Chapter

Microstructure Features in Paleo and Neoproterozoic Granitic Rocks, Southeastern Region of Brazil

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Abstract

In this section we present the characteristic microstructures of granitic rocks and mylonites exposed in the southeastern region of Brazil, belonging to the geological context of the Neoproterozoic Araçuaí orogen and the Paleoproterozoic Mineiro belt. The studied rocks include most biotite and biotite hornblende tonalite and granodiorite and minor granite showing similar signatures to magnesian, calc-alkalic, metaluminous to peraluminous magmas. As a representative of continental or oceanic magmatic arcs, these granitoids are composed of plagioclase, K-feldspar, quartz, biotite, hornblende, garnet, muscovite, and sillimanite as major phases and pyroxene, apatite, epidote, allanite, titanite, zircon, monazite, rutile, magnetite, ilmenite, hematite, Fe-Ti oxides, pyrite, chalcopyrite, pyrrhotite, and graphite as accessory minerals. Typical magmatic textures include concentric and oscillatory zoning and exsolution, while isolated deformation microstructures and biotite replacing hornblende represent late-magmatic features. On the other hand, wide-spread undulose extinction, mechanical twinning, deformation bands, and recrystallized grains register crystal-plastic deformation under a variable temperature condition. Pyroxene and garnet fish and quartz ribbons are microstructures that record the temperature peak, under granulite facies in mylonites. Indeed, unshaped quartz grains and extremely lobated phase boundaries indicate the partial melting process.

Keywords: microstructure, granitic and mylonitic rocks, magmatic arcs, Araçuaí orogen, Mineiro belt

1. Introduction

Plate tectonic movement has been known at least for the last 50 years as a key mechanism responsible for remodeling the Earth surface to what we observe nowadays. It is linked to processes that occur in the most external layer of the planet and also to those acting in its inner parts including the terrestrial magnetic field created during the rotation of the liquid lower mantle against the solid core [1]. Someone studying the evolution of the Earth and trying to understand why intelligent life is present only here thus might keep in mind the role played by plate tectonics. Many researchers have attributed the success of the Earth as a living mechanism due to processes involved in the plate movements, such as those triggered by consumption and creation of crust in subduction zones and mid-oceanic ridges, respectively, capable of providing the fuel for life (oxygen and water, among other gases). Importantly, these processes have no longer been documented in other planets in the solar system [2] and where there is consumption or production of crust is the place quartz-feldspathic rocks can be found. In subduction zones, magnesian, calc-alkalic granitic rocks are predominantly found, while the formation of plagiogranite is linked to mid-oceanic ridge areas.

The lithosphere—the skin layer of the Earth—comprising the upper mantle and the whole crust, both of continental and oceanic origin, plays a critical role for the evolution of the continents. The geological processes involved in this hard rheological structure that moves from time to time are very unique and essential to constrain and reconstruct the geological history of a region. Particularly, regarding the continental crust that covers around 30% of the Earth surface today, become very important the study of its main composite, the granitic rocks. Essentially composed of quartz and feldspar minerals, these rocks could tell us their complete history, from the initial crystallization to metamorphic and post-deformational events, and thus reveal the behavior of a major part of the lithosphere in a geological area ([2] and references therein).

In this sense, we present the main characteristic microstructures of granitoids and mylonites exposed in the southeastern region of Brazil. The granitic rocks, belonging to the Paleoproterozoic Mineiro belt and the Neoproterozoic Araçuaí orogen (**Figure 1**), regions which could be used as two natural laboratories, provide preserved igneous as well as deformational features that show how

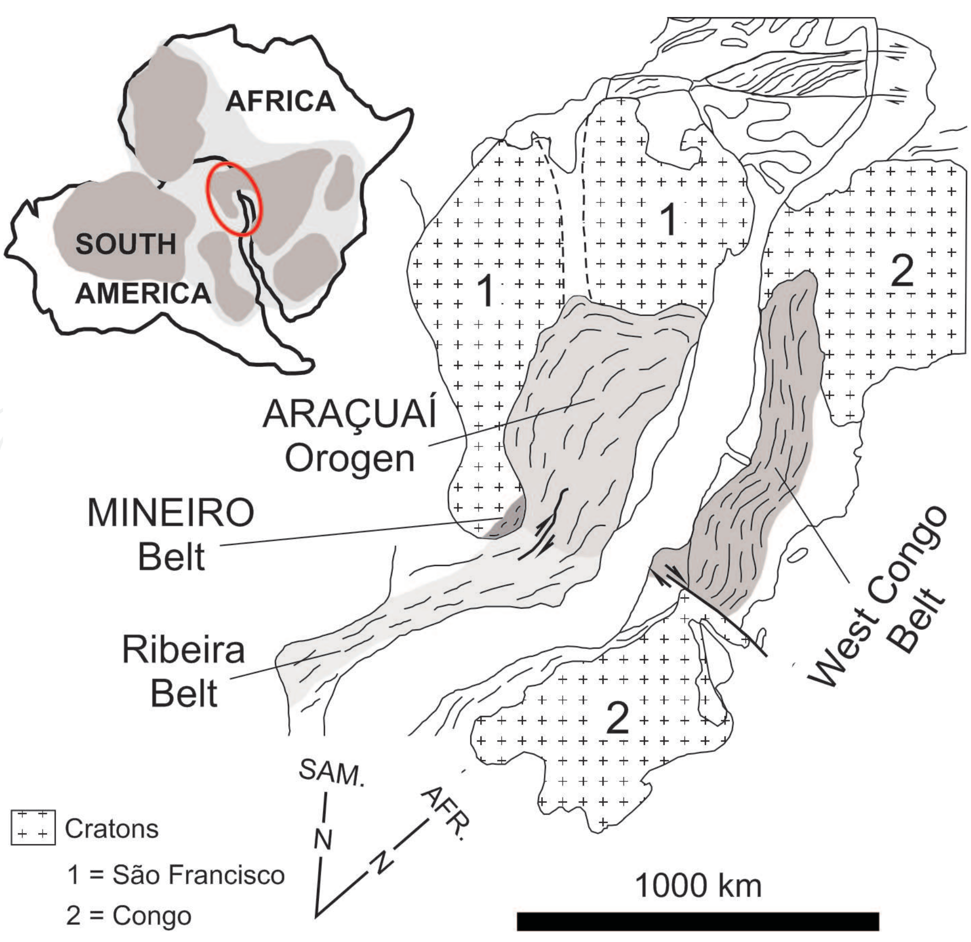

Figure 1.
Upper left image showing the geotectonic scenario of West Gondwana (modified from [3]). Dark gray, cratons; light gray, orogenic belts. Relative positions of the Paleoproterozoic Mineiro belt and Araçuaí orogen presently exposed along south American and African margins of the Atlantic (modified from [4]).

small structures tell a big history, involving, for example, the deformation of the lithosphere in orogenic systems.

2. Geological context

2.1 The Paleoproterozoic Mineiro belt

The Mineiro belt represents a segment of a Paleoproterozoic accretionary orogen preserved in the southern part of the São Francisco Craton, southeastern Brazil. It forms a region of approximately NE–SW trending with 180-km-long and 50-km-wide dimensions [5]. This region consists mainly of orthogneisses and metavolcanic sedimentary rocks intruded by Paleoproterozoic granitic rocks and records metamorphic conditions ranging from greenschist to amphibolite facies [6]. Geochronological data available in the literature spans its evolution from Siderian to Rhyacian times, ca. 2.46 to 2.09 Ga (see [7] for a comprehensive review).

Regarding the granites exposed in the region, they consist mainly of biotite hornblende tonalite and biotite trondhjemite, with common occurrence of dioritic and/or tonalitic enclaves. They show a magnesian, metaluminous to slightly peraluminous character, and many of them have TTG-like affinity [8, 9]. Indeed, these granitic bodies show chemical and isotopic characteristics similar to rocks formed in a subduction-related magmatic environment, being interpreted as both oceanic and continental magmatic arcs, which were responsible for building this orogenic system [7, 9].

2.2 The Neoproterozoic Araçuaí orogen

The Araçuaí-West Congo orogenic system is developed between the São Francisco and Congo cratons during the Brasiliano-Pan-African event [10]. The Brazilian counterpart, or Araçuaí, represents a segment of this Neoproterozoic collisional orogen located eastward to the São Francisco Craton, central eastern Brazil. It forms an area of approximately N-S trending with 700-km-long and 400-km-wide dimensions that curves to NE–SW in its southern part toward the Neoproterozoic Ribeira belt [11]. The whole area encompasses rift-related volcanic and sedimentary units, ophiolite slices, arc-related volcanic-sedimentary rocks, and granites that record regional metamorphism not higher than amphibolite facies conditions (see [12] for a comprehensive review).

Regarding the granites, they mark the pre-, syn-, and post-collisional stages of the Araçuaí orogen evolution and evolved from the Ediacaran to the Cambrian times, between ca. 630 and 480 Ma [13]. Composed mostly of biotite hornblende tonalites, hornblende biotite granodiorites, two mica, and garnet sillimanite granites, with local occurrence of mafic and intermediate enclaves, they show slightly peraluminous signature, with minor metaluminous terms. With magnesian and calc-alkaline characteristics, these granitic rocks show chemical and isotopic features compatible with subduction-related magmatism and peraluminous collisional type granites, such as those from Himalayan chain. In addition, some of them, mostly the younger ones, present mantle-like signature interpreted to be formed during mantle decompression or extensional orogenic collapse [13–15].

3. Microstructures and their implications

Granitoids or granitic rocks are defined as felsic plutonic rocks, composed of quartz, plagioclase, and K-feldspar as major phases, and vary from tonalite (Ca-rich member) to K-feldspar granite, including the Na-rich term, trondhjemite, and also Si-poor members. These rocks can be produced by a combination of magmatic processes, with mantle contribution or exclusively related to crustal sources, and thus could reveal a complex geological history in a region. Such a conundrum must be kept in mind when using granitoid and mylonite features to unreveal the geological processes of an area.

Macro- and microstructures show the interaction with adjacent rocks, regarding emplacement mechanisms, internal crystallization and magma mixing processes, and also post-crystallization metamorphism, deformation, or even partial melting. For example, characterizing the microstructures in granites is the way to recognize how one of the main constituents of the lithosphere is formed and behaves through the geological time. Keeping in mind the understanding of Earth dynamics based on rock rheology, it is the way to better constrain the mechanical behavior of the lithosphere and its variations with depth, which should be closely linked to plate tectonics [2]. Thus, we show representative microstructures preserved in the granitic and mylonitic rocks from the Paleoproterozoic Mineiro belt and the Neoproterozoic Araçuaí orogen, interpreted to be formed during collisional and subduction-related events, thus building either continental or oceanic magmatic arcs.

These rocks are composed, in general, of plagioclase, K-feldspar, quartz, biotite, hornblende, garnet, muscovite, and sillimanite as major phases and pyroxene, apatite, epidote, allanite, titanite, zircon, monazite, rutile, magnetite, ilmenite, hematite, Fe-Ti oxides, pyrite, chalcopyrite, pyrrhotite, and graphite as accessory minerals and have been largely investigated in previous studies (see [8, 9, 14, 16, 17] for details). The characteristic microstructures of quartz and feldspars, the main phases and the most studied minerals among those observed, are shown as the record of magmatic, late-magmatic, deformation, and partial melting processes. Pyroxene, hornblende, and garnet microstructures are presented as features that allow constraining thermodynamic boundary conditions for the recorded processes, from igneous to metamorphic rocks.

Feldspar features may represent key ways to better understand the magmatic and post-magmatic features [18–22], among which may be highlighted the different zoning patterns, exsolution, corrosion features, and those regarding deformation processes. Even a normal zoning, with grains showing Ca-rich cores and Na-rich rims, can show a more complex magmatic process when the Na enrichment from the core is not progressive, and there is an abrupt transition to a Na-rich boundary (**Figure 2A**). It should not represent a progressive cation exchange during a continuous crystallization process (fractioning) and may be related to the partial melting process if the Ca content in the grain core is in disagreement with what is expected for the An content in plagioclase from granites [23]. In this case, the high An content core may regard the magma source. It possibly reflects a low-temperature granite, when the temperature condition that led to the melting process was not high enough to consume the high An plagioclase from the source, in this case, possibly a mafic rock. Instead of normal zoning, euhedral plagioclase grains from the Alto Maranhão Suite, Mineiro belt, show an oscillatory changing in their composition evidencing cycles of Ca input in the system. Although it may be confirmed by microchemical analysis, the occurrence of Ca-rich second phases highlights such zoning pattern (**Figure 2B**). Besides, coarse plagioclase grains are, sometimes, rounded, showing corroded borders (**Figure 2C**). These features reflect the magma mingling processes, which, in that case, is supported by macro- and microstructures related to the occurrence of dioritic enclaves [8, 17].

Perthite and anti-perthite (**Figure 2D**, **E**) are widespread features and can be observed in granites from both geological regions. Besides the compositional

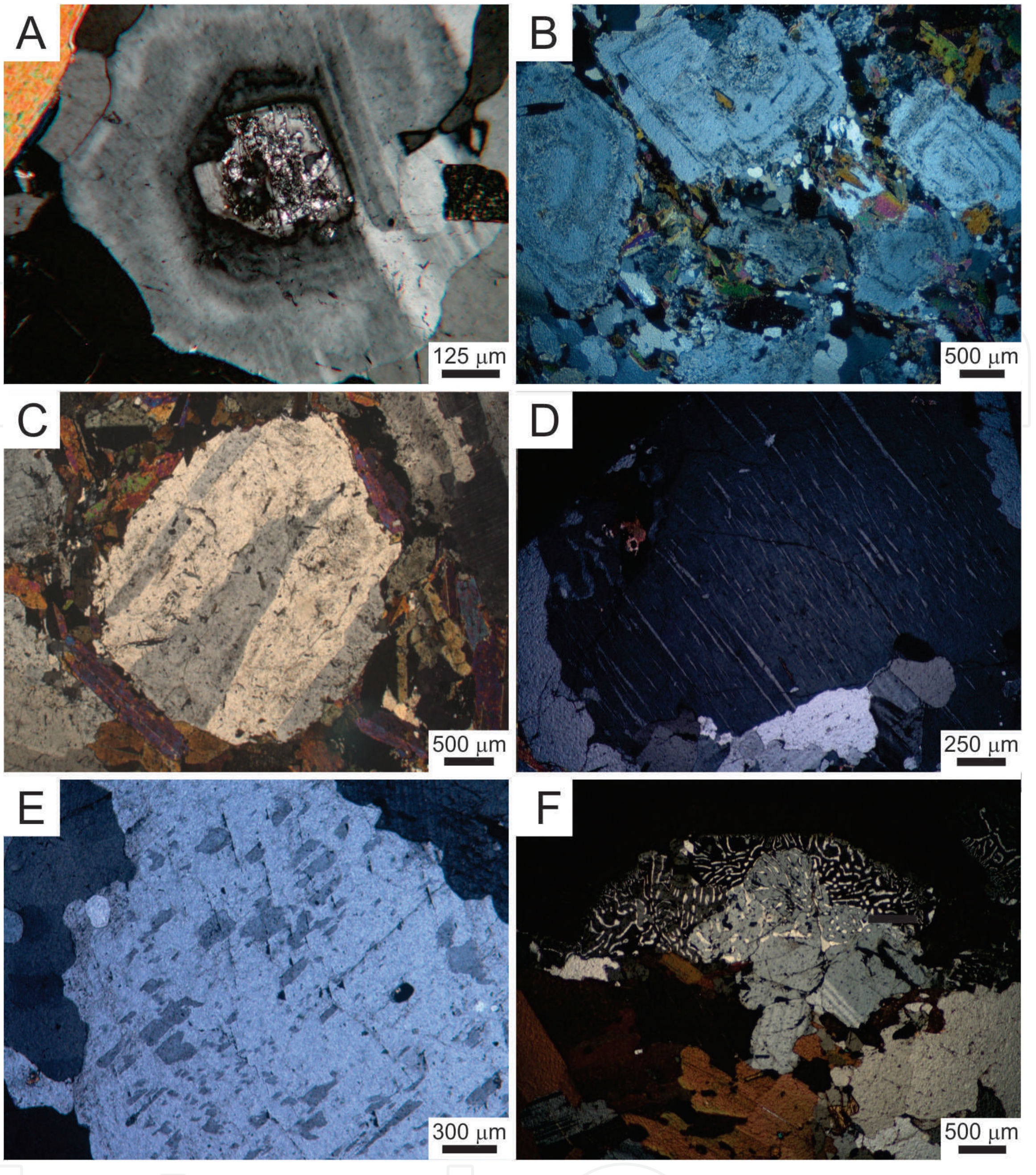

Figure 2.
Cross-polarized optical photomicrographs showing typical igneous textures—Granitic rocks. (A, B) Normal concentric zoning in plagioclase: (A) abrupt transition from a Ca-rich core, with Ca content anomalously high, to boundary progressively Na richer; (B) cyclical interchange between Ca- and Na-rich strips. (C) Coarse rounded plagioclase grain surrounded by biotite. Exsolutions in feldspar: Perthitic (D) and anti-perthitic (E) grains. (F) Myrmekite texture records the interaction between plagioclase and K-feldspar. (A, D–F), Araçuaí orogen; (B, C), Mineiro belt.

implications, occurrence of K (perthite) and Na (anti-perthite) rich terms [24], these features reveal crystallization and cooling process conditions. The coexistence of K and Na feldspar indicates subsolvus crystallization condition that should reflect low-temperature and/or high-H_2O pressure [24, 25], possibly under eutectic point. The exsolutions record condition below the solvus temperature into the immiscibility gap of alkali-feldspars. If perthite and anti-perthite coexist in the case of a subsolvus granite, otherwise it is a hypersolvus granite. Once plagioclase and K-feldspar coexist and share boundaries, under tension, a reaction along these phase boundaries is induced liberating silica (SiO_2) [26]. In this case vermicular quartz appears to have a myrmekite texture, which is common in a variety of crystallization or even post-crystallization condition (**Figure 2F**).

Considering the stress state at the late stages of crystallization, when the melt fraction is much lower than the crystal volume, one could observe myrmekite and a bunch of reactions among mineral phases or between minerals and the residual melt, as exemplified by the biotite nuclei in hornblende crystals (**Figure 3A**). At this point localized deformation features representing crystal-plastic deformation related to the current crystallization process also become common. Quartz always portrays this final crystallization stage, showing undulose extinction or deformation bands (**Figure 3B**) that can evolve to subgrain formation. Initial and localized feldspar deformation can be observed through the formation of mechanical twinning in plagioclase grains (**Figure 3C**).

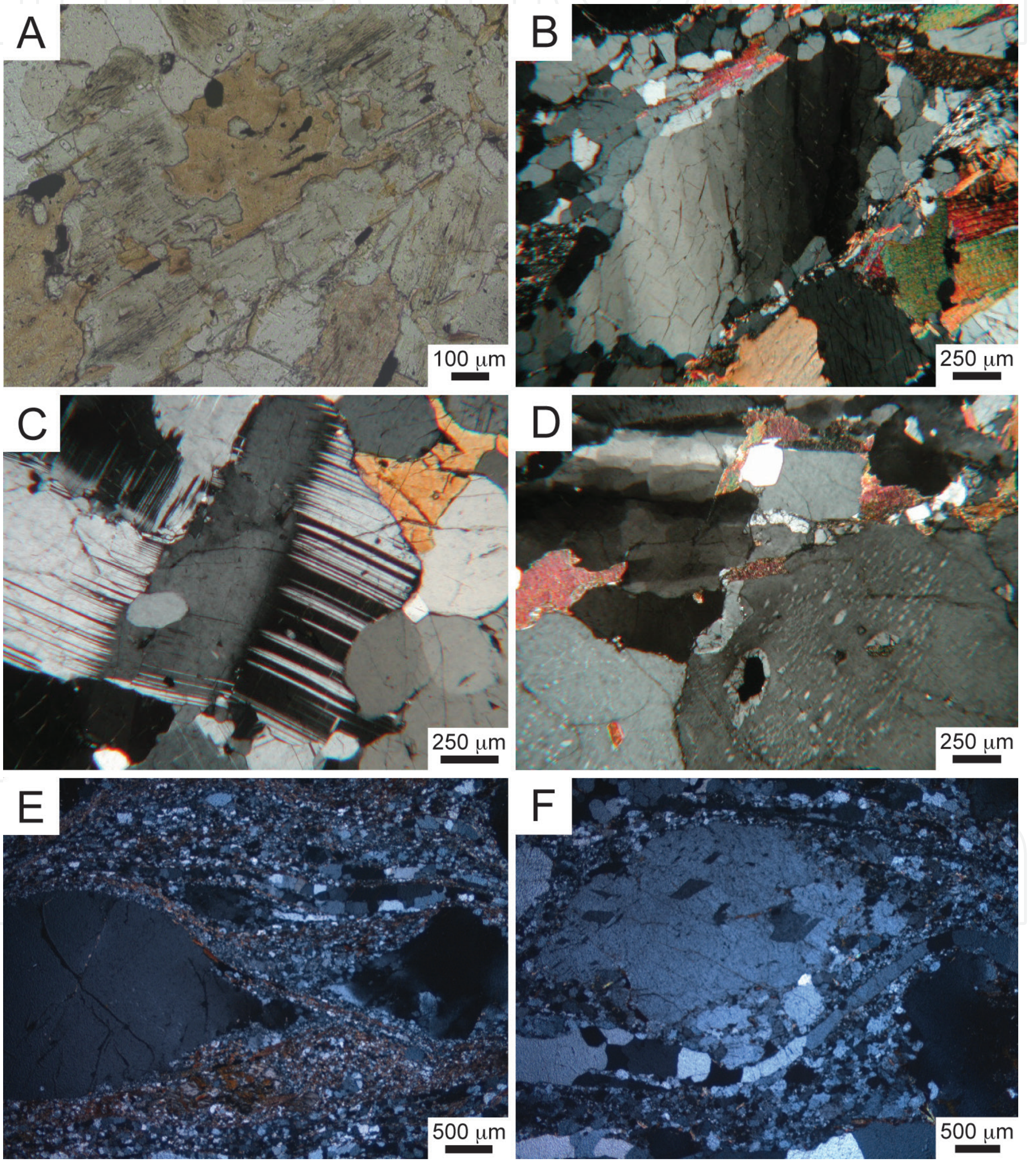

Figure 3.
Optical photomicrographs showing late-magmatic (A–D) and deformational (E, F) features, slightly deformed granites and mylonites, respectively. (A) Biotite core in hornblende grain (plane-polarized light). (B) Quartz grain with deformation bands. (C) Mechanical twinning in a kinked plagioclase grain. (D) Quartz grain showing undulose extinction in a chessboard pattern (upper left corner) and perthitic feldspar (lower right corner). (E, F) feldspar fish surrounded by a quartz-feldspathic recrystallized matrix: K-feldspar (E) and anti-perthitic feldspar (F) porphyroclasts surrounded by recrystallized grains and quartz ribbons (B–F: Cross-polarized photomicrographs). (A) Mineiro belt; (B–F) Araçuaí orogen.

In a post-crystallization condition, under an imposed stress, the localized crystal-plastic deformation features that record grain interaction during the late crystallization stage become the main microstructures, widespread through the aggregates. In a progressive process, quartz grains develop subgrains, under high temperature showing a chessboard pattern [27] (**Figure 3D**). Progressively, new recrystallized grains are formed, defining a matrix surrounding strong porphyroclast grains (**Figure 3E**), feldspar, hornblende, pyroxene, and garnet. If this matrix is not weak enough or its proportion and distribution have not achieved a critical value to localize deformation, the porphyroclasts will also accommodate deformation. Feldspar grains initially showing mechanical twinning will develop undulose

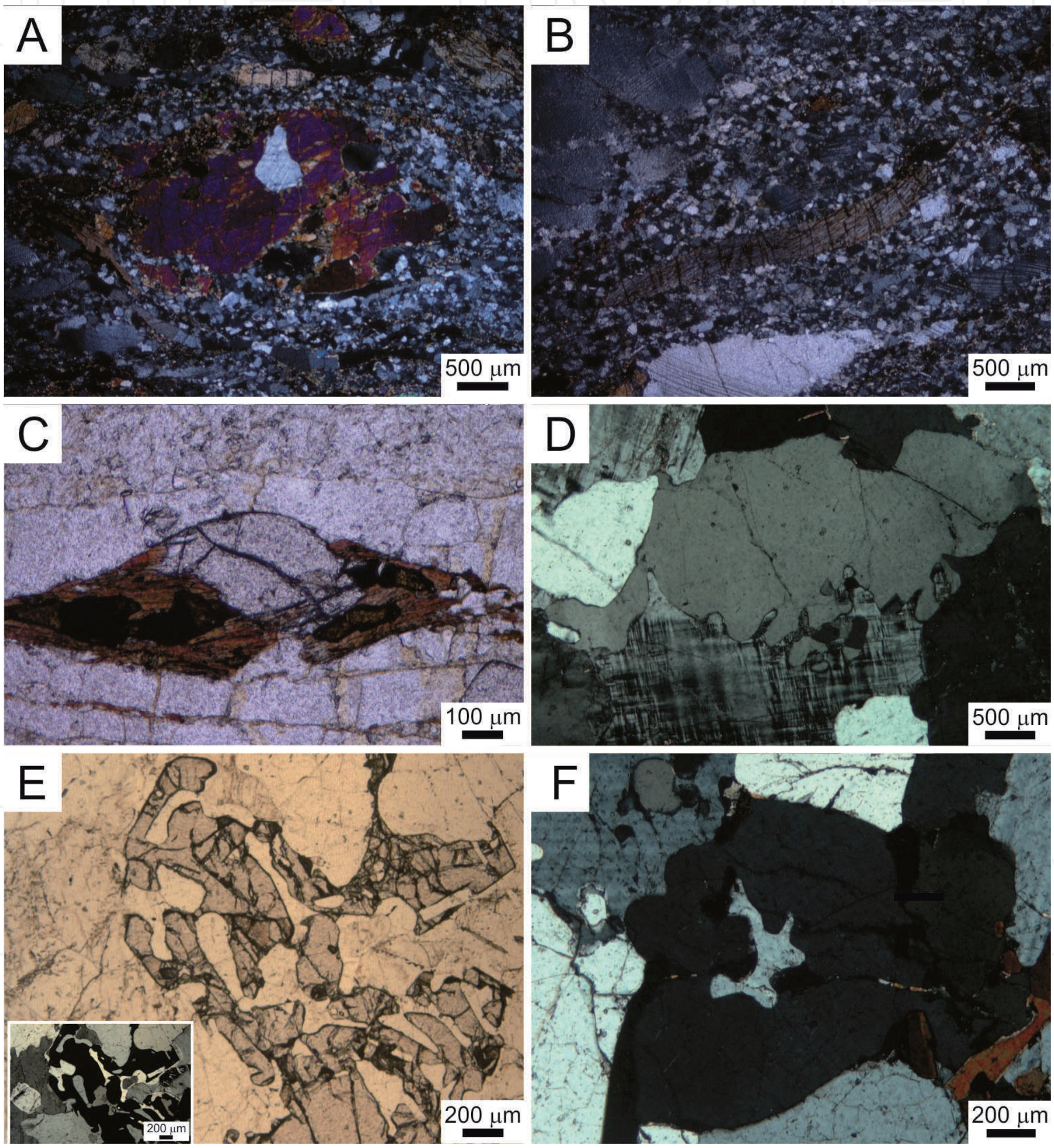

Figure 4.
Optical photomicrographs recording high-temperature deformation (A–C; mylonites) and partial melting process in granites (D–F). (A, B) plastically deformed pyroxene porphyroclasts: Pyroxene fish (A) and twisted pyroxene grain (B) surrounded by recrystallized quartz-feldspathic matrix and feldspar porphyroclasts (cross-polarized photomicrographs). (C) Garnet fish partially replaced by biotite and surrounded by quartz ribbons (plane-polarized light). (D) Strongly lobated quartz-microcline interphase boundary (cross-polarized light). (E) Interdigitated garnet and quartz grains showing, as seen in the previous image, highly lobated interphase boundaries (plane-polarized light for the main image and cross-polarized light for the image in the inset, lower left corner). (F) Unshaped quartz grain within a feldspar grain (center) (cross-polarized light). (A–F) Araçuaí orogen.

extinction, subgrains, and progressively new recrystallized grains, which will compound the quartz-feldspathic matrix (**Figure 3E**). At this point, the porphyroclast shape may reflect the deformation pattern and stress field, mainly if they are asymmetrical, as feldspar fish, when they reflect the vorticity of the deformation mechanism (**Figure 3E**, **F**). Considering the increasing temperature, quartz grains, with low misorientation, coalesce and form ribbons, parallel to the rock foliation and surrounding the remnant porphyroclasts (**Figure 3E**, **F**).

The highest deformation temperature is registered by the crystal-plastic deformation of the high-temperature minerals, in the case of such granitic mylonites, pyroxene and garnet. The Araçuaí orogen is cut by bundles of shear zones in which sheared granites are found from greenschist to granulite facies conditions [28]. **Figure 4A–C** shows the microstructures that record high-temperature deformation, typical of granulite facies, when crystal-plastic deformation condition of pyroxene is achieved. Pyroxene fish with strain shadows and recrystallized tails (**Figure 4A**) and/or twisted pyroxene grains (**Figure 4B**) are surrounded by a recrystallized quartz-feldspathic matrix in which quartz ribbons are recognized. The same is observed for garnet, whose grains many times are replaced by biotite (**Figure 4C**).

If the temperature is high enough to overcome the solidus temperature for the granite, it melts. In this case microstructures regarding the partial melting process are seen. Strongly lobated phase boundaries, melt pools, and features related to mineral reactions should be recognized, as well as perithetic mineral phases [29, 30]. This is the case of granites outcropping in the intracontinental part of the Rio Doce Arc—Araçuaí Orogen [31]. These granites show strongly lobated phase boundaries shared by quartz and feldspars (**Figure 4D**), remains of garnet which are interdigitated with quartz grains (**Figure 4E**) and anhedral quartz grains with very irregular boundaries filling triple junctions of feldspar grains, along their boundaries or as unshaped inclusions, regarding melt pools (**Figure 4F**).

4. Concluding remarks

From this quick view of microstructure features in granites and mylonites, there is no doubt that recognizing and quantifying them is a critical step to better understand and define magmatic, late-magmatic, and deformational processes. There is no substantial petrological study without a consistent description and analysis of the microstructural pattern(s) in the considered aggregates. The identified relations among different mineral phases and grain boundary and phase boundary geometries are fundamental to conduct petrology studies based on mineral chemistry, P–T–t trajectories, geothermobarometry, or even geochronology. It is not possible to conduct a petrology project if the aggregate is not known, for example, the mineral phases, their internal features, and how they interact. Besides, the understanding of rock rheology necessarily passes by the definition of processes responsible for the aggregate formation and its stabilization through time. Talking about typically igneous and sheared granites, the mechanical behavior of these quartz-feldspathic rocks represents the way to understand how the crustal part of the lithosphere is formed and accommodates stress through time.

Invariably, geoscientists trying to reproduce in laboratory what happens at large scale in nature need to use microstructural observations to establish comparisons between the experimental and natural microstructures and solve geologic problems. Researchers looking deep into the microstructure features of granites allow the characterization of processes such as fractional crystallization in a magmatic chamber, chilling mechanisms, mineral reactions, and ultimately how these rocks behave under stress. That is possible because the grain-scale mechanisms are unveiled. As a consequence a better knowledge about the lithosphere is achieved, and questions such as why its deformation is localized in narrow zones in their boundaries may be better discussed, as well as what are the mechanisms controlling the plate movements. Specifically, the presented microstructures show that in the Araçuaí orogen, granites and mylonites register from typical crystallization to partial melting processes, some of them showing features of high-temperature deformation. On the other hand, in the Mineiro belt, granites show typical magmatic to late-magmatic features, including an important process of magma mingling.

Based on the observed features, some processes can be depicted:

i. Magmatic differentiation through concentric zoning in plagioclase crystals (**Figure 2A**)

ii. Magma mingling due to oscillatory zoning in plagioclase grains (**Figure 2B**, **C**)

iii. Cooling processes associated with perthite and anti-perthite textures (**Figure 2D**, **E**)

iv. Reactions between K-feldspar and plagioclase grains recorded by myrmekitic texture (**Figure 2F**)

v. Late-magmatic stages during magmatic crystallization by localized deformational features (bands in quartz, mechanical twinning in feldspar) and reaction between minerals and final melts (e.g., biotite replacing hornblende) (**Figure 3A–D**)

vi. Ductile deformational processes by crystal-plastic deformation features such as undulose extinction, chessboard texture, quartz ribbons, recrystallized quartz feldspathic matrix, porphyroclasts of garnet, feldspar, and pyroxene with asymmetrical shapes sometimes showing recrystallized tails (**Figures 3E**, **F** and **4A–C**)

vii. Partial molting process due to the occurrence of quartz pools, interdigitated phase boundaries seen between quartz and feldspars, and also quartz and garnet with high density of inclusions, as well as unshaped inclusions (**Figure 4D–F**)

Acknowledgements

The authors thank everybody working at the Laboratory of Microscopy and Microanalyses (LMic-DEGEO-UFOP) for all sorts of facilities and the excellent work environment. We are also grateful to Carolina Ribeiro, Jessyca Carneiro, Marcos Pimenta, Reginaldo Vieira, and Wilker Soares for providing part of the micrographs that illustrate this chapter. We would like to acknowledge the IntechOpen for the invitation and opportunity and for financially supporting this publication. We also want to thank Dr. Gaafar El Bahariya for the editorial handling and suggestions that improved the manuscript and Kristina Kardum for the service management (CCG acknowledges the CNPq - Brazilian Research Council - grant: 429072/2016-3, for the financial support).

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