TitaniQ temperatures and textural analysis as a record of the deformation history in a major continental shear zone system, Borborema Province, Brazil

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1. Introduction

Deformation in the continental crust is commonly recorded by quartz due to its responsiveness to variations in several factors, such as temperature, recrystallization, strain rate and fluid activity. Because of this, quartz has been the target of several experimental and field-based studies that use a wide range of techniques for investigating crustal deformation and recrystallization processes (e.g., Hirth and Tullis, 1992; Kidder et al., 2013; Ashley et al., 2013; Negrini et al., 2014; Cross et al., 2015). One such technique is the Titanium-in-quartz geothermobarometer (or TitaniQ; Wark and Watson, 2006), which is commonly applied to explore temperature conditions during shearing and recrystallization of quartz in mylonitic rocks (e.g., Kohn and Northrup, 2009; Bestmann and Pennacchioni, 2015; Cavalcante et al., 2018). However, the influence of dynamic recrystallization on Ti substitution in quartz remains poorly understood, and the application of the TitaniQ to estimate temperature in mylonitic rocks has been questioned (e.g., Negrini et al., 2014). Some authors suggest that Ti is only completely re-equilibrated if rocks recrystallize by grain boundary migration (GBM), generally at temperatures >500 ºC, and that mylonites recrystallized by bulging (BLG) and subgrain rotation (SGR) likely yield inherited temperatures (e.g., Grujic et al., 2011). Other authors suggest that concentrations of Ti correlate well with recrystallization by either GBM, SGR and BLG and that reliable deformation temperatures estimated from TitaniQ can be obtained down to ~350 ºC (e.g., Haertel et al., 2013; Ashley et al., 2013; Bestmann and Pennacchioni, 2015). Therefore, it is necessary to further explore the application of TitaniQ in naturally deformed and recrystallized rocks to better evaluate its applicability to revealing deformation temperatures in mylonitic rocks.

Quartz-bearing mylonitic rocks from shear zones often display microstructures that may be related to different stages of deformation, which may occur over a long thermal history, especially in mature shear zone systems, such as the Borborema Province (NE Brazil), where interconnected networks develop. The deformation history of these rocks, as well as the interplay between the different factors responsible for their structural aspects, can be assessed by textural analysis by means of the SEM-EBSD technique (Scanning Electron Microscopy – Electron Backscatter Diffraction). The SEM-EBSD along with detailed microstructural characterization is a powerful tool for addressing the rheology of the crust (dynamic processes in Earth's crust), as it allows for a complete evaluation of crystallographic orientations of rock-forming minerals. Therefore, it has been widely used to investigate the way quartz deforms in shear zones at different temperatures (e.g., Kilian et al., 2011; Lee et al., 2020; Conte et al., 2020), and has been fundamental to the investigation of crystal-plastic deformation recorded in mylonitic rocks.

In this study, we apply TitaniQ together with detailed textural analysis via SEM-EBSD in quartz from mylonitic rocks of the Sucuru dike swarm to investigate the late stages of deformation in the central domain of the Borborema Province, and to explore the influence of dynamic recrystallization on the uptake of Ti in quartz. Our results show that TitaniQ is a powerful tool to access deformation temperatures down to ~350 ºC, a temperature poorly documented by TitaniQ so far, and that progressive grain-size reduction of quartz by bulging (BLG) and subgrain rotation recrystallization (SGR) only partially re-equilibrate to low Ti. We demonstrate that: (1) older high temperature (>500 to <740 °C) deformation is well preserved in the core of quartz ribbons and quartz porphyroclasts while later low temperature (>340 to <500 °C) occur in the edges of coarse-grains and in the fine-recrystallized matrix; (2) recrystallized quartz grains on the edges of quartz porphyroclasts tend to inherit the crystallographic fabrics of the porphyroclasts and; (3) the generally weak textures observed in whole EBSD-mapped areas are likely due to activation of grain-size sensitive deformation mechanisms such as DisGBS (dislocation creep-accommodated grain boundary sliding) that are facilitated by the presence of large amounts of fine-grained quartz in an polymineralic matrix. Our findings suggest that the Sucuru dike swarm recorded a progressive deformation from its emplacement, in which a NW-SE magmatic fabric was recorded, followed by solid-state deformation, in response to the long-lasting E-W dextral Neoproterozoic shear regime of the Borborema Province.

2. Geologic Setting

The Borborema Province in NE Brazil and its West-central Africa counterpart (e.g., Caby 1989; Trompette 1997; Neves 2003; Van Schmus et al., 2008) are situated in the central portion of West Gondwana and characterized by a network of interconnected shear zones formed during the Braziliano–Pan-African orogeny (Fig. 1). The province can be separated into three main domains (e.g., Van Schmus et al., 2008; Hollanda et al., 2010) limited by major strike-slip shear zones (Fig.1). The northern domain consists mainly of Paleoproterozoic gneissic basement including minor Archean rocks and Neoproterozoic metasedimentary rocks. The central or transverse domain, located between the Patos and Pernambuco shear zones, is composed of elongated belts of different lithologies, including meta-volcanoclastic and meta-plutonic rocks of ca. 950 Ma, late Neoproterozoic basins, Paleoproterozoic basement and Phanerozoic cover. This domain is strongly affected by conjugate sets of interconnected shear zones of both sinistral and dextral kinematics that connect the major Patos and Pernambuco shear zones (Fossen et al., 2022).

The southern domain, south of the Pernambuco shear zone, consists of higher-grade rocks (gneisses and migmatites) similar to those in the central domain. Late tectonic (630 and 520 Ma) intrusions of plutonic and igneous rocks occur in these domains.

The Patos and Pernambuco shear zones are major dextral shear zones that developed in the wake of the main Brasiliano orogenic event, with peak activity around 590-560 Ma (Archanjo et al., 2008; Ganade et al., 2021). Their Neoproterozoic offsets appear to be on the order of two hundred kilometers for the Pernambuco shear zone and close to 350 km for the Patos shear zone (Fossen et al., 2022). Both shear zones show a range of ductile fabrics that developed from high to low temperature plastic deformation, with local brittle reactivation related to Cretaceous rifting (e.g., Françolin et al., 1994; Araujo et al., 2018; Miranda et al., 2020). They are also associated with syn-kinematic magmatism that must have heated and softened the crust during shearing (Cavalcante et al., 2016).

The Sucuru dike swarm, located in the central domain, records the final magmatic episode of the Brasiliano orogeny in the Borborema Province (Neves et al., 2000; Hollanda et al., 2010; Amorim et al., 2019). The Sucuru dikes occur south of the dextral E-W trending Coxixola shear zone (Fig. 2), the largest of the dextral shear zones internally in the central domain that parallel the Pernambuco and Patos shear zones (Figs. 1, 2). The dikes have compositions equivalent to basaltic andesite and rhyolite (e.g., Hollanda et al., 2010; Santos et al., 2012), and are intrusive into metaplutonic and migmatitic rocks. They are typically 10 to 30 m wide and up to several kilometers long and occur in map-view as parallel curvilinear dikes spaced a few hundred meters apart with a classical segmented geometry (Fig. 2). The dikes do not cross-cut each other, consistent with emplacement during a single magmatic event. Textures from two Sucuru dikes are typically magmatic, with local solid-state deformation attributed to the reactivation of shear zones that affected the dikes and their country rocks (Hollanda et al., 2010; Archanjo, 2020). AMS (Anisotropy of Magnetic Susceptibility) measurements from two Sucuru dikes of andesitic and dacitic compositions show a steep NW-SE-trending magnetic foliation and a subhorizontal magnetic lineation plunging to NW and SE, parallel to the trend of the dikes (Archanjo, 2020). Given the absence of solid-state deformation in the mineral assemblage of the Sucuru dikes and the "normal" type of magnetic fabric, Archanjo (2020) suggests that the magnetic fabrics record the crystallization of magma along the stretching direction in a syntectonic setting.

An age of 548.1 ± 4.3 Ma (U-Pb in zircon) was obtained in a porphyritic hornblende-biotite- andesite dike and interpreted as the crystallization age of the Sucuru swarm (Hollanda et al., 2010). More regionally, Ar-Ar dating of muscovite in upper greenschist to lower amphibolite facies mylonites from the Coxixola shear zone yielded ages of 548-546 ± 2 Ma in the east part of the shear zone, and 513-511 ± 1.8/3.0 Ma in greenschist facies mylonites in the west part. While the oldest ages can be interpretated to date cooling through roughly 400 °C following the main deformation along the Coxixola shear zone (Hollanda et al., 2010), the much younger 513-511 Ma muscovite plateau ages more likely date late-stage shearing in this western part of the Coxixola shear zone. Our study area is located relatively far away from this location, and the biotite age from the nearby Prata intrusion is more applicable. Biotite records cooling of the Prata intrusion (Fig. 2) through roughly 300 ± 50 °C as reflected by an Ar-Ar plateau age of 531-530 ± 2 Ma, which coincides in time with the end of the 548-533 Ma age range of late intrusions in the Sucuru area (Hollanda et al., 2010).

3. Analytical methods

3.1. Titanium-in-quartz (TitaniQ)

TitaniQ analyses were performed on a JEOL JXA-8530FPlus electron microprobe at the University of Minnesota (USA). Operating conditions for Ti in quartz analyses were beam energy of 20 keV, beam current of 150 nA, and beam diameter 3 μm. Ti ka was acquired using two spectrometers with analyzing crystals PETL simultaneously, and then aggregated using the Probe for EPMA software (ProbeSoftware, Inc.). A TAPL monochromator was used to acquire Al ka (Donovan et al., 2011). The on peak counting time was 260 seconds for Al ka and an aggregated 520 seconds for Ti ka. The MAN background intensity data was calibrated, and continuum absorption corrected for Ti ka and Al ka (Donovan and Tingle, 1996; Donovan et al., 2016). A SiO_2 matrix was specified and included in the matrix correction. The quantitative blank correction was utilized. The primary calibration standards used were Orthoclase, Taylor, $KAlSi_3O_8$ for Al ka, and Rutile, Taylor, TiO_2 for Ti ka. A set of synthetic quartz doped at different Ti and Al levels were used as secondary standards (Nachlas, 2017). Herkimer Quartz was used as a blank. The Phi-Rho-Z matrix correction algorithm used was Armstrong/Love Scott (CitZAF) (Armstrong, 1988), and the mass absorption coefficients dataset was FFAST (Chantler et al., 2005).

TitaniQ temperatures were calculated using the calibration by Thomas et al. (2010). The alternative calibration by Huang and Audétat (2012) is not considered because of the analytical issues involved (Thomas et al., 2015). We consider a_{TiO2} to be equal to 1, as rutile is observed in the assemblage of the analyzed sample, aligned parallel to the ribbons (e.g., Ghent and Stout, 1984; Cherniak et al., 2007), and a pressure of 2 kbar, based on the reported greenschist metamorphic conditions in the studied area (e.g., Santos et al., 2012). Further arguments in favor of using 2 kbar are as follows: 1) the biotite Ar-Ar cooling age of 530 Ma suggests a ca. 300 °C regional temperature once the intrusive activity and the related thermal peak came to an end. The region is characterized by extensive Ediacaran intrusive activity that heated the crust and produced a high thermal gradient. Hence it seems reasonable that the depth of intrusion was close to 10 km, which for a crustal density of 2.7 g/cm^3 corresponds to a lithostatic pressure of 2.65 kbar. Given that our Ti temperature estimates presented below are all well above 300 °C, the 530 Ma cooling age puts a lower time constraint on the deformation, and dike intrusion and their deformation both occurred within the time interval 548-533 Ma. The pressure is unlikely to have changed much over this time interval of fading Neoproterozoic deformation. For comparison, however, TitaniQ temperatures for pressures of 4 and 6 kbar were also calculated and are shown in the Supplementary Material, and Table 1 shows results for both 2 and 4 kbar. Temperature uncertainties related to pressures of 2 versus 4 kbar range from 34 to 55 °C. The 1σ standard error (ppm/weight) for the titanium measurements from each spot is ∼2 ppm; analytical uncertainty related to calibration is ± 20 ºC in the TitaniQ temperature estimates if we assume pressure is constrained to within ± 1 kbar (Thomas et al., 2010). Titanium contents above 700 ppm that could be related to spots in impurities or in grain boundaries were excluded from the temperature calculations.

3.2. Crystallographic texture and element analyze

EBSD analysis was performed at the Scanning Electron Microscopy laboratory, at University of Tromsø (UiT), and at Lactec Institute, at Federal University of Paraná (UFPR). At UiT we used the Zeiss Merlin field emission microscope equipped with EDS (Energy Dispersive Spectroscopy), WDS (Wavelength Dispersive Spectroscopy), CL and EBSD, and at UFPR the Tescan Mira3 LM field emission gun scanning electron microscope equipped with EDS, WDS and EBSD. These analyzes were performed on thin sections that were cut perpendicular to the foliation and parallel to the stretching lineation (XZ plane of the finite strain ellipsoid). An Oxford Nordlys/HKL detector was used for measuring diffraction patterns, which were collected and indexed using the Aztec software at both universities. Work conditions at UiT were: 15 kV accelerating voltage, 28 mm of working distance and 70° specimen tilt. Work conditions at UFPR were: 20 kV accelerating voltage, 15 mm of working distance and 70° specimen tilt. Step-size were between 3 to 5 μm. EBSD data were processed using the MTEX Toolbox version 5.2.8 for Matlab™ (Bachmann et al., 2010). Grain boundaries were defined at misorientation angle above 10° using the "calcGrains" function in MTEX. For each sample, [c], <a> directions, and poles for crystallographic planes {m}, {r}, {z}, {π} and {π'} for quartz, the main phase deformed plastically, were plotted. The pole figures (PFs) and inverse pole figures (IPFs) have all been plotted with the same color scale to highlight strength of the CPO. They are equal area, lower hemisphere projections, and as one point per grain. Quantitative element analysis for identification and determination of mineral phase composition was conducted using a ZEISS SUPRA 55 VP field emission equipped with EDS and WDS detectors and a Raman spectrometer equipped with a VIS-CCD camera at University of Bergen (UiB). EDS image resolution was 512 x 384 and acceleration voltage 15 kV. Magnification for EDS analyzes in the fine-grained matrix were often > 2000 times.

4. Samples: field observations and location

Six samples (01A, 01B, 01C, 02A, B76E e B76) from the borders of a single dike from the Sucuru swarm were collected (Fig. 2). The sampled dike is segmented, ~ 3000 m long and ~35 m wide. Solid-state deformation characterized by mylonitic foliation occurs only in the dike margins, while grains without preferred orientation and with no evident solid-state deformation are observed at ~ 10 m from the east margin (Fig. 3). The boundary between the sampled, more fine-grained marginal portion of the dike and its undeformed main part is gradual over a few tens of centimeters, locally less. Samples B76 and B76E are from the same hand-sample collected from the margins of the southern portion of the dike, where the matrix of these rocks is extremely fine-grained. Samples 01 (A, B and C) and 02A are from the margins in the central portion of the dike, where matrix grains have fine and medium sizes (Figs. 4a, b). One polished section from each sample was made for detailed microscopic and textural analysis via the SEM-EBSD. Sample B76E was selected for Titanium-in-quartz analysis.

The sampled rocks of the Sucuru dike are predominantly bluish gray in color and display a sub-vertical anastomosing mylonitic foliation parallel to the trend of the dike, with orientation ranging from N to NE. In stepover regions of the dikes, the mylonitic foliation becomes E-W trending and subvertical (Fig. 2a). On the map scale, however, the dikes have a general NNW-SSE orientation and show a folded geometry in map view (Fig. 2b). The mineral stretching lineation has a main orientation of 15/038 and is characterized by strongly elongated quartz ribbons (Fig. 3a). Quartz ribbons embedded in a fine and recrystallized matrix wrap feldspar porphyroclasts with sizes ranging from 0.5 cm to 2 cm, and are often affected by shear bands to form an S-C fabric (Figs. 3b, 3c). Feldspar porphyroclasts, especially orthoclase, preserve euhedral habit and present bookshelf-type fractures (Fig. 3c). Euhedral feldspar and quartz grains without preferred orientation (not sampled) are observed a few meters away from the dike margin, where the dike seems to be free of solid-state deformation (Fig. 3d). Plagioclase locally exhibits δ-shapes (Fig. 4a).

5. Microstructures and element analysis

The sampled Sucuru dike has porphyritic texture and rhyolitic composition consisting of quartz (55%), K-feldspar (orthoclase, 25%) and albite (15%), ± biotite, hornblende, and oxides. Muscovite, chlorite, and sericite occur as feldspar alteration and rutile, zircon, alanite and opaque minerals as accessory phases. The proportion of minerals are semiquantitative and based on EBSD, backscattered electron images, EDS, Raman spectroscopy and optical microscopy. All samples show a mylonitic anastomosing foliation characterized by quartz ribbons and porphyroclasts of quartz and feldspar embedded in a recrystallized matrix (Figs. 5a-c and Figs. 6a-f). The matrix makes up ca. 60% of the rock in samples 01A, 01B, 01C, B76 and B76E, and more than 70% in sample 2A (ultramylonite). It consists mainly of a fine-grained (5 to ~60 μm) mixture of quartz, K- and Na-feldspar and minor Ca-feldspar, and biotite (Fig. 7). Grain boundaries in the matrix are irregular and slight curved (Figs. 7a, b).

Quartz grains in the matrix have little optical signs of intracrystalline deformation, unlikely quartz porphyroclasts, which often show subgrains and undulose extinction (Figs. 6a-e). Quartz grains also form ca. 300 μm wide recrystallized layers, in which recrystallized quartz grains have sizes up to 130 μm. These layers are folded around large feldspar porphyroclasts (Fig. 6f), and often occur in association with smaller amounts of zircon, micas, and feldspars grains (Fig. 7c). Quartz-grain boundaries both in the matrix and in the recrystallized layers are straight (up to 15 mm segments), occasionally forming triple or irregular junctions (Fig. 7a, c).

Quartz grains that occur as ribbons have an axial ratio of 1:7 in samples 01A, 01B and 01C, and 1:4 in sample 02A, and show evidence of intracrystalline deformation, such as undulose extinction and subgrains (Figs. 5a-c); they can also be partially or completely recrystallized (Figs. 5b, c). The ribbons are surrounded by coarse grains of feldspar (up to 130 μm) and quartz.

Quartz porphyroclasts display σ or lens geometry (Figs. 6a-e) and are wrapped by recrystallized quartz grains, sometimes showing a mantle-core structure (Fig. 6c). These new grains of recrystallized quartz (here also called daughter grains) have an average size of 35 μm. Boundaries between neighbor-daughter grains (recrystallized grains immediately in contact with porphyroclasts) and porphyroclasts (here also referred to as parent grains) are serrated, and daughter quartz-grain boundaries are commonly slightly curved or straight, but locally, lobate (Fig. 8). Subgrains observed in the porphyroclasts of samples 01A, 01B, 01C, B76 and B76E have an average size of 90 μm, and locally have serrated boundaries (Fig. 6b). In sample 02A, the subgrains have an average size of 115 μm. Occasionally the subgrains are similar in size to the new grains (Fig. 6a). However, it is common for subgrains in porphyroclasts to be larger in size than the new neighbor-daughter and daughter grains (Figs. 6c-e; Fig. 8).

K-feldspar and albite grains occur as porphyroclasts with sizes up to 8 mm and subhedral to euhedral shapes. These porphyroclasts are wrapped in a mixture of small grains of quartz, feldspar and micas. They frequently present irregular fractures, locally of bookshelf type (Figs. 9a, b). Porphyroclast grains with prismatic and σ-shapes commonly preserve igneous (primary) structures, such as Tartan, Carlsbad and polysynthetic twinning (Figs. 9c, d), but porphyroclasts with deformation twins (sample B76E; Figs. 9e, f) or evidence of partial recrystallization (sample 1B; Fig. 6e) are also observed. K-feldspar porphyroclasts often have lamellae of albite and albite porphyroclasts lamellae of anorthite (Fig. 10). Feldspar occurs also as <100-mm neoblasts on the edges of feldspar porphyroclasts, preferentially between igneous twins, or in feldspar porphyroclast tails together with quartz. Several fine-grained feldspars show evidence of alteration to sericite, and medium to coarse grains have inclusions of zircon, biotite and opaque minerals.

Biotite and hornblende are fine-grained (~ 15 μm) and display anhedral shapes. Both grains form narrow and elongated bands, and have a strong preferred orientation, parallel to the mylonitic foliation. They are also present in fractures and along grain boundaries of feldspar aggregates. Fine-grained oxides, opaque minerals, rutile and alanite crystals occur associated with these bands.

6. TitaniQ results

We selected ten areas for TitaniQ analyses in sample B76E, which shows typical mylonitic microstructures from the Sucuru dike (Fig. 11). These areas are quartz ribbons, layers of recrystallized quartz grains, recrystallized quartz grains in the matrix and transitional quartz porphyroclasts-ribbons. All the analyzed quartz grains, except for those in the matrix, present evidence of intracrystalline deformation such as subgrains and undulose extinction and sizes larger than 30 μm. A summary of Ti concentrations showing maximum and minimum values measured in each area is presented in Table 1 and the complete Ti analytical data are presented in the Supplementary Material.

In general, the Sucuru mylonite has a heterogenous Ti distribution that is closely related to the quartz grain sizes, with the highest concentrations of Ti in coarse grains (Fig.11). The fine recrystallized quartz grains in the matrix (sizes up to 20 μm) have the lowest Ti concentrations and the core of quartz ribbons have the highest. Ti contents in the matrix range from 3.5 to 14 ppm, corresponding to TitaniQ temperatures between 346 and 423 °C (maximum probability at 396 °C), while Ti concentrations in the ribbons range much wider from 10 to 454 ppm, corresponding to 401 to 739 °C (maximum probability at 617 °C). Transitional quartz porphyroclast-ribbon present Ti contents ranging from 22 to 257 ppm, corresponding to TitaniQ temperatures from 454 to 669 °C (maximum probability at 610 °C). The highest Ti concentrations tend to occur in the core of quartz ribbons and in the transitional quartz porphyroclast-ribbons, gradually decreasing towards their edges. Layers of recrystallized quartz grains have Ti contents between 4.2 and 294 ppm, corresponding to TitaniQ temperatures between 355 and 685 °C (maximum probability at 573 °C) (Fig. 11).

Sample B76E	Ti (ppm)	T (°C) for P=2 Kbar	T (°C) for P=4 Kbar	T(°C) uncertainity related to pressure
Area 1 (layer of recrystllized quartz+matrix)	5	364	398	34
Area 1 (layer of recrystllized quartz+matrix)	246	665	715	50
Area 2 (transitional qtz-porph.-ribbon+matrix)	3,5	346	380	34
Area 2 (transitional qtz-porph.-ribbon+matrix)	257	669	720	51
Area 3 (quartz ribbon)	23	455	494	39
Area 3 (quartz ribbon)	212	648	698	50
Area 4 (quartz ribbon)	10	401	437	36
Area 4 (quartz ribbon)	454	739	794	55
Area 5 (transitional qtz-porph.-ribbon)	22	454	493	39
Area 5 (transitional qtz-porph.-ribbon)	191	636	686	50
Area 6 (layer of recrystallized quartz)	4	355	389	34
Area 6 (layer of recrystallized quartz)	163	620	668	48
Area 7 (quartz ribbon)	43	501	542	41
Area 7 (quartz ribbon)	380	717	770	53
Area 8 (layer of recrystallized quartz)	22	453	493	40
Area 8 (layer of recrystallized quartz)	294	685	737	52
Area 9 (layer of recrystallized quartz)	78	550	594	44
Area 9 (layer of recrystallized quartz)	193	638	687	49
Area 10 (quartz ribbon)	11,5	411	448	37
Area 10 (quartz ribbon)	187	635	684	49
Matrix	*3,5-14*	*346-423*	*380-460*	*34-37*
Ribbons	*10-454*	*401-739*	*437-794*	*36-55*
Layers of recrystallized quartz grains	*4-294*	*355-685*	*389-737*	*34-52*
Transitional quartz porphyroclasts-ribbons	*22-257*	*454-669*	*493-720*	*39-51*

Table 1. Maximum and minimum values of titanium for each analyzed area (see Figure 11 for locations) and for matrix, ribbons, layers of recrystallized quartz grains and transitional quartz porphyroclasts-ribbons. The temperature distributions for each group are shown in the probability density plot in Fig. 11).

7. Textural Analysis (EBSD) results

Five samples were selected for textural analysis by EBSD (#1A, #1B, #1C, #2A and #B76). Samples #1A and #1B are in the Supplementary Material together with the pole figures for all crystallographic directions and planes of all samples. We selected one area in each of the samples, except for sample #B76, from which we selected three areas (A, B and C) (Fig. 12). Poles figures are for whole mapped areas and for quartz from different domains, such as porphyroclasts, ribbons, and recrystallized grains on the edges of porphyroclasts, forming isolated layers, and in the matrix. Those that have correlations with X and Z are presented here together with the EBSD maps.

Recrystallized quartz grains have sizes up to 60 μm in the matrix and up to 130 μm in the layers of recrystallized grains and on the edges of porphyroclasts (Fig. 7). In general, crystallographic preferred orientations for whole EBSD mapped areas are weak (m.u.d. ≤ 3), except for areas A and C in sample B76, which have m.u.d. equal to 3.7 (M-index = 0.04) and 5.3 (M-index = 0.09), respectively. However, the crystallographic preferred orientations for many quartz domains tend to be moderate to strongly developed.

7.1. Crystallographic preferred orientation (CPO)

Sample 1C

Pole figures for sample 1C are shown in Figure 13. The EBSD mapped area consists of three quartz porphyroclasts I, II and III, recrystallized grains IV, V, VI, VIII, aggregates of recrystallized grains VII, and recrystallized grains in the matrix IX. The pole figures for the whole EBSD area display [c] axes distributed over a NW-SE crossed-girdle. Porphyroclast I shows [c] axis at high angle to the foliation, while porphyroclast II exhibits [c] axis with a slight tendency to be close to Z. Porphyroclast III shows [c] axis parallel to X. Recrystallized grains IV have [c] axes on the periphery of the pole figure at 40° counterclockwise to Z, and <a> axes distributed over a NE-SW girdle with one weak maximum in Y. IPFs show significant concentrations of {m} in Z and some [c] in X, suggestive of prism <c> slip (e.g., Schmid et al., 1981). Recrystallized grains V display four small maxima of [c] axes at 20-30° to Z and three maxima of <a> axes, one of them close to Y. Recrystallized grains VI show strong [c] axis concentration between Y and Z. Some concentrations of <a> axes occur parallel to X. Concentrations of rhomb {π} occur close to Z, suggesting {π}<a> slip for some recrystallized grains VI. [c] axes from recrystallized grains VII are distributed over a E-W girdle with some concentrations parallel to X. Some poles to {m} form small weak maxima, some of them close to Z. IPF displays concentrations of poles to {π} and {m} parallel to Z, but PF for poles to {π} do not show concentrations close to Z. This CPO suggests {m}<c> slip for recrystallized grains VII. Recrystallized grains VIII on the edges of porphyroclast II display a strong maximum of [c] axes close to Z, while <a> axes are distributed over an E-W girdle, with three maxima, one of them close to X, compatible with basal <a> slip (e.g., Schmid and Casey, 1986). Recrystallized grains in the matrix IX have a crystallographic fabric similar to the whole mapped area, in which <c> axes are distributed along a NW-SE crossed-girdle, but for this area IX a weak maximum is observed around Y. The IPF shows some concentrations of [c] parallel to Z. This CPO, although weak, is suggestive of prism <a> and basal <a> slips (e.g., Schmid and Casey, 1986).

Sample 2A

Pole figures for sample 2A are shown in Figure 14. The EBSD mapped area consists of one quartz porphyroclast divided in three isolated grains I, II and III separated by recrystallized grains, layers of recrystallized grains IV, V and VI, and recrystallized grains VII and VIII. The pole figures for the whole mapped area display [c] axes distributed over a NE-SW girdle, <a> axes forming large concentrations on the periphery of the pole figure around X and close to Y, and some poles to {z} oriented at low angle to Z. Single grains of porphyroclasts I, II and III have similar orientations with [c] axes on the periphery of the pole figure at 20° clockwise to Z, favorably oriented for basal slip. [c] axes from recrystallized IV are distributed over a E-W girdle with weak concentrations close to X, as also observed in the IPF, and weak concentrations of poles to {m} close to Z. <a> axes are concentrated around Z, as also observed in the IPF. This CPO, even though being weak, is compatible with prism <c> slip. Recrystallized grains V show [c] axes maxima around Y and close to Z and concentrations of <a> axes spread on the periphery of the pole figure, suggestive of prism <a> slip and additionally basal <a> slip, as also indicated by the IPFs. Recrystallized grains VI exhibit strong concentrations of <c> axes close to Y and some <a> axes around X; the strongest concentration in Z in the IPF is however in {π'}. This CPO is suggestive of prism <a> and {π'}<a> slips (e.g., Law et al., 1990). Recrystallized grains VII display [c] axes distributed over large great circles around Z and some concentrations of <a> axes around X, compatible with basal <a> slip. Recrystallized grains VIII have [c] axes forming great circles from Z to close to Y and some <a> axis maxima close to X. PFs for poles to {π} are the strongest between the rhombohedral forms, although the maximum m.u.d. (1.7) is still weak. The IPF is also not strong, but one can see concentrations of [c] and rhombohedral forms in Z, suggesting basal<a> and {π}<a> slips.

Sample B76

Pole figures for the three areas (B76A, B76B and B76C) in sample B76 are shown in Figures 15a-c. The pole figure for the whole area B76A (Fig. 15a) displays [c] axes distributed over a N-S girdle with moderate small maxima around Y, and concentrations of <a> close to X (also observed in the IPF), suggestive of prism <a> slip (e.g., Law et al., 1990). Significant concentrations of poles to {r} parallel to Z in the PF and the strongest concentration of {π} in Z in the IPF suggests activation of {π}<a> slip in addition to prism <a>. Porphyroclast I display [c] axes forming two concentrations between Y and X and Y and Z. IPF shows poles to {π} and {π'} close to Z. The ribbon single grain II exhibits [c] axis concentration between Y and Z, and pole to {π} parallel to Z, as observed in the IPF. Recrystallized grains III show [c] axes distributed along a N-S girdle with a strong maximum close to Y. Some concentrations of <a> occur parallel to X and some poles to {r} and {π} occur close to Z. This CPO suggests dominance of prism <a> slip, and additional activation of rhomb <a> slip, as supported by the IPFs. Recrystallized grains IV display weak crystallographic orientations, with some planes {r} and {π} oriented close to Z and <a> axes spread on the periphery of the pole figure, suggestive of rhomb <a> slip.

The pole figures for the whole area B76B (Fig. 15b) display [c] axes distributed along a N-S girdle with weak maximum close to Y and Z, and <a> axis with weak maxima close to X, which is also observed in the IPFs. Such a crystallographic fabric, even though being weakly developed, is consistent with prism <a>, basal <a>, {r}<a> and {π}<a> slips. Porphyroclast grains I and II have [c] axes close to Z, and the IPF for porphyroclast I shows <a> axis in X. Recrystallized grains from area III, at the edges in between porphyroclasts I and II, display quartz [c] and <a> axes orientations close to Z and X, similar to those from the porphyroclasts. This is compatible with dominant activation of basal <a> slip. Recrystallized grains IV at the border of porphyroclast II and in the matrix display different crystallographic orientations in comparison with the porphyroclast, being their [c] axes oriented in a large N-S girdle with maximum close to Y, compatible with dominance of prism <a> slip. Significant concentrations of poles to {r} parallel to Z in the PF and concentrations of poles to {π} and (c) in Z in the IPF, suggest rhomb <a> and basal <a> slips in addition to prism <a>.

The EBSD area B76C (Fig. 15c) contains folded layers of recrystallized grains and some recrystallized grains in the matrix in which [c] axes form a strong maximum around Y, suggestive of prism <a> slip. Additionally, significant concentrations of poles to {r} parallel to Z in the PF together with concentrations of poles to {π'} and {π} in Z in the IPF also suggest activation rhomb <a> slip.

7.2. Misorientation angle distribution

The misorientation angles and the corresponding misorientation axes (Lloyd et al., 1997; Wheeler et al., 2001) for the whole EBSD mapped areas are shown in Figure 16. The misorientation angle histograms for uncorrelated quartz grains approach the theoretical curve for uniform distributions in all samples, except for B76C. In contrast, the misorientation angles for correlated quartz grains diverge significantly from the theoretical curve for uniform distributions. The misorientation angles for uncorrelated grains that approach the theoretical curve attest to random distributions (e.g.,Wheeler et al., 2001).

The correlated misorientation angle distribution histograms for sample B76A and B76C show a progressive increase up to 60°, and up to 90° in sample 1C, decreasing thereafter towards the maximum misorientation angle of 104.5°, as expected for nonrandom textures (e.g., Morawiec, 1996).

All samples show discrete peaks at 60° differing only in the frequency values, with the the highest (~9%) in sample B76C. These peaks are associated with rotation axes in [c] and represent Dauphiné twins (e.g., Neumann, 2000). Peaks at low angles up to 15° in all samples that are associated with rotation axes in [c] are related to subgrains and recrystallized grains and may indicate the activity of {m}<a> (Neumann, 2000). This is confirmed by the maxima around Y observed for recrystallized grains from all samples, such as: recrystallized IX (sample 1C), recrystallized V and VI (sample 2A), recrystallized III (sample B76A), recrystallized IV (B76B), and the whole mapped area B76C (Fig. 15; Table 2). For sample 1C weak (m.u.d. = 2.0) peak at low angles (2-10°) is associated with rotation in <a> in addition to [c], suggesting activation of {m}[c] slip. Interestingly, pole figures for recrystallized grains IV on the edges of porphyroclast III and recrystallized VII, for this sample, show that some recrystallized grains have [c] axes oriented close to X, as does the porphyroclast III. Such an CPO therefore can be interpreted as suggestive of prism <c> slip, which is also supported by the IPF (Fig. 13). Weak peaks ($2 < \text{m.u.d} \leq 2.6$) at large angles between 60 and 65° associated with rotation axes in {π} and {π'} indicate activation of rhomb forms in <a> direction, which is supported by the CPO for samples B76A, B76B, 1C, and 2A. The misorientation angle distributions therefore support the suggested slip systems, and consequently, solid-state deformation in quartz grains.

8. Discussion

8.1. TitaniQ interpretation

All the quartz grains analyzed by TitaniQ geothermometry display evidence of intracrystalline deformation, such as subgrains and undulose extinction, except for the very small grains (≤ 20 μm) in the matrix. Microstructures on the deformed quartz grains suggest that the recrystallization mechanism responsible for progressive grain-size reduction of quartz is bulging recrystallization (BLG), and subgrain rotation recrystallization (SGR) to some extent, considering the relationship between the sizes of recrystallized grains and subgrains and the predominantly serrated and irregular grain-boundaries. Local GBM is inferred by the presence of lobate grain boundaries between daughter grains (Fig. 8) and interpreted as formed pre-recrystallization by BLG and SGR. We therefore interpret that TitaniQ temperatures reflect the temperatures during crystal-plastic deformation and dynamic recrystallization of the Sucuru mylonitic rocks. This is also supported by the indication of slip along <c> direction and evidence of intracrystalline deformation in feldspars. Electron microprobe analysis in deformed quartz grains from different textural sites reveals a distinct Ti signature in quartz ribbons, transitional quartz porphyroclasts-ribbons, layers of recrystallized quartz and recrystallized quartz in the matrix (Fig. 11). This suggests inefficient equilibration of Ti and different temperature regimes corresponding to lower granulite to lower greenschist facies, under approximately the same pressure conditions. Such a temperature variation under isobaric conditions might reflect a heat source in the early stage of ductile deformation that in the study area may be related to the intrusion of large late Ediacaran to early Cambrian magmatic bodies, such as the granitic and gabbroic Prata, Santa Catarina and Serra da Engabelada units (Fig. 2).

Qtz domain	**CPO strength*	*Slip system*	*Def. Mechanism*	*Remark*
Sample 1C				
Whole Area	very weak	-	disl. accomodated GBS	
Porphyroclast I	-	-	dislocation creep	basal plane oriented hard for slip
Porphyroclast II	-	-	dislocation creep	basal plane oriented favorably for slip
Porphyroclast III	-	-	dislocation creep	<c> // X
Coarse recrystallized IV	moderate	prism <c>	dislocation creep	{m} <c>
Coarse recrystallized V	strong	-	dislocation creep	
Coarse recrystallized VI	strong	rhomb <a>	dislocation creep	{π} <a>
Coarse recrystallized VII	weak	prism <c>	disl. accomodated GBS	{m}<c>
Coarse recrystallized VIII	strong	basal <a>	dislocation creep	recryst. grains on the edge of porphy. II
Recryst. Matrix IX	very weak	prism <a> + basal <a>	disl. accomodated GBS	
Sample 2A				
Whole Area	very weak	-	disl. accomodated GBS	
Porphyroclast I	-	-	dislocation creep	basal plane oriented favorably for slip
Porphyroclast II	-	-	dislocation creep	basal plane oriented favorably for slip
Porphyroclast III	-	-	dislocation creep	basal plane oriented favorably for slip
Layer Recryst. IV	weak	prism <c>	disl. accomodated GBS	{m} <c>
Layer Recryst. V	weak	prism <a> + basal <a>	disl. accomodated GBS	
Layer Recryst. VI	strong	prism <a> + rhomb <a>	dislocation creep	{π'} <a>
Recryst.VII	weak	basal <a>	disl. accomodated GBS	recryst. grains on the edges of porphyroclasts
Recryst.VIII	moderate	basal <a> + rhomb <a>	dislocation creep	recryst. grains on the edges of porphyroclasts/(c)<a> and {π} <a>
Sample B76A				
Whole Area	moderate	prism <a> + rhomb <a>	dislocation creep	{π} <a>
Porphyroclast I	-	-	dislocation creep	basal plane oriented hard for slip
Quartz ribbon	-	-	dislocation creep	basal plane oriented hard for slip
Recryst.III	strong	prism <a> + rhomb <a>	dislocation creep	recryst. grains on the edges of porphyroclasts/{m}<a> + {r}<a> + {π} <a>
Layer recryst + ribbon + Matrix	very weak	rhomb <a>	disl. accomodated GBS	{π} <a> and {r} <a>
Sample B76B				
Whole Area	weak	prism <a> + basal <a> + rhomb <a>	disl. accomodated GBS	{m}<a> + {r}<a>+{π}<a>
Porphyroclast I	-	-	dislocation creep	basal plane oriented favorably for slip
Porphyroclast II	-	-	dislocation creep	basal plane oriented favorably for slip
Recryst.III	weak	basal <a>	disl. accomodated GBS	recryst. grains on the edges of porphyroclasts
Recryst. + Matrix IV	moderate	prism <a> + basal <a> + rhomb <a>	dislocation creep	recryst. grains on the edges of porphyroclast + matrix
Sample B76C				
Whole Area	strong	prism <a> + rhomb <a>	dislocation creep	(folded) layer of coarse recryst. grains + matrix

Table 2: Summary of textural (CPO) aspects for the Sucuru mylonitic rocks. *CPO strength: very weak = m.u.d. ≤ 2; weak = 2 < m.u.d. ≤ 3; moderate = 3 < m.u.d. ≤ 4; strong = 4 < m.u.d. ≤ 7; very strong = m.u.d. > 7.

Application of TitaniQ considering P = 2 kbar shows that recrystallized grains in the matrix record the lowest temperatures, ranging from 346 to 423 °C. This temperature interval is interpreted as the minimum temperature of quartz recrystallization. TitaniQ estimates suggest that plastic deformation recorded in coarse, recrystallized quartz that form layers of recrystallized grains occurred at temperatures between 376 and 685 °C, while plastic deformation characterized by the presence of large subgrains in transitional quartz porphyroclasts-ribbons occurred between 454 and 669 °C. Furthermore, TitaniQ estimates suggest that plastic deformation responsible for quartz-ribbon development occurred between 401 and 739 °C. Alternatively, one could suggest that the highest temperatures (> 700 °C) in the ribbons reflect incomplete chemical resetting and thus are related to the crystallization of the Sucuru dikes. However, given the evidence for GBM recrystallization and that GBM efficiently re-equilibrate Ti (e.g., Grujic et al., 2011; Haertel et al., 2013), we again interpret these temperatures as a record of solid-state deformation. Solid-state deformation under high temperature is also supported by the indication of prism <c> slip in daughter grains from samples 1C and 2A (Figs. 13, 14), given that prism <c> is a slip system activated at high (650-750 °C) temperatures (e.g., Mainprice et al., 1986), and by the presence of deformation twins in feldspars (sample B76E; Fig. 9e).

Taking into consideration that the temperatures above the brittle-ductile transition for quartz (~350 °C) are well preserved in quartz from different textural areas, one could suggest that rapid cooling must have occurred from the 500 °C isotherm, which marks the onset of GBM (e.g., Stipp et al., 2002). However, given that lobateness of quartz grain boundaries is only observed locally (Fig. 8), which points to limited GBM, the microstructural evidence for extensive BLG and SGR overprinting recrystallization, slow cooling must have occurred. We therefore interpret the record of high temperature (>500 to <740 °C) to be inherited from the early stages of ductile deformation, that gradually decreased to >340 to <500 °C during a later stage, as reflected by partial re-equilibration to low Ti, likely because the dynamic recrystallization is dominated by BLG and SGR. Thus, the variance in Ti concentrations from the core of ribbons and transitional porphyroclast-ribbon to their rims and in recrystallized grains that form layers, potentially reflects the influence of the recrystallization mechanisms (BLG and SGR), which are generally considered incapable of efficiently mobilizing and completely resetting to lower Ti concentrations in mylonitic rocks (e.g., Grujic, et al., 2011; Nachlas et al., 2014; Bestmann and Pennnacchioni, 2015). The dominance of BLG microstructures along with remnants of SGR, and GBM to a lesser extent, certainly accounts for the large range in TitaniQ temperatures (>340 to <740 °C) observed in these rocks. Such a large range is scarcely reported in the literature, although a range of TitaniQ estimates between 360 and 540 °C associated with a switch in recrystallization mechanisms has been documented for mylonitic rocks from the Swiss Alps (e.g., Haertel et al., 2013).

8.2. Microstructures and textural analysis

Microstructural characterization shows that the Sucuru rocks present typical mylonitic aspects with quartz ribbons forming an anastomosing pattern wrapping porphyroclasts of feldspar and quartz embedded in a fine-grained (5-60 μm) quartz-feldspar (± micas ± accessories) matrix, which makes more than 60% of the thin section areas. The general smaller grain-sizes between the neighbor–daughter grains and the subgrains in the parent grains, along with irregular serrated grain boundaries, suggest that BLG was the dominant recrystallization mechanism responsible for grain-size reduction during dynamic recrystallization. However, the presence of some subgrains with similar sizes to neighbor-daughter grains (Fig. 8), indicate that SGR also contributed to the recrystallization process (e.g., Stipp et al., 2002). Additionally, the local lobateness of some daughter grain boundaries (Fig. 8) suggests a contribution of GBM to a minor extent in the initial shear deformation.

Microtextural analysis shows that the CPOs for the whole EBSD mapped areas are weak to very weak, except for two areas of B76 (A and C) and are very similar to those domains of recrystallized grains in the matrix (Fig. 13). This suggests that the CPO of the Sucuru mylonites is mainly controlled by the mechanical properties of the fine-grained matrix. Fine-grained quartz-feldspar mixtures are often weaker than pure quartz domains (e.g., Stünitz and Fitz Gerald, 1993) and prone to deform by activation of grain-size sensitive deformation mechanisms during grain-boundary sliding process (GBS). Polymineralic matrices such as those observed in our rocks may prevent grain growth, facilitating therefore the maintenance of small grains generated during dynamic recrystallization and the activation of GBS. In addition, GBS can result in weakening of pre-existing CPOs as it often promotes dispersion of crystal axes during deformation (e.g., Fliervoet et al., 1997; 1999: Jiang et al., 2000; Wightman et al., 2006).

If deformation occurs by activation of DifGBS (diffusion creep-accommodated grain boundary sliding), one expects no development of CPO (e.g., Kashyap and Mukherjee, 1985; Walker et al., 1990), which is not the case of our samples. Furthermore, the maximum temperatures determined for deformation and recrystallization does not favor solid-state diffusion (DifGBS). In our samples the weakest CPOs occur in the matrix domains (Fig. 13 and Table 2), while the strongest occur in coarse quartz pure domains, such as those on the edges of quartz porphyroclasts (Fig. 14; Table 2) and those forming recrystallized layers (Fig. 15c). We therefore interpret that the general weak CPOs in the Sucuru mylonites are due to the dominant operation of GBS through DisGBS (dislocation creep-accommodated grain boundary sliding), given the several evidence of intracrystalline deformation, especially in relict grains. GBS is also supported by the presence of straight quartz-grain boundaries in the matrix (Fig. 7a) and matrix grain sizes mostly smaller than the subgrain sizes (e.g., Fliervoet et al., 1997 and references therein).

The generally weak CPO observed in our samples makes it difficult to infer active slip systems, but the ones inferred were supported by the misorientation angle distributions (Fig. 16). However, even though the CPO is generally weak, the CPO of many neighbor-daughter and daughter grains are similar to those of their parent. For example, parent grain II in sample 1C is suitably oriented for basal <a> slip, and neighbor-daughter grains VIII show texture suggestive of operation of basal <a> (Fig. 13). The same relationship is observed between porphyroclasts I and II (which are parts of a single porphyroclast) and the neighbor-daughter grains III in sample B76B (Fig. 15b). Likewise, if parent grains are not suitably oriented for basal <a> slip and rather for prism <a> slip, neighbor-daughter grains tend to show CPOs suggestive of operation of prism <a> slip (Fig. 15a; B76A porphyroclast I and recrystallized III). Besides, if parent grains are suitably oriented for prism <c> slip (porphyroclast III in Fig. 13), neighbor-daughter grains texture suggests prism <c> slip (recrystallized IV in Fig. 13). This suggests that the CPO of the new recrystallized grains, especially the neighbor-daughter grains, is strongly controlled by the orientation of their parents. The parent grains in turn are interpreted to have been deformed by dislocation creep during initial shear deformation, given their several evidence of intracrystalline deformation, such as subgrains, elongate, ribbon and lens shapes, and undulose extinction (Figs. 5, 6 and 12), and their high content of Ti suggestive of high temperature conditions. The effect of GBS in weakening the crystallographic texture appears to be less significant in areas dominated by coarse pure quartz domains, such as those that form recrystallized layers (Figs. 15a, c, B76A and B76C) or those immediately in contact with parent grains (neighbor-daughter grains). In such domains, the moderate to very strong crystallographic textures are interpreted as the result of the dominant activation of dislocation creep during strain localization.

Besides the generally weakly developed crystallographic fabrics, the interpretation of active slip systems is not straightforward because multiple slip systems (basal, rhomb and prism) might have operated simultaneously during plastic deformation of the Sucuru dikes, as suggested by the frequent girdle distribution of [c]-axes from recrystallized grains in many samples (for example, B76A, B76B, 1C and 2A) (e.g., Stipp et al., 2002). The variety in active slip systems is ascribed, to a large extent, to the initial orientation of the parent grains, which plays a critical role in the fabric evolution of the neighbor-daughter grains that tend to inherit the orientation of their parents. Additionally, the activation of several slip systems may also indicate variations in temperature during plastic-deformation, which is attested by

TitaniQ estimates ranging from >340 to <740 °C, as discussed previously. The high temperature (> 500 to < 740 °C) deformation is interpretated as taking place at an early stage of deformation, likely during the intrusion of late Ediacaran to early Cambrian magmatic bodies. This stage might have been progressively succeeded by low temperature (> 340 to < 500 °C) conditions due to cooling of these bodies.

The high temperature deformation induced dynamic recrystallization and produced coarse recrystallized grains on the edges of porphyroclasts, recrystallized grains that form (folded) layers, and intracrystalline deformation in quartz-ribbons and transitional quartz porphyroclast-ribbon. Under such a high temperature condition quartz could well have deformed by activation of prism<c> forms, as suggested by the CPOs of some samples that are also supported by the misorientation angles distribution (Figs. 13, 14 and 16; Table 2). Such a high temperature deformation must also have been responsible for deformation twins in feldspar porphyroclasts. However, the presence of many feldspar porphyroclasts preserving primary (igneous) twining indicate that intense high temperature strain localization in feldspar did not occur. This implies that deep-seated localized strain under temperatures >500 °C, the limit for feldspar plastic deformation, at the early stages of the deformation evolution of the Sucuru mylonites, is unlikely. Low temperature (> 340 to < 500 °C) deformation induced recrystallization is likely responsible for the formation of the large amounts of fine-recrystallized grains that form the matrix and the smaller grains that occur together with coarse grains in the recrystallized layers and on the edges of porphyroclasts. Such a low temperature deformation is also recorded by the presence of fractured feldspar porphyroclasts, which attest to the operation of brittle mechanisms.

The detailed textural study suggests that strain was localized by operation of DisGBS in quartz during the later low temperature stage of the deformation and that dislocation creep was dominant at an early high temperature stage. Dislocation creep may have produced a strong CPO by the activation of prism <c> slip, capable to be preserved after intense low temperature recrystallization. Alternatively, quartz porphyroclasts suitable for prism <c> slip would probably be difficult to reorient to a position that would allow slip along <a> direction in a progressive shear regime. DisGBS seems to be fundamental to weaken the crystallographic fabrics, especially in whole EBSD areas that are not dominated by pure quartz domains.

8.3. Age and kinematics of the deformation

The timing of deformation is constrained by the similar ~548 Ma U/Pb age of the Prata intrusion and one of the dikes, and less directly by a few $^{40}Ar/^{39}Ar$ cooling ages. A ca. 530 Ma $^{40}Ar/^{39}Ar$ age was obtained for biotite from the mafic Prata intrusion and 513 Ma for muscovite from mylonites from the Coxixola shear zone (Hollanda et al., 2010). Biotite and muscovite are generally thought to record cooling through roughly 300-400 °C, with biotite ideally representing the lowest closure temperature (300 ± 50°C). In this case, muscovite from low-grade sheared rocks is younger, which may indicate that the 512 Ma age represents a deformation age. Hence, interpretation of the $^{40}Ar/^{39}Ar$ data is not straightforward, but they indicate that both the high and low temperature deformation happened in the time interval from 548 to 530 Ma. The lower constraint (530 Ma) relies on our Ti temperature estimates being above ~350 °C, i.e. above the closure temperature for biotite. Although more geochronologic work is needed to explore this evolution in more detail, we can conclude that ductile (plastic) deformation of the Borborema shear zone system in this region continued until the end of the Ediacaran and possibly also into the Cambrian. This agrees with recent U-Pb ages of high-temperature plastic deformation in the eastern Patos shear zone (Fig. 1), dated between 563 and 555 Ma from core to rim of monazite grains (Cioffi et al., 2021).

The orientation of the dikes, their deformation and their relation to the transcurrent deformation regime all suggest that the deformation described in this work represents a continuation of shearing on the E-W dextral Neoproterozoic Patos-Pernambuco shear system rather than some separate later event. The main local structure of reference is the Coxixola shear zone, which again relates to the major Patos shear zone to the north in terms of kinematics and orientation. First, the NW-SE to NNW-SSE trend of the dikes, recorded by AMS measurements (Archanjo, 2020) and observed at map scale (Fig. 2), fits a dextral shear where strain is not limited to the shear zone itself, but also to some extent expressed in the surrounding rocks. In the dextral setting of the Patos-Pernambuco shear system, the fastest instantaneous stretching (ISA_1) will occur at an angle to the shear zone (Fossen, 2016). For simple shear, which we use as a reference here, the angle is 45°. Perpendicular to this direction is the fastest shortening direction (ISA_3). Dikes will preferentially open perpendicular to ISA_1, as illustrated in Fig. 17. As shearing continues, they will rotate clockwise and, for limited amounts of rotation, undergo dike-parallel shortening. Solid dikes represent competent layers and will therefore buckle in this situation. The fold pattern and the orientation of their axial plane trace (APT in Fig. 17) is consistent with this model. The harmonic fold style and the long wavelength–thickness ratio also indicate that the dikes folded together through multilayer buckling. Hence, we find strong evidence that the dextral shear regime that dominated the Borborema province from ca. 600 Ma was still in place at the dawn of the Cambrian some 60-70 million years later.

9. Conclusion

We integrated field mapping observations, remote sensing image interpretations, detailed textural analysis and TitaniQ geothermobarometry to investigate the late stages of strain localization in the Central domain of the Borborema Province, and the influence of dynamic recrystallization on the Ti signature in quartz, in quartz-bearing mylonitic rocks from the Sucuru dike swarm. Our results show that:

- Microstructures typically indicate solid-state deformation associated with extensive dynamic recrystallization dominated by BLG, and by SGR to some extent. The large amount of fine-grained polymineralic matrix (60-70%) with very little or no optical evidence of intracrystalline deformation might have favored the activation of grain-size sensitive deformation mechanisms, such as DisGBS, which resulted in an overall weakened CPO and low Ti concentrations. DisGBS is therefore interpreted as the main deformation mechanism activated during the last stages of strain localization.
- The textural analysis of quartz domains allows for a deeper evaluation of crystallographic fabrics. From the domains that show well-develop CPOs, dislocation creep deformation mechanisms can be inferred from slip systems, which are also supported by the misorientation angles distributions. Dislocation creep is interpreted as the main mechanism accommodating high-temperature strain in the initial stage of the deformation history.
- Many recrystallized grains on the edges of porphyroclasts tend to inherit the crystallographic orientation of the porphyroclasts, indicating that the crystallographic orientation of parent grains exert a strong control on the CPO evolution of neighbor-daughter, especially, and daughter grains. Therefore, the indication of operation of multiple slip systems for many recrystallized grains can be considered, at least in part, due to the variety in crystallographic orientations of the parent grains.
- The Titanium-in-quartz geothermometry combined with field observations and detailed crystallographic textural analysis can be used to estimate deformation/recrystallization temperatures down to 350 ºC in natural shear zones.
- Ti concentrations are not completely reset during deformation associated with extensive BLG and SGR. This makes the TitaniQ geothermometer a powerful tool for

recording the thermal/tectonic history of quartz over a wide range of temperature conditions.

- BLG and SGR promote only partial re-equilibration to low Ti concentrations, i.e., they are not efficient enough to promote complete resetting. Thus, they allow for a Ti variance that can be related to dynamic recrystallization at different stages of the deformation history.
- The Ti variance occurs under isobaric conditions and suggests that the early stage of crystal-plastic deformation in the Sucuru mylonites occurred at high temperature (>500 to <740 °C), and gradually decreased to lower temperature (>340 to <500 °C). The heat source for the high temperature stage is likely the intrusion of synkinematic late Ediacaran to early Cambrian magmatic bodies.
- The wide range in temperatures, as recorded by TitaniQ geothermometry (>340 to <740 °C), must also have been an important factor contributing to the operation of multiple slip systems (rhomb, basal and prism) through the deformation history, in addition to the variety in crystallographic orientations of the parent grains. In such a thermal deformation setting prism <c> slip associated with dislocation creep might have been activated at early stages of the deformation history.
- The dike orientations, geometry and deformation are compatible with an overall E-W progressive dextral shearing, in which they intruded and crystallized in a NW-SE to NNW-SSE trend (normal to ISA_3), followed by solid-state deformation characterized by the folded geometric pattern at map-scale and by N-S, NNE-SSW and E-W trending mylonitic foliation, which is preferentially localized in their margins, i.e., in the interface between competent dikes and less competent country rocks.

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