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Quartz grain microstructures and microscopic shear sense indicators in the outer Lesser Himalaya, Barahakshetra-Tribeni-Raighat area of Arun Valley, eastern Nepal

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ABSTRACT

The outer Lesser Himalaya in eastern Nepal has gone through intense ductile shearing and recrystallization due to the emplacement of Higher Himalayan thrust sheet. It has resulted in the formation of various microstructures in the footwall rocks of the Lesser Himalaya. Present study focuses on the study of the quartz grain microstructures and shear sense indicators in the Lesser Himalayan metasedimentary rocks to interpret the deformation characteristics of the area. Thin sections were prepared from oriented rock samples collected from various formations and were studied under the petrographic microscope. The occurrence and diversity of quartz grain microstructures and shear sense indicators in the area manifests uneven distribution of stress regime and temperature conditions. Nevertheless, it suggests a progressive transition from the southern to the northern part. The vicinity of the Dharapani Thrust represents mechanical deformation of higher strain and lower temperature conditions. The Chimra Thrust Sheet exhibits mild- to medium deformation at the basal section while high-temperature high-strain deformation at the upper section in the vicinity of the MCT.

Keywords: Ductile, metasedimentary, deformation, progressive

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INTRODUCTION

Geological structures of any scale are the imprints of the events the rock or the area had undergone through geological time during its evolution to the present state. Analysis of geological structures at different scales helps to interpret the deformation history the area had undergone. Nepal Himalaya occupies the central arc of the youngest thrust-and-fold belt that has undergone a series of deformation and metamorphic events through time due to the application of tectonic shear forces aroused from the collision of Indian continental mass and the Eurasian tectonic plate (Gansser, 1964; Le Fort, 1975). The Lesser Himalaya in eastern Nepal consists of Pre-Cambrian metasedimentary rocks unconformably overlain by Permian to Miocene sedimentary rocks (Bashyal, 1980; Dhital, 1992; Bhandari et al., 2018; Baral et al., 2022). The Lesser Himalaya in eastern Nepal is limited within the inner window structures exposed as domal anticline in the deep gorges of the Arun, Tamor, and Dudhkoshi River valleys and outer metasedimentary front forming the belt of Mahabharat Hills (Bordet, 1961; Akiba et al., 1973; Maruo et al., 1979; Andrews, 1985; Schelling and Arita, 1991; Schelling, 1992; Meir and Hiltner, 1993; Dhital, 2015; Adhikari et al., 2021). The outer Lesser Himalaya of the Arun River valley section is exposed along the Barahakshetra-Tribeni-Raighat area. Precambrian metasedimentary and Permo-carboniferous to Miocene Gondwana and post-Gondwana sediments comprise the frontal belt of the Lesser Himalaya in this section (Dhital, 2015; Rai et al., 2016; Bhandari et al., 2018; Baral et al., 2022). Due to thrusting, nappe emplacement, and folding, the Lesser Himalayan rocks are intensely deformed and recrystallized resulting in various kinds of microstructures. Rai (2012) plotted the ellipticity and Brethorton Shape Indices of quartz and feldspar grains against the ellipse angle using ImageJ software. He analyzed simple shear patterns in the case of Higher Himalaya and complex shearing in Lesser Himalaya and interpreted it to be due to multiple phases of deformation. A systematic study of microstructure covering the entire section of the outer Lesser Himalaya in the area is still lacking. The aim of the present study is to investigate the microstructures in the Lesser Himalayan rocks in the outer Lesser Himalaya in the Barahakshetra-Tribeni-Raighat area (Fig. 1). An attempt has been made to establish the deformation history of the area based on microstructural analysis.

GEOLOGICAL SETTING OF THE STUDY AREA

Geological surveys at a 1:25,000 scale have been conducted in the Barahakshetra-Tribeni-Raighat area, with resulting data used to prepare a preliminary geological map and cross section (Figs. 2 and 3). The area can be subdivided into three tectonic units, namely the Chimra Thrust Sheet, the Dharapani Thrust Sheet and the Tribeni Paraautochthon, divided by two regional thrusts, the Cimra Thrust and the Dharapani Thrust, from north to south respectively (Fig. 2). The former two tectonic units are comprised of the metasedimentary rock sequences of the Precambrian age. The Tribeni Parautochthon comprises the Pre-Cambrian dolomite unconformably overlain by Permo-

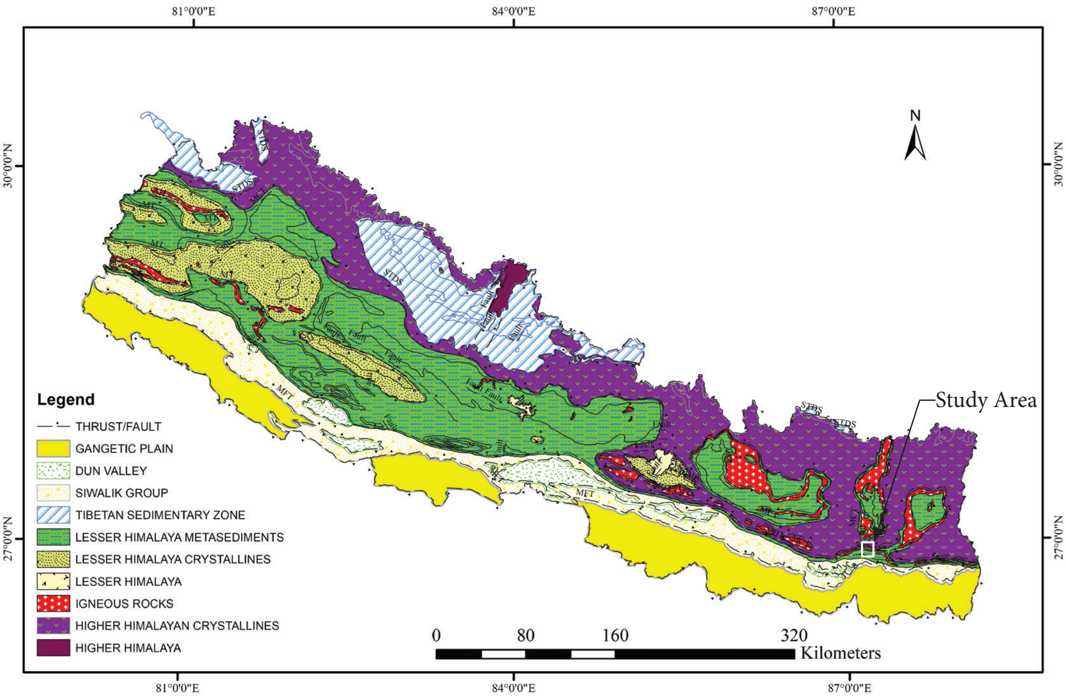

Fig. 1: Location map of the study area (redrawn and modified after Dhital, 2015).

Carboniferous to Miocene Gondwana and post-Gondwana sedimentary rocks.

The rocks of the Chimra Thrust Sheet are further subdivided into the Mulghat Formation, the Okhre Formation, the Jyamire Gneiss, and the Belhara Formation from bottom to top, respectively. The Mulghat Formation consists of grey to dark grey carbonaceous phyllite and schist with abundant quartz veins and lenses, grey quartzite, and dolomite. The Okhre Formation is composed of grey to green phyllite and schist, grey, green meta-sandstone, and quartzites. The Jyamire Gneiss is quartzo-feldspathic augen gneiss. The Belhara Formation is comprised of grey to greenish-grey schist alternating with grey to creamy quartzite, garnet-mica schist, actinolite schist, and limestone.

The rocks of the Dharapani Thrust Sheet are described under the Bhendetar Group and are subdivided into the Chiuribas Formation, the Sangure Quartzite, and the Karkichhap Formation. The Chiuribas Formation comprises grey, green, and purple phyllite alternating with grey-green meta-sandstone and greenish-to-greyish quartzite. The grey-to-white monotonous quartzite band named the Simle Quartzite is the member situated at the upper part of this formation. The Sangure Quartzite consists of greyish-white, pink, purple, and greenish-grey quartzite beds. The Karkichhap Formation comprises grey phyllite and quartzite.

The rocks of the Tribeni Paraautochthon are composed of the Lukuwa Dolomite and Barahakshetra Group. The Lukuwa Dolomite consists of light grey dolomite profound with stromatolites of Pre-Cambrian ages. The Barahakshetra Group is further subdivided into the Kokaha Diamictite and Baraha Volcanics, the Sapt Koshi Formation, and the Tamrang Formation. The Kokaha Diamictite is composed of grey diamictite, pebbly conglomerate. Brown-grey tuff and agglomerate represent the Baraha Volcanics. The Sapt Koshi Formation is composed of carbonaceous quartzite, grey shale, sandstone, and coal lenses. The Tamrang Formation comprises bluish, brownish to greyish sandstone beds.

SAMPLING, THIN-SECTION PREPARATION AND MICROSCOPIC STUDY

Geological surveys were conducted across various routes within the study area. About 30 oriented samples were collected predominantly consisting of pelitic and psammatic schist, phyllites, meta-sandstone, quartzites, and gneiss representing different formations and structural positions (Fig. 3).

About 30 thin sections were prepared at the laboratory of the Central Department of Geology, Tribhuvan University. Thin sections were cut perpendicular to the dominant foliation, and parallel to mineral/stretching lineations. The thin sections were examined focusing on the interpretation of the quartz grain microstructures and shear sense indicators in the rocks. The interpretation of photomicrographs was facilitated by utilizing the Motic Plus Software.

RESULTS

Quartz grain microstructures

Quart grain microstructures were analyzed in 8 thin sections representing different formations and lithologies (Figs. 2, 3). It was observed that the characteristics of quartz grain microstructures systematically change from south to north going close to the MCT.

Sample 41 (Tamrang Formation): The sandstone sample taken from the upper section of the Tamrang Formation of the Tribeni Paraautochthon near Sankama village exhibits

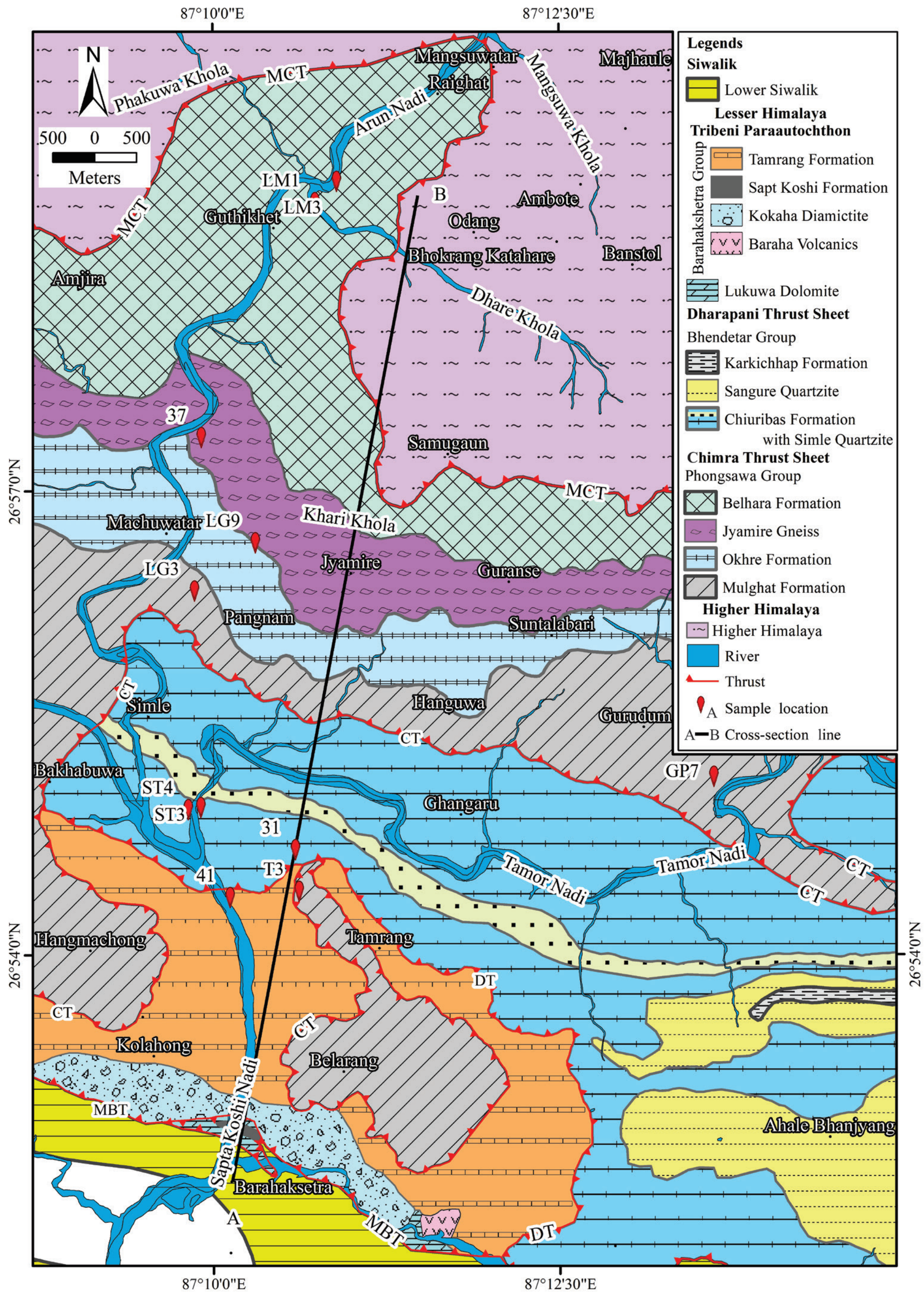

Fig. 2: Geological map of the Barahakshetra-Tribeni-Raighat area of eastern Nepal Lesser Himalaya showing the approximate positions of the samples analyzed. MCT: Main Central Thrust, CT: Chimra Thrust, DT: Dharapani Thrust, MBT: Main Boundary Thrust.

preferred alignment along with the mica and chlorites (Fig. 4a). They are flattened and elliptical in form, with their longer axes aligned parallel to the preferred orientation of the mica minerals.

Sample T3 (Mulghat Formation): The rocks of the Mulghat Formation of the Chimra Thrust Sheet have its extension in the southward direction and is present on top of the Tribeni Paraautochthon and the Dharapani Thrust Sheet at the Belhara region forming a klippe structure. Grey schist from the upper reaches of the Tankera Khola, contains flattened ellipsoidal quartz grains within a finer sericitic matrix, showing a mylonitic texture (Fig. 4b). The elongated axis of these ellipsoidal grains aligns in the NW-SE direction. These quartz grains also exhibit undulose extinction. Smaller quartz grains on the edges of the larger ones suggest a process of recovery or recrystallization.

Sample 31 (Chiuribas Formation): Dark grey phyllite collected in the upper area of Tankera Khola near Tankera village, contains mantled quartz grains dispersed among finer

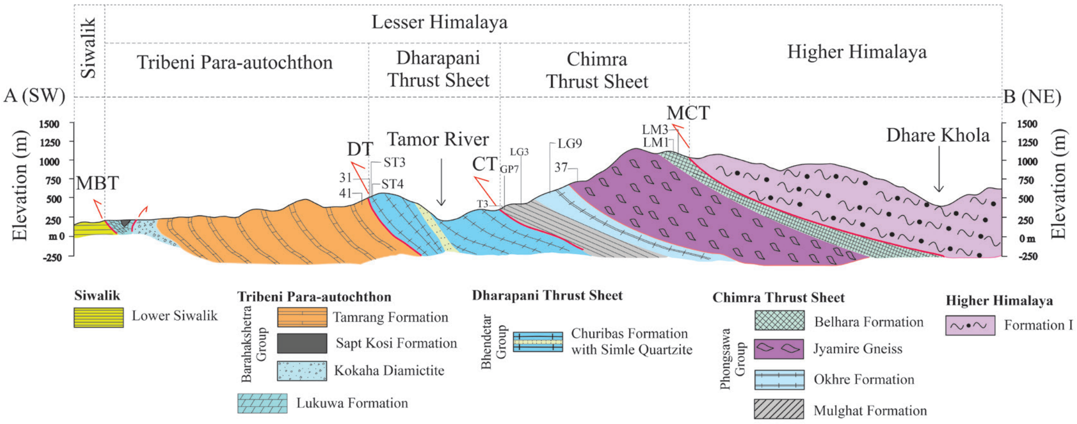

Fig. 3: Geological cross-section of the present study area along A-B in Figure 2 showing the approximate positions of the samples analyzed. MCT: Main Central Thrust, CT: Chimra Thrust, DT: Dharapani Thrust, MBT: Main Boundary Thrust.

platy minerals (Fig. 4c). The quartz grains exhibit pronounced deformation and exhibit 2 sets of fractures oriented perpendicular to each other suggest plastic shear or cataclasis activities in the vicinity.

Sample ST3 and ST4 (Chiuribas Formation): Greenish grey meta-sandstone taken from the left bank of the Tamor river (ST3) shows deformation lamellae and undulose extinction within the quartz grains (Fig. 4d). Grey, coarse grained meta-sandstone obtained from the right bank of the Tamor River near Tribeni (ST4) bears quartz grains with sub grains rotation. Some of the grains are elongated forming ribbon like fabric (Fig. 4e).

Sample GP7 (Mulghat Formation): The schist sample with quartz porphyroclasts of the Mulghat Formation was taken from the Akhuwatar-Mulghat road in the Beltar village. The sample comprises the polycrystalline quartz grains developed by sub grain rotation recrystallization (Fig. 4f). The old grain shows patchy undulose extinction with new grains surrounding it representing the recrystallization.

Sample LG9 (Jyamire Gneiss): The gneiss sample dominated by platy minerals was taken from the upper reaches of the Khari Khola. The sample represents the boundary region between the Okhre Formation and the Jyamire Gneiss. The quartz grains are flattened and form elongated ribbon like structure defining foliation (Fig. 5a). Further, the pinning microstructure, the leftover grains and the dragging microstructure are evident in the photograph. The muscovite mineral acts as pin in the formation of pinning structure and barrier for dragging structures during the process of formation of these microstructures. The muscovite mineral exhibit preferred orientation in two different directions forming acute angle to each other.

Sample LM3 (Belhara Formation): Dark grey schist collected from the left bank of the Arun River near Guthikhet village exhibits irregular undulating boundaries of quartz grains giving the loboid or amoeboid shape (Fig. 5b). The deformation twin observed in calcite mineral also adds up the crystallization mechanism (Fig. 5c). In contrary, a section of the same sample consists of polycrystalline quartz crystals representing static recrystallization (Fig. 5d). The triple junction formed by the granoblastic quartz grains forming triple junction is evident for the process.

Shear sense indicators

The microstructures representing the sense of shear acting on the region were analyzed in 5 thin sections. The asymmetric porphyroclast, strain shadow, σ-shear shadows, S-C fabric, and fish structures were observed which represented the direction of shearing in the region.

Sample GP7 (Mulghat Formation): Dark grey schist-bearing quartz and feldspar porphyroclast bears the asymmetrical mantled porphyroclast of quartz and feldspars in thin sections (Fig. 5e). The non-crystallized quartz grain has occupied the core while recrystallized quartz grains are at the rim forming wings. The asymmetric shape indicates the top to the south directed shear acted upon it.

Sample LG3 (Mulghat Formation): The dark grey schist collected from the Akhuwatar – Jyamire road section near Pannam village consists strain shadow structure with opaque minerals at the core and recrystallized quartz grains at the rim (Fig. 5f). The stair stepping shape of the strain shadow indicates the top to south sense of shear.

Sample LG9 (Jyamire Gneiss): The gneiss sample extracted near the Jyamire Village exhibits the mica fish in the central part of the thin section indicating top to south sense of shear (Fig. 6a). The similar sample bears the C' shear band which is oblique to the older foliation S (Fig. 6b). It is generated late during shear zone activity after a strong mineral orientation has already been developed. It indicates the top to south sense of shear and was developed during the MCT propagation.

Sample 37 (Jyamire Gneiss): The ortho-augen gneiss collected near the Piliyatar village has quartz and plagioclase feldspar porphyroclasts with σ-shear shadow around these porphyroblast indicating the top to the south sense of shear (Fig. 6c). Mica mineral exhibits 3 foliation directions Se, S1 and S2. Se is the predominant foliation plane, S1 and S2 are the foliations developed around the porphyroblasts as a result of shear. The quartz grains are elongated or exaggerated forming ribbon shapes oriented in N-S direction. The bulging microstructures can be observed within these quartz grains indicating dynamic recrystallization.

Sample LM1 (Belhara Formation): The grey garnet schist of the Belhara Formation collected from the right bank of Dhare Khola near Guthikhet village exhibits the mica fish

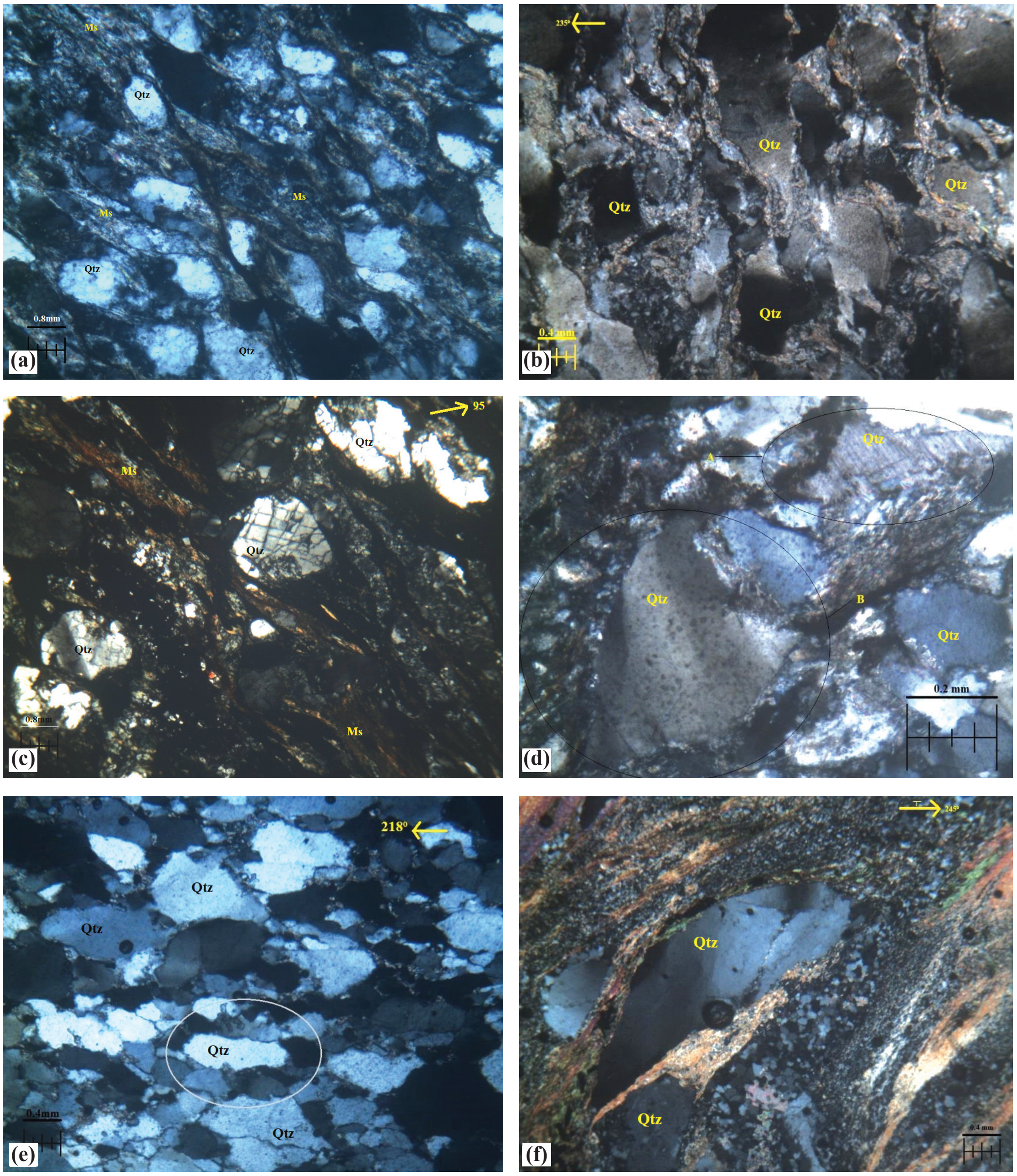

Fig. 4: (a) Ellipsoidal quartz grains mantled in the platy mineral grains exhibiting foliation in the sandstone beds of the Tamrang Formation, (b) mylonitic texture with flattened and ellipsoidal quartz grains with sweeping undulose extinction in dark grey schist of the Mulghat Formation, (c) quartz cataclasite with fractures and strong undulatory extinction suspended between the finer sericitic matrix in the dark grey phyllite of the Chiuribas Formation, (d) A- deformation lamellae and B- wavy undulose extinction in quartz grains in metasandstone of the Chiuribas Formation, (e) elongated quartz showing ribbon fabric in the grey metasandstone of the Chiuribas Formation, (f) polycrystalline quartz grains developed by subgrain rotation recrystallization around the old fabric in the porphyroclast bearing dark grey schist of Mulghat Formation.

of muscovite (Fig. 6d). The mica fish has its shear direction giving top to the south sense of shear.

DISCUSSION

The presence and variation of quartz grain microstructures and shear sense indicators in the area represent uneven distribution of stress regime and temperature conditions. However, it presumes the increasing deformation condition from south to north.

The samples from the southernmost part near the MBT, which is the sandstone from the Tamrang Formation, displaying flattened ellipsoidal quartz grains, signify prominent deformation. The fractured quartz grains enveloped in the phyllite of the Chiuribas Formation indicate new mineral growth or recrystallization around their edges. The two sets of fractures in it infer the biaxial stress regime. Characteristics such as deformation lamellae, undulose extinction, and ribbon quartz suggest plastic deformation. This type of deformation

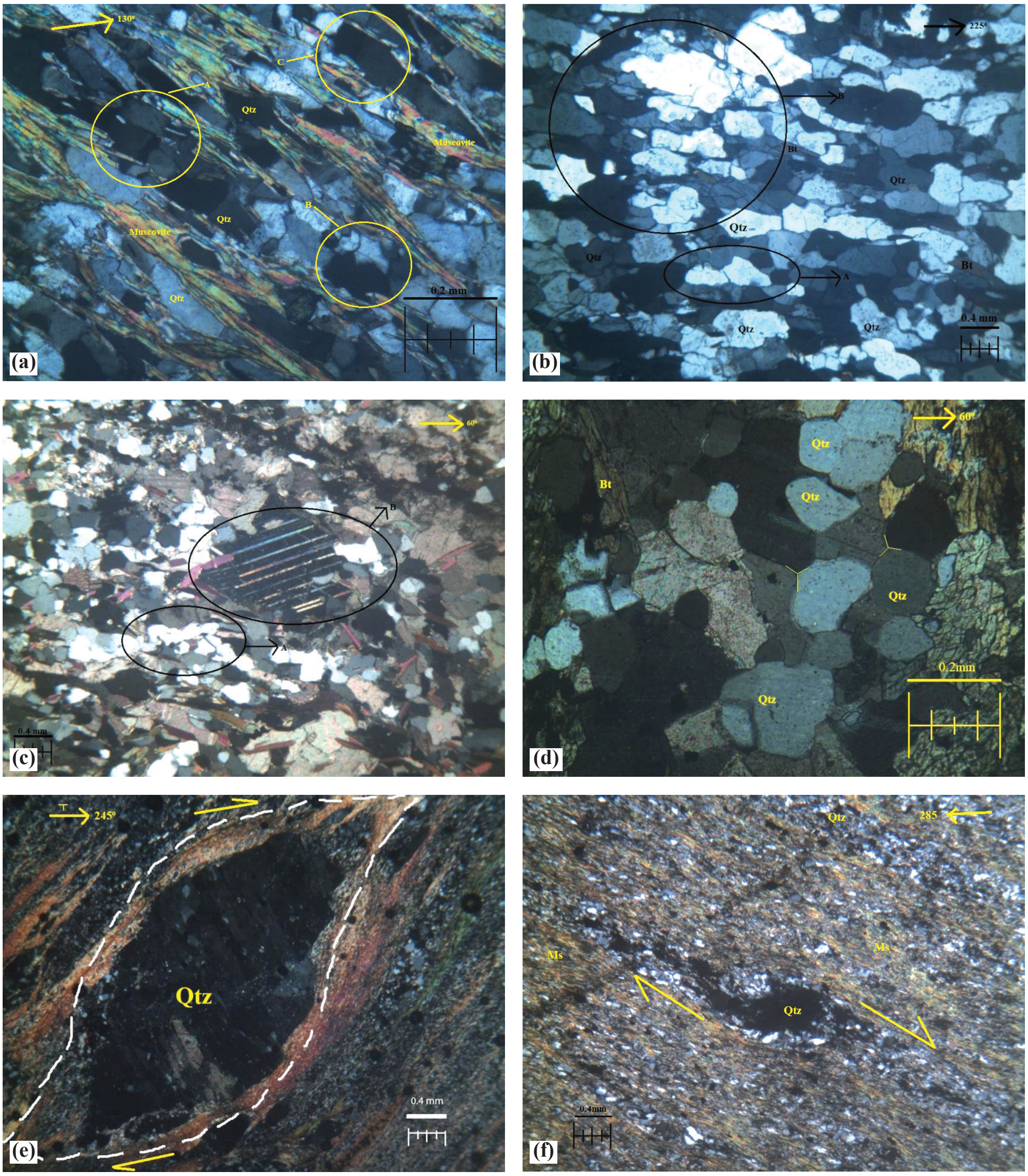

Fig. 5: (a) A-pinning microstructure, B-left over grains, and C-dragging microstructure in the gneiss of the Jyamire Gneiss, (b) A-suture contact and amoeboid shape and B-window microstructure of quartz grains in the micaceous schist of the Belhara Formation, (c) A-irregular grain boundaries in quartz grains and B- deformation twins in calcite minerals in the grey schist of the Belhara Formation, (d) polygonal fabric of the quartz grain showing triple junction in the dark grey schist of the Belhara Formation, (e) asymmetric quartz porphyroclast in the dark grey schist of the Mulghat Formation showing top to the south sense of shear, (f) strain shadow in the dark grey psammatic schist of the Mulghat Formation.

arises from shearing or localized high-strain conditions at lower temperatures (Passchier and Trouw, 2005). Given that these microstructures are confined to the periphery of the regional thrust, the Dharapani Thrust, it can be inferred that the thrust has induced a deformation regime characterized by high stress and low temperatures in its proximity.

Moving slightly to the north, the schist found in the lower section of the Mulghat Formation displays signs such as polycrystalline quartz grains, subgrain rotation, irregular undulose extinction, and recrystallization. These features are indicative of the initiation of ductile deformation under conditions of elevated temperatures and stress (Passchier and Trouw, 2005). The deformation occurs at the region of crustal thickening accompanied by thrusting, the Chimra Thrust. The shear sense indicators within the Mulghat Formation indicate the top to south sense of shearing at that region.

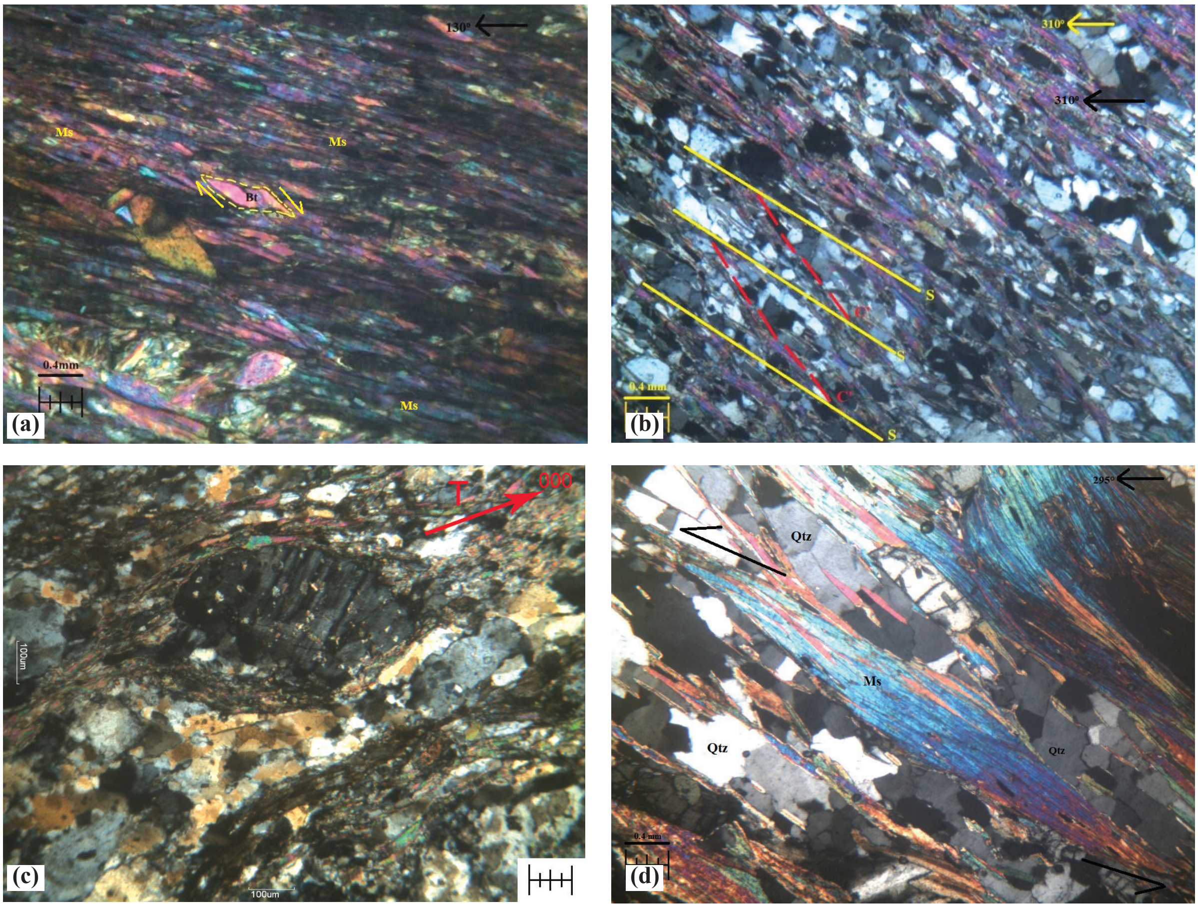

Fig. 6: (a) Biotite fish in the Jyamire Gneiss exhibiting top to the south sense of shear, (b) C' shear band oblique to the older foliation S in the schist of the Belhara Formation, (c) plagioclase feldspar porphyroclast mantled within mica flakes forming wing-like structure indicating top to the south sense of shear in the Jyamire Gneiss, (d) mica fish in the grey garnet schist of the Belhara Formation.

Moving further north, the gneiss within the Jyamire Gneiss formation exhibits elongated quartz ribbons, pinning features, dragging structures, and residual grains. These attributes arise from mineral migration in the midst of vigorous deformation, occurring in regions where tectonic forces are concentrated (Passchier and Trouw, 2005). The presence of bulging microstructures suggests the occurrence of dynamic recrystallization. These conditions portray a higher level of deformation characterized by elevated temperatures and heightened strain. The obliquely oriented mica minerals and c-shear bands indicate their formation during the later stages of shear zone activity, resulting from localized strain accumulation (Passchier and Trouw, 2005). The presence of biotite mica fish and σ-shear shadows indicates a shear sense directed toward the south. Taken together, these microstructural features collectively indicate intense deformation typical of shear zones, likely situated in the lower extents of the MCT zone.

The prevalence and abundance of microstructures intensify in the upper segment of the Belhara Formation. The presence of lobate-shaped grain boundaries in quartz minerals, as well as pinning, dragging microstructures, residual grains, and window structures, serves as evidence for the dynamic recrystallization of quartz grains in the schist of this formation. These quartz grain microstructures, which signify dynamic recrystallization, form at higher temperatures ranging from 500ºC to 700ºC (Passchier and Trouw, 2005). Microstructures indicating shear sense, such as mica fish observed in thin sections of the Belhara Formation, point towards southward-directed shearing in the region. These pieces of evidence collectively suggest the presence of ductile shearing in this area. This southward-directed ductile shearing acts as a transitional zone between the metasedimentary Lesser Himalaya and the crystalline metamorphic Higher Himalaya, identified as the Main Central Thrust (MCT) in works by Heim and Gansser (1939), Macfarlane (1993), Schelling and Arita (1991), and Martin (2017).

An important characteristic of the MCT is the occurrence of inverted metamorphism, closely associated with the MCT zone (Le Fort, 1975; Arita, 1983). The Barahakshetra-Tribeni-Raighat area, comprising metasedimentary rocks of the outer Lesser Himalaya in the Arun Valley region, displays the inverted metamorphic sequence within the Belhara Formation of the Chimra Thrust sheet. The MCT marks the base of a broad-scale zone, ranging from 100 m to 10 km, characterized by substantial strain due to ductile deformation and coinciding with the base of inverted metamorphism (Searle et al., 2008; Yin et al., 2010; Gibson et al., 2016). These observations are exemplified in the upper part of the Chimra Thrust Sheet, representing the area designated as the MCT Zone. The polygonal fabric of the quartz crystals in the schist of Belhara Formation indicates static recrystallization probable to be formed post-MCT period.

CONCLUSIONS

The presence and varying characteristics of quartz grain microstructures and shear sense indicators highlight an irregular distribution of stress regimes and temperature conditions in the metasedimentary sequence of the Lesser Himalaya in the outskirts of the Arun Valley in the Barahakshetra-Tribeni-Raighat area. Nonetheless, this suggests a progression towards more intensified deformation conditions from the southern to the northern regions. In the southern region close to the Dharapani Thrust, plastic deformation results from localized high-strain shearing at lower temperatures. Moving northward from the Chimra Thrust Sheet's base, mild to medium deformation is evident with the onset of dynamic recrystallization and southward shearing. The Jyamire Gneiss exhibits concentrated tectonic forces creating intense deformations, likely due to MCT propagation. The Belhara Formation in the northernmost area signifies high-temperature, high-strain ductile deformation, acting as a transition zone between the Lesser Himalaya and the Higher Himalaya within the Main Central Thrust Zone.

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