

Pegmatites: Evolution of concepts and classification systems

Pegmatitos: evolução dos conceitos e sistemas de classificação

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Abstract: Pegmatites are granitic igneous rocks characterized by coarse to very coarse graining and marked by a wide granulometric heterogeneity. This textural complexity is normally associated with mineralogical variations, which, in conjunction, define an internal structure composed of primary zones (contact, wall, intermediate and core) and, sometimes, secondary replacement zones. According to the most widely accepted petrogenetic models, pegmatite-forming melts may derive from magmatic fractionation of parental granitic plutons or by anatexis. The most comprehensive and widely used classification systems are based on criteria such as temperature and pressure of formation, as well as mineralogical and chemical composition, providing fundamental support for understanding the genesis of these melts. Considering the high textural, mineralogical, structural and petrogenetic complexity of pegmatites, this paper aims to present a synthesis of the key concepts necessary for an introductory understanding of these rocks, including definition, petrogenetic models, internal structure and main classification systems. Reading this material is recommended before first direct contact with pegmatites, in order to highlight the main features to be observed in any petrographic or petrogenetic study of these rocks.

Keywords: Internal structure of pegmatites; Textural and mineralogical zoning; Petrogenetic models.

Resumo: Pegmatitos são rochas ígneas graníticas caracterizadas por granulação grossa a muito grossa e marcada por uma ampla heterogeneidade granulométrica. Essa complexidade textural normalmente está associada a variações mineralógicas, que, em conjunto, definem uma estruturação interna composta por zonas primárias (contato, parede, intermediária e núcleo) e, por vezes, zonas secundárias de substituição. De acordo com os modelos petrogenéticos mais aceitos, os *melts* formadores de pegmatitos podem derivar do fracionamento magmático de plutões graníticos parentais ou por anatexia. Os sistemas de classificação mais abrangentes e amplamente utilizados baseiam-se em critérios como temperatura e pressão de formação, além de composição mineralógica e química, fornecendo subsídios fundamentais para a compreensão da gênese desses *melts*. Considerando a elevada complexidade textural, mineralógica, estrutural e petrogenética dos pegmatitos, este artigo tem como objetivo apresentar uma síntese dos conceitos-chave necessários à compreensão introdutória dessas rochas, incluindo definição, modelos petrogenéticos, estrutura interna e principais sistemas classificatórios. A leitura deste material é recomendada antes de um primeiro contato direto com pegmatitos, com o intuito de destacar as principais feições a serem observadas em qualquer estudo petrográfico e/ou petrogenético dessas rochas.

Palavras-chave: Estrutura interna de pegmatitos; Zonamento textural e mineralógico; Modelos petrogenéticos.

1. Introduction

Pegmatites have increasingly become the subject of scientific investigation mainly due to their association as lithium deposits, a rare metal with growing global demand in the electronic industry (GRUBBER *et al.*, 2011). The genesis of pegmatites is closely related to the fractional crystallization of melts enriched in critical elements and volatile components, such as B, Li, F, P, H₂O and CO₂. This process leads to the enrichment of economically significant rare elements, which include Be, Cs, Ga, Nb, Ta, Ti, Y and rare earth elements (REEs) in the residual melt (ČERNÝ, 1991; LONDON, 2018; SIMMONS *et al.*, 2003). As a result, pegmatites are regarded not only as important lithium-bearing deposits, but also as deposits of the other aforementioned rare elements, as well as important source of industrial minerals (e.g., quartz, feldspar, micaceous minerals) and gemological minerals (e.g., beryl, garnet, tourmaline) (SIMMONS *et al.*, 2012; LONDON, 2018).

Pegmatites are igneous rocks of granitic composition that differ from other igneous lithologies (e.g., tonalites, granitoids) due to their complex textures, which is characterized by very coarse grain size, granulometric heterogeneity, and a wide variety of textural features, including graphic texture, directional growth, radial and/or skeletal textures (LONDON, 2008, 2018). This pronounced textural complexity is often accompanied by mineralogical variations which, collectively, enable the characterization of internal zoning of the pegmatitic bodies. This zoning may be simple, comprising only primary zones, or complex, which exhibit additional secondary late-stage replacement units. In addition to internal zoning, pegmatites may also contain miarolitic cavities formed during the final crystallization stages of their melts (CAMERON *et al.*, 1949; LONDON, 2018). According to the most widely accepted petrogenetic models, pegmatitic melts may originate through the magmatic fractionation of parental granitic plutons, or by anataxis, a low-degree partial melting process of pre-existing rocks (SIMMONS, 2007; SIMMONS and WEBBER, 2008).

The most comprehensive and widely used pegmatite classification systems include the Classification System by Černý (1991), later revised by Černý and Ercit (2005), and the New Classification System proposed by Wise *et al.* (2022). The former is based on the pressure-temperature conditions of pegmatite formation and their chemical composition as classification criteria, whereas the latter uses mineralogical composition as a first-order classification criterion. According to Wise *et al.* (2022), these systems use the main measurable criteria for the study of pegmatites (chemical and mineralogical composition). These classification systems provide crucial insights into the origin and evolution of pegmatitic melts and are, therefore, fundamental to their petrogenetic investigation.

Despite the extensive study of pegmatites in international literature, primarily due to their high concentrations of rare elements, there remains a notable scarcity of sources in Portuguese that address the fundamental concepts necessary for understanding these rocks. Such resources are highly relevant for scientific dissemination, serve as valuable educational tools in undergraduate geology courses, and provide essential guidance for field identification. Accordingly, the aim of this article is to present a comprehensive review of the key concepts for an introductory understanding of pegmatites, including their definition, petrogenetic models, internal structure, and the principal classification systems based on measurable characteristics.

2. Definition of pegmatite

The term pegmatite was originally used by Brogniart in 1813 to refer to igneous rocks exhibiting intergrowths of quartz and perthitic microcline (K-feldspar), with granites displaying this texture being referred to as graphic granites. Later, in 1845, Haidinger broadened the concept of pegmatite to also include very coarse-grained granitic segregations and dikes, regardless of the presence of graphic granite (LONDON, 2008). According to more recent definitions, pegmatite in the strict sense is a textural term used to describe the coarse to very coarse texture of intrusive igneous rocks (ČERNÝ *et al.*, 2003; SIMMONS, 2007; SIMMONS and WEBBER, 2008).

A more comprehensive and widely adopted definition of pegmatites is provided by London (2008) and revisited by London (2018). According to these studies, pegmatites are essentially igneous rocks, predominantly of granitic composition, derived from silica-rich magmas also enriched in volatile components (e.g., B, Li, F, P, CO₂ and H₂O) and rare elements (e.g., Be, Cs, Ga, Nb, Ta, Ti, Y, REEs). These rocks are distinguished from other igneous rocks by their complex textures, characterized by very coarse grain size, granulometric heterogeneity, mineralogical zoning, and a wide variety of textural features, which may include graphic texture, directional growth, radial and/or skeletal textures (Figure 1).

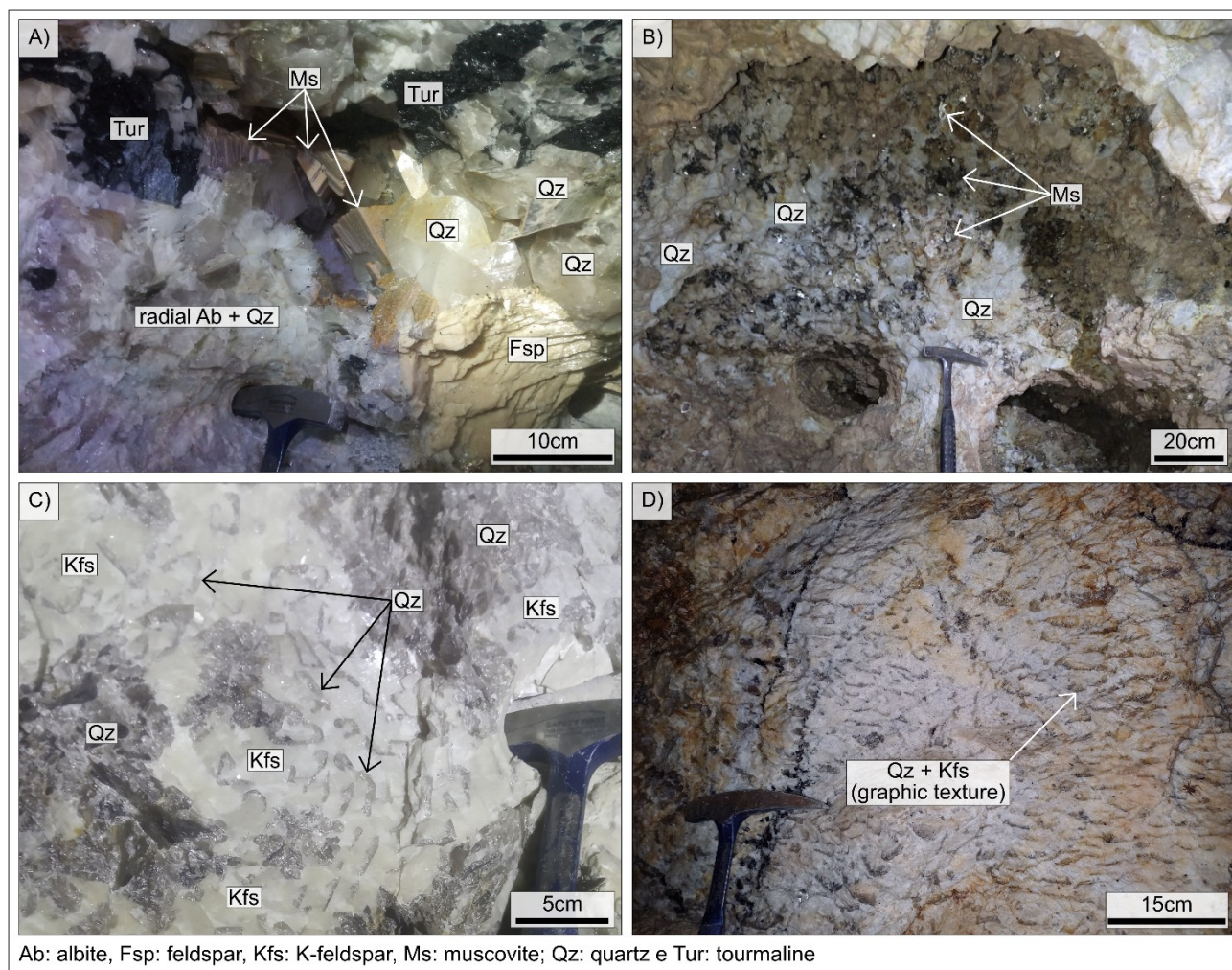


Figure 1 – Examples of pegmatites from the São José da Safira Pegmatite District/MG, showing their granitic composition and textural complexity. A-B) Very coarse texture formed by a predominantly granitic mineralogy. C-D) Graphic texture characterized by the intergrowth of quartz (colorless) and microcline (K-feldspar - white). Source: Authors (2025).

The predominant granitic composition of pegmatites consists of quartz, plagioclase, and K-feldspar in roughly equal proportions, which generally account for more than 80% of the total composition. In addition, apatite, beryl, fluorite, and tourmaline are the most common minor (<5%) and accessory (<1%) minerals. Pegmatites may also exhibit gabbroic, syenitic, komatiitic and carbonatitic compositions, however, these varieties are uncommon and rarely described in the literature (LONDON, 2008, 2018; SIMMONS, 2007).

The average intrusion temperature of pegmatitic magma into its country rock is around $700 \pm 50^\circ\text{C}$ (SIRBESCU *et al.*, 2008), while the crystallization temperature of these magmas ranges between 400 and 700°C (MCCAFFREY and JOWITT, 2023).

The crystallization of pegmatitic magmas occurs rapidly (BARROS, 2017; LONDON, 2018; SIMMONS *et al.*, 2003), on the timescale of days (WEBBER *et al.*, 1999) to months or years (CHAKOUMAKOS and LUMPKIN, 1990). This rapid crystallization is attributed to the enrichment of pegmatitic magmas in volatile components, which reduces their nucleation rate, crystallization temperature and viscosity, leading to the formation of supercritical fluids. The volatile enrichment also increases ion diffusion rates, solubility and mineral growth rates, resulting in the crystallization of fewer but significantly larger mineral grains, which gives rise to the coarse to very coarse texture characteristic of pegmatites (SIMMONS, 2007; SIMMONS and WEBBER, 2008; VERNON, 2004).

3. Petrogenetic models

The most widely accepted petrogenetic models for the origin of pegmatites currently include: (i) magmatic fractionation of parental granitic plutons, or (ii) anatexis, a low-degree partial melting process of pre-existing rocks (SIMMONS, 2007; SIMMONS and WEBBER, 2008) (Figure 2).

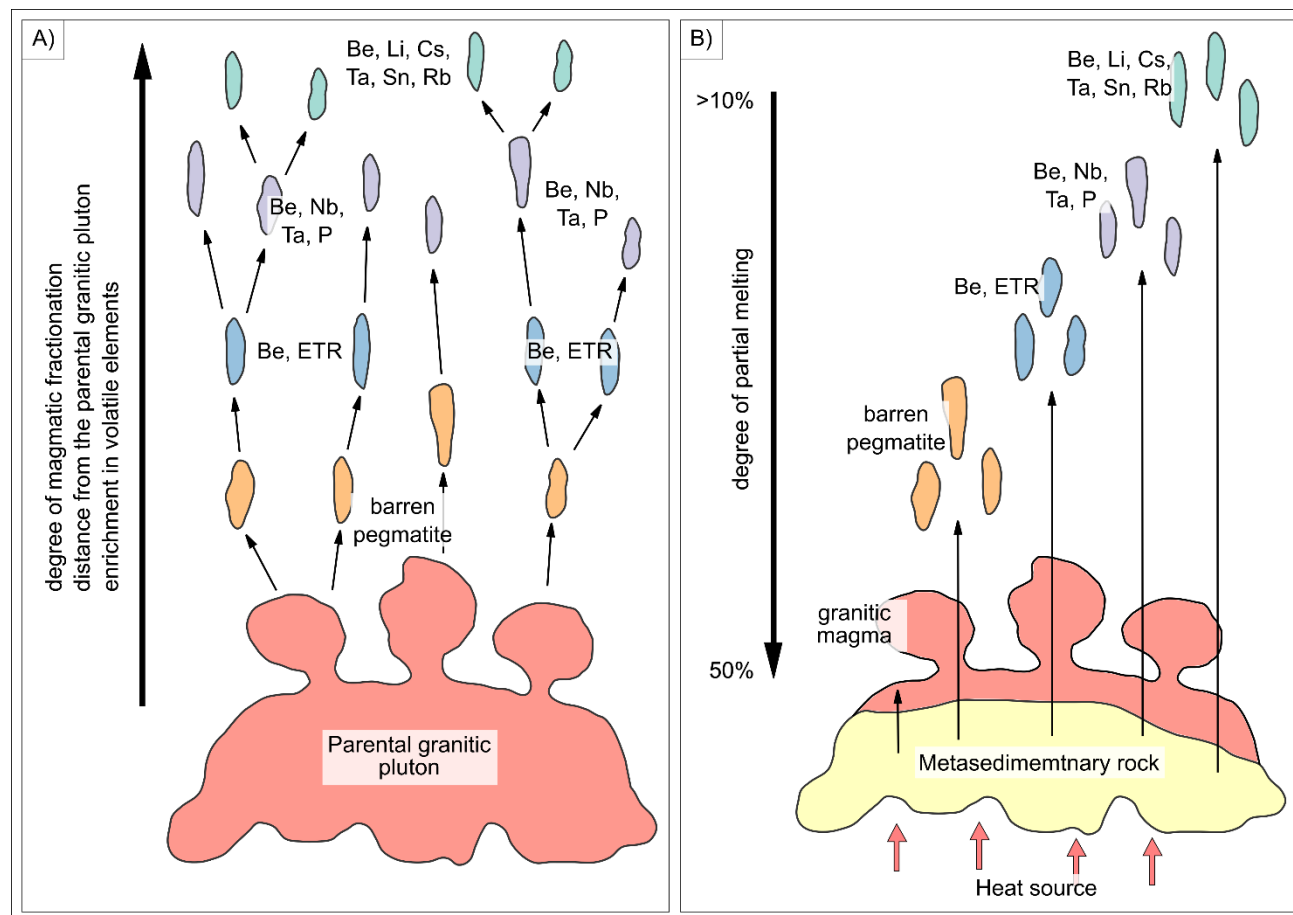


Figure 2 – Petrogenetic models for pegmatite formation. A) Model of magmatic fractionation showing pegmatites formed at different fractionation degrees. B) Model of anatexis indicating pegmatites generated at different degrees of partial melting.

Source: Modified from Shearer *et al.* (1992).

3.1. Magmatic fractionation

In the magmatic fractionation model, pegmatites are formed from the crystallization of residual melts derived from the final stages of magmatic fractionation of parental granitic plutons (Figure 2A). In this model, pegmatites and their respective parental granites are syn-orogenic, comagmatic and contemporaneous (SIMMONS and WEBBER, 2008).

The early crystallization stages of the parental granitic plutons are dominated by the formation of K-feldspar, Na-plagioclase, quartz and muscovite \pm biotite. The crystallization of these minerals results in the incorporation of elements such as Si, Al, K, Na and O. However, elements with very large or very small ionic radii and/or charges (e.g., Cs^+ , Rb^+ , Sr^{2+} , Ta^{5+} , Nb^{5+} , P^{5+} , Th^{4+} , Ti^{4+} , ETR^{3+} , Li^+ , Be^{2+} and B^{3+}) are poorly accommodated within the crystal structures of these minerals. These are referred to as incompatible elements. Incompatible elements tend to remain in the residual melt during the fractional crystallization process. The same behavior is observed for water and other volatile components present in

the system (e.g., B, F, Li e CO₂). Consequently, incompatible elements and volatile components become progressively enriched in the residual melt throughout the fractional crystallization of the parental granitic pluton. The residual melts resulting from the final stages of this process are the pegmatitic melts which, upon crystallization, give rise to pegmatites formed through magmatic fractionation (SIMMONS, 2007; SIMMONS *et al.*, 2003).

In this model, the continuous enrichment of volatiles leads to a progressive decrease in the viscosity of the residual melt. As a result, there is a progressive increase in the capacity of these fluids to migrate over longer distances (SIMMONS and WEBBER, 2008). Thus, pegmatites formed through magmatic fractionation tend to exhibit a concentric spatial distribution around the parental granitic pluton. The farther a pegmatite body is from its granitic parental pluton, the higher its degree of magmatic fractionation (Figure 2A). As a result, a regional geochemical zoning is established (ČERNÝ, 1991; LONDON, 2008; SIMMONS and WEBBER, 2008).

3.2. Anatexis

In the anatexis model, pegmatites are formed from the crystallization of pegmatitic melts generated by low-degree partial melting of pre-existing rocks (Figure 2B). Among the main protoliths involved in this process, marine metasedimentary sequences with evaporite intercalations stand out. These rocks may serve as sources of both incompatible elements (e.g., Be, Ba, Cs, Nb, Rb, Sr, Ta, Ti, Th, U, Zr and REEs) and volatile components (e.g., B, F, Li, P, H₂O and CO₂), which are essential for the generation of pegmatitic melts (SIMMONS and WEBBER, 2008).

In general, high-degree melting of metasedimentary rocks can generate large volumes of peraluminous S-type granitic magmas, whose subsequent fractionation can generate pegmatitic melts. However, if a low-degree partial melting event occurs, incompatible elements and volatiles may be preferentially partitioned into the fluid phase, resulting in the direct formation of pegmatitic melts without the need for derivation from a parental granitic magma (SIMMONS, 2007; SIMMONS *et al.*, 1995; SHAW *et al.*, 2016) (Figure 2B).

According to Černý *et al.* (2012), most of the incompatible elements and volatiles that define the signature of pegmatitic melts formed by anatexis are present in the white micaceous minerals (muscovite, paragonite, phengite) and biotite of their metasedimentary protoliths. These micaceous minerals tend to undergo significant dehydration at the onset of partial melting (low-degree melting), making incompatible elements and volatiles available in the generated melt. This process generally does not continue for long due to the low concentrations of fluxing agents (e.g., Na and Li) in the bulk rock. As a result, melting of these metasedimentary sequences tends to be arrested at low degrees of partial melting, giving rise to pegmatitic melts formed by anatexis.

In this model, the heat source responsible for low-degree partial melting may be related to adjacent granitic intrusions, without the need for these intrusions to be comagmatic with the pegmatitic melts (BARROS, 2017). Unlike pegmatites formed by magmatic fractionation, the spatial distribution of pegmatites formed through anatexis does not exhibit an evident regional geochemical zoning (ČERNÝ, 1991).

4. Internal structure of pegmatites

Pegmatites can be described based on their internal structure as: (i) simple or unzoned; (ii) simply zoned; or (iii) complexly zoned. When present, internal zoning in pegmatites is characterized by textural and/or mineralogical variations (Figures 3 and 4) (CAMERON *et al.*, 1949; LONDON, 2018).

Simple or unzoned pegmatites are textural and mineralogical homogeneous bodies and represent the most common variety. These pegmatites are generally associated with high-grade metamorphic host rocks, formed under temperatures around 800°C and pressures above 2.5 kbar (CAMERON *et al.*, 1949; LONDON, 2008). The mineralogical composition of simple pegmatites predominantly consists of K-feldspar, plagioclase and quartz, along with subordinate amounts of mica-group minerals (SIMMONS *et al.*, 2003; LONDON, 2018).

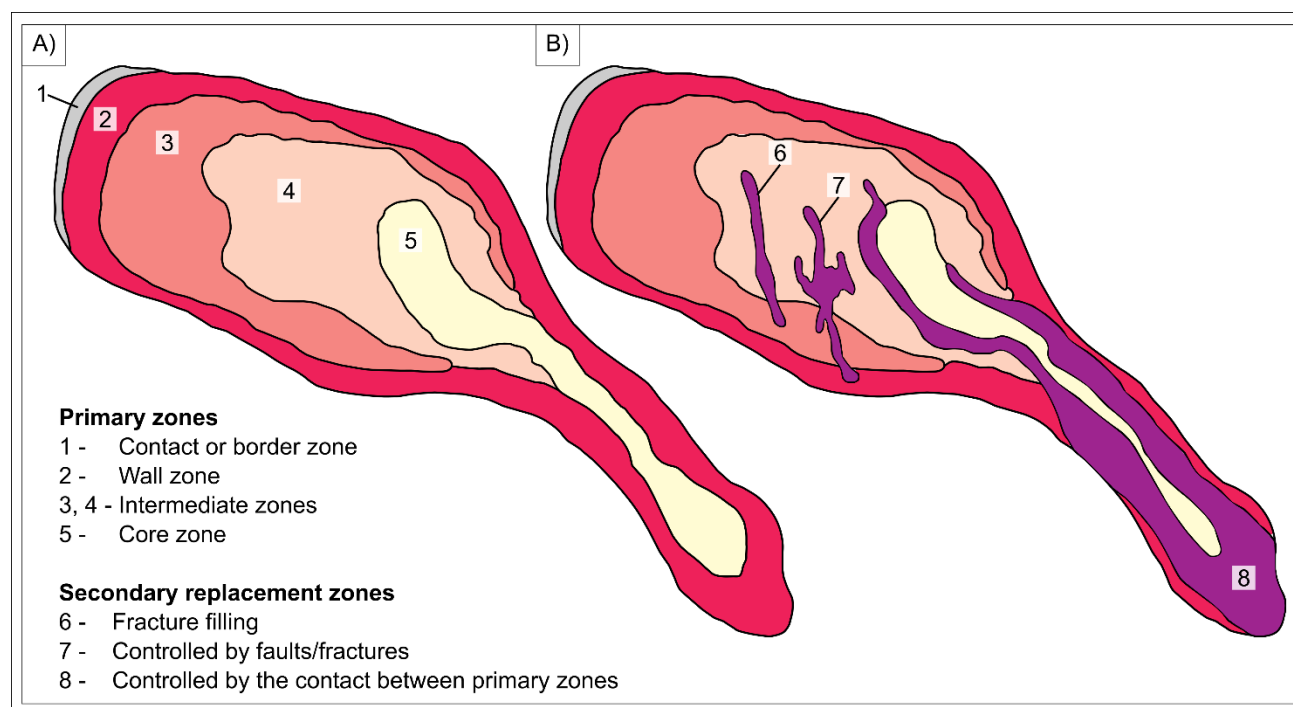


Figure 3 – Schematic representation of the internal structure of pegmatites. A) Pegmatite with simple zoning. B) Pegmatite with complex zoning.

Source: Modified from Simmons *et al.* (2003).

Simply zoned pegmatites are heterogeneous bodies that exhibit internal zoning marked by textural and/or mineralogical variations. From the outermost to the innermost part, the zoning of these pegmatites typically consists of the border or contact zone, wall zone, one or more intermediate zones and the core zone (Figures 3A and 4). These zones are primary structures formed during the cooling and fractional crystallization of the pegmatitic melt itself, with crystallization progressing from the margins toward the core, as evidenced by increasing grain size and directional growth of minerals toward the center. This zoning is generally concentric and tends to follow the external shape of the pegmatitic body (CAMERON *et al.*, 1949; LONDON, 2008, 2018; SIMMONS, 2007). Figure 5 presents the main characteristics of each of these zones.

Complexly zoned pegmatites exhibit the same primary zones as the simply zoned pegmatites (contact or border, wall, intermediate and core zones), with the addition of superimposed secondary zones resulting from late-stage replacement or metasomatic alteration. These secondary zones occur as irregular masses, often concentrated along the contact between the core and intermediate zones, or as fillings of internal fractures (Figure 3B). Apparently, the replacement zones result from the interaction between a highly fractionated residual pegmatitic melt and the primary minerals, promoting albitization of K-feldspars. This replacement reaction releases K_2O back into the residual melt and typically leads to the formation of a secondary mineral assemblage composed of albite + mica \pm lepidolite (CAMERON *et al.*, 1949; SIMMONS, 2007). Unlike the primary zones, secondary replacement zones may not be concentric or follow the external shape of the pegmatitic body (SIMMONS, 2007).

Complexly zoned pegmatites are formed through the crystallization of highly fractionated residual pegmatitic melts enriched in incompatible elements and volatile components (SIMMONS, 2007). These pegmatites are generally located farther from their parental granites and are very rare compared to other types, representing less than 1% of the occurrences within a pegmatite district (CAMERON *et al.*, 1949).

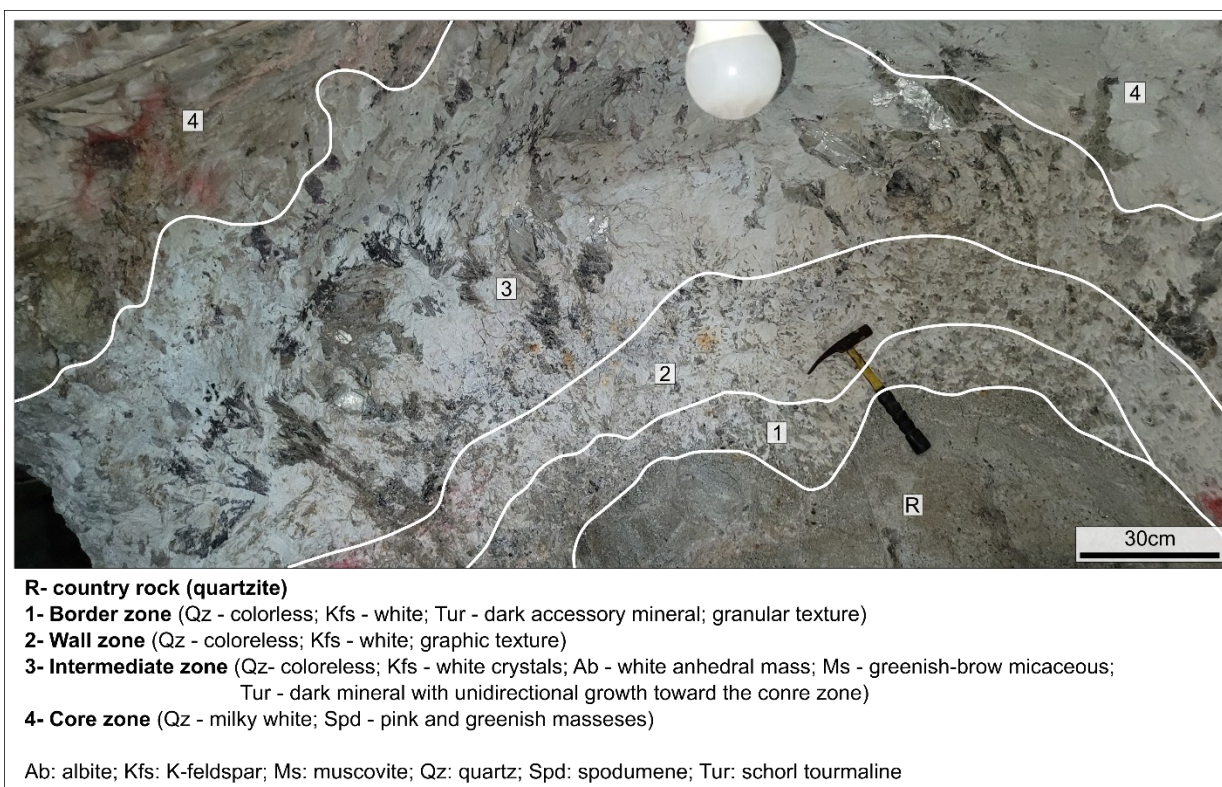


Figure 4 – Photo of the Quintos pegmatite from the Borborema Pegmatite Province/RN showing its primary internal zones.

Source: Authors (2025).

Zone	Texture	Main mineralogy	Accessory minerals	Others characteristics
Contact or border	fine grain size, granular texture, possible aplitic layer with millimetric grains	plagioclase, quartz ± muscovite	apatite, beryl, biotite, columbite, garnet, magnetite, microcline, schorl tourmaline	contact with the country rock
Wall	coarse grain size, graphic texture, unidirectional growth texture	K-feldspar or plagioclase, quartz ± muscovite	apatite, beryl, garnet, schorl tourmaline	abrupt increase in grain size
Intermediate (one or several)	very coarse grain size, miarolitic cavities	K-feldspar, quartz, muscovite, Na-plagioclase	beryl, phosphates, Nb and Ta oxides, schorl to elbaite tourmaline	thickest zone, highest concentration of K-feldspar
Core	coarse grain size, massive texture	quartz	albite, beryl, spodumene, phosphates	usually monomineralic

Figure 5 – Main characteristics of the primary internal zoned of zoned pegmatites. The colors used for each primary zone are the same as those shown in Figure 3.

Source: Compiled from Cameron *et al.* (1949), London (2008, 2018), Simmons (2007).

4.1. Mirolitic cavities

Mirolitic cavities in pegmatites can be either primary or secondary. Primary cavities are more favorable for the growth of gem-quality minerals and, therefore, have greater economic importance in gemstone production (CASSEDANNE and PHILIPPO, 2015; SIMMONS, 2007; SIMMONS *et al.*, 2003). These primary mirolitic cavities tend to concentrate in the intermediate zone of simply or complexly zoned pegmatites, near the contact with the core zone. They may be filled with minerals, aqueous fluids and/or clay-rich material (CAMERON *et al.*, 1949; LONDON, 2008; SIMMONS, 2007).

Primary mirolitic cavities represent volatile-rich bubbles trapped in a low-density pegmatitic melt. Their formation occurs through the exsolution of volatile components as a result of two main processes, or a combination of both: i) adiabatic decompression during the ascent of the pegmatitic melt through the crust; and/or ii) supersaturation due to residual enrichment in volatile elements during the ongoing fractional crystallization of the pegmatitic melt (SIMMONS, 2007; SIMMONS *et al.*, 2003). These cavities typically form during the final stages of crystallization of the pegmatitic melt (SIMMONS, 2007), under temperatures around $420 \pm 45^\circ\text{C}$, which are always lower than those during the crystallization of the rest of the pegmatite body, usually between 400 and 700°C (MCCAFFREY and JOWITT, 2023). Primary mirolitic cavities may take thousands of years to reach their final crystallization stage, in contrast to the rapid crystallization of the rest of the pegmatite body, which occurs over a timespan of days, months, or years (LONDON, 2018).

In contrast, secondary mirolitic cavities, also known as dissolution cavities, are formed through secondary replacement reactions that dissolve part of the primary mineral assemblage and result in the formation of secondary minerals. These reactions may occur due to the introduction of metasomatic or hydrothermal fluids and/or meteoric water during post-crystallization stages of the pegmatitic melt (CASSEDANNE and PHILIPPO, 2015; SIMMONS, 2007; SIMMONS *et al.*, 2003).

5. Classification systems

According to Müller *et al.* (2022), any classification system, as a process of naming and categorizing objects based on observable similarities, must be founded on measurable criteria. This section presents the pegmatite classification systems proposed by Černý (1991), later revised by Černý and Ercit (2005), and the New Classification System proposed by Wise *et al.* (2022). These systems are based on measurable criteria (such as P–T conditions of formation, chemical composition and mineralogy), and are also considered the most comprehensive and widely used at present for classification of pegmatites.

5.1. Classification System by Černý (1991) and revisited by Černý and Ercit (2005)

The pegmatite Classification System proposed by Černý (1991) and later revisited by Černý and Ercit (2005) is primarily based on the depth and P–T conditions of pegmatite formation, inferred from the metamorphic P–T conditions of their country rock. This system distinguishes five pegmatite classes: Abyssal, Muscovite, Muscovite–Rare-Element, Rare-Element and Mirolitic (Figure 6). Based on geochemical signatures and mineralogical constituents, these classes are further subdivided into subclasses, types and subtypes (Figure 6).

In addition, Černý (1991) and Černý and Ercit (2005) also propose an independent classification system for pegmatites that relies on their geochemical signature as the main criterion. This approach aims to investigate their petrogenesis and the compositional characteristics of their parental granitic plutons and/or partial melting source rocks. This classification defines three families: NYF) pegmatites enriched in niobium–yttrium–fluorine; LCT) pegmatites enriched in lithium–cesium–tantalum; and NYF+LCT) pegmatites with a mixed geochemical signature (Figure 6).

5.1.1. Classes

The Abyssal class comprises pegmatites formed under pressure conditions ranging from 4 to 9 kbar and temperatures between 700 and 800°C , associated with country rocks of upper amphibolite to granulite facies (Figure 7). Their geochemical signature is characterized by the presence of B, Be, REEs, Th and U. Pegmatites of this class are generally generated by anatexis and are rarely associated with a parental granite (ČERNÝ and ERCIT, 2005).

The Muscovite class includes pegmatites generated under pressure conditions between 5 and 8 kbar and temperatures ranging from 580 to 650°C , associated with country rocks of high-pressure amphibolite facies (Figure 7). Pegmatites of this class are barren, characterized by a predominance of feldspar, quartz and industrial micas. Their geochemical signature

may include Ba, Ca, Fe > Mn and Sr. Genetically, these pegmatites may represent products of anatexis or can be associated with restricted magmatic fractionation of parental granites (ČERNÝ and ERCIT, 2005).

Class	Subclass	Type	Subtype	Family
Abyssal	heavy RRE	-	-	NYF
	light REE	-	-	NYF
	U	-	-	NYF
	B, Be	-	-	LCT
Muscovite	-	-	-	LCT
Muscovite - Rare-element	REE	-	-	NYF
	Li	-	-	LCT
Rare-element	REE	Allanite-monazite	-	NYF
	REE	Euxenite	-	NYF
	REE	Gadolinite	-	NYF
	Li	Beryl	Beryl-columbite	LCT
	Li	Beryl	Beryl-columbite-phosphate	LCT
	Li	Complex	Spodumene	LCT
	Li	Complex	Petalite	LCT
	Li	Complex	Lepidolite	LCT
	Li	Complex	Elbaite	LCT
	Li	Complex	Ambligonite	LCT
	Li	Albite-spodumene	-	LCT
	Li	Albite	-	LCT
Mirolitic	REE	Topaz-beryl	-	NYF
	REE	Gadolonite-fergusonite	-	NYF
	Li	Beryl-topáz	-	LCT
	Li	Spodumene	-	LCT
	Li	Petalite	-	LCT
	Li	Lepidolite	-	LCT

Figure 6 – Classification of granitic pegmatites according to the system of Černý (1991) and Černý and Ercit (2005).
Source: Černý and Ercit (2005).

The Muscovite–Rare-element class is characterized by pegmatites formed under moderate pressure (3 to 7 kbar) and temperature (520 to 650°C) conditions, associated with country rocks of amphibolite facies (Figure 7). These pegmatites occupy an intermediate position between the Muscovite and Rare-element classes, exhibiting features of both. They may contain both industrial minerals (e.g., feldspars, muscovite, quartz) and rare-element minerals (e.g., beryl, cassiterite,

columbite-group minerals, Li-silicates and oxides of REEs, Nb and U). Their geochemical signature tends to be characterized by the presence of Be, REEs, Li, Nb–Ta, Th, Ti, U and Y. Genetically, these pegmatites tend to be discordant with the metamorphic foliation of the country rock and may occasionally exhibit regional geochemical zoning related to the evolution of a parental granite (ČERNÝ and ERCIT, 2005).

The Rare-element class comprises pegmatites generated under low-pressure conditions (2 to 4 kbar) and temperatures ranging from 450 to 650°C, associated with country rocks of greenschist to amphibolite facies (Figure 7). Their geochemical signature may include B, Be, Cs, REEs, F, Li, Nb > Ta, P, Rb, Sn, Th, Ti, U, Y and Zr. Genetically, this class is subdivided into: i) pegmatites formed by the fractionation of post-orogenic to anorogenic metaluminous to peraluminous granite plutons, in an extensional crustal setting; or ii) pegmatites derived from the fractionation of syn- to late-orogenic peraluminous granite plutons, typical of compressional orogenic regimes (ČERNÝ, 1991).

The Miarolitic class represents pegmatites rich in primary miarolitic cavities. Miarolitic cavities can be found in all other pegmatite classes, but in much smaller quantities and dimensions. Pegmatites of the Miarolitic class form under extremely low-pressure conditions (1.5 to 3 kbar) and temperatures between 400 and 500°C, associated with country rocks of low-pressure greenschist to amphibolite facies (Figure 7). Their geochemical signature is marked by the presence of B, Be, REEs, F, Li, Nb, Ti, U, Y and Zr. Genetically, these pegmatites may originate from: i) the fractionation of anorogenic parental granites; or ii) the fractionation of syn- to late-orogenic peraluminous granite plutons, typical of compressional orogenic regimes (ČERNÝ and ERCIT, 2005).

5.1.2. Families

NYF-family pegmatites are characterized by enrichment in niobium–yttrium–fluorine, as well as Nb > Ta, Be, heavy REEs, Sc, Ti, Th, U, Zr and high FeO/MgO ratios. Their typical mineralogy includes Nb-columbite, euxenite (an oxide of Y, Ce, U, Th and Nb), fergusonite (an oxide of Nb and Y), gadolinite (a silicate of Ce, La, Nd and Y), hematite, magnetite, beryl, feldspar and quartz, in addition to allanite, monazite and xenotime (a Y-phosphate) as accessory minerals (ČERNÝ, 1991; ČERNÝ and ERCIT, 2005). Considerable amounts of fluorite and topaz are commonly found in these pegmatites, evidencing their fluorine enrichment (ČERNÝ and ERCIT, 2005; MAHMOUD, 2019). Biotite is the predominant mica in NYF-family pegmatites (LONDON, 2018). These pegmatites typically exhibit a metaluminous signature (ČERNÝ and ERCIT, 2005). Compared to LCT-family, the NYF-family pegmatites tend to show a lower degree of fractionation (BARROS, 2017; ČERNÝ, 1991; ČERNÝ and ERCIT, 2005).

As summarized by Černý and Ercit (2005) and discussed in detail by Černý (1991), geochemical, petrological and isotopic evidence suggests several models for the generation of melts which form the NYF-family pegmatites: i) differentiation of mantle-derived basaltic magmas; ii) partial melting of intermediate to lower crustal protoliths previously modified by earlier melting events that mobilized Li, Cs and Ta, while preserving Ni, Y and F; iii) melting of juvenile, undepleted lithologies in an orogenic setting; iv) a combination of models (ii) and (iii); or v) melting of sialic crust enriched in NYF elements by mantle-derived fluids.

LCT-family pegmatites are typically enriched in lithium-cesium-tantalum, in addition to Ta>Nb, B, Be, Cs, Ga, F, Hf, Mn, P, Rb and Sn, and display a high degree of fractionation (BARROS, 2017; ČERNÝ, 1991; ČERNÝ and ERCIT, 2005; LONDON, 2008; SIMMONS and WEBBER, 2008). The mineral assemblage of this family is characterized by the presence of spodumene, lepidolite, petalite (Li and Al phyllosilicate), amblygonite-montebrazite (Li and Al phosphates), albite, K-feldspar, muscovite and quartz, as well as fluorapatite, beryl, Ta-columbite, elbaite-group tourmaline (Na- and Li-rich tourmaline), garnet and topaz as accessory minerals. Li enrichment is the main characteristic of these pegmatites (ČERNÝ and ERCIT, 2005). The high Li content is generally attributed to the melting of micaceous minerals present in the source rock and the incompatibility of this chemical element in residual minerals (LONDON, 2008). The greater abundance of Ta relative to Nb in LCT pegmatites indicates a higher degree of fractionation compared to NYF-family pegmatites (LINNEN *et al.*, 2012). LCT pegmatites tend to be peraluminous (ČERNÝ and ERCIT, 2005).

As summarized by Černý and Ercit (2005), melts forming LCT-family pegmatites may originate from: i) anatexis of metavolcanic and/or metasedimentary protoliths of the undepleted upper to middle crust; ii) low-grade anatexis of basement rocks; or iii) high-degree magmatic fractionation of parental granitic plutons.

NYF+LCT-family pegmatites display mixed geochemical and mineralogical characteristics from the two aforementioned families. NYF+LCT pegmatites tend to exhibit a moderately peraluminous to metaluminous geochemical signature. The main proposed models for the origin of NYF+LCT pegmatitic melts include: i) contamination of NYF-element-bearing magmas derived from depleted crust by melting of undepleted supracrustal lithologies; ii) melting of partially depleted crustal protoliths; or iii) anatexis of mixed depleted and undepleted protoliths (ČERNÝ and ERCIT,

2005).

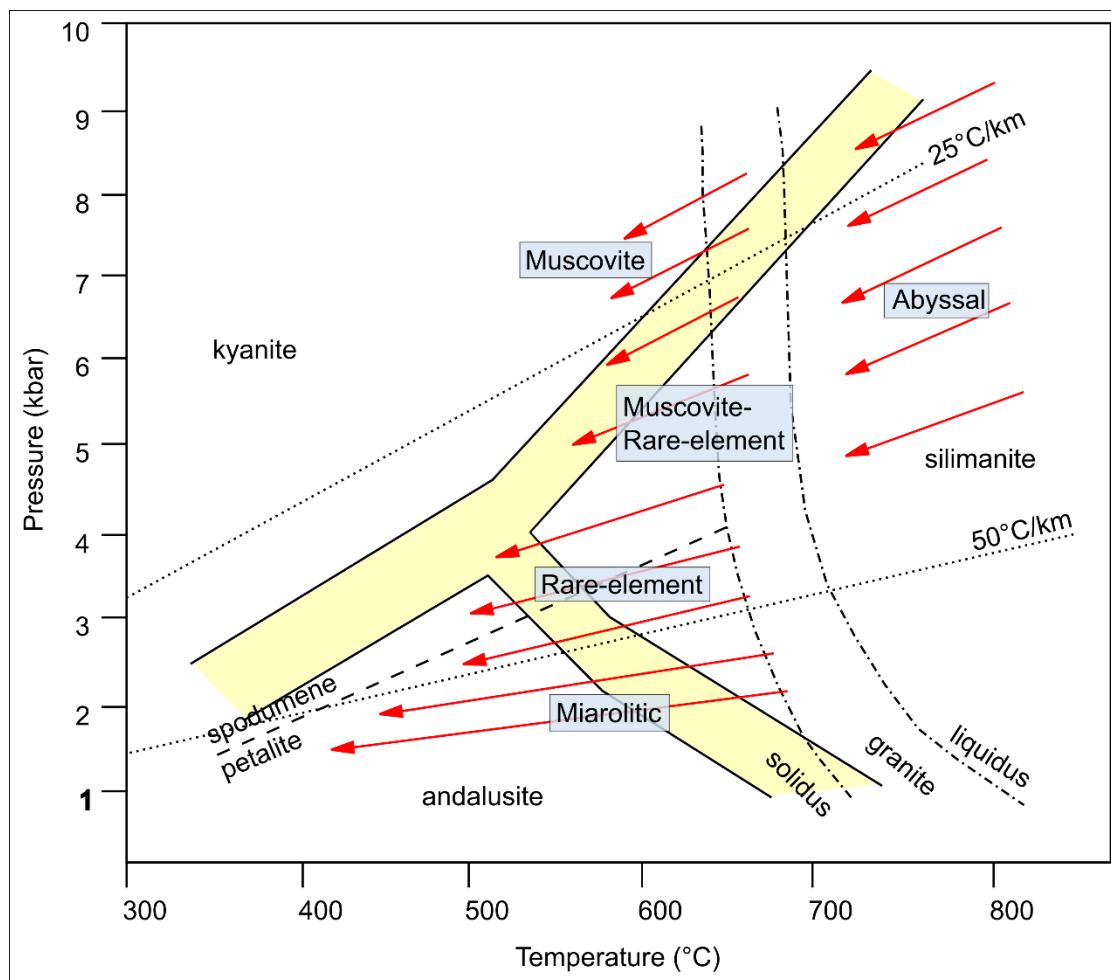


Figure 7 – P–T diagram showing the pressure and temperature conditions for the formation of pegmatites of the Abyssal, Muscovite, Muscovite–Rare-element, Rare-element and Mirolitic classes. The arrows indicate pegmatitic fractionation trends related to the metamorphic grade of the host rocks.

Source: Modified from Černý and Ercit (2005).

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

The New Classification System for pegmatites proposed by Wise *et al.* (2022) uses the primary mineral assemblage as the first-order classification criterion, defining Groups 1, 2 and 3 (Figure 8), followed by a refinement based on the mineral chemistry of the pegmatite body, which allows its petrogenetic classification as either RMG (residual melts from granitic magmatism) or DPA (direct product of anatexis) (Figure 9). According to Wise *et al.* (2022), in addition to the mineralogical and geochemical constituents being measurable characteristics, they can also be identified through initial field observations.

5.2.1. Groups

Group 1 includes pegmatites enriched in B, Be, Cs, F, Ga, Li, P, Rb, Sn and Ta>Nb, which can be subdivided into three types: i) pegmatites with beryl ± phosphate; ii) Li-enriched pegmatites with dominant spodumene or petalite; or iii)

pegmatites with lepidolite or elbaite-tourmaline as the main Li-bearing mineral phases (Figure 8). In general, pegmatites of this group tend to exhibit enrichment in P compared to the other groups and are characterized by the presence of fluorapatite, graftonite, sarcopside and triphylite-lithiophilite. The most highly fractionated pegmatite occurrences in this group may also contain minerals of the amblygonite–montebrasite series and cleavelandite-type albite (WISE *et al.*, 2022).

Group 1	Group 2	Group 3
pegmatites with beryl ± phosphates	pegmatites enriched in Fe-bearing minerals	pegmatites with primary andalusite, kyanite, cordierite or sillimanite
Beryl ± columbite ± triphylite ± graftonite	Arfvedsonite-ribeckite ± faialite	Andalusite ± sillimanite ± corundum
Beryl + amblygonite + columbite	Arfvedsonite-ribeckite ± aegirine ± fluorite	Kyanite ± rutile
Li-enriched pegmatites with dominant spodumene or petalite	pegmatites with magnetite ± uraninite ± REE oxides and silicates	Cordierite ± beryl
Amblygonite + spodumene	Uraninite ± magnetite	Sapphirine + sillimanite
Spodumene ± petalite	Fayalite ± magnetite	pegmatites with chrysoberyl
pegmatites with lepidolite or elbaite tourmaline as the main Li-bearing phases	Allanite ± gadolinite	Chrysoberyl ± beryl ± schorl
Spodumene ± elbaite	Allanite ± monazite ± euxenite	pegmatites with borosilicate, dumortierite, grandidierite and werdingite as B mineralization
Spodumene + lepidolite + elbaite	Allanite ± beryl ± columbite	Dumortierite ± grandidierite ± borosilicate
Spodumene + albite	Gadolinite ± euxenite ± fergusonite	Dumortierite ± schorl
Lepidolite + elbaite	pegmatites enriched in Be and F	
Elbaite ± danburite ± hambergite ± zeolite	Beryl ± topaz ± fluorite	
	Beryl ± phenakite	
	Microcline (amazonite) ± fluorite	
	Microcline (amazonite) ± topaz ± fluorite	

Figura 8 – Classification of pegmatites into groups based on their mineral constituents according to the New Classification System proposed by Wise *et al.* (2022).

Source: Wise *et al.* (2022).

Group 2 includes pegmatites predominantly composed of quartz and feldspar, as well as fluorite, helvite, magnetite and hyalite opal as accessory minerals that contribute to distinguishing them from Group 1 pegmatites. Other notable features that differentiate Group 2 pegmatites from the others include a predominance of microcline with amazonite levels among the alkali feldspars, biotite as the dominant micaceous mineral, the presence of amethyst as a variety of quartz, and, when present, spessartine as a garnet variety. The main types of pegmatites in this group are: i) pegmatites enriched in Fe-bearing minerals, such as biotite, fayalite and sodic amphibole; ii) pegmatites with magnetite, uraninite and REE oxides and silicates; and iii) pegmatites enriched in Be and F, containing beryl, fluorite and topaz (Figure 8). Cryolite, fluorite and topaz are the main F-bearing mineral phases in the pegmatites of this group, while Fe-lepidolite and zinnwaldite are the principal Li-bearing minerals (WISE *et al.*, 2022).

Group 3 categorizes highly peraluminous pegmatites with a mineral assemblage composed essentially of K-feldspar, plagioclase and quartz, along with biotite, garnet, muscovite and tourmaline as accessory minerals. The main types of pegmatites in this group are: i) pegmatites with primary andalusite, kyanite, cordierite or sillimanite; ii) pegmatites with chrysoberyl; and iii) pegmatites with borosilicates such as dumortierite, grandidierite and werdingite as B-bearing

mineralization (Figure 8). Additionally, pegmatites of this group may contain corundum, ilmenite, ferberite, fluorapatite, Ce-monazite, rutile and Y-xenotime (WISE *et al.*, 2022).

5.2.2. Types

RMG-type pegmatites (residual melts of granitic magmatism) originate from the magmatic fractionation of parental granitic plutons with peralkaline, metaluminous, or peraluminous compositions and may be classified as S-, A- or I-type. RMG pegmatites enriched in B, Be, Cs, F, Li, Nb, P, Rb and Ta and with low concentrations of REEs, Ti, Y and Zr tend to belong to Group 1 and are typically derived from peraluminous S-type granitic plutons. These pegmatites and their respective parental plutons are interpreted as orogenic. Pegmatites with high concentrations of Cl, F, Ga, REEs, Nb, Ti, Th, U, Y, Zn and Zr tend to belong to Group 2 and are associated with peralkaline or metaluminous A-type granitic plutons. These pegmatites and their corresponding parental granitic plutons are interpreted as originating in a post-orogenic or anorogenic setting. Pegmatites derived from I-type metaluminous to peraluminous granites may belong to either Group 1 or Group 2 (Figure 9 – WISE *et al.*, 2022).

RMG (pegmatites formed by residual melts from granitic magmatism)			
Source rock	S-type granite	A-type granite	I-type granite
Chemical composition of the parental granite	Peraluminous	Peralkaline or metaluminous	Peraluminous to metaluminous
Relation between pegmatite/source	Inner to marginal	Inner to marginal	Inner to marginal
Pegmatite group	Group 1	Group 2	Group 1 or 2
Geochemical signature	B, Be, Cs, Li, Nb, P, Sn, Ta	Be, F, ETR, Nb	B, Be, Ca, ETR, Li, Nb, Ti
DPA (pegmatites formed by direct produtos of anatexis)			
Source rock	Rocks of amphibolite to granulite facies	Rocks of amphibolite to granulite facies	Rocks of amphibolite to granulite facies
Relation between pegmatite/source	Segregation of anatectic melts	Segregation of anatectic melts	Segregation of anatectic melts
Pegmatite group	Group 1	Group 2	Group 3
Geochemical signature	B, Be, Li, Nb, P, Ta	Be, ETR, U	Al, B, Be

Figure 9 – Main characteristics of RMG type pegmatites (residual melts from granitic magmatism) and DPA type pegmatites (direct product of anatexis) according to the New Classification System proposed by Wise *et al.* (2022).

Source: Wise *et al.* (2022).

DPA-type pegmatites (direct product of anatexis) originate from the partial melting of supracrustal rocks (e.g., metasedimentary rocks) and lithologies related to mantle-derived sources (e.g., amphibolites, gneisses), without any genetic relation to parental granitic plutons. These pegmatites generally occur as lenses and dikes intruded into high-grade metamorphic terrains (amphibolite to granulite facies). DPA-type pegmatites have representatives in Groups 1, 2 and 3, ranging from barren pegmatites to those highly enriched in rare-element minerals. Low-fractionation DPA pegmatites tend to contain hornblende, magnetite, titanite and uraninite as main accessory minerals, whereas moderately to highly fractionated DPA pegmatites include Ce-allanite, beryl, columbite-group minerals, elbaite, spodumene, (Li, Fe, Ca)-phosphates, Ce-monazite and Y-xenotime in their mineral assemblage (Figure 9 – WISE *et al.*, 2022).

6. Final considerations

Considering the significant textural, structural and mineralogical complexity of pegmatites summarized in this paper, it is recommended that any pegmatitic petrographic characterization study, investigation of their genetic evolution, or even understanding of the main features which should be observed in a field visit, be preceded by a review of the key concepts of pegmatites. This paper has therefore presented such a review, which includes the definition of pegmatites, a synthesis of the most widely accepted petrogenetic models, their internal structure and the most comprehensive and widely used pegmatite classification systems currently available, as an intention to offer a foundational source, written in Portuguese (the original paper), suitable for consultation prior to any petrographic and/or petrogenetic investigations. If a deeper understanding of pegmatites is still required, it is strongly recommended to consult the following internationally recognized publications: Černý (1991), Černý and Ercit (2005), London (2008, 2018), Simmons (2007), Simmons and Webber (2008) and Wise *et al.* (2022).

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