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Petrographic characterization and genetic implications of pegmatites from São José da Safira (MG), Eastern Brazilian Pegmatite Province

Caracterização petrográfica e implicações genéticas de pegmatitos de São José da Safira (MG), Província Pegmatítica Oriental do Brasil

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Abstract: The São José da Safira Pegmatite District belongs to the Eastern Brazilian Pegmatite Province and is situated within the Araçuaí Orogen. In addition to their economic importance related to the production of gem-quality minerals and enrichment in rare elements, the pegmatites of this district also exhibit well-defined internal zoning, which make them valuable natural laboratories for investigating the origin and evolution of pegmatite-forming melts. This study presents a detailed petrographic characterization of three pegmatites from this district, located in the northern (Mutuca mine), central (Pederneira mine) and southern (Golconda mine) sectors. These bodies are free of regional deformation and metamorphism. They are mineralogically and texturally similar to one another, exhibiting complex zoning composed of border (Kfs+Qz, granular texture), wall (Kfs+Qz±Pl±Ms±Tur, graphic texture and unidirectional growth toward the core), intermediate (Kfs+Ms+Qz+Pl±Spd, saccharoidal texture and unidirectional growth toward the core) and core zones (Qz±Spd, massive texture), in addition to secondary albitization zones (Ab±Lep±Tur) and abundant miarolitic cavities. Based on their mineralogical and geochemical composition, these pegmatites were classified as Miarolitic, LCT, Group 1 and RMG. Field, mineralogical and textural evidences suggest that these pegmatites were formed through magmatic fractionation of the G4 supersuite during the late- to post-collisional stages the Araçuaí Orogen evolution.

Keywords: Mineralogical and textural zoning; Pegmatite classification; Pegmatite genesis.

Resumo: O Distrito Pegmatítico de São José da Safira integra a Província Pegmatítica Oriental do Brasil e está inserido no Orógeno Araçuaí. Além da importância econômica associada à produção de minerais gema e ao enriquecimento em elementos raros, os pegmatitos deste distrito ainda exibem zonamento interno bem definido, o que os torna laboratórios naturais ideais para a investigação da origem e evolução de *melts* pegmatíticos. Este estudo apresenta uma caracterização petrográfica de detalhe de três pegmatitos deste distrito, situados nos setores norte (mina Mutuca), central (mina Pederneira) e sul (mina Golconda). Esses corpos são livres de deformação e metamorfismo regionais. São mineralógica e texturalmente semelhantes entre si, exibindo zonamento complexo formado pelas zonas de contato (Kfs+Qz, textura granular), parede (Kfs+Qz±Pl±Ms±Tur, textura gráfica e crescimento unidirecional em direção ao núcleo), intermédia (Kfs+Ms+Qz+Pl±Spd, textura sacaroidal e crescimento unidirecional em direção ao núcleo) e núcleo (Qz±Spd, textura maciça), além de zonas secundárias de albitização (Ab±Lep±Tur) e abundantes cavidades miarolíticas. Com base na composição mineralógica e geoquímica, foram classificados como Miarolítico, LCT, Grupo 1 e RMG. Evidências de campo, mineralógicas e texturais sugerem que esses pegmatitos foram formados por fracionamento magmático a partir da supersuíte G4 durante os estágios tardi- a pós-colisionais de evolução do Orógeno Araçuaí.

Palavras-chave: Zonamento mineralógico e textural; Classificação de pegmatitos; Gênese de pegmatitos.

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1. Introduction

Pegmatites have attracted increasing scientific attention, mainly due to their potential as lithium deposits, a rare element with growing global demand in the electronics industry (AMBROSE and KENDALL, 2020). These rocks may also represent important sources of other rare and strategic elements for the technological sector, including Be, Cs, Ga, Nb, Ta, Ti, Y and REE, as well as industrial minerals (e.g., feldspar, mica and quartz) and gem minerals (e.g., beryl, garnet and tourmaline) (LONDON, 2018; SIMMONS *et al*., 2012).

Pegmatites are igneous rocks, predominantly granitic, and characterized by coarse to very coarse-grained textures with a wide granulometric heterogeneity. These bodies may be either unzoned or zoned. In zoned pegmatites, granulometric and mineralogical variations define an internal structure composed of primary zones (border, wall, intermediate and core) and, in some cases, secondary replacement zones (LONDON, 2008, 2018). According to the main petrogenetic models, pegmatitic melts may be generated by anatexis of metasedimentary rocks or by magmatic fractionation of parental granitic plutons (LONDON, 2008; SIMMONS, 2007; SIMMONS and WEBBER, 2008). The origin and evolution of these bodies can be investigated through the identification of their mineral assemblages and textural features, followed by detailed mineral chemical and isotopic analyses (e.g., ČERNÝ *et al.,* 2003; LONDON, 2008).

In this context, the São José da Safira Pegmatite District (SJSPD) is part of the Eastern Brazilian Pegmatite Province (EBPP), which extends over an area of c. 150,000km^2 in southeastern Brazil and represents one of the largest and most economically important pegmatite provinces in the world (PEDROSA-SOARES *et al*. 2011, 2025). The pegmatites of the SJSPD are notable for their production of tourmaline, beryl and exotic specimens of high gem-quality (MORTEANI *et al.,* 2000), as well as for their Li enrichment evidenced by the occurrence of spodumene and lepidolite in significant amounts (PEDROSA-SOARES *et al.,* 2011, 2025). In addition to their economic importance, the well-defined internal zoning of these pegmatites makes them valuable natural laboratories for investigating the origin and evolution of pegmatite-forming melts and for applying the classification systems of Černý (1991), Černý and Ercit (2005) and Wise *et al*. (2022), which provide robust support for petrogenetic interpretations.

Despite their economic and scientific relevance, detailed petrographic characterization of the pegmatites of the SJSPD, particularly regarding their mineral assemblages, textural features and possible petrogenetic models, remains limited.

Based on the above, this study presents a macro- and microscopic petrographic characterization, combined with SEM-EDS mineral chemical analyses, of three pegmatites from the SJSPD: one in the northern sector (Mutuca mine), another in the central sector (Dilo/Novo Dilo dyke – Pederneira mine) and a third in the southern sector (Golconda mine). These bodies were selected due to their well-developed internal zoning, excellent exposure in mine galleries and economic relevance as sources of gem minerals. The petrographic data was integrated with pegmatite classification systems and genetic interpretations to address the following questions: i) which mineral assemblages and textural features occur throughout the internal zones of these pegmatites? and ii) what are the most likely petrogenetic model and source responsible for the formation of these bodies?

2. Geological setting

2.1. Eastern Brazilian Pegmatite Province (EBPP)

The EBPP comprises a swarm of granitic–pegmatitic intrusions that host economically significant deposits of rare elements, such as Be, Li, Nb and Ta, as well as a wide variety of gem minerals (MORTEANI *et al.,* 2000; PEDROSA-

SOARES *et al.,* 2011). Based on their petrogenetic model, crystallization age, parental granite or source rock type and P-T metamorphic conditions of the country unit, these intrusions are grouped into 12 pegmatite districts. Collectively, they represent the magmatic arc of the Araçuaí Orogen (PEDROSA-SOARES *et al*. 2011, 2025) (Figure 1).

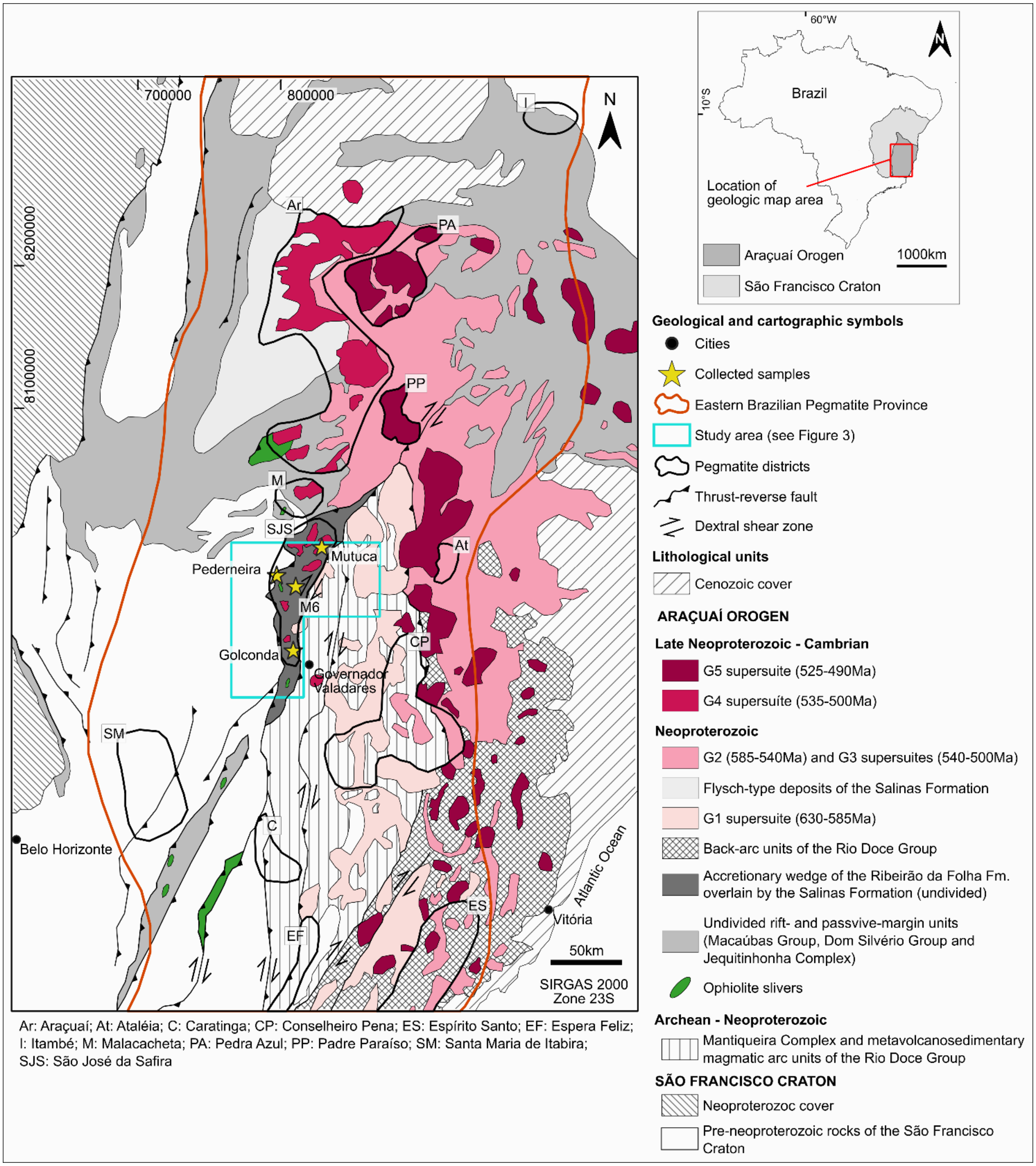


Figure 1 – Simplified geological map of the Araçuaí Orogen highlighting the G1 to G5 supersuites.

Source: Pedrosa-Soares et al. (2011, 2025) and Peixoto et al. (2015).

The magmatic arc of the Araçuaí Orogen was developed within a partially confined active continental-margin orogenic system (ALKMIM *et al*., 2006; PEDROSA-SOARES *et al*., 2007, 2011). Its origin and evolution are related to the Neoproterozoic-Cambrian amalgamation of the western sector of the Gondwana Supercontinent during the Brasiliano Orogeny (630-490Ma; PEDROSA-SOARES *et al*., 2025). A remarkable feature of this orogen is the voluminous emplacement of granitic-pegmatitic intrusions that compose de EBPP and record the pre- to post-collisional stages of the tectonic evolution of this orogen. These intrusions are grouped into five supersuites: G1 (pre-collisional, 630-585 Ma), G2 (syn-collisional, 585-540 Ma), G3 (late- to post-collisional, 540-500 Ma), G4 (late- to post-collisional, 535-500 Ma) and G5 (post-collisional, 525-490 Ma) (PEDROSA-SOARES *et al*., 2001, 2007, 2011, 2025), as summarized in Figure 2.

Supersuite (U-Pb ages)	Lithotype	Litochemistry	Genetic type	Tectonic stage	Interpretation
G1 (630-585Ma)	mostly tonalite to granodiorite, minor diorite to gabbronorite with biotite, amphibole and/or pyroxene	metaluminous to slightly peraluminous, magnesian, calcic to calc-alkaline, medium- to high-K	mostly peraluminous I-type, minor peraluminous I-type	pre-collisional to early collisional	subduction of oceanic lithosphere with formation of a magmatic arc in an active continental margin (Rio Doce magmatic arc), commonly enriched in meso- to melanocratic enclaves
G2 (585-540Ma)	mostly biotite-garnet syenogranite to alkali feldspar granite, minor monzogranite to tonalite rich in garnet, and garnet-two-mica granite, locally with sillimanite	peraluminous, calc-alkaline a sub-alkalic (K>Na)	mostly S-type, minor peraluminous I-type	syn-colisional (late pre-collisional to late collisional)	partial melting of Rio Doce Group metasedimentary units during crustal thickening and shortening, containing restites and xenoliths of metasedimentary units
G3 (540-500Ma)	alkali feldspar granite to syenogranite with cordierite and/or garnet, poor to free biotite	peraluminous, sub-alkalic (K>Na)	S-type	late collisional to post-collisional	autochtonous partial melting of G2 superusite granites
G4 (535-500Ma)	syenogranites (leucogranite to two-mica granite, commonly with albite-muscovite or tourmaline, and pegmatoid granites at the top)	peraluminous, sub-alcalic (K>Na) to alcalic (Na>K)	S-type	late to post-collisional	allochthonous partial melting of G2 supersuite granites
G5 (525-490Ma)	alkali feldspar granite to granodiorite, minor charnockite with orthopyroxene, norite and enderbite	metaluminous to slightly peraluminous, high K and Fe, calc-alkaline	A-type and I-type	post-colisional	partial melting of the lower continental crust associated with manlte contributions, showing magma mingling and mixing, with meso- to melanocratic microgranular enclaves

Figure 2 – Main characteristics of the G1 to G5 supersuites of the Araçuai Orogen.
Source: Modified from Pedrosa-Soares et al. (2011, 2025).

2.2. São José da Safira Pegmatite District (SJSPD)

The SJSPD is situated in the central-western portion of the Araçuaí Orogen. It is bounded to the west by the pre-Neoproterozoic rocks of the São Francisco Craton, where the contact is marked by the Itambacuri thrust-reverse fault system (OLIVEIRA *et al*., 1997; SILVA, 1997), and to the east by the Abre Campo dextral shear zone (PEIXOTO *et al*., 2015) (Figures 1 and 3). Both structures were developed during the Brasiliano Orogeny (630-490Ma; PEDROSA-SOARES *et al*., 2025) and exhibit a predominantly westward vergence (OLIVEIRA *et al*., 1997; PEIXOTO *et al*., 2015; RIBEIRO, 1997; SILVA, 1997).

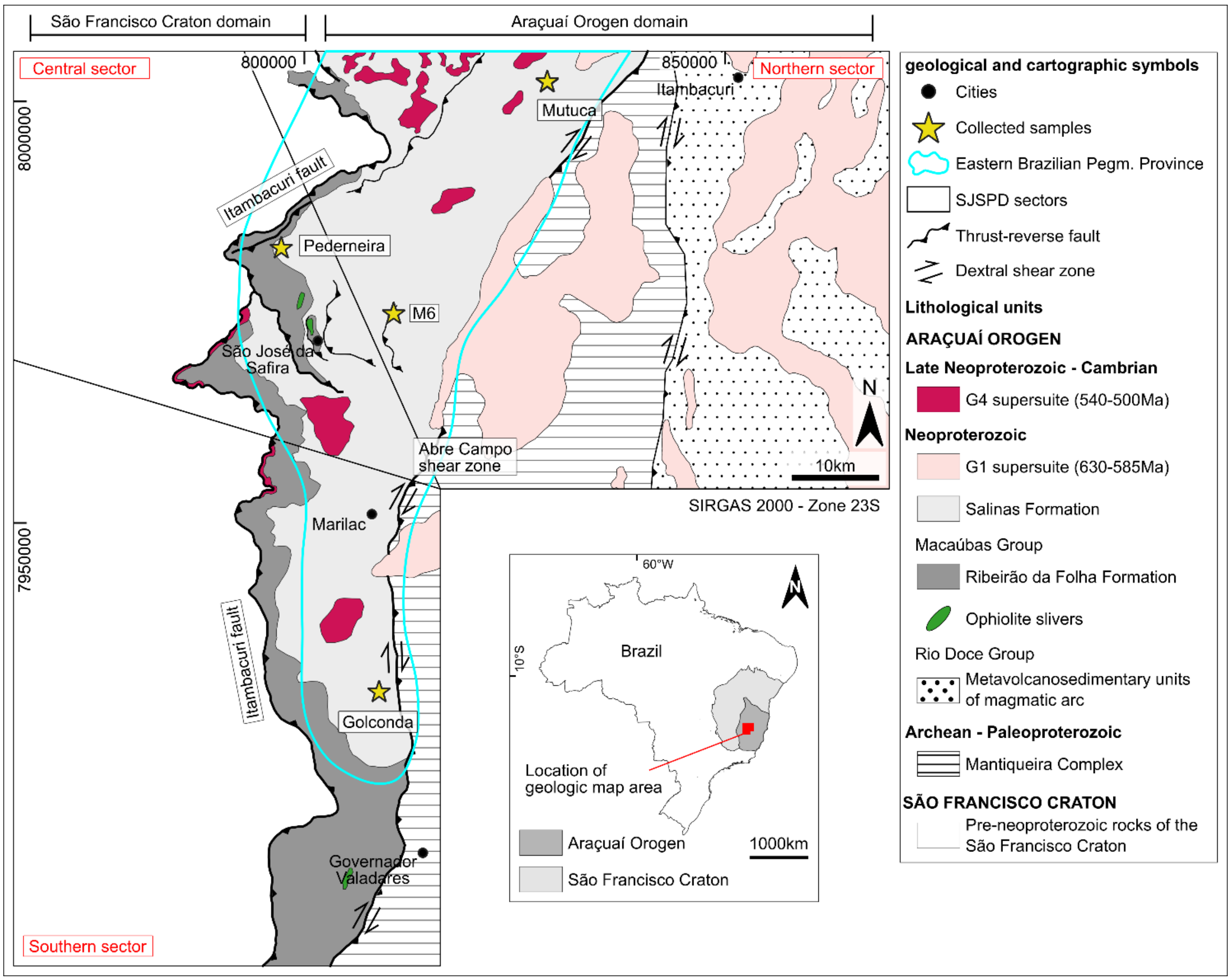


Figure 3 – Simplified geological map of the SJSPD and location of the studied pegmatites.
Source: Pedrosa-Soares et al. (2007, 2011, 2025), Peixoto et al. (2015), Ribeiro (1997), Signorelli (1997), Silva (1997).

The basement of the SJSPD comprises the Archean to Paleoproterozoic orthogneisses of the Mantiqueira Complex, overlain by Neoproterozoic arc-related metavolcanosedimentary units of the Rio Doce Group and by the Neoproterozoic metasedimentary sequences of the Ribeirão da Folha (Macaúbas Group) and Salinas formations (PEDROSA-SOARES *et al*., 2007, 2011; PEIXOTO *et al*., 2015; RIBEIRO, 1997; SIGNORELLI, 1997; SILVA, 1997). The Ribeirão da Folha Formation is interpreted as a distal passive-margin deposit associated with the generation of oceanic crust (QUEIROGA *et al*., 2007), whereas the Salinas Formation corresponds to a syn-orogenic flysch-type deposit related to the closure of the Araçuaí Orogen (ALKMIM *et al*., 2006).

Neoproterozoic granitic intrusions of the G1 supersuite occur within rocks of the Mantiqueira Complex and Rio Doce Group, whereas Neoproterozoic–Cambrian granitic intrusions of the G4 supersuite are emplaced within the Ribeirão da Folha and Salinas formations. The latter formation represents the country unit for the studied pegmatites (Figure 3).

Regional metamorphism recorded by the Ribeirão da Folha and Salinas formations at the SJSPD reached conditions ranging from lower amphibolite (5.5kbar and 553°C) to intermediate amphibolite facies (6-8kbar and 600-700°C). This metamorphism is related to the syn-collisional stage of the Araçuaí Orogen evolution (585-540Ma; PEDROSA-SOARES *et al*., 2025), as a result of the Brasiliano Orogeny (PEIXOTO *et al*., 2015; QUEIROGA, 2006)

According to Pedrosa-Soares *et al*. (2001, 2011, 2025), the pegmatites of the SJSPD were generated by magmatic fractionation, with G4 supersuite granites representing the most likely parental plutons. The rocks of this supersuite consist of S-type, peraluminous, subalkaline to alkaline syenogranites formed by partial melting of the G2 supersuite, during gravitational extensional collapse associated with the late- to post-collisional stages of the Araçuaí Orogen evolution (535-500Ma; Figure 2). Pegmatites of this district are typically enriched in gem-quality tourmaline, industrial spodumene and feldspars, with high concentrations of B, Be, Cs, Li, Na, P and Ta (CORREIA-NEVES *et al*., 1986; NETTO *et al*., 1998; PEDROSA-SOARES *et al*., 2001, 2011).

3. Methodology

In this study, three pegmatites from the SJSPD were investigated: one in the northern sector (Mutuca mine), another in the central sector (Dilo/Novo Dilo dyke – Pederneira mine) and a third in the southern sector (Golconda mine), as well as country unit represented by the Salinas Formation (Figures 1 and 3). Mineral abbreviations follow Whitney and Evans (2010). The relationship between samples and the applied analytical methods is summarized in Figure 4. The analytical methods comprised in:

- macroscopic petrographic analyses of field outcrops and hand specimens using a hand lens (20x) and a binocular stereomicroscope (40x) to identify mineral assemblages and textural features;
- petrographic analyses of polished thin sections under transmitted light using a ZEISS microscope at the Department of Geology, Federal University of Ouro Preto (DEGEO/UFOP), to characterize mineral assemblages and microstructures. Petrographic descriptions were based on Deer *et al*. (2013), Melgarejo (2003) and Shelley (1992). Polished thin sections were prepared at the Lamination Laboratory of DEGEO/UFOP;
- mineral chemical analyses by energy-dispersive X-ray spectroscopy (EDS) coupled to a scanning electron microscope (SEM) at the Microanalysis Laboratory of DEGEO/UFOP. Analytical results were compared with data from Deer *et al*. (2013) to support mineral identification. Analyses were performed using an Oxford Instruments EDS detector coupled to a JEOL JSM-6510 SEM operating at 20kV, with a spot size of 68-72µm and a working distance of 13-16mm. Minerals identified with support of the SEM-EDS analyses are indicated by the suffix (SEM). The SEM-EDS analytical dataset is provided as Supplementary Material.

4. Results

4.1. Northern sector

The pegmatite investigated in the northern sector of the SJSPD is exposed at the Mutuca mine, an underground mine located approximately 35 km east of Itambacuri (MG) (Figure 3). It is hosted within a biotite–quartz schist of the Salinas Formation. Under optical microscopy, the country rock shows a fine-grained equigranular texture (0.1 to 0.4mm), composed of quartz (50%), biotite (35%), muscovite (10%), tourmaline (3%) and chlorite (2%), with feldspar, pyrite (SEM) and arsenopyrite (SEM) as accessory minerals. The pegmatite occurs as a tabular dyke concordant with the schistosity of the country rock, dipping approximately 70° to the NW (JONCEW *et al*., 2019). It is undeformed and shows no evidence of regional deformation or metamorphism.

The pegmatite exhibits a complex internal zoning, consisting of primary wall, intermediate and core zones, as well as secondary replacement zones. Border zones were not observed in the exposed mine galleries. A notable feature is the abundance of miarolitic cavities. The internal structure of this pegmatite is described below, from the margin toward the center.

(1) Wall zone: fine- to very coarse grained (1.0mm to 3.0cm), displaying graphic texture (quartz and K-feldspar

intergrowths) and alignment of subhedral to euhedral garnet and tourmaline crystals (Figure 5A). It is marked by the predominance of K-feldspar forming anhedral masses and subhedral quartz (Figure 5B). Accessory minerals include apatite (SEM), beryl (SEM), garnet (almandine–spessartine; SEM), muscovite, albite (SEM), tourmaline (SEM) and zircon (SEM).

(2) Intermediate zone: characterized by an abrupt increase in grain size (1.0cm to 1.5m) and composed mainly of K-feldspar, muscovite and quartz. It contains spodumene crystals that grow toward the core zone, together with accessory lepidolite, tourmaline and anhedral beryl.

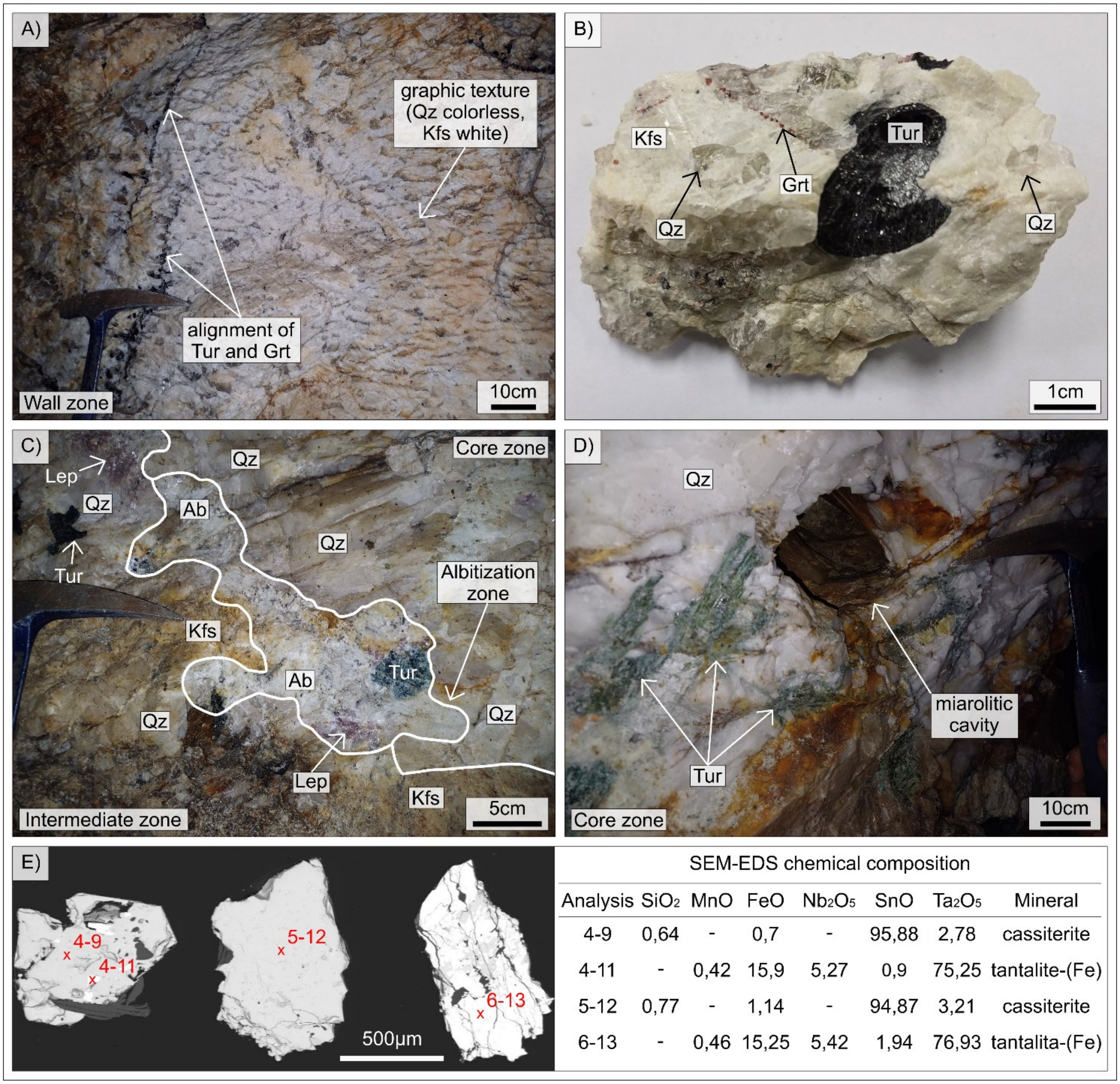
(3) Core zone: very coarse-grained with a massive texture, dominated by subhedral to euhedral quartz (Figures 5C and 5D). It may also contain spodumene crystals up to 2.0m in length, locally showing tourmaline growth perpendicular to the crystallographic c-axis (comb texture).

Sector (mine) UTM coordinates	Sample	Lithotype	Unit / internal zone	Applied analytical methods		
				macroscopic	microscopic	SEM
Northern (Mutuca) 193607/8002627	M1	pegmatite	miarolitic cavity	x		x
	M2	pegmatite	wall zone	x		x
	M3	pegmatite	miarolitic cavity	x		x
	M4	pegmatite	wall zone	x		x
810616/7974803	M6	country rock	Salinas Fm.	x	x	x
Central (Pederneira - dyke Dilo/Novo Dilo) 797271/7982586	P-ND1-A	country rock	Salinas Fm.	x	x	x
	P-ND1-B	pegmatite	intermediate zone	x	x	x
	P-ND1-C	pegmatite	intermediate zone	x		
	P-ND1-D	country rock	Salinas Fm.	x		
	P-ND2-A	pegmatite	intermediate zone	x	x	x
	P-ND2-B	pegmatite	wall zone	x		x
	P-ND2-C	pegmatite	intermediate zone	x		
	P-ND2-D	pegmatite	intermediate zone	x		
	P-ND2-E	pegmatite	intermediate zone	x		
	P-ND3-A	pegmatite	intermediate zone	x	x	
	P-ND3-B	country rock	Salinas Fm.	x	x	
	P-ND3-C	pegmatite	intermediate zone	x		
	P-ND4-A	pegmatite	intermediate zone	x	x	x
	P-ND5-A	pegmatite	miarolitic cavity	x	x	x
Southern (Golconda) 808894/7929921	G1-A	country rock	Salinas Fm.	x	x	x
	G1-B	pegmatite	border zone	x	x	
	G1-C	pegmatite	intermediate zone	x		
	G2-A	pegmatite	miarolitic cavity	x		x
	G2-B	pegmatite	intermediate zone	x		x

Figure 4 – Summary of sampling and applied analytical methods.
Source: Authors (2026).

Secondary replacement zones are characterized by albitization, expressed by the replacement of primary K-feldspar by lamellar albite (cleavelandite) forming radial aggregates. These zones may also include anhedral masses of lepidolite and subhedral garnet and tourmaline crystals (Figure 5C). They are mainly developed within the intermediate zones, close to the contact with the core zones.

Miarolitic cavities occur at the contact between the intermediate and core zones (Figure 5D), with diameters ranging from 10.0cm to 1.0m. They may host apatite, lamellar albite (cleavelandite; SEM), cassiterite (SEM; Figure 5E), columbite-(Fe) (SEM), K-feldspar, tantalite-(Fe) (SEM), garnet (almandine; SEM), microlite (SEM), muscovite, albite (SEM), quartz, tourmaline, zircon (SEM), Mn oxide/hydroxide concretions and autunite as a secondary U-bearing mineral. The modal grain size is very coarse and ranges from 5.0mm to 7.0cm.



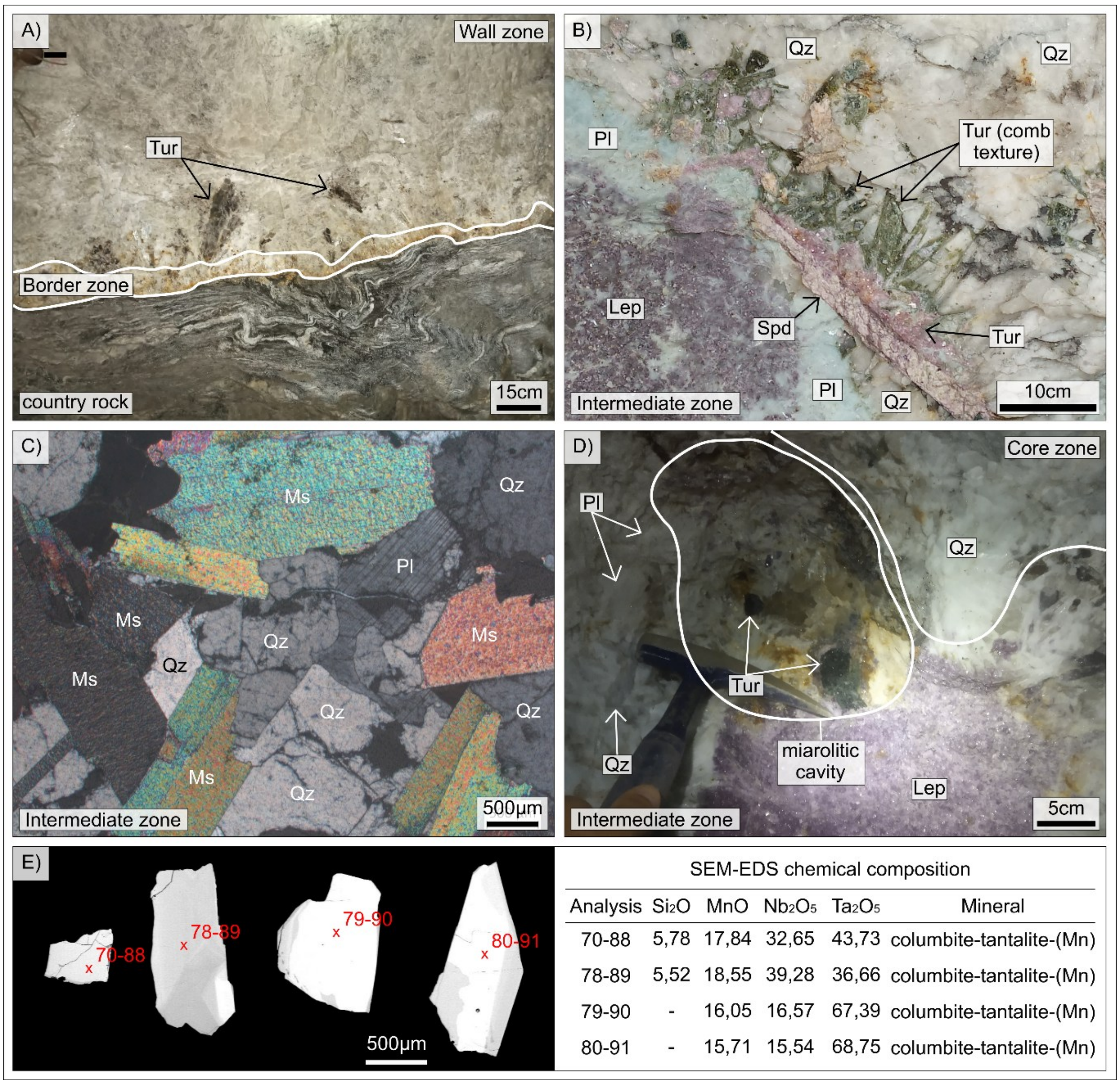
Analysis	SiO_2	MnO	FeO	Nb_2O_5	SnO	Ta_2O_5	Mineral
4-9	0,64	-	0,7	-	95,88	2,78	cassiterite
4-11	-	0,42	15,9	5,27	0,9	75,25	tantalite-(Fe)
5-12	0,77	-	1,14	-	94,87	3,21	cassiterite
6-13	-	0,46	15,25	5,42	1,94	76,93	tantalita-(Fe)

Figure 5 – Pegmatite from the SJSPD northern sector (Mutuca mine). A) Wall zone showing graphic texture. B) Hand specimen of the wall zone highlighting the predominant mineral assemblage. C) Secondary albitization zone at the contact between the intermediate and core zones. D) Core zone containing a miarolitic cavity. E) Backscattered electron

(BSE) images of minerals from a miarolitic cavity and SEM–EDS chemical analysis results.
Source: Authors (2026).

4.2. Central sector

The pegmatite investigated in the central sector of the SJSPD corresponds to the Dilo/Novo Dilo dyke, exposed in the underground Pederneira mine, approximately 20 km north of São José da Safira (MG) (Figure 3). It is hosted within a biotite-quartz schist of the Salinas Formation, which, under optical microscopy, exhibits a fine- to coarse-grained texture (0.4 to 8.4mm), composed of quartz (35-50%), biotite (26-35%), muscovite (7-15%) and plagioclase (5-10%), with locally tourmaline-enriched domains (up to 25%). Accessory minerals include monazite-(Ce) (SEM), chlorite, K-feldspar (microcline), garnet and zircon (SEM). Apatite (SEM) and ilmenite (SEM) occur as inclusions within tourmaline.



SEM-EDS chemical composition

Analysis	SiO_2	MnO	Nb_2O_5	Ta_2O_5	Mineral
70-88	5,78	17,84	32,65	43,73	columbite-tantalite-(Mn)
78-89	5,52	18,55	39,28	36,66	columbite-tantalite-(Mn)
79-90	-	16,05	16,57	67,39	columbite-tantalite-(Mn)
80-91	-	15,71	15,54	68,75	columbite-tantalite-(Mn)

Figure 6 – Pegmatite from the SJSPD central sector (Pederneira mine). A) Abrupt contact between the pegmatite and locally migmatized country rock. B) Intermediate zone showing the mineral assemblage with comb-textured tourmaline. C) Photomicrograph of the intermediate zone showing an inequigranular microstructure with planar to interlobate crystal boundaries (crossed nicols). D) Contact between the intermediate and core zone showing a miarolitic cavity. E)

BSE images of minerals from a miarolitic cavity and SEM–EDS chemical analysis results.
Source: Authors (2026).

The pegmatite occurs as a tabular body concordant with the schistosity of the country rock, striking N80W and dipping subvertically to the SW. It is up to 20m thick, 40m along strike and extends for approximately 150m down dip (SOUZA, 1999). The body is undeformed and shows no evidence of regional deformation or metamorphism. The contact between the pegmatite and the country rock is abrupt and locally marked by migmatitic structures in the country rock (Figure 6A). However, the absence of deformation and metamorphic features within the pegmatite, together with the abrupt nature of the contact, indicates that the migmatization of the country rock predates pegmatite emplacement.

The pegmatite exhibits complex internal zoning, comprising primary border, wall, intermediate and core zones, as well as secondary replacement zones. Miarolitic cavities are common. The internal zones are described below, from the margin toward the center.

(1) Border zone: defined by an abrupt contact between the pegmatite and the locally migmatized country rock, with migmatization predating the pegmatite emplacement (Figure 6A). This zone is 2.0 to 5.0cm thick and consists of medium-grained (<4.0mm) feldspar-quartz aggregates with a granular texture.

(2) Wall zone: characterized by an increase in grain size and by tourmaline crystals up to 15.0cm in length showing unidirectional growth toward the core (Figure 6A), locally extending into the intermediate zone. Plagioclase and quartz are dominant, with minor muscovite. Accessory minerals include apatite (SEM), monazite-(Ce) (SEM), garnet, tourmaline, zircon (SEM) and uraninite (SEM), partially covered by pyrite (SEM).

(3) Intermediate zone: coarse- to very coarse-grained, hosting spodumene crystals up to 70.0cm in length. It is dominated by anhedral K-feldspar and subhedral to saccharoidal quartz. Accessory minerals include apatite, beryl, biotite, monazite-(Ce) (SEM), garnet (almandine–spessartine; SEM) as euhedral crystals and anhedral masses, lepidolite, microcline, muscovite locally rimmed by lepidolite, massive albite, uraninite (SEM), xenotime-(Y) (SEM), zircon (SEM) and tourmaline, locally forming comb textures associated with spodumene crystals (Figure 6B). In thin section, finer-grained portions of this zone show a fine- to coarse-seriate inequigranular microstructure (0.6mm to 2.4cm), with planar to interlobate crystal boundaries (Figure 6C).

(4) Core zone: composed predominantly of massive anhedral quartz (Figure 6D).

Secondary replacement zones are characterized by albitization, expressed by abundant lamellar albite (cleavelandite) forming radial aggregates, commonly associated with spodumene, quartz, tourmaline and anhedral lepidolite. These zones are mainly developed within the intermediate zone, near to the core zones.

Miarolitic cavities occur within the intermediate zone, close to the core zones (Figure 6D), reaching up to 35.0cm in diameter. They may contain apatite, beryl (SEM), spodumene, K-feldspar (SEM), lepidolite, columbite–tantalite-(Mn) (SEM; Figure 6E), muscovite, lamellar albite (cleavelandite; SEM), quartz, tourmaline and zircon (SEM), as well as autunite as a secondary U-bearing mineral (SEM) and Mn oxides (SEM). Grain size ranges from medium to very coarse (1.0mm to 2.0cm).

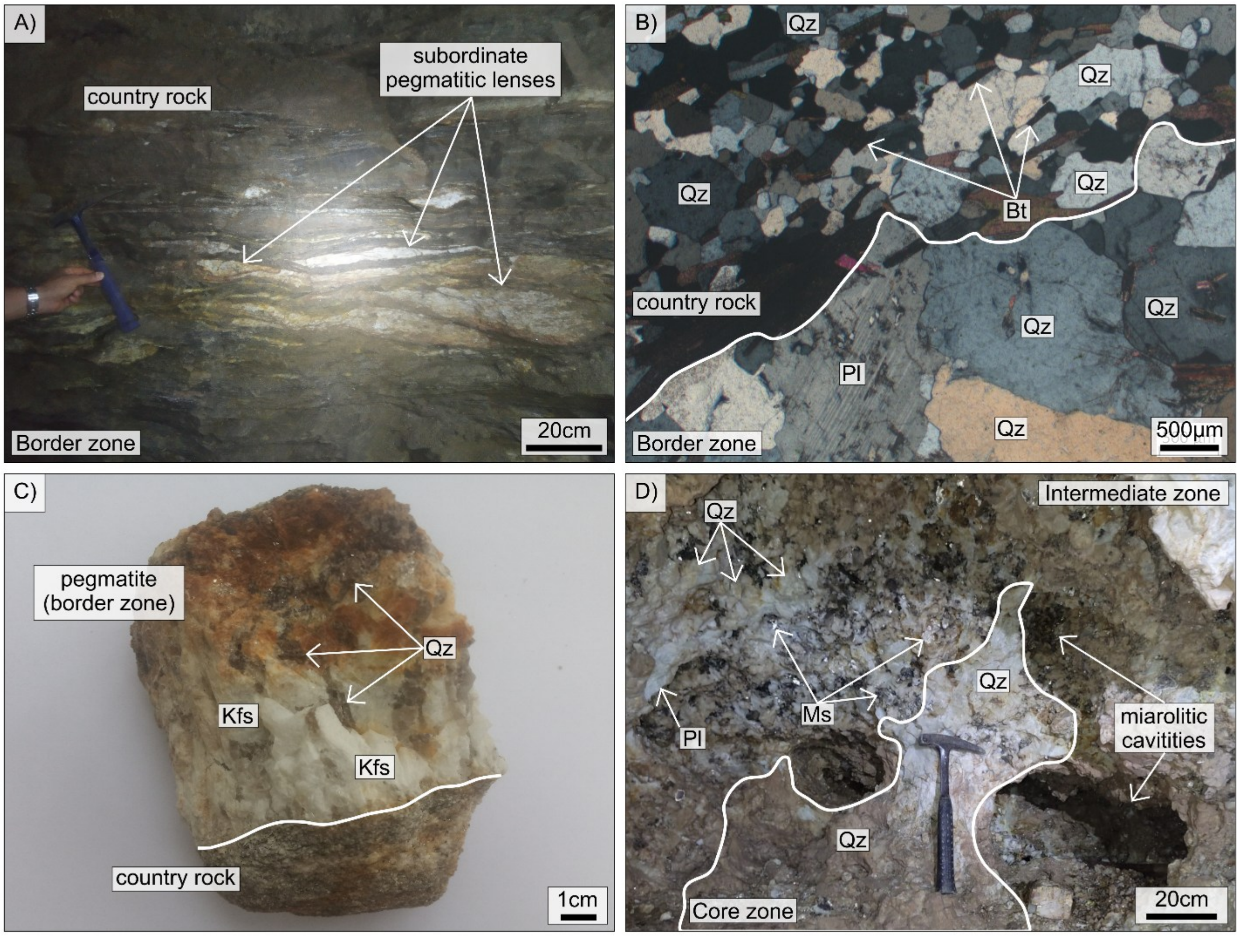
4.3. Southern sector

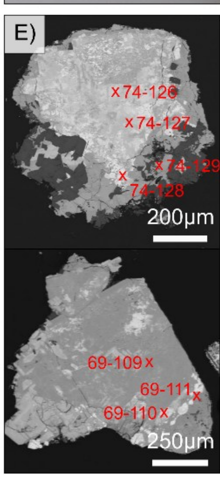
The pegmatite investigated in the southern sector of the SJSPD occurs at the Golconda underground mine, located approximately 30km northwest of Governador Valadares (MG) (Figure 3). It is hosted within a biotite-quartz schist of the Salinas Formation, which, under optical microscopy, exhibits a fine- to medium-grained texture (0.2 to 4.0mm), composed of quartz (62%), biotite (20%), muscovite (12%), plagioclase (4%) and chlorite (2%), with apatite, monazite-(Ce) (SEM), garnet, pyrite and zircon as accessory minerals. The pegmatite forms a tabular body, 3 to 11 m thick, subhorizontal, elongated along N50°W, and concordant with the gently undulating schistosity of the country rock (NETTO *et al*., 1998; PECORA *et al*., 1950). The body is undeformed and shows no evidence of regional deformation or metamorphic overprint. The contact with the country rock is abrupt at both macroscopic (Figures 7A and 7C) and microscopic scales (Figure 7B).

The pegmatite exhibits complex internal zoning, consisting of primary border, intermediate and core zones, as well as secondary replacement zones. Primary wall zones were not observed in the exposed mine galleries. Miarolitic cavities are common. The internal structure of this pegmatite, from the margin toward the center, is described below.

(1) Border zone: defined by an abrupt contact between the pegmatite and the country rock, locally marked by a swarm of pegmatitic lenses subordinate to the main body. These lenses are concordant with the gently undulating schistosity of the country rock and are unaffected by regional deformation or metamorphism (Figure 7A). In thin section, this zone consists of a fine- to coarse-grained (0.2mm to 2.7cm) with scarce biotite in the pegmatite domain, in contrast to the fine-grained (0.2 to 4.4 mm) biotite-rich country rock (Figure 7B). The dominant assemblage is

K-feldspar and quartz (Figure 7C), with biotite, garnet, muscovite, and plagioclase as accessory phases. Graphic texture is common.





SEM-EDS chemical composition

Analysis	SiO_2	P_2O_5	CaO	TiO_2	MnO	FeO	Y_2O_3	Nb_2O_5	Gd	Dy	Er	Yb	Ta_2O_5	PbO	UO_2	Mineral
74-126	-	-	0,72	-	-	-	24,43	27,31	-	2,6	4,5	8,79	26,92	-	3,69	euxenita-(Y)
74-127	4,82	-	0,3	1,34	9,95	9,08	-	47,73	-	-	-	-	24,73	-	2,05	columbita-(Mn)
74-128	8,49	-	0,39	1,13	1,64	2,12	-	15,71	-	-	-	-	45,72	21,87	2,94	columbita-tantalita
74-129	-	32,17	-	-	-	-	37,63	-	2,1	5,29	8,4	12,51	-	-	-	xenotimo-(Y)
69-109	-	32,92	0,38	-	-	-	44,23	-	1,04	3,62	5,85	8,76	1,49	-	0,77	xenotimo-(Y)
69-110	5	2,59	1,11	9,36	-	0,38	-	7,2	-	-	-	-	9,02	5,47	59,86	uraninite
69-111	-	-	6,36	6,81	0,29	0,47	-	10,87	-	-	-	-	62,11	-	10,06	microlite

Figure 7 – Pegmatite from the SJSPD southern sector (Golconda mine). A) Border zone showing subordinate pegmatitic lenses. B) Photomicrograph of the contact between the pegmatite and the country rock (crossed nicols). C) Hand specimen showing the contact between the pegmatite and its country rock. D) Limit between the intermediate and core zones highlighting miarolitic cavities. E) BSE images of minerals from a miarolitic cavity and SEM–EDS chemical

analysis results.

Source: Authors (2026).

(2) Intermediate zone: marked by a pronounced increase in grain size (2.0 to 8.0cm) and dominated by graphic intergrowths of K-feldspar and quartz, with subordinate albite and muscovite (Figure 7D). Accessory minerals include apatite with rare xenotime inclusions (SEM), as well as beryl, biotite, monazite-(Ce) (SEM), garnet, xenotime-(Y) (SEM), and zircon with rare uraninite inclusions (SEM).

(3) Core zone: predominantly composed of massive anhedral quartz (Figure 7D).

Secondary replacement zones are characterized by albitization, characterized by abundant lamellar albite (cleavelandite) forming crystals up to ~1.0cm, commonly associated with tourmaline (up to 3.0cm) and anhedral lepidolite masses. These zones are mainly developed within the intermediate zone.

Miarolitic cavities occur at the boundary between the intermediate and core zones, reaching up to 40.0cm in diameter (Figure 7D). They may contain beryl, K-feldspar (SEM), garnet (almandine–spessartine; SEM), muscovite, albite (SEM), quartz, tourmaline (SEM), and zircon (SEM), as well as aggregates of euxenite-(Y) (SEM), columbite-tantalite (SEM), columbite-(Mn) (SEM), columbite-tantalite-(Mn-Fe) (SEM), and/or xenotime-(Y) (SEM), locally with uraninite rims (SEM) or microlite inclusions (SEM) (Figure 7E). Xenotime-(Y) also occurs as isolated octahedral crystals, yellowish, translucent, and magnetic (SEM). Fe-oxide phases (SEM) and anhedral masses of nontronite occur as secondary Na–Fe minerals. Grain size is very coarse, ranging from 1.0 to 30.0cm.

5. Discussion

The petrographic characterization of the pegmatites from the northern (Mutuca mine), central (Dilo/Novo Dilo dyke – Pederneira mine), and southern (Golconda mine) sectors of the SJSPD (Figure 3) reveals that these bodies are free of regional deformation or metamorphism, and are mineralogical and textural similar to one another, which suggest a common origin and evolutionary history for their forming melts. The studied pegmatites exhibit complex internal zoning, comprising primary zones (border, wall, intermediate and core), secondary albitization zones and abundant miarolitic cavities. They correspond to granitic pegmatites enriched in rare-element minerals, including beryl, columbite-tantalite, spodumene, lepidolite and tourmaline (Figure 8). These pegmatites were classified according to the Černý (1991), Černý and Ercit (2005), and Wise *et al*. (2022) classification systems, as they represent the most comprehensive and widely adopted systems and provide a robust basis for petrogenetic interpretation.

5.1. Classification System of Černý (1991) and Černý and Ercit (2005)

The classification system proposed by Černý (1991) and Černý and Ercit (2005) uses mineralogical and geochemical composition as the main criteria, grouping pegmatites into five classes: Abyssal, Muscovite, Muscovite-rare element, Rare element and Miarolitic. In addition, Černý and Ercit (2005) proposed a complementary geochemical classification that subdivides pegmatites into three families: NYF (Nb-Y-F enriched pegmatites); LCT (Li-Cs-Ta enriched pegmatites); and NYF+LCT (pegmatites characterized by a mixed geochemical signature).

The occurrence of significant amounts of beryl, lepidolite, columbite-tantalite and tourmaline in the pegmatites analyzed from the SJSPD (Figure 8) indicates enrichment in Be, Li, Nb and B, which, associated with the abundance of miarolitic cavities, allows to classify the studied pegmatites as Miarolitic (Figure 9). According to Černý and Ercit (2005), pegmatites of this class may also be enriched in REE, F, Ti, U, Y and Zr. In this context, the occurrence of monazite-(Ce) (LREE phosphate), uraninite (U oxide), and xenotime (Y phosphate) in the pegmatites from the central and southern sectors provides additional support for this classification.

Considering the geochemical signature, the occurrence of lepidolite in the pegmatites from the northern, central and southern sectors of the SJSPD, associated with the presence of spodumene in the pegmatites from the northern and central sectors, and microlite in the pegmatites from the northern and southern sectors (Figure 8), indicates Li ad Ta enrichments. According to Černý (1991) and Černý and Ercit (2005), these enrichments, combined with the predominance of muscovite as the main micaceous mineral and the occurrence of apatite, beryl, columbite-tantalite, garnet and tourmaline as the main accessory minerals, allows to classify the studied pegmatites as LCT (Figure 9).

Sectors of the São José da Safira Pematite District	Northern	Central	Southern
Undeground mine	Mutuca	Pederneira	Golconda
Pegmatite mineral assemblages			
Almandine [1]	x	x	x
Apatite	x	x	x
Autunite	x	x	
Beryl	x	x	x
Biotite		x	x
Cassiterite	x		
Monazite-(Ce)		x	x
Cleavelandite [3]	x	x	x
Columbite-tantalite			x
Spessartine [1]	x	x	
Spodumene	x	x	
Columbite-(Fe)	x		
Feldspar	x	x	x
K-feldspar [2]	x	x	x
Tantalita-(Fe)	x		
Garnet	x	x	x
Lepidolite	x	x	x
Microcline [2]		x	
Microlite	x		x
Columbite-(Mn)			x
Columbite-tantalite-(Mn)		x	
Columbite-tantalite-(Mn-Fe)			x
Muscovite	x	x	x
Nontronite	x		x
Pyrite		x	
Plagioclase	x	x	x
Albitic plagiocalse [3]	x	x	x
Quartz	x	x	x
Tourmaline	x	x	x
Uraninite		x	x
Xenotime			x
Euxenite-(Y)			x
Xenotime-(Y)		x	x
Zircon	x	x	x

Minerals of the following groups: 1) garnet; 2) feldspar; e 3) plagioclase.

Figure 8 – Mineral assemblages of the studied SJSPD pegmatites.
Source: Authors (2026).

5.2. New Classification System of Wise *et al*. (2022)

The new classification system proposed by Wise *et al*. (2022) uses mineral assemblages as the primary classification criterion, grouping pegmatites into: Group 1 (pegmatites with beryl ± phosphates; with spodumene ± petalite; or with lepidolite ± elbaite tourmaline); Group 2 (pegmatites with biotite ± fayalite ± sodic amphibole; with magnetite ± uraninite ± REE oxides and silicates; or with beryl ± fluorite ± topaz); and Group 3 (pegmatites with andalusite ± kyanite ± cordierite ± sillimanite; with chrysoberyl; or with borosilite ± dumortierite ± grandidierite ± werdingite). This system also includes a petrogenetic classification based on geochemical signature, distinguishing pegmatites as either DPA (direct products of anatexis) or RMG (residual melts derived from granitic magmatism).

Group 1 pegmatites of Wise *et al*. (2022) can be related to the LCT family of Černý and Ercit (2005), as both classifications encompass pegmatites characterized by Li-enriched mineral assemblages. In this context, the occurrence of significant amounts of lepidolite in the pegmatites from the northern, central and southern sectors of the SJSPD, associated with the presence of spodumene in the pegmatites from the northern and central sectors, supports the classification of the studied pegmatites as Group 1. In addition, similarly to the LCT family, Group 1 pegmatites may also be enriched in B, Be, Cs, F, Ga, P, Rb, Sn and Ta. Accordingly, the occurrence of phosphates (apatite and xenotime), Be- and B-bearing silicates (beryl and tourmaline), and Sn- and Ta-bearing oxides (cassiterite, microlite and columbite-tantalite) provides further support for this classification (Figures 8 and 9).

The classification of these pegmatites as Group 1, combined with their enrichment in B, Be, Li, P, Sn and Ta, allows them to be interpreted as either DPA or RMG pegmatites. However, DPA pegmatites typically occur in high-grade metamorphic terranes under upper amphibolite- to granulite-facies conditions (WISE *et al*., 2022). On the other hand, even if the pegmatites analyzed in the SJSPD were formed during regional metamorphism, the metamorphic peak recorded by their country unit reached lower- to intermediate-amphibolite facies conditions (PEIXOTO *et al*., 2015), considerably below those required for the generation of DPA pegmatites. Therefore, the most likely petrogenetic classification for the studied pegmatites is RMG (Figure 9).

Classifications and genetic implications	Northern sector pegmatite (Mutuca mine)	Central sector pegmatite (Pederneira mine)	Southern sector pegmatite (Golconda mine)
Classification System of Černý (1991) and Černý and Ercit (2005)			
Class	Miarolitic (pegmatites enriched in Be, Li, Nb, B, ETR, U and Y, with abundant miarolitic cavities)		
Genetic implications	Pegmatites formed by magmatic fractionation of peraluminous parental plutons, emplaced during syn- to late-orogenic compressional regimes		
Family	LCT (pegmatites enriched in lithium-cesium-tantalum)		
Genetic implications	Peraluminous pegmatites, genetically associated with: **i)** anatexis of undepleted upper- to midle-crustal metavolcanic and/or metasedimentary protoliths; or **ii)** high-degree magmatic fractionation of parental granitic plutons, generally peraluminous, S-type, I-type, or a mixture of both		
New Classification System of Wise *et al.* (2022)			
Group	Group1 (pegmatites with lepidolite and spodumente, enriched in Li)		
Type	RMG (residual melts derived from granitc magmatism)		
Genetic implications	Pegmatites formed by magmatic fractionation of peraluminous S-type parental granitic plutons. Both the pegmatites and their parental plutons are typically orogenic		

Figure 9 – Classification of the SJSPD pegmatites according to Černý (1991, Černý and Ercit (2005) and Wise et al. (2022).
Source: Authors (2026).

5.3. Genetic implications

The classification of the SJSPD pegmatites as Miarolitic (ČERNÝ, 1991; ČERNÝ and ERCIT, 2005), associated with their assignment to Group 1 and the RMG type (WISE *et al*., 2022), converges on the hypothesis that these bodies were formed through magmatic fractionation of peraluminous, S-type, syn- to late-orogenic parental granitic plutons (Figure 9). However, their classification as LCT pegmatites (ČERNÝ, 1991; ČERNÝ and ERCIT, 2005) also allows an alternative hypothesis, according to which these bodies were possible originated through anatexis of undepleted upper- to middle-crustal metavolcanic and/or metasedimentary protoliths (Figure 9). Field, mineralogical, geochemical, and textural evidences, integrated with the regional geological setting, are discussed below to evaluate the most likely hypothesis.

The absence of regional deformation and metamorphic overprints in the studied pegmatites, associated with their abrupt contact with the country unit (biotite-quartz schists of the Salinas Formation), suggests that the emplacement of these bodies postdates regional metamorphism, which is dated to the syn-collisional stage of the Araçuaí Orogen evolution (585-540 Ma; PEDROSA-SOARES *et al*., 2011, 2025). Accordingly, field relationships indicate a clearly late- to post-collisional origin for the melts that crystallized these pegmatites.

Furthermore, the classification of these bodies as Miarolitic pegmatites (Figure 9) suggests P-T formation conditions of approximately 1.5-3kbar and 400-500°C (ČERNÝ, 1991; ČERNÝ and ERCIT, 2005). These values are significantly lower than the P-T conditions recorded by the country unit during regional metamorphism (Salinas Formation; 5.5-8kbar and 553-700°C; PEIXOTO *et al*., 2015). Considering the geological evolution of the Araçuaí Orogen, this discrepancy suggests that regional metamorphism preceded the emplacement of the studied pegmatites, further supporting a late- to post-collisional origin for their forming melts (535-500Ma; PEDROSA-SOARES *et al*., 2011, 2025).

Conversely, under an anatectic origin hypothesis, the studied pegmatites would be expected to have formed during regional metamorphism, which would have provided the increase of temperature and pressure required for the partial melting of pre-existing units. However, as discussed above, field relationships indicate that these pegmatites postdate regional metamorphism. Moreover, in an in situ anatectic scenario, the country unit should display migmatitic structures as evidence of partial melting and segregation of newly formed quartz–feldspathic leucosomes, that would have generate the pegmatitic melts, as occur in the anatectic pegmatites of the Caratinga and Itambé districts (Figure 1) (PEDROSA-SOARES et al., 2025). However, no migmatites genetically related to the pegmatitic melts were identified in the SJSPD. Therefore, an anatectic origin for the studied pegmatites appears unlikely.

Thus, considering i) the post- regional deformation and metamorphism origin for the studied pegmatites; ii) the abrupt contacts between these bodies and their country units; iii) the absence of migmatites genetically related to the pegmatitic melts; and iv) the rejection of the anatectic hypothesis, the most likely petrogenetic model for the origin and evolution of the studied SJSPD pegmatites is the magmatic fractionation of parental granitic plutons (Figure 10).

Based on Černý (1991), Černý and Ercit (2005), and Wise *et al*. (2022), mineralogical, geochemical and regional geologic evidences further supports this interpretation. The studied pegmatites are zoned and chemically complex, with mineral assemblages characterized by significant amounts of beryl, euxenite, Y- and REE-bearing phosphates, Sn-Nb-Ta oxides, Li-bearing silicates, tourmaline, and uraninite (Figure 8), all of which are rare-element minerals indicative of advanced magmatic fractionation. Furthermore, the late- to post-collisional setting of the Araçuaí Orogen, within which these bodies occur, was marked by extensional gravitational collapse, a geotectonic environment favorable for the emplacement of granitic magmas that may have acted as parental plutons (PEDROSA-SOARES *et al*., 2021, 2025).

Among the granitic rocks mapped in the SJSPD (G1 and G4 supersuites; Figures 1 and 3), the syenogranites of the G4 supersuite are considered the most likely parental plutons for the origin of the studied pegmatites (Figure 10). These syenogranites are geochemically compatible with the rare-element-enriched granitic composition of the pegmatites (e.g., B, Be, REE, Li, Nb, Sn, Ta, U and Y), being peraluminous, subalkaline to alkaline and S-type in composition (Figure 2). They were emplaced during the same tectonic interval (late- to post-collisional stages of the Araçuaí Orogen evolution; 535-500Ma; PEDROSA-SOARES *et al*., 2011, 2025), are widely distributed throughout the SJSPD, and occur in areas spatially associated with the studied pegmatites (2-12 km apart; Figure 3).

In summary, the presented evidences suggests that the SJSPD studied pegmatites were formed through magmatic fractionation of parental granites belonging to the G4 supersuite, during the late- to post-collisional stages of the Araçuaí Orogen evolution (535-500Ma) (Figure 10), as also proposed by Pedrosa-Soares *et al*. (2011, 2025). This model has also been applied to the Malacacheta and Araçuaí pegmatite districts, located north of the study area (PEDROSA-SOARES *et al*., 2025; Figure 1), indicating that pegmatites derived from parental granites do not represent an isolated case within the EBPP.

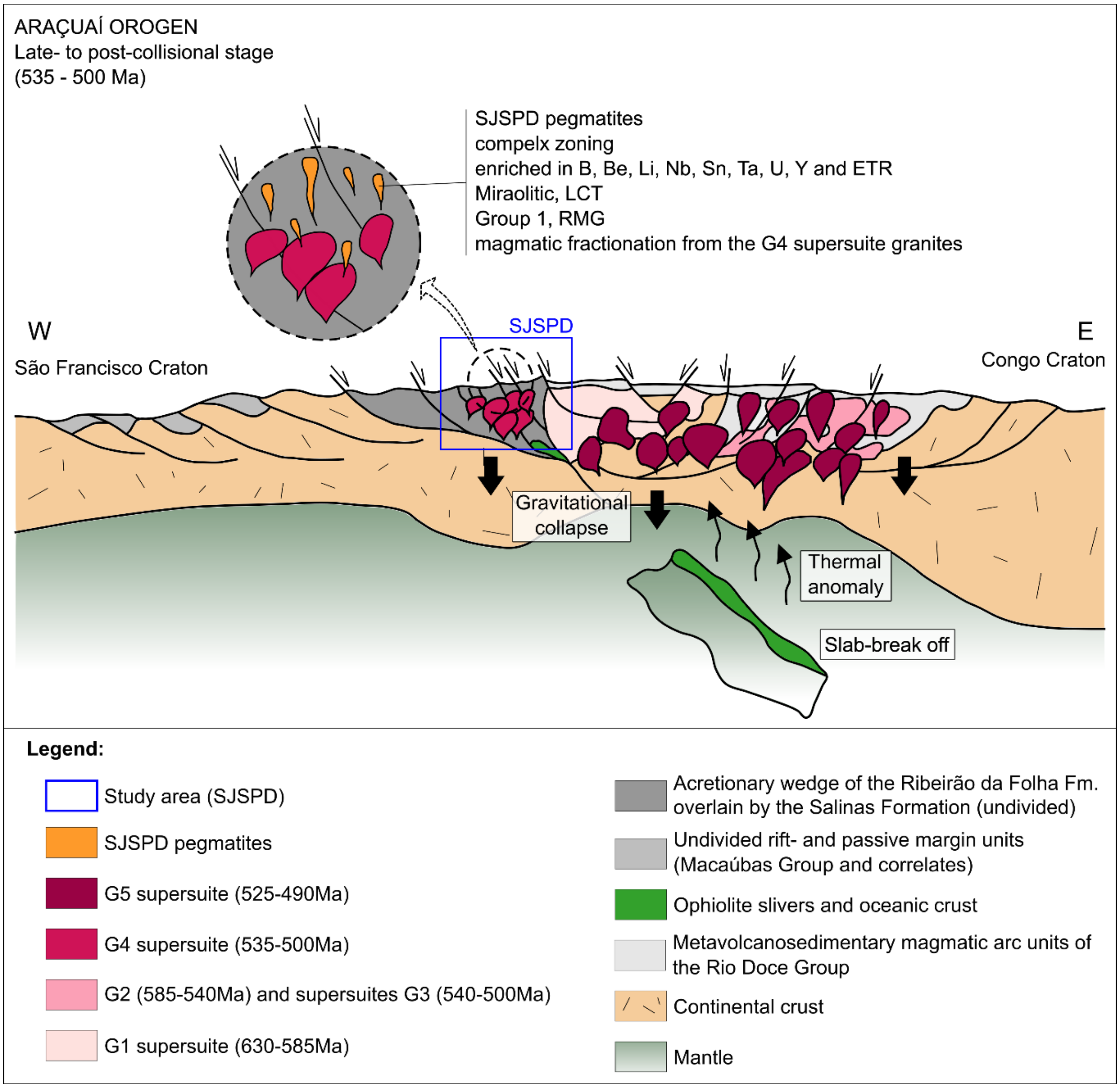


Figure 10 – Schematic model for the formation of the SJSPD pegmatites through magmatic fractionation. Source: Modified from Gradim et al. (2014).

6. Final Considerations

The petrographic characterization of the pegmatites investigated in the northern (Mutuca mine), central (Dilo/Novo Dilo dyke – Pederneira mine), and southern (Golconda mine) sectors of the SJSPD allows the following considerations:

- the studied pegmatites are free of regional deformation and metamorphism. They are mineralogically and texturally similar to one another, displaying complex internal zoning composed of **i) border zone** (dominantly Kfs + Qz, with granular texture); **ii) wall zone** (dominantly Kfs + Qz ± Pl ± Ms ± Tur, with graphic and unidirectional crystal-growth textures toward the core); **iii) intermediate zone** (dominantly Kfs + Ms + Qz + Pl ± Spd, with saccharoidal and unidirectional crystal-growth textures toward the core); and **iv) core zone** (Qz ± Spd, massive texture). Secondary albitization zones (lamellar albite ± Lep ± Tur) and abundant miarolitic cavities are also present, both concentrated near the boundary between the intermediate and core zones;

- they correspond to granitic pegmatites enriched in rare elements, as evidenced by the occurrence of B-, Be- and Li-bearing silicates (tourmaline, beryl, spodumene and lepidolite), Sn-, Nb-, Ta-, U- and REE-bearing oxides (cassiterite, columbite-tantalite, microlite, uraninite and euxenite), and Y- and REE-bearing phosphates (xenotime and monazite) as accessory minerals;
- based on their mineral assemblages and geochemical signature, these pegmatites were classified as Miarolitic (enriched in Be, Li, Nb, B, REE, U and Y, with abundant miarolitic cavities) and LCT (Li-Cs-Ta-enriched pegmatites) according to Černý (1991) and Černý and Ercit (2005). According to Wise *et al*. (2022), they are further classified as Group 1 (pegmatites with lepidolite and spodumene, Li-enriched) and RMG (pegmatites formed through residual melts derived from granitic magmatism); and
- the presented evidences suggest that the studied pegmatites were formed through magmatic fractionation of parental granites belonging to the G4 supersuite during the late- to post-collisional stages of the Araçuaí Orogen evolution (535-500Ma), as also documented by Pedrosa-Soares *et al*. (2011, 2025).

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