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| RESEARCH ARTICLE

Mineralogical investigation of Chumbalak Pegmatites in Eastern Afghanistan Kunar province Chapadara

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| ABSTRACT

Pegmatites represent a significant magmatic or segregated rock unit that constitutes a critical host for precious gemstones and rare-metal mineralization, rendering them a principal focus of economic geology research. This investigation presents a petrographic characterization of pegmatite bodies within the Chumbalak area, Darah Pech District, Kunar Province, eastern Afghanistan. Field reconnaissance confirmed the presence of numerous pegmatite veins, from which 5 representative samples were collected, comprising 3 from pegmatite bodies and two from the adjacent country rock. Petrographic analysis identifies quartz, K-feldspar, plagioclase, and mica as the dominant mineral assemblage, confirming the pegmatitic texture and composition, also accessory phases, notably schorl (Fe-rich tourmaline), muscovite, and biotite. Geochemical data indicate that the pegmatites were derived from the crystallization of residual, highly fractionated acidic melts. The enrichment of incompatible elements within these differentiated melts is consistent with their role as a source for rare-element mineralization.

| KEYWORDS

Pegmatite, Kunar Province, Dara Pech, Chumbalak, Petrographic, eastern Afghanistan,

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1. Introduction

Pegmatites represent a quintessential component of the Earth's upper crust, forming as the terminal products of protracted magmatic differentiation within granitic systems ([London, 2018]. Their exceptional grain size, intricate internal zoning, and remarkable mineralogical diversity are direct manifestations of crystallization from volatile-rich, highly evolved silicate melts. These residual melts, enriched in fluxes such as H_2O, F, and B, exhibit extreme fractionation, leading to the significant concentration of Large-Ion Lithophile Elements (LILE) and High-Field Strength Elements (HFSE), including lithium (Li), cesium (Cs), tantalum (Ta), niobium (Nb), beryllium (Be), tin (Sn), and rare-earth elements (REE) ([Černý, 1991]; [Linnen et al., 2012]. Consequently, granitic pegmatites are not only crucial for deciphering the final stages of crustal anatexis and melt evolution but are also the world's primary source of these technologically critical raw materials ([Simmons & Webber, 2008]; [Dill, 2015].
The genesis and classification of pegmatites have been subjects of extensive research, with models evolving to incorporate depth of emplacement, geochemical affinity, and the nature of the parental pluton ([Černý, 1991] [Martin & De Vito, The widely applied

classification by [Černý & Ercit (2005)]. delineates pegmatite families based on their petrogenetic lineage, with the rare-element (REL) and miarolitic classes being of paramount economic interest due to their association with strategic-metal and gemstone mineralization ([Tkachev, 2011]. The crystallization dynamics within these systems—spanning magmatic, magmatic-hydrothermal, and subsolidus regimes—create a complex paragenetic sequence that hosts an unparalleled array of mineral species ([London, 2005]; [Thomas & Davidson, 2012]. Understanding these processes is fundamental to global exploration models aimed at securing the supply of critical minerals essential for electronics, renewable energy infrastructure, and aerospace technologies ([U.S. Geological Survey, 2022]; [European Commission, 2023].
Geologically, Afghanistan is situated within the Tethyan Metallogenic Domain, a vast, complex orogenic belt formed by the closure of the Neo-Tethys Ocean and the subsequent collision between the Indian and Eurasian plates ([Şengör & Natal'in, 1996]; [Treloar & Izatt, 1993]. This protracted tectonic history, involving multiple episodes of subduction, accretion, and post-collisional magmatism from the Paleozoic through the Cenozoic, has endowed the Afghan crust with extraordinary mineral wealth, including world-class deposits of copper, gold, and gemstones ([Peters et al., 2011]; [Orris et al., 2014]. Specifically, eastern Afghanistan, encompassing the Kabul Block and the Hindu Kush ranges, is characterized by extensive belts of peraluminous granitoids of Mesozoic to Tertiary age, which serve as fertile parents for widespread pegmatite fields ([Debón & Le Fort, 1983]; [Heinhorst et al., 2000].

The pegmatites of the Hindu Kush region, including Kunar and neighboring provinces, have been historically renowned for yielding high-quality gem minerals such as tourmaline, beryl (including emerald), corundum, and kunzite (spodumene) ([Bowersox & Chamberlin, 1995]; [Giuliani et al., 2000]. Despite this recognized potential, the region remains markedly underexplored from a modern, systematic geological perspective. Decades of conflict and limited infrastructure have precluded detailed field mapping, petrographic analysis, and geochemical characterization, leaving significant gaps in our understanding of the petrogenesis, metallogenic specialization, and economic potential of these pegmatite systems ([Kettle & Anderson, 2018] [Shroder & Eqrar, 2021].
This study aims to address this critical knowledge deficit by presenting the first detailed petrographic and geochemical analysis of pegmatite bodies in the Chumbalak area, Darah Pech District, Kunar Province, eastern Afghanistan. Through integrated field reconnaissance, petrographic microscopy, and whole-rock geochemistry, this research seeks to: (1) characterize the mineralogical assemblage and textural relationships that define the pegmatites and their host environment; (2) determine the geochemical signature and degree of fractionation of the parental melts; (3) classify the pegmatites within established genetic frameworks; and (4) provide a preliminary evaluation of their rare-element mineralization potential, thereby contributing to the foundational geological knowledge required for future resource assessment in this strategically important region.

2. Methodology

2.1. Field Reconnaissance and Sampling

A systematic geological reconnaissance was conducted in the Chumbalak area, Darah Pech District, Kunar Province. The investigation focused on mapping the distribution, orientation, and field relationships of pegmatite veins with the surrounding metamorphic country rock. Following standard field protocols (Compton, 1985), (5) representative and fresh samples were selectively collected. The sample suite comprised (3) samples from the central, coarse-grained zones of prominent pegmatite bodies and (2) samples from the adjacent country rock to provide geological context. The geographic coordinates for each sample location were recorded using a handheld GPS unit.

2.2. Petrographic Thin Section Preparation

The rock samples were processed at the ministry of Petroleum and Mine and studied in the laboratory of KPU (Kabul Polytechnic University). Each sample was cut with a diamond saw to obtain a fresh, unweather slab. Standard petrographic thin sections, polished to a thickness of 0.027ml, were prepared from these slabs. The sections were mounted on glass slides with epoxy resin and polished on both sides, and were left uncovered to allow for detailed analysis of mineral optical properties under both plane-polarized (PPL) and cross-polarized (XPL) light.

2.3. Petrographic Microscopic Analysis

Detailed petrographic analysis was performed using a polarizing optical microscope. The examination protocol was designed to systematically characterize the samples (Humphries, 1992) and included:

2.4. Mineral Identification: Minerals were identified based on their diagnostic optical properties, including color, pleochroism, relief, cleavage, birefringence, and twinning patterns, following standard determinative criteria (Deer et al., 2013).
2.5. Modal Mineralogy: The volume percentage (modal abundance) of constituent minerals was estimated using visual comparison charts (Terry & Chilingar, 1955).

2.6. Textural Analysis: A detailed description of rock texture was undertaken, documenting grain size, shape, mutual boundaries, and specific intergrowths (e.g., graphic texture, perthitic exsolution) critical for confirming pegmatitic fabric and interpreting crystallization history (London, 2008).

2.7. Paragenetic Interpretation: The sequence of mineral crystallization was inferred based on textural relationships such as inclusions, replacements, and overgrowths.

2.8. Accessory Mineral Documentation: Special attention was paid to identifying and characterizing accessory phases (e.g.,Feldspar, micas), which are key petrogenetic indicators in pegmatite systems (Černý & Ercit, 2005).

3 Objective of the research

This study aims to characterize the petrographic and geochemical features of pegmatite bodies in the Chumbalak area, eastern Afghanistan, to determine their petrogenetic evolution and evaluate their potential for rare-element mineralization.

3.1 Importance of research

This study provides the first systematic geological assessment of pegmatite bodies in the underexplored Chumbalak area of eastern Afghanistan. By establishing the petrogenetic framework and rare-element potential of these rocks, the research delivers crucial foundational data for regional mineral exploration models and contributes to the global understanding of pegmatite-hosted critical raw material resources in the Tethyan metallogenic belt.

3.2 Research question

1. What is the neighbor rock of Chumbalak Pegmatite?
2. What is the mineral composition of Chumbalak Pegmatite?
3. Which minerals is abundant in this Pegmatite

3.3. Study area

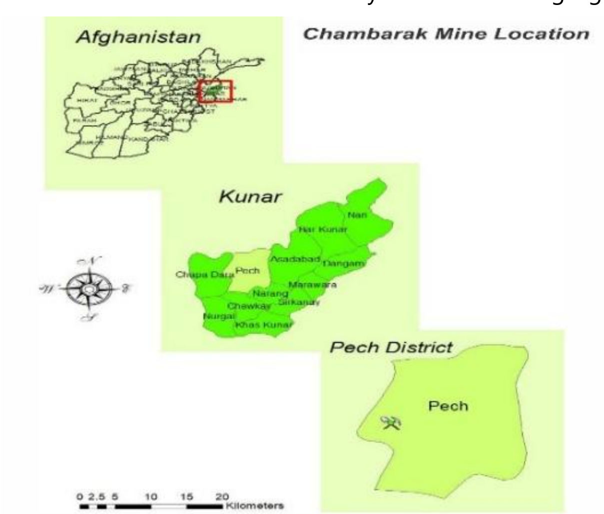
3.4. Geographical and Administrative Location

The study area is centered on the Chumbalak locality within the Darah Pech District of Kunar Province, situated in eastern Afghanistan (Figure 3). Geographically, it lies within the rugged terrain of the Hindu Kush mountain range, approximately between latitudes 34°45' N and 35°00' N and longitudes 71°00' E and 71°15' E. The area is characterized by steep valleys and high relief, with elevations ranging from approximately 1,200 to 2,800 meters above sea level. Access is primarily via unpaved mountain tracks from the provincial center of Asadabad.

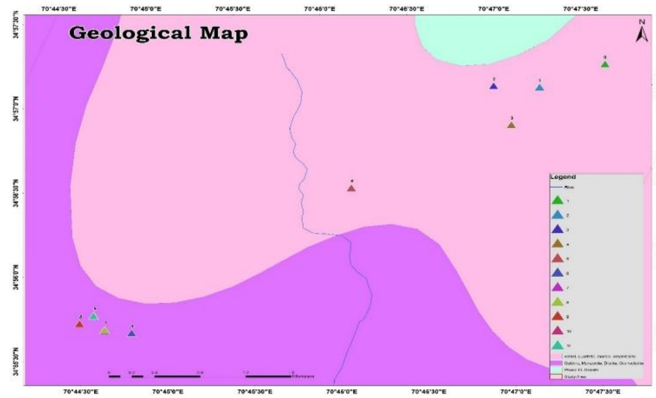
(Figure 3: a location map of Chumbalak.)

3.56. Local Geology and Host Environment

The local bedrock is dominated by medium- to high-grade metamorphic rocks of the Precambrian to Paleozoic basement, specifically comprising biotite-muscovite schist and quartz-feldspathic gneiss (Figure 4). These rocks exhibit a strong NE-SW trending foliation, consistent with regional structural trends imposed during the Himalayan orogeny. This metamorphic package is intruded by several generations of granitoids, ranging from Paleozoic to Tertiary in age, which form the plutonic core of the region.



The pegmatite bodies investigated in this study occur as discrete, steeply dipping veins and lens-shaped intrusions within the schistose country rock. Field observations indicate that the pegmatites range from 0.5 to 3 meters in width and can be traced along strike for tens of meters. They exhibit sharp, discordant contacts with the foliated host rocks, indicating forceful emplacement along structurally controlled planes, likely joints or minor shear zones related to regional deformation.

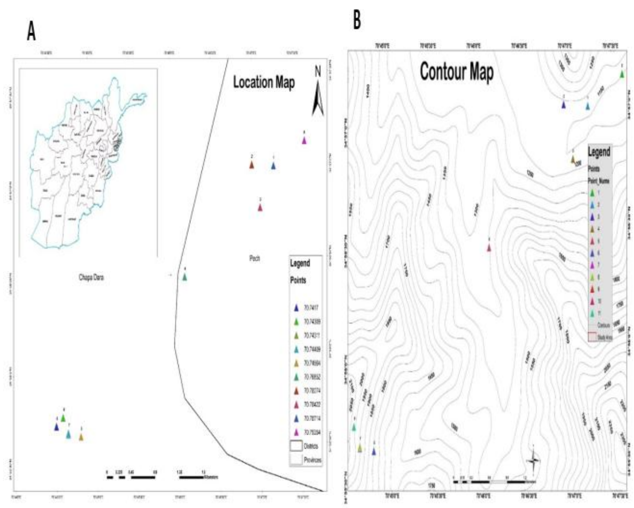


(Figure 4 : A Geological map of Chumbalak area.)

3.67. Field Characteristics of the Pegmatites

Macroscopically, the sampled pegmatites display a typical coarse- to very coarse-grained texture, with individual crystals of potassium feldspar and quartz commonly exceeding 3-5 cm in length. A simple mineral assemblage is visible in hand specimen, dominantly comprising smoky quartz, pinkish-white potassium feldspar (microcline), white plagioclase, and black, prismatic tourmaline (schorl). Micas (muscovite and biotite) occur as large books. The pegmatites show limited visible internal zoning in the sampled outcrops, primarily consisting of a relatively homogeneous core with sporadic miarolitic cavities.

(Figure 5 : A(a geological kit used in fieldwork, B(Samples selected for the lab, C(The mine area, D(scale photo of the Granite contact containing coarse grain of Schorl Tourmaline and Plagioclase Feldspar, E(A scale photo of the Pegmatite intrusion between Granite which is a solid prove of fractional solidification in Chumbalak Pegmatite.)



(Figure 6. A(Location map of the study area, B(contour map of Darah Pech District with the Chumbalak study site marked.)

3.8. Geological Setting

The study area is situated within the eastern **Afghan mobile belt**, a geologically complex segment of the broader **Tethyan orogenic** collage formed by the prolonged convergence and eventual collision between the Indian and Eurasian plates (Şengör & Natal'in, 1996; Treloar & Izatt, 1993). This protracted tectonic history, spanning from the Paleozoic to the Cenozoic, involved multiple cycles of subduction, accretion, and post-collisional magmatism (Figure 1). These processes have resulted in a heterogeneous crust characterized by stacked terranes, major suture zones, and widespread, temporally distinct magmatic activity, creating a highly fertile metallogenic environment (Peters et al., 2011; Heinhorst et al., 2000).

3.79. Stratigraphy and Lithology of the Kunar Region

The bedrock geology of Kunar Province and the surrounding Hindu Kush is dominated by a Precambrian to Paleozoic metamorphic basement, primarily comprising schists, gneisses, and amphibolites of the Kabul Block (Debón & Le Fort, 1983). This crystalline basement is intruded by extensive Mesozoic to Paleogene granitoid plutons, which are part of the Hindu Kush granitoid belt (Figure 2). These peraluminous to metaluminous granites are typically classified as I-type and S-type, with their emplacement linked to subduction-related and subsequent post-collisional tectonic settings (Heinhorst et al., 2000).

The country rocks in the immediate vicinity of the Chumbalak pegmatites consist predominantly of medium- to high-grade micaceous schists and gneisses, which represent the metamorphosed equivalents of former pelitic to psammitic sedimentary sequences. These units exhibit strong foliation and are the typical host rocks for the region's pegmatite veins.

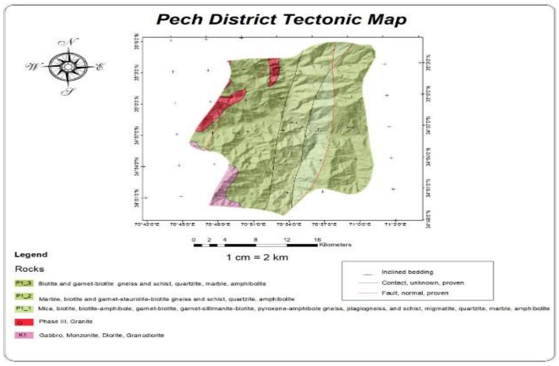
3.8. Pegmatite Province Context

Eastern Afghanistan is renowned as a significant pegmatite province within the Tethyan belt, historically famous for gemstone production, including emerald (beryl), tourmaline, kunzite (spodumene), and aquamarine (Bowersox & Chamberlin, 1995; Giuliani et al., 2000). The pegmatites are genetically associated with the Hindu Kush granitoid belt. They are interpreted as the crystallized products of highly fractionated residual melts derived from these parental granitic intrusions (Orris et al., 2014). The pegmatites commonly occur as steeply dipping veins, dykes, and irregular bodies intruding both the granitoids and the surrounding metamorphic basement, often exploiting structural weaknesses such as joints and shear zones.

The Chumbalak area is located within this proven pegmatite terrain. The pegmatites investigated in this study intrude the micaceous schists of the regional basement. Their field occurrence, mineralogy, and texture are consistent with derivation from local granitic sources, aligning with the established regional petrogenetic model for rare-element and gem-bearing pegmatite formation in collisional orogenic settings (Černý, 1991; Tkachev, 2011).

3.9 Tectonic

The formation of pegmatite systems in eastern Afghanistan is a direct consequence of the region's complex, multi-stage tectonic evolution within the Alpine-Himalayan orogenic belt. The study area lies within a crucial segment of this collision zone, recording events from ancient subduction to continental collision (Figure 7).



(Figure 7: Tectonical map of Chumbalak area.)

Pre-Collision History: Subduction and Arc Magmatism (Mesozoic - Early Cenozoic)

Prior to the India-Eurasia collision, the region was dominated by the northward subduction of the Neo-Tethyan oceanic lithosphere beneath the southern margin of the Eurasian plate (Karakoram block) (Şengör & Natal'in, 1996). This prolonged subduction, active throughout much of the Mesozoic and early Cenozoic, led to the development of a continental magmatic arc. The emplacement of the regional Hindu Kush granitoid belt, which serves as the likely parental source for the pegmatites, is primarily attributed to this subduction-related magmatic phase (Heinhorst et al., 2000). These I-type and S-type granitoids formed at mid-crustal levels and provided the initial fertile melts that would later undergo extreme fractionation.

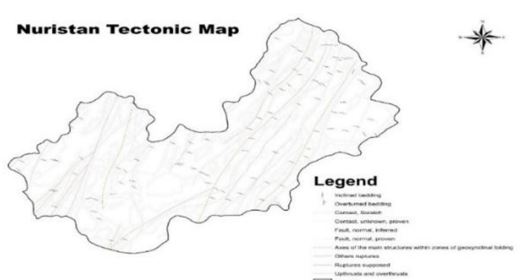
Syn- to Post-Collision Stage: Crustal Thickening and Post-Collisional Magmatism (Cenozoic)

The terminal closure of the Neo-Tethys Ocean and the onset of the continental collision between India and Eurasia around 50-55 Ma initiated a new tectonic regime (Treloar & Izatt, 1993). This collision caused intense crustal shortening, thickening, and regional-scale metamorphism of the basement sequences. The resulting thermal and structural reworking of the crust played a critical role in pegmatite genesis through two key mechanisms:

- **Anatexis:** Crustal thickening and radiogenic heat buildup triggered partial melting of metasedimentary rocks, generating peraluminous (S-type) granitic melts (Debón & Le Fort, 1983).
- **Decompression Melting and Fluid Release:** Subsequent tectonic uplift and exhumation led to decompression melting of previously emplaced granitoids and the release of late-stage, volatile-rich fluids.

Structural Controls on Pegmatite Emplacement

The final emplacement of pegmatite veins was structurally controlled. They intruded along extensional fractures, shear zones, and foliation planes within the metamorphic country rock, which were generated during the transition from compressional to transpressional/trans tensional stress regimes in the post-collisional phase (Dill, 2015). This tectonic model—involving subduction-related arc magmatism followed by collisional crustal melting and structurally controlled fluid migration—provides the essential framework for understanding the source, timing, and localization of rare-element pegmatite systems in the Chumbalak area and the wider Hindu Kush region.



(Figure 8: Chumbalak area is also included in Nuristan zone and the map shows the Tectonic structure of the mentioned zone.)

3.10. Mineral Deposit

The pegmatites of the Chumbalak area represent potential expressions of a rare-element pegmatite system within the tectonically complex Hindu Kush region. Pegmatites are not merely coarse-grained rocks but are the crystallized remnants of highly fractionated, volatile-rich melts derived from parental granites, and they constitute a primary global source for critical metals and gemstones (Černý, 1991; Linnen et al., 2012). Their economic significance is directly tied to their internal evolution, where extreme geochemical fractionation leads to the pronounced enrichment of incompatible elements like Li, Cs, Ta, Nb, Be, and Sn in residual melts (London, 2008).

The genetic model for such deposits involves multi-stage processes. Initial crustal melting generates peraluminous granitic magmas. As these magmas crystallize, water and fluxing elements (B, F, P) become concentrated in the residual melt, lowering viscosity and enabling the growth of exceptionally large crystals (Thomas & Davidson, 2012). During the final stages of crystallization, a separate, hydrous fluid phase may exsolve, facilitating the transport and precipitation of rare elements into discrete mineral phases, forming zoned deposits ranging from barren margins to mineralized cores (Černý & Ercit, 2005).

The economic potential of a pegmatite field is assessed through key indicators, which in this study are addressed petrographically as following:

I. **Parental Melt Fertility:** The presence of minerals like muscovite and biotite suggests a peraluminous, S-type granite provenance, which is commonly fertile for rare elements (Černý, 1991).

II. **Degree of Fractionation:** Textural features (e.g., graphic intergrowths, blocky feldspar) and the assemblage of accessory minerals (notably schorl, an Fe-rich tourmaline) are classic markers of a highly evolved melt (London, 2005). Schorl, in particular, indicates boron saturation—a key flux that enhances element partitioning and is common in evolved pegmatite systems.

III. **Mineralization Indicators :** While the absence of distinct Li-minerals (e.g., spodumene, lepidolite) or Ta-Nb oxides (e.g., coltan) in the studied sections may suggest a less fractionated or differently specialized subtype, the presence of accessory schorl and muscovite is a positive indicator. These phases can host significant trace concentrations of rare elements and often precede the crystallization of more exotic phases in the most evolved pegmatite cores (Dill, 2015).

Regionally, the Hindu Kush is part of the Tethyan Pegmatite Belt, known for gem-quality mineral occurrences (Bowersox & Chamberlin, 1995). The Chumbalak pegmatites, based on the observed dominant mineralogy (quartz, K-feldspar, plagioclase, mica, schorl), can be preliminarily classified as part of the Muscovite ± rare-element Pegmatite class (Černý & Ercit, 2005). Their true economic character—whether gem-, rare-metal-, or industrially-oriented—requires further investigation through targeted geochemistry and mineral chemistry to quantify trace element enrichment. This petrographic study establishes the essential geological framework for such future resource-oriented exploration.

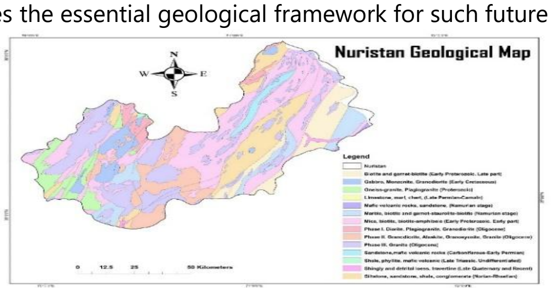


Figure 9: Nuristan zone Geological map.)

4. Results & Discussion

Petrographic analysis of the three pegmatite **samples (CH-01, CH-02, CH-03)** confirms a simple mineral assemblage dominated by quartz, potassium feldspar, plagioclase, and mica (muscovite and biotite), consistent with granitic pegmatites. The defining pegmatitic texture is characterized by anhedral to subhedral crystals exceeding 1 cm, with common graphic intergrowths of quartz within feldspar.

Accessory minerals are a Schorl, the iron-rich member of the tourmaline group, is ubiquitous as subhedral to euhedral, strongly pleochroic (brown to dark blue) prisms, often included within feldspar or quartz (Figure 10.3). Muscovite occurs as large, flexible sheets with high birefringence, while biotite is present as smaller, pleochroic (brown to dark brown) flakes (Figure 10.2). The country rock samples (CH-04, CH-05) are confirmed as muscovite-biotite schist and quartzofeldspathic granite, exhibiting a pronounced foliated texture defined by the parallel alignment of micaceous minerals. (Figure 12)

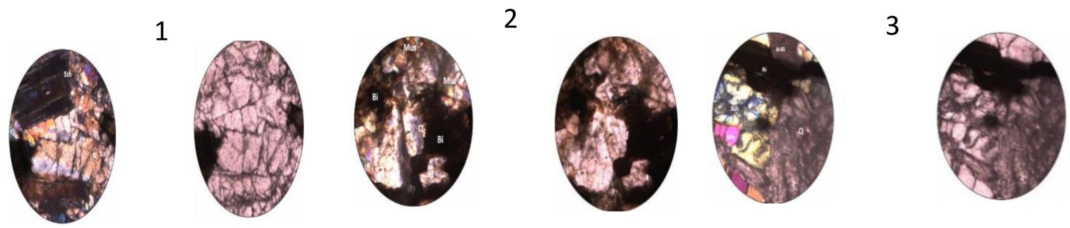


Figure 10: Photomicrographs under plane-polarized (PPL) and cross-polarized light (XPL). (1) Euhedral schorl (Sch) crystal included in Quartz (Q). Width of view ~5 mm. (2) Muscovite (Mus) adjacent to quartz (Q) and Biotite (Bi). Width of view ~3 mm. (3) perthitic K-feldspar (K-Fl), Muscovite (Mus), schorl (Sch), quartz (Q) and Biotite (Bi). Width of view ~2 mm.

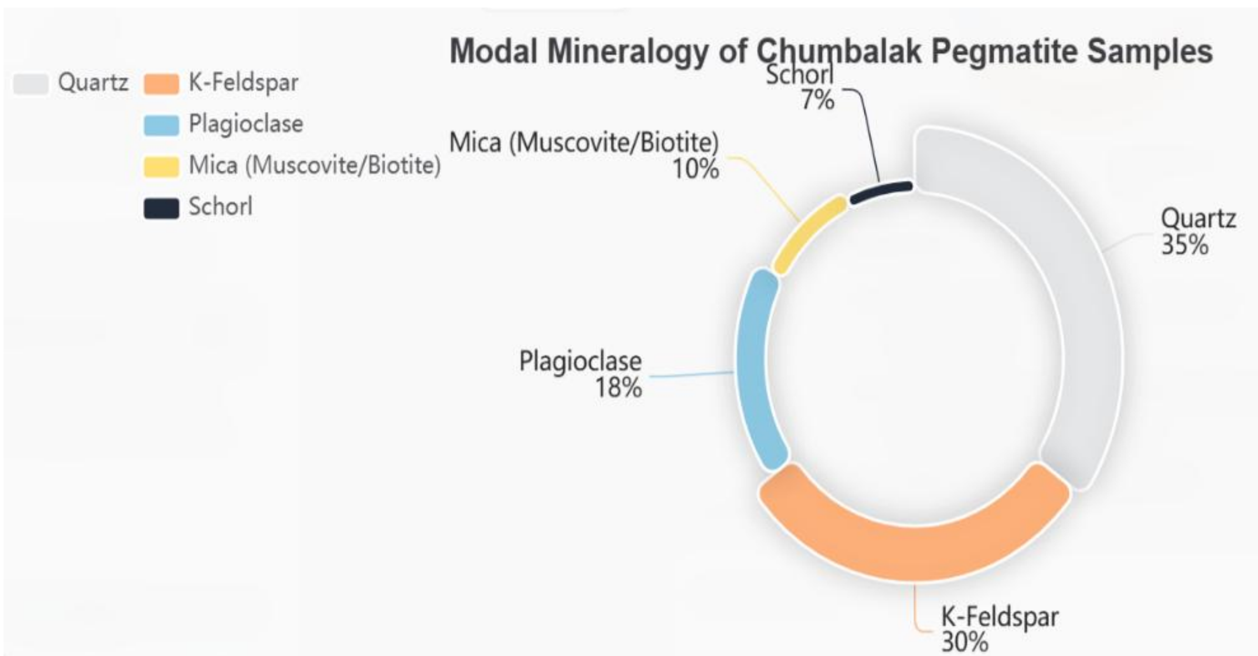
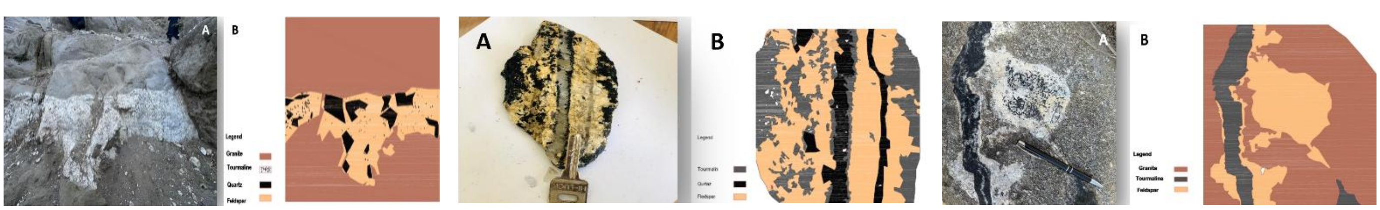


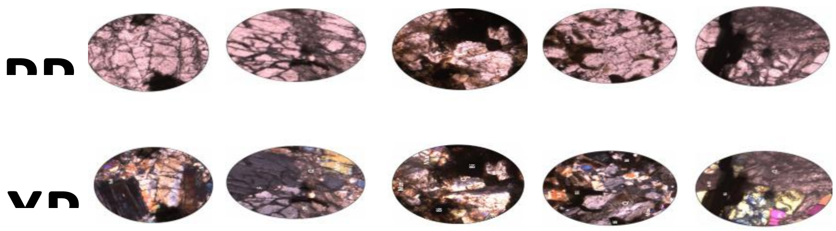
Figure 11: Modal mineralogy of Chumbalak pegmatite samples presented as a rose-style pie chart. Colors correspond to standard geological representations: light gray for quartz, salmon-pink for K-feldspar, pale blue for plagioclase, pale yellow for mica, and black for schorl tourmaline. Mineral abundances reflect the dominant pegmatite assemblage observed in thin section analysis, highlighting quartz and feldspar as the principal constituents, with mica and schorl tourmaline as significant accessories.

4.1. Textural Analysis and Paragenesis

Textural analysis reveals a consistent crystallization sequence. Feldspars (microcline and plagioclase) crystallized early, forming the framework of the rock, as evidenced by their large, blocky habit. Quartz crystallized interstitially, often filling spaces between feldspar grains and exhibiting undulose extinction. The accessory Tourmaline (schorl) and micas crystallized concurrently with or slightly after the major feldspathic phase, as shown by their common inclusion within feldspar but also by their interstitial presence. Minor myrmekitic texture at plagioclase-K-feldspar boundaries indicates subsolidus re-equilibration.



(Figure 12: 2D models of the Geological structures of the field sample, A1(Pegmatite body between Granite, A2(Clear naked sample of the Granite, A3(Schorl Tourmaline vein as an injected intrusion to a fractural zone.)



(Figure 13: all XPL & PPL photographs of the five samples.)

5 Discussion

The mineral assemblage—quartz, K-feldspar, plagioclase, muscovite, biotite, and schorl—is diagnostic of peraluminous (S-type) affinity, indicating derivation from partial melting of metasedimentary crust (Černý, 1991). The ubiquitous presence of primary schorl (Fe-rich tourmaline) is a critical petrogenetic indicator. Tourmaline saturation signifies a boron-rich melt, a hallmark of highly fractionated granitic systems where volatile fluxes (B, H_2O) become concentrated in the residual liquid, lowering solidus temperatures and facilitating the growth of large crystals (Thomas & Davidson, 2012; London, 2008). This, coupled with the observed graphic and myrmekitic textures, strongly supports the interpretation that the Chumbalak pegmatites crystallized from a residual, volatile-rich, highly fractionated melt derived from a peraluminous granitic parent.

Based on the absence of distinct Li, Cs, or Ta-Nb oxide minerals in the studied sections, and the dominance of muscovite and schorl, these pegmatites are preliminarily classified within the muscovite type of the rare-element (REL) pegmatite class, specifically of the relatively less fractionated subtypes (e.g., Muscovite or Muscovite-Rare-Element) according to the genetic scheme of Černý & Ercit (2005). They represent a level of fractionation where boron and water saturation (indicated by tourmaline and muscovite) has been achieved, but the extreme enrichment necessary to precipitate discrete Li or Ta minerals may not have been reached in the sampled zones or in these particular dykes.

The petrographic results have direct implications for assessing mineralization potential. While the studied samples do not contain visible ore minerals (e.g., coltan, spodumene), the presence of schorl and muscovite is a positive exploration indicator. In pegmatite systems, these minerals are known to incorporate trace but significant amounts of rare lithophile elements (e.g., Li in muscovite, Sn in schorl) and typically precede the crystallization of more exotic phases in the most evolved core zones (Dill, 2015; Linnen et al., 2012). Therefore, the Chumbalak pegmatites represent a fertile but likely incompletely fractionated system.

The potential for more evolved, mineralized zones (e.g., lithium- or tantalum-rich cores) cannot be ruled out and may exist either at depth, along strike, or in other, more fractionated veins within the swarm not captured by this limited sampling. This study identifies the critical petrogenetic conditions—Be-rich, peraluminous, fractionated melt—that are necessary, though not sufficient, for rare-element mineralization. It establishes that the system evolved along a chemically favorable path.

For Regional Correlation and Future Research Directions, The characteristics of the Chumbalak pegmatites align with the regional model for pegmatite genesis in the Hindu Kush, where collision-related crustal melting produces peraluminous granites that differentiate into pegmatite swarms (Peters et al., 2011). They share the common accessory mineralogy (tourmaline, mica) of gem-bearing pegmatites in the region (Bowersox & Chamberlin, 1995) but appear to represent a more common, less specialized fractionation product compared to world-class gem or rare-metal deposits.

This petrographic foundation dictates clear future research directions:

- Systematic geochemical mapping to identify geochemical halos and vector towards more evolved zones,
- Mineral chemistry analysis (e.g., electron microprobe) of tourmaline and mica to quantify trace element contents,
- Detailed field mapping to understand structural controls on pegmatite emplacement and internal zonation.

6. Conclusion

This study presents the first detailed petrographic characterization of pegmatite bodies in the Chumbalak area, eastern Afghanistan, establishing a foundational geological framework for this underexplored region. Petrographic analysis identifies a mineral assemblage of quartz, K-feldspar, plagioclase, muscovite, biotite, and, critically, primary schorl (Fe-tourmaline), which collectively confirm a peraluminous (S-type) affinity and crystallization from a volatile-rich, highly fractionated granitic melt. The ubiquitous presence of schorl signifies boron saturation—a key petrogenetic indicator of advanced melt evolution—while the textural features are consistent with classic pegmatitic crystallization. Based on the Černý & Ercit (2005) classification, the investigated pegmatites are preliminarily categorized as belonging to the muscovite type within the rare-element (REL) class, representing a fertile but incompletely fractionated system. While no discrete rare-element ore minerals were observed in the studied sections, the mineralogical suite identified—particularly tourmaline and mica—constitutes a direct and positive indicator for a geochemically evolved system with inherent potential for rare-element enrichment. Consequently, the Chumbalak pegmatites represent a legitimate exploration target within the wider Hindu Kush pegmatite province.

These findings directly address the critical knowledge deficit in the region and provide an essential petrogenetic baseline. To advance this assessment, future work must prioritize whole-rock and mineral-scale geochemistry to quantify fractionation trends and trace element concentrations, complemented by detailed field mapping to delineate zoning and structural controls. This research confirms the geological significance of the area and underscores its potential for hosting critical raw material resources, thereby contributing valuable data to the economic geology of Afghanistan and the broader Tethyan metallogenic belt.

7. Suggestion

To advance the findings of this preliminary study, a multi-method investigation is recommended. First, a systematic geochemical survey employing whole-rock XRF/ICP-MS analysis is essential to quantify the degree of fractionation and to definitively classify the pegmatites within the LCT or NYF families. Second, targeted mineral chemistry via electron microprobe analysis of tourmaline and mica would reveal trace element (Li, Cs, Sn) concentrations and provide vectors toward mineralized zones. Finally, detailed field mapping and structural analysis on a broader scale are needed to delineate the internal zonation of the pegmatite bodies and understand the structural controls on their emplacement.

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