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Geochemical characteristics and tectonic interpretation of garnet mica schists of Patharkhola area in Kumaun Lesser Himalaya, Uttarakhand Himalaya, India

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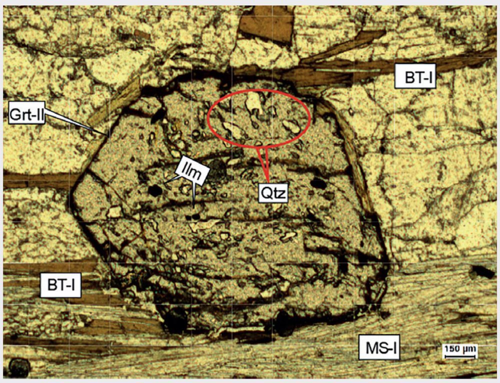
Abstract: The Patharkhola area is exposed in the core of the southern limb of the Dudhatoli syncline in the Kumaun Lesser Himalaya. Garnet mica schists of the Patharkhola occur in the folded outcrop pattern being located in between the limbs. They are dominantly composed of garnet, biotite, muscovite, chlorite, plagioclase and a subordinate amount of quartz. Garnet, both xenoblastic as well as idioblastic, is wrapped round by phyllosilicates minerals. These investigated rocks exhibits slightly LREE depleted patterns ($La_N/Sm_N = 0.7$, $La_N/Yb_N = 0.64$) with flat HREE patterns ($Sm_N/Yb_N = 0.89$). Field evidence along with geochemical characteristics suggests that the Patharkhola schists are peraluminous in nature, showing sedimentary sources having silt to silty clay protolith. They were formed in active continental margins in arc-type setting where the sediments were received both from arc and continental crust.

Key words: Garnet, Schist, Geochemistry, Tectonic settings, Lesser Himalaya

Graphical abstract



Highlights

- The garnet mica schists from Patharkhola, Kumaun Lesser Himalaya forms a part of Dudhatoli Almora group.
- The geochemical data clearly demonstrates that the Patharkhola schists are characterized by their high alkali content and silica-saturated nature exhibiting slightly LREE depleted patterns (LaN/SmN = 0.7, LaN/YbN = 0.64) with flat HREE patterns (SmN/YbN = 0.89).
- Shale dominated protolith representing nearby source sediments in arc type environment is inferred for the Patharkhola schists.

1 Introduction

The Himalaya, an arc-shaped mountain belt covering whole boundary of northern India is a type example of intercontinental collision between Indian and Asian plates around 55 Ma ago (Mukherjee, 2015; Yin, 2006). In the past, the structure, stratigraphy and tectonics of the Kumaun Lesser Himalaya have been described by Joshi & Tiwari (2009), Joshi et al. (2017) and Rana & Thomas (2018). In Kumaun region, the Lesser Himalayan sequence is delineated by Main Central Thrust (MCT) from the Higher Himalayan in the north and by Main Boundary Thrust (MBT) from the Siwaliks in south (Thakur et al., 2010). The rocks of the Dudhatoli group (Rana & Thomas, 2018) are exposed in the Patharkhola area. The "Inner Schistose Series" or the "Metamorphic and Crystalline Nappe' Tectonic Zone" of Lesser Himalaya forms a distinct structural unit which has witnessed multiple deformation and polyphase metamorphism. The Dudhatoli Crystallines extend from Garhwal in WNW to Kumaun in ESE. Kumar & Agarwal (1975) included Mandhali, Chandpur and Nagthat Formations and Dudhatoli-Almora Crystallines under a newly constituted group namely Dudhatoli group where the Dudhatoli-Almora Crystallines are the topmost horizon. Rocks of the Dudhatoli group have been considered to be of Precambrian age (Kumar & Agarwal, 1975). In Kumaun Himalaya, the Munsiari gneisses of Almora Group were dated as 1830 ± 200 Ma. old (Bhanot et al., 1977). Islam et al. (2005) proposed Proterozoic granitoids of Lesser Himalaya grouped into older clusters of 2200–1800 Ma and younger clusters of 1400–1200 Ma. Rana & Thomas (2023) studied the thermal and structural character of garnets from garnet mica schists of Patharkhola which is found to be of magnesian rich showing decomposition at higher temperatures. The metamorphic terrain exhibits multiple deformation patterns

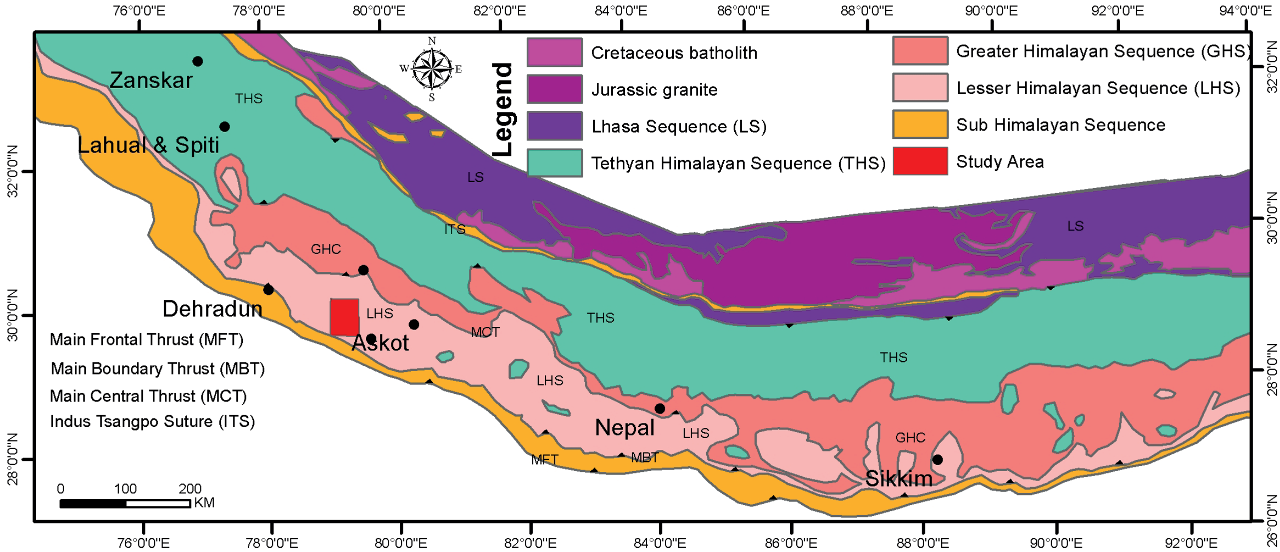


Fig. 1a. Generalized geological map of Himalaya, Modified after Yin (2006).

and polyphase metamorphism (Joshi & Tiwari, 2009) which is well exposed in the central part of Almora nappe.

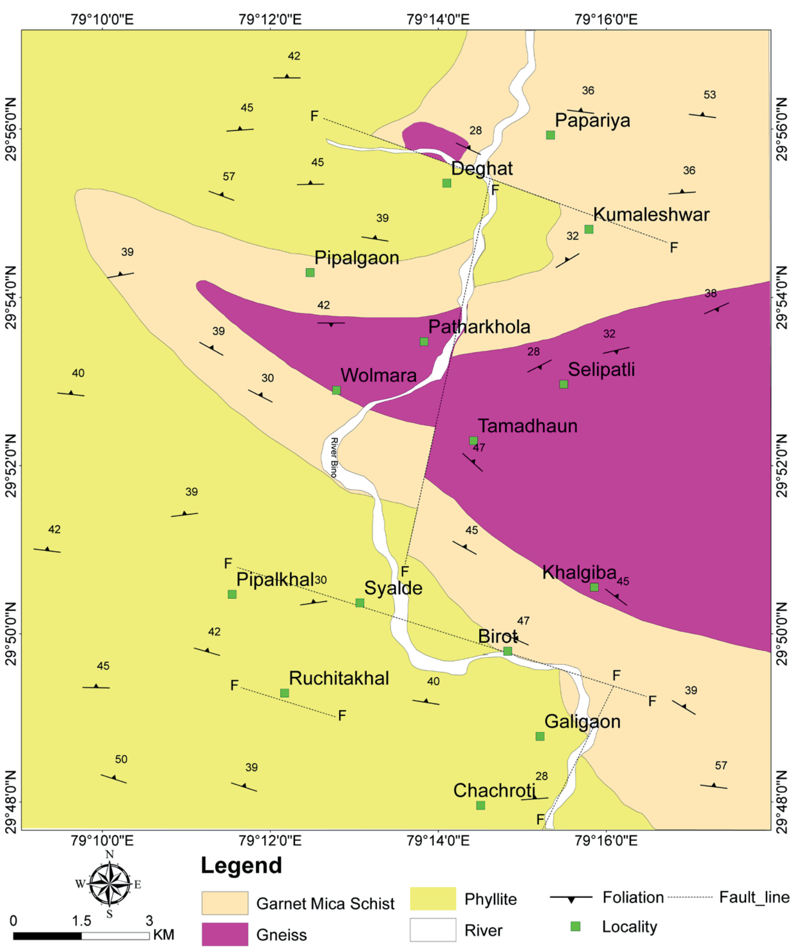


Fig. 1b. Geological map of the study area (Modified after Thomas & Thomas, 1992).

In Lesser Kumaun Himalaya, extensive work has been carried out on the pelitic gneisses and granites, rather less on the low-grade metamorphic i.e. schists and phyllites (Phukon et al., 2018; Das et al., 2019). Rana et al. (2023) studied the phyllites of Patharkhola and opined that the phyllites have high alumina content with enrichment of trace elements formed in active continental margins. The area around Patharkhola, exposes rocks of Lesser Kumaun Himalaya, lies between longitude 79°09'E to 79°17'56"E and latitude 29°47'42"N to 29°56'69"N with an approximate area of around 120 square kilometres (Fig. 1a). The rock types exposed in the area are gneisses, schists and phyllites (Fig. 1b). The main aim of the present paper is to provide geochemical character and petrogenesis of schists.

2 Macroscopic properties

In the area under investigation, schists are highly fragile and powdery in nature. Depending upon the biotite, muscovite and/or chlorite content, they exhibit a variation in colour from pinkish brown, dark brown, light grey to greenish green, (Fig. 2a, c). Increased percentage of quartz and feldspar imparts compaction. The schists of the area are characterized by the presence of garnet which ranges in size from 0.1 cm to 0.2 cm in hand specimens (Fig. 2a). On weathering, pink garnet crystals impart a reddish brown tinge to the rock and when removed, leave behind small pits of reddish-brown colour. These are foliated medium to coarse-grained rocks where schistosity is defined by the parallel alignment of phyllosillicates showing folding and crenulations due to deformation.

3 Petrography

Rock samples have been collected from the entire area of the exposure of garnet mica schist terrain. Samples showing well-developed internal structures have been studied in detail and discussed here. Schists of the area is dominantly composed of garnet, biotite, muscovite, chlorite, plagioclase and subordinate amount of quartz. Two distinct varieties of garnet have been identified. Garnet-I occurs as pre-kinematic porphyroblasts, shattered and stretched parallel to the foliation, (Fig. 2b), containing ilmenite and quartz as inclusions and are highly fractured. Garnet has both xenoblastic as well as idioblastic textures suggesting the reaction:

Muscovite + Chlorite + Quartz = Garnet + Biotite + Water

Garnet-II occurs as rolled garnet wrapped round by flaky minerals and imparts a closed eye structure, (Fig. 2d). Two variants of Biotite recognised as Biotite-I, (Fig. 2b, d), as coarse lepidoblastic in intimate association with Muscovite-I defining the foliation while Biotite-II occurs as cross-cutting relationship with Biotite-I. Chlorite-I occurs as lepidoblasts, light greenish in colour showing pleochroism from light green to green in colour, defining the schistosity plane in close association with Biotite-I and Muscovite-I. Chlorite-II occurs as very similar to Chlorite-I, occurring as lepidoblasts cross cutting the schistosity plane varying from sub-parallel to low angles. Tiny shreds of plagioclase occur in the schists lying parallel to the schistosity plane in close association with quartz. At a few places, it is usually altered to sericite as a common alteration product. Apatite occurs as inclusion in feldspar and muscovite.

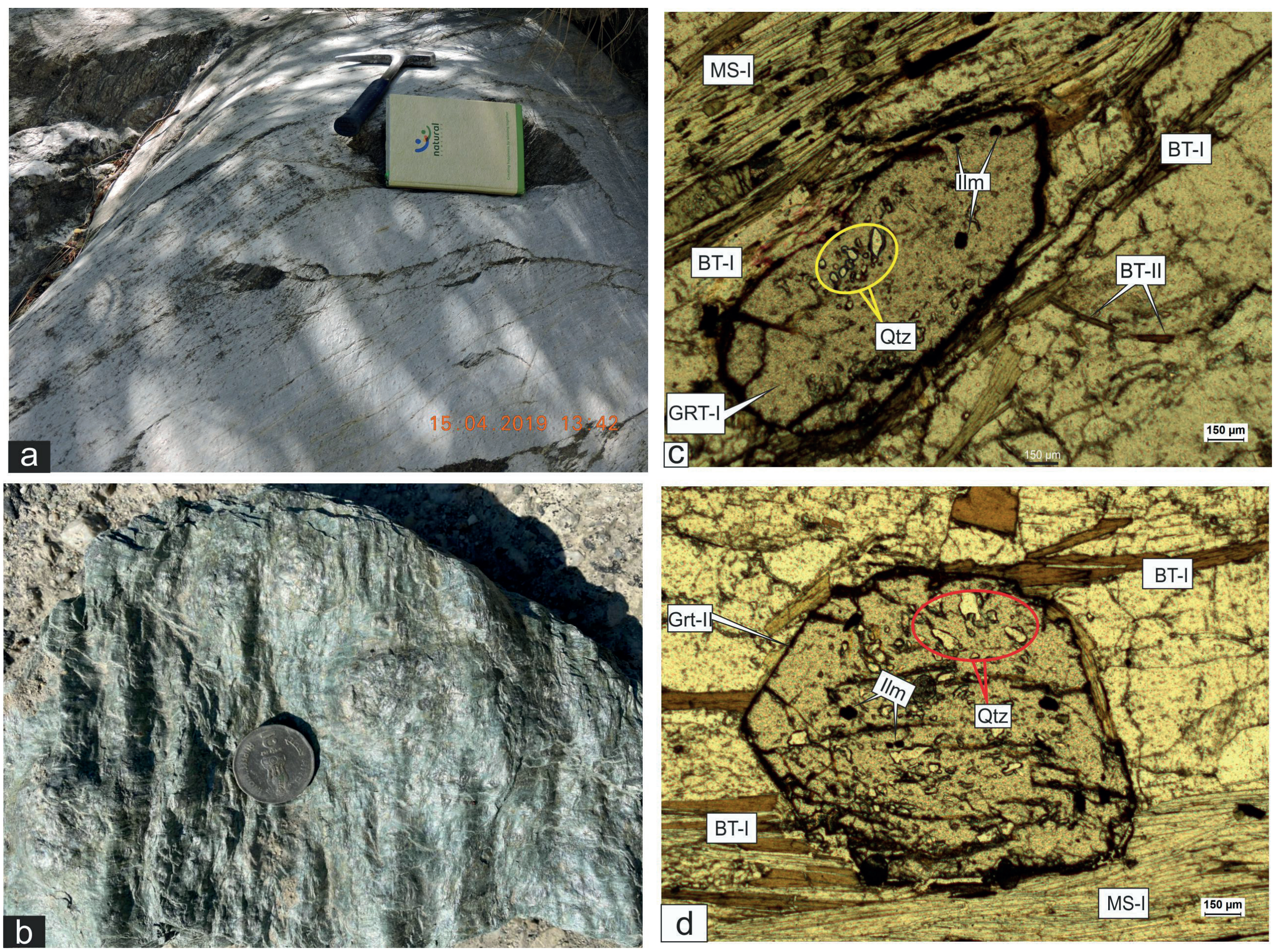


Fig. 2. (a, b) Field photograph showing pitted garnet; (c) Photomicrograph of stretched garnet parallel to foliation (d) Rolled garnet wrapped by flaky minerals (under plane polarised light).

4 Geochemistry and petrogenesis

The results of the major oxides, trace elements along with rare earth elements (REE) are tabulated below in Table 1. Rock samples were crushed, and then pulverized using an agate carbide ring grinder. Major oxides and selected trace element concentrations present in the rock were measured on powder pellets by X-ray Fluorescence Spectrometer (XRF; Siemens SRS-3000) in the Wadia Institute of Himalayan Geology (WIHG), Dehradun. The samples were analysed in the same institute for their REE and some trace elements by Inductively Couple Plasma-Mass Spectrometer (ICP-MS; PerkinElmer SCIEX ELAN DRC-e) using the open system rock digestion method. Rock powders were first thoroughly dissolved in HF and HNO_3 in Teflon crucibles and heated over a hot plate for three hours to prepare solutions from which trace elements and REE abundances were determined. Analytical precision for major elements is well within ± 2 – 3 % and ± 5 – 6 % for trace elements. Accuracy of rare earth elements ranges from 2 to 12 % and precision varies from 1 to 8 %.

The SiO_2 and Al_2O_3 content varies from 64.74 to 75.78 % and from 10.53 to 19.88 %, respectively. The average Na_2O and K_2O content in the schists is 2.59 % and 2.67 %, respectively. The average K_2O/Na_2O ratio of these rocks is 1.06; whereas TiO_2 content of the rocks varies from 0.61 to 0.8 %, as per Herron (1988), Fig. 3 (a) plot log(Fe_2O_3/K_2O) versus log(SiO_2/Al_2O_3) plot for classification of terrigenous sediments and shale, all studied samples of garnet mica schists fall within the shale to wacke-shale junction field specified for silty to silty clay protolith. This is due to the high Fe_2O_3/K_2O ratio with less SiO_2/Al_2O_3 ratio representing that the schists have been derived from shale-dominated environment.

The A/CNK values of schists ranging from 1.8 to 2.8 support its characterization as a strongly peraluminous, relatively potassic-rich source. The plot of K_2O/Al_2O_3 versus Na_2O/Al_2O_3, (Fig. 3b) has clearly differentiated the sedimentary from igneous rocks, Garrels and Mackenzie (1971). It is evident that all samples fall within the field specified for sedimentary rock. The plot between SiO_2 and other oxides, (Fig. 3c) shows good correlation, which indicates coherent behaviour of elements during different processes. SiO_2 versus Al_2O_3, CaO, K_2O, MnO and TiO_2 have shown positive regression while others have poor regression values. The representation of good regression values of alumina and potash with silica represents the dominance of peraluminous nature and is substantially supported by the good regression of silica with Rb, La, Y and Ce. The behaviour of trace elements in the schists has also been studied with the help of variation diagrams presented in (Fig. 3d). Trace elements show good correlation with respect to SiO_2.

During metamorphism, the REE are very little fractionated and also immobile during sedimentary processes. It is also considered that during metamorphism the REE remains unaffected up to the upper amphibolite facies regional metamorphism, (Taylor & McLennan, 1985). On the other hand,

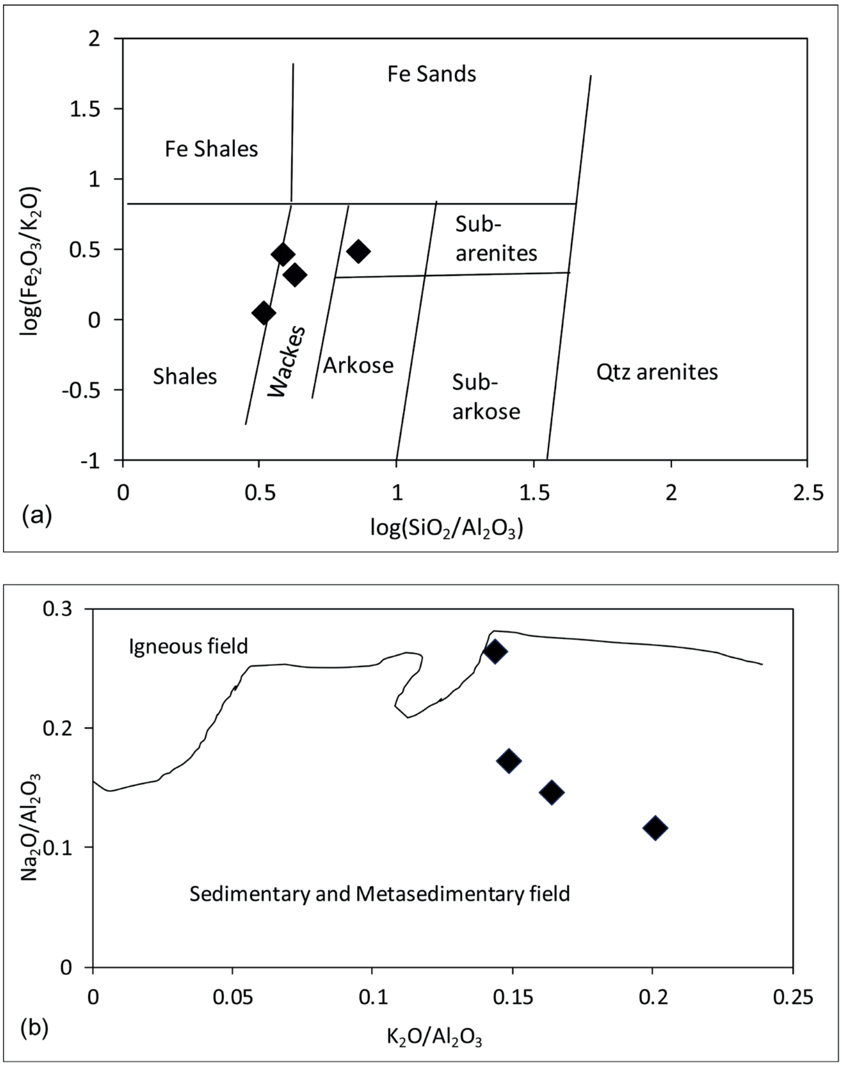


Fig. 3. (a) log (SiO_2/Al_2O_3) versus log (Fe_2O_3/K_2O) after Herron (1988) for classification of terrigenous sediments and shales; (b) K_2O/Al_2O_3 versus Na_2O/Al_2O_3 after Garrels & Mackenzie (1971).

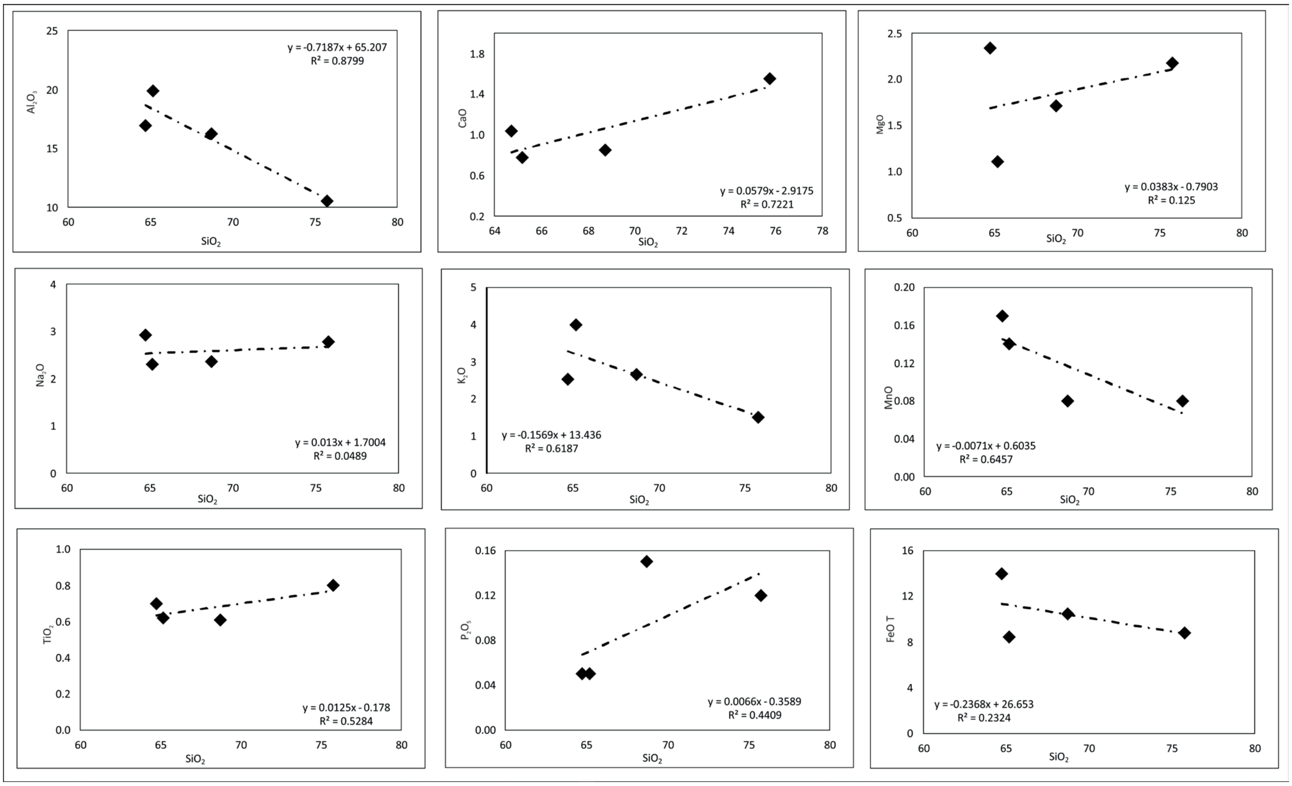


Fig. 3. (c) Silica versus major oxides for garnet mica schists.

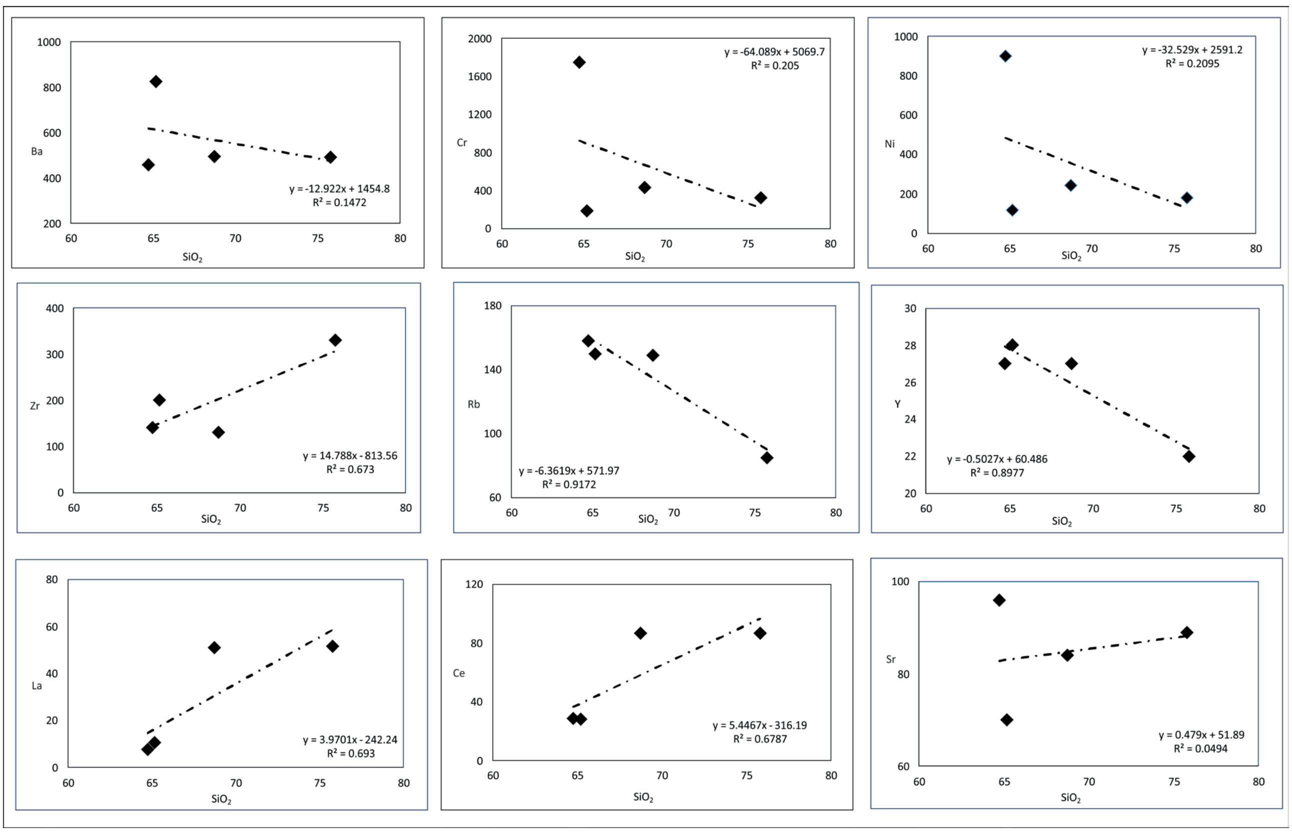


Fig. 3. (d) Silica versus trace elements.

REEs have been shown to be mobile to some extent during metamorphism (McLennan, 1982).

The REE content of a metamorphic rock directly mimics that of the pro-tolith. This assumption has formed the basis for a great number of studies in which the evolution of the protolith was examined in detail without specifically testing for the immobility of the REEs (Grauch, 1989). In this context, the issue of REE

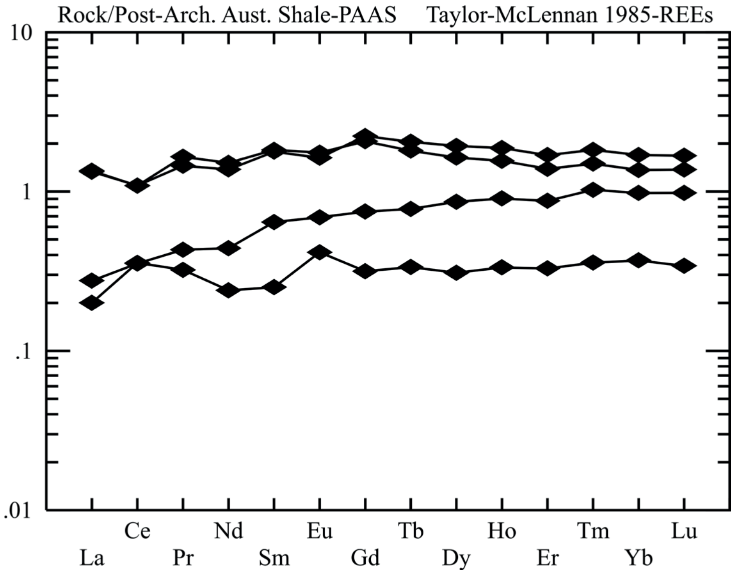
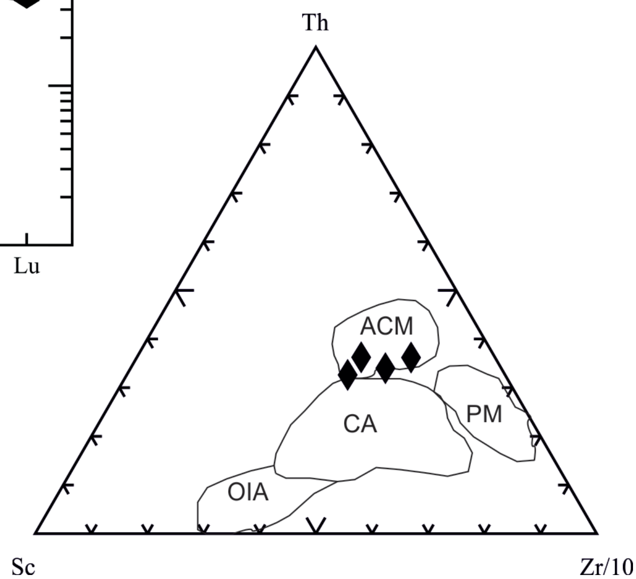


Fig. 3. (e) REE normalised plot (Taylor & Mclennan, 1985).

migration during metamorphism has been long debated between proponents of isochemical metamorphism and those of metasomatism. The only certainty is that REEs are mobile in certain circumstances (Vocke et al., 1987) and immobile in others (Rolland et al., 2003). Despite some progress in this direction, the nature of these circumstances has rarely been determined. Further research on a typical lithologically and chemically distinct types of sample suites may help our understanding of REE contents in metamorphic rocks, because they may contain a record of REE mobility or immobility (Grauch, 1989).

The analyzed REE data for the schists were normalized to Post Archean Australian Shales (PAAS), normalised values are from Taylor & Mclennan (1985).

They exhibits slightly LREE depleted patterns (LaN/SmN = 0.7, LaN/YbN = 0.64) with flat HREE patterns (SmN/YbN = 0.89). Concentration of lithophile elements (Rb, Cs, Ba and Sr) along with HFSE (Y, Nb and Zr) have shown values in close proximity to the PAAS. The higher LREE/HREE ratio indicates a high degree of fractionation during the metamorphic stage as no such chemical heterogeneity has been observed in the protolith. The steep LREE and gentle HREE with negative europium anomaly are depicted by the Patharkhola schists. The similarity in the values of schists with PAAS is interpreted to be steaming from the chemical homogeneity of the protolith which has changed a very little during the metamorphism (Likhanov, 2008). These aforementioned features are typical of post Archean clay shales which are caused by the occurrence of erosional products of upper continental crust material (an average of 23 Australian shales of Post Archean age), (Taylor & Mclennan, 1985) which imputes



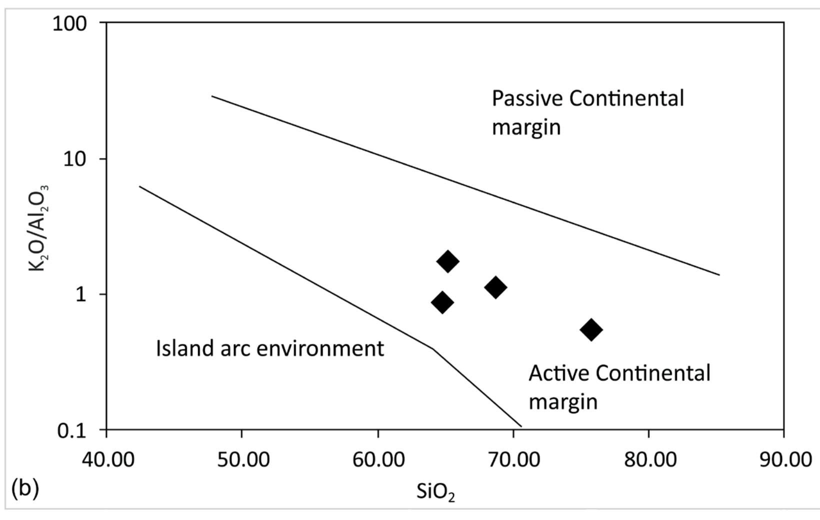


Fig. 4. (a) Th-Sc-Zr/10 triangular plot (Bhatia, 1983); (b) SiO_2 versus K_2O/Al_2O_3 (Bhatia, 1983).

the presence of erosional products of sedimentary rocks in the detritus accompanied by the decrease in the Eu content during the sedimentation process of residual plagioclase (Taylor & Mclennan, 1985).

5 Tectonic implications

Studies have traditionally shown that geochemistry plays a crucial role as sensitive indicator in determining the provenance of sedimentary and metasedimentary rocks and also to constrain the tectonic setting in which they were deposited (e.g., Bhatia, 1983; Bhatia & Crook, 1986; Roser & Korsch, 1986; Madukwe et al., 2015; Grizelj et al., 2017). Trace elements such as Co, Sc, Ni, Zr, Th, La and others are used for tectonic environment discrimination due to their fractionation and low mobility in sedimentary environments. Bhatia, (1983) proposed ternary plots of Sc-Th-Zr/10 and Sc-La-Th to ascertain the tectonic settings. The process of collisional tectonics and deformation is formed during the mechanism of orogeny or plate convergence leading to the formation of continental arc or active continental margin settings. These depositional environments forming in these regions are usually underlain by thick and elevated continental crust, (Bhatia & Crook, 1986). Geochemical composition of schists plotted in these ternary plots, falls in the active continental settings (Fig. 4a). Conversely, the plot of SiO_2 versus K_2O/Na_2O, shows that schists of Patharkhola have been formed in the active continental margin (Fig. 4b).

6 Conclusion

The garnet mica schists of the Patharkhola area forms a part of Dudhatoli Almora group in Kumaun Lesser Himalaya. Petrographically, the garnet mica schist is dominantly composed of garnet, biotite, muscovite, chlorite, plagioclase and a subordinate amount of quartz. It is observed that the Prekinematic garnet wrapped round first generation biotite and muscovite. Second generation Biotite-II and Muscovite-II occur as cross-cutting relation with the Biotite-I and Muscovite-I.

The geochemical data reflects that Patharkhola schists are alkali rich with silica-saturated nature. These investigated schist exhibits slightly LREE depleted patterns (LaN/SmN = 0.7, LaN/YbN = 0.64) with flat HREE patterns (SmN/YbN = 0.89). The log(Fe_2O_3/K_2O) versus log(SiO_2/Al_2O_3) plot shows that the protolith of schists is mainly shale-dominated, representing nearby source sediments formed in arc-type environment. Their geochemical signature further suggests that the schists of patharkhola have formed in active continental margins. Thus we considered that the Lesser Himalayan rocks have formed in arc-type active continental setting where the sediments where received from both from the arc and continental crust.

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Geochemické charakteristiky a tektonická interpretácia granatických svorov oblasti Patharkhola v Kumaunských Malých Himalájach, Uttarakhandské Himaláje, India

Pohorie Himaláje tvorí oblúkový horský pás pokrývajúci celú hraničnú zónu severnej Indie. Je typovým príkladom zrážky medzi indickou a ázijskou litosférickou platňou v období pred približne 55 miliónmi rokov (Mukherjee, 2015; Yin, 2006). Štruktúre, stratigrafii a tektonike územia Kumaun v Malých Himalájach sa venujú viaceré práce (Joshi a Tiwari, 2009; Joshi et al., 2017; Rana a Thomas, 2018). V oblasti Kumaun je sekvencia Malých Himalájí oddelená hlavnou centrálnou prešmykovou zónou (*Main Central Thrust;* MCT) od Vyšších Himalájí na severe. Hlavný hraničný prešmyk (*Main Bondary Thrust;* MBT) oddeľuje túto sekvenciu od oblasti Siwalikov na juhu (Thakur et al., 2010). Horninové súbory skupiny Dudhatoli (Rana a Thomas, 2018) vystupujú v oblasti Patharkhola.

Vnútorná bridličnatá séria, označovaná aj ako tektonická zóna príkrovu metamorfovaných a kryštalinických hornín, tvorí v Malých Himalájach výraznú štruktúrnu jednotku s polyfázovou deformáciou a metamorfózou. Kryštalinikum masívu Dudhatoli vystupuje od lokalít Garhwal na ZSZ po Kumaun na VSV. Kumar a Agarwal (1975) zahrnuli Mandhali a formácie Chandpur a Nagthat, rovnako ako kryštalinikum Dudhatoli-Almora, do novovytvorenej skupiny Dudhatoli, v ktorej kryštalinikum Dudhatoli-Almora reprezentuje najvyšší horizont. Horniny skupiny Dudhatoli sa považovali za prekambrické (Kumar a Agarwal, 1975). V Kumaunských Himalájach boli ruly jednotky Munsiari skupiny Almora datované na 1 830 ± 200 mil. r. (Bhanot et al., 1977). Islam et al. (2005) rozčlenili proterozoické veky granitoidov Malých Himalájí do dvoch skupín: 2 200 – 1 800 mil. r. a 1 400 – 1 200 mil. r. Rana a Thomas (2023) študovali termálny a štruktúrny charakter granátov z granatických svorov v bridliciach z lokality Patharkhola. Zistilo sa, že sú bohaté na Mg, čo dokladá ich vyššieteplotný rozklad.

Študovaný terén vykazuje polyfázovú deformáciu a metamorfózu (Joshi a Tiwari, 2009). Je to dobre pozorovateľné v centrálnej časti almorského príkrovu. V Kumaunských Malých Himalájach sa realizoval rozsiahly výskum pelitických rúl a granitov a v menšom rozsahu aj nízkostupňových bridlíc a fylitov (Phukon et al., 2018; Das et al., 2019). Rana et al. (2023) štúdiom patharkholských fylitov dospeli k záveru, že fylity s vysokým obsahom Al a obohatené stopovými prvkami vznikli na aktívnom kontinentálnom okraji.

Oblasť okolo lokality Patharkhola s vystupovaním hornín Malých Kumaunských Himalájí je ohraničená zemepisnou dĺžkou 79° 09' V až 79° 17' 56" V a zemepisnou šírkou 29° 47' 42" S až 29° 56' 69" S. Má rozlohu približne 120 km^2 (obr. 1a). Vystupujúcimi horninami sú ruly, bridlice a fylity (obr. 1b). Článok je zameraný na geochemický charakter a petrogenézu bridlíc.

Pri tektonickej interpretácii je dôležitý geochemický výskum sedimentárnych a metasedimentárnych hornín, ktorý dokáže citlivo preukázať ich pôvod a tektonické prostredie ich vzniku. Analyzované údaje o REE bridlíc boli normalizované podľa *Archean Australian Shales* (PAAS) s normalizovanými hodnotami podľa Taylora a Mclennana (1985).

Vykazujú mierne ochudobnené LREE (LaN/SmN = 0,7, LaN/YbN = 0,64) s plochým priebehom HREE (SmN/YbN = 0,89). Koncentrácia litofilných prvkov (Rb, Cs, Ba a Sr) spolu s HFSE (Y, Nb a Zr) má hodnoty v tesnej blízkosti PAAS. Vyšší pomer LREE/HREE označuje vysoký stupeň frakcionácie počas metamorfnej fázy, keďže takáto chemická heterogenita sa nezistila v protolite. Patharkholské bridlice vykazujú strmé LREE a mierne HREE s negatívnou európskou anomáliou. Podobnosť hodnôt bridlíc s PAAS je interpretovaná ako kontaminácia z primárneho prostredia, pretože protolit sa málo zmenil počas metamorfózy (Likhanov, 2008). Uvedené znaky sú typické pre postarchaickú hlinu bridlíc s výskytom erozívnych produktov z vrchnej kontinentálnej kôry (priemer z 23 austrálskych bridlíc postarchaického veku). Prítomnosť erozívnych produktov sedimentárnych hornín v detrite je sprevádzaný poklesom obsahu Eu počas procesu sedimentácie zvyškov plagioklas (Taylor a Mclennan, 1985).

Štúdie mnohých autorov preukázali, že geochémia je citlivý indikátor určujúci provenienciu sedimentárnych a metasedimentárnych hornín a tektonické prostredie, v ktorom sa nachádzali (napr. Bhatia, 1983; Bhatia a Crook, 1986; Roser a Korsch, 1986; Madukwe et al., 2015; Grizelj et al., 2017). Na určenie tektonického prostredia sa využívajú predovšetkým stopové prvky ako Co, Sc, Ni, Zr, Th, La a ďalšie. Na určenie tektonického prostredia Bhatia (1983) navrhol ternárne diagramy Sc-Th-Zr/10 a Sc-La-Th. Prejavy kolíznej tektoniky a deformácie sú v rámci orogenézy produktom konvergencie litosférických platní vedúcej k vzniku kontinentálneho oblúka alebo prostredia aktívneho kontinentálneho okraja. Depozičné prostredia v takýchto regiónoch sú zvyčajne podostielané hrubou a vyklenutou kontinentálnou kôrou (Bhatia a Crook, 1986). Geochemické zloženie bridlíc zobrazených v ternárnych diagramoch spadá do prostredia kontinentálnej kolízie (obr. 4a). Naopak, diagram SiO_2 vs. K_2O/Na_2O indikuje, že bridlice z Patharkholy sa vytvorili na aktívnom kontinentálnom okraji (obr. 4b).

V záverečnom zhrnutí je možné konštatovať, že granatické svory v oblasti Patharkhola, ktoré sú súčasťou skupiny Dudhatoli-Almora v Kumaunských Malých Himalájach, petrograficky pozostávajú z granátu, biotitu, muskovitu, chloritu, plagioklasu a druhoradého množstva kremeňa. Zistilo sa, že predkinematický granát je obalený prvou generáciou biotitu a muskovitu. Druhá generácia biotitu-II a muskovitu-II sa vygenerovala priečne v mikrofraktúrach biotitu-I a muskovitu-I. Geochemické údaje dokladajú, že svory sú bohaté na alkálie a nasýtený SiO_2. Vykazujú mierne ochudobnené LREE (LaN/SmN = 0,7, LaN/YbN = 0,64) s plochým priebehom HREE (SmN/YbN = 0,89). Diagram log(Fe_2O_3/K_2O) vs. log(SiO_2/Al_2O_3) dokladá, že protolitom svorov bola predovšetkým bridlica reprezentujúca zdrojové sedimenty z aktívneho kontinentálneho okraja. To indikuje, že horniny z Malých Himalájí sa vytvorili v prostredí kontinentálneho oblúka, kde detrit sedimentov pochádzal z tohto oblúka, ako aj z kontinentálnej kôry.

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