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Geochemical constraints on the petrogenesis of Patharkhola gneiss, Kumaun Lesser Himalaya, India

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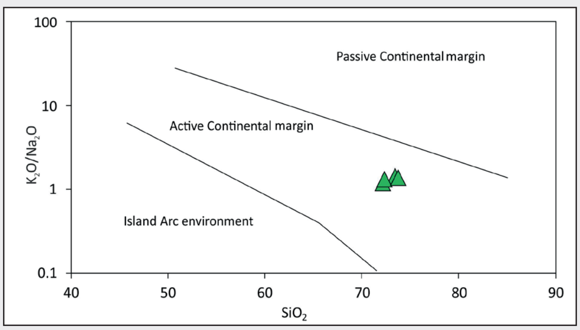
Abstract: A new set of geochemical and mineralogical data of gneisses from the Patharkhola region of the Dudhatoli syncline, Kumaun Lesser Himalaya is discussed to elucidate their petrogenesis and tectonic environment of India. These Patharkhola gneisses exhibit foliated texture and are primarily composed of K-feldspar ($KAlSi_3O_8$) and plagioclase ($NaAlSi_3O_8$) with perthite ($K,NaAlSi_3O_8$), biotite ($K(Mg,Fe)_3AlSi_3O_{10}(F,OH)_2$), muscovite ($KAl_2(AlSi_3O_{10})(OH)_2$), and tourmaline ($Na(Mg,Fe,Mn,Li,Al)_3Al_6[Si_6O_{18}](BO_3)_3(O,OH,F)_4$) as accessory minerals. They exhibit SiO_2 > 70 % with average K_2O/Na_2O = 1.31 % while Nb, V, Zr, La, and Eu show strong negative anomalies normalized to Post Archean Australian Shale (PAAS). The chondrite-normalized rare earth element (REE) concentrations of light rare earth elements (LREE) to heavy rare earth elements (HREE) exhibit varying ratios, ranging from 4.8 to 10.6 for (La/Yb)N. Additionally, there is a significant europium (Eu) anomaly, with Eu/Eu* ratios between 0.3 and 0.6. The authors have done Post Archean Australian Shale (PAAS) normalization as well as chondrite normalization separately and dealt with the variation in both normalizations.
The ratios of Al_2O_3/TiO_2 (82–112), Th/Sc (1.3–9.4), and Eu/Eu* (0.3–0.6) suggest that the precursor materials of these gneisses were felsic in nature. Based on the petrological and geochemical characteristics of the studied gneisses, it is proposed that the Patharkhola gneisses formed in an active continental margin, where the sediments originated from felsic sources.

Key words: geochemistry, petrogenesis, gneiss, Almora, Patharkhola, Himalaya

Graphical abstract



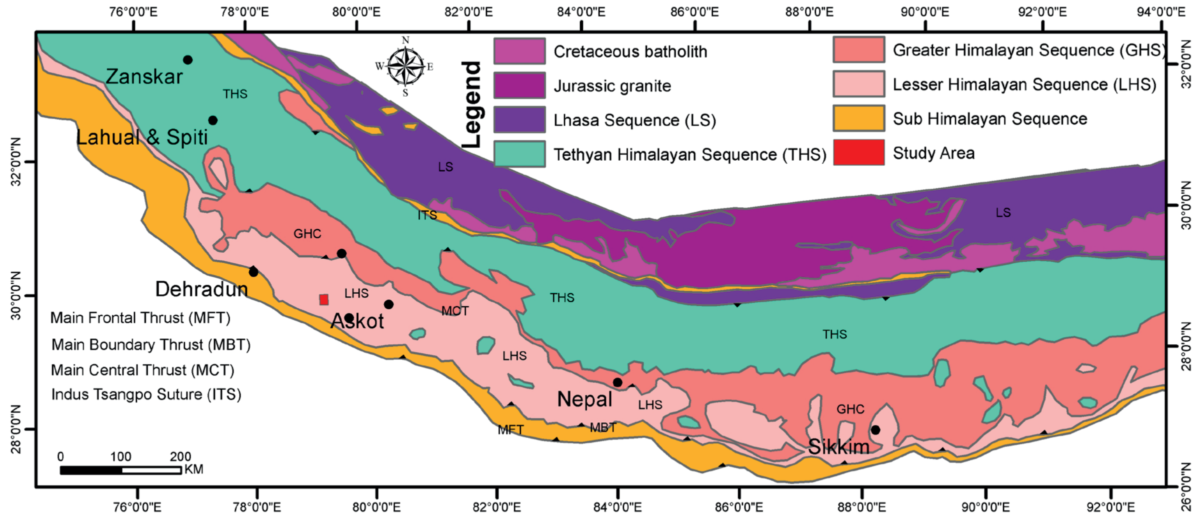
Highlights

- The Patharkhola gneisses exhibit elevated levels of SiO_2, potassic elements, and LREE/HREE (La/Yb) N ratios between 4.8–10.6 along with Eu/Eu* ratios falling between 0.3–0.6 with Th/Sc ratios between 1.3–9.4. These geochemical characteristics suggest that the gneisses are derived from felsic sediments.
- The Patharkhola gneisses are believed to be developed in an environment characterized by an arc type setting, where sediments rich in silt and clay are found in close proximity to the area.

Introduction

Around 55 million years ago, a significant event occurred when the Indian and Asian tectonic plates collided, leading to the formation of the majestic Himalayan mountain range. This geological wonder stretches along the entire northern boundary of India and serves as a remarkable example of intercontinental collision in Earth's geological history. Notable scientific studies conducted by Molnar and Tapponnier (1975), Valdiya (1980a, b, 1988), Yin (2006), and Webb (2011, 2013) have offered valuable insights into the complex processes that shaped this iconic mountain belt. The collision of these continents causes continental shortening, which results in the arrangement of Himalayan rocks through various thrust systems. Key thrust systems include the Main Central Thrust (MCT), Main Boundary Thrust (MBT), and Himalayan Frontal Thrust (HFT) (Srivastava & Mitra, 1994). The MCT forms the northern boundary of the Lesser Himalayan rocks, while the MBT marks the southern boundary.

The tectonics of the Lesser Himalaya have been studied extensively (Gansser, 1964; Valdiya, 1980a, b, 1988; Joshi et al., 2017, 2019; Rana, 2023; Rana & Thomas, 2018, 2023; Rana et al., 2023a, b; Thomas, T. & Thomas, H., 2003). Research by Mehdi et al. (1972), Saxena and Rao (1975), Agarwal (1994), Srivastava and Mitra (1996), and Bhattacharya (1999, 2000) has provided insights into the structural setup of the Lesser Himalayan rocks. In contrast, Ghosh et al. (1974), Srivastava and Mitra (1996), and Joshi



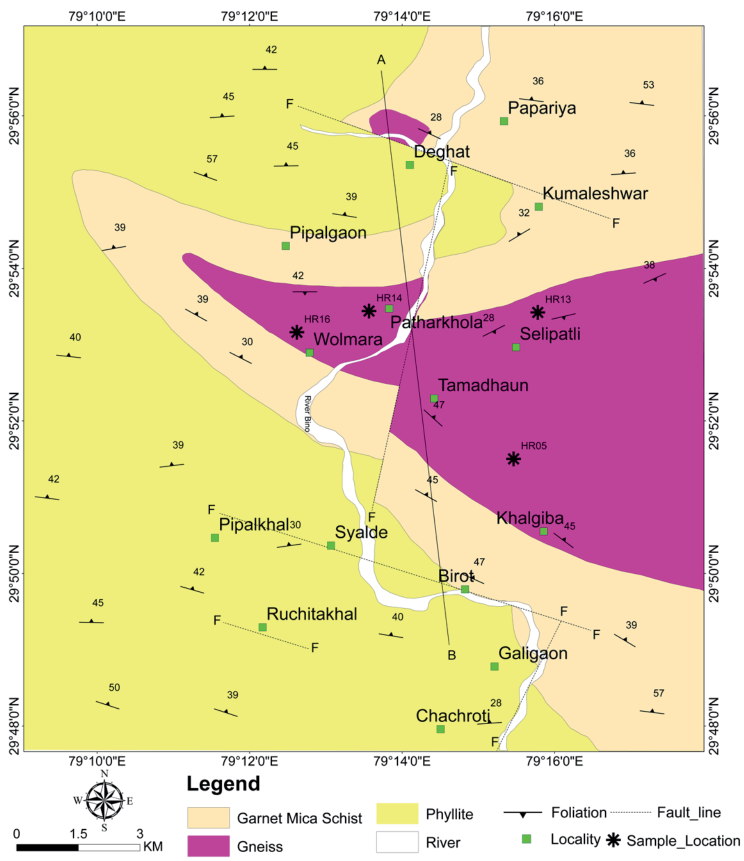


Fig. 1. Detail geological map around Patharkhola, Kumaun Lesser Himalaya, Uttarakhand, India (modified after Thomas & Thomas, 1992). Location of this detail map in regional map is shown in upper picture**.**

and Tiwari (2009) have explored the metamorphic history of the Almora Crystallines.

The central part of the Almora nappe exhibits a variety of deformation patterns and polyphase metamorphism, as documented by Gairola and Joshi in 1978. The Munsiari gneisses of the Almora Group in the Lesser Himalaya have been dated to approximately 1,830 ± 200 million years old (Bhanot et al., 1977). Islam et al. (2005) classified the Proterozoic granitoids of the Lesser Himalaya into two clusters: an older cluster ranging from 2,200 to 1,800 million years old, and a younger cluster from 1,400 to 1,200 million years old.

Although various studies have proposed different ages for the rocks in this region, there is a lack of extensive research focusing on their geochemical investigation. Kohn et al. (2010) utilized U-Pb dating to suggest an age of 1,830 ± 50 million years. In contrast, Mandal et al. (2016) proposed an age of 1,878 ± 2.4 million years for the augen gneisses discovered in the Askot area.

Geological settings

Numerous tectonic movements have shaped the geological structure of the Lesser Himalayan rocks, resulting in a complex arrangement. In the Patharkhola area, the exposed rocks belong to the Dudhatoli Group (Rana & Thomas, 2018). This group is part of the "Inner Schistose Series" or the "Metamorphic and Crystalline Nappe Tectonic Zone" of the Lesser Himalaya, which constitutes a distinct structural unit that has undergone multiple deformations and polyphase metamorphism. The authors have discussed the geochemical constraints of the gneisses found in

Patharkhola. Regarding the metamorphism of the Almora Group rocks, these have experienced at least two phases of deformation, characterized by well-developed F1 and F2 folds. The older S1 schistosity planes, which were formed during D1 deformation, are defined by muscovite and biotite flakes along with inequant quartz; these have been affected by tight to isoclinal folds (F2). The S2 schistosity planes, which developed parallel to the crenulation cleavages during D2 deformation, are defined by the mica flakes. Four metamorphic zones have been identified: chlorite-biotite, garnet-biotite, kyanite-biotite, and sillimanite-K-feldspar (Joshi & Tiwari, 2001). Rana (2023), Rana et al. (2023a, b) Rana and Thomas (2023), noted that the rocks of Patharkhola exhibit a clockwise pressure-temperature path characteristic of the Barrovian zone of metamorphism, with temperatures ranging from 350 °C to 600 °C and pressures between 3.3 to 6.5 kilobars. In the Kumaun and Garhwal regions, there are two significant outliers of crystalline rocks. The southern outlier is known as the Garhwal nappe, while the northern outliers are referred to as the Dudhatoli-Almora Nappe. The Dudhatoli Crystallines extend from Garhwal in the west-northwest to Kumaun in the east-southeast. In 1972, Mehdi et al. classified the Mandhali, Chandpur, and Nagthat Formations, along with the Dudhatoli-Almora Crystallines, as part of the newly established Dudhatoli Group. The Dudhatoli-Almora Crystallines form the uppermost horizon of this group and are believed to be of Precambrian age.

Gneisses can be observed between Wolmara village and Patharkhola, where they come into contact with garnet-bearing schists ($Mg_3Al_2Si_3O_{18}$). These foliated gneisses have a medium grain size and are characterized by their hardness and compactness. They contain abundant biotite ($K(Mg,Fe)_3AlSi_3O_{10}(F,OH)_2$) and muscovite ($KAl_2(AlSi_3O_{10})(OH)_2$), which contribute to their foliation. Ad-

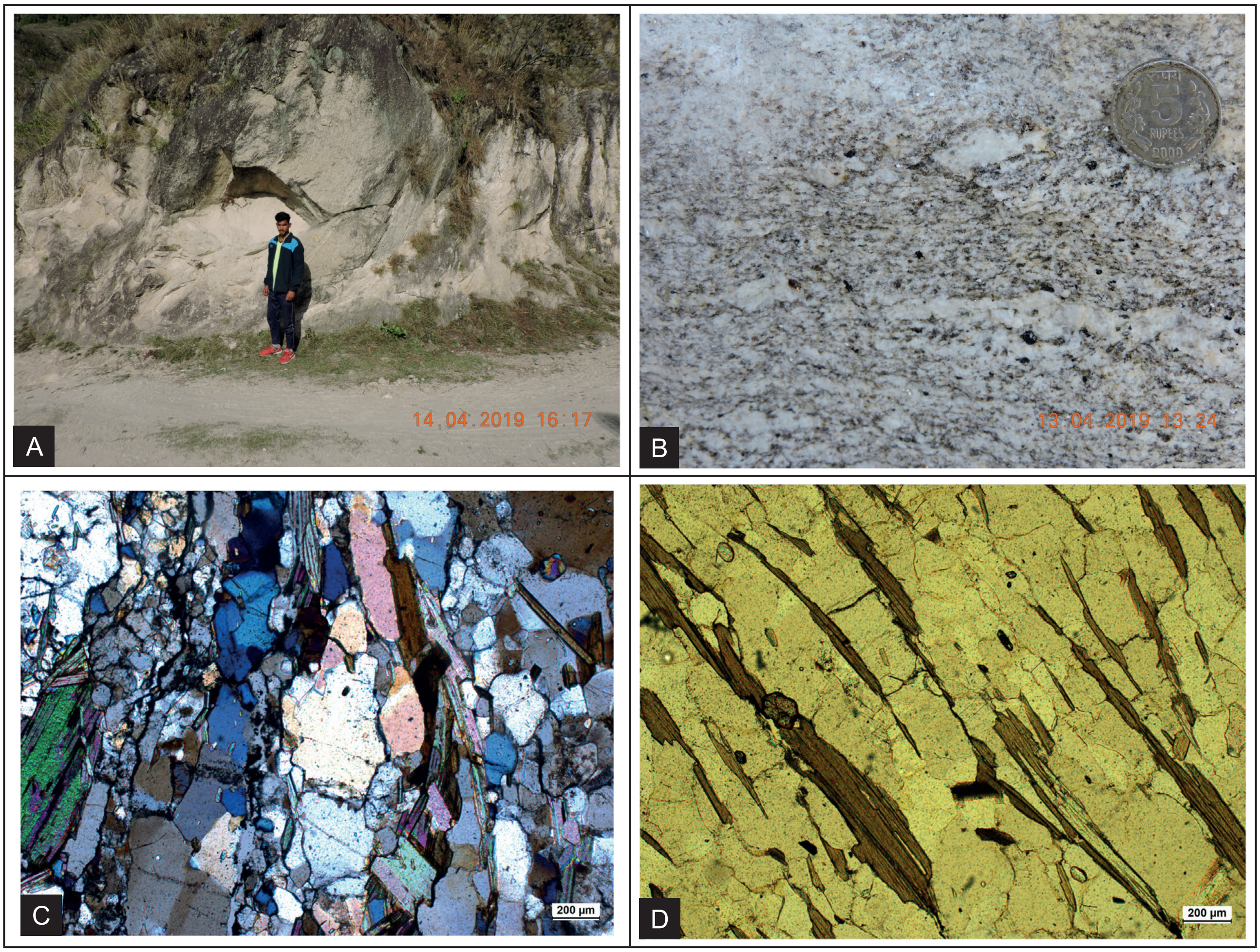


Fig. 2. Representative field and microscopic photographs of Patharkhola gneiss presented in this study: A – Foliated gneiss exposed at road section of Patharkhola village. B – Freshly cut foliated gneiss showing quartz, feldspar and phyllosilicates. C – Foliated gneiss showing biotite-muscovite-quartz-feldspar assemblage. D – Foliated gneiss showing alternated bands of phyllosilicates and quartzo-feldspathic layer in plane polarised light.

ditionally, porphyroblasts of feldspar ($KAlSi_3O_8$) can be found within these gneisses. Notably, near the Tamadhaun Primary School and around Khalgiba village, randomly oriented tourmaline ($Na(Mg,Fe,Mn,Li,Al)_3Al_6[Si_6O_{18}](BO_3)_3(O,OH,F)_4$) laths measuring 3 to 4 cm in length have been observed (Rana & Thomas, 2018).

Analytical methods

Thin section petrographic studies have been carried out with polarizing microscope having mounted photo camera. Whole-rock major oxides and trace element concentrations were determined by using pressed pellets on a wavelength dispersive X-Ray Fluorescence (WD-XRF) Bruker S8 Tiger at the Wadia Institute of Himalayan Geology (WIHG), Dehradun. Loss on Ignition (LOI) for every sample was determined by heating silica crucible containing 5 mg rock powder of each sample at 950 °C. XRF technique analytical precision for both major and trace elements lies within ± 2–3 % and ± 5–6 %, respectively (Saini et al., 2007). The rare earth elements (REEs) of the representative volcanic rocks were analysed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS, ELAN DRC-E, Perkin Elmer), strictly following the open digestion method at WIHG, Dehradun. Approximately 100 mg of powdered sample was measured with the help of an electronic weighing balance, which is treated with a mixture of 10 ml distilled acids (HF: HNO_3) in the ratio of 1 : 2. The crucibles made of Teflon containing acid treated samples were put on a hot plate heating at ~200 °C for a few hours. About ~2 ml of perchloric acid ($HClO_4$) was added, and the entire mixture was left to evaporate until dry. After the samples were turned into a thick brown paste form, 10 ml of 1 : 1 HNO_3

Tab. 1

Major, trace and REE of Patharkhola Gneiss of Kumaon Lesser Himalaya

Sample No.	HR05	HR13	HR14	HR16	Sample No.	HR05	HR13	HR14	HR16
SiO_2	72.2	73.46	72.31	73.36	Sc	2	2	4	1
Al_2O_3	15.63	15.36	15.79	15.3	V	11	11	15	10
Fe_2O_3	2.02	1.9	2.55	1.96	Cr	808	967	8 192	857
FeO	1.8	1.69	2.27	1.74	Co	252	127	1 169	459
MnO	0.03	0.03	0.06	0.03	Ni	934	989	8 665	839
MgO	0.26	0.23	0.24	0.23	Cu	2	7	18	9
Cao	0.62	0.64	0.66	0.69	Zn	82	50	41	54
Na_2O	3.83	3.36	3.6	3.43	Ga	21	14	17	16
K_2O	4.53	4.82	4.72	4.68	Rb	460	323	323	303
TiO_2	0.19	0.15	0.14	0.17	Sr	49	81	73	84
P_2O_5	0.27	0.26	0.28	0.26	Y	41	32	32	31
Total	99.58	100.21	100.35	100.51	Zr	71	57	59	64
K_2O/Na_2O	1.182	1.434	1.311	1.364	Nb	26	14	15	15
Na_2O/Al_2O_3	0.245	0.218	0.227	0.224	Ba	160	210	196	221
Rare Earth Elements					Pb	32	39	36	41
La	1.579	2.671	0.717	2.747	Th	17	5	5	7
Ce	5.776	5.412	36.882	16.406	U	4.7	1.1	2.2	BDL
Pr	0.717	1.144	5.019	2.913					
Nd	2.747	4.344	17.709	10.848					
Sm	0.847	1.397	4.88	3.192					
Eu	0.077	0.283	0.823	0.582					
Gd	0.674	1.445	5.513	3.47					
Tb	0.098	0.293	0.998	0.647					
Dy	0.42	1.56	4.964	3.398					
Ho	0.06	0.242	0.759	0.517					
Er	0.133	0.475	1.504	1.024					
Tm	0.019	0.063	0.191	0.131					
Yb	0.106	0.399	1.09	0.683					
Lu	0.014	0.05	0.15	0.093					
REE total	13.267	19.778	81.19	43.73					
LREE/HREE	14.6	5.41	9.25	7.08					
La/Eu	20.2	9.43	22.55	14.77					
Eu/Lu	5.5	5.66	5.48	6.25					

*BDL = Below detection limit

was added, and the samples were kept on the hot plate for another 10 minutes. The final solution is left up to 100 ml in a volumetric flask and ready for REE analysis.

Petrography

The gneisses found in Patharkhola exhibit a medium to coarse-grained texture when examined under a microscope. These rocks are primarily composed of feldspar, including both potassium feldspar ($KAlSi_3O_8$) and plagioclase ($NaAlSi_3O_8$), and they are devoid of garnet. Other minerals present in the gneisses include perthite ($(K,Na)AlSi_3O_8$), biotite ($K(Mg,Fe)_3AlSi_3O_{10}(F,OH)_2$), muscovite ($KAl_2(AlSi_3O_{10})(OH)_2$), secondary muscovite, and tourmaline ($Na(Mg,Fe,Mn,Li,Al)_3Al_6[Si_6O_{18}](BO_3)_3(O,OH,F)_4$). The gneissosity of these rocks is characterized by alternating layers of quartzo-feldspathic material and mica. In some portions muscovite and biotite are noticeably aligned, giving an appearance of lepidoblastic texture. Furthermore, the gneisses display compositional layering and foliation.

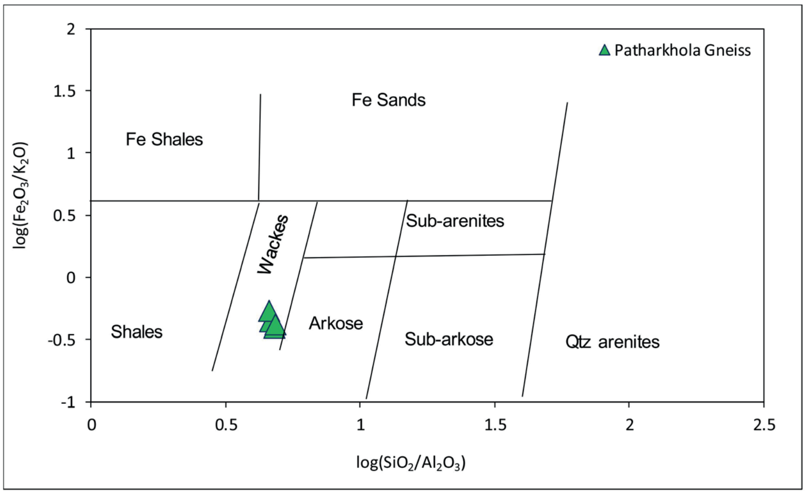
Following mineral assemblages has been observed:

a) Quartz-K-feldspar-Plagioclase-Muscovite-Sericite,
b) Biotite-Muscovite-Quartz-K-Feldspar.

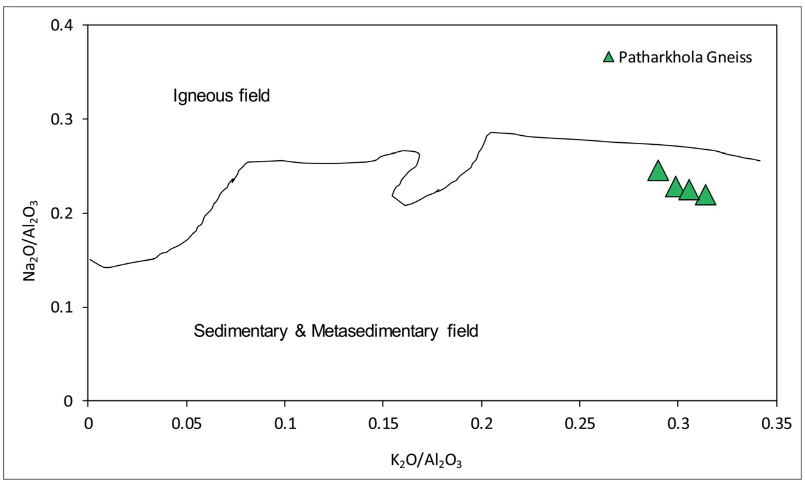
The majority quartz grains display characteristics ranging from xenoblastic to subidioblastic. These grains often feature sutured edges, showing bulging boundaries and the pinning of adjacent grains. The undulose extinction observed in the grains indicates that they have experienced ductile deformation followed by recrystallization.

It is common to observe undistorted quartz grains containing tiny sericite inclusions that exhibit strain-free extinction. Additionally, there are flattened and elongated quartz grains that display undulose extinction. K-feldspars are predominantly perthitic in nature, with patches occurring both at the core and rim of the grains. In some instances, the K-feldspar undergoes alteration, resulting in sericitization which is primarily observed at the boundaries between grains.

Plagioclase feldspars are typically observed as subidioblastic grains, exhibiting albite type twinning in most areas and mechanical twinning in a few areas. The measured extinction angles on these grains range from An_{16} to An_{38}, indicating that the plagioclase is of the oligoclase to andesine variety. The foliation is defined by the preferred alignment of brownish biotite lepidoblasts, which display light brown to dark brown pleochroism commonly associated with muscovite. Additionally, a second generation of biotite can be observed, forming an angular relationship with the earlier biotite and defining a major foliation.



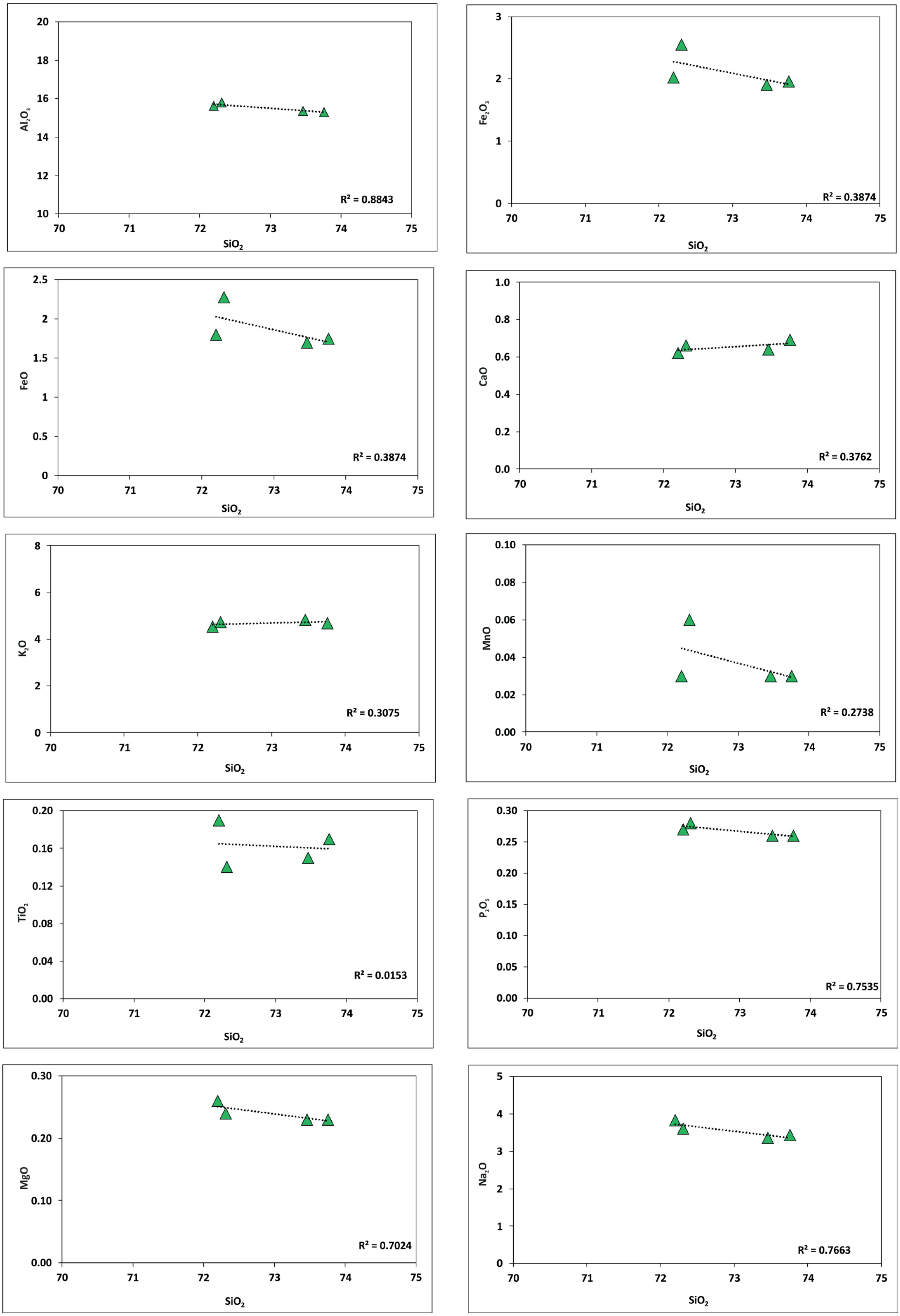
a)



b)

Fig. 3. a – Log (SiO_2/Al_2O_3) versus log (Fe_2O_3/K_2O) after Herron (1988). **b** – K_2O/Al_2O_3 versus Na_2O/Al_2O_3 after Garrels and Mackenzie (1971) for classifications of Patharkhola gneiss of Kumaon Lesser Himalaya.

Fig. 3c. Harker Variation diagrams of SiO_2 versus other major oxides of Patharkhola gneisses, Kumaon Lesser Himalaya.


Al2O3
SiO2
R² = 0.8843
Fe2O3
SiO2
R² = 0.3874
FeO
SiO2
R² = 0.3874
CaO
SiO2
R² = 0.3762
K2O
SiO2
R² = 0.3075
MnO
SiO2
R² = 0.2738
TiO2
SiO2
R² = 0.0153
P2O5
SiO2
R² = 0.7535
MgO
SiO2
R² = 0.7024
Na2O
SiO2
R² = 0.7663

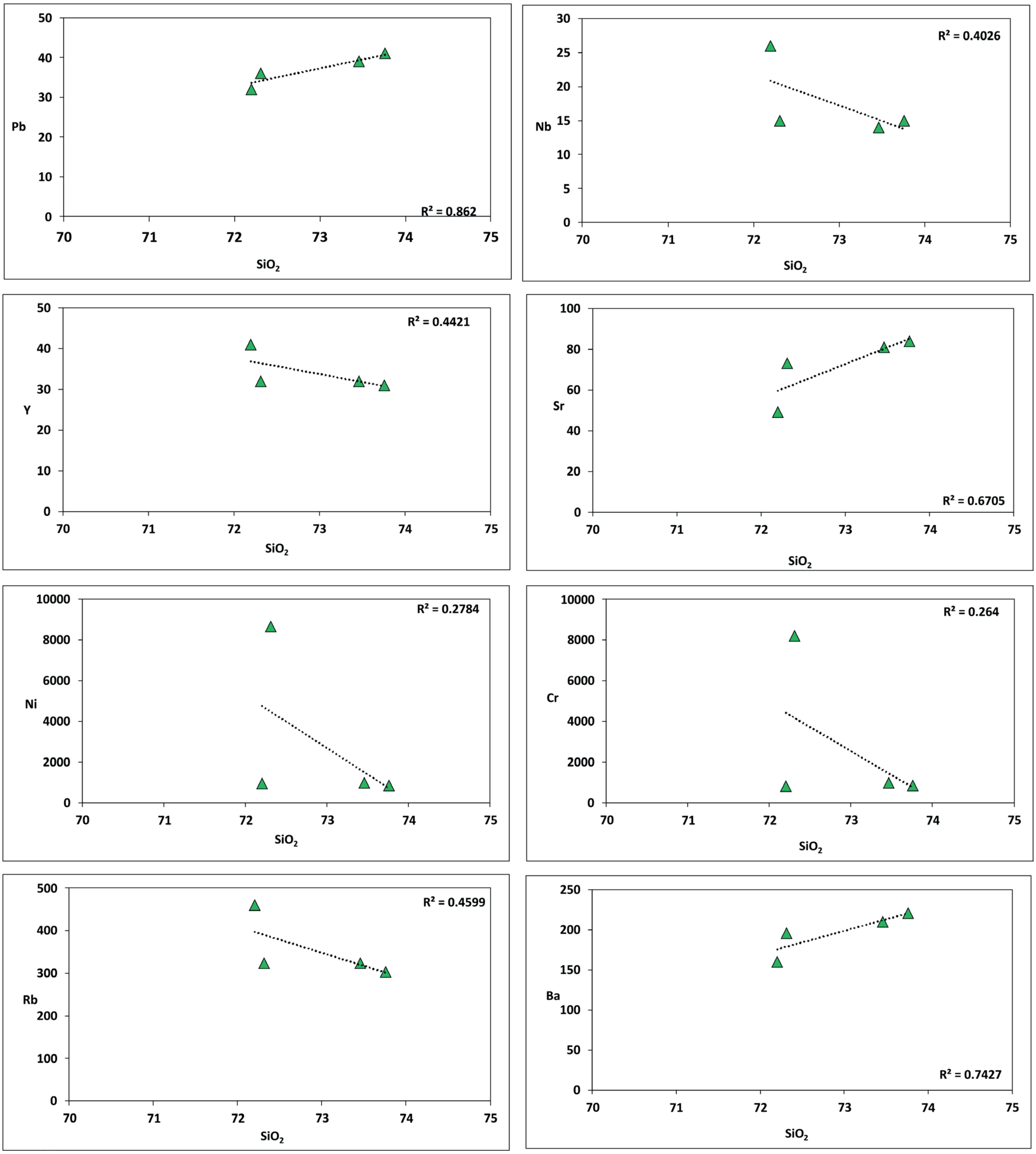


Fig. 3d. Harker variation diagrams of SiO_2 versus trace elements of Patharkhola gneisses, Kumaun Lesser Himalaya.

Geochemical characteristics of Patharkhola gneiss

The findings of the four chosen gneissic rocks, including major oxides, trace elements and REE, have been presented in Tab. 1. The content of SiO_2 ranges from 72.20 % to 73.76 %, while the content of Al_2O_3 ranges from 15.30 % to 15.79 %. It is worth noting that all four selected samples have a SiO_2 content exceeding 70 %. The average content of Na_2O and K_2O in the gneiss is 3.56 % and 4.69 % respectively. Generally, the Patharkhola gneisses exhibit a higher potassium enrichment than sodium. The average K_2O/Na_2O ratio for these rocks is 1.31 %. The TiO_2 content in the rocks varies from 0.03 % to 0.06 %.

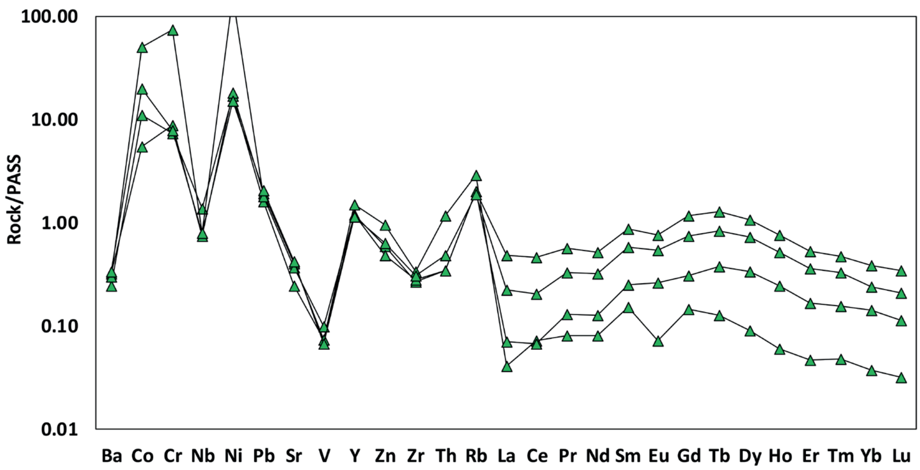
The FeO/MgO ratio ranges from 6.91 % to 9.45 % for these rocks.

Herron (1988) established a classification system for the origin of terrigenous sediments based on logarithmic ratios of SiO_2/Al_2O_3 versus Fe_2O_3/K_2O. By plotting the Patharkhola gneiss on the Herron classification plot (Fig. 3a), it can be determined that the investigated gneiss belongs to the wacke type that indicates the gneiss has originated from a source with a silty to clayey composition. The presence of high SiO_2 concentration in the samples within the wacke field suggests a significant contribution of quartz debris in the sedimentary environment. The relationship between K_2O/Al_2O_3 and Na_2O/Al_2O_3 has effectively distinguished between sedimentary and igneous rocks, as demonstrated by Garrels and Mackenzie in 1971. It is clear that all samples fall within the specified range for sedimentary rock, as depicted in Fig. 3b. In the Harker variation diagram, SiO_2 exhibits regression values greater than 0.5 for Al_2O_3, P_2O_5, MgO, and Na_2O. Despite these regression values exceeding 0.5, all the major oxides display a nearly horizontal or inverse trend with SiO_2, as shown in Fig. 3c. The significant presence of K_2O, in conjunction with Al_2O_3, indicates an enrichment of mica and chlorite concentration. Furthermore, the behaviour of trace elements in the gneissic assemblages has been examined using variation diagrams, with the plot of SiO_2 against trace elements depicted in Fig. 3d.

Sedimentary processes have a significant impact on the composition of alkali and alkaline earth elements. This is mainly due to their high solubility in aqueous solutions and their transportation as dissolved phases from the source to the deposition sites. Throughout the processes of weathering, transportation, and diagenesis, elements like Ti, Al, and HFSE can easily dissolve in high-temperature aqueous solutions without being fractionated relative to each other.

The Patharkhola gneisses exhibit an Al_2O_3/TiO_2 ratio ranging from 82 to 112, which suggests that they originated from felsic source rocks. In order to determine the composition of the provenance, characteristics of trace

a)



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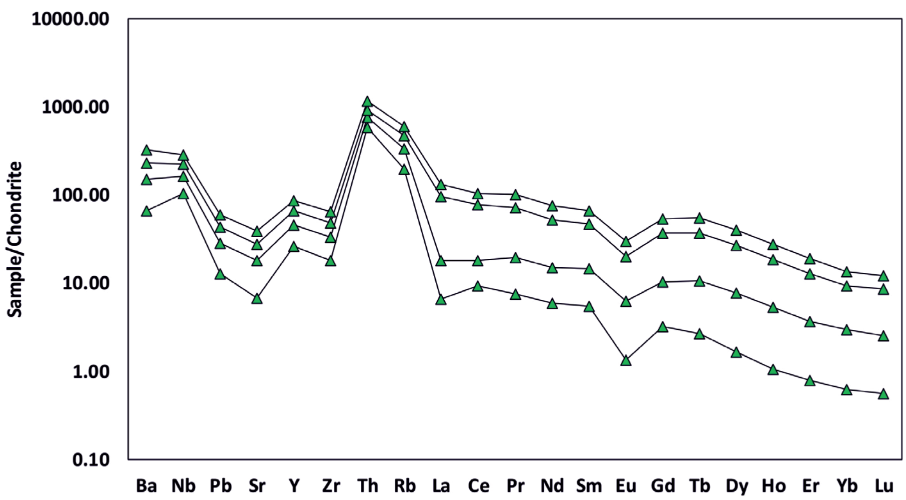
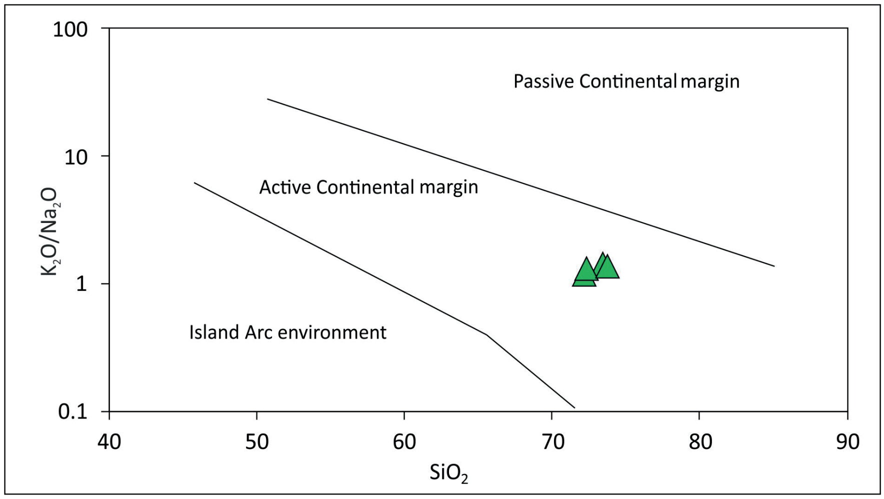


Fig. 4. a – REE Rock/PAAS normalized plot (Taylor & McLennan, 1985); **b** – REE chondrite normalized plot (Sun and McDonough 1989) of Patharkhola gneisses, Kumaon Lesser Himalaya.

elements such as REE, Cr, Co, Sc, and Th are studied, as they remain immobile under surficial conditions and have a short residence time in aqueous phases (Taylor & McLennan, 1985). These elements are commonly transported from the source to the depositional sites in terrigenous sediments. Felsic sources typically contain high concentrations of highly incompatible elements like REE and Th. The Th/Sc and Eu/Eu* ratios of felsic-derived sediments range from 0.8 to 20.5 and 0.4 to 0.9, respectively (Cullers & Podkovyrov, 2000). The Th/Sc (1.3–9.4) and Eu/Eu* (0.3–0.6) values of the Patharkhola gneisses fall within the range of felsic source sediments, indicating that these gneisses originated from felsic sedimentary sources.

a)



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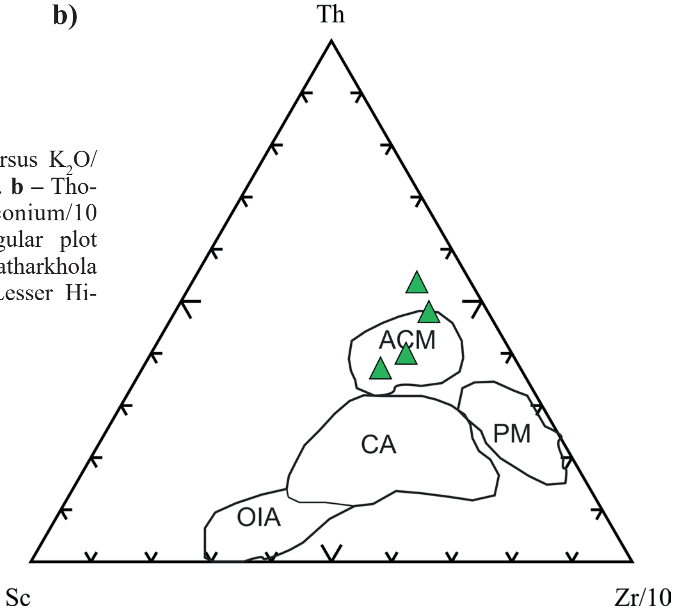

Fig. 5. a – SiO_2 versus K_2O/Na_2O (Bhatia, 1983). **b** – Thorium-Scandium-Zirconium/10 (Th-Sc-Zr/10) triangular plot (Bhatia, 1983) of Patharkhola gneisses, Kumaon Lesser Himalaya.

The Eu anomaly and REE patterns are important indicators for examining the characteristics of source rocks (Altrin et al., 2013). It is considered that high LREE/HREE ratios and negative Eu anomalies are typically associated with felsic sources, while flat REE patterns with fewer Eu anomalies are associated with mafic sources. In the case of the Patharkhola gneisses, the data shows fractionated trends with high LREE/HREE ratios (La/Yb)N ranging from 4.8 to 10.6, as well as Eu/Eu* values ranging from 0.3 to 0.6, which further support the presence of felsic sources.

The elements Nb, Y, Ni, Cr, and Rb exhibit a negative correlation, while Ba, Sr, and Pb show a positive correlation in relation to SiO_2. The content of Nb ranges from 14 to 26 ppm, with an average of 17.5 ppm, which is slightly lower than the content in Post Archean Australian Shale (PAAS) at 19 ppm. In the multi-element diagram normalized to PAAS, the gneisses from Patharkhola exhibit strong negative anomalies of Nb, V, Zr, La, and Eu. On the other hand, Cr, Ni, Y, and Rb show enrichment relative to PAAS. The total REE (ΣREE) content in the gneisses ranges from 13.26 to 81.19 ppm. The chondrites-normalized REE concentrations display varying LREE/HREE ratios (La/Yb)N, ranging from 4.8 to 10.6. The authors have done Post Archean Australian Shale (PAAS) normalization as well as chondrite normalization separately and dealt with the variation in both normalizations. The REE patterns are fractionated, with highly enriched LREE and fractionated HREE, featuring a prominent Eu anomaly with an Eu/Eu* anomaly range of 0.3–0.6. In terms of trace elements, Ba, Sr, V, Zn, and Zr in the Patharkhola gneiss exhibit low concentrations compared to PAAS.

The gneisses rare earth data was standardized to chondrites, as documented by Sun and McDonough in 1989. An interesting observation reveals that the light rare earth elements (LREE) exhibit steeper patterns, characterized by a La/Eu ratio of 16.73. In contrast, the heavier rare earth elements (HREE) display a less pronounced trend, with an Eu/Lu ratio of 5.72.

Tectonic implications

The role of geochemistry as a sensitive indicator in determining the origin of sedimentary and metasedimentary rocks, as well as providing insights into the tectonic setting of their deposition, has been extensively explored in scientific literature. Esteemed researchers such as Bhatia (1983), Bhatia and Crook (1986), Roser and Korsch (1986), Madukwe et al. (2015), and Grizelj et al. (2017) have significantly contributed to our understanding of this subject matter. Their studies have consistently demonstrated the importance of geochemical analysis in unraveling the provenance and tectonic history of these rocks.

Geochemical study is crucial in understanding the tectonic setting of ancient depositional sedimentary environments. Through the analysis of geochemical data, various discriminant diagrams have been developed to determine the tectonic setting in which sediments were deposited. For instance, the classification plot of SiO_2 versus K_2O/Na_2O, introduced by Bhatia and Crook in 1986, indicates that the protolith of Patharkhola gneisses was formed in an active continental margin. Another diagram, the triangular plot of Zr/10, Sc, and Th proposed by Bhatia in 1983, also confirms that the Patharkhola gneisses belong to an active continental margin.

Almora pelitic gneisses from Askot klippe have shown similar geochemical characteristics as of Patharkhola gneisses. The Eu/Eu* anomaly for Almora pelitic gneisses from Askot shows 0.15–0.54 having similar pronounced negative Eu anomaly. Negative Nb anomaly for both of these Patharkhola gneiss and Almora gneiss (Das et al., 2019) along with the garnet mica schist of Patharkhola (Rana et al., 2023b) Rana and Thomas (2023) shows similar sedimentation and metamorphism conditions.

Conclusion

The Patharkhola gneisses from Almora Dudhatoli Group of Kumaun Lesser Himalaya have shown the following characteristics:

The gneisses are composed of quartz, predominantly K-feldspar and minor amount of Na-plagioclase with mica group of minerals that represent pelitic assemblage. SiO_2 and Al_2O_3 total around 87–88 % with average Na_2O and K_2O values are 3.56 and 4.69 % respectively.

LREE/HREE ratios $(La/Yb)_N$ ranging from 4.8 to 10.6 showing notable enrichment of LREE and fractionated HREE, along with a prominent Eu anomaly (Eu/Eu* anomaly = 0.3–0.6).

Based on the petrological and geochemical characteristics, it is concluded that Patharkhola gneisses were formed in an active continental margin originating from felsic sources.

The rocks of Patharkhola formed during the Paleo-Proterozoic period in an arc-type setting where in between the arc and Indian continental plate, simultaneously the rifting of back-arc basin followed by the receiving of sediments both from the arc and the continental crust leads to the formation of lesser Himalayan rocks.

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Geochemické charakteristiky petrogenézy rúl oblasti Patharkhola z kumaunských Malých Himalájí v Indii

Himalájska horská reťaz vznikla kolíziou indickej a ázijskej litosférickej platne pred zhruba 55 miliónmi rokov (Molnar a Tapponnier, 1975; Valdiya, 1980a, b, 1988; Yin, 2006; Webb, 2011, 2013). Tektoniku Malých Himalájí – zóny situovanej južne od hlavného hrebeňa Himalájí – intenzívne skúmali Gansser (1964), Mehdi et al. (1972), Thomas a Thomas (1992, 2003), Agarwal et al. (2010, 2016), Joshi et al. (2017, 2019), Rana (2023), Rana a Thomas (2018, 2023) a Rana et al. (2023a, b). Práce autorov Ghosh et al. (1974), Srivastava a Mitra (1996) a Joshi a Tiwari (2004, 2007, 2009) priniesli nové poznatky o metamorfnej histórii kryštalického masívu Almora, ktorého geochemické charakteristiky sú náplňou tejto štúdie.

Minerálne zloženie skúmaných rúl paleoproterozoického veku z oblasti Patharkhola – kremeň, dominantne draselné živce a sľudy – indikuje pelitický protolit rulových metamorfitov. SiO_2 a Al_2O_3 majú zastúpenie 87 – 88 %. Hodnoty Na_2O a K_2O sú 3,56 a 4,69 %. Pomery LREE/HREE (La/Yb)N v rozsahu 4,8 – 10,6 spolu s anomáliou Eu/Eu* (0,3 – 0,6) a Th/Sc (1,3 – 9,4) indikujú, že protolitom týchto rúl boli felzitické sedimenty. Ich primárna pozícia sa spája s prostredím vulkanického oblúka s blízkou prítomnosťou sedimentov bohatých na silt a íl.

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