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# Thrust boundary delineation and metamorphic zonation mapping through petrography in the Tamghas-Arkhabang section, western Nepal

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## ABSTRACT

This study analyzes the mineral paragenesis and microstructural characteristics of rocks from the Tamghas-Arkhabang section to delineate a thrust boundary and create a detailed metamorphic zonation map. A 1:25,000 scale geological map was prepared, and representative rock samples from each stratigraphic unit were systematically collected for petrographic analysis. Fourteen thin sections were examined to understand the deformation and metamorphism in the region. Field observations such as fault breccias, fault gouge, lineation, and slickensides, along with petrographic evidence of inverted and dynamic metamorphism, cataclastic deformation, and ribbon quartz, suggest the presence of a thrust equivalent to the Mahabharat Thrust (MT), a significant tectonic feature in the study area. Microstructural indicators like undulose extinction, grain boundary migration, recrystallisation, and deformation lamellae in quartz further confirm this thrust's existence. Two distinct carbonate successions were identified: the southern unit correlates with the Lesser Himalayan sequence, while the northern, more metamorphosed carbonate unit is associated with the Bhimphedi Group, part of the Jajarkot Thrust Sheet. Stratigraphic continuity is disrupted in some sections, where quartzite and schist replace the basal carbonate strata, likely due to thrusting. The thrust's propagation has impacted both footwall and hanging wall rocks, evidenced by features such as rotated garnets with spiral inclusions. Three metamorphic zones—chlorite, biotite, and garnet isograd—indicate progressive metamorphism linked to thrust tectonics, revealing an inverted metamorphic sequence in the region.

**Keywords:** Petrography; metamorphism; Jajarkot Thrust Sheet; Lesser Himalaya; central Nepal

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## INTRODUCTION

The Lesser Himalaya is considered as the fold-and-thrust belt in the Himalaya. The regional geology of the Lesser Himalaya in Nepal has been extensively studied and its general framework is presented in the form of a geological map of Nepal (Amatya and Jnawali, 1994; Dhital, 2015) as depicted in Fig. 1. Early geological frameworks provided by Hagen in 1969 introduced the concept of nappe. Stöcklin and Bhattarai (1977) and Stöcklin (1980) carried out a comprehensive geological mapping of the Lesser Himalaya and the Kathmandu Nappe in central Nepal. Their stratigraphic classification of the Lesser Himalaya and the Kathmandu Nappe from central Nepal has been still widely adopted. They divided the rocks of this region into the Kathmandu Complex (crystalline rocks of the Kathmandu Nappe) and the Nawakot Complex (Lesser Himalayan metasediment). Dhital (1995) prepared a geological map of the Gorkha–Ampipal area and showed that the metamorphic isograds follow the thrust boundaries. Similarly, the geological setting and thrust tectonics of the Muglin-Damauli area of west-central Nepal were well-studied by Paudyal and Paudel in 2013. They have reported the rocks of both Nawakot Group and Kahun Klippe in the region. The geological setting and lithostratigraphy of the Bandipur-Gondrang area are well correlated with the rocks of the Nawakot Group (Paudyal et. al., 2012). However, in this section, two younger geological units the Malekhu Limestone and the Robang Formation are missing. Petrography and illite crystallinity of low-grade metasediments was studied in the Gorkha-Narayangarh section of west-central Nepal with an emphasis on metamorphic zonation mapping (Paudyal et. al., 2011). Inverted metamorphic zones were observed in this area as in the other parts of the Lesser Himalaya.

The Tamghas - Arkhabang section from Gulmi district of Lumbini province consists of extensive exposure to the Lesser Himalayan rocks including both the autochthonous as well as allochthonous sequences. The autochthonous succession consists of low-grade metasedimentary rocks from the area and the rocks of the medium-to-high-grade Lesser Himalayan thrust sheet are part of the allochthonous sequences (Fig. 1). While prior research in this area has primarily emphasized tectonics and stratigraphy, there has been a notable absence of studies investigating the petrography and deformation of rocks (Lamsal et al., 2023)

The primary aim of the petrographic study was to identify the correct naming of the various rock types, delineation of the thrusts and determine the grade of metamorphism present in the region. Additionally, the investigation of microstructures aimed to elucidate the effects of deformation and metamorphism in the rocks.

To address the research gaps, the present study consists of the following objectives:

- Identify the mineral paragenesis in the rocks.
- Determine the nature and grade of metamorphism in the rocks of the region.

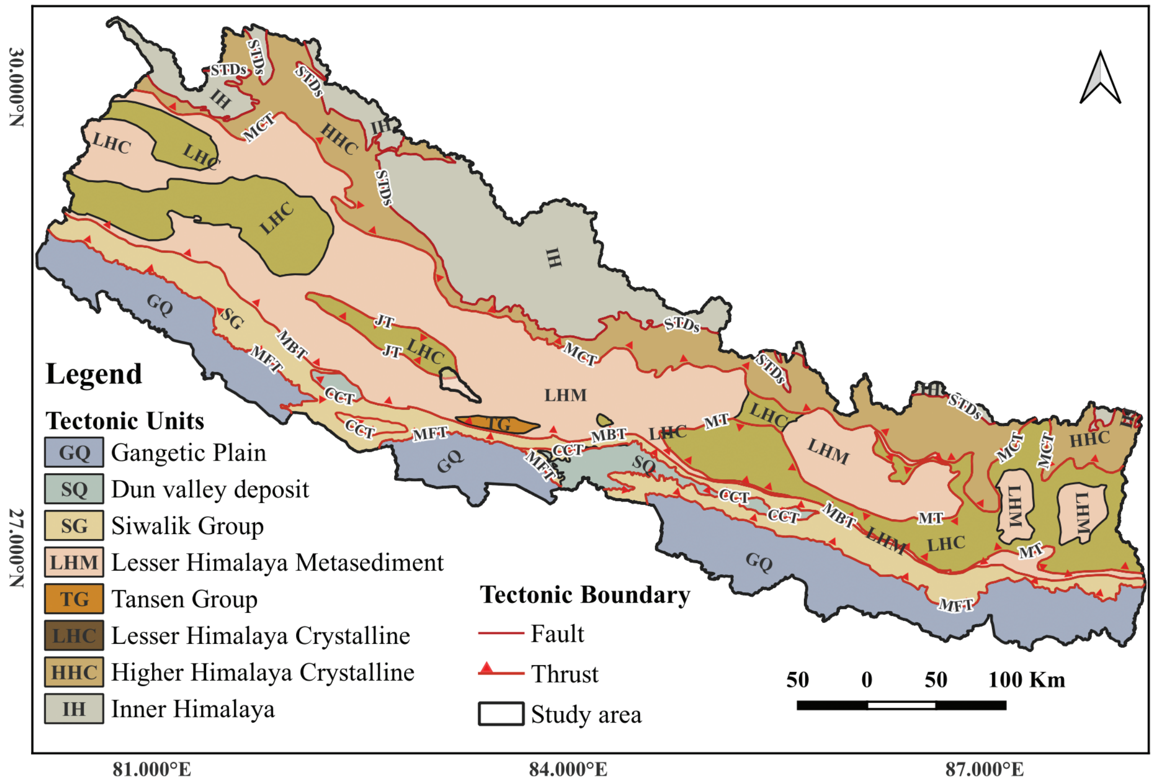


**Fig. 1: Generalized geological map of Nepal showing the study areas in black polygon (Modified after Amatya and Jnawali, 1994).**

- Study the microstructures developed in the rocks due to the ongoing tectonism and deformation.
- Study the effects of regional and local geological structures on the rocks.

## METHODOLOGY

After a thorough review of the previous studies and relevant literature, fieldwork was carried out to prepare the geological map of the Tamghas-Arkhabang section in 1:25,000 scales. Topographical map of the region available in 1:25,000 scales along with geological compass, GPS, geological hammer, dil HCl of normality 1:10, and the sample bags of various sizes were used in the geological mapping. During field investigation, systematic samples were collected from each rock type from each stratigraphic unit. Thin sections of representative samples were prepared cutting the rocks as possible as perpendicular to foliation and bedding and parallel to the linear features. A well-equipped thin section laboratory of the Central Department of Geology was used for the preparation and study of the thin sections. The study was focused on mineral paragenesis under a petrological microscope. The volumetric concentrations were determined by visual inspection. The focus of the analysis includes mineral's textural and compositional zoning, grain size measurement, and sketch out the metamorphic structures developed in the rocks. Features such as foliation, schistosity, and cleavage, as well as their orientations, micro folds, and shear sense indicators, were investigated under the microscope. Various forms of recrystallization within the sample grains were examined to understand deformation patterns within the rock samples. Emphasis was given to the quartz and garnet microstructures to examine the deformation and metamorphic conditions. Finally, the microstructures and metamorphic index minerals were linked to locate the geological structures in the region and distinguish the metamorphic zonation.

## PREVIOUS WORKS

The study area encompasses the eastern segment of the Jajarkot Thrust Sheet (Jajarkot Nappe by Upreti 1999; Upreti and Le Fort 1999). The base thrust is defined as the Marma Khola Thrust (Fuch and Frank 1970; Sharma et.al 1984; Upreti 1999; Upreti and Le Fort 1999). The footwall rocks belong to the Nawakot Group, as described by Stöcklin and Bhattarai (1977). The petrography description of low-grade metamorphic rocks of the Nawakot Group from the Malekhu section was carried out by Acharya and Paudyal (2015). On the other hand, the rocks within the thrust sheet are attributed to the Bhimphedi Group (Stöcklin and Bhattarai, 1977) and the Kahun Klippe, as identified by Paudyal and Paudel (2013) and Paudyal (2014) in the southwestern part of the Damauli (Table 1). These two distinct tectonic units are demarcated by a thrust equivalent to the Mahabharat Thrust (Stöcklin and Bhattarai, 1977) in central Nepal and the Dubung Thrust (Paudyal, 2014) in west-central Nepal. Paudel (2008) studied the petrography of metabasites from the Modi Khola section and highlighted both pre-collisional and post-collisional thermal events, which contribute to understanding the inverted metamorphism in the region. Thapaliya and Paudel (2011) conducted a study on the inverted metamorphic zonation along the footwall and hanging wall of the Mahabharat Thrust in the Kathmandu-Trishuli area of central Nepal. Their research defined the biotite zone within the Kunchha Formation, while the garnet zone was observed in the stratigraphically younger Benighat Slates and Robang Formations. Subedi and Acharya (2016) traced the Mahabharat Thrust (MT) from the Bhainse-Manahara area of central Nepal using lithology and microstructural features. They found that rocks above the MT had garnet development in the Raduwa Formation, which decreased to biotite grade northward. The rocks near the MT footwall showed a low biotite grade, which further decreased to chlorite grade, illustrating an inverted metamorphic sequence. Lamsal et al. (2023) reviewed the metamorphic successions in the Lesser Himalaya, focusing on the study area and discussing lithostratigraphic features. They emphasized the importance of understanding metamorphic processes in relation to tectonic activities within the MT zones. However, there remains a need for further petrographic studies to pinpoint geological structures through microstructures and deformation features. Additionally, metamorphism in the region still requires detailed work on metamorphic zonation and isograde mapping.

## GEOLOGICAL SETTING OF THE AREA

The geological map (Fig. 2) shows the rock distribution of three autochthonous units and three allochthonous units. The Birbas Slate in this region is composed of very thinly bedded, light grey to black, greenish grey, brown, and dark grey slates, with carbonaceous and ferruginous varieties. It transitions to overlying carbonate successions named the Tamghas Dolomite, extending from Birbas to Gaudakot. This vertical distribution of the Birbas Slate occurs with intermittent patches of carbonates. This unit consists of highly fractured, thin-to-medium-bedded, chlorite to biotite grade, ferruginous slate and thinly laminated, shiny and soapy, chlorite grade phyllite (Fig. 3a). Transitioning from the Birbas Slate, the area features with the rocks of the Tamghas Dolomite extending from Gaudakot to Tamghas (Fig. 3b). This unit consists of gray to white, massive beds of siliceous dolomite and limestone beds in some regions. Some algal mats and stromatolites are observed in some horizons of this monotonous succession of grey siliceous dolomite.

The Resunga Formation with mixed lithology of phyllite, metasandstone, and quartzite, transitioning over the Tamghas Dolomite is predominantly observed within the Resunga hill area. This sequence comprises varying proportions of medium-to-thick-bedded, medium-to-coarse-grained, grey metasandstone/quartzite, and medium-bedded, fine-to-medium-grained, grey, psammitic phyllite (Fig. 3c). A large concordant body of metabasic rock with about 4 km lateral extension is mapped along the Durkot (Hadhade) area, bounded by dolomite and phyllite at the bottom and top (Fig. 3d), respectively. These metasedimentary rocks of autochthonous sequences are separated by the thrust contact defined by the Panahgad Thrust with the allochthonous crystalline thrust sheet.

The allochthonous succession in the area comprises three major crystalline rock units within the Jajarkot Thrust Sheet. The Jaisithok Marble, the lowermost sequence of the thrust sheet from this area consists of fine to moderately crystalline, bluish, thick-bedded marble distributed around the Hastichaur area (Fig. 4a). The Purkotdaha Formation transitionally overlies the Jaisithok Marble. It consists of coarse-grained metasandstone, and quartzite, with interbeds of schist in various proportions (Fig. 4b). The Purkotdaha Formation is transitionally underlain by moderately weathered, brown-coloured psammitic and pelitic schist, with varying sizes of the garnets of the Simaltari Formation (Fig. 4c and Fig. 4d).

### Petrography

Fourteen thin sections representing each stratigraphic unit were studied to analyse the texture, structures, and mineral parageneses under a polarizing microscope (Table 2 and Fig. 2).

**Table 1 : Stratigraphy of various sections of the Lesser Himalayan thrust sheets**

| | | Central Nepal (Stöcklin and Bhattarai, 1977; Stöcklin 1980) | | Jaljala Unit (Fuch and Frank 1970; Sharma et.al 1984) | | Jajarkot Nappe (Upreti 1999; Upreti and Le Fort 1999) | | Kahun Klippe (Paudyal and Paudel 2013; Paudyal, 2014) |
|---|---|---|---|---|---|---|---|---|
| Allochthonous | Bhimphedi Group | Bhainsedobhan Marble | Chaurjahari Group | Thabang Formation | Jajarkot Nappe | Thabang Formation | Tanahun Group | — |
| | | Raduwa Formation | | Chaurjahari Formation with Augen Gneiss | | Chaurjahari Formation | | Shivapur Schist |
| | | | | | | | | Musimarang Formation |
| | | — | | — | | — | | Gwaslung Formation |
| | | -Mahabharat Thrust--- | | --Marma Khola Thrust- | | Marma Khola Thrust | | ---Dubung Thrust---- |
| Autochthonous | Nawakot Group | Benighat Slates | | Nawakot Group | Nawakot Group | Upper Nawakot | (Nawakot Group) | Benighat Slates<br>Dhading Dolomite<br>Nourpul Formation and other older units |
| | | Kuncha Formation | | Kuncha Group | | Lower Nawakot | | |

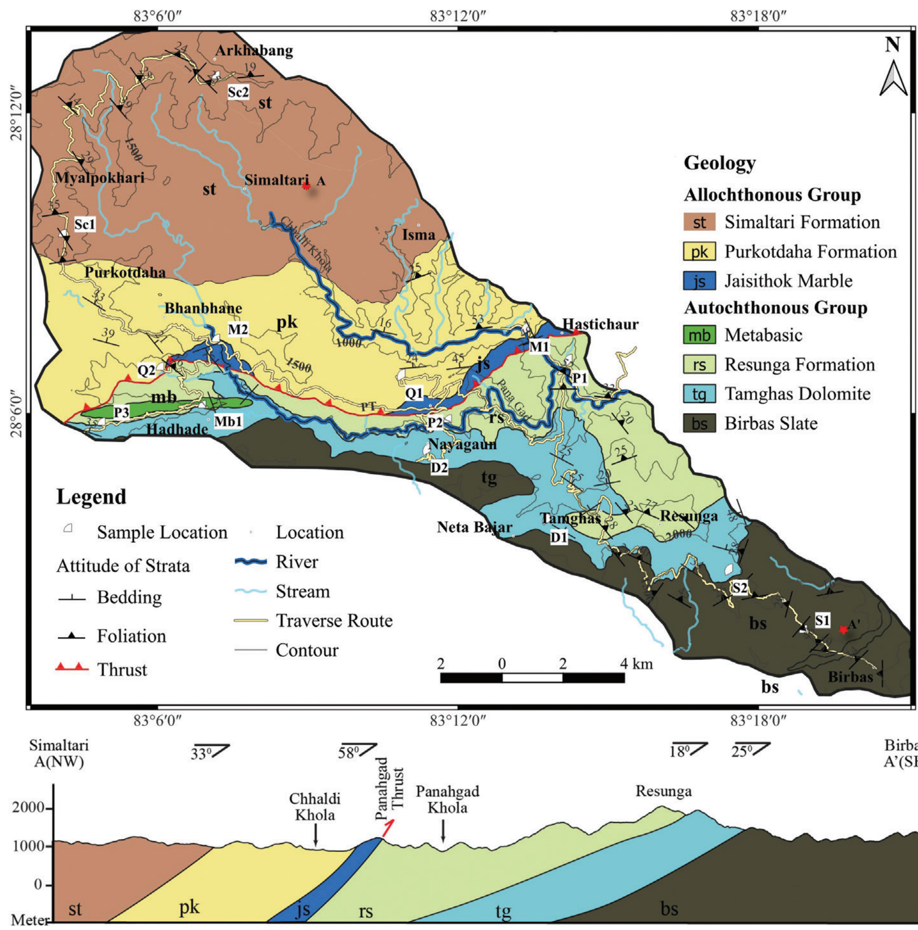


**Fig. 2: Geological map of Tamghas-Arkhabang section (prepared after present study) with petrography sample locations and the cross section along Simaltari (A) - Birbas (A').**

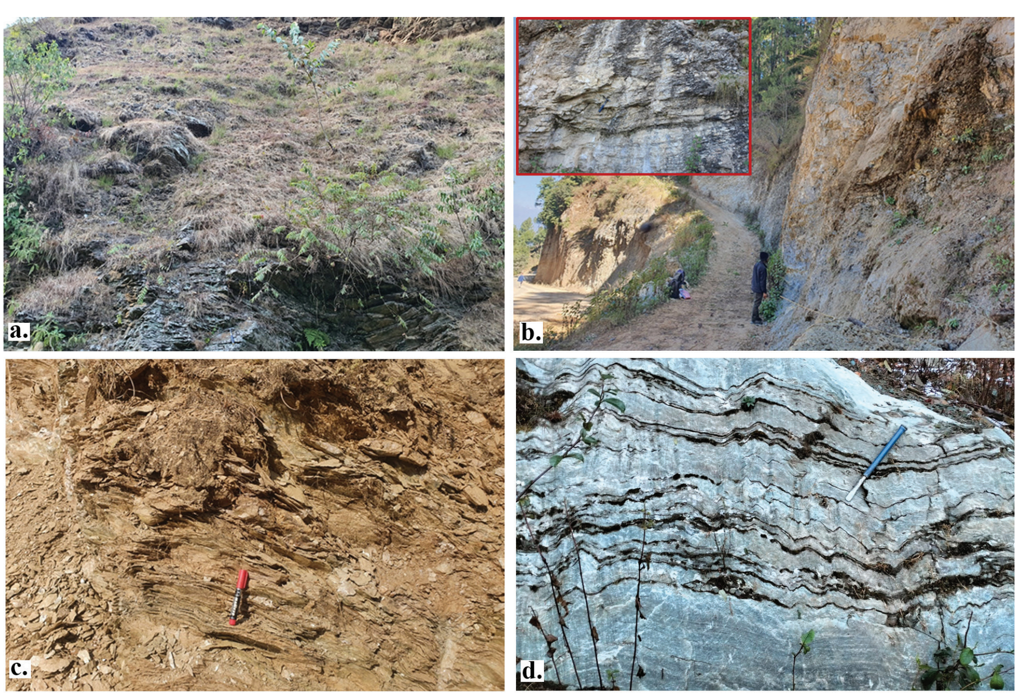


**Fig. 3: Outcrop photographs: a) Dark brown carbonaceous slate of the Birbas Slate observed at Chaldi Khola section; b) Bedded strata of dolomite of the Tamghas Dolomite from the uphill side of the road section from Tamghas to Neta-Deurali. (Outcrop scale photograph in the inset); c) Green-grey-brown phyllite observed in the Resunga Formation on the uphill section of the road towards Simaltari about 2 km from Chhaldi-Panah; d) Metabasic rock observed at Hadhade area.**

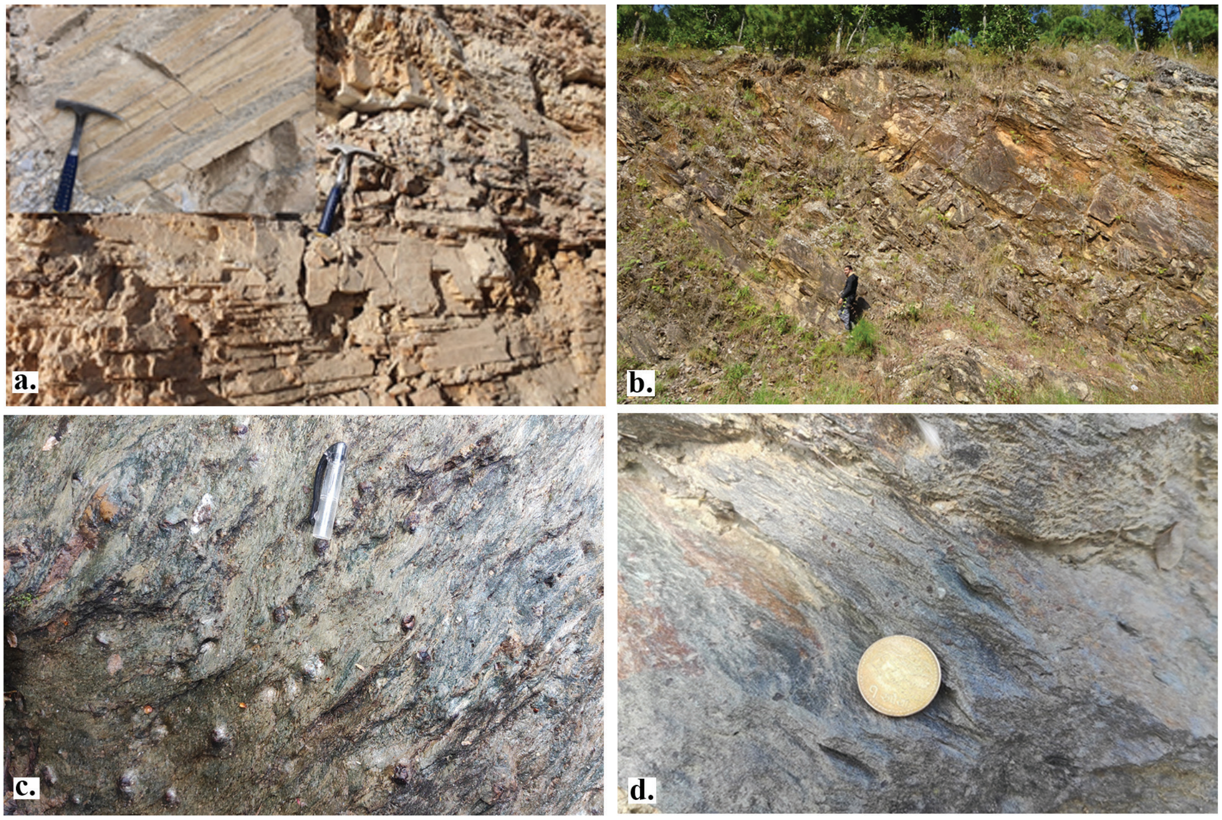


**Fig. 4: Outcrop photographs of various lithological units: a) Gray-brown fine-to medium-grained marble of the Jaisithok Marble. Marble is with the partings of schist (photograph in inset); b) Quartzite from the Purkotdaha Formation with schist parting; c) Pelitic garnet schist of the Simaltari Formation from the Dhurkot area: and d) Psammitic schist of the Simaltari Formation from the Arkhaban area.**

**Table 2 : Sample details used for the petrographic analysis.**

| S.N. | Sample | GPS | Rock type | Stratigraphic Unit |
|---|---|---|---|---|
| 1. | S1 | 28° 1' 37.56" N, 83° 18' 58.20" E | Slate | Birbas Slate |
| 2. | S2 | 28° 2' 42.2" N, 83° 17' 28.5" E | Slate | Birbas Slate |
| 3. | D1 | 28° 03' 41.81" N, 83° 13' 50.61" E | Dolomite | Tamghas Dolomite |
| 4. | D2 | 28° 05' 05.21" N, 83° 11' 27.2" E | Dolomite | Tamghas Dolomite |
| 5. | P1 | 28° 06' 52.14" N, 83° 14' 16.73" E | Quartzite | Resunga Formation |
| 6. | P2 | 28.091418 N, 83.071308 E | Phyllite | Resunga Formation |
| 7. | P3 | 28.091418 N, 83.071308 E | Phyllite | Resunga Formation |
| 8. | Mb1 | 28° 6' 9.6264" N 83° 7' 9.3036" E | Metabasic | Resunga Formation |
| 9. | M1 | 28° 7'29.78"N 83°13'25.19"E | Marble | Jaisithok Marble |
| 10. | M2 | 28° 7' 25.7" N 83° 7' 14.4" E | Marble | Jaisithok Marble |
| 11. | Q1 | 28° 6' 39.5"N, 83° 10' 56.4"E | Bedded Quartzite | Purkotdaha Formation |
| 12. | Q2 | 28° 6'51.96"N 83° 6'7.58"E | Bedded Quartzite | Purkotdaha Formation |
| 13. | Sc1 | 28° 9'31.24"N 83° 4'10.71"E | Garnet Schist | Simaltari Formation |
| 14. | Sc2 | 28° 12' 40.3"N 83° 7' 14.5"E | Psammitic garnet schist | Simaltari Formation |

*Sample no.: S1*

The S1 sample of slate from the Birbas Slate (Fig. 5a and 5b) was collected from the Birbas area along the Ridi-Tamghas road section. The rock is primarily composed of quartz, graphitic materials, mica, and calcite, with a phase assemblage dominated by chlorite, quartz, and muscovite. It has a very fine-grained texture, displaying alternating bands of white recrystallized quartz and dark minerals, likely clay minerals, which define bedding parallel to foliation. A visual estimate of the modal composition suggests that quartz makes up about 30%, black graphitic minerals around 10%, while sericite and chlorite together account for 28%. Calcite constitutes approximately 12%, and fine lithic fragments make up roughly 20% of the rock. Most of these minerals are detrital, with some showing signs of recrystallization to the chlorite grade of metamorphism.

*Sample no.: S2*

The S2 slate sample (Fig. 5c and 5d) was collected from Gaudakot. This sample contains minerals up to 100 µm in size and is well-foliated parallel to the bedding plane. The rock consists primarily of quartz, calcite, and mica, with the overall phase assemblage of quartz-calcite-chlorite-muscovite. The modal composition includes approximately 30% quartz, 30% calcite, 10% chlorite, 15% muscovite, and 15% unidentified fine detrital groundmass.

Both the S1 and S2 samples belong to the Birbas Slate and have undergone Barrovian-type prograde metamorphism, reaching the greenschist facies within the chlorite zone. However, they represent different stages within the Barrovian sequence. Both samples display prominent deformation with bedding-parallel foliation (S0 = S1). Evidence of bulging recrystallization (BLG) and grain boundary migration (GBM) due to stress perpendicular to the foliation (S1), applied from east to west, indicates dynamic recrystallization in quartz.

*Sample no.: D1*

The D1 dolomite sample from the Tamghas Dolomite (Fig. 6a and 6b) was collected from the Arjun Dada area along the Tamghas Neta road section. The phase assemblage consists of dolomite, calcite, chlorite, quartz, and muscovite. The sample is dominated by carbonate minerals (calcite and dolomite), which make up around 80% of the rock, with quartz comprising about 15%, and the remaining 5% consisting of non-differentiated minerals. Approximately 50% of the grains are detrital, and recrystallized quartz is notably dominant in the sample.

*Sample no: D2*

The D2 dolomite sample from the Tamghas Dolomite (Fig. 6c and 6d) was collected from the Dhurkot, Nayagaun area. The mineral assemblage consists of dolomite, chlorite, quartz, and muscovite. Dolomite makes up about 60% of the sample, while quartzite constitutes around 30%. The rock is dominated by fine-grained minerals with varying grain sizes. Layers of silicified algae (stromatolites) are distinguishable under the thin section, indicating the presence of ancient biological activity.

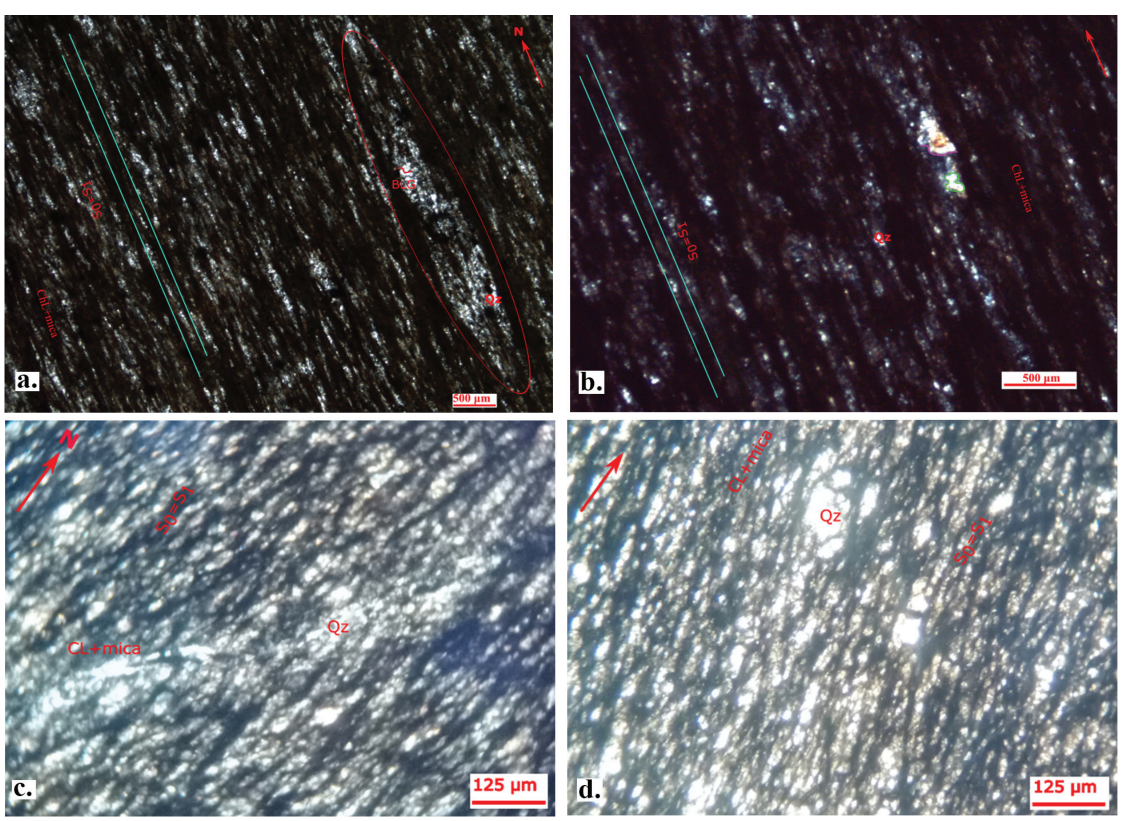


**Fig. 5: Photomicrograph of samples under cross-polarizing light: a) carbonaceous slate with symmetric quartz veins with BLG (inside red polygon) observed under 40x magnification; b) carbonaceous slate observed under 100x magnification; c) calcareous slate observed under 100X magnification with two sets of foliations where S1 is parallel to S0 and S2 is oblique to S1; d) calcareous slate observed under 100X magnification with single set of foliation where S1 is parallel to S0.**

Both dolomite samples (D1 and D2) consist of a mineral assemblage of dolomite, calcite, chlorite, quartz, and muscovite, which have undergone low-grade greenschist facies metamorphism, reaching the chlorite grade. Quartz grains show noticeable undulose extinction, with dynamic recrystallization indicating twin boundary migration recrystallization (TBMR) (Fig. 6b). The presence of dynamic recrystallization and cataclasis in quartz points to deformation likely associated with tectonic activity. The cataclastic recrystallization of quartz suggests that deformation occurred after the initial crystallization of the rock. Furthermore, the dynamic recrystallization and the development of S0 = S1 foliation suggest two deformation stages, possibly connected to the same tectonic event.

*Sample no.: P1*

The sample (P1) from the Resunga Formation, collected from the confluence of Chhaldi and Panah Khola, consists of fine- to medium-grained quartzite (Fig. 7a and 7b). The rock is predominantly composed of recrystallized quartz grains, which account for over 90% of its composition, while the remaining minerals are detrital. The mineral assemblage includes chlorite, biotite, muscovite, and quartz. Phyllosilicates, such as muscovite and chlorite, constitute about 8%, and the remaining 2% consists of an indistinct fine groundmass.

*Sample no.: P2*

The phyllite sample (P2) from the Resunga Formation (Fig. 7c and 7d), collected from Nayagaun, shows nearly complete recrystallization, with only a few detrital grains visible under the thin section. The rock's phase assemblage consists of chlorite, biotite, muscovite, and quartz. Quartz makes up approximately 20% of the sample (excluding quartz veins), while phyllosilicates, including biotite, constitute around 60%, and the remaining 20% is composed of fine groundmass.

This sample (P2) contrasts with the quartzite sample (P1) in terms of metamorphic grade. P1 experienced greenschist facies metamorphism at the lower boundary, within the chlorite grade, reflecting a lower level of metamorphism. In contrast, P2 reached the low to medium greenschist facies, attaining the biotite grade, which indicates higher temperatures within the Barrovian metamorphic sequence. The sequence does not exhibit a clear Barrovian-type metamorphic gradient but instead shows localized variations in metamorphic grade and deformation styles, likely influenced by the thrust sheet and pre-existing tectonic structures. These variations suggest that tectonic processes and structural controls played a significant role in shaping the metamorphic patterns, leading to differences in metamorphic grade and deformation intensity across the area.

*Sample no.: P3*

The phyllite sample (Fig. 8a) from Lohari, Malarani, exhibits a chlorite-biotite-muscovite-quartz mineral assemblage, with over 95% of the grains being recrystallized. Collected near a thrust contact, the presence of biotite confirms greenschist facies metamorphism, indicating a higher metamorphic grade compared to samples from the stratigraphically older Birbas Slate, Tamghas Dolomite, and the basal part of the Resunga Formation. The sample shows deformation in quartz veins,

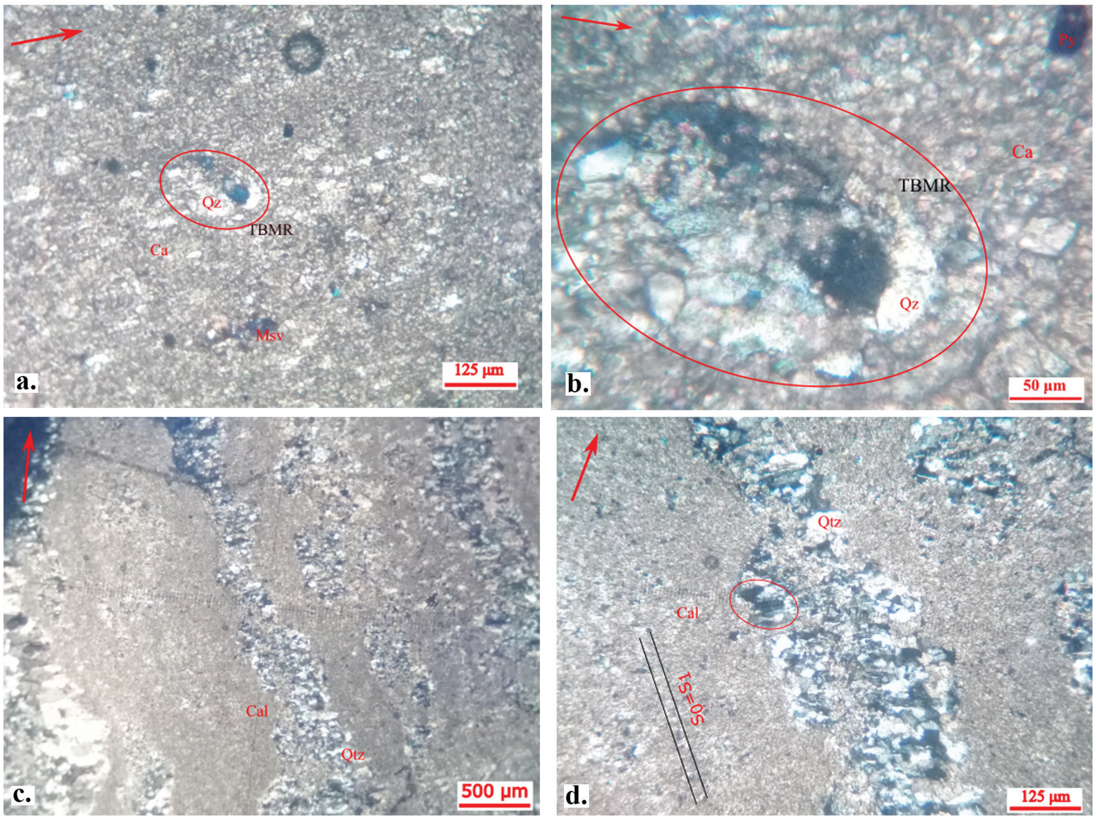


**Fig. 6: Photomicrograph of samples under cross polarizing light; a) fine-grained limestone with 40x magnification; b) fine-grained limestone with 400x magnification. c) fine grained silicious limestone/dolomite with 40x magnification; d) fine-grained siliceous limestone/dolomite with 100x magnification.**

indicating a top-to-the-south shear sense (Fig. 8a), suggesting that deformation occurred after the crystallization of quartz. The S0 = S1 foliation relationship is clearly distinct. Additionally, the pinning and dragging structures (green polygon) suggest grain boundary migration (GBM) perpendicular to the foliation (S1). The microcracks observed within the quartz vein (green cross lines) at the apex of a microfold are notable features in the rock.

*Sample no.: Mb1*

A concordant body of metabasic rock (Mb1) within the Resunga Formation (Fig. 8b) was collected from the Hadhade section. This sample is rich in green minerals, primarily chlorite and other amphibole group minerals, including hornblende, actinolite, and tremolite, along with quartz. Due to the dominance of amphibole minerals, this metabasic rock can be classified as amphibolite. Schistosity is well-developed and

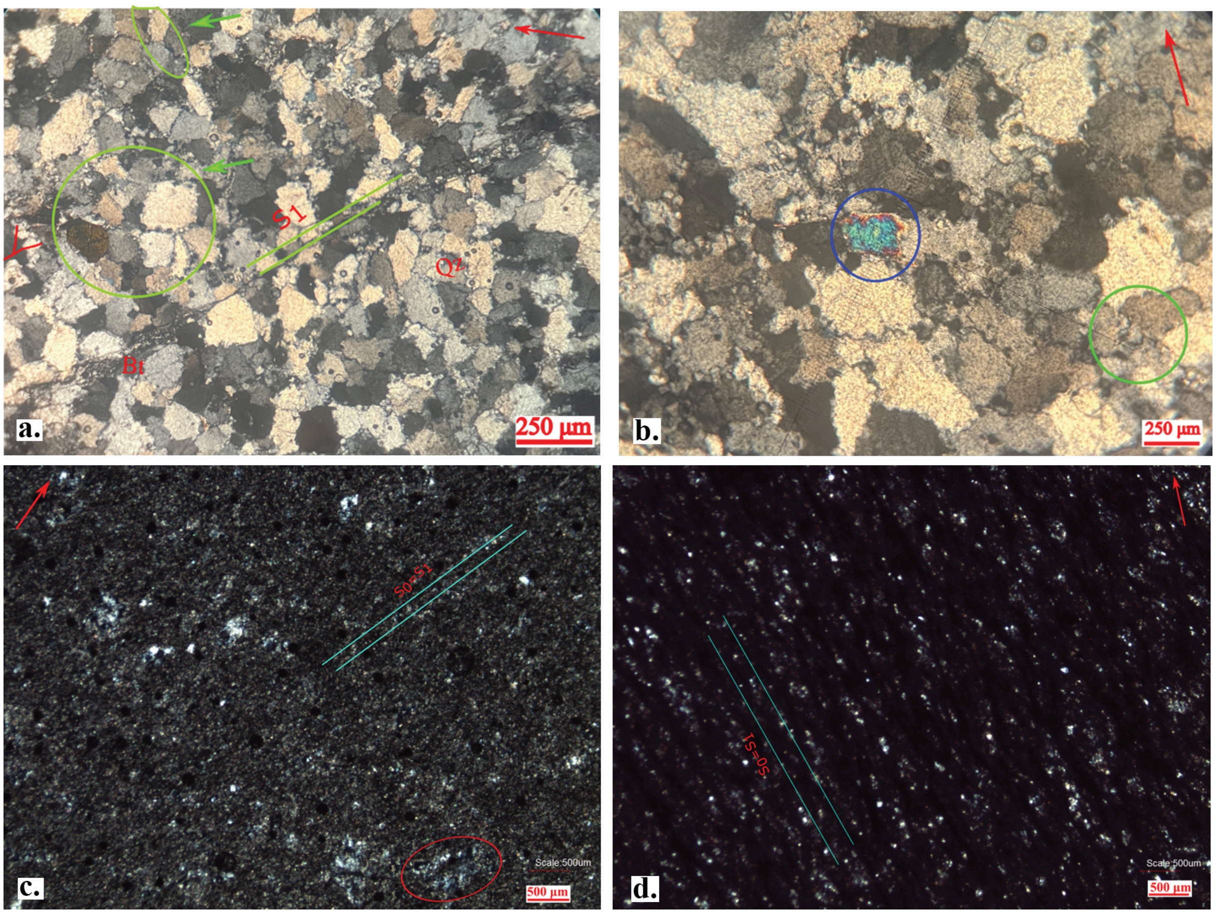


**Fig. 7: Photomicrograph of samples under cross-polarizing light; a) medium to coarse grain quartzite with 100x magnification; b) medium to coarse grain quartzite with 400x magnification. c) fine to medium grain laminated siliceous phyllite with 40x magnification; d) deformed slate with folded quartz veins observed with 40x magnification.**

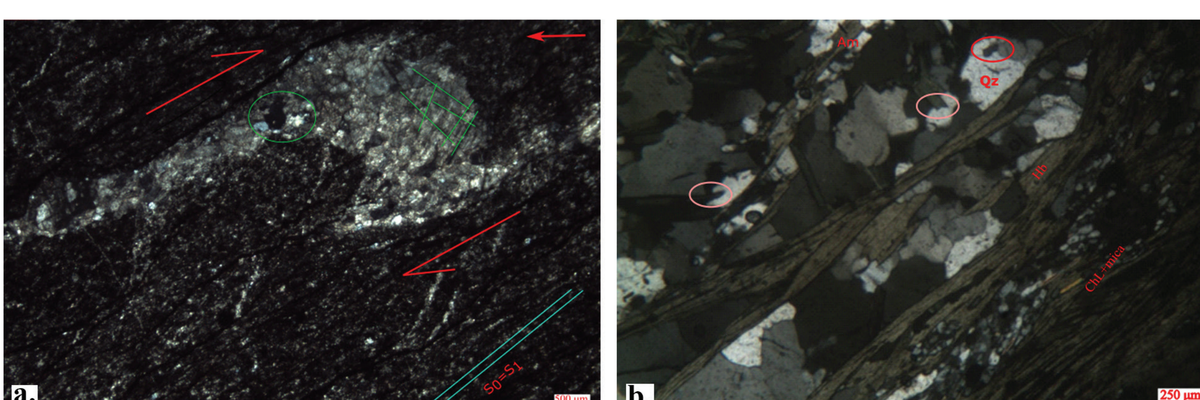


**Fig. 8: Photomicrograph of samples under cross-polarizing light; a) fine to medium grain laminated siliceous slate with 40x magnification. b) Medium-to-coarse grain metabasic rock observed under 100X magnification.**

visible both in outcrops and thin sections, indicating retrograde metamorphism and indicates the greenschist facies. Quartz grain recrystallization is prominent, exhibiting features such as pinning, grain boundary migration, and leftover grains, all indicative of dynamic metamorphic processes.

*Sample no.: M1*

The sample (M1) was collected from the Jaisithok Marble in the Hastichaur area and represents a 2-mica marble (Fig. 9a). The mineral assemblage is composed of chlorite, biotite, muscovite, quartz, and calcite, with over 95% of the mineral grains showing recrystallization. Calcite constitutes approximately 72% of the sample, making it the dominant mineral. Quartz accounts for 15%, biotite for 8%, and muscovite for 3% of the recrystallized mineral grains. The remaining portion consists of non-differentiated mineral matter.

*Sample no.: M2*

The sample (M2) of Jaisithok Marble, collected from the Bhanbhane area (Fig. 9b), exhibits a mineral assemblage of chlorite, biotite, muscovite, quartz, and calcite. Over 90% of the mineral grains are recrystallized. Calcareous minerals dominate the composition, making up approximately 80% of the sample. Quartz constitutes 10%, biotite 6%, and muscovite 4% of the recrystallized mineral grains, with the remaining portion consisting of indistinct grains. The M2 sample displays biotite-grade metamorphism within the greenschist facies, suggesting higher temperatures in the Barrovian metamorphic sequence.

These rock samples have experienced two primary deformation events. The first event involved high stress and elevated temperatures, leading to dynamic recrystallization processes such as twin boundary migration recrystallization (TBMR) and grain boundary migration (GBM), as well as the development of deformation features. The second event, characterized by high temperature but low stress, resulted in static recrystallization, which overprinted and modified the earlier deformation fabric.

*Sample no.: Q1*

The Q1 sample of bedded quartzite (Fig. 9c) from the Purkotdaha Formation, collected from Deurali, Dhurkot, consists primarily of quartz (87%) and a muscovite/biotite association (12%), with over 90% of the grains showing recrystallization and a small proportion remaining detrital. The overall mineral assemblage includes chlorite, biotite, muscovite, and quartz. The sample exhibits a distinct foliation that is parallel to the bedding, indicative of the metamorphic and tectonic processes that have affected the rock.

*Sample no.: Q2*

Another bedded quartzite sample (Q2) from the Purkotdaha Formation was collected from Bhanbhane, Dhurkot (Fig. 9d). This coarse-grained, medium-bedded quartzite consists almost entirely of recrystallized minerals. The overall mineral assemblage includes chlorite, biotite, muscovite, and quartz, with quartz being the dominant mineral, comprising about 80% of the rock's volume. Additionally, approximately 10% of the rock consists of calcite, while the remaining 10% is made up of mica minerals and an indistinct fine-grained groundmass.

These samples exhibit characteristics of biotite-grade metamorphism within the greenschist facies, suggesting higher temperatures in the Barrovian metamorphic sequence. The rocks likely underwent a complex deformation history, beginning with a period of static deformation that produced foliation. This was followed by dynamic deformation involving oblique stress, which led to grain boundary migration (GBM) recrystallization and the formation of pressure shadows.

*Sample no.: Sc1*

A sample of garnet schist (Sc1) from the Simaltari Formation was collected from the Myalpokhari area and associated with the Simaltari Formation, is nearly fully recrystallized, with only about 5% detrital grains remaining (Fig. 9e). The mineral composition of this sample include quartz (~40%), biotite (~30%), muscovite (~10%), other platy minerals (~10%), garnet (~5%), and minor amounts of unidentified minerals. The overall mineral assemblage of the rock is garnet-biotite–muscovite–quartz.

This garnet schist sample features a spiral garnet porphyroblast (Fig. 9e). The spiral garnet, located in the center of the photomicrograph and containing quartz inclusions, is particularly distinctive. The geological unit belonging to the spiral garnet is attributed to tectonic forces, which caused the garnet to rotate in a top-to-south orientation. Furthermore, the twisting of surrounding platy minerals along with the garnet crystal exemplifies syntectonic deformation.

*Sample no.: Sc2*

Another rock sample (Sc2) of psammitic garnet schist from the Simaltari Formation (Fig. 9f) collected from Arkhabang is almost recrystallized with few detrital grains. This sample is composed of quartz (~65%), biotite (~20), muscovite (~50%), other platy minerals (~5%), garnet (~5%), and unidentified minerals in few volumetric amounts. The overall phase assemblage of the rock is the garnet-biotite–muscovite–quartz.

Both samples show the garnet grade of metamorphism with amphibolite facies. These rocks experienced a static deformation event that created the foliation as well as a dynamic deformation event with oblique stress caused by GBM recrystallization, pressure shadows, and rotated garnets.

The crystalline nappe exhibits increasing metamorphic grade from the south (biotite) to the north (garnet). Garnet schist records the highest peak of metamorphic conditions and multiple deformation stages in this geological unit.

**Thrust Zone**

There is a distinct and sharp thrust contact between the low-grade metasedimentary rocks (autochthonous succession), and the high-grade crystalline rock strata (allochthonous succession). The autochthonous succession acts as the foot wall whereas the allochthonous succession acts as the hanging wall of the thrust. The later succession (hanging wall) consists of marble in certain areas and quartzite and schist in others, suggesting evidence of regional structural discontinuity. Furthermore, the higher metamorphic grade (ranging from biotite to garnet) overlies the lower chlorite grade (extending up to biotite in some areas) metamorphic rocks.

Numerous shear zones and slickensides are also found in this zone as strong evidence of the thrust. Also, drag folds observed in outcrops as well as in thin sections defines the southward movement of the thrust. Fault breccias developed during the thrust movement in the past are also significantly distributede throughout the thrust zone in this region (Fig. 10 ).

Rock samples taken from the area exhibit distinct deformation features under the thin section. Among the samples mentioned above P3 and Sc1 prominently demonstrate major features supporting the presence of thrust with movement from north to south.

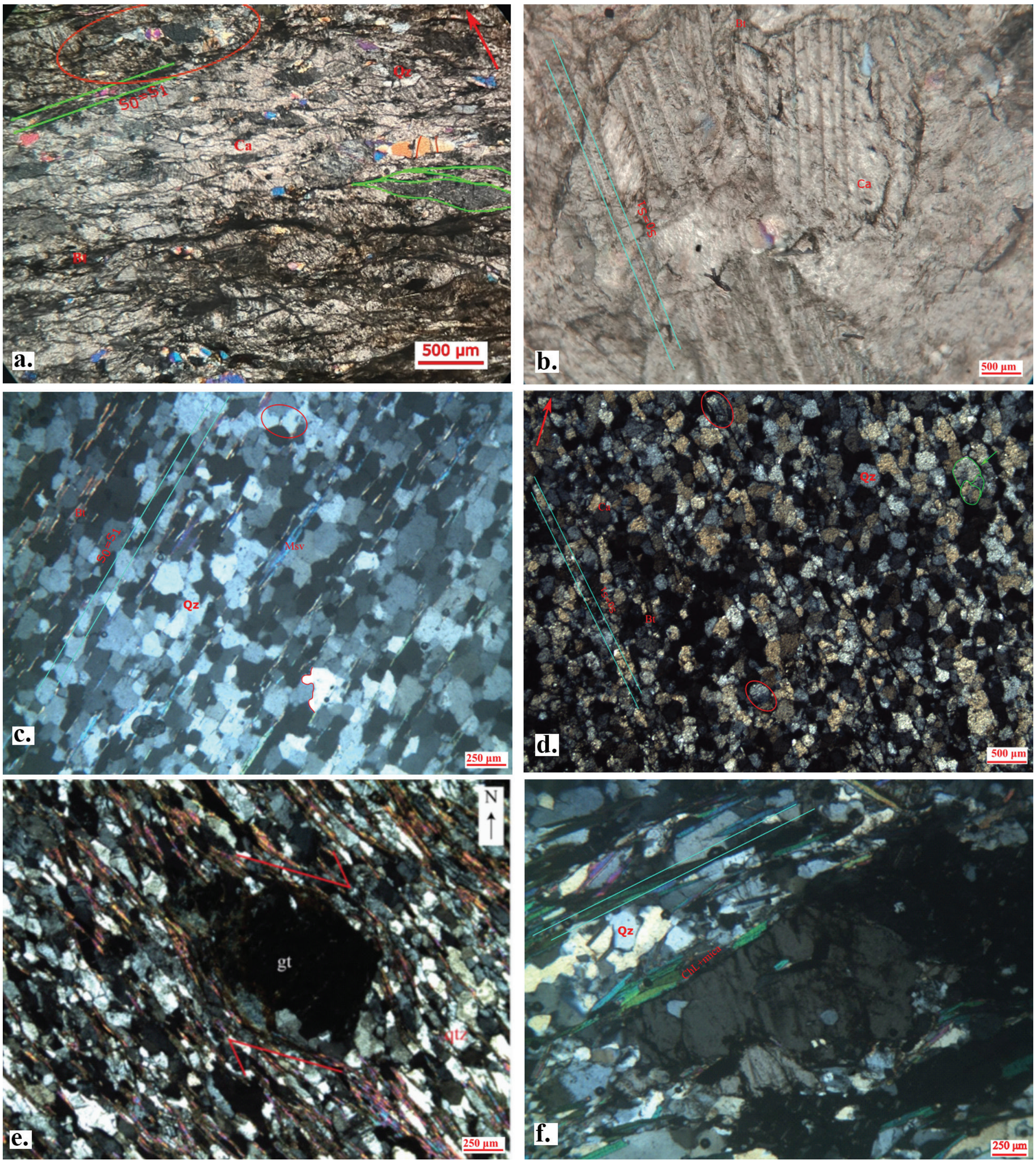


**Fig. 9: a and b) Photomicrograph of medium-to-coarse-grained foliated marble with 100x magnification under cross-polarizing light; TBMR and GBM can be observed inside the red and green polygon c) Photomicrograph of medium-to coarse-grained foliated quartzite with 100x magnification under cross polarizing light; d) Photomicrograph of well-foliated metasandstone and quartzite; e) Photomicrograph of medium-to coarse-grained foliated psammitic schist with coarse-grained garnet in the pelitic layer with 100x magnification under cross polarizing light; f) Photomicrograph of psammitic schist.**

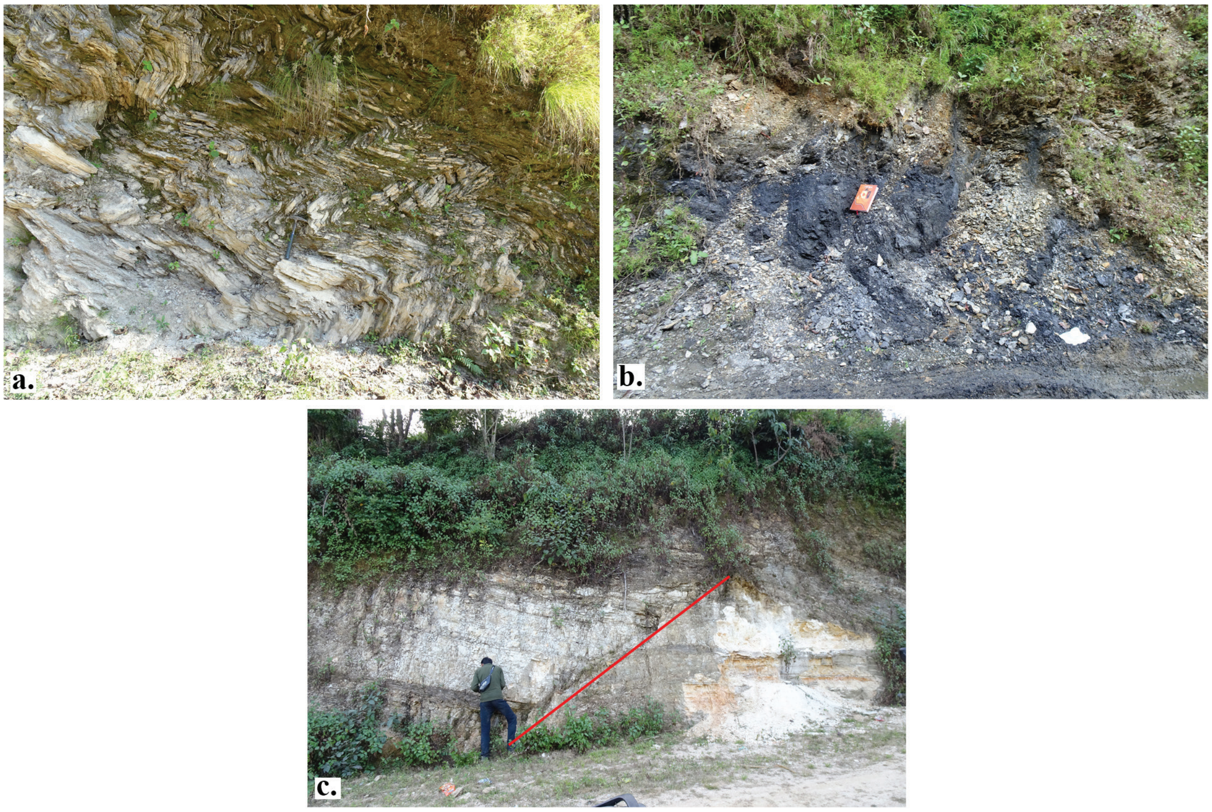


**Fig. 10: Outcrop photographs showing various deformation features: a) highly deformed folds b) shear zone with breccia and fault gauge c) field photograph showing outcrop scale fault in quartzite unit.**

## DISCUSSIONS

The region's rock formations encompass a spectrum of low-to-medium-grade metamorphism, including slate, phyllite, dolomite, dolomite marble, metasandstone, quartzite, and schist, occasionally interspersed with metabasic rocks.

In the study area, there are two major carbonate units, i.e., the Tamghas Dolomite and the Jaisithok Marble. Differentiating between them posed challenges during field mapping, whether they belonged to a single unit or different units in their stratigraphic position. For instance, telling apart dolomite within the low-grade metamorphic terrain from fine-grained dolomite marble proved difficult in the field, especially when the rocks displayed varying colour tones due to weathering.

The southern carbonate unit, i.e. the Tamghas Dolomite composed of fine-grained dolomite, calcite, chlorite, quartz, and muscovite. It has experienced low-grade metamorphism. It can be correlated with the Malekhu Limestone of central Nepal (Stöcklin and Bhattarai, 1977; Stöcklin 1980). Whereas the northern carbonate strata of the Jaisithok Marble adjoint to the southern carbonate strata in some areas has a medium-grade crystalline limestone that displays a biotite grade of metamorphism with greenschist facies. This sequence shows the similarity with the stratigraphic position of the Gwaslung Formation of the Kahun Klippe (Paudyal and Paudel 2013; Paudyal, 2014).

Similarly, distinguishing between quartz arenites and metasandstones in the field also presented challenges. Identifying differences between phyllite and schist was particularly problematic, especially in ridge sections where weathering and alteration processes heavily influenced the rocks. Here, petrographic features of rocks proved highly useful not only for distinguishing rock types but also for identifying metamorphic index minerals and hence for the isograde mapping.

The quartzite sample from the metasedimentary sequence, i.e. the Resunga Formation comprises fine-to medium-grained quartzite. It is primarily composed of finely recrystallized quartz grains, accounting for more than 90% of its composition. This defines a lower boundary of biotite grade of metamorphism. Whereas the quartzite from the thrust sheet, i.e. from the Purkotdaha Formation has more than 90% coarse recrystallized grains and few amounts of detrital grains with an overall mineral assemblage of chlorite, biotite, muscovite, and quartz. This unit shows a biotite grade of metamorphism with greenschist facies.

Based on the mineral assemblage observed through the thin section and field observation for lithology and stratigraphic positions, the following correlation is proposed after present study (Table 3).

Similarly, identifying structural discontinuities such as the existence of a thrust in the region is greatly aided by the petrographic characteristics of rocks, particularly through the development of microstructures that are difficult to observe on low-grade metamorphic rocks under field conditions. A progressive increase in metamorphic grade can be observed from south to north. The slate succession in the south exhibits zeolite facies (low-grade) characteristics. Similarly, the carbonate sequence uniformly displays zeolite facies across the studied area. However, the youngest autochthonous unit in the region transitions from zeolite facies (low grade) in the southwest to greenschist facies (low-medium grade) near structural discontinuities observed in the field, indicating the presence of a thrust. A notable observation is an abrupt change in metamorphic grade from chlorite to biotite in younger stratigraphy (footwall of the thrust sheet) within similar rock types adjacent to the thrust zone, resembling inverted metamorphism as in the other sections of the Lesser Himalaya (Paudyal et al., 2011 and Paudyal, 2014). This is due to the dynamic change in temperature and pressure near the thrust zone. These features serve as compelling evidence to locate the thrust in the region. The rock of the crystalline thrust sheet shows greenschist facies with low-medium (biotite) grade in older strata of the Jaisithok Marble and the Purkotdaha Formation whereas the amphibolite facies with medium-high (garnet) grade in younger strata of the Simaltari Formation (Fig. 11).

Based on field investigation and study of the index minerals under thin sections the metamorphic zonation within the area is delineated and a zonation map is prepared (Fig. 11 ). In general, there can be observed three different metamorphic zones from chlorite and biotite to the garnet zone.

In the study, prograde metamorphism, characterized by increasing temperature and pressure with depth, appears to be dominant. There is also a localized inverted metamorphism at the contact with the thrust sheet. It is potentially influenced by the dynamic metamorphism along the thrust zone, which is evident as seen in the P3 sample. Additionally, further evidence of cataclasis is observed in the D2 sample, indicating tectonic activity with minimal directional deformation. The transition from biotite to garnet grade of metamorphism from older to younger strata in the rocks of the thrust sheet suggests compositional changes in the basin environmental conditions conducive to the growth of garnet minerals. It is also noticeable that the smaller size of garnets observed in the thin partings of pelitic layers within the older succession can be attributed to the larger size of garnets in higher stratigraphic positions within the pelitic schist as the increase in the proportion of the clay/pelitic minerals in the rock.

The area under study has undergone a complex deformation history characterized by both static and dynamic deformation events. Static deformation is evidenced by features such as foliation, mineral overprint, and pinned crystallization, while dynamic deformation is indicated by cataclasis, undulose extinction in quartz, grain boundary migration recrystallization, and pressure shadows. Deformation directions primarily appear oblique to the foliation, suggesting non-linear movement during metamorphism. Sample P3 further demonstrates shearing and static deformation with a top-to-south shear sense during north-south collision and thrust sheet propagation towards the south. Similarly, sample Sc1 displays a rotational garnet, indicating a syn-to-post tectonic event. The presence of such garnets further validates the existence of a thrust fault in the vicinity. Multiple deformation stages are observed in the crystalline sheet, particularly in the geological unit consisting of the garnet schist, with evidence of top-to-south movement direction. Overall, the crystalline sheet has undergone complex tectono-metamorphic evolution with varying grades and deformation styles across the region.

**Table 3 : Correlation of lithological units from the various sections of the Lesser Himalayan thrust sheet with the present study area**

| | | Central Nepal (Stöcklin and Bhattarai, 1977; Stöcklin 1980) | | Kahun Klippe (Paudyal and Paudel 2013; Paudyal, 2014) | | Jaljala Unit (Fuch and Frank 1970; Sharma et.al 1984) | | Jajarkot Nappe (Present Study) |
|---|---|---|---|---|---|---|---|---|
| Allochthonous | Bhimphedi Group | Bhainsedobhan Marble | Tanahun Group | ___ | Chaurjahari Group | Thabang Formation | Allochthonous Group | ___ |
| | | Raduwa Formation | | Shivapur Schist | | Chaurjahari Formation with Augen Gneiss | | Simaltari Formation |
| | | ___ | | Musimarang Formation | | ___ | | Purkotdaha Formation |
| | | | | Gwaslung Marble | | | | Jaisithok Marble |
| | | -Mahabharat Thrust--- | | ---Dubung Thrust---- | | --Marma Khola Thrust- | | ---Panahgad Thrust--- |
| Autochthonous | Nawakot Group | Benighat Slates | (Nawakot Group) | Benighat Slates<br>Dhading Dolomite<br>Nourpul Formation and other older units | | Nawakot Group | Autochthonous Group | Resunga Formation |
| | | Kuncha Formation | | | | Kuncha Group | | Tamghas Dolomite |
| | | | | | | | | Birbas Slate |

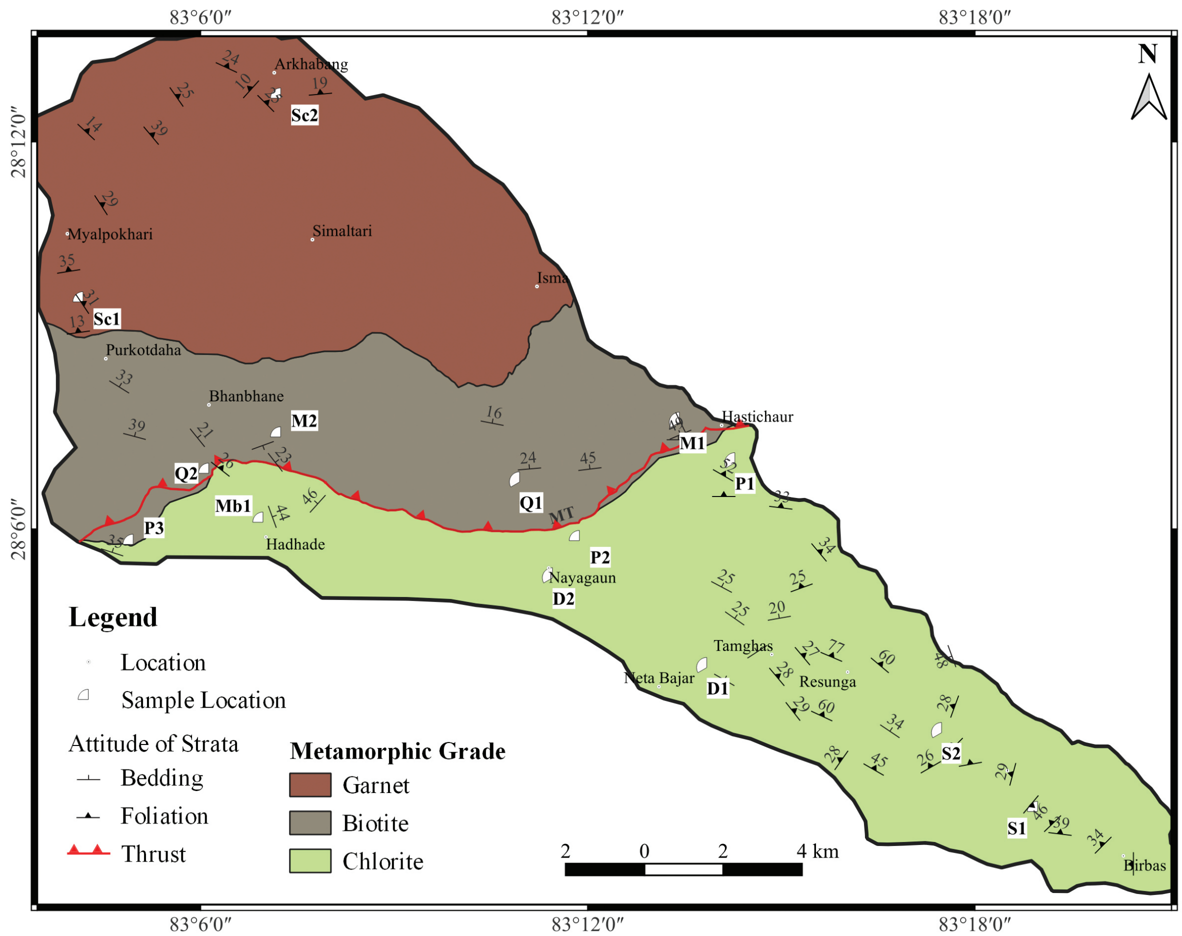


**Fig. 11: Metamorphic zonation map of the area.**

## CONCLUSIONS

Present study highlights the tectonometamorphic evolution of the region, connecting local geology to broader Himalayan tectonics. Two distinct carbonate successions were identified: (1) dolomite marble at the base of the Jajarkot Thrust Sheet, and (2) southern carbonate rocks, each representing different structural and metamorphic histories. In the Tamghas area, an inverted metamorphic gradient is evident, with chlorite at the base and biotite at the top, reflecting regional tectonic patterns.

A major structural discontinuity separates the southern autochthonous and northern allochthonous successions. Field evidence of thrust faulting, inverted metamorphism, and microstructural features like ribbon quartz and pressure shadows point to a regional thrust fault system. The thrust can be correlated with the Mahabharat Thrust (MT) in central Nepal. The metamorphism of the Purkotdaha and Simaltari Formations, from biotite- to garnet-grade, indicates deep burial and tectonic uplift, typical of the Himalayan hinterland.

Deformation features, including elongated quartz grains and spiral garnet inclusions, suggest high strain and tectonic activity. Garnet schists with rotational garnets further support complex tectonic activity, particularly south-directed thrusting, aligning with the region's history of multiple deformation and metamorphism episodes.

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