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Geochemical and Petrographic Analysis of Metamorphic Rocks in Aliabad Mountain, Kabul Block, Afghanistan

Shekeb Shamal✉[1], Hafizullah Rasouli[2], Abdul Wares Nabizada[3]

[1,2,3]Kabul University, Department of Geology, Geoscience Faculty, Kabul, Afghanistan

✉E-mail: ShekebShamal@yahoo.com (corresponding author)

ABSTRACT

The Kabul Block, a key geological feature in Afghanistan, comprises sedimentary, metamorphic, and volcanic rocks, including those of Aliabad Mountain. Despite its significance, Aliabad Mountain has received limited geochemical study. This research characterizes the lithological variations, chemical composition, and mineralogical properties of its metamorphic rocks to elucidate their protolith nature and tectonothermal history. X-ray fluorescence (XRF) and petrographic analyses were conducted on ٧ rock samples collected from five localities across Aliabad Mountain. Tow Samples for XRF analysis were powdered, pelletized, and analyzed using a calibrated XRF spectrometer. Results indicate a silicate-rich composition, with SiO_2 ranging from 60–72 wt%. One lithological unit shows elevated Fe (5.0–6.5 wt%), Ti (0.3–0.5 wt%), Mn (0.05–0.08 wt%), and Zr (0.015–0.02 wt%), suggesting a mafic or hydrothermally altered protolith. Another unit is enriched in phosphorus (0.1–0.5 wt%) and contains apatite and trace Cu (0.001–0.003 wt %), indicating a felsic, phosphate-bearing origin. Ni (0.002–0.004 wt%) and Co (0.008–0.012 wt%) were detected only in the oxide-rich lithology, while Au, Ag, Pd, Nb, and W were below detection limits, ruling out metallic mineralization. Petrographic analysis reveals biotite gneisses and amphibolites with sedimentary textures, supporting a paragneiss origin. These findings enhance understanding of the Proterozoic Kabul Block's geological evolution and suggest potential for construction material sourcing due to the rocks' stable mineralogy, despite limited economic mineral potential.

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INTRODUCTION

To understand the geological framework controlling Afghanistan's diverse landforms, a comprehensive study of its rock formations is essential, as many of these rocks were initially emplaced through complex tectonic processes originating elsewhere. The Kabul Block, a microcontinental fragment in Afghanistan, encompasses the Aliabad Mountain region, which comprises sedimentary, metamorphic, and volcanic rocks formed between the Paleozoic and Cenozoic eras (Peter, 2000). Geological maps at a 1:100,000 scale indicate that the Welayeti Formation, primarily composed of mica schists and quartzites interbedded with amphibolite lenses, unconformably overlies the Neoarchean Shir Darwaza Formation (Wittekindt and Weippert, 2014). These rocks, located near the Kabul Basin, have been transported by watercourses such as the Shir Darwaza stream, resulting in deposits of varying thicknesses (Rasouli and Vaseashta, 2023). Petrological studies have documented peak metamorphic conditions in this area, reaching temperatures of 650°C and pressures of up to 9 kbar, reflecting significant tectonothermal events (Faryad et al., 2016).

The Kabul Block is tectonically active within a transpressional plate-boundary region, with the Kabul Basin overlain by quaternary sediments (Shamal and Rasouli, 2018; Motamed, 2020). The surrounding mountain ranges, including Paghman, Qorogh, Qargha, Shir Darvazeh, Chehelston, Shakh Buranti, Aliabad, Asmaei, and Khaja Baghra, exhibit slopes averaging 30–40 degrees, with some areas reaching steep inclines of 70–90 degrees due to tectonic flattening of structural elements (Shamal, 2023). The block's geological structure has been examined in terms of stratigraphy, magmatism, and tectonics, with Paleo-Proterozoic gneisses dominating the surrounding mountains (Alekseev, 2020; Rasouli and Vaseashta, 2023). Many gneiss domes record positive feedback between decompression and partial melting of the orogenic middle crust (Teyssier & Whitney, 2019). The Kabul Block is one of several small continental blocks within Afghanistan's geological framework, with tectonic activity linked to the Indian plate's collision approximately 60 million years ago, which traveled over 5,000 kilometers along its margin (Tahiryan, 2019; Collett et al., 2015). Gneisses in the region are likely of Precambrian age, and the metamorphic formations of Aliabad Mountain are compositionally and structurally related to the Shir Darwaza course (Barber et al., 2017; Sahak, 2021; Collett et al., 2015). Petrographic studies have determined that these rocks, including biotite gneisses, partially leucocratic amphibolites, marbles, and quartzites, are paragneisses derived from sedimentary precursors (Peter, 2000; Faryad et al., 2016). Ortho-amphibolites can often be distinguished chemically from para-amphibolites by their higher contents of Cr, Ni, and Ti, and lower Niggli k ratios, though alkali metasomatism in metamorphic terrains may obscure these signatures (Faryad et al., 2016). Tectonic studies have identified various fold elements in the Kabul region, including hinge lines, hinge zones, hinge points, hinge traces, fold axes, inflection points, inflection lines, limbs, and interlimb angles, as shown in Figure 1 (Boulin, 1988; Barber et al., 2017; Collett et al., 2015).

Despite these studies, the chemical composition of Aliabad Mountain's gneisses and associated metamorphic rocks remains underexplored, with prior research focusing primarily on tectonic and geomorphological aspects (Alekseev, 2020; Win, 2016). This gap in geochemical and petrographic analysis highlights the need for a detailed investigation of the geological formation conditions, mineralogical composition, physico-mechanical properties, petrographic characteristics, stability, and coloration of these rocks. The purpose of this research is to investigate the chemical composition of Aliabad Mountain's metamorphic rocks using X-ray fluorescence (XRF) analysis, complemented by petrographic methods. With permissions obtained from Kabul University and relevant authorities, preliminary XRF analysis has revealed the presence of elements such as sulfur and phosphorus, which may indicate diagenetic incorporation of biogenic material, suggesting an organic-rich protolith (Rasouli and Vaseashta, 2023). These chemical signatures are critical for reconstructing the metamorphic and depositional history of the Kabul Block.

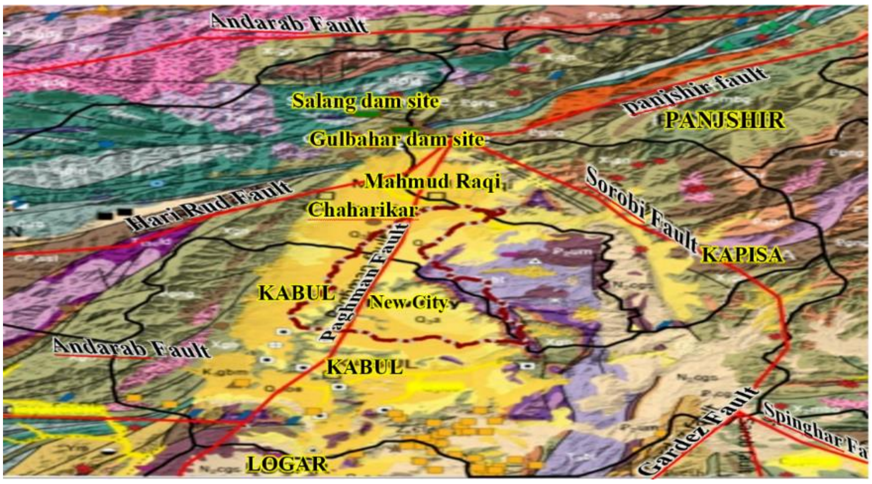

Figure 1. *Tectonic Map of Kabul and its neighboring provinces (Collett et al., 2015)*

The primary objective of this study is to conduct a detailed chemical and petrographic analysis of the rocks from the Aliabad Mountain region to determine their mineralogical composition, origin, and metamorphic evolution. Through thin-section microscopy and XRF techniques, this research aims to identify key geochemical indicators that reflect the protolith nature and tectonothermal history of the studied units.

The significance of this research lies in its potential to provide a deeper understanding of the geological evolution of the Kabul Block, contribute to regional tectonic models, and offer insights into the mineral potential of the area, particularly for construction materials given the region's stable mineralogy and strategic location (Safi et al., 2024). Afghanistan's landscape, characterized by tall, forbidding mountains, deserts, and tectonically active areas like the Kabul Basin, underscores the importance of this study for both academic and practical purposes, supporting future exploration and sustainable development initiatives in the region.

METHODS AND MATERIALS

This study employed field investigations and laboratory analysis to investigate the chemical and mineralogical characteristics of metamorphic rocks from Aliabad Mountain. Field investigations were conducted in at Aliabad Mountain, with permissions from Kabul University and local security authorities to ensure ethical and safe operations. Seven rock samples, including gneisses and amphibolites, were collected from five distinct localities along a 10-km transect across the mountain to capture lithological variability. Sampling sites were selected based on outcrop exposure and geological mapping at a 1:100,000 scale

(Wittekindt and Weippert, 2014), with GPS coordinates recorded (e.g., 34.5°N, 69.1°E). Samples were collected using a geological hammer, labeled, photographed, and stored in sterile bags to prevent contamination. Observations of outcrop structures, bedding, and tectonic features (e.g., fold elements) were documented to contextualize the samples. Logistical challenges, such as restricted access to some areas, limited the spatial coverage, but the selected sites represent the dominant lithologies of the region.

Laboratory analyses were conducted at Kabul University's Geology Department over three weeks, with one week dedicated to fieldwork and two weeks to laboratory processing. Two complementary techniques were employed: X-ray fluorescence (XRF) analysis for chemical composition and petrographic analysis for mineralogical and textural characterization. For XRF analysis, only two samples were analyzed due to equipment availability constraints, though additional samples are planned for future studies to enhance data robustness. The selected samples were crushed to a grain size of less than 75 µm using a jaw crusher and agate mortar, then pressed into 30-mm pellets using a hydraulic press at 20 tons pressure.

Measurements were conducted using a multifunctional energy dispersive X-ray fluorescence spectrometer equipped with a micro-beam, capillary optics, a broad X-ray beam from a molybdenum secondary target, and total reflection X-ray techniques. The instrument was operated at 55 kV and 30 mA, with a measurement duration of 10,000 seconds under atmospheric air conditions. Calibration was performed using thin-film standards to calculate element concentrations, with detection limits of 0.001 wt% for most elements and an error margin of ±5%. Concentrations of Si, Fe, Al, Ti, Mn, P, S, Cr, Zr, Zn, Cu, Nb, W, As, Pd, Au, and Ag were determined, and volume percentages of these elements were calculated to assess the chemical composition of the rocks.

For petrographic analysis, rock samples were prepared into thin sections for microscopic examination. Samples were cut into 30 mm x 46 mm slabs using a diamond saw, polished to a thickness of 30 µm with 1 µm diamond paste, and mounted on glass slides using Canada balsam as an adhesive. Thin sections were analyzed using a Nikon ECLIPSE E200 polarizing microscope at 40x magnification under plane-polarized light (PPL) and cross-polarized light (XPL). Mineral percentages were estimated using a point-counting technique (500 points per section) to quantify the volume percentage of rock-forming minerals, such as quartz, plagioclase, biotite, amphibole, and accessory minerals (e.g., zircon, apatite). Textural features, including grain alignment and deformation, were documented to infer metamorphic and depositional histories.

The integration of field investigations and laboratory analysis ensures a robust approach to characterizing Aliabad Mountain's metamorphic rocks. Fieldwork provided representative samples for laboratory analysis, and XRF and petrographic data were cross-referenced to validate geochemical and mineralogical findings, enhancing the reliability of the results despite the limited XRF sample size.

FINDINGS

In this study, an empirical analysis that was performed in order to study geochemical and petrographic analysis of metamorphic rocks in Aliabad Mountain. Only two sample were analyzed though XRF due to high price. The XRF analysis of the two samples reveals that silicon (Si) is the dominant component, comprising 19.525% in sample 1 and 17.630% in sample 2. Aluminum (Al) follows at 3.160 % and 3.839 %, respectively, while iron (Fe) is present at 3.610 % in sample 1 and 5.892 % in sample 2. Titanium (Ti) and manganese (Mn) occur at 0.286 %–0.398 % and 0.042 %–0.074 %, respectively. Phosphorus (P) was measured at 0.435 % in sample 1 and 0.150 % in sample 2, and sulfur (S) at 0.138 % and 0.145 %, respectively. Chromium (Cr) ranges from 0.018 % to 0.022 %, lead (Pb) from 0.002 % to 0.004 %, vanadium (V) from 0.015 % to 0.021 %, and zirconium (Zr) from 0.011 % to 0.017 %. Zinc (Zn) appears at 0.006 %–0.009 %, copper (Cu) at 0.002 % in sample 1, but below the detection limit in sample 2. Nickel (Ni, 0.003 %) and cobalt (Co, 0.010 %) were only detected in sample 2. Palladium (Pd), niobium (Nb), tungsten (W), gold (Au), silver (Ag), and arsenic (As) all fall below the limit of detection in both samples.

Table 1: *The elements present in samples 1 and 5 of Aliabad mountain based on XRF analysis.*

Element %	Sample No: 1	Sample No: 2
Cr	0.018	0.022
Fe	3.610	5.892
Cu	0.002	<LOD[1]
Ni	<LOD	0.003
Co	<LOD	0.010
Au(g/t)	<LOD	<LOD
Ag	<LOD	<LOD
As	<LOD	<LOD
S	0.138	0.145
Pb	0.002	0.004
Al	3.160	3.839
Ti	0.286	0.398
Mn	0.042	0.074
Zn	0.006	0.009
Pd	<LOD	<LOD
P	0.435	0.15
V	0.015	0.021
Si	19.525	17.63
Nb	<LOD	<LOD
Zr	0.011	0.017
W	<LOD	<LOD

These results indicate a siliceous–aluminosilicate matrix with variable iron content and trace heavy metals. The presence of phosphorus in XRF diffraction studies indicates that this area was a shallow marine area and that the organisms whose crust was made of phosphorus dissolved after their disappearance and these materials contributed to the gneisses. Also, petrographic studies revealed that some minor minerals have rounded and lost their corners and edges, indicating that these minerals were transported by water. In the Lower and Middle Proterozoic in this area, granites after destruction have caused the

[1]. Limit of detection

formation of arkosic sands, which later in the Upper Proterozoic of this area have been affected by regional metamorphism and these sands have caused the formation of gneisses. Also, the existing layers of mud have caused the formation of amphibolites with small thicknesses.

The following are the studies and findings we had in the thin section studies section:

Table 2: *Volume percentage of rock-forming minerals in thin Section number 1*

No:	Minerals	Volume percentage	Rock Name
1	Biotite	5-25	Biotite Gneiss
2	Plagioclase	15-25	
3	Quartz	20-30	
4	Epidote	10-20	
5	Feldspar	10-30	

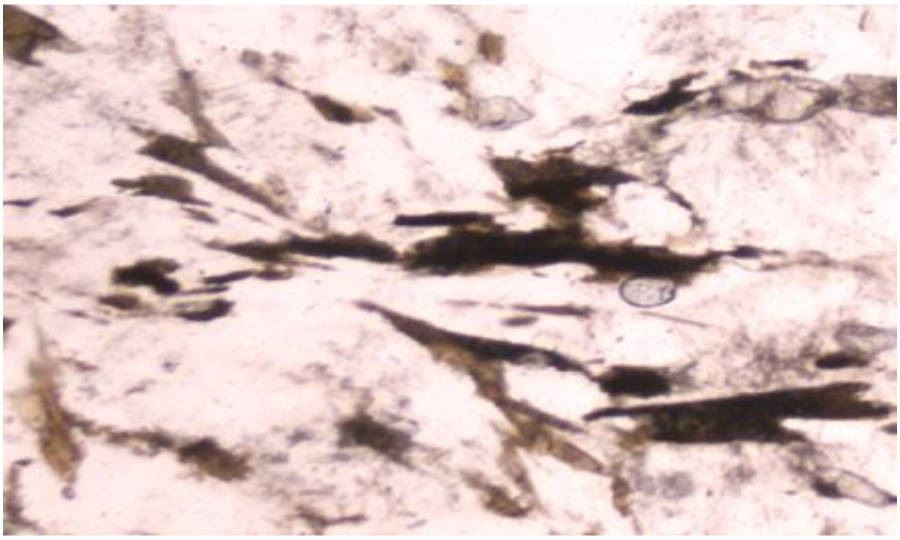

Figure 2. *Thin Section number 1 under PPL with 40 magnification of a polarization microscope. (Researcher Photo)*

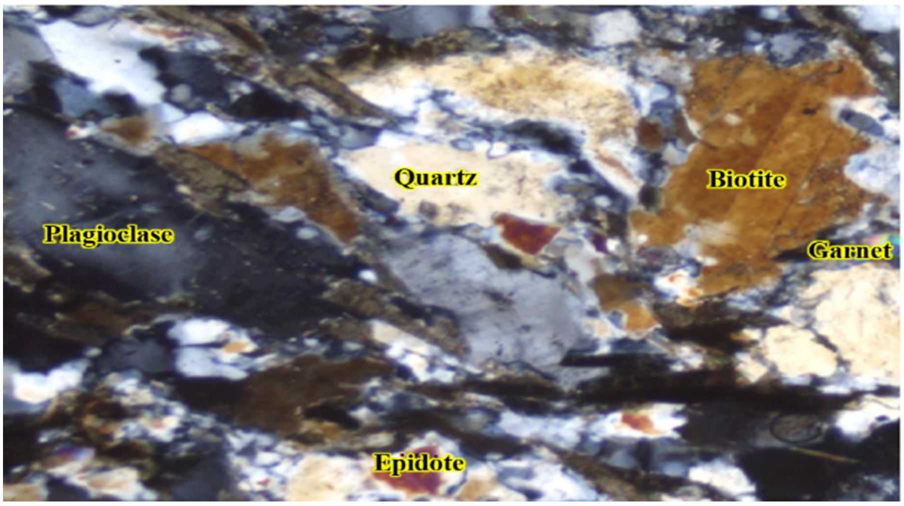

Figure 3. Thin Section number 1 under XPL with 40 magnification of a polarization microscope. (Researcher Photo)

Description of Thin Section 2

In this thin section, Biotite can be observed in large quantities. In this thin section, Biotite has assumed a more justified shape and has given a gneiss-like texture. Its texture is grainy, and the size of the grains sometimes reaches more than a centimeter. Based on these grains, its structure can be considered lepidogranular blastid. According to the justification of Biotite, linear texture can also be observed in some parts. Its composition is average, with plagioclase 10-25%, Biotite 30-40%, and quartz around 40-50% in this thin section. A small amount of garnet and Epidote can also be observed, indicating that this rock is biotite gneiss-like (figures 4 and 5).

Table 3: *Volume percentage of rock-forming minerals in thin section number 2*

No	Minerals	volume percentage	Rock Name
1	Biotite	30-40	
2	Plagioclase	10-25	
3	Quartz	40-50	Biotite gneiss
4	Epidote	1-20	
5	Garnat	2-5	

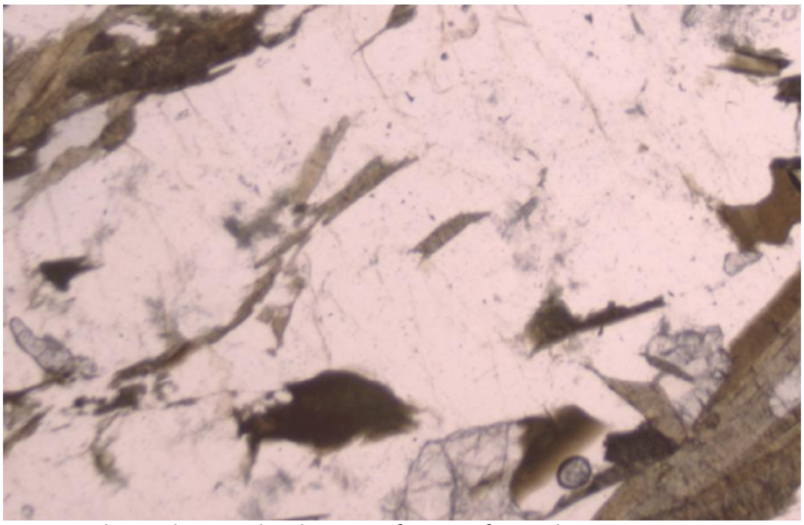

Figure 4. *Thin section grade 2 under a nicol with a magnification of 40, polarization microscope. (Researcher Photo)*

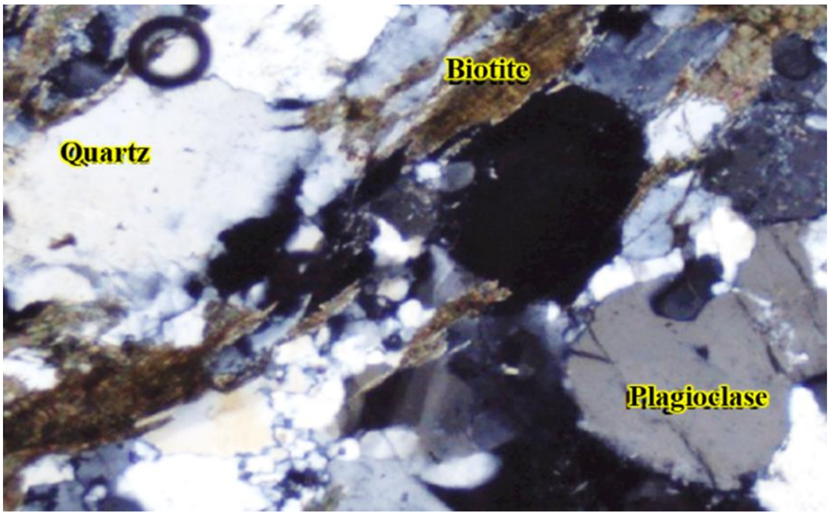

Figure 5. *Thin section number 2 under two nicols with a magnification of 40 under a polarization microscope. (Researcher Photo)*

Description of Thin Section 3

In this thin section, which includes mica group minerals, besides Biotite, muscovite, phlogopite, and apatite can be observed. Precisely, microcline is observed within the microcline network, and partite and antipartite structures are also visible. In addition to sphene apatite, this thin section reveals that muscovite has formed the structure of the rock, contributing to its linear texture. The rock structure is lipidogranoblastic. In this thin part, the grains of rocks vary in size, sometimes reaching half to one centimeter. The amount of quartz is 40-60%, and the amount of plagioclase is 20-40%, as shown in Figure 6. The amount of apatite and phosphine in this thin part is low. Biotite is a famous mineral that is included in metamorphic rock (Rasouli et al., 2020).

Table 4: *Volume percentage of rock-forming minerals in thin section number 3*

No	Minerals	Volume percentage	Rock Name
1	Biotite	20-30	
2	Plagioclase	20-40	Biotite gneiss
3	Quartz	40-60	
4	Epidote and sphene	5-10	

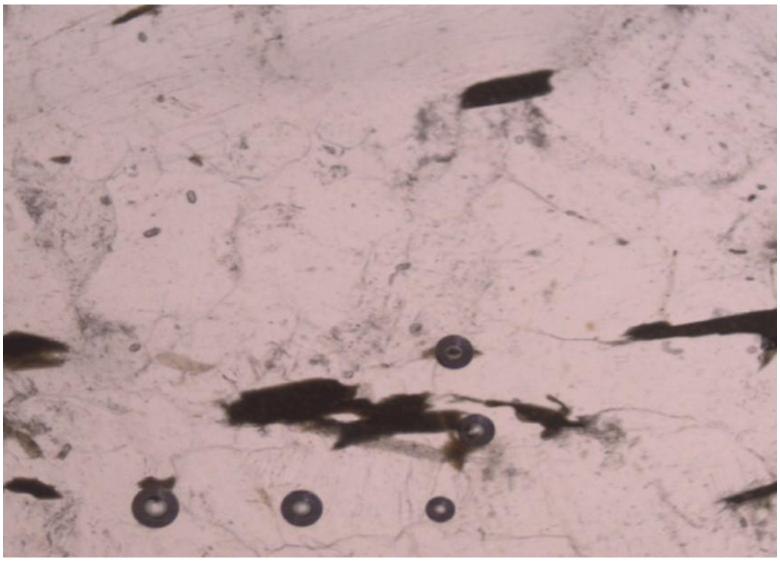

Figure 6. *Thin section No. 3 under a Nicol with 40 magnification of a polarization microscope. (Researcher Photo)*

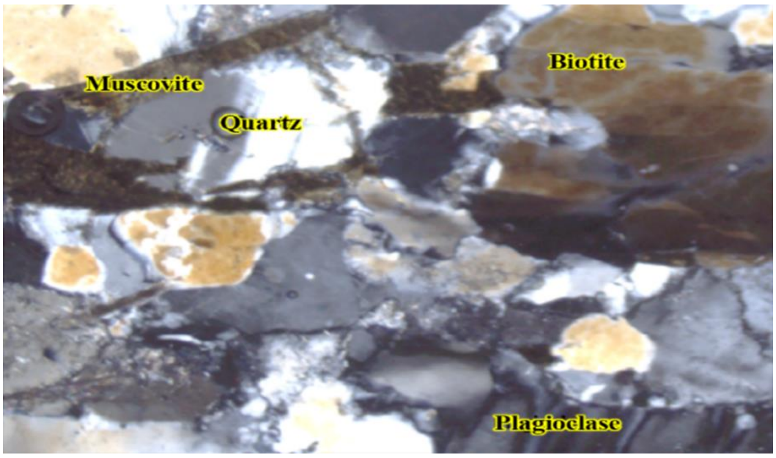

Figure 7. *Thin section No. 3 of the two-Nicol bed with 40 magnification of a polarization microscope. (Researcher Photo)*

Description of Thin Section 4

In the composition of this rock, quartz (30-40%), plagioclase (20-30%), and Biotite (20-25%) can be observed in this thin section. Polysynthetic dichotomies can be observed very clearly in some parts of the rock. There is a microcline network, and Biotite is very evident in this thin section, which gives the rock a nearly linear texture, and its structure is lipidogranoblastic. In this thin section, secondary changes can also be observed, as a result of which one can see the secondary changes of plagioclase to sericite. In some areas, the quartz particles exhibit wave extinction, indicating a high degree of metamorphism. Additionally, due to the pressure exerted by its particles, quartz has interfered with each other. Under a nicol, the color of the rock looks almost earthy. In some minerals, polychorism is also observed, which is extremely weak. This rock is a biotite gneiss-like (Figures 8 and 9). In nature, every metamorphic rock can move, along with its elements; we can say this action is a part of geochemistry. (13)

Table 5: *Volume percentage of minerals that make up the thin section number 4*

No	Minerals	Volume percentage	Rock Name
1	Quartz	30-40	
2	plagioclase	20-30	Biotite gneiss
3	Biotite	20-35	

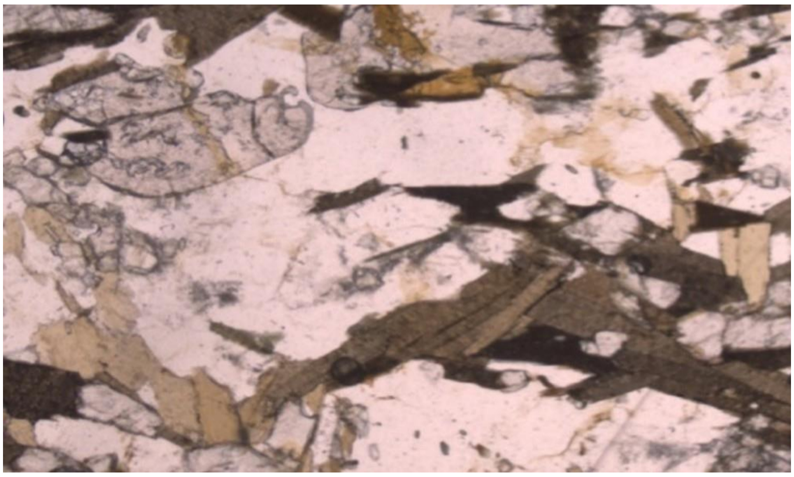

Figure 8. *Thin section number 4 under a nicol with a magnification of 40 polarization microscope. (Researcher Photo)*

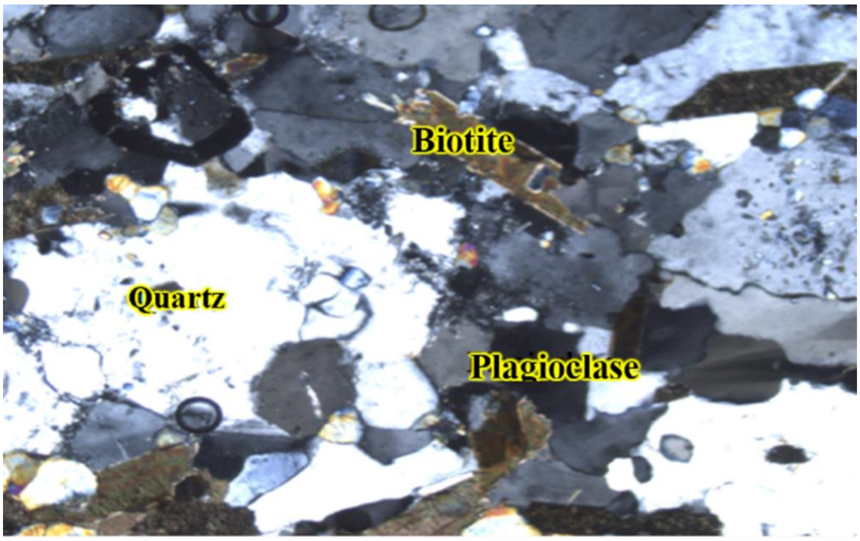

Figure 9. *Thin section No. 4 under two nicols with a magnification of 40 under a polarization microscope. (Researcher Photo)*

Description of Thin Section 5

The rock appears in a dark color under the PPL mode of the microscope, which contains 30-40 percent quartz, 15-70 percent plagioclase, 30-35 Percent Biotite, and about 5-10 percent epidote. In the quartz grains, an extinction angle is observed, and polysynthetic duality is also visible in the plagioclase particles. The Biotite particles have a justified state, which gives the rock a schist texture (Figures 10 and 11). In some areas, the feldspars are affected by secondary alterations, and the process of sericitization is observed. Quartz particles have been affected by strong tectonic movements and have overlapped. Wave quenching is observed in some minerals. The particle size ranges from 0.5 to 1 cm, allowing the structure to be described as granular. The plagioclases in this rock are close to their acidic composition and are strongly affected by deformation, with no polysynthetic duality in some parts. This rock is a Biotite gneiss-garnet.

***Table 6**: Volume percentage of rock-forming minerals in thin section number 5*

No	Minerals	Volume percentage	Rock Name
1	Biotite	30-35	
2	Plagioclase	15-20	Gneiss-garnet-Biotite
3	Quartz	30-40	
4	Epidote	4-5	

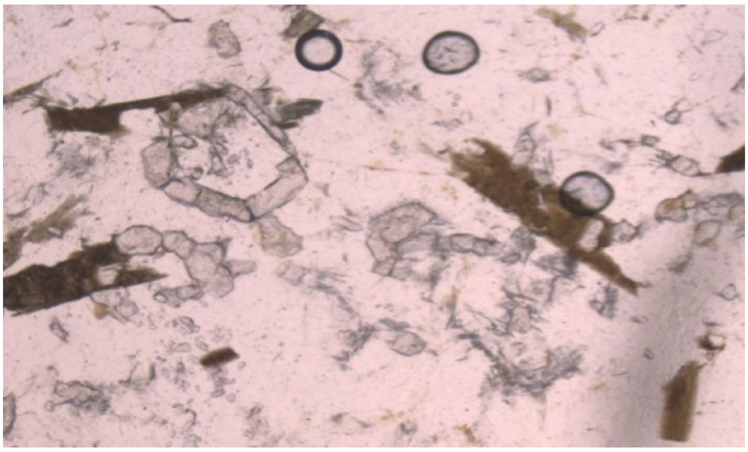

***Figure 10.** Thin section number 5 under a nicol with 40 magnification of a polarization microscope. (Researcher Photo)*

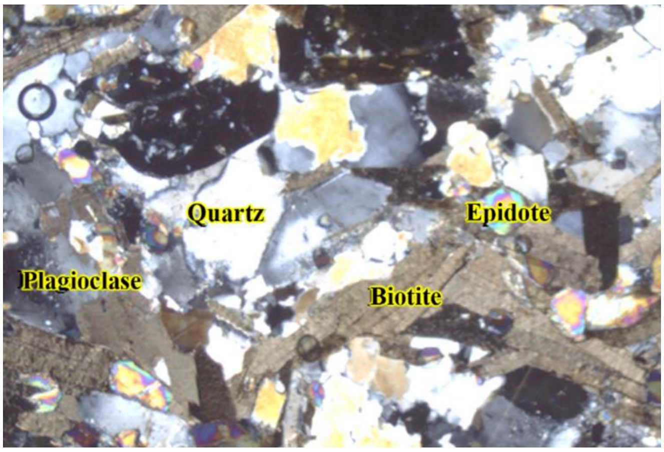

***Figure 11**. Thin section number 5 under two nicols with a magnification of 40 under a polarization microscope. (Researcher Photo)*

Description of Thin Section 6

The color of the rock under PPL is earthy, with some parts appearing pale green. The composition of this rock includes amphibole (20-25%), quartz (20-30%), plagioclase (10-20%), and Biotite (10-20%). However, in rock, including the above-mentioned minerals, chlorite can be observed in large quantities (Figures 12 and 13). The mineral particles are excellent, which has given the rock a completely schistose texture. The size of its particles reaches 0.5 cm, and its structure is granoblastic in some parts, but it can be seen towards the base that the minerals exhibit a lepidogranoblastic structure. In this rock, the accessory mineral is Clinozoisite, and the amphibole has larger sizes, which is probably of the hornblende type. The minerals biotite and chlorite are oriented in one direction, whereas feldspar and plagioclase have undergone secondary changes, resulting in irregular orientation. It is composed of chlorite, and the amount of Biotite is low. This gneiss is Biotite-chlorite amphibolite. In the mentioned thin section, an apparent polysynthetic dichotomy has been observed; however, in some parts, it has been affected by the schist texture.

Table 7: *Volume percentage of rock-forming minerals in thin section number 6*

No	Minerals	Volume percentage	Rock Name
1	Biotite	15-25	
2	Plagioclase	15-20	Biotite-amphibole-Gneiss
3	Quartz	15-20	
4	and sphen	20-30	
5	Chlorite	10-20	
6	Epidote	5-10	

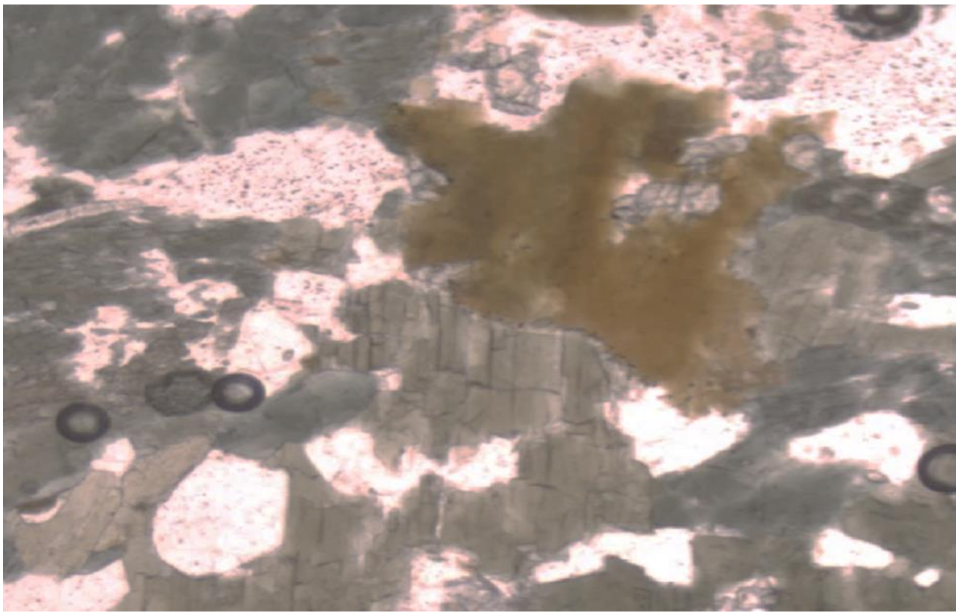

Figure 12. *Thin section No. 6 under PPL with a magnification of 40 polarization microscope. (Researcher Photo)*

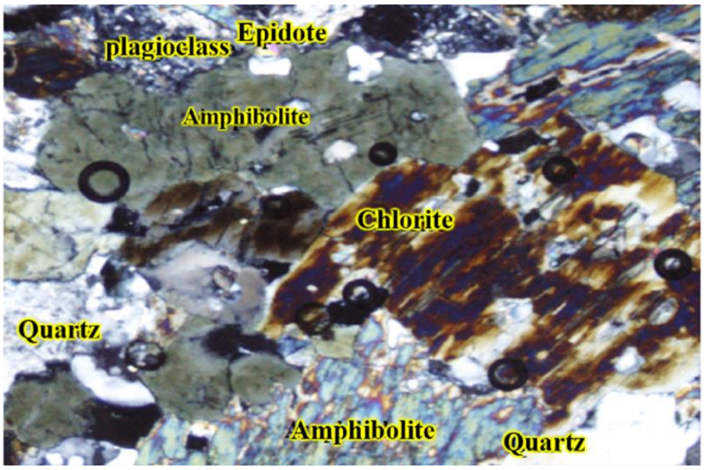

Figure 13. *Thin section number 6: under XPL with 40 magnification of a polarization microscope. (Researcher Photo)*

Description of Thin Section 7

In this thin section, chlorite and Biotite have been observed in large amounts, which contain about 10-20% Biotite and 10-20% chlorite. Under a microscope, the rock shows a dark, earthy color, and towards the amphibole mineral, its pale green color can be seen. Under simple light or PPL, some minerals, except for quartz, exhibit polychromatism. However, under crossed nicol, quartz displays oblique extinction, and in some parts, it also appears to exhibit wave extinction. The rock has been strongly justified; based on this, it has adopted the texture of schist, and its structure is grainy. From the petrographic perspective, it can be classified as lepidogranoblastic. Amphibole minerals exhibit a precise twisting in two directions, with the torquing angle between these directions approximately 60 degrees. Amphibole 20-30%, quartz 30-40%, plagioclase 5-10%, Biotite 10-20% and chlorite 10-20% are observed, so this gneiss rock is Biotite-chlorite amphibolite-like (figures 14, 15).

Table 8: *Volume percentage of rock-forming minerals in thin section number 7*

No	Minerals	Volume percentage	Rock Name
1	Biotite	10-20	
2	Chlorite	10-20	Biotite-amphibole-Gneiss
3	Amphibole	20-30	
4	Quartz	30-40	
5	Plagioclase	10-5	

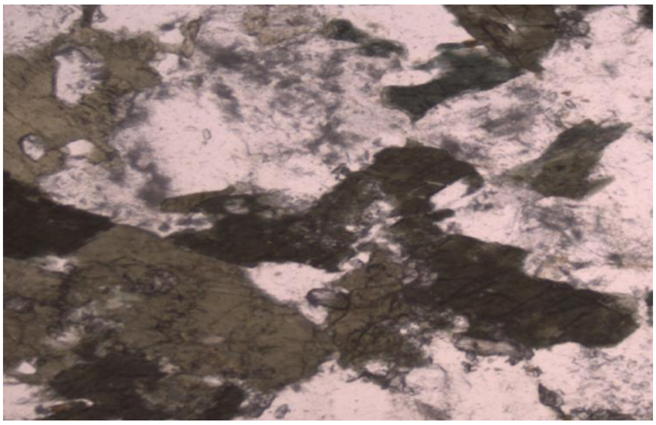

Figure 14. *Magnification 40 polarization microscope. (Researcher Photo)*

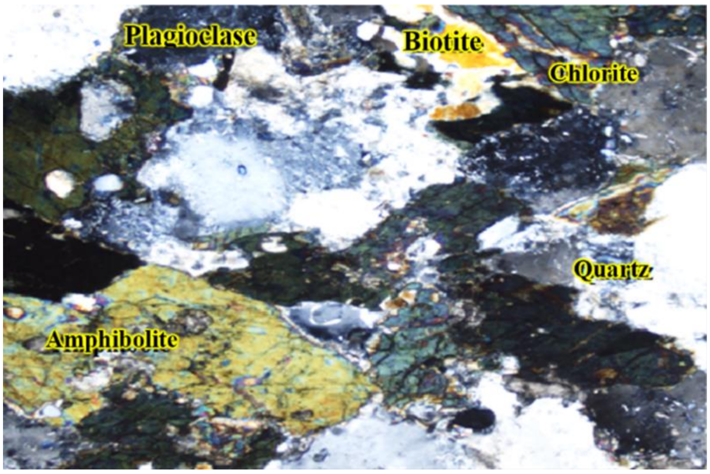

Figure (15). *Thin section 7: under cross-polarized light with 40 magnification of a polarization microscope. (Researcher Photo)*

DISCUSSION

This study investigates the lithological and geochemical characteristics of the Aliabad Mountain metamorphic sequence, identifying biotite gneisses, leucocratic gneisses, and amphibolites as the predominant lithological units. Petrographic analysis of thin sections reveals limited rounding of mineral detritus, indicating short-distance sediment transport and a proximal source area, likely in a shallow marine to coastal depositional environment. These observations suggest that the detrital material underwent minimal mechanical abrasion before lithification, consistent with a nearby sediment source (Rasouli & Vaseashta, 2023).

X-ray fluorescence (XRF) analysis indicates a sedimentary protolith with high concentrations of Si, Al, P, and S. The presence of apatite suggests potential organic productivity during deposition, possibly linked to biogenic material in an organic-rich environment. Elevated levels of Ti and Zr are consistent with the weathering of felsic rocks and the contribution of acidic sediments, a pattern also observed in the Proterozoic formations of the Shir Darwaza Series and the broader Kabul Block (Faryad et al., 2016). The Kabul Block, a distinct microcontinental fragment, comprises primarily Precambrian and Paleozoic rocks, separated by the Paghman fault to the northwest and the Gardez fault to the south, and is overlain by younger quaternary sediments of the Kabul Basin (Broshears et al., 2005). The Aliabad Mountain sequence shares a similar composite stratigraphy, with interlayered gneisses and amphibolites indicating a depositional environment influenced by fluctuating energy conditions.

These findings align with regional studies but provide a localized perspective on Aliabad Mountain's lithological evolution. Unlike the Khair Khana formations, which exhibit high-grade metamorphism and extensive granitization, the Aliabad sequence retains clearer evidence of its sedimentary protoliths and a moderate metamorphic overprint (Rasouli and Vaseashta, 2023). The repetition of gneiss and amphibolite layers suggests cyclic sedimentation, likely in a shallow marine to coastal setting, as supported by the geochemical homogeneity of principal oxides (SiO_2, Al_2O_3) and structural patterns observed during fieldwork, such as fold elements and bedding remnants (Doebrich and Wahl, 2006). The subsequent burial and metamorphism of these sediments are consistent with Proterozoic orogenic events, aligning with regional geodynamic models that propose alternating cycles of uplift and subsidence (Faryad et al., 2016).

While the rocks lack significant concentrations of economically valuable elements such as gold (Au), silver (Ag), or niobium (Nb), the consistent presence of phosphorus (P) and accessory minerals like zircon suggests moderate potential for phosphate resources and refractory trace minerals, which could be relevant for industrial applications. However, the study has limitations that must be acknowledged. The sample set was constrained by logistical challenges, such as restricted access to certain areas, resulting in incomplete coverage of lithological variability. Future research should increase sampling density to better represent the region's diversity, employ isotopic techniques (e.g., U-Pb zircon dating) to confirm protolith ages, and compare the Aliabad sequence with adjacent geological units, such as those in the Panjshir or Logar regions, to refine regional correlations.

CONCLUSION

This research investigates the chemical and mineralogical composition of metamorphic rocks from Aliabad Mountain, a distinctive geological feature within Afghanistan's Kabul Block, aiming to characterize lithological variations and their origins. Petrographic analysis of thin sections from the gneisses reveals that many accessory minerals exhibit partial edge and corner rounding, suggesting that detrital material was transported over short distances before lithification, indicative of a sedimentary origin. The dominance of biotite gneiss, along with occurrences of biotite-garnet gneiss, is evident in the studied samples. The presence of interlayered amphibolite within the gneiss sequences points to intense pre-metamorphic tectonic activity, likely associated with the deposition of arkosic sands and muds in shallow coastal environments. Subsequent subsidence facilitated the accumulation of finer sediments, which were later subjected to regional metamorphism, transforming mudrocks into amphibolites and arkosic sands into gneisses.

XRF geochemical analysis supports these findings, revealing elevated concentrations of silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3), consistent with an original felsic, acidic sedimentary composition. The high aluminum content particularly indicates the presence of alumina-rich mudrocks in the protolith. Although the massive nature of the outcrops and the lack of visible stratification in the field make it challenging to distinguish original depositional structures, both petrographic and geochemical evidence strongly support the conclusion that the gneisses of Aliabad Mountain are paragneisses derived from sedimentary precursors that have undergone substantial tectonometamorphic transformation. These findings enhance the understanding of the Kabul Block's Proterozoic evolution and suggest a depositional model involving shallow marine to coastal sedimentation followed by regional metamorphism. While the absence of economically significant metallic minerals limits mining potential, the rocks' stable mineralogy suggests suitability for construction material sourcing. Future studies should focus on increasing sample size, employing isotopic dating, and conducting comparative analyses with adjacent formations to further refine the geological history of the region.

Recommendations

X-ray fluorescence (XRF) analysis indicates that Aliabad Mountain's metamorphic rocks are silicate-rich, with high SiO_2 content, reflecting a felsic sedimentary protolith. One lithological unit shows elevated Fe, Ti, Mn, and Zr, suggesting oxide phases and a possible mafic or hydrothermally altered protolith, while another is enriched in P, indicating apatite and a phosphate-bearing sedimentary origin. Sulfur concentrations are similar across units, Cu is present only in the P-enriched lithology, and Ni and Co are exclusive to the oxide-rich lithology. The precise timing of geological evolution, genesis, and detailed protolith composition were not addressed due to limited sample size and analytical scope.

To address these gaps, future research should prioritize three actions. First, isotopic dating, such as U-Pb on zircon, is recommended to determine the timing of protolith formation and metamorphism, enabling correlation with Kabul Block's Proterozoic orogenic cycles. Second, a comprehensive geochemical analysis, using techniques like ICP-MS to detect trace and rare earth elements, should be conducted over a larger region of the Kabul Block with increased sample size to better define protolith composition and lithological variability. Third, comparative studies with adjacent formations (e.g., Panjshir, Logar) should integrate petrographic, geochemical, and structural data to assess regional metamorphic trends and source terrains, enhancing tectonic models. These steps will refine the geological history and evaluate the rocks' suitability for construction materials based on their stable silicate and phosphate compositions.

AUTHORS CONTRIBUTIONS

- Shakeeb Shamal developed the initial research proposal, played a central role in designing the research methodology, and provided overall supervision throughout the research process. He also contributed to the interpretation of the findings and the final revision of the manuscript.
- Shakeeb Shamal, Hafizullah Rasooli, and Abdulwaris Nabizadah collaborated closely on fieldwork, data collection, and laboratory analyses. They also actively contributed to the preliminary analysis and interpretation of the data.
- Shakeeb Shamal and Abdulwaris Nabizadah jointly participated in drafting the manuscript, structuring its scientific content, and carrying out the final academic editing of the paper.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

DATA AVAILABILITY

Data are available upon request from the corresponding author, subject to approval of the relevant ethics committee.

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