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Structural and microtectonic analyses of Barpak of Gorkha district, west-central Nepal

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ABSTRACT

Geological mapping was carried out in the Barpak-Bhachchek area of the Daraudi River valley, Gorkha district, West-Central Nepal for structural analyses. The area comprises rocks of the Higher Himalayan Crystalline and the Lesser Himalayan Sequence. Pelitic and psammitic schist, quartzite, calc-quartzite, dolomitic marble, graphitic schist, gneiss are the main rock types within the Lesser Himalayan Sequence. In contrast, banded gneiss and quartzite form a significant portion of the Higher Himalayan Crystalline. The area is affected by poly-phase deformation. The Lesser Himalayan Sequence has suffered five deformational phases (DL_1-DL_2, D_3-D_5),whereas the Higher Himalayan Crystalline has suffered four deformational events (DH_1, D_3-D_5). Among these deformational phases, early deformational phases (DL_1-DL_2) of the Lesser Himalayan Sequence and (DH_1) of the Higher Himalayan Crystalline are pre-Himalayan, whereas later three (D_3, D_4, D_5) of both the Higher Himalayan Crystalline and the Lesser Himalayan Sequence are Himalayan. The Lesser Himalayan Sequence lying to the northern limb of the Gorkha-Kuncha anticlinorium is contorted into doubly plunging to dome-and-basin like *en echelon* type of non-cylindrical folds as Baluwa Dome and Pokhartar Basin (DL_2 and D_4). The direction of shearing as indicated by shear sense indicators (C' Shear band and Mica fish) is top-to-south coinciding with the regional sense of shear due to the MCT propagation. The dynamic recrystallization direction, obtained from rock dominant with phyllosilicate minerals, is top-to-south and coincides with mineral lineation, indicating the mineral lineation is contemporary with dynamic recrystallization during the MCT propagation.

Key words: Structural analyses; Microtectonic; Gorkha-Kuncha anticlinorium; Dome and basin; Main Central Thrust; Dynamic recrystallization

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INTRODUCTION

The Himalaya is an active Alpine orogenic belt resulted from the collision of the Indian Plate and the Eurasian Plate. Out of 2400 km of southwardly convex Himalayan arc, Nepal Himalaya almost occupies one third portion of the central segment (~800 km). Himalaya is tectonically divided into four different longitudinal units having different stratigraphic and evolutionary characters from south to north; namely the Siwaliks, the Lesser Himalayan Sequence, the Higher Himalayan Crystalline and the Tibetan-Tethys Himalaya (Gansser, 1964). Large-scale intra-continental thrusts separate each unit, they are the Main Frontal Thrust (MFT), the Main Boundary Thrust (MBT), the Main Central Thrust (MCT) and the South Tibetan Detachment System (STDS) - a normal fault from south to north, respectively (Gansser, 1964). The Lesser Himalayan Sequence is the litho-tectonic unit extending between MBT in the south and MCT in north. This unit is basically composed of intensely folded, highly deformed, faulted, and fractured metasedimentary clastic, non-clastic and carbonate rocks. The Higher Himalayan Crystalline is the litho-tectonic unit extending between the MCT in the south and the STDS in north. It is composed of banded gneiss, quartzite, calc-gneiss and leucogranites.

In central Nepal, the Lesser Himalaya Sequence characterized by large-scale fold known as the Mahabharat Synclinorium (Stöcklin and Bhattarai,1977) and the Gorkha-Kuncha Anticlinorium (Otha et al., 1973; Pêcher, 1977). The southern limb of the Gorkha-Kuncha Anticlinorium is composed of low-grade meta-sedimentary rocks, have been extensively studied by different geoscientists (Stöcklin and Bhattarai, 1977; Stöcklin, 1980; Paudyal and Paudel, 2013; Paudyal, 2014). However, in the anticlinorium's northern limb, the strata have undergone medium- to high-grade of metamorphism on approaching the MCT. The rocks in the northern limb of the anticlinorium at the proximity of MCT show ductile deformational behavior (Brunel, 1986) in contrast to the brittle deformational behavior in the southern limb of anticlinorium (Paudyal, 2014). Only regional maps (Ohta et al., 1973; Pêcher, 1977; Colchen et al, 1980, 1986; Dhital, 1995) have been published for the area. Few noticeable works have been done by Ohta et al. (1973), Pêcher (1977), Colchen et al.(1980, 1986), Gautam and Koshimizu (1991), Adhikari (1993), Dhital (1995), Gautam and Fujiwara (1998), Oli et al. (2019).

Le Fort (1975) divided the rocks of the Higher Himalayan Crystalline into Formation I, Formation II and Formation III in Kali Gandaki Section, and similar classification was followed in Annapurna-Manaslu-Ganesh Himal area (Colchen et al., 1986). Colchen et al. (1986) also revealed inverted metamorphism in area based on metamorphic grade. The Lesser Himalayan sequence adjacent to MCT is metamorphosed to garnet grade, and the rocks of Higher Himalayan Crystalline are metamorphosed to kyanite grade at the bottom and sillimanite grade at the top where the thickness of Crystalline slab is maximum, such as the neighborhood east of Mount Annapurna. Dhital (1995) carried out geological mapping of Gorkha-Ampipal area and divided the rocks from south to north as Kuncha Formation with phyllite and quartzite, Garnet schist with augen and banded gneiss, Graphitic schist and marble, and Kyanite-schist and gneiss. Oli et al. (2019) carried out geological mapping of Barpak–Bhachchek area and classified the rocks of the Lesser Himalayan Sequence and the Higher Himalayan Crystalline into different lithological units that have been affected by inverted metamorphism.

The present study covers the Daraudi River valley and surrounding areas between Jhyallaphat to Barpak (Fig. 1). This study aims to carry out structural and microtectonic analyses to explore the deformation history of Baluwa-Barpak area of the Gorkha district, west-central Nepal. A geological map at a scale of 1:25,000 has been prepared, geological structures and deformational history were studied.

METHODOLOGY

The topographic map of 1:25000 scale published by the Department of Survey, Nepal, was used for the field mapping. Various lithological units were mapped along with their attitudes, descriptions and rock characters. Roads, trails, rivers and streams were used for field traverses to observe the lithostratigraphy, geological structures of the area and to collect necessary data for structural analyses. Altogether eighteen oriented representative samples were used for preparation of thin sections and were cut perpendicular to dominant foliation and parallel to mineral lineation for microtectonic analysis using the technique of optical microscopy. The deformational history and events were interpreted by using various

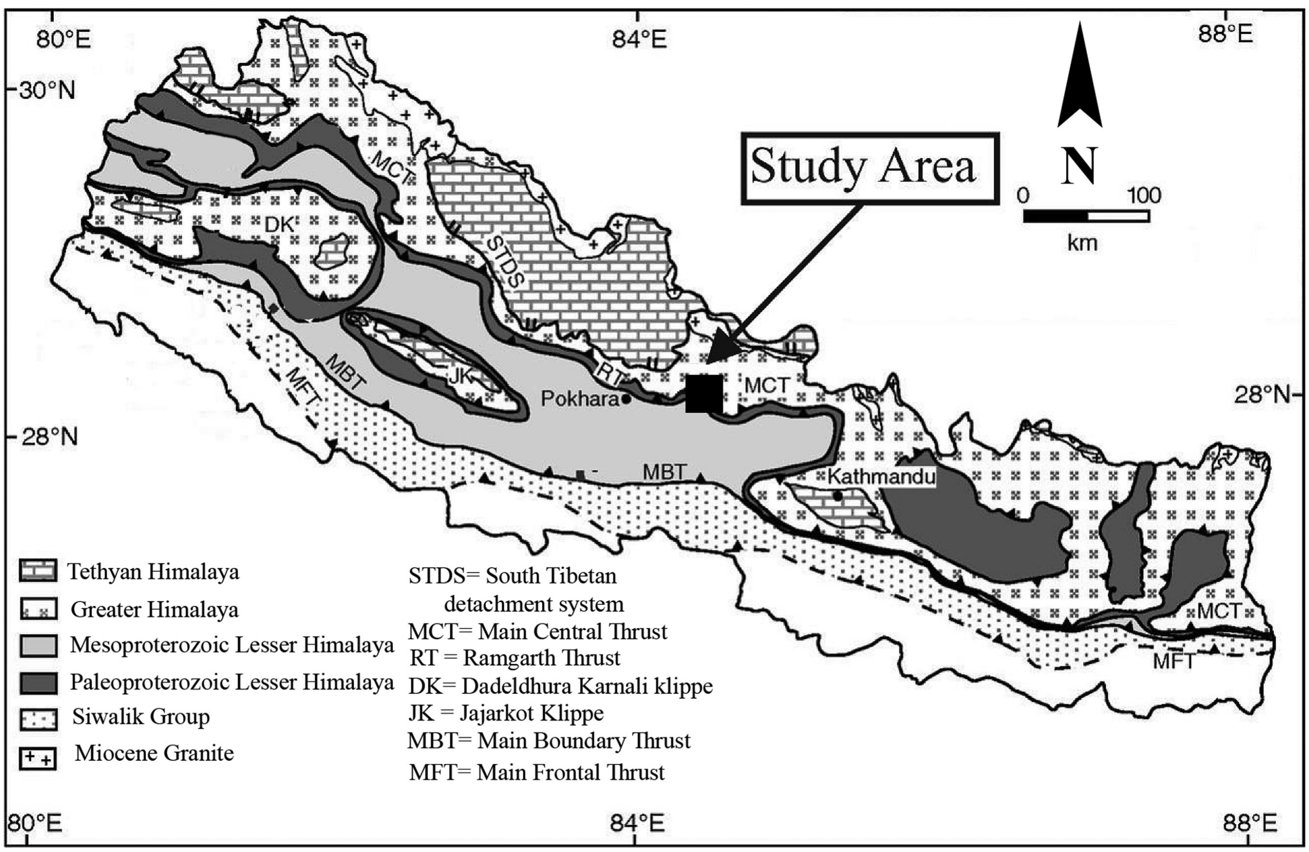

Fig. 1: Geological map of Nepal showing the location of the study area (after Amatya and Jnawali, 1994) .

fabrics, growth sequence of minerals, lineations, folds, joints and faults in the Lesser Himalayan Sequence and the Higher Himalayan Crystalline. Structural features were observed in microscopic to regional scales. Graphical tools/programs such as ArcGIS were used to digitize map whereas DIPS 5.0 was used to analyze the collected data.

LITHOLOGY

The study area can be separated into two major tectonic units: the Lesser Himalayan Sequence and the Higher Himalayan Crystalline separated by the MCT (Fig. 2). Pelitic and psammitic schist, quartzite, calc-quartzite, dolomitic marble, graphitic schist are the major rock types within the Lesser Himalayan Sequence, whereas quartzite and banded gneiss form the significant portion of the Higher Himalayan Crystalline.

Lesser Himalayan Sequence

In the study area, Lesser Himalayan Sequence is well-exposed at Jhyallaphat, Muchchoktar, Saurpani, Rangrung, Mandre, Barpak and especially on the central south and southeast part. The Lesser Himalayan Sequence, in this section, consists of pelitic and psammitic schist, quartzite, calcareous quartzite, dolomitic marble and graphitic schist. The study area has been divided into five lithological units are 'Calcareous Metasandstone and Marble unit', 'Psammitic Schist unit', 'Calcareous Quartzite and Psammitic Schist unit', 'Calcareous Quartzite and Marble unit' and ‘Graphitic Schist, Marble, Gneiss and Quartzite unit’, from bottom to top respectively (Fig. 2). The lithological units of the Lesser Himalayan Sequence are discussed below.

Calcareous Metasandstone and Marble

This unit is well exposed at Baluwa, lower section of the Mahabir Khola and lower section of the Andheri Khola. This unit consists of white to grayish white, well foliated, coarse-grained, slightly to moderately weathered calcareous metasandstone (2 - 50 cm thick) alternate with white to dirty white, well foliated, slightly to moderately weathered, coarse grained dolomitic marble (2 - 30 cm thick). At some places grey to grayish black, coarse-grained, well-foliated, moderately weathered psammitic schist (up to 5 cm thick) have been observed.

Psammitic Schist

This unit is well exposed along the Baluwa-Rangrung road section. This unit consists of grey to greyish black, coarse-grained, well-foliated, moderately weathered, psammitic schist (2 - 30 cm thick) with biotite and garnet minerals alternately banded with gray, coarse-grained, well-foliated, moderately weathered metasandstone (up to 5 cm thick).

Calcareous Quartzite and Psammitic Schist

This lithogical unit is well exposed along the Baluwa-Rangrung road section at Rangrung village and at the confluence of the Daraudi River and the Rangrung Khola. This unit is characterized by dirty white to pinkish white, sometimes grey, coarse-grained, well-foliated, moderately weathered calc. quartzite (2-25 cm thick) alternate with light pink to pink, coarse-grained, well-foliated, psammitic schist (2 - 50 cm thick). The upper part of this unit consists of pinkish white, coarse-grained, well-foliated, moderately weathered marble (upto 20 cm thick). At some spots, the marble is lined with fibers of actinolite.

Calcareous Quartzite and Marble

This unit is well exposed at Jhyalla, Jhyallphat, Gauthali, Kalibote, Mandre, Kaldunswara and along the Daraudi River section at l00 m upstream from the confluence of the Rangrung Khola and the Daraudi River. This unit is characterized by milky white to white, coarse-grained, well-foliated, slightly weathered calcareous quartzite (20 cm- 5 m thick) alternate with white to grayish white, coarse grained, well-foliated, slightly dolomitic marble (3 cm- 3 m thick). At some spots, the marble beds are lined with fibers of actinolite minerals.

Graphitic Schist, Marble, Gneiss and Quartzite

This unit is well exposed at Barpak, Ghychok, Lamachhanitar, Phaplu, Darigauda, Sourpani, Ranchok and Polchari. This unit is characterized by black, coarse-grained, well-foliated, moderate to highly weathered graphitic garnet schist (up to 5 cm thick). In the Ranchok village, greyish blue to grey, coarse grained, well foliated, fresh to slightly weathered dolomitic marble (3 - 20 cm thick) with distinct fissility due to mica partings has been observed.

Moderately weathered, paragneissis well exposed at the confluence of the Chhichha Khola and the Daraudi River. Moving stratigraphically upward, few meters thick green, coarse-grained, well-foliated, moderately weathered marble (20 - 50 cm thick) with abundant actinolite minerals alternately banded with white to greenish white, coarse-grained, well-foliated, slightly weathered calcareous quartzite (10 - 30 cm thick) has been observed. It is immediately followed by moderately weathered paragneiss. Milky white, coarse-grained, well-foliated, quartzite (50 cm- 2 m thick) with mica parting can be observed on moving stratigraphically upward. This unit is about 20 m thick in the study area, but the band becomes considerably thick towards the eastern part of the Daraudi River valley, on the foot trail towards Larpak from Barpak.

Quaternary Deposits

In the study area, older rock successions around the Daraudi River valley are capped by quaternary deposits. Quaternary deposits have been identified and classified as river terraces, alluvial fan and colluvial deposits (Fig. 2a.). Three level of river terraces are found; T0, T1 and T2, where T0 is lower terrace and T2 is upper terrace. Four alluvial fans and two colluvial deposits have been recognized. The Lesser Himalayan Sequence has been eroded to form Inlier, an erosional structure at Baluwa (Fig. 2a).

The Lesser Himalayan Sequence of this area, being northern limb of the Gorkha-Kuncha Anticlinorium (Otha et al., 1973; Pêcher, 1977), has retained inverted metamorphism. The area can be compared with the Midland Group of rocks (Le Fort, 1975; Pêcher 1977; Colchen et al. 1986); the Nawakot Complex, Central Nepal (Stöcklin and Bhattarai, 1977) and the Kaligandaki Supergroup, west-central Nepal (Sakai, 1985). The correlation is very difficult as primary structures like mud cracks, ripple marks, cross bedding, stromatolites have been rarely preserved due to intense metamorphism and marker horizons are also rarely distinguishable due to the intense metamorphism and ductile deformation associated with the movement of the MCT.

Higher Himalayan Crystalline

The Higher Himalayan Crystalline has been divided into Formation I, Formation II and Formation III (Le Fort, 1975). In the study area, only lower part of the Formation I has been observed, which is well-exposed at Bhachehek, Taple, Simjung, Bhalu Kharka areas in the northwest and northeast parts (Fig. 2).

Formation I begins with greyish black mylonitic quartzite. This mylonitic quartzite is followed by kyanite-garnet bearing banded gneiss. Off-white, with dominant mica rich dark striation, coarse-grained, well foliated, highly jointed, moderately weathered gneiss (10 cm- 2 m thick), which are alternate with dirty white to dark grey, coarse-grained, well foliated, highly jointed, moderately weathered quartzite (10 - 25 cm thick). The gneissic band at the basal part, with alternate quartzite band gradually transits to dark colored mica rich massive gneiss on moving stratigraphically upward.

GEOLOGICAL STRUCTURES

The structures of the area can be observed at different scales from regional (mega) to microscopic structures. All the structures observed and interpreted are secondary/deformational structures, which have been produced by different deformational events (DL_1-DL_2, D_3-D_5) in the Lesser Himalayan Sequence and (DH_1, D_3-D_5) in the Higher Himalayan Crystalline related to pre-Himalayan and Himalayan deformation phases. Mega structures have been observed and interpreted by using regional geological mapping; mesostructures have been observed and interpreted in outcrops, and microstructures have been studied under petrographic microscope.

Mega structures

Mega structures are regional geological structures that have been interpreted by preparing a geological map and field observations (Fig. 2). The mega structures present in the study area are as follows:

Main Central Thrust (MCT)

The location and definition of the MCT is one of the widely debated issues in the Himalayan geology and controversial structure till date (Heim and Gansser, 1939; Gansser, 1964; Le Fort, 1975; Valdiya, 1980; Pêcher, 1977, 1989; Arita et al., 1982; Arita, 1983). The concept of the MCT was first introduced by Heim and Gansser (1939) and Gansser (1964) in order to define a thrust fault, as a structural discontinuity that places high-grade metamorphic rock of the Higher Himalayan Crystalline over low-grade rocks of the Lesser Himalayan Sequence. Valdiya (1980) brought the concept of two intracrustal thrusts, the Lower Munsiri Thrust (Equivalent MCT of Heim and Gansser, 1939) and the upper Vikarita Thrust. Various researchers such as Valdiya (1980); Pêcher (1977, 1989); Arita et al. (1982) and Arita (1983) have described the existence of two thrusts instead of single MCT. Arita et al. (1982) and Arita (1983) have described the MCT zone as deformational zone which exist between garnet isograde at base and kyanite isograde at top. The thrust at the base is designated as MCT I, and the upper limiting boundary of the MCT zone is named as the MCT II. MCT II is the tectonic boundary that separates Higher Himalaya with Lesser Himalaya. So, in the study area, the MCT refers to MCT II of Arita et al. (1982) and Arita (1983).

There is no sharp structural discontinuity that separates the Lesser Himalayan Sequence and the Higher Himalayan Crystalline as the Lesser Himalayan Sequence immediately beneath the MCT have been metamorphosed to paragneiss of garnet

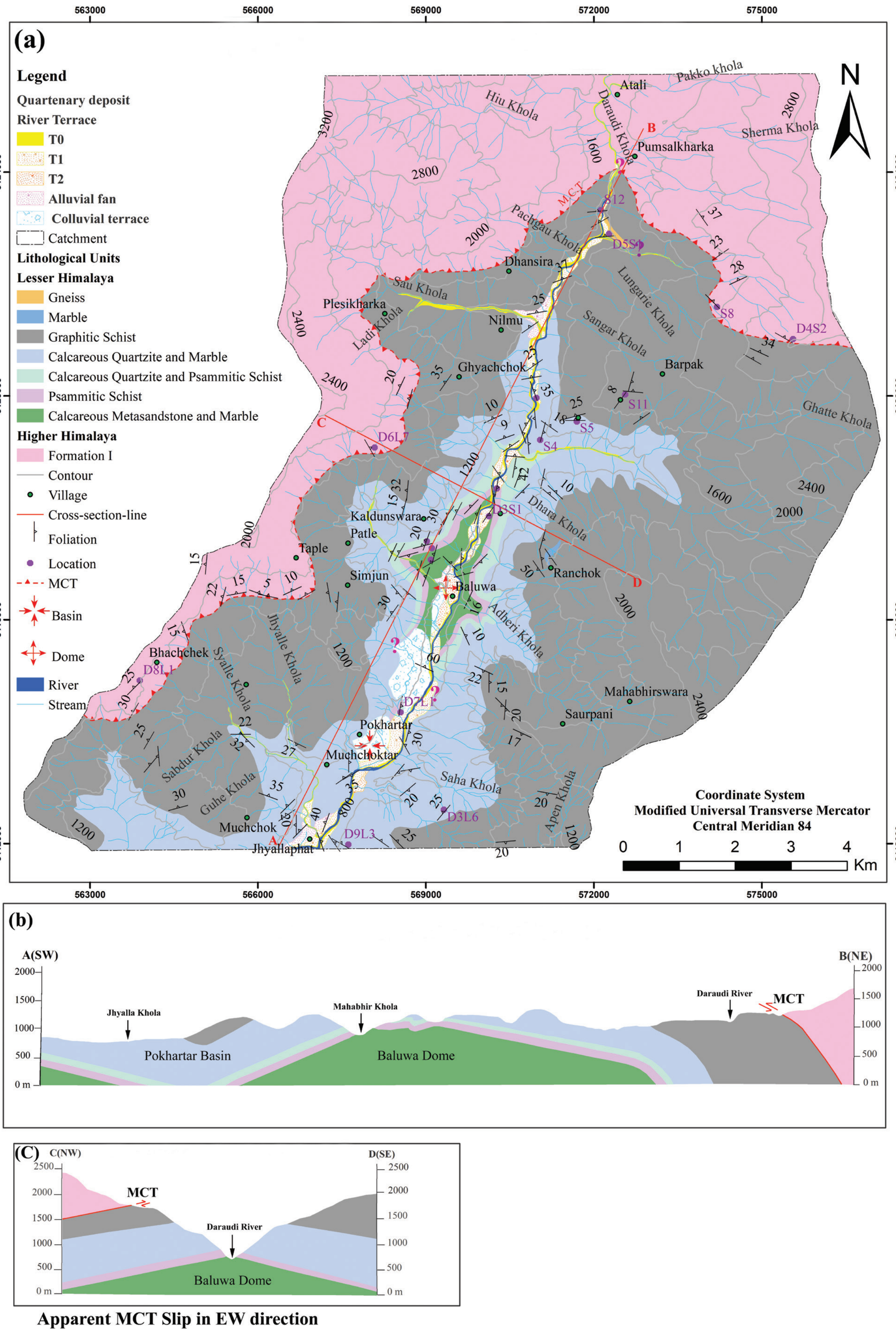

Fig. 2: (a) Geological map of Barpak-Bhachchek area (b) Geological cross section along line A-B (c) Geological cross section along line C-D. (Modified after Oli et. al., 2019).

grade. Searle et al. (2008) have defined the MCT as the base of the large scale zone of high strain and ductile deformation, commonly coinciding with the base of inverted metamorphic isograds, which places high-grade metamorphic rocks of the Higher Himalayan Crystalline over meta-sedimentary rocks of the Lesser Himalayan Sequence. In the study area, the MCT has been traced based on this definition, as a thick ductile shear zone lying at the base of the kyanite grade, evidenced with various mylonitic structures and shear sense indicators (Fig. 2).

The MCT in the study area has been demarcated with the first appearance of kyanite mineral in gneissic succession (Fig. 2 a.). The MCT is located at Bhachchek village on southwest part of study area and then it trend along NNE direction just below Taple village, above Plesikharka and Dhansira villages and ultimately reach the Daraudi River and then trend SEE direction. The MCT is gentle towards south west part i.e. Bhachchek and Taple but the dip angle gradually increases on moving towards north i.e. about 45^0 in the Daraudi river section.

Baluwa Dome

It is a non-cylindrical fold formed in the Lesser Himalayan Sequence of study area in which stratigraphically older Calcareous Metasandstone and Marble unit form the core and younger Graphitic Schist unit forms the limbs of the dome (Fig. 2). The two geological cross-sections, along A-B shows rocks folding in N-S direction whereas along section C-D shows rocks folding in E-W direction (Fig. 2b and c). Lower hemispherical stereographic projection of the poles to the foliation (Fig. 3) shows non-cylindrical nature of the fold. The foliation of the rocks dips away from core in all possible direction (Fig. 2 a.), i.e., doubly plunging nature of fold. It also consists of numerous parasitic folds in the study area. Inlier can be observed (Fig. 2a.) with nearly concentric to oval rings of strata and each ring is growing progressively older while moving inward, which is the characteristic feature of dome. The foliations also dip outward of core in all directions indicating the nature of dome.

Baluwa dome is non-cylindrical fold present in the northern limb of Gorkha-Kuncha anticlinorium, where younger meta-sedimentary sequence is exposed. In the Gorkha-Ampipal area of Gorkha-Kuncha anticlinorium, the Kuncha Formation (core) is folded into doubly plunging to dome and basin like, *en echelon* type of non-cylindrical folds (Dhital, 1995). In Kusma-Pokhara section of Gorkha-Kuncha anticlinorium, the Kuncha Formation (core) consists of number of NW-SE trending, doubly plunging, *en echelon* type of non-cylindrical folds (Dhital et al, 1998).

Pokhartar Basin

It is non-cylindrical fold formed in the Lesser Himalayan Sequence, which is a counterpart of Baluwa dome (Fig. 2). In this fold, stratigraphically younger Calcareous Quartzite and Marble unit as well as Graphitic Schist unit forms the core. The geological cross-section along A-B shows synform folding in N-S direction (Fig. 2b) whereas along the section C-D shows folding in E-W direction (Fig. 2c). Lower hemispherical stereographic projection indicates non-cylindrical nature of fold (Fig. 4). All the foliations dip towards core in all direction i.e. doubly plunging nature of basin.

Mesostructures

Beside mega folds and major thrust, various mesostructures are often present in the study area. The major outcrop-scale mesostructures observed in the study are as follow:

Mesoscale fold

There are several mesoscale folds. These folds are mostly concentrated in the core of the dome and basin. These folds are closed and observed in the outcrop scale in many places. Lower hemispherical stereographic projection shows the trend and plunge of these folds (Fig. 5), and the majority of the folds are trending towards W-E to WNW-ESE. The average trend/plunge of fold is about $127^0/23^0$.

Foliation

In the study area, primary foliation (S_1) is nearly parallel to the original bedding (S_0). The foliation observed all over the area is shown in the lower hemispherical stereographic projection of poles to foliation (Fig. 2; Fig. 6) and it indicates gentle dipping of foliation in all possible directions.The foliations just beneath the MCT are following the trend of the MCT. The dip angle of foliations just beneath the MCT is gentle at Bhachchek but on moving towards Taple, Simjung, Ghyalchok, Pelsikharka villages, i.e., northeast direction, the dip angle gradually increases and eventually reaches up to 40^0-45^0 at the Daraudi River section. The average dip angle is 21^0 but ranges from 7^0 up to 60^0.

Lineation

The mineral lineations are frequently observed. The stereographic projection of trend and plunge of lineation shows NNE-SSW trend with a gentle plunge (Fig. 7). The stretching (Fig. 9) and mineral lineations

(Fig. 10) having NNE-SSW trend with gentle plunge are consistent with silicate mineral lineation of the region, as observed by Ohta et al. (1973). Regionally, the MCT movement is towards the south and the mineral lineation and stretching lineation also show NNE-SSW trend indicating the top to the SSW sense of shear during the MCT propagation.

Joints

In the field, joints were observed most frequently in the calc-quartzite, quartzite, marble and metasandstone and less commonly in schist due to weathering (except psammitic schist). There are mainly three major joint sets J1, J2 and J3 (Fig.8). J1 is foliation parallel joint set in the area.

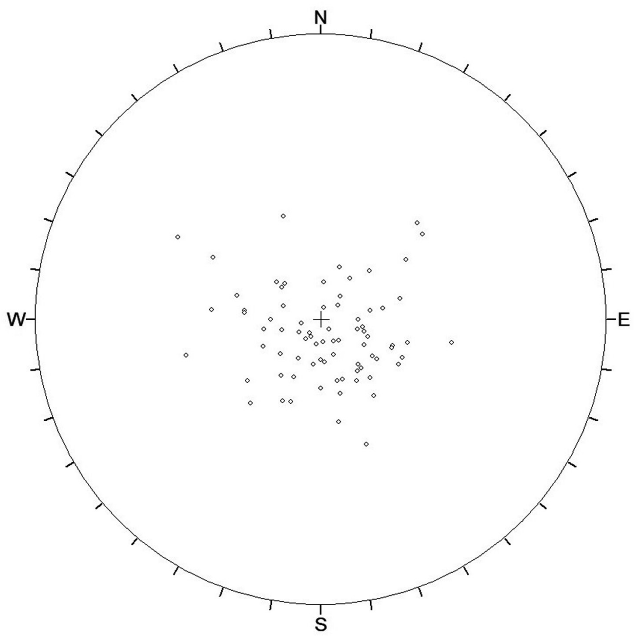

Fig. 3: Lower hemispherical projection of foliation (N=81) of Baluwa dome showing poles scattered in all possible direction.

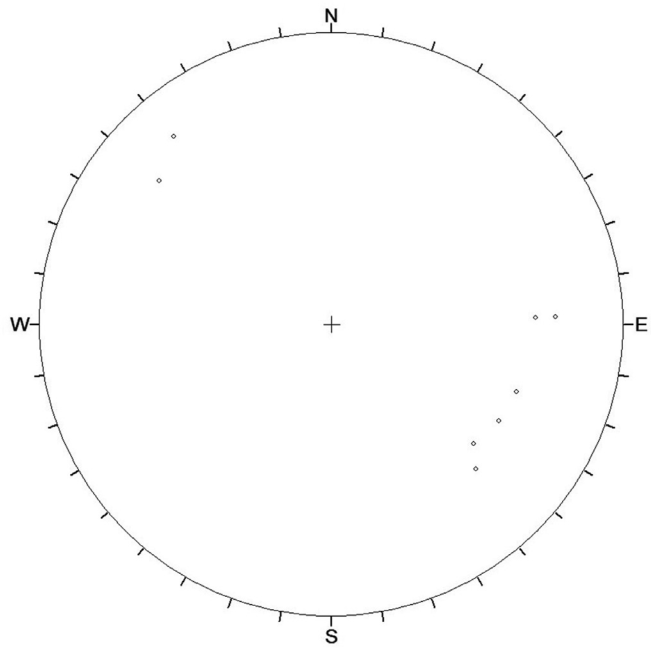

Fig. 5: Lower hemispherical projection of trend and plunge of mesoscale folds (N=8) showing W-E to WNW-ESE trend.

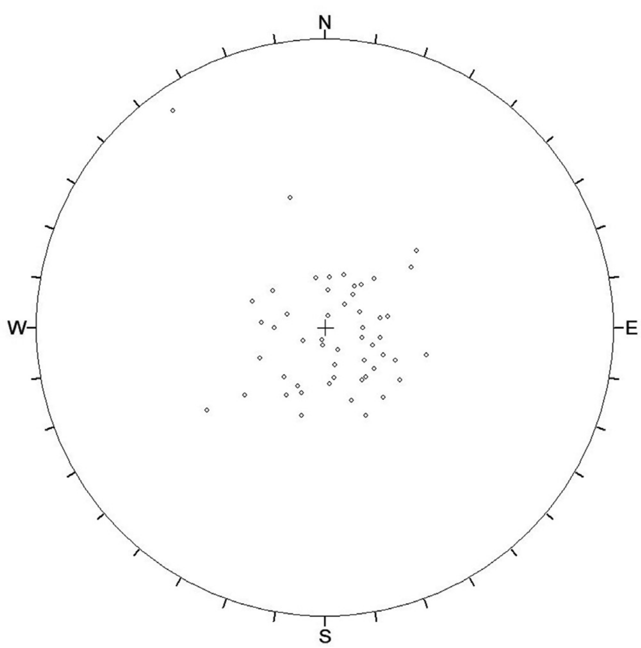

Fig. 4: Lower hemispherical projection of foliation (N=54) of Pokhartar basin showing poles scattered in all possible direction.

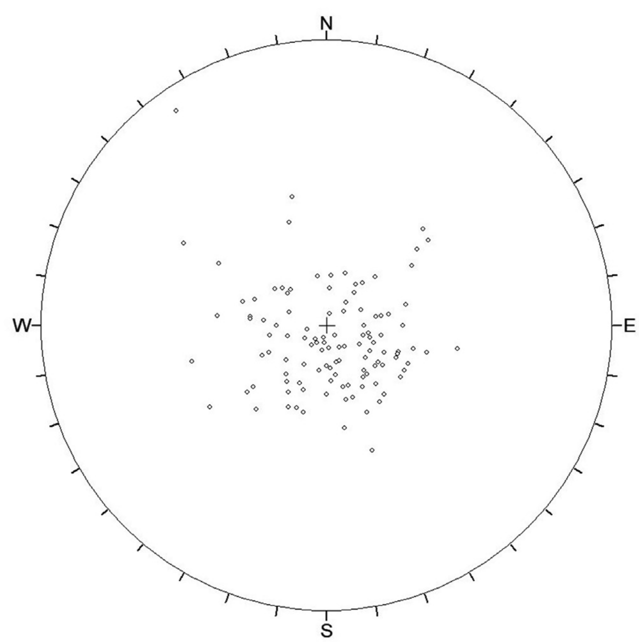

Fig. 6: Lower hemispherical projection of foliation (N=163) of whole study area showing poles to the foliations scattered in all possible direction.

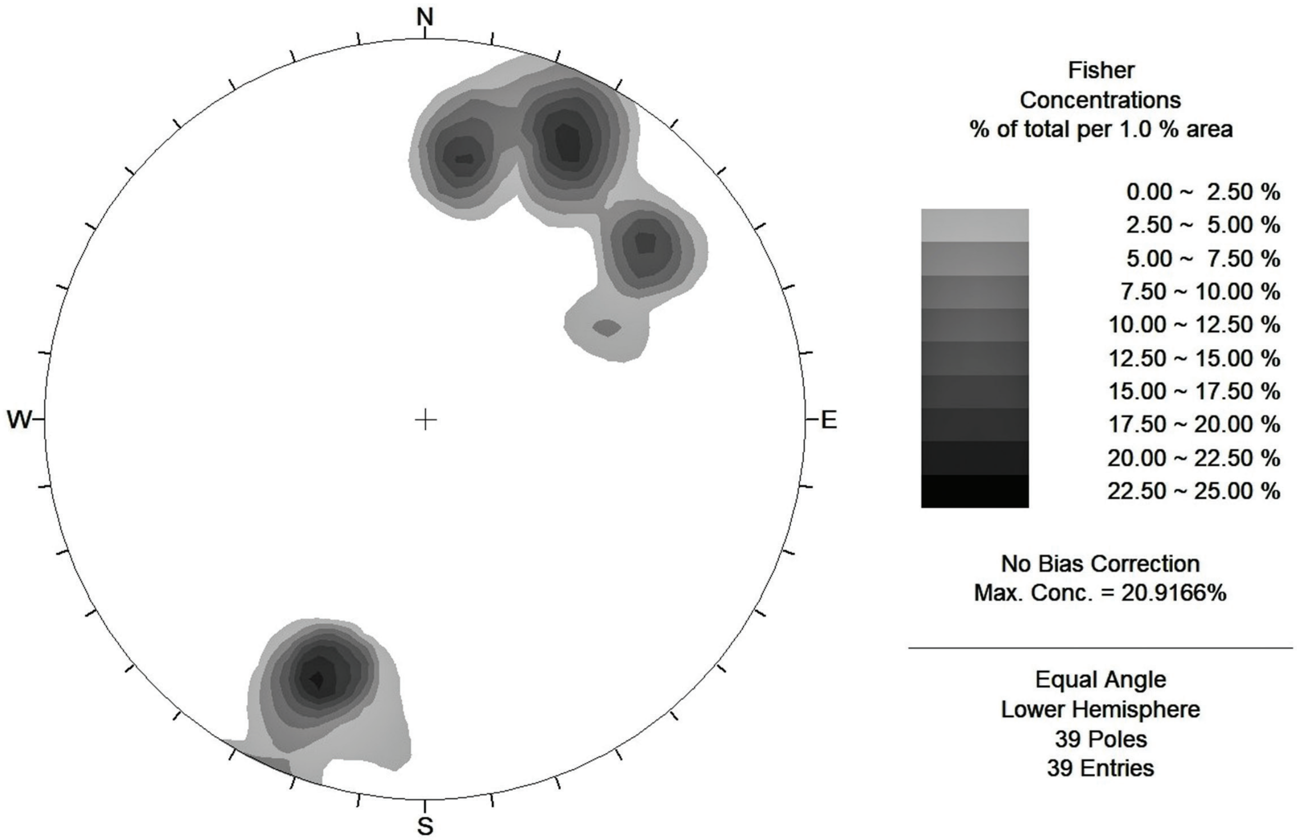

Fig. 7: Lower hemispherical projection of lineation showing NNE-SSW trend.

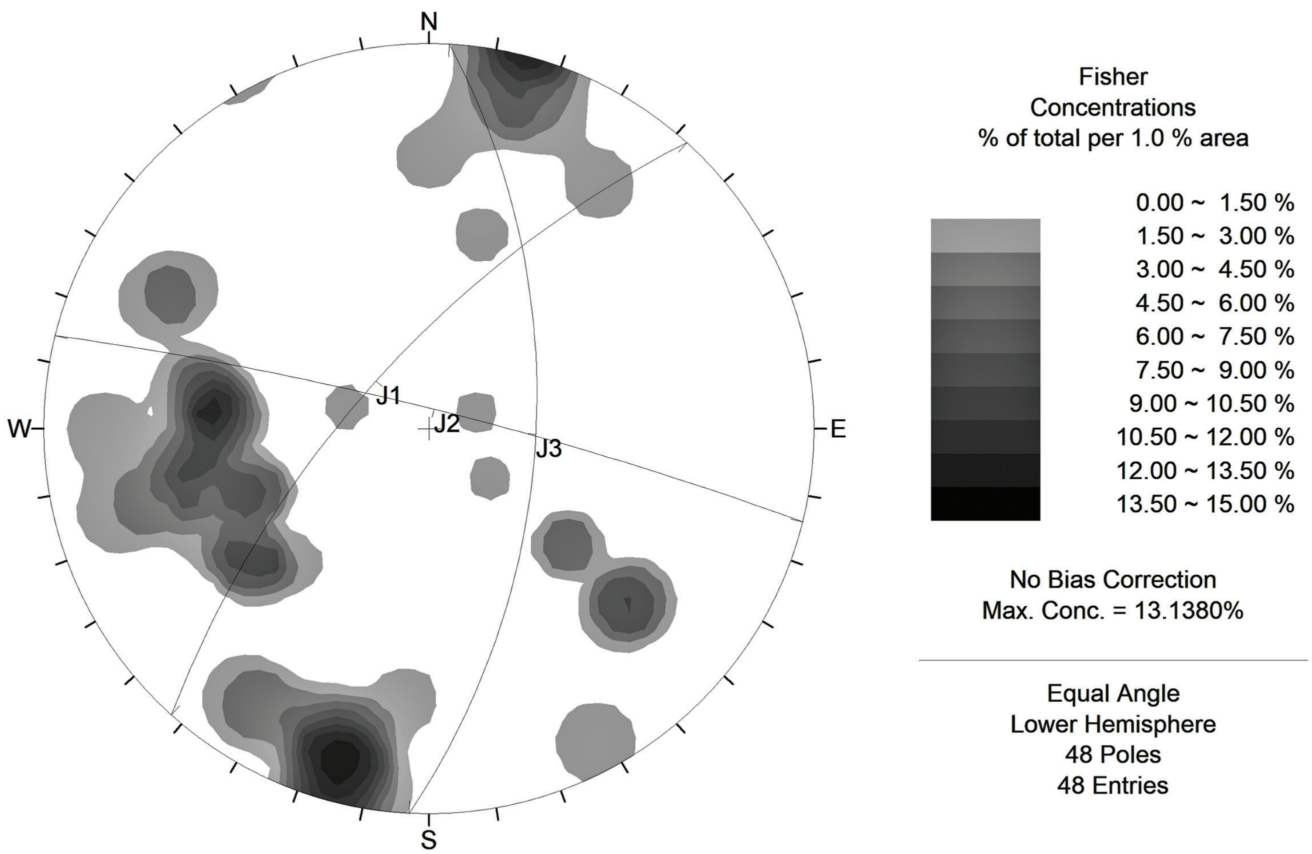

Fig. 8: Lower hemispherical projection showing three major joints sets.

Boudinage and ptygmatic folds

Boudinages are well-observed in the paragneiss belonging to Formation I of the Higher Himalayan Crystalline and the Graphitic Schist unit of the Lesser Himalayan Sequence (Figs. 11 and 12). Boudinages from the Lesser Himalayan Sequence indicate top to south sense of shear (Fig. 11). Abundant quartz veins and ptygmatic folds have been observed in the Higher Himalayan Crystalline (Fig. 12).

Fig. 9: NW facing psammitic schist with well-developed stretching lineation exposed at Balphe, on the Baluwa-Rangrung road section.

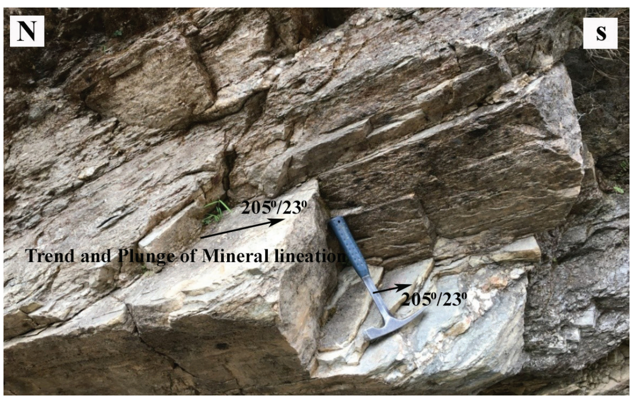

Fig. 10: NW Facing gneiss from the Higher Himalayan Crystalline with joints and mineral lineation having trend and plunge $21^0/18^0$ near Barpak village.

Fig. 11: Boudinage on the rock belonging to the Lesser Himalayan Sequence rock observed at Basbot village, on the way to Ghyachok from Rangrung.

Fig. 12: Boudinages and ptygmatic foldsobserved in gneiss of the Higher Himalayan Crystalline along the foot trail towards Pumsalkharka village from Barpak village.

Microstructures

The microstructures and the shear sense indicators were mostly observed in the samples of psammatic schist, graphitic schist, and gneiss of the Lesser Himalayan Sequence and banded gneiss of the Higher Himalayan Crystalline. The microstructures and shear sense indicators are described below.

Quartz grain microstructures

Sample D4S2 is a gneiss from the Higher Himalayan Crystalline, collected from the foot trail towards Larpak from Barpak. The photomicrograph of D4S2 (Fig. 13) shows five types of microstructures indicated by five circles; namely, A is dragging microstructure, B left over grains, C pinning microstructure, D subgrain rotation recrystallization and E window microstructure (Figs. 13 and 14)**.** These structures indicate the direction of grain boundary migration during dynamic recrystallization towards top-to-south indicating the MCT movement. Along with these, subgrain rotation recrystallization is also present in the same sample, which is evidence of dynamic recrystallization developed during the MCT propagation (syn-MCT deformation).

In the sample D5S1, gneiss of the Lesser Himalayan Sequence found on the right bank of the Chhichha Khola, shows ribbon-shaped quartz structure (Fig. 15). The ribbon shaped structure was developed during deformation phase D_3 (syn-MCT deformation).

The oriented gneiss sample D8L1 (Fig. 16) from the Higher Himalayan Crystalline shows bulging recrystallization. The small grain present in the photomicrograph may be isolated grain through grain boundary migration. The grain contact is strongly sutured and the grain boundaries are amoeboid with strong curved and lobate interlocking grain boundaries. The structures in the sample D8L1 were developed during deformational phase D_3 (syn-MCT deformation).

Grain boundary area reduction (GBAR) can be observed in oriented gneiss sample D4S2 from the Higher Himalayan Crystalline (Fig. 17). The quartz grains have attended polygonal crystal, thus attending minimum surface area. Foam like aggregate is visible in two dimensions, especially in gneiss and quartzite samples where three grains meet at a point (trigonal contact), and the interfacial angle are approximately 120° (Vernon, 2004). Triple junction (Figs. 16 and 17) is the crucial structure that denotes the state of textural equilibrium that have occurred during post-MCT deformation as grain boundary recovery where irregular grains/crystals produced as a result of grain boundary migration (GBM) during syn-MCT deformation (D_3) regain its polygonal shape from rim of grains in form of small polygonal crystals.

Sample S8 was collected on the foot trail towards Pumsalkharka from Barpak. The rock has been identified as a mylonitic quartzite from petrography as it shows continuous foliation indicating strong ductile deformation, which is typical fabric of dynamically recrystallized quartz (Fig. 18). The grains have a weak ribbon shaped preferred orientation and defines foliation. The recrystallization direction is top-to-south indicating it as syn-MCT deformation.

Lepidoblastic texture defines two sets of foliations (S_1 and S_2). Here S_1 (Figs. 13, 14, 17, 18, 19) is bedding parallel foliation (S_0=S_1) developed during deformation event DL_1 in the Lesser Himalayan Sequence and DH_1 in the Higher Himalayan Crystalline. The paragneiss (Fig 15; Fig 20) from the Lesser Himalayan Sequence consists of well-developed foliation S_1 (developed during pre-Himalayan deformation) marked by parallelism of biotite and well developed quartz mica differentiation. The garnet porphyroblast (Fig 20) has two sets of foliation S_1 and S_2, among which S_1 is inherited from original bedding (S_0=S_1) and S_2 is later developed foliation during Syn-MCT deformation (D_3) around garnet crystal, which is discordant with initial foliation S_1. Development of two distinct foliations around garnet indicate poly-phase deformational phases.

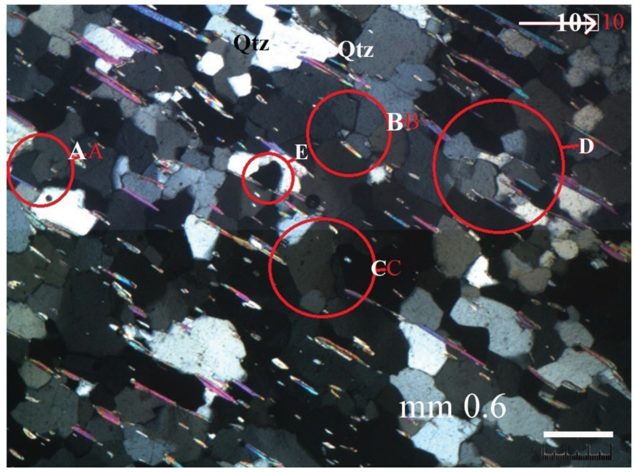

Fig. 13: Photomicrograph of D4S2, shows evidences of dynamic recrystallization; A-dragging microstructure, B-leftover grains, C-pinning microstructure, D-Subgrain rotation recrystallization, E-window microstructure.

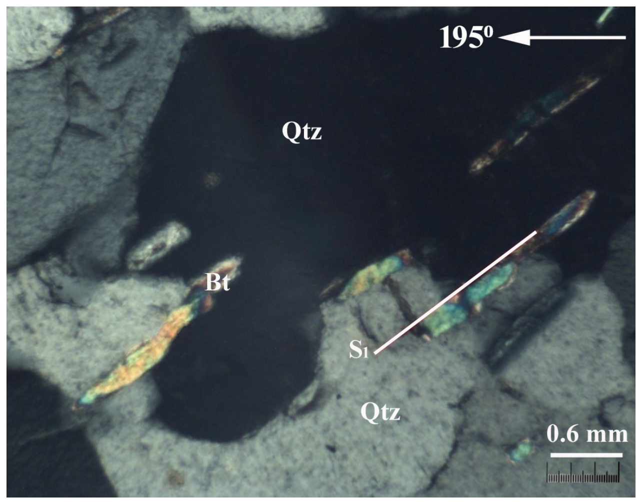

Fig. 14: Photomicrograph showing ‘window’ microstru cture, an evidence of dynamic recrystallization of gneiss found at Bhachchek.

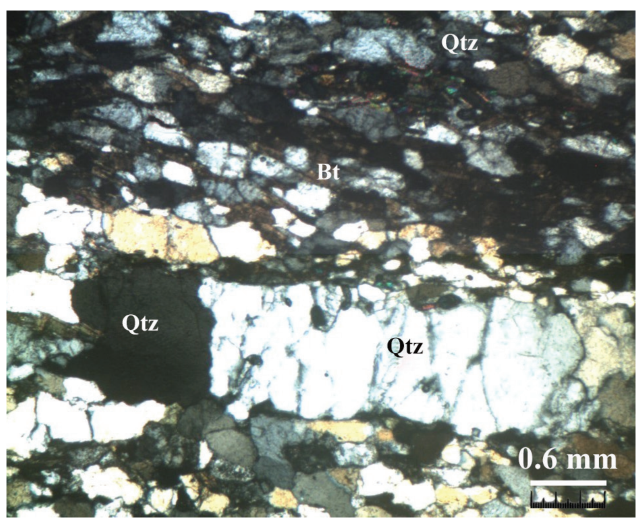

Fig. 15: Photomicrograph of ribbon shaped quartz from gneiss at Chhiachha Khola.

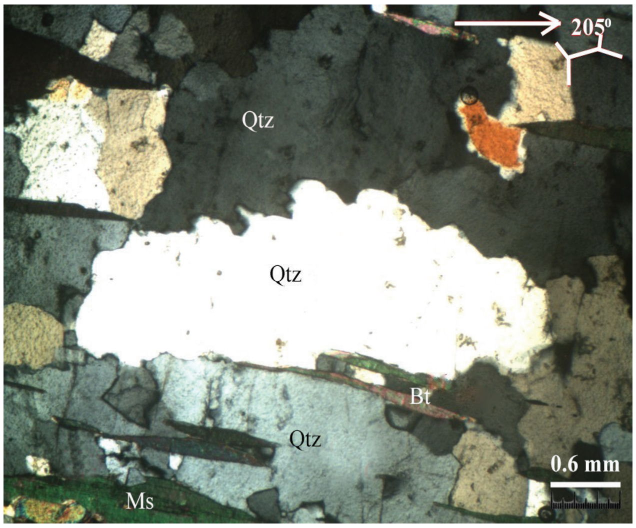

Fig. 16: Photomicrograph of quartz showing polygonal contact and sutured contact from the gneiss near Bhachchek village.

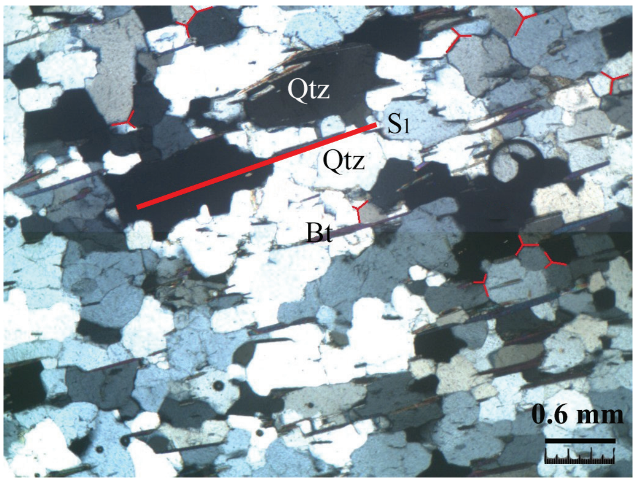

Fig. 17: Photomicrograph showing trigonal contact and foliation S_1 from quartzite of the Lesser Himalayan Sequence taken from the foot trail towards Larpak village from Barpak village.

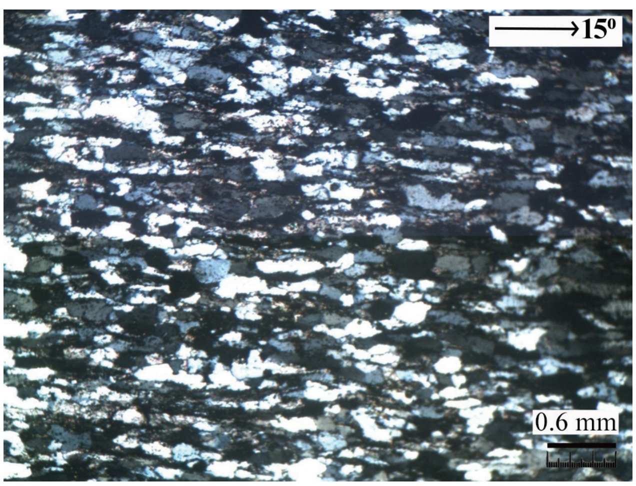

Fig. 18: Typical fabric of dynamically recrystallised quartz grains that have weak preferred continuous foliation in mylonitic quartzite collected from the foot trail towards Pumsalkharka village from Barpak village.

Garnet porphyroblasts with S-shaped inclusions

Garnet porphyroblasts with S-shaped inclusions trail of quartz are visible in a thin section of gneiss from the Lesser Himalayan Sequence (Figs. 20 and 21). In the photomicrograph of gneiss from the Lesser Himalayan Sequence, S-shaped inclusions trail or foliation of inclusion (Si) is different than external foliation (S_1 and S_2) (Fig. 21). The Presence of minor amount of quartz and chlorite on the garnet's rim indicates retrograde metamorphism (Fig. 21).The primary foliation (S_0=S_1) and foliation of inclusion (S_i) are contemporary, i.e., they were the same foliation (S_1) initially, but the secondary foliation S_2 is later developed foliation (Macqueen and Powell, 1977). These garnet porphyroblasts from the Lesser Himalayan Sequence are syn-tectonic as they show 'S' shape of inclusion trails and are formed during the MCT propagation. Poly-phase deformation is shown by external foliation (S_1 and S_2) and foliation of inclusion (S_i).

Shear sense indicators

Gneiss from the Higher Himalayan Crystalline (Fig. 22) shows C' type of shear band. It indicates the top-to-south sense of shear. In the quartz-dominant rocks like gneiss and quartzite, the shear band is oblique to the direction of shear, and foliation is parallel to sense of shear. The C' type shear band was developed during the MCT propagation.

Gneiss of the Higher Himalayan Crystalline shows mica fish on central part (Fig. 23). The gneisses (sample D8L1) from the Higher Himalayan Crystalline have mica fish in central and upper right portion (Fig. 24).

DEFORMATION HISTORY

Various fabrics, growth Sequence of minerals, lineation, folds, joints and faults in the rocks of the Lesser Himalayan Sequence and the Higher Himalayan Crystalline indicate the poly-phase deformation that the rocks suffered before and during Himalayan orogeny. The Lesser Himalayan Sequence has suffered five deformational events (DL_1-DL_2, D_3-D_5) whereas the Higher Himalayan Crystalline has suffered four deformational events (DH_1, D_3-D_5).

Among these, early deformational phases (DL_1-DL_2) are pre-Himalayan and the later three deformations (D_3-D_5) are Himalayan. The bedding parallel foliation (S_0=S_1) and foliation of inclusion (S_i) in garnet were formed during first deformational phase (DL_1). Though N-S trending isoclinal folds has not been observed in the area as they were observed in Tansen-Pokhara section (Paudel and Arita, 2000) but presence of dome and basin in study area and Ampipal area which is further south of study area (Dhital, 1995) indicate second deformational event (DL_2). The absence of dome and basin in the Higher Himalayan Crystalline, but presence of WNW-ESE trending folds further supports that already folded Lesser Himalayan Sequence during DL_2 has been contorted to dome and basin during D_4 deformational phase. The NNE-SSW mineral lineation, foliation (S_2) around Garnet rim, and C' type of shear band are the result of third deformation phases D_3in the Lesser Himalayan Sequence. The WNW-ESE trending folds observed on the Lesser Himalayan Sequence are the result of fourth deformational event D_4. The brittle fractures, joints and faults are the results of fifth deformational event D_5.

Higher Himalayan Crystalline suffered four deformational events (DH_1, D_3-D_5). The first deformational phase (DH_1) is pre-Himalayan,whereas later three deformational phases (D_3, D_4, D_5) are Himalayan. The bedding parallel foliations (S_0=S_1) were formed during first deformation phase (DH_1). C' type of shear band, Mineral lineation and drag folds were developed during D_3 deformational phase (syn-MCT deformation). The folds observed in the Higher Himalayan Crystalline are the result of third deformational phase (D_4) of the Higher Himalayan Crystalline (which is fourth Deformational phase of the Lesser Himalayan Sequence). Brittle fractures, joints and faults were formed during fourth deformation phase of the Higher Himalayan Crystalline D_5 (fifth deformation phase of the Lesser Himalayan Sequence).

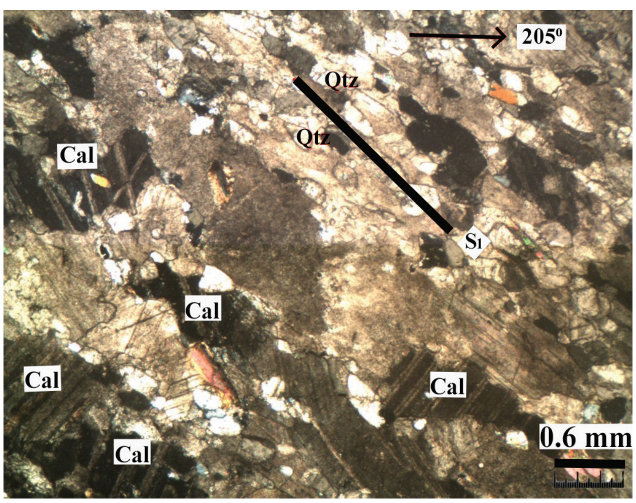

Fig. 19: Subhedral quartz grain, allied within foliation S1 preferred orientation, defines foliation at Baluwa village.

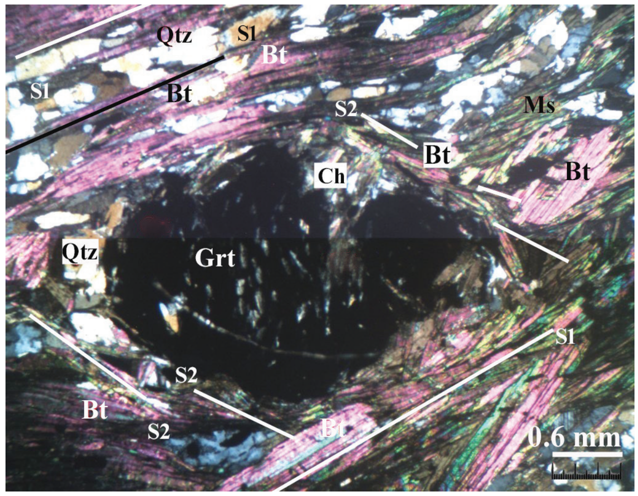

Fig. 20: Photomicrograph of garnetiferous gneiss of the Lesser Himalayan Sequence with mica showing two sets of foliation.

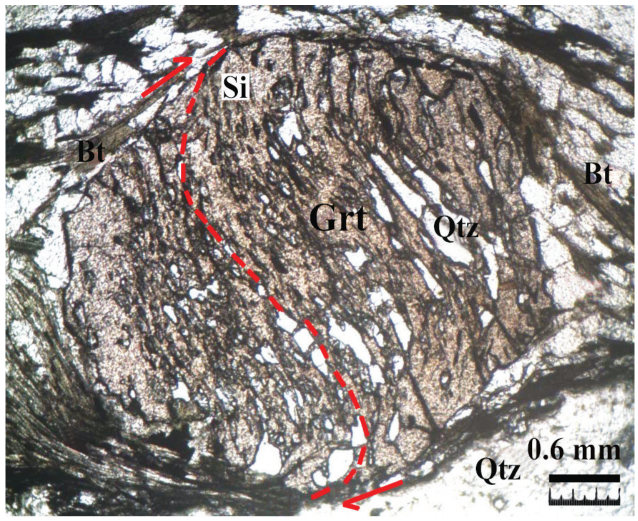

Fig. 21: Garnet porphyroblast (under PPL) with sigmoidal inclusion trail indicating shear sense and syntectonic origin from gneiss at Chhichha Khola.

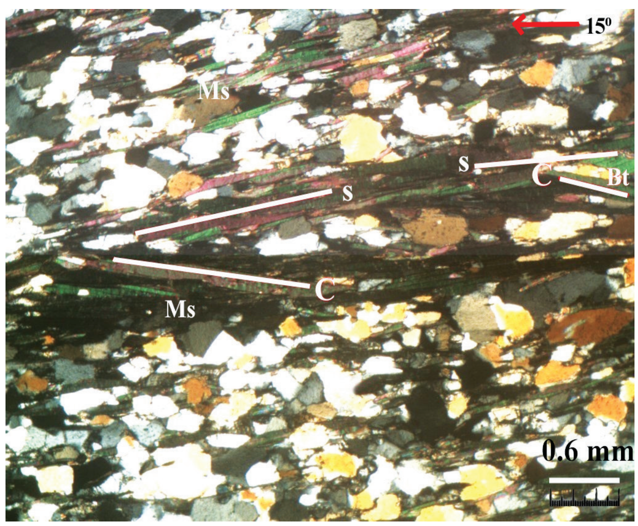

Fig. 22: Photomicrograph of C'-type shear band cleavage in gneiss from the Higher Himalayan Crystalline.

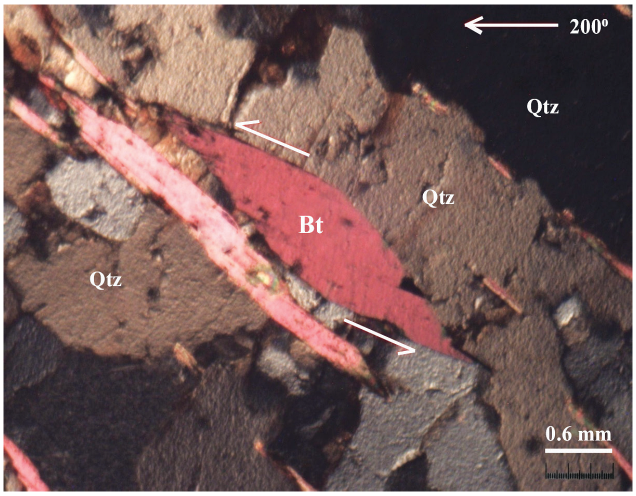

Fig. 23: Photomicrograph of mica fish showing top-to-south sense of shear in gneiss of the Higher Himalayan Crystalline near Bhachek.

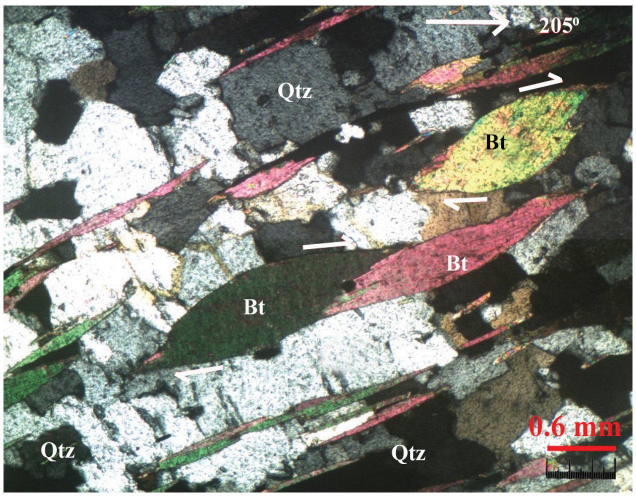

Fig. 24: Photomicrograph of mica fish showing top towards south sense of shear in gneiss from Bhachchek area.

DISCUSSION

In the study area, the Lesser Himalayan Sequence is metamorphosed to garnet grade (amphibolite facies). It is highly deformed as rocks show the evidence of ductile deformation related to the MCT propagation. The lithology of the area is quite different from the Lesser Himalayan Sequence in the southern part (Stöcklin and Bhattarai, 1977; Paudyal, 2014) due to relatively higher grade of metamorphism and an intense ductile deformation on approaching the MCT. The primary structures like mud cracks, ripple marks, cross bedding, stromatolites have rarely been preserved and marker horizons are also rare; as a result, the area is difficult to correlate with the Nawakot Complex, Central Nepal (Stöcklin and Bhattarai, 1977) and the Kaligandaki Supergroup, West-central Nepal (Sakai, 1985). The area is comparable with the Midland Group of rocks (Le Fort, 1975; Pêcher 1977; Colchen et al. 1986), the Nawakot Complex, Central Nepal (Stöcklin and Bhattarai, 1977) and the Kaligandaki Supergroup, West-central Nepal (Sakai, 1985).

There is no sharp lithological as well as structural discontinuity that separates the Higher Himalayan Crystalline with the Lesser Himalayan Sequence so, the MCT can't be placed with the appearance of first gneiss succession as placed by Heim and Gansser (1939), Gansser (1964), and Valdiya (1980). Arita et al. (1982) and Arita (1983) have described the MCT zone as deformational zone with no distinct lithological break. They said that it exists between garnet isograd at the base and kyanite isograd on the top. The thrust at the base is designated as the MCT I, and the upper limiting boundary of the MCT zone is named as the MCT II. The metamorphic isograd variation from the garnet grade in footwall to the kyanite grade in hanging wall is the main criteria in identifying the MCT. The appearance of first kyanite mineral on outcrop was used to map the MCT. In study area, therefore, the MCT refers to MCT II of Arita et al. (1982) and Arita (1983).

In the Himalayas, several dome and basin structures have been reported, such as the Siang dome (Acharyya and Sah, 2008) in eastern Himalaya, Tista Dome (Bose et al., 2014) in Sikkim Himalayas. Dome and basin structures have also been reported in Nepal Himalaya, the Kusma area, west Nepal (Paudel and Dhital, 1996) and Baitadi area, far-west Nepal (Dhital, 2015). Dhital (1995) also mentioned that the Kuncha Formation of Gorkha-Aampipal area is warped into doubly plunging to dome and basin like *en echelon* type of non-cylindrical fold. Dhital et al. (1998) reported number of NW-SE trending, doubly plunging, *en echelon* type of non-cylindrical folds in Kaski-Parbat area. Paudel and Arita (1998) observed rocks in the Pokhara and Syanja zone are strictly folded giving rise to number of WNW-ENE trending non cylindrical, double plunging, dome and basin like *en echelon* type of folds.

The non-cylindrical nature of fold (dome and basin) in an area indicates the poly-phase deformation (Davis and Reynolds, 1996). The Baluwa dome and the Pokhartar basin, *en echelon* type of non-cylindrical folds, is the result from poly-phase deformation (DL_2 and D_4). The already formed N-S trending folds (DL_2) were folded along orogen parallel direction during the fourth deformation phase (D_4). The superimposed folding was presumably related to the movement of thrust sheet.

The microstructures, shear sense indicators, and deformation indicate the top-to-south sense of shear (Figs. 22-24). The quartz microstructures indicate quartz grains have undergone intense deformation during the MCT propagation and the dynamic recrystallization direction in the Lesser Himalayan Sequence and the Higher Himalayan Crystalline is top-to-south as indicated by the evidences of dynamic recrystallization (Figs. 13-20). Sigmoidal poikiloblastic inclusion trails within porphyroblast indicate syn-tectonic origin of porphyroblasts. The shear sense indicators, mica fish and C' type of shear band indicate top-to-south sense of shear developed during syn-MCT deformation.

Acharya (2008) carried out deformation analysis along the Mahabharat Thrust (MT) and concluded the MT is the southward extension of the MCT as the nature of deformation is identical, although the grade of metamorphism is different along the MT and the MCT. Microtextural and structural analysis in the Malekhu area, central Nepal revealed dynamic recrystallization of the footwall and static recrystallization of the hanging wall rocks of the MT (Chamlagain and Hayashi, 2007); however, the dynamic recrystallization was found prominent in the rocks of both footwall and hanging wall of the MCT in the study area.

The Lesser Himalayan Sequence has experienced poly-phase deformation history (DL_1-DL_2, D_3-D_5). The early two deformational phases (DL_1-DL_2) are pre-Himalayan, and the later three (D_3-D_5) are Himalayan. The foliation of inclusion (S_i), bedding-parallel foliation (S_1=S_0) are the structures related to the deformation phase (DL_1). The N-S trend folds whose superimposed folding resulted dome and basin are related to the deformational phase (DL_2). Pre-Himalayan deformation phases (DL_1-DL_2) of the area are in accordance with Tansen-Pokhara section (Paudel and Arita, 2000) as similar structures like foliation preserved as inclusion trails in garnet (S_i) and bedding parallel foliation (S_1=S_0) are related to deformational phase D_1 and NNE-SSW trending, west verging isoclinal folds and drag folds are related to deformational phase (D_2).

In the Lesser Himalayan Sequence during Himalayan deformation, NNE-SSW trending mineral and stretching lineations, shear sense indicators and foliation (S_2) around garnet's rim were developed during third deformational phase (D_3) or syn-MCT deformation. During the deformation phase (D_4), which is post-MCT deformation, WNW-ESE trending folds were formed and already formed N-S trending folds were folded to dome and basin. During deformation phase (D_5), brittle faults, fractures and joints were developed.The deformation phases (D_3-D_5) in the study area are in accordance with Tansen-Pokhara section (Paudel and Arita, 2000) as similar structures like S-C fabric, mineral and stretching lineations were developed during the deformational phase (D_3) which is syn-MCT deformation. WNW-ESE large scale open folds and minor folds, NE or SW dipping crenulation cleavage were developed during the deformational phase D_4 and small-scale brittle faults are the structures related to the deformational phase D_5, which are post-MCT deformation.

The Higher Himalayan Crystalline demonstrates four poly-phase deformations (DH_1, D_3–D_5). The early deformational phase in Higher Himalayan Crystalline (DH_1) is pre-Himalayan and the later three (D_3-D_5) are Himalayan. The bedding-parallel foliations (S_1=S_0) are the result of pre-Himalayan deformation (DH_1). This deformational phase of the Higher Himalayan Crystalline is entirely different from the deformational phase D_1 of Tansen-Pokhara section (Paudel and Arita, 2000) as the Higher Himalayan Crystalline and the Lesser Himalayan sequence have different phases and chronology of the deformations.

During the Himalayan deformational phases in the Higher Himalayan Crystalline NNE-SSW trending mineral lineation were developed by second deformational phase (D_3) or syn-MCT deformation of Higher Himalayan Crystalline (the third deformational phase of the Lesser Himalayan Sequence). The WNW-ESE folds developed in the Higher Himalayan Crystalline is the result of the deformational Phase D_4 (post-MCT deformation)and during the deformational phase D_5, brittle joints and faults were developed.

CONCLUSIONS

The Barpak-Bhachchek area consists rocks of both the Lesser Himalayan Sequence and the Higher Himalayan Crystalline separated by the MCT. The Lesser Himalayan Sequence consists of five lithological units, and they are; 'Calcareous Metasandstone and Marble unit', 'Psammitic Schist unit', 'Calcareous Quartzite and Psammitic Schist unit', 'Calcareous Quartzite and Marble unit' and 'Graphitic Schist, Marble, Gneiss and Quartzite unit.' from bottom to top respectively. These rocks show medium-to high-grade metamorphic condition from bottom to top. The Higher Himalayan Crystalline in the study area consists of paragneisses and quartzites (upper amphibolite to lower granulite facies rocks).

The area has been affected by poly-phase deformations. The Lesser Himalayan Sequence has suffered five deformational events (DL_1-DL_2, D_3-D_5) whereas the Higher Himalayan Crystalline has suffered four deformational events (DH_1, D_3-D_4). Among these, early deformational phases (DL_1-DL_2)

of the Lesser Himalayan Sequence and DH_1 of the Higher Himalayan Crystalline are pre-Himalayan, and later three deformation phases (D_3-D_5) of both the Higher Himalayan Crystalline and the Lesser Himalayan Sequence are Himalayan. The Lesser Himalayan Sequence of the study area is folded into dome and basin, en echelon type of non-cylindrical folds (DL_2 and D_4). The meso-scale structures and microscopic shear sense (C' and mica fish) indicators show dominant top-to-south sense of shear. The mineral and stretching lineations show the NNE-SSW trend with gentle plunge showing the Higher Himalayan Crystalline movement's direction over the Lesser Himalayan Sequence along the MCT.

The quartz grain microstructures indicate dominant dynamic recrystallization in the hanging wall and footwall of the MCT indicating ductile shearing along the MCT. Pressure shadow, rotated quartz and garnet porphyroblasts indicate deformation condition developed during syn-MCT deformation. The grain boundary migration direction during dynamic recrystallization is top-to-south which is consistent with top-to-south sense of shear related to the movement of the MCT.

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AUTHOR'S CONTRIBUTIONS

S. Poudel, L.M. Oli and L.P. Paudel conceived and planned the work. S. Poudel and L.M. Oli carried out the field work, geological mapping and collected required data. S. Poudel and L.M. Oli prepared thin sections under the supervision of L.P. Paudel. S. Poudel and L.P. Paudel contributed to the interpretation and analysis of the results. S. Poudel took the lead in writing the manuscript. L.P. Paudel provided critical feedback and helped in shaping the manuscript. All authors finalized and approved the final manuscript.

ABBREVIATION

The abbreviations of minerals used in Photomicrographs is adopted from Whitney and Evans (2010)

Bt.: Biotite
Cal.: Calcite
Ch.: Chlorite
Grt.: Garnet
Ms.: Muscovite
Qtz.: Quartz

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