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KINEMATICS, RECRYSTALLIZATION MECHANISMS AND AR-AR AGES IN CAL SHEAR ZONE, CURITIBA MICROPLATE, CENTRAL MANTIQUEIRA PROVINCE, BRAZIL

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Abstract - *Mylonites and ultramylonites derived from plastic deformation of gray quartzo-feldspathic rocks and granites are described in the Cal shear zone, western margin of the Curitiba microplate, Central Mantiqueira province. Ultramylonites and mylonites occur along several hundred meters along the São Jorge quarry main front. Mylonite foliation strikes N40E/90, while stretching lineation strike N40/15. Sigmoidal structures, S/C/C' surfaces, mica fish and secondary foliation in quartz ribbons indicate sinistral sense. Quartzo-feldspathic mylonites and leucogranitic mylonites are interlayered in subparallel steep dipping portions forming a conspicuous banding. Quartz recrystallization controlled by grain boundary migration and subgrain rotation suggest temperatures higher than 500 °C in the plastic shear zone. These temperature conditions are coherent with the feldspars recrystallization. The presence of veins of quartz suggests that pressure solution was a subordinated deformation mechanism. Ar-Ar dating of feldspar from ultramylonites yielded the age of 608 Ma for the Cal strike-slip shear zone. A thermotectonic phase attributed to brittle-plastic reactivation during dextral transcurrent shear is thought to have occurred at ca. 553 Ma.*
Keywords: *Central Mantiqueira province, strike-slip, Ar-Ar ages, deformation mechanisms.*

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1. INTRODUCTION

Shear zones correspond to discontinuity surfaces developed along previously existing anisotropic elements such as geological contacts, major lithological layering, folding or shearing macroscopic structures, elongated plutons, or tectonic boundaries (Woodcock and Daly, 1986; Vauchez et al., 1998; Moores and Twiss, 2014). Shear zones have long been studied, mainly from the 1970s on, with significant progress being achieved by authors such as Ramsay and Graham (1970), Harland (1971), Sibson (1977), Coward (1980), Butler (1982), Ramsay and Huber (1983, 1987), Simpson and Schmidt (1983), Sanderson and Marchini (1984), Simpson (1986), Woodcock and Daly (1986), Fossen and Tikoff (1993), Simpson and De Paor (1993), Cobbold et al. (1987), Fossen et al. (1994), Fossen and Tikoff (1998), Stipp et al. (2002), Poblet and Lisle (2011), and Finch et al. (2020).

In Brazil, pioneering studies on shear systems date from the 1980s (Hasui, 1982; Hasui and Costa 1988; Hasui and Mioto 1992; Ebert and Hasui 1998). Particularly in the state of Paraná, the first studies to define thrust-and-fold and strike-slip systems were carried out by Fiori (1985, 1987, 1990, 1992, 1993) and Fiori and Gaspar (1993).

In the Paranaense shield, central Mantiqueira province, regional strike-slip shear zones and a major thrust-and-fold system control the classic tectonic evolution that characterizes, especially in the Apiaí terrane, the Neoproterozoic orogenic system (Fiori 1992, 1993; Campanha and Sadowski 1999). Strike-slip shear zones as extensive as about a hundred kilometers in central Mantiqueira province are the Lancinha-Cubatão-Além Paraíba, Ribeira, Morro Agudo, Itapirapuã, and Putunã shear zones (Fiori, 1985; Campanha and Sadowski, 1999). The Lancinha-Cubatão-Além Paraíba shear zone extends for 1,200 km between the states of Espírito Santo and Paraná. In Paraná, this major lineament is covered by Phanerozoic rocks of the Paraná basin (Zalán 1986; Sadowski and Montidome, 1987). However a dextral shear sense is broadly defined in some such strike-slip shear zones (Fiori 1985 a, b; Soares 1987; Fassbinder 1990), authors have presented evidence for sinistral criteria to some transcurrent lineaments (Faleiros et al., 2011; Zanella and Cury, 2017; Conte et al., 2020; Dehler et al., 2007; Machado et al. 2007). Fassbinder (2000) identifies sinistral shear criteria in the Cal shear zone, which are discussed in the present paper. Despite the very well-constrained structural evolution of the Apiaí terrane, the tectonic structures involved are still poorly stablished in terms of age.

In the state of Paraná, studying plastic deformation of transcurrent shear zones is rendered difficult by the scarcity of outcrops. Near the western border of Curitiba microplate (Basei et al., 1992) in central Mantiqueira province , however, good exposure of the Cal strike-slip shear zone makes São Jorge quarry (25°28'21''S, 49°37'20'W) an excellent site to investigate the effects of plastic deformation on quartzo-felspathic rocks. Continuous rock exposure along the approximately 400-meter wide outcrop allows for a remarkably good 3D viewing of deformation features. This paper presents structures found in the Cal shear zone at different observation scales, and also whole-rock and mineral Ar-Ar ages for mylonitic rocks that form it. Based on microscopic features present, a discussion is put forward on the deformation/recrystallization mechanisms operating in the Cal shear zone.

2. GEOLOGICAL SETTING

Basement Archean-Paleoproterozoic gneisses and migmatites, Statherian granitic augen gneisses, Mesoproterozoic and Neoproterozoic metamorphic supracrustal series, and several Neoproterozoic granites form the Apiaí belt.

In the Curitiba microplate, gneisses and migmatites of the Atuba complex form the basement unit. Shrimp U-Pb zircon indicate

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Paleoproterozoic ages and inherited Archean cores (Siga Jr. et al., 2011; Sato et al., 2003). Siga Jr. et al., (1995) dated migmatites belonging to the Atuba complex. Biotite and amphibole K-Ar ages are vary from 611 ± 19 Ma to 566 ± 15 Ma. Whole-rock and minerals Rb-Sr ages vary from 618 Ma ± 48 Ma to 588 ± 27 Ma. As pointed out by these authors, the strong dispersion of Rb-Sr ages is due to isotopic disequilibrium.

Antiformal granitic augen gneiss nuclei (Althoff and Fiori, 1991) are surrounded by Mesoproterozoic metamorphic supracrustal series. U-Pb on zircon ages of these augen gneisses range from 1.77 to 1.75 Ga (Cury et al., 2002; Siga Jr. et al., 2007). These rocks were deformed by Putunã transcurrent and Cal shear zones (Fassbinder 2000, Faleiros et al., 2011).

Mesoproterozoic volcano-sedimentary sequences occur to the north of the Lancinha shear zone. These series are composed of phyllites, schists, marbles, marls, quartzites and amphibolites (Marini et al., 1967) of the Perau, Betara, Votuverava and Água Clara formations. U-Pb dating on zircon from amphibolites indicates ages from 1.50 Ga to 1.45 Ga (Weber et al., 2004; Siga Jr et al., 2011).

In contact with basement rocks to the south of the Lancinha shear zone are low-grade metapelites, metasandstones, metarhythmites and metadolomites of the Capiru formation (Bigarella and Salamuni, 1956) whose deposition is attributed to passive margin processes. A Neproterozoic age has been established based on stromatolites (Sallun Filho et al., 2010).

The Mesoproterozoic and the Neoproterozoic supracrustal sequences were regionally affected by a thrust-and-fold system and by an NE-SW strike-slip system (Fiori, 1992, 1993, 1985; Campanha and Sadowski, 1999). Lancinha, Morro Agudo, Itapirapuã and Ribeira are examples of strike-slip shear zones (Fiori, 1992; Faleiros et al., 2010). R and R' faults, antithetic faults, en-echelon folds belonging to the Apiaí fold system are recognized (Hasui et al., 1975; Soares et al., 1987; Fiori, 1990; 1992; 1993b). According to various authors, these strike-slip shear zones show dextral movement (Fiori, 1985; Campanha and Sadowski, 1999). Sinistral shear sense is identified in the Lancinha and Putunã shear zones (Conte et al., 2020; Faleiros et al., 2010, 2011). Ages around 609 Ma and 560 Ma were determined by Ar-Ar dating to the Putunã shear zone (Faleiros et al., 2011).

The granite bodies are of diverse age and geodynamic significance. In the western parts of the Paranaense shield, two granite batholiths stand out, the Cunhaporanga and Três Córregos granite complexes. Both suites, aged at ca. 630 Ma, are attributed to continental arc magmatism (Prazeres Filho et al., 2003b). Between Morro Agudo and Lancinha shear zones, elongated granite bodies are described: Passa Três, Cerne, Piedade, Morro Grande and Varginha. The U-Pb zircon ages of these granite bodies range from 612 Ma to 564 Ma (Prazeres Filho et al. 2003 a, b; Cury et al., 2008; Dressel et al., 2018). Ar-Ar ages of 527 ± 10 Ma and 510 ± 32 Ma were obtained from sericite and pyrite from the Passa Três granite, respectively (Picanço, 2000).

Several A-type granites and syenites from the Serra da Graciosa Suite have been studied to the east of the Curitiba microplate (Gualda and Vlach, 2007). U-Pb and ID-TIMS on zircon ages of 580 Ma were determined for these rocks by Vlach et al. (2011). Transitional volcano-sedimentary basins (Camarinha, Castro and Guaratubinha) (Fuck et al., 1967) were dated to 593 Ma (Barbosa, 2018).

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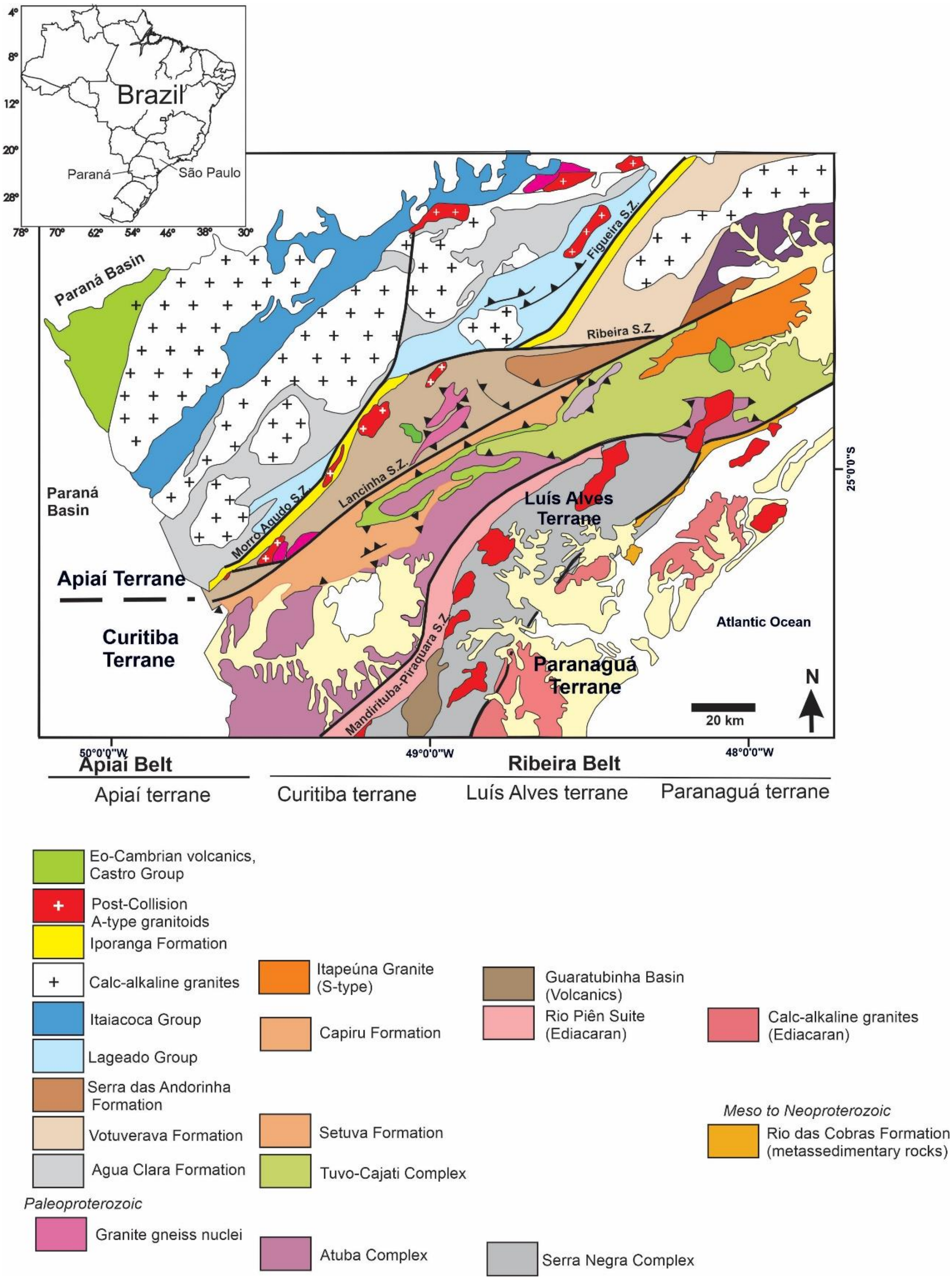

Figure 1 - A) Location map. B) Geological map of the Paranaense shield, Central Mantiqueira province, south Brazil (adapted from Faleiros et al. 2011)

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3. MYLONITES AND ULTRAMYLONITES OF THE CAL SHEAR ZONE

The main front of São Jorge quarry is 400 m long and 50 m high. Its most prominent planar structure is a steep compositional layering defined by alternating pink levels and dark gray domains (Figures 2a,b). The pink levels are formed by meter- to decimeter tabular or slightly boudinated hololeucocratic granite concordant to the foliation. The dark gray domains are quartz-feldspathic, containing approximately 10% of biotite. A previous foliation affected by open vertical folds is very locally recognized in the dark grey portions. Most likely, preexisting gneisses form these dark-gray domains, which are almost completely transposed. Both domains are aphanitic and present a strong mylonitic foliation striking N40E/subvertical (Figures 2 a, b, d). This main planar structure is classified as a C foliation.

In the steep mylonitic foliation, a stretching lineation plunges N30E/15 (Figure 2 c) attests for the strike-slip nature of the major structure. In some places, oblique foliation indicates to the presence of the S/C pair. Locally, less intensely deformed rocks exhibit K-feldspar porphyroclasts in augen fabric.

Meter-long and centimeter-wide veins of quartz parallel to the mylonitic foliation may be locally found. A strong plastic deformation also affected these veins of quartz.

Asymmetric foliation planes oblique to the C surface occur in some places, corresponding to S and C' foliations that indicate sinistral shear sense (Figure 3a, b). The strong widespread deformation caused the parallelism of these planar structures along the C direction. Other kinematic criteria are the asymmetric sigma porphyroclasts of K-feldspar and the sigmoid-shaped veins of quartz oblique to the C foliation. Microscopically, the spatial configuration of these surfaces defines the sinistral shear sense of the mylonitic foliation. The same sense was observed in neighbor quartzite mylonites in the same structural lineament (Cabrita et al., 2017).

Parallel to the C mylonitic foliation, five- to ten-centimeter-wide biotite-rich levels are observed. Fault planes parallel to the mylonite foliation cut some meter-wide surfaces, with low-angle striation marks developed under brittle conditions and steps indicative of dextral sense.

Very-fine grained neoblasts of quartz, microcline, plagioclase and biotite (±10%) can be observed on thin mylonite and ultramylonite sections. The dark color of the ultramylonite is not due a high amount of ferromagnesian minerals, but to tectonic grain-size reduction, as classically observed in strongly recrystallized tectonites. Quartz may occur in the matrix or as elongated aggregates of very fine neoblasts. Small, rare quartz porphyroclasts are surrounded by fine neoblasts, forming a mantle-and-core texture. Neighbor quartz grains may exhibit lobate boundaries. The presence of mantle-and-core quartz suggests subgrain rotation, while lobate margins indicate grain boundary migration. According to Stipp et al. (2000), these mechanisms point to temperatures between 400 °C and 500 °C, and up to 500 °C, respectively. Such temperatures are in agreement with the conditions suggested by the widespread dynamic recrystallization of feldspar (cf. Tulllis, 1983; Olsen and Kohlstedt, 1985; Passchier and Trouw, 1996; Blenkinsop, 2008).

On thin sections, the biotite-enriched levels (Figure 4a) are characterized by the presence of medium-to coarse-grained biotite crystals displaying strong preferred orientation, wavy extinction and kink bands. Partial recrystallization of biotite resulted in some trails of finer new grains along larger crystals (Figure 3b).

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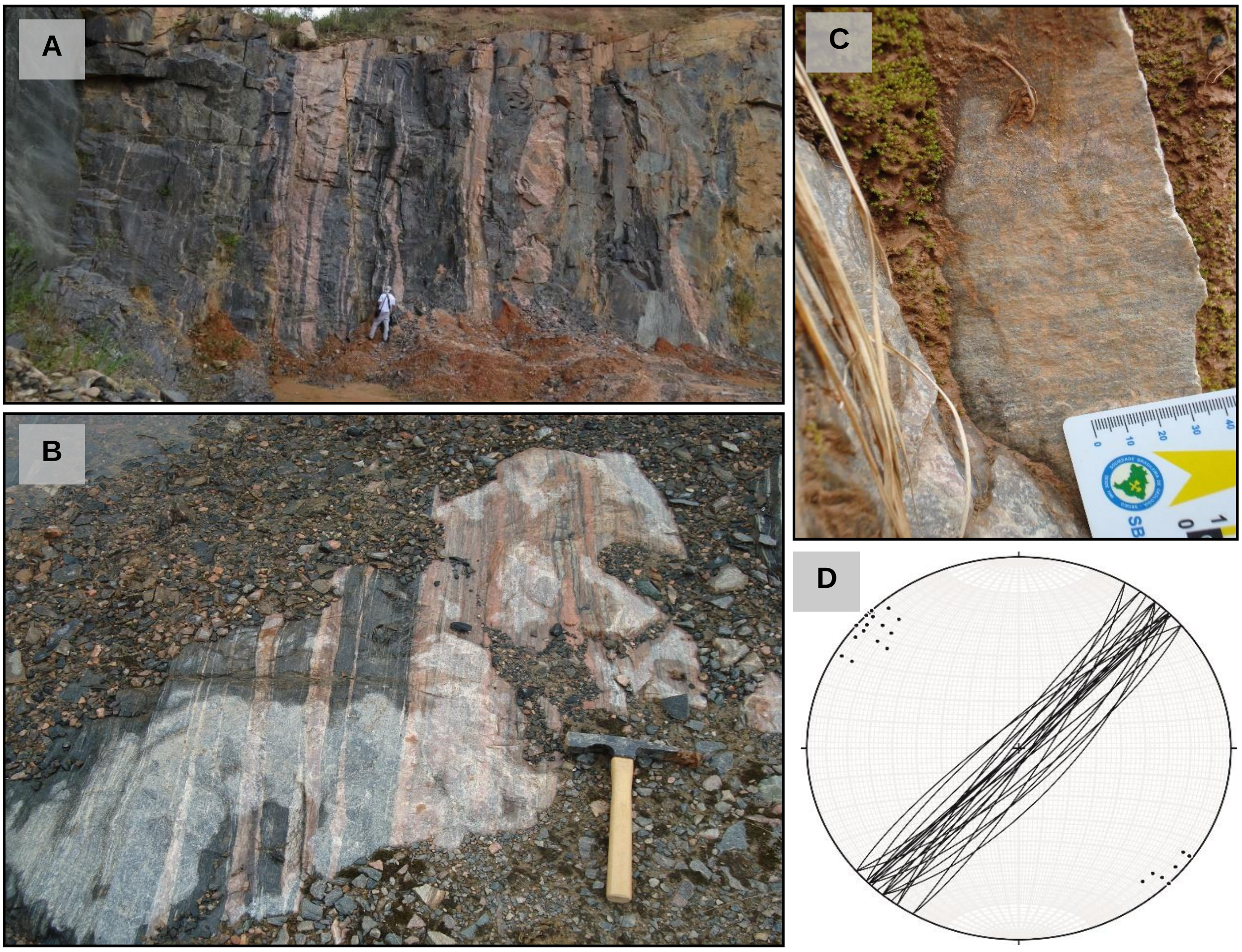

Figure 2 - Ultramylonites from the Cal shear zone (São Jorge carry), Curitiba Microplate, Central Mantiqueira Province. A) Ultramylonites derived from gneisses (grey colored) and from leucogranites (rose colored). B) Compositional banding related to the plastic deformation. C) Low-plunging stretching lineation. D) Stereogram with data of mylonitic foliation.

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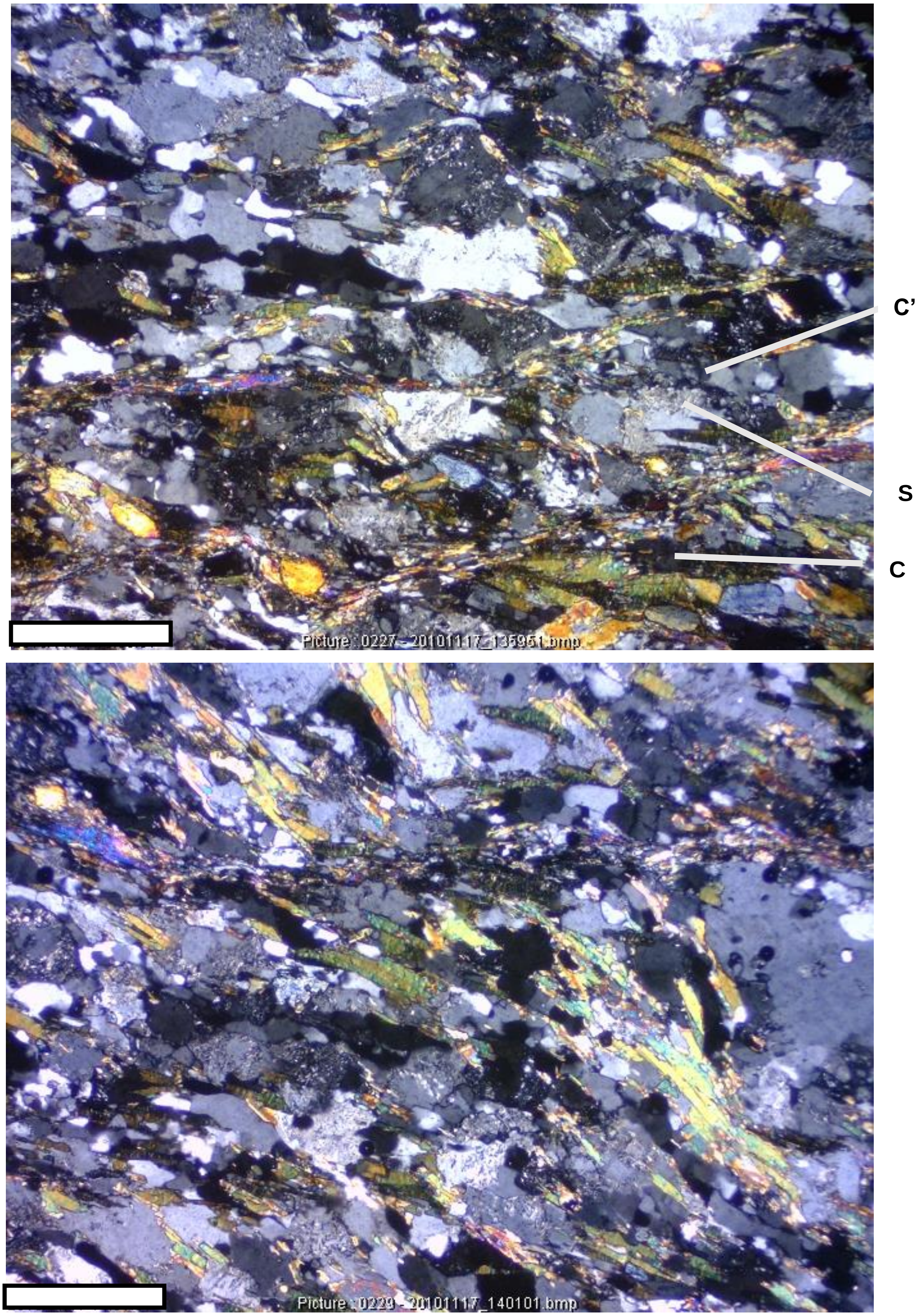

Figure 3 - A-B) Photomicrographs (polarized light) of mylonites from the São Jorge quarry, Curitiba Microplate. The section is parallel to stretching lineation and perpendicular to the foliation. Notice the S, C and C' surfaces indicating sinistral shear sense. Scale bar = 1 mm

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4. Ar-Ar AGES

Samples of dark grey ultramylonite (sample EF-25-2) and biotite crystals (EF-25-5) from a biotite-enriched level parallel to the mylonitic foliation were chosen to be dated by the Ar-Ar method. The analyses were carried at the Argon Geochronology Laboratory of the University of Queensland. The analytical procedures employed are described in Vasconcelos et al. (2002).

Two step-heating profiles (7294-01 and 7294-02) (whole-rock) were obtained for the ultramylonite, neither one yielding plateau ages according to the definition of Fleck (1977). In two released 39Ar cumulative percent vs. apparent age diagrams, ages obtained range continuously from 563 ± 4 Ma to 529.1 ± 3.0 Ma to (Figure 5a,b; Table 1). Both step-heating profiles show perturbation, with varying K/Ca ratios suggesting various phases of different compositions, and slightly different ages. The phases may also record variable 40Ar and/or K loss due to alteration or post-formation thermal effects. The age probability plot shows a continuous range of ages, from a minimum of 529.1 ± 3.0 Ma to a maximum of 597 ± 16 Ma (Table 1).The 40Ar loss is due to thermal effects, the data indicate 529 Ma as the probable minimum age of the thermal event. A usable isochron plot for this dataset could not be achieved because both steps cluster together on the isochron plot. This suggests that the sample may have been partially re-set by some heating event younger than ca. 530 Ma, and that the rock had a pre-reset age of at least ca. 600 Ma.

For the biotite crystals (EF-25-5), only aliquot 7295-01 produced a plateau age of 608 ± 4 Ma (Figure 6a) in accordance with the definition of Fleck (1977). With the exception of a single heating step, step heating profile 7295-02 records ages that are significantly younger than the plateau age obtained for grain 7295-01. As the biotite underwent some degree of recrystallization, is likely that the step heating profile of grain 7295-02 is perturbed by variable 40Ar loss due to post-formation thermal effects and partial recrystallization. The age probability diagrams show that the single older heating step from grain 7295-02 corresponds, within error, to the older plateau age of 608 ± 4 Ma for grain 7295-01. The age probability diagram of the plateau steps for Sample 7295-01 combined with the old step for Sample 7295-02 results in a maximum probability peak at 606 Ma, defining a mean-weighted age of 607 ± 4 Ma that is compatible at the 2-sigma level with the age given by the plateau. A usable isochron plot for this dataset could not be achieved because all steps cluster together on the isochron plot. The maximum age of the thermal event can be considered equivalent to the youngest step heating age recorded for the Sample or 552 ± 11 Ma (Figure 6b). Due to recrystallization of the at least some of the biotite in the sample, the plateau age of 608 ± 4 Ma is regarded as possibly corresponding only to the maximum age of the biotite. The minimum age of the recrystallization thermal event is ca. 550 Ma.

The maximum Ar-Ar age of 608 ± 4 Ma falls very close to the U-Pb on zircon one obtained by Dressel et al. (2018) in the Passa Três granite. Plastic strike-slip would seem to be coeval to granite magmatism at the Apiaí terrane. At São Jorge quarry, deformed leucogranites could exemplify magma emplacement during plastic shear zone development. The maximum Ar-Ar age obtained in the Cal shear zone is also very similar to the Ar-Ar age of 610 Ma determined in the sinistral Putunã shear zone (Faleiros et al., 2011) to the north of the Cal strike-slip shear zone.

The younger ages (550 Ma) obtained for Cal shear zone are similar to the Ar-Ar ones from white micas from the mineralized Passa Três granite from 573 Ma to 554 Ma (Dressel et al., 2018). These authors attribute such ages to reverse reactivation of faults. Similar younger ages were also determined in the Putunã shear zone (Faleiros et al., 2011).

To the northeast, in the Serra do Azeite shear zone, Ar-Ar ages between 600 Ma and 570

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Ma were obtained by Machado et al. (2007) in hornblende and muscovite, respectively. The former ages were obtained in orthogneisses and are considered to record transpressional tectonics. The same authors attribute the latter age to regional metamorphic cooling.

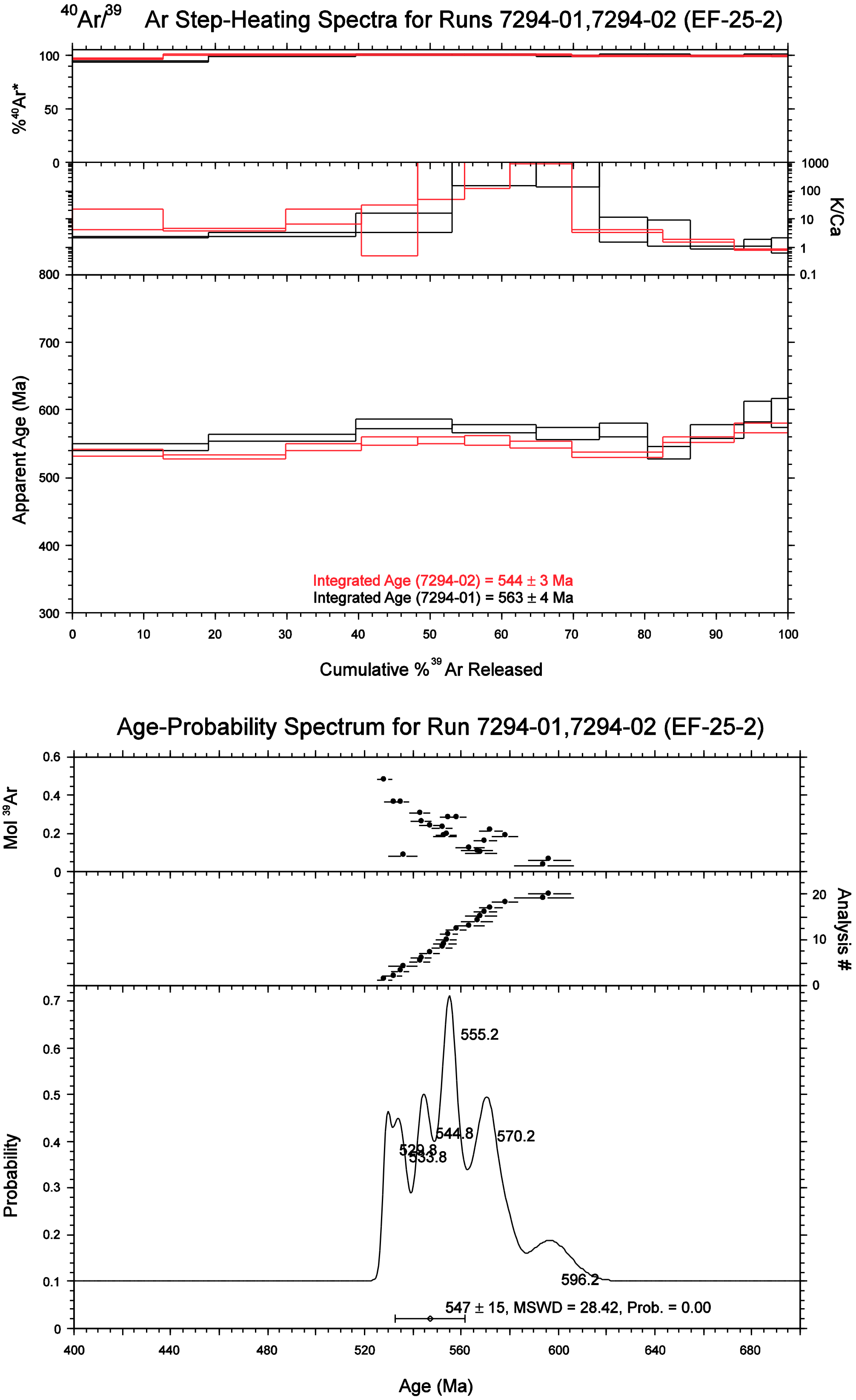

Figure 4 - A) Cumulative % 39Ar released vs. Age diagram and B) ideogram Ar-Ar age vs. probability of quartz-feldspathic ultramylonite (whole-rock) from the Cal shear zone, Curitiba Microplate, Central Mantiqueira Province.

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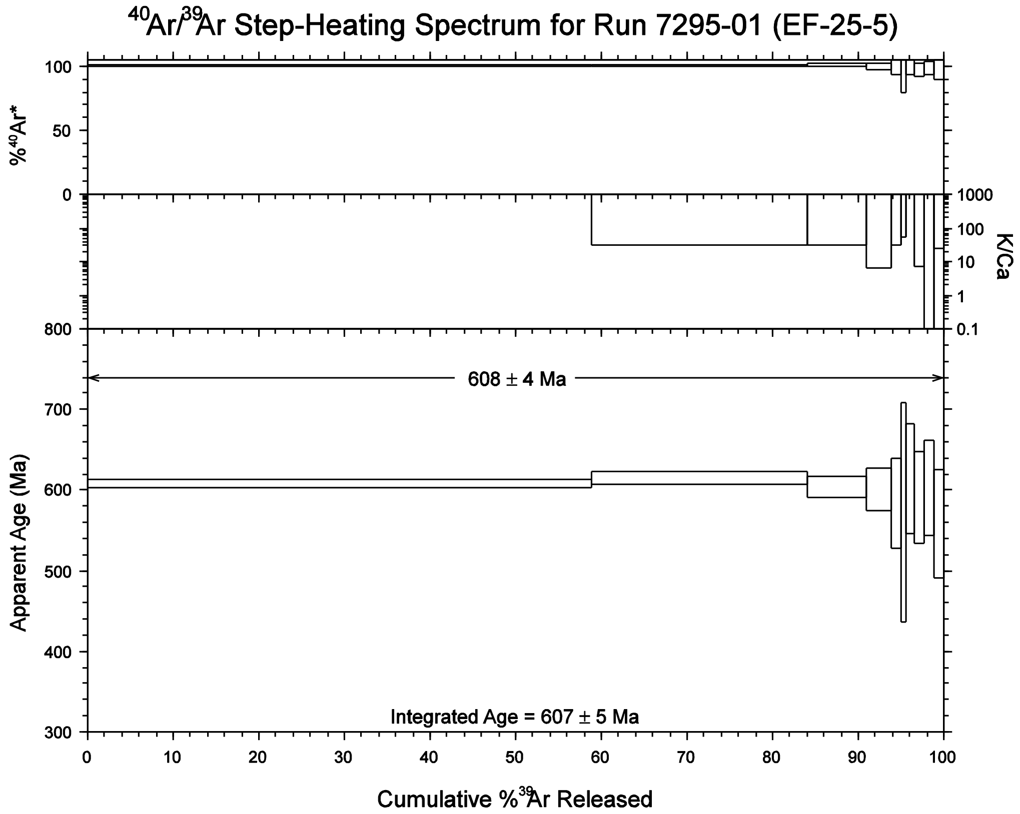

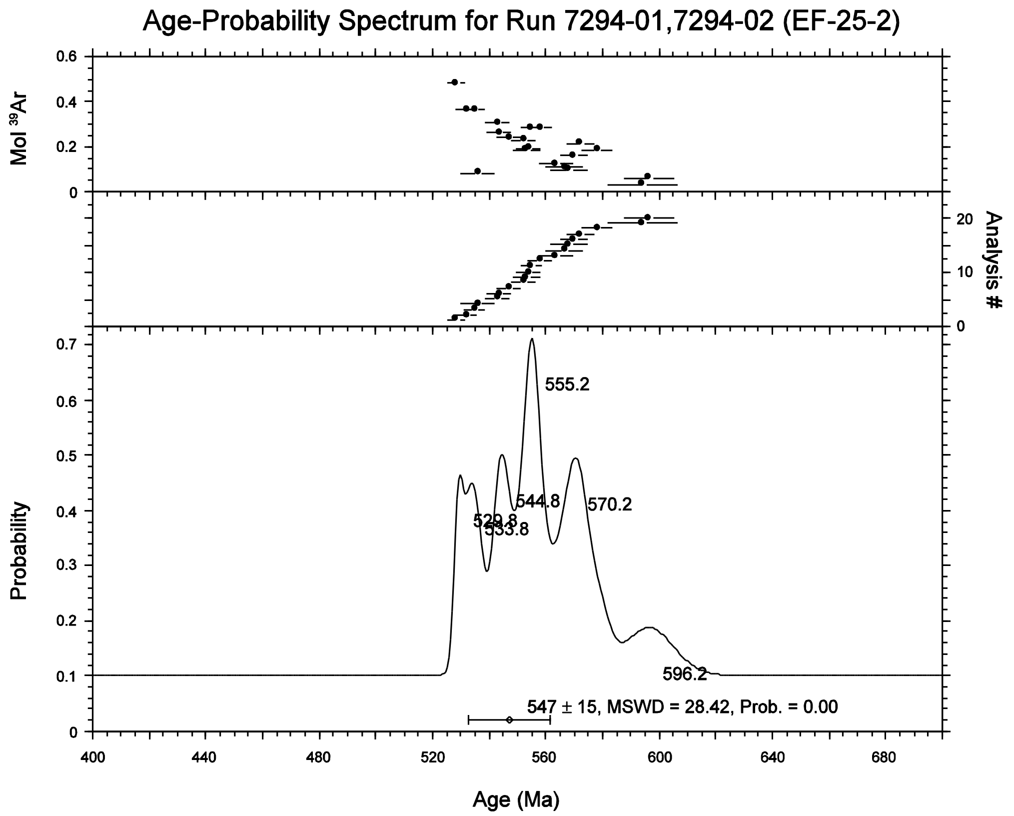

Figure 5 - A) Cumulative % 39Ar released vs. apparent age diagram. B) ideogram Ar-Ar age vs. probability of biotite-rich levels parallel to the mylonitic foliation from the Cal shear zone, Curitiba Microplate, Central Mantiqueira Province.

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Table 1 - Ar-Ar data of ultramylonite (whole-rock) and biotite-enriched levels from the Cal shear zone, Curitiba Microplate, South Brazil.

Run ID	Sample	$^{37}Ar/^{39}Ar$	$^{38}Ar/^{39}Ar$	$^{40}Ar/^{39}Ar$	$^{40}Ar^{*}/^{39}Ar$	$\%Ar^{40*}$	Age (Ma)
7294-01[a]	EF-25-2	0.244	0.01702	106.55	100.25	94.08	544.1
7294-01B	EF-25-2	0.192	0.01285	103.82	103.31	99.5	558.4
7294-01C	EF-25-2	0.057	0.01338	108.14	107.68	99.58	578.5
7294-01D	EF-25-2	0.014	0.01274	106.19	105.98	99.8	570.7
7294-01E	EF-25-2	0.017	0.01313	105.86	104.58	98.79	564.2
7294-01F	EF-25-2	0.082	0.0152	105.5	105.5	100.03	568.7
7294-01G	EF-25-2	0.106	0.0121	99.2	98.6	99.41	536.4
7294-01H	EF-25-2	0.552	0.0174	106.5	105.2	98.68	566.9
7294-01I	EF-25-2	0.363	0.0164	111.9	111.7	99.79	596.8
7294-01J	EF-25-2	0.41	0.0158	112.1	111.3	99.27	595
7294-02A	EF-25-2	0.041	0.01434	102.19	98.44	96.33	535.6
7294-02B	EF-25-2	0.1381	0.01214	97.37	97.07	99.68	529.1
7294-02C	EF-25-2	0.039	0.01277	100.21	100.14	99.93	543.5
7294-02D	EF-25-2	0.035	0.0117	102.38	102.08	99.7	552.6
7294-02E	EF-25-2	0.027	0.01157	102.47	102.47	100	554.4
7294-02F	EF-25-2	0.016	0.01252	102.79	102.35	99.57	553.8
7294-02G	EF-25-2	0.004	0.01294	101.35	100.96	99.62	547.4
7294-02H	EF-25-2	0.151	0.01283	98.31	97.75	99.42	532.3
7294-02I	EF-25-2	0.328	0.01206	103.25	102.71	99.45	555.5
7294-02J	EF-25-2	0.647	0.01174	107.16	106.43	99.27	572.8
7295-01A	EF-25-5	-0.0152	0.01277	114.07	113.74	99.71	606.2
7295-01B	EF-25-5	-0.015	0.01208	115.81	115.46	99.7	614
7295-01C	EF-25-5	-0.034	0.011	112.8	113.1	100.32	603.5
7295-01D	EF-25-5	-0.1	0.0119	112.6	112.2	99.6	599
7295-01E	EF-25-5	-0.09	0.0052	109.4	108.4	99.1	582
7295-01F	EF-25-5	0.12	-0.038	114	106	93.3	572
7295-01G	EF-25-5	-0.79	-0.0212	115.7	115.4	99.7	613
7295-01H	EF-25-5	-0.17	-0.0086	114.1	110.2	96.6	590
7295-01I	EF-25-5	-0.55	-0.0202	115.1	112.7	98	601
7295-01J	EF-25-5	-0.11	0.0065	106.1	103.2	97.3	558
7295-02A	EF-25-5	0.0223	0.0126	107.11	106.63	99.56	573.7
7295-02B	EF-25-5	0.3424	0.01179	113.96	113.61	99.67	605.6
7295-02C	EF-25-5	-0.021	0.01132	105.9	105.56	99.67	568.7
7295-02D	EF-25-5	-0.058	0.0126	104.73	104.3	99.63	563.1
7295-02E	EF-25-5	-0.035	0.0114	105.1	104.3	99.25	563.1
7295-02F	EF-25-5	-0.084	0.0092	106.9	107.8	100.85	579.2
7295-02G	EF-25-5	-0.15	0.0072	102.8	104.7	101.9	565
7295-02H	EF-25-5	0.1	-0.0013	101.8	102.4	100.57	554
7295-02I	EF-25-5	1.06	0.014	105	106.3	101.1	572
7295-02J	EF-25-5	6.21	0.0087	100.4	101.8	101.02	551.5

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5. DISCUSSION AND CONCLUSIONS

Located next to the Curitiba Microplate border within the Lancinha system and oriented to N40E, the Cal shear zone was subject to important strike-slip tectonics, being considered by several authors as a suture zone. The hectometric width of this mylonite corridor and the predominance of quartzo-feldspathic ultramylonites testify the relatively homogeneous plastic nature of its deformation and the moderate to high temperature conditions under which it developed. The widespread dynamic recrystallization of feldspars indicates shearing under temperatures higher than 500 °C. Subgrain rotation and grain boundary migration mechanisms predominated during dynamic recrystallization. The presence of quartz veins that are concordant to the foliation suggests that some pressure solution may have acted as a subsidiary mechanism. Some biotite neoblasts were formed by planar plane slip. Several shear sense criteria point to sinistral movement across the shear zone. As intracrystalline deformation features on quartz and feldspars seem to be erased, despite the strong preferred orientation, initial static recrystallization would have played a role. Therefore, most tectonites that occur in São Jorge quarry are in fact blastomylonites. This is coherent with the moderate to high temperatures estimated to have been reached during shearing. A point to be clarified is whether the moderate to high temperatures reached by this mylonite corridor are due to the local crustal level or have been increased by the emplacement of leucogranite bodies, the second hypothesis seeming to be the more plausible one.

The presence of several levels of hololeucocratic pinky mylonites/ultramylonites parallel to dark Grey mylonites/ultramylonites could preliminary suggest that the hololeucocratic granites are coeval with the strike-slip movement.

Ar-Ar dating indicates an oldest age of 608 ± 4 Ma, that could be attributed to main plastic deformation during the Cal shear zone development. Continuous Ar-A ages from 563 ± 4 Ma to 529.1 ± 3.0 Ma seem to record reactivation phases, most probably at 552 ± 11 Ma.

Comparing the Ar-Ar ages presented above with several K-Ar ages obtained by other authors elsewhere in the Curitiba microplate, it can admitted that the Cal strike-slip shear zone was coeval to granitogenesis, migmatization of the Atuba complex to the east of the plate and magmatic arc development to the southeast at ca. 610 Ma.

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