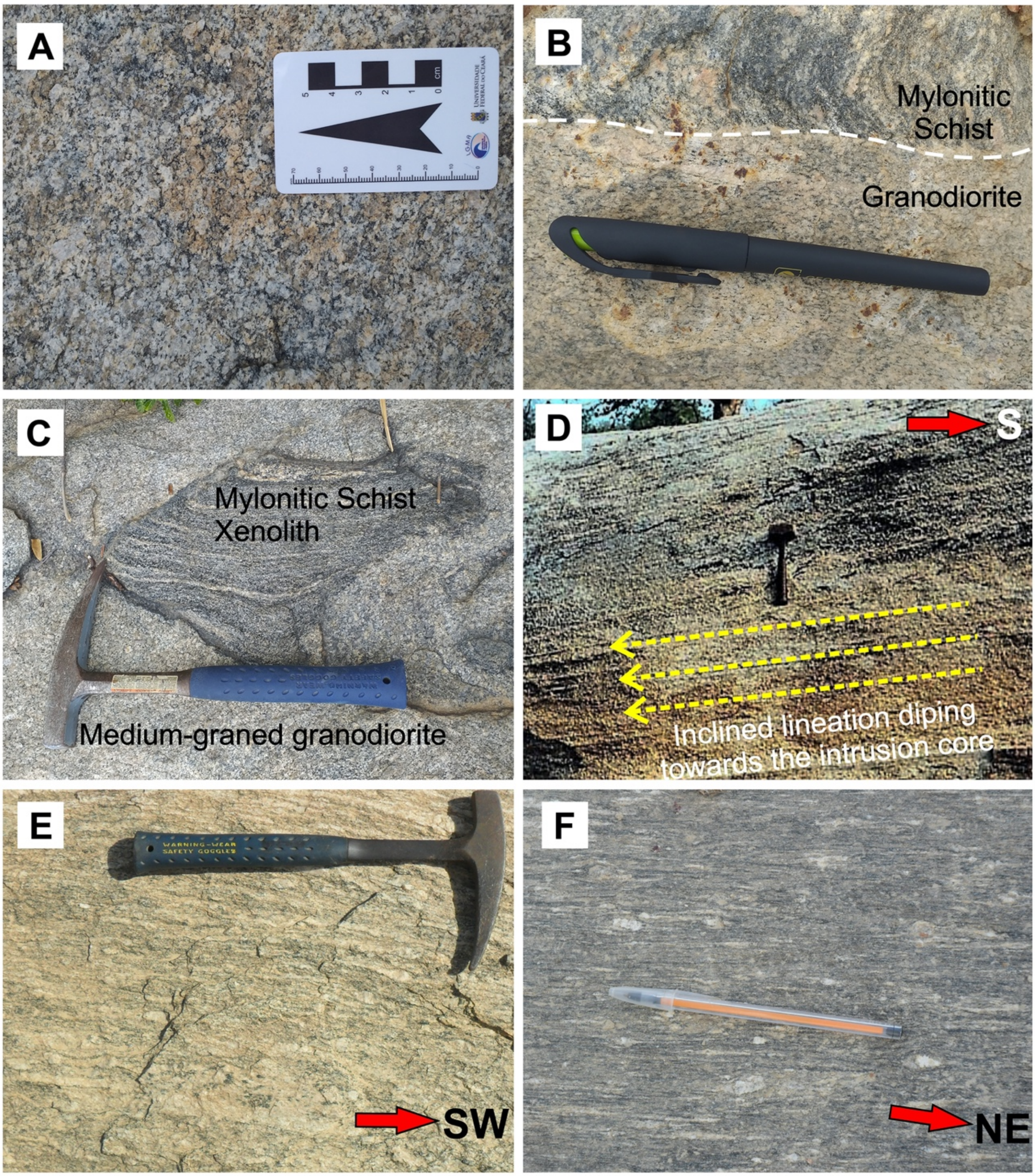


Figure 3. Mesoscopic structures of the Riacho do Icó stock. (A) equigranular medium-graded texture of the well preserved magmatic facies; (B) chilling margin contact between the intrusion and xenolithic, mylonitic schist of the São Caetano Complex; (C) irregular xenolith of mylonitic schist slightly oriented parallel to the magmatic foliation; (D) inclined mineral stretching lineation that tends to dip to the core region of the intrusion; (E) metagranitic to gneissic facies of the Riacho do Icó stock; (F) well-developed mylonitic fabrics on the marginal zones of the stock with rotated K-feldspar crystals.

Hectometric, peridotitic, pyroxenitic and gabbroic xenoliths are present in the core region of the intrusion, alongside ilmenite-titanomagnetite orebodies. These rocks represent the main economic occurrences of iron and titanium in the region. Heterogeneous breccia tends to follow the pervasive foliation away from the central region, being characterized by heavily rotated clasts of metamafic xenoliths, granitic rocks and K-feldspar crystals oriented along the Afogados da Ingazeira shear zone.

Additional mesoscopic observations on the different facies of the Riacho do Icó stock heavily point to increasing deformation, which is evidenced by planar and linear structural markers from the core to the rims of the intrusion. Within the core, flat-lying foliation and high-pitch mineral stretching lineation tend to transpose the early planar magmatic fabric and, probably due to later folding, both planar and linear fabrics tend to dip concentrically to the center the intrusion (Figure 3D). Foliation rotation is noticeable towards the boundary of the stock.

The rock structures vary gradually from the core to the rims, ranging from slightly foliated metagranites (Figure 3E) in the inner zones to protomylonite, mylonite and local ultramylonite at the marginal zones of the granite. In areas where the granitic fabric is totally mylonitized (Figure 3F), kinematic criteria are abundant, being reliable markers of the left-lateral NE-SW-trending, sinistral Afogados da Ingazeira shear zone, including S-C type surfaces and σ-type porphyroclasts. The latter fabrics and kinematic indicators are cut across by quartz-bearing and pegmatitic veins, as well as later fractures that are mostly NW-SE oriented, possibly marking a final deformation stage in these rocks.

Microstructure of the Riacho do Icó stock

As in the mesoscopic observations, petrographic data of the Riacho do Icó stock show variations regarding deformation conditions suggestive of strain increase from the core to its borders, *i.e.,* towards the Afogados da Ingazeira shear zone (Figure 2). In the inner portions, igneous features are well-preserved, including myrmekitic textures and abundant euhedral to subhedral K-feldspar (orthoclase) phenocrysts in a quartz-plagioclase groundmass. These orthoclase crystals are 1 to 3-cm long; showing abundant flame perthites that may be partially deformed in the grain boundaries, as well as oval to circular quartz or quartz-plagioclase aggregates pocket melt inclusions of 50 μm in size (Figure 4A). In addition, a conspicuously well-defined magmatic foliation is also observed, being characterized by small amphibole needles and biotite lamellae elongated along a quartz-plagioclase dominated groundmass (Figure 4B). This quartz-plagioclase domain is progressively transposed by the mylonitic foliation.

A systematic crystal-size comminution is observed in the most deformed samples, including K-feldspar phenocrysts that tend to be rotated in centimetric mylonitic bands. In samples collected in the boundaries of the stock, microscale observations revealed the presence of minor phyllonites, which are present but not abundant. Typical boundary zone mylonites show parallel biotite and muscovite neoblasts ranging from 0.2 to 0.5 mm-long in average, whilst most of the quartz-plagioclase aggregates define a granoblastic to well-developed mylonitic fabric. In the less deformed mylonites, irregular grain-size distributions dominate, in which K-feldspar porphyroclasts present sweeping to undulose extinction. Polygonized crystal textures might be present in the transition portions between metagranites and mylonites, suggesting moderate conditions of recrystallization which are progressively replaced by grain boundary migration microstructures.

Recrystallized quartz crystals tend to exhibit chessboard extinction as well as lobate subgrain boundaries surrounding minor relics of partially preserved magmatic crystals. Also, in some phyllonites, local grain boundary bulges in the host grain are common, suggesting the development of lobate boundaries. In some samples, they might exhibit foam textures and heterogeneously deformed lenses, despite minor ameboid quartz grains as well as ribbons that are aligned with anastomosed foliation planes on the most mylonitized members (Figure 4C).

Several preserved kinematic criteria are also present in thin sections, allowing us to confirm the dominantly sinistral kinematics of the Afogados da Ingazeira shear zone, previously constrained by mesoscopic observations. The microstructures are S-C fabrics and σ-type porphyroclasts. Nevertheless, on the phyllonitic samples, rotated K-feldspar porphyroclasts are the most common kinematic criteria, also causing strong deflections on the rock foliation, including the development of open microfolds (Figure 4D). Lastly, in some samples, brittle structures are abundant, including microcracks in feldspars and heterogeneously distributed microfractures in different phases. Some of them are filled up by later silica-rich injections and minor unidentified clay minerals, and irregularly crosscuts the ductile foliation.

Mesoscopic characteristics of the Espinho Branco-Santa Luzia leucogranitic belt

These rocks define an E-W to NE-SW oriented belt (Figures 1B and 5) that comprises biotite-leucogranites and magnetite-bearing granites intruded in the Espinho Branco and Santa Luzia anatexites (Archanjo et al., 2013; Viegas et al., 2013). Leucogranite bodies are mostly metric to a few km in size, commonly displaying sub-elliptical to asymmetrical, sigmoidal shapes in map scale (Figure 5). Contact relationships with the host migmatites are mainly synkinematic, with the leucogranites being emplaced as meter-sized granitic sheets parallel to the migmatitic fabric. Additionally, the granitoids also truncate the migmatite and/or host rock contacts (Figure 6).

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The biotite-leucogranite is mostly associated with the Espinho Branco migmatite and crops out in local quarries or in contact with metaxites and diatexites from the main anatexite body (Figures 6A and 6B). It is characterized by a coarse-grained, leucocratic, quartz-feldspathic rock with biotite as the main ferromagnesian phase. Grain size is mostly homogenous in the mesoscale, and a faint shape-preferred orientation of biotite laths can be observed (Figure 6C), defining a magmatic foliation oriented in the E-W direction. This fabric has steep dips to both N and S, consistent with the ductile fabric of the Patos shear zone.

The magnetite-bearing granite is observed intruding the Santa Luzia anatectic dome and is also in contact locally with the basement orthogneisses (Figure 6D). It consists of a coarse-grained, equigranular leucogranite with cm-thick magnetite crystals that are responsible for strong magnetic susceptibilities identified in the Santa Luzia anatexite (Archanjo et al., 2013). Main rock phases are K-feldspar, quartz, plagioclase and biotite, with local magnetite, titanite and tourmaline. The mesoscale fabric is defined by the preferred orientation of biotite grains (Figures 6E and 6F) oriented in the NE-SW direction, with shallow to moderate dips to NW and SE.

Brittle fabrics are locally developed in the leucogranites, being mainly marked by mm-scale fracture arrays that crack phenocrysts of feldspar and quartz and result in a fine-grained, dark-colored groundmass of felsic composition, alongside phyllosilicates. Such structures may be locally associated with pegmatite intrusions within the main anatexite bodies.

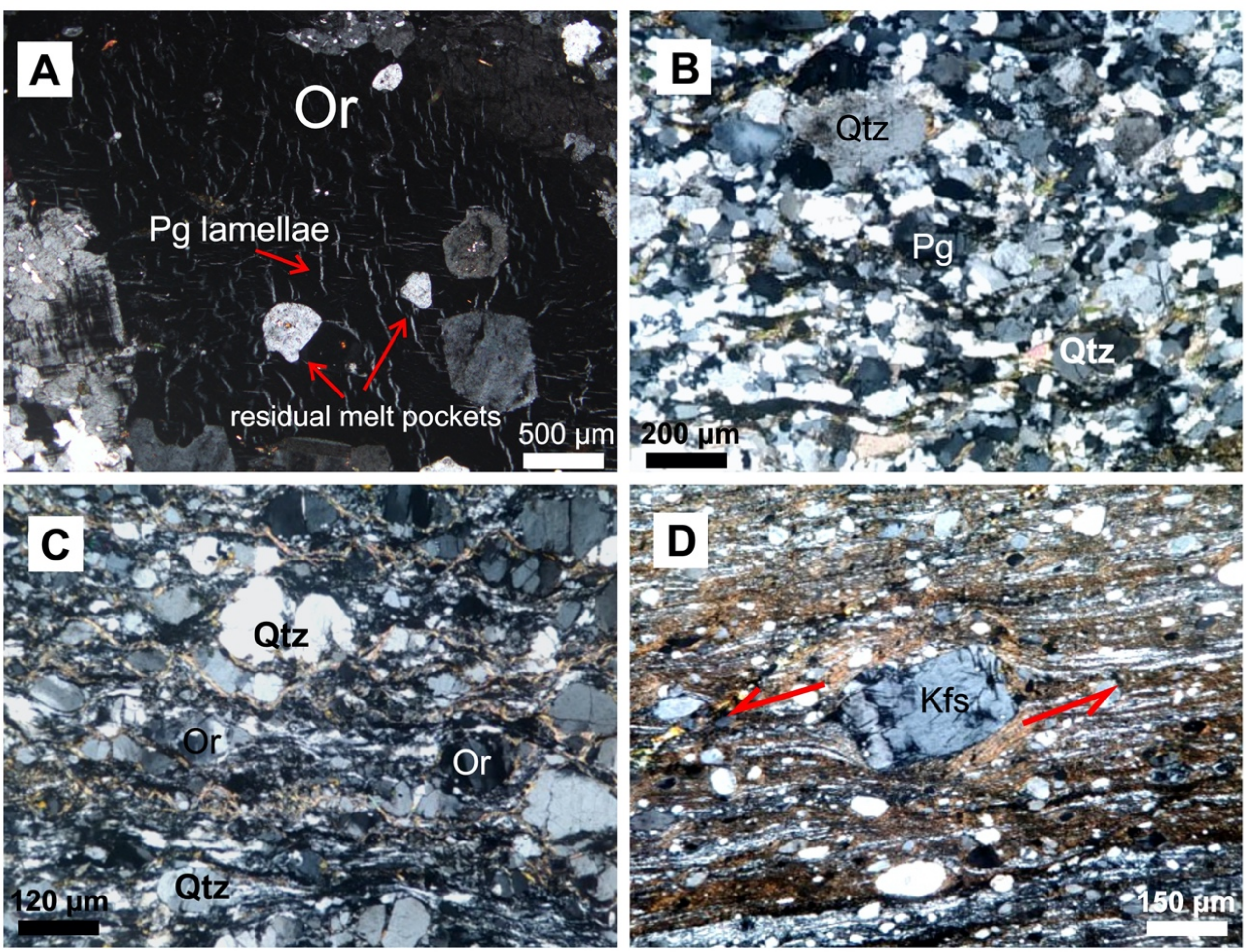


Figure 4. Microstructures observed on the Riacho do Icó studied samples: (A) flame perthite on orthoclase porphyroclast and inclusions of residual quartz melt pockets; (B) transition between magmatic and solid-state foliation exhibiting biotite and amphibole needles as well as poorly-developed quartz ribbons; (C) mylonitic fabric in a sample collected away from the intrusion core exhibiting intense recrystallization of quartz and orthoclase grains as well as micro-cracking; (D) rotated orthoclase porphyroclast with asymmetrical recrystallization tails along the anastomosed foliation of a phylonite collected in the transition between the Riacho do Icó stock and the Afogados da Ingazeira shear zone.

Microstructure of the Espinho Branco-Santa Luzia leucogranites

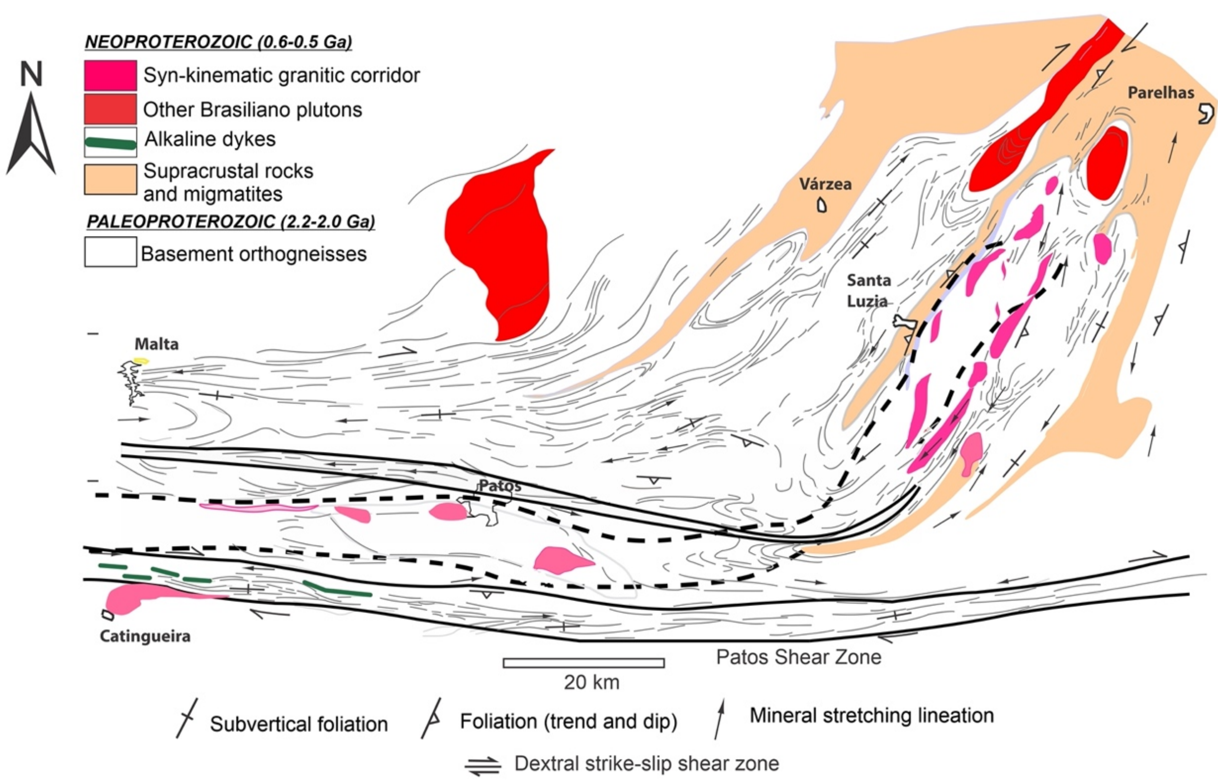
Quartz occurs mainly as two distinct types: coarse, elongated grains parallel to the magmatic foliation (Figure 7A), and as a residual melt product that is mainly observed as an interstitial phase along grain boundaries of other phases (e.g. feldspar, Figures 7A–7D).

Relict, coarse-grained quartz crystals show straight boundaries and range from 500 µm to ~ 2 mm in size (Figure 7A). They are elongated with their main axes oriented parallel or subparallel to the E-W magmatic foliation observed in the field. The grains have undulose extinction and show subgrain boundaries commonly oriented with oblique angles to the grain mean orientation. Subgrain sizes range from 50 to 100 µm (Figure 7A). Fine-grained bulges can be observed alongside grain boundaries, and several small-sized quartz grains (≤ 50 µm) are also intermixed with the bulges in lobate contacts (Figures 7A and 7F). Locally, mm-thick fractures can crosscut the elongated grains and are filled with fine-grained trails of fluid inclusions; these fractures are oriented with oblique positions in comparison to the grain main elongation (Figure 7A).

Fine-grained (≤ 20 µm), anhedral, interstitial quartz grains are mainly observed as isolated grains or filling fractures within feldspar phenocrysts (Figures 7A, 7B and 7C). These "amoeboid" quartz grains also occur forming trails of fine-grained crystals along feldspar boundaries, resulting in a percolating melt boundary along the contact between two rigid phases (Figures 7B, 7C and 7D). Locally, the interstitial quartz melt can crystallize outside the fracture walls, suggesting that the volume of the percolating melt phase exceeded the boundaries of the channeling discontinuity (Figure 7C). This fine-grained, anhedral quartz is thought to be crystallized from the residual melt during the late, cooling stages of pluton solidification (Vernon, 2004).

K-feldspar occurs mostly as coarse (~ 100 µm), magmatic grains that have straight boundaries (Figures 7A, 7B, 7D, 7E and 7F). These grains are commonly decorated with fine-grained quartz crystals derived from the residual melt phase (Figures 7B and 7F) and show local myrmekite exsolution at grain boundaries. Microfractures are observed crosscutting the grains in oblique orientations to the grain mean elongation (Figure 7B).

The plagioclase is mostly fractured and occurs as medium- to coarse-grained (50 – 200 µm) magmatic crystals mainly



Source: modified from (Viegas et al., 2014).

Figure 5. Schematic geological map of the occurrence of syn-kinematic leucogranites along the Patos-Seridó shear system. The granitoids are distributed along a belt that parallels the E-W mylonitic foliation of the Patos shear zone and follows its bend to NE-SW along the Seridó belt.

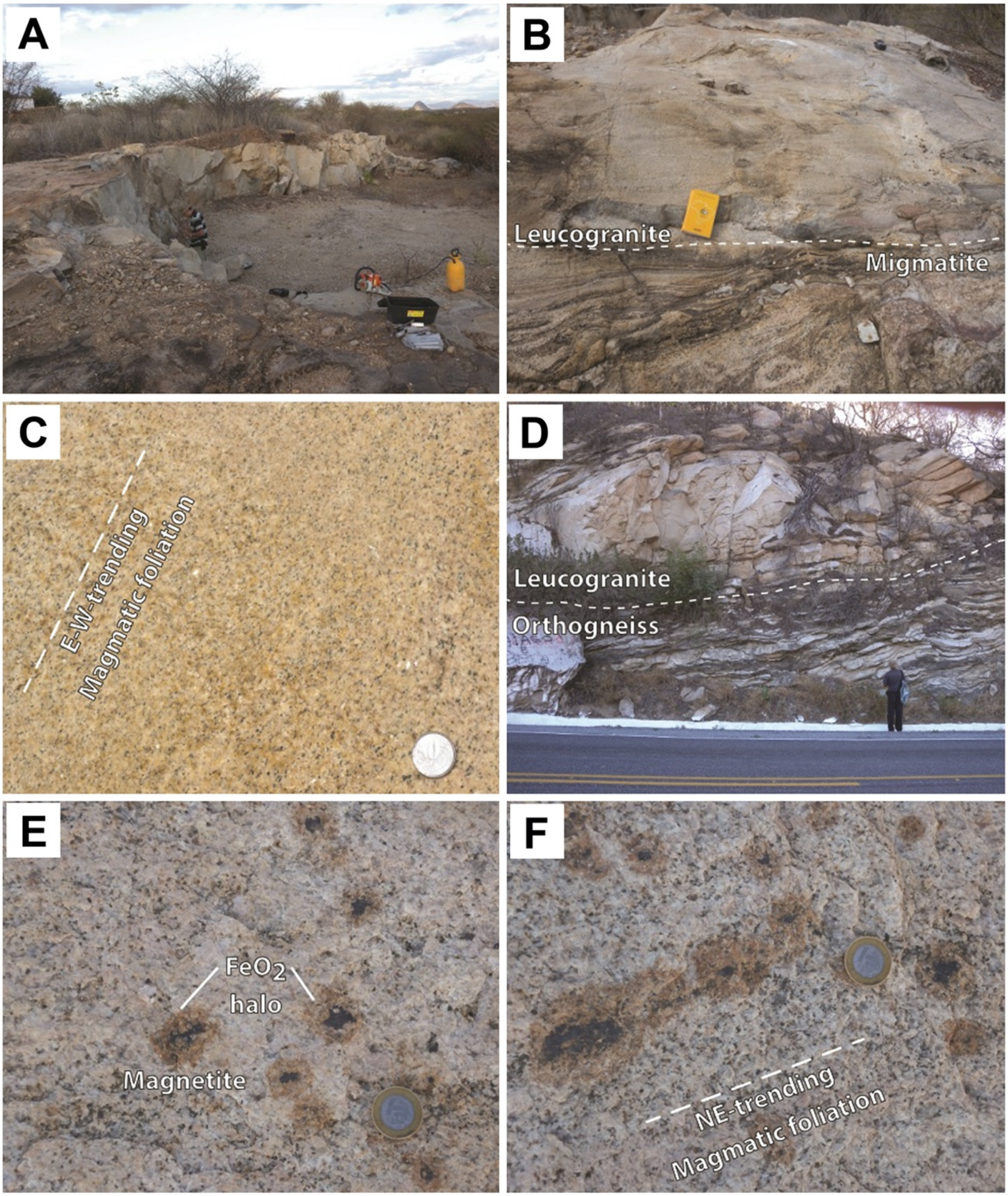


Figure 6. (A, B, C) Field structures in the Espinho Branco and (D, E, F) Santa Luzia leucogranites: (A) Outcrop of the Espinho Branco leucogranite in local quarries located in Patos town; (B) intrusive contact marked by leucogranite crosscutting the migmatitic foliation of the Espinho Branco migmatite; (C) Magmatic foliation defined by the shape-preferred orientation of biotite laths parallel to the E-W trend of the Patos shear zone; (D) Intrusive contact of the Santa Luzia magnetite-leucogranite with the basement orthogneiss of the Caicó complex; (E and F) mesoscale magmatic foliation defined by the preferred orientation of biotite grains that locally surround cm-thick magnetite crystals. A mm-sized FeO_2-halo is observed around the Fe-oxides.

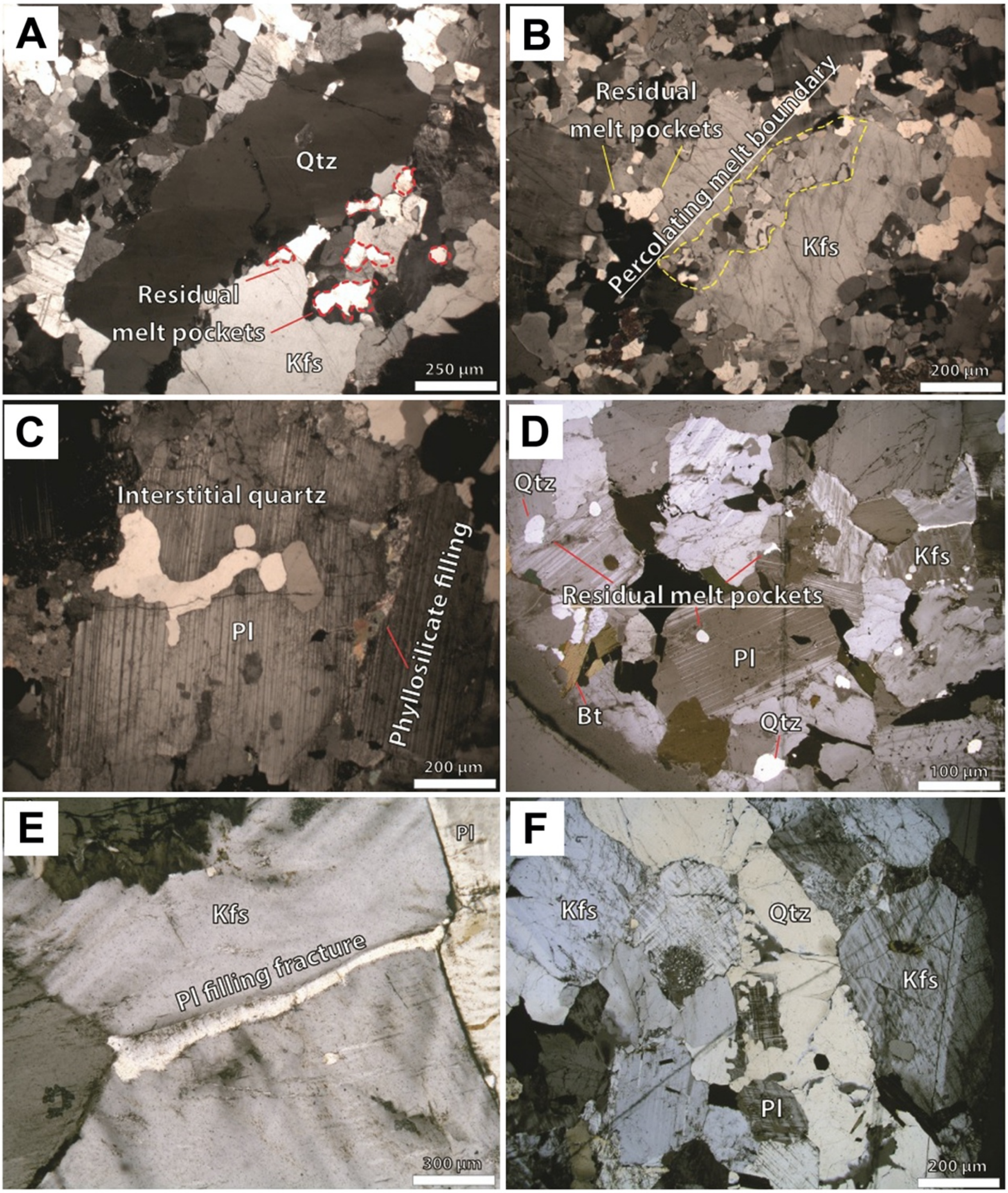


Figure 7. Microstructures in (A, B, C) the Espinho Branco and (D, E, F) Santa Luzia leucogranites: (A) coarse-grained, magmatic quartz grains with oblique fractures and subgrains half the size of the magmatic grain. Fine-grained quartz crystallized from the residual melt is observed on the borders of the coarse grain; (B) Fine-grained quartz intermixed with ≤ 50 µm feldspar crystals on the borders of two rigid, feldspar grains; (C) Anhedral, interstitial quartz grain in the form of a "melt film" filling fracture in plagioclase crystal. The quartz filling is also locally detached from the fracture wall. Phyllosilicates also occur as fine grains filling an adjacent fracture; (D) Fine-grained (≤ 50 µm) quartz grains as residual melt products located o the borders of feldspar crystals. Some grains are preferentially located along triple junctions; (E) Plagioclase melt film (~ 30 µm thick) filling a feldspar fracture; (F) Quartz lobate boundaries locally embaying feldspar crystals.

in contact with quartz (Figures 7A, 7C, 7D, 7E and 7F). Fractures in these grains are mm-thick and are filled by quartz and minor phyllosilicates (Figure 7C). In a local scale, plagioclase grains have a smaller grain size (≤ 50 μm) and occur as fine-grained "films" filling fractures in K-feldspar, or as isolated grains embayed by newly crystallized quartz (Figures 7C and 7F). Such microstructures suggest that the fine-grained plagioclase is the result of late stage crystallization from the residual melt during cooling (Bouchez et al., 1992).

DISCUSSION

Granites emplaced within shear zones are widely used as tectonic markers of the regional strain pattern due to their rheological transitions from emplacement to cooling and subsequent solidification (Rosenberg et al., 1995). Fabrics developed in such rocks record the entire spectrum from magmatic to solid state flow and can therefore be used as proxies for the distinct rheological changes that occur during the accommodation of granitic bodies within the continental crust (Paterson and Fowler Jr., 1993).

The tear-like/*en cornue* geometry in map scale of the Riacho do Icó stock and the sub-spherical to elliptical shapes of the leucogranite bodies that outcrop along the Patos-Seridó shear system are typical of late-stage magmatic intrusions (e.g. Vernon and Paterson, 1993) that were emplaced along deep-seated shear zones (*e.g.* Ávila et al., 2019), such as the Afogados da Ingazeira shear zone and the Patos Lineament. The spatial relationship between elongated plutons located in the vicinities and/or within shear zones has been widely discussed by previous authors (e.g. Neves and Vauchez, 1995; Weinberg et al., 2004) and constitutes one of the main mechanisms invoked to explain the emplacement of large volumes of syn-kinematic plutons in the Borborema Province (e.g. Neves et al., 1996; Brito Neves et al., 2014).

As pointed out by Santos et al. (2020), the variety of structural markers in the Riacho do Icó stock makes it difficult to precisely track the processes that resulted in the intrusion emplacement. For instance, diapirism can be considered due to the near-ellipsoidal shape that imposed the deviation of supracrustal host rock foliation, whilst high-pitch down-dip stretching lineation dips straight to the intrusion core (*e.g.* Petford et al., 2000). Such structural elements may be explained by the early developed basement-core nappe model that is interpreted as the docking mechanism between the Alto Pajeú and Alto Moxotó terranes (Santos et al., 2017a).

On the other hand, the abundance of xenoliths observed in mesoscopic scale with numerous geometries as well as heterogeneous breccia structures may represent evidences of early crustal stopping (Žák et al., 2006). Indeed, the presence of heterogeneous mega-xenoliths that show tabular to irregular shapes, including fragments of older mafic-ultramafic rocks of the *c.* 1.0 Ga Serrote das Pedras Pretas Suite, imply roof pendant collapse in response to gravitational flow, via forceful injection on the feeder zones as originally suggested by Santos (1995). This naturally creates space for magma rise and solidification (e.g. Culshaw and Bhatnagar, 2001).

The transition between the original magmatic facies and the mylonitized structure from the core to the intrusion rims is akin to magmas that ascent, crystallize and are subsequently submitted to regional deformation (Cruden and Weinberg, 2018 and references therein). Petrographic data also reinforces such hypothesis by showing that progressive deformation was accompanied by grain size reduction from the primary magmatic textural fabric to subsolidus deformation conditions. Progressive microstructural changes involved bulging on metagranitic samples that were replaced by subgrain rotation and later grain boundary recrystallization mechanisms, especially on the phyllonites (*i.e.,* contact between the granite and the mylonitized host rocks), and are also suggestive of deformation increase towards the Afogados da Ingazeira shear zone (*e.g.,* Stipp et al., 2002).

Several authors have suggested that *en cornue* intrusions tend to be injected in feeder zones away from the main structures, being subsequently deformed, which is the case of the Riacho do Icó stock (*e.g.* Román-Berdiel et al., 1997). We suggest that the Riacho do Icó stock may have been emplaced in the continental crust via crustal step-overs and oblique shearing (*i.e.,* pull-apart tectonics), allowing magma percolation, crystallization and subsequent recrystallization by regional strike-slip deformation, common in crustal granites in several orogenic belts worldwide (Hutton and Reavy, 1992; Brown, 2013; Cruden and Weinberg, 2018).

Concerning the Espinho Branco-Santa Luzia leucogranites, the meso- and microscale structural evidence suggest a feedback between magmatism and deformation in different scales:

- Leucogranites intrude the migmatites and result in discordant relationships in the field scale (Figures 6B and 6D);
- in the field, foliations are mainly magmatic and do not show evidence of solid-state overprint (Figures 6C, 6E and 6F);
- fine-grained quartz grains occur as widespread melt pockets typically located on grain boundary triple junctions of feldspars (Figure 7B and 7D);
- interstitial quartz grains may fill fractures in feldspar clasts (Figure 7C);
- fine-grained, plagioclase "films" occur within fractures in coarser crystals (Figure 7E).

Taken together, these characteristics all point out to deformation mainly in the magmatic state, *i.e.,* magmatic flow (Vigneresse and Tikoff, 1999), contrasting with the magmatic- to mylonitic transitional pattern observed in the Riacho do Icó stock. The close association of these leucogranites with migmatites and host orthogneisses that are also affected by partial melting, mainly observed as the emplacement of leucogranitic sheets along the gneissic compositional layering (Viegas et al., 2014), further suggests that these leucogranites may be the result of late-stage magmatic batches of the main partial melting event that originated the migmatites. Furthermore, magmatic fabrics studied via the anisotropy of magnetic susceptibility (AMS) technique further indicate that these granites were emplaced within the strain field of the Patos-Seridó shear system (Archanjo et al., 2013; Viegas et al., 2013).

However, there are field evidences of discordant contact relationships between leucogranites and migmatite/orthogneisses (Figures 7B and 7D), and the dominance of magmatic structures in these rocks, mainly in the Espinho Branco leucogranite. This happens in contrast with the solid-state, ductile behavior of the Patos shear zone, which is a high-temperature, amphibolite-facies structure (Viegas et al., 2014).

In the Espinho Branco-Santa Luzia leucogranitic belt, the magmatic foliations and the microstructural evidence of magmatic flow indicate that these granitoids were emplaced while still in their magmatic/molten state, being further crystallized and solidified during the dextral shearing of the Patos-Seridó shear belt. It is worth pointing that, despite being emplaced within the Patos lineament, the Espinho Branco biotite-leucogranite does not record the ductile strain of the shear zone. Additionally, the Santa Luzia magnetite-leucogranite, which is emplaced in the Santa Luzia anatexite, is also crystallized in the magmatic state, further indicating that deformation is localized mainly in the magmatic state.

Hence, we postulate that the emplacement of the Espinho Branco-Santa Luzia leucogranitic belt was heterogeneously controlled by the presence of deep-seated shear zones at distinct crustal levels. In the Espinho Branco region, the Patos Lineament served as a tectonic conduit that assisted in magma migration, ascent and emplacement during continuous injection of magmatic material within the shear zone (Cavalcante et al., 2016). On the other hand, the magnetite-leucogranite of Santa Luzia was emplaced mainly as a result of the transpressive tectonics that affected the Seridó belt in the junction with the Patos Lineament (Corsini et al., 1991); this region is marked by mostly dextral shearing that is laterally transferred to oblique, NE-SW compressive shortening in the Seridó belt (Archanjo and Bouchez, 1991).

The inherently magmatic character of both leucogranitic intrusions within the Patos-Seridó shear system further suggests that the roots of this shear zone system propagate to the intermediate levels of the continental crust, thus allowing for magma transfer at mid-crustal levels, slow cooling of the granites and subsequent crystallization without major influence from the external ductile strain field. In addition, the relationship between these leucogranites and migmatites also points out to a possible deep-seated nature of these shear structures. Such characteristics commonly result from slow heat exchange rates between rock masses due to elevated geothermal gradients observed in deep crustal levels (Chardon et al., 2011).

In both cases mentioned in the current study, we are dealing with granitic intrusions associated with development of granitic injections associated with regional shear zones. They contrast in several meso- and microscale aspects, possibly reflecting the distinct strain conditions experienced by these rocks. On the other hand, the studied leucogranites related to the Patos-Seridó shear zone system fall in the interval of ~575 – 565 Ma, which is in agreement with the estimated age of collision-related and extrusion tectonics (ca. 570 Ma; Ganade de Araujo et al., 2014). A possible explanation to this diachronism lies upon the model in which early strike-slip shear belt may have been progressively developed by the rotation of thrust-related markers combined with the reactivation of ancient suture zones through lateral scape during the Ediacaran (*e.g.,* Tapponnier et al., 1982).

Alternatively, long-lived magmatic activity along deep crustal shear zones may have resulted in continuous magma ascent and emplacement in the mid-to upper levels of the crust during repeated injections associated with tectonic reactivation (Neves et al., 1996). Despite a number of evidences concerning Neoproterozoic subduction episodes (Caxito et al., 2020a), these processes can also be observed in intracontinental settings in which heat advection due to magmatic activity weakens the rheology of previously rigid crustal masses, ultimately resulting in a softened crust that is able to localize ductile strain in the form of shear zones (Cochelin et al., 2018).

CONCLUSION

Meso- and microscopic observations of the Riacho do Icó stock, which is closely associated to the Afogados da Ingazeira shear zone and the smaller granitic bodies along the Espinho Branco-Santa Luzia leucogranitic belt, are related to the Patos-Seridó shear zone system; they constrain the relationships between granitic magma ascent along deep-seated structures and emplacement in mid-crustal levels in the Borborema Province.

The Riacho do Icó stock presents evidence of strain increase from the core to its margins. Related structural markers include foliation and lineation rotation as well as recrystallization from the early developed polygonal porphyroblastic texture to mylonitic/ultramylonitic structure.

In contrast, rocks from the Espinho Branco-Santa Luzia leucogranitic belt present meso- and microstructures that reflect crystallization with minor tectonic overprint. This is suggested by the dominant magmatic flow, absence of mylonitic structures and a close relationship with partially molten rocks, indicating the predominance of slow rates of heat exchange between rock masses, also typical in deep crustal levels. The emplacement of these leucogranitic stocks was mainly controlled by shear zone kinematics and is attributed to advanced stages of magma differentiation. This results from efficient melt channeling through planar anisotropies that vertically propagate into deep-crustal levels (Cavalcante et al., 2016).

The marked contrast on the emplacement and deformational conditions in both study cases is also characterized by the magma crystallization time (ca. 40 Ma). It suggests that the extrusion episodes involved distinct events of strike-slip deformation during the Brasiliano Orogeny in NE Brazil.

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