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Review Article

REVIEW OF THE GEOLOGY OF THE ARUN-TAMOR REGION, EASTERN NEPAL: PRESENT UNDERSTANDINGS, CONTROVERSIES AND RESEARCH GAPS

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ABSTRACT

Systematic study of the eastern Nepal Himalaya was started after 1950 when Nepal opened up for foreigners. Thereafter, several geological studies have been carried out in the Arun-Tamor region of eastern Nepal Himalaya. The Tibetan-Tethys sedimentary sequence, the Higher Himalayan amphibolite to granulite facies metamorphic crystalline sequence, the Lesser Himalayan sedimentary and greenschist facies metasedimentary sequences, and the Siwalik foreland molassic sedimentary sequence are the four major tectonic units of this area. The individual nomenclature schemes of stratigraphic units, the correlational dispute, the positions and interpretations of regional geological structures are some examples that have created controversies regarding the lithostratigraphy and structural arrangements. The difference in age and genesis of the Main Central Thrust and its effects in the metamorphism of the eastern Nepal Himalaya are the exemplification of the contradiction in the interpretation of the tectonometamorphic history. There is a gap in research in the tectonics and episodic metamorphic evolution of the area owing to the bare approach in the microstructural and geochronological investigation. Future investigations should be focused on solving the above mentioned controversies and narrowing down the research gaps in tectonic and metamorphic evolution.

Keywords: Arun-Tamor, eastern Nepal, lithostratigraphy, structural arrangements, tectonometamorphic history

INTRODUCTION

The Nepal Himalaya occupies the central part of the Himalayan arc. The tectonic units of the Himalaya are well-established and named as the Siwalik (or Sub-Himalaya), the Lesser Himalaya, the Higher Himalaya, and the Tibetan-Tethys Himalaya, from south to north, respectively (Gansser, 1964; Frank & Fuchs, 1970; Upreti, 1999). These lithotectonic units are separated by east-west extending south propagated intracrustal thrusts. The Siwalik are bounded by the Main Frontal Thrust (MFT) in the south and the Main Boundary Thrust (MBT) in the north. The Lesser Himalaya is bounded by the Main Boundary Thrust (MBT) in the south and the Main Central Thrust (MCT) in the north. The Higher Himalaya lies between the MCT in the south and the South Tibetan Detachment System (STDS) in the north. The Tibetan-Tethys Himalaya is bounded between the STDS to the south and the Indus Tsangpo-Suture Zone (ITSZ) in the north. Although the Siwalik and the Lesser Himalayan units in central and western Nepal have tens of kilometers of the exposed section, and stratigraphy and tectonics are more inquired in central and western Nepal, they have very narrow and limited exposures in eastern Nepal, east of Dudh Koshi River (Gansser, 1964; Maruo *et al.*, 1979). The crystalline rocks of the Higher Himalaya are exposed over a broad area in east Nepal, while the Lesser Himalayan rocks are confined to a narrow stretch parallel to the MBT in the Mahabharat range (Ulak, 2016a). In the Midland regions, the Lesser Himalayan low-grade metasedimentary rocks are exposed along the river valleys of the Arun and Tamor Rivers Tectonic Windows (Schelling, 1992).

The history of geological study of east Nepal dates back to 1854 when Hooker visited eastern Nepal up to the Tamor Valley in 1854 (Hooker, 1854). Systematic study of the region, however, was started only after 1950 when Nepal opened up for foreigners. Since then, a number of geologists have carried out geological studies in the area. The studies are related to core geological studies as regional geological mapping, stratigraphic classification, structural analysis, petrography, metamorphic zonation and geochronology.

In this paper, a review of major geological works in the Arun-Tamor region, eastern Nepal (Fig. 1) has been presented. For this purpose, available research papers, reports and books related to geological mapping, stratigraphy, structural setting, metamorphic evolution and depositional environment were reviewed. The article begins with the present understanding of the geology of the area. Then an attempt has been made to point out the major geological controversies on stratigraphy, structural settings, metamorphism and depositional setups and research gaps in the area. Finally, the authors views as recommendations have been made for future research to sort out the controversies and full-fill the research gaps.

The article has followed the chronological order to discuss the findings of earlier researchers of the Arun–Tamor region. The investigations of whole time period has been categorized into three series, early investigations (period prior to 1950 A.D.) as the time bears very few investigations, investigation between 1950 and 1990 A.D. which was the period of descriptive investigations, and latest investigation (the period after 1990 A.D.) which includes diversification and remarkable growth in geological investigations and explained in the following sections.

Early investigations

Prior to 1950, research publications were dispersed and poorly linked to each other. Beginning with the early 1900s, Lóczy (1907) carried out geological work in the Sikkim area in India, published a geological cross-section extending from Kanchenjunga to Darjeeling, and presented a large scale recumbent nappe structure. Heron (1922) climbed up to 8200m of Mt. Everest and revealed that the top of the world is composed of weakly metamorphosed sedimentary rocks, i.e., dark green banded hornfels, calcareous and siliceous schist and white crystalline limestone. Wager (1934) studied the river system and related geomorphological landforms of the Arun River and concluded that the Himalayan region was the result of upheaval during younger geological ages.

Auden (1935) carried out geological studies in eastern Nepal in relation to the Nepal-Bihar Great Earthquake-1934. The author stated that a large part of eastern Nepal is occupied by the rock sequences of the Darjeeling Gneiss and the Daling series. The schist granulites, quartzites and calc. granulites of Udayapur Garhi and Dhankuta, gneiss and biotite granite of the Arun Valley, garnet-mica schists, quartzites, ortho- and para-gneisses, kyanite schists from Chainpur towards Milke has been classified as Darjeeling Gneiss. The slates, phyllites, quartzites from Dharan up to Dhankuta, chlorite grade phyllites at the Arun Valley and also of the Tamor River is expressed as the rock sequence of the Daling series of India. The author proposed a thrust between these contrasting metamorphic grades of the Darjeeling Gneiss and the possibly Krol belt of United Province of India (Auden, 1934). The author mentioned about the presence of the Gondwana coals near the junction of the Arun and Sun Koshi Rivers. The boundary between the Pre-Tertiary rocks (purple and dark pebbly quartzite, arkoses, dark phyllites, purple and white quartzites, pale schistose quartzite) and the Siwalik are marked by the MBT.

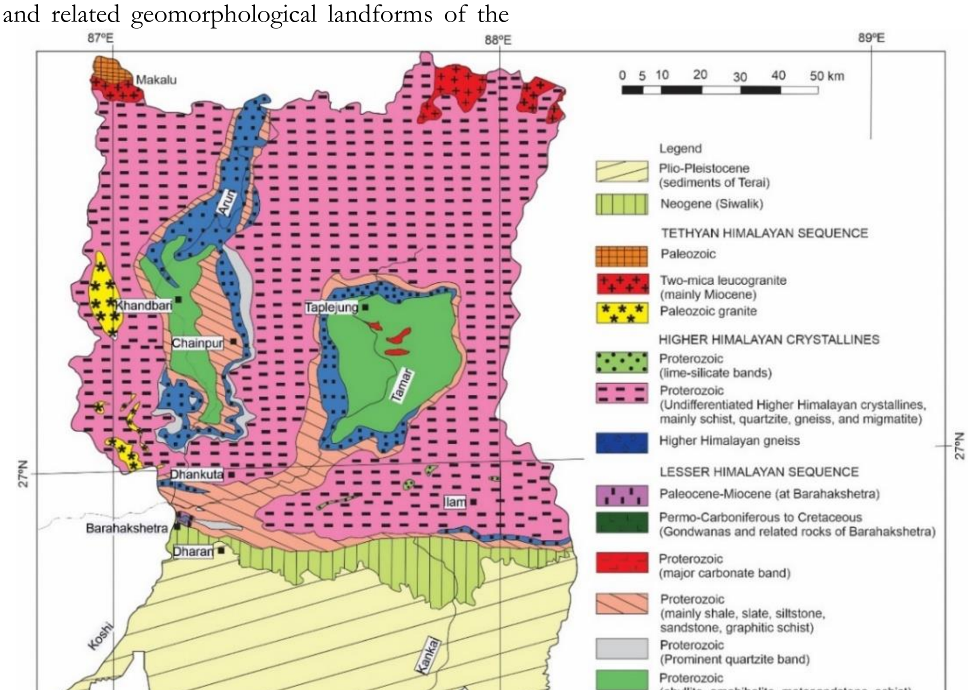

Figure 1. Geological map of the Arun-Tamor region (modified after Dhital, 2015)

Investigation between 1950 – 1990 A.D.

Lombard (1958), a member of the Swiss Everest expedition, studied the Tibetan-Tethys sediments and grouped these units as the Everest Formation. The gneisses and migmatites structurally underlie the Everest Formation. The author prepared a geological cross-section from the Everest region down to the Ganges Plain along the Dudh Kosi River and showed the concept of large-scale schuppen or thrust slices as part of the construction of the Himalaya.

Bordet (1961) carried out structural and petrographic studies along the Arun River upto the Mt. Makalu and established lithological units of the area (Table 1). Structurally, the author presented large-scale nappes, namely, the Lower Himalayan Migmatite, the Barun Gneisses and the Barun Migmatites, overlain by the Tibetan-Tethys sediment or the Everest Formation. The Everest Formation is divided into the Lapchi Beds, the Tso Chamo Beds, the Spiti Beds and the Kampa Beds from bottom to top. The swarms of tourmaline granite, the Makalu Granite, are intruded at the base of the Tibetan-Tethys sediments that conceals the very boundary. The Arun Window is composed of phyllite and meta-sediments (metasandstones, crystalline limestones, quartzites) as a double plunging anticline structure. The synclinal sheet of Patigaun, the anticline of Nurg-La, the syncline of Tamor, and the Dhankuta Anticline are additional regional scale fold structures of the area. The maybe thrust or fault that separates the Dharan Series from the Ganges Plain, the thrust separating the Lower Himalayan Unit from the Sanguri Series, and the MCT are the major thrusts of the area.

Sharma (1966, 1990) divided the eastern Nepal Himalaya into the Basement Gneisses Complex or Himal Gneiss, the Mahabharat Limestone Group, the Gondwana and Carboniferous, and the Pliocene to Pleistocene units from bottom to top, respectively. The Basement Gneissic Complex is comprised of crystalline rocks such as augen gneiss, migmatite, and sillimanite bearing biotite gneiss. The MCT separates the Basement Gneissic Complex from the underlying Mahabharat Limestone Group which has been subdivided into the Argillaceous Formation, the Calcareous Formation and the Arenaceous Formation, from bottom to top, respectively. The Argillaceous Formation consists of chlorite phyllite, which is further subdivided into arbitrary units as grey phyllite and slates as a lower unit and the green chlorite phyllite as an upper unit. The Calcareous Formation is also divided into a lower and upper unit in which the former consists of grey to white quartzite, green phyllite, dolomite, marble or calcareous phyllite and the later unit is regarded as a carbonaceous unit. The Arenaceous Formation is comprised of loosely cemented quartzite or sandy phyllite along with white quartzite and calcareous bands. The author divided the study area into different metamorphic zones. The upper horizon is subdivided into a kyanite-sillimanite zone in the top, garnet-biotite-muscovite zone in the middle, garnet-chlorite schist in the lower part and chlorite schist of the Argillaceous Formation at the bottom. The Gondwana sediments are sandwiched between the Argillaceous Formation and the Churia Group and are exposed in Kampughat, Barahakshetra and Mai Khola. The Gondwana sediments consist of purple shale, ash-colored shale, brown sandstone and a small graphite coal seam containing quartzite pebbles. On the northern flank of Mt. Everest, Tibetan-Tethys sediment is present, which is comprised of Permo-Carboniferous biotite schist to yellow argillaceous beds of Eocene age. Below the MBT, sedimentary rocks of the Churia Group are present and are subdivided into the Lower and the Upper Formation. The Lower Formation reappears above the upper formation, indicating the presence of a thrust.

Tater (1968) mapped the Dharan-Dhankuta area and subdivided the units into the Grit Complex, the Dhankuta Schists, the Chirling Khola Formation, the Mulghat Argillites, the Telia Khola Formation, the Sanguri Formation and the Siwalik from north to south, respectively. The Sanguri Formation is bounded on the south by the MBT, separating it from the Siwalik, and on the north by a fault, separating it from the Telia Khola Formation. Similarly, the Dhankuta Schist is bounded on the north by a fault, separating it from the Grit Complex, and on the south by the Khadam Khola Fault, separating it from the Chirling Khola Formation.

Hagen (1969) prepared a geological map from Mt. Everest to the Gangetic Plain (Fig. 2). The author identified the Angbung zone, the Kathmandu nappes, the Khumbu nappe 1, 2 and 3, the Lumbasumba nappe and the Kangchedzonga nappe tectonic zones for the Higher and Lesser Himalaya for the area east of the Arun and added the Nawakot nappes, the Sakyetan schuppen and the Makalu and higher schuppen for the area west of the Arun River. The author concluded that the phyllite of the Sanguri Series of Bordet (1961) corresponds to his Nawakot Nappe, and the Barun Gneiss and Migmatites of Bordet (1961) are grouped as Khumbu Nappe. The author mentioned the presence of a large anticline, the Arun Anticline, extending from the Gangetic Plain in the south to more than 50 km north of the great Himalayan range. The Mahabharat Syncline or the Singhalila Syncline is orthogonal to the Arun Anticline and lies east of the Tamor River. Kayastha (1969) mapped the southeast part of the Dhankuta and western Ilam Districts. The author divided the area into Pre-Tertiary metamorphic rocks and the Tertiary Siwalik rocks. Vaidya (1969) worked along the Kampughat area and reported the occurrence of a slice of the Gondwana rocks as calcareous shale, quartzite, coal beds, and the lithology of Krol Formation (Gansser, 1964) as cherty dolomite and magnesite between the Siwalik and the older metamorphic succession of the Lesser Himalaya. Bashyal (1970) divided the Lesser Himalaya of the Taplejung area into units of phyllite and quartzite with granitic intrusions; also chlorite schist, feldspathic schist, biotite-muscovite-quartz schist with amphibolite, a garnetiferous quartz-biotite-muscovite Schist, and kyanite schist from bottom to top and he illustrated the presence of domal anticline structure in the area.

Amma and Akiba (1967) focused their research on the petrography of the Everest-Dharan region. Later, along with a review of Bordet (1961), Ishida (1969), and the Hashimoto team in 1973 (Akiba *et al.*, 1973) reconstructed the lithological sequences for the Everest-Dharan region as the Basement crystalline rocks or Basement gneisses, the Midland Metasediment group, the Tibetan zone, the Makalu Granite, and the Siwalik from bottom to top, respectively (Table 1). The Basement Crystalline is comprised of the Chamalang migmatite schuppe, the Barun gneiss schuppe and a part of the Irkhua crystalline nappe. The Midland metasediment group comprises three geologic units: the Midland autochthonous zone, the south marginal zone and two phyllite schuppen of the Midland schuppen zone. The Midland Metasediments are mostly autochthonous, while all crystalline rocks are in allochthonous occurrence. The authors illustrated altogether 10 thrust sheets in the area and presented the MCT equivalent with four-fold schuppens, i.e., the Midland schuppen comprising the Midland Thrust, the Gudel Thrust, the Irkhua Thrust and the Barun Thrust. Several longitudinal faults and a transverse fault, Arun Fault, are present in the section. Several regional-scale folds occupy the Everest-Dharan section. The Dudh Kosi Dome is formed through the superimposition of the Dudh Kosi Anticline and the Dolakha-Bhandar Anticline; similarly, the Arun Dome is formed by the Tumlingtar-Tamar Anticline and the Arun Anticline. Also, it is illustrated that the thrust faults and the folds should have formed simultaneously. The longitudinal faults follow the axial zone of the anticline. The lineation of sillimanite-bearing gneiss in the Barun Chamalang Schuppe zone has indicated multiple phases of deformation and mineralization. The foliation data also supports this concept in the overall section of eastern Nepal.

The Tibetan-Tethys sediments exhibit contact metamorphism in their basal succession, and the basement crystalline have undergone regional gneissification and migmatization. From the results of petrography, it has been concluded that the rocks of the crystalline nappe and schuppen belong to the middle to high amphibolite facies, whereas that of the Midland Metasediments are of greenschist to lower amphibolite facies. Prograde metamorphism is abundant in the Midland Metasediments, in the gneissic rocks of the Dhankuta Anticline and the Mahabharat Subzone. The petrographical nature of overlying phyllites and gneisses of the basement are known to be similar. Hence, the authors interpreted the possibility of a basement below the metasediments composed of a similar kind of gneissic rock. Furthermore, the Midland Metasediment has been interpreted as a miogeoclinal deposit of the Eo-Cambrian age.

Maruo *et al.* (1979) carried out geological work between the Dudh Kosi River and the Arun River of eastern Nepal, emphasizing the mineral assemblages of the lithologic units and the establishment of the metamorphic grades along with a stratigraphic interpretation (Table 1). The literature presented the MCT as two thrust model, the MCT I at the base of the Himalayan Gneiss and MCT II at the base of the Augen gneiss. The Augen gneiss is considered to be derived from the sediments of upper horizons of the Lower Himalayas (equivalent to Lesser Himalaya) and is considered metamorphosed during the thrust movement. In the case of metamorphism, each lithologic unit of the Lower Himalayas, initially slightly metamorphosed, has undergone later metamorphism near the MCT thrust zone. The Lower Himalayan rocks show an immediate increase of metamorphism below the augen gneiss. The high-grade metamorphism is represented by the assemblage of staurolite-almandine-biotite, and it decreases both downwards and south-westward. In the case of the calc-silicate schist zone, staurolite-almandine-biotite and kyanite-staurolite-biotite mineral grade metamorphism are observed at the boundary regions with the augen gneiss and the MCT I, respectively. Similarly, the kyanite-almandine-biotite grade rock is present in the lower and upper part of the Himalayan Gneiss. The Tethys affinity of the Mahabharat Zone has the metamorphic assemblage of sillimanite-almandine-biotite.

Bashyal (1980a, 1980b) established the lithostratigraphy of the area between the Sunsari and Sindhuli Districts. The area has been classified into the kyanite gneiss, the garnetiferous-mica schist, the phyllite and quartzite, the augen gneiss, the Sanguri Formation, the Barahakshetra Formation, and the Siwalik from north to south, respectively. The Barahakshetra Formation is further divided into five units, Unit I-V, on a lithological basis and has been correlated with different units of Gondwana sequence defined in India. The author correlated Unit II with the Blaini Infra Krol of the Kumaon Himalaya (Auden, 1937), Unit III with the Rangit Pebble-Slate (Acharya & Ray, 1977), Unit IV with the Damuda and Unit V with the Buxa Formation. The occurrence of volcanic agglomerates and tuffs on the Barahakshetra Formation and the Gondwana succession with evidence of the plant fossil *Shizoneura gondwanensis* at the Takure Khola, were mentioned by the author which made easy correlation with that of the Gondwana sequence of the Sikkim-Darjeeling area.

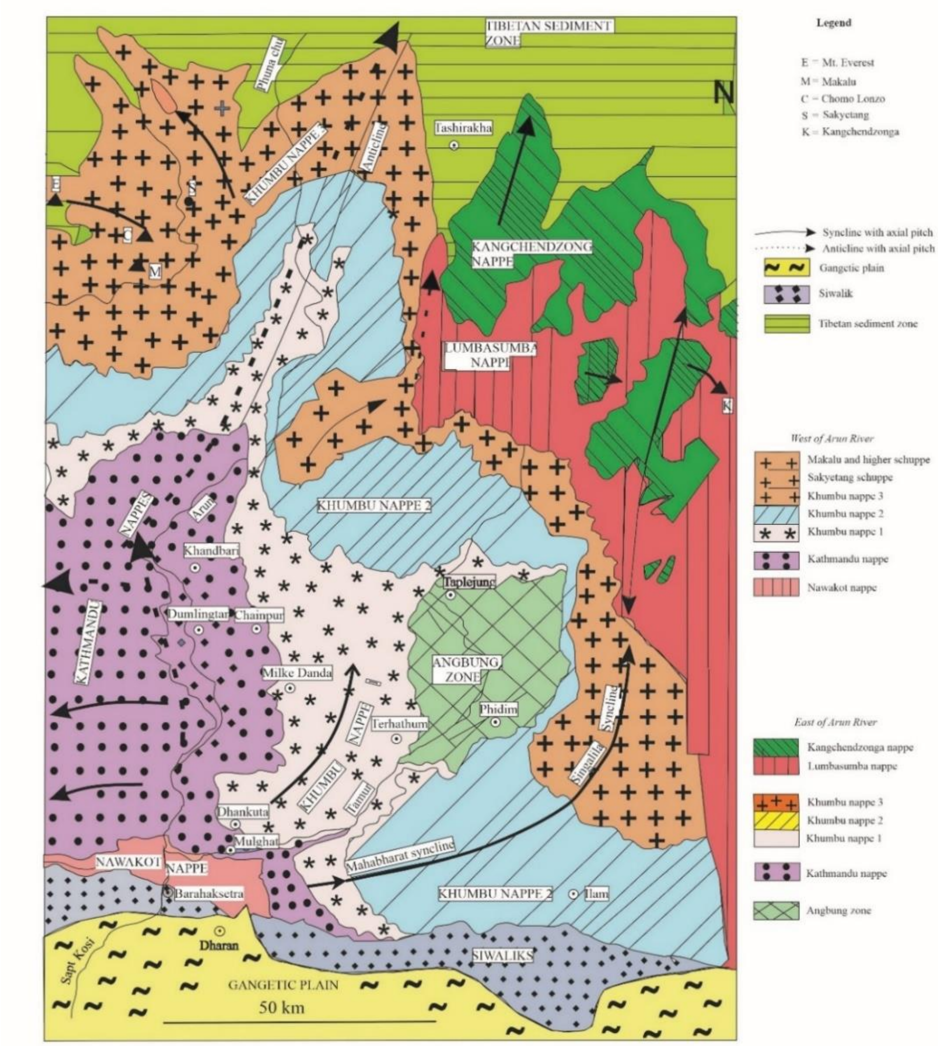

Figure 2. Tectonic sketch map of Kanchendzönga Group (modified after Hagen, 1969)

Andrews (1985) carried out stratigraphic work around the Tumlingtar-Milkedanda area (Fig. 3) and established the stratigraphy of the area (Table 1). Besides the MCT, a thrust is present which separates the Chainpur Group from the Phakuwa Group of the Kathmandu Complex. The Milke Gneiss is comprised of an anticline-syncline pair separated by a fault, and a large synclinal axis runs through the Milkedanda area. The metamorphism of the High Himalaya is of epidote-amphibolite facies. Similarly, Phakuwa Group consists of metamorphic rocks having mineral assemblages of almandine-amphibolite facies, Chainpur Group of epidote-amphibolite facies and Nawakot Complex of greenschist facies. The author also mentioned the contact metamorphism in the Kitya Khola Formation. The Khadbari Gneiss, pegmatite in Kitya Khola and several amphibole intrusions are the products of the magmatic activity of the section.

Maskey (1987) has established the lithostratigraphy of the Higher Himalaya, the Lesser Himalaya and the Siwalik during his study along the Dharan-Mulghat section. The Lesser Himalaya is divided into two sections separated by an unconformity. The lower section is comprised of the Phalametar Formation, the Kositar Quartzite, the Phusre Phyllite, the Sanguri Quartzite, the Phasuwa Khola Phyllite, Quartzite, and the Takure Dolomite from bottom to top, respectively. The upper section consists of the Lasune Khola Carbonate, the Chirling Khola Formation and Augen Gneiss, and the Belahara Quartzite in ascending order. These lower and upper sections are correlated with the Lower and Upper Nawakot Complex, respectively (Stöcklin & Bhattarai, 1977). The Higher Himalaya is comprised of the Dhankuta Schist, the Mica Schist, Augen Gneiss, Calc. Sericite Rocks, Pegmatite, and the Dhankuta Gneiss and Schist with garnet and is correlated with the rock sequence of the Kathmandu Complex. The Siwalik have been subdivided into the Lower, Middle and Upper Siwalik.

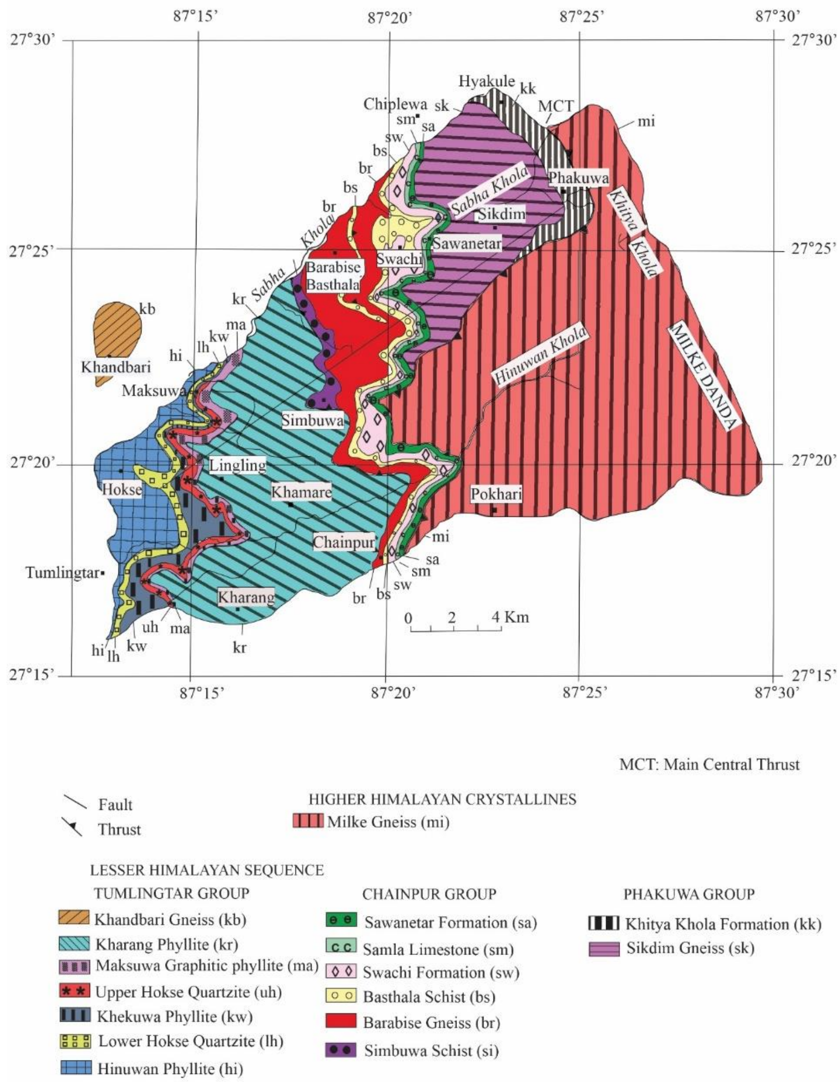

Figure 3. Geological map of Sabha Khola area, east Nepal (modified after Andrews, 1985).

Latest investigations

Schelling and Arita (1991) conducted work related to tectonics and crustal shortenings of far-eastern Nepal by constructing a geological map, balanced and restored structural section. The authors divided the whole region into three thrust bound tectonic packages as the Higher Himalayan thrust sheet (HHC), the Lesser Himalayan thrust sheet (LHM) and the Sub-Himalayan Imbricate Fan. The HHC is further divided into higher, middle and basal portions. The sillimanite-bearing biotite-rich paragneiss, quartzite, calc. silicate gneiss and migmatitic augen gneiss comprises the higher section. This sequence is intruded by the Jannu Granite. The middle section consists of sillimanite-bearing, quartz-feldspathic, migmatitic gneiss interlayered with biotite rich schistose gneiss. The basal section includes kyanite-bearing, biotite rich schistose gneiss and quartzofeldspathic gneiss. The Tibetan-Tethys Himalaya, having Cambrian or Ordovician to Eocene sediments, overlies the HHC separated by a normal-sense shear zone. The age of the HHC is interpreted to be Precambrian. The LHM is comprised of chlorite-sericite, graphite and biotite-chlorite-sericite (± garnet) phyllite, quartz-rich phyllite, micaceous quartzite, myonitic augen gneiss and rare actinolite schist. The Sisne Khola Augen Gneiss resembles to the Ulleri Gneiss (Le Fort, 1975; Arita, 1983). On the basis of reported overthrust Lesser Himalaya and underthrust of the Gondwana type sediments west of Dharan, these sequences are suggested to be Precambrian to lower Paleozoic of age. Schelling (1992) divided the HHC into the Rolwaling-Khumbu-Makalu, Shisha Pangma and Jannu Granites, the Narayan Than, Sindhuli and Dobare Thumka Granites, the Rolwaling-Khumbu-Kanchenjunga Paragneiss, the

Rolwaling-Khumbu-Kanchenjung Migmatite, the Junbesi Paragneiss, and the Mahabharat Crystallines. Further, the author presented the Khare Phyllite, the Sun Kosi Phyllite, the Melung-Salleri, Khandbari and Sisne Khola Augen Gneiss, the Dolakha Phyllite, the Suri Doban Augen Gneiss, the Ramechhap-Tumlingtar-Taplejung Group, the Tamar Khola Granite and the Gondwana lithounits for the LHM. The Sub-Himalayan Imbricated Fan is subdivided into the Lower Siwalik, the Middle Siwalik and the Upper Siwalik. Structurally, the whole area is comprised of a decollement, namely the Main Detachment Fault (MDF), which is approximately 6 to 10 km underneath the Mahabharat Lekh, 5.5 km to 6 km beneath the Siwalik hills and 20 to 25 km north of the Tamar Khola Dome. The MFT, the Dabmai Thrust, and the MBT are all splay thrusts of the MDF, whereas the Tamar Khola Thrust act as an out of sequence breach thrust. The MCT is the roof thrust, and the MDF is the floor thrust. The internal structure of the LHM is a hinterland dipping duplex. The total north-south crustal shortening since the activation of the MCT is to be 185 km to 245 km, in which the MCT consumed 140 km to 175 km of shortening. The remaining portion is shortened through folding and thrusting of the LHM and the Siwalik. The Jannu leucogranites and the granites in the Tamar Khola are major intrusive features of the area. The HHC majorly consists of kyanite-sillimanite grade units along the MCT. The LHM at the Tamar Khola Window displays an inverted metamorphic sequence with garnet, biotite and chlorite zones in a deeper structural level. This kind of metamorphic distribution made Schelling and Arita (1991) agree with the 'hot' HHC thrust sheet over LHM sediments along the MCT concept of Le Fort (1975).

Rai (1991) conducted geological work around the Dharan-Mulghat area and constructed a tectonostratigraphy of the area. The author divided the whole area into two tectonic zones, the Mahabharat zone and the Siwalik zone, separated by the MBT. The Mahabharat zone is comprised of the Raguwa Formation, the Phalametar Quartzite, the Chyuribas Formation, the Sanguri Quartzite, the Ukhudanda Amphibolite, the Namje Augen Geniss, the Mulghat Formation, the Okhre Formation and the Danda Bazar Formation. The Tamor Thrust transects the Ukhudanda Amphibolite at the top and the Namje Augen Gneiss overrides it.

Dhital (1992) investigated the occurrence of the diamictites around Tribeni-Dharan-Dhankuta and prepared a geological map of the area. The author has focused on the comparison of the occurrence of three diamictite successions from the Barahakshetra at east, Tansen at the central part and Salyan at the west of Nepal Himalaya. The author divided the Barahakshetra Group into the Sapt Koshi Formation, the Kokaha Diamictite with Baraha Volcanics, and the Tamrang Formation. Lithologically, diamictite, quartzites, carbonaceous, non-carbonaceous to calcareous sandstone, carbonaceous to non-carbonaceous shale occupies this sedimentary sequence. The author also suggested the youngest stromatolitic dolomite unit of Bashyal (1980a) was actually the oldest one and did not belong to the Gondwana rocks. The author concluded that the Kokaha Diamictite, the Sisne Diamictite, and the Salyan Diamictite are of the Lower Gondwana in age. In 2015, the author published a book where the work of the Tribeni-Dhankuta area has been revised and combined the works of Sunuwar (1993), Timsina (2011) and Rai (2012) and prepared a geological map (Fig. 4) (Dhital, 2015). The author divided the Tribeni-Barahakshetra area into the Higher Himalayan Crystalline, the Lesser Himalaya, and the Siwalik succession (Table 1). The Gondwana section of the area comprises profound thrusts, which makes it structurally complex terrain.

Lombardo *et al.* (1993) worked along the Chomolungma-Makalu Transect. The region is composed of the Lesser Himalayan, the Higher Himalayan and the Tethyan tectonic units. The Lesser Himalayan unit is comprised of the Tumlingtar Unit consisting of chlorite to biotite grade metamorphic rocks and other crystalline units, comprising the Lower Thrust Sheets, the Num Orthogneiss Unit and the Higher Thrust Sheet Unit, composed of garnet-muscovite-kyanite-staurolite assemblages of metamorphic minerals. This sequence exhibits the inverse metamorphism and the recrystallization of metagranites and metasediments formed under higher pressure and temperature. The Higher Himalayan Crystallines is composed of the Barun Gneiss, the Namche Migmatite Orthogneiss, the Black Gneisses and the Rongbuk Formation. The grade of metamorphism reached upper amphibolite facies and was intruded by the tourmaline leucogranites or the Miocene intrusive rocks, which resulted from the decompression melting in muscovite bearing amphibolite grade rocks of the Higher Himalayan Crystallines. The Early Himalayan (Barrovian type) and the Late Himalayan (high temperature and low pressure) metamorphic events are proposed by the authors in the case of the Higher Himalaya. In Tethys Himalaya, the North Col Formation is separated from the Yellow band and the Mt. Jolmo Lungma Formation through a low angle normal fault. The Tibetan-Tethys sediments occupy the northern section and are separated from others through an unconformity.

Meier and Hiltner (1993) investigated the tectono-metamorphic history of the Arun Valley on the basis of small-scale and micro-scale textural analysis. The research has adopted the subdivision of Stöcklin (1980) as the Nawakot Complex and the Kathmandu Complex separated by the Main Central Thrust Zone (MCTZ), a transition zone between the Lesser Himalaya and the kyanite grade Higher Himalayan Crystalline rocks. The authors divided the Nawakot Complex into the Unit A (chlorite-biotite), the Unit B (biotite-garnet), the Unit C (staurolite-kyanite) metamorphic subzones and the Kathmandu Complex into the Ultramylonitic Gneisses and the Augen Gneiss lithological units. The literature establishes the relationship between the deformation event and the corresponding occurrence of metamorphism of the Arun Tectonic Window. Before the thrusting or the formation of the MCTZ, the rocks of the Higher Himalayan Crystalline reached amphibolite to granulite grade metamorphism, while the Lesser Himalayan rocks were weakly metamorphosed. The intracontinental underthrusting of the Nawakot Complex beneath the Pre-Cambrian gneiss of the Kathmandu Complex had increased the metamorphic grade of the Nawakot Complex and formed the concentric zonation of inverted metamorphism. The cooling of the orogeny was initiated before the shortening of the crust along the MBT. This shortening was followed by the formation of the Arun Dome, and finally, the erosional unroofing of the Arun Window occurred.

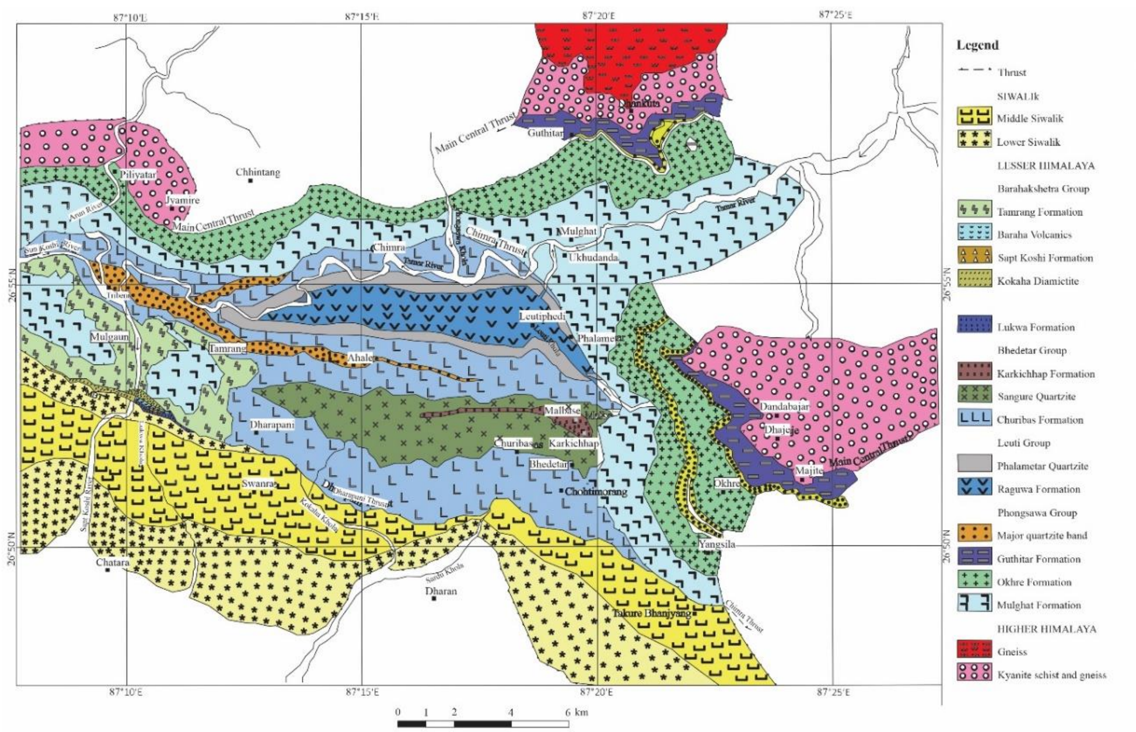

Figure 4: Geological map of Tribeni-Dharan-Dhankuta region (modified after Dhital, 2015).

Sunuwar (1993) worked around the Tribeni-Barahakshetra area focusing on petrography and constructed five tectonic units which are the Chhintang Group, the Phongsawa Group, the Tribeni Supergroup, the Barahakshetra Group including the Lukuwa Dolomite, and the Siwalik, successively younger in age from north to south, respectively. The Chhintang Group is comprised of banded gneiss, garnet schist, and quartzite and is subdivided into the Jyamire Gneiss and Belhara Formation from bottom to top, respectively. The Phongsawa Group is bounded by the Dhankute Khola Thrust in the north, which separates it from the Chhintang Group and the Chimra Thrust at the south, separating it from the Tribeni Supergroup, and it is composed of mylonitic schist, muscovite-biotite schist, black slate and quartzites. The Phongsawa Group is further classified into the Ukhudanda Formation and the Mulghat Formation in ascending order. The Tribeni Supergroup is separated from the Siwalik by the MBT at the south and is comprised of phyllite, quartzite, slate, and amphibolite. It is further subdivided into the Leoti Group and the Bhedetar Group, in which the former is separated into the Raguwa Formation, the Phalametar Quartzite, and the Churibas Formation from bottom to top, whereas the latter group is composed of the Sanguri Quartzite and the Karkichhap Formation in ascending order, respectively. The Barahakshetra Group is separated from the Tribeni Supergroup by the Asganga Thrust and is further categorized into the Kokaha Diamictite and Baraha Volcanics, the Sapt Koshi Formation, and the Tamrang Formation in ascending order along with an individual Lukuwa Dolomite lithological unit. The doubly plunging Phasuwa Anticline and the west plunging Ahale Syncline are the regional fold structures found. From the petrographic analysis, the author concluded that the grade of metamorphism gradually increases towards the north. The Tribeni Supergroup, the Phongsawa Group and the Chhintang Group belong to green schist facies, green schist to epidote-amphibolite facies and amphibolite facies, respectively.

Goscombe and Hand (2000) analyzed the petrology and phase equilibria with the help of microprobe analysis and thermocalc modelling of the rocks of the Lesser Himalayan Sequences (LHS), across the MCTZ and into the Greater Himalayan Sequences (GHS) of the Makalu and Kangchenjunga profiles of eastern Nepal. The Makalu profile consists of the rock sequences of the GHS and LHS separated by the MCTZ in which the former is subdivided into the Black Gneisses, the Namche Migmatite Orthogneiss, and the Barun Gneiss from bottom to top, respectively and the latter is composed of the Himal Group. The GHS of the Kangchenjunga profile consists of the Jannu-Kangchenjunga Gneiss, and the LHS is comprised of the Biotite Gneiss, the Himal Group, the Kushma Formation, the Ulleri Formation, and the Seti Formation from bottom to top, respectively. These two profiles are a Paired Metamorphic Mountain Belt consisting of two thrust bound metamorphic terrains having different metamorphic styles. The GHS experienced prograde metamorphism after the Formation of the Eohimalayan Thrust and reached its peak temperature (837 ± 59ºC T and 6.7 ± 1.0 kbar P) accompanied by the crustal thickening at about ~22 Ma. The high-grade metamorphism and partial melting continued in the GHS as a result of overthrusting at the MCT. This overthrusting and leucogranitic intrusions (26-17 Ma) resulted in the burial metamorphism and inverse metamorphism with the high pressure condition (557 ± 39ºC T and 10 ± 1.2 kbar P) in the LHS at the age range of 22-16 Ma. The prograde metamorphism in both metamorphic terrains constituted the Eohimalayan event. The rapid decompression terminated the prograde metamorphism of the LHS and started the cooling ages ranging from 15 Ma to 6 Ma.

Upreti *et al.* (2000) stated the presence of a large domal shaped anticline named as the Tamor Khola Dome and correlated it with the Gorkha-Pokhara Anticlinorium as well as with Likhu Khola Anticline of central Nepal. The metasedimentary rocks of the window display the inverted metamorphic sequence with increasing metamorphic grade from chlorite to garnet grade. The authors' interpretation was that the Taplejung Window was the one among many longitudinal folds and extensional features which are related to the post metamorphic deformation during the southward propagation of the MCT.

Ghimire (2001) carried out geological work around the Pachthar District of eastern Nepal giving emphasis on structural setting and metamorphism. The area bears rocks of the Higher Himalaya and the Lesser Himalaya separated by the MCT. The Higher Himalaya is comprised of high-grade kyanite-sillimanite bearing gneisses and is correlated with Formation I of central Nepal (Le Fort, 1975). The Lesser Himalaya as a whole bears the rocks of the Taplejung Formation and the Sisne Khola Augen Gneiss. The Taplejung Formation is further subdivided into the Bharapa Phyllite, the Phyame Khola, and the Phidim members which is characterized by phyllites and quartzites. The Lesser Himalaya exhibits the inverted metamorphism and belongs to green schist facies. The Sisne Khola Augen Gneiss and basal portion of the Higher Himalaya fall towards the amphibolite facies and further falls under the high amphibolite grade of metamorphism. Tectonomorphic evolution has been categorized as the pre-, syn- and post-MCT stage. The pre-MCT stage is characterized by prograde metamorphism, the syn-MCT phase has undergone the inverted metamorphism. The formation of the domal anticline and the formation of window through extensive denudation has followed the syn-MCT phase.

Chamlagain *et al.* (2003) concentrated their research on the geological structure and metamorphism in the southwest part of the Ilam Bazaar. The area includes the Siwalik, the Lesser Himalaya and the Higher Himalaya Crystalline thrust sheet, from south to north. The Higher Himalayan Crystallines are comprised of garnet-kyanite-sillimanite gneiss and white to grey quartzites. The Lesser Himalaya is subdivided into the phyllite and quartzite, the augen gneiss and the garnet-hornblende schist from bottom to top, respectively. Structurally, the MCT, the MBT and a syncline exist in the area. The Lesser Himalaya bears rocks of green schist-amphibolite facies, while the Higher Himalayan Crystallines are characterized by amphibolite to granulite facies metamorphism.

Table 1. The established tectonostratigraphy of different sections of the Arun-Tamor region, eastern Nepal.

Arun River- Mt. Makalu (after Bordet, 1961)

Higher Himalaya Unit	Everest Series
Higher Himalaya Unit	Makalu Granite
Higher Himalaya Unit	Black Gneiss
Higher Himalaya Unit	Migmatite of Barun
Higher Himalaya Unit	Ectinitic Gneisses of Barun.
----MCT---	
Lower Himalaya Unit	Upper Phyllites
Lower Himalaya Unit	Calcareous Schist
Lower Himalaya Unit	Upper Quartzites
Lower Himalaya Unit	Lower Phyllite
Lower Himalaya Unit	Lower Quartzites
Lower Himalaya Unit	Mica Schist
Lower Himalaya Unit	Migmatite Gneiss
--Thrust--	
The Border Unit	Dharan Series
The Border Unit	Sanguri Series
--Thrust--	
Ganges plain	

Everest-Dharan (after Akiba *et al.*, 1973)

Tethys zone	Tibetan-Tethys Sediment Zone
Makalu Granites	
Basement gneiss zone	Chamalang Migmatite Schuppe
Basement gneiss zone	*--Khumbu Thrust--*
Basement gneiss zone	Barun Gneiss Schuppe
--Barun Thrust II--	
Midland	Barun Phyllite Schuppe
Midland	*--Barun Thrust I--*
Midland	Irkhua Crystalline Nappe
Midland	*--Irkhua Thrust--*
Midland	Gudel Phyllite Schuppe
Midland	*--Gudel Thrust--*
Midland	Augen Gneiss Schuppe
--Midland Thrust--	
Midland Autochthonous Zone	Dudh Kosi Dome Zone
Midland Autochthonous Zone	Tumlingtar Autochthonous Window
Midland Autochthonous Zone	*--Yaku Bilte Thrust--*
Midland Autochthonous Zone	Dhankuta Autochthonous Zone
Midland Autochthonous Zone	*--Dhankuta Thrust--*
Midland Autochthonous Zone	Murghat Autochthonous Zone
--Murghat Thrust--	
South Marginal Zone	Mahabharat Subzone
South Marginal Zone	Western Subzone
--Main Boundary Thrust--	
Siwalik Zone	Neogene Tertiary zone

Dudh Kosi- Arun Area (after Maruo *et al.*, 1979)

Tethys		
--Thrust--		
Crystalline Nappe	Himalayan Gneiss Zone	
Crystalline Nappe	*--MCT I--*	
Crystalline Nappe	Calc-silicate Schist Zone	
Crystalline Nappe	Augen Gneiss Zone	
--MCT II--		
Lower Himalayas	Dudh Koshi Tectonic Window	Okhaldhunga Stratigraphic Unit
Lower Himalayas	Dudh Koshi Tectonic Window	Lamidanda Stratigraphic unit
Lower Himalayas	Arun Tectonic Window	Tumlingtal Stratigraphic Unit
--Fault--		
Mahabharat Zone	Tethys Affinity	
Mahabharat Zone	*--Thrust--*	
Mahabharat Zone	Crystalline Thrust Nappe	
Mahabharat Zone	*--MCT II--*	
Mahabharat Zone	Lower Himalayas	Udayapur Stratigraphic Unit
Mahabharat Zone	Lower Himalayas	Dharan Stratigraphic Unit
Mahabharat Zone	Lower Himalayas	Tribeni Stratigraphic Unit
--MBF--		
Siwalik		

Tumlingtar- Milkedanda section (after Andrews, 1985)

High Himalaya	Milke Gneiss		
--MCT--			
Lesser Himalaya	Kathmandu Complex	Phakuwa Group	Khitya Khola Formation
Lesser Himalaya	Kathmandu Complex	Phakuwa Group	Sikdim Gneiss
Lesser Himalaya	Kathmandu Complex	*--Thrust--*	
Lesser Himalaya	Kathmandu Complex	Chainpur Group	Swanetar Formation
Lesser Himalaya	Kathmandu Complex	Chainpur Group	Samla Limestone
Lesser Himalaya	Kathmandu Complex	Chainpur Group	Swanchi Formation
Lesser Himalaya	Kathmandu Complex	Chainpur Group	Basthala Schist
Lesser Himalaya	Kathmandu Complex	Chainpur Group	Barabise Gneiss
Lesser Himalaya	Kathmandu Complex	Chainpur Group	Simbuwa Schist
Lesser Himalaya	Nawakot Complex		Kharang Phyllite
Lesser Himalaya	Nawakot Complex		Maksuwa Graphytic Phyllite
Lesser Himalaya	Nawakot Complex		Upper Hokse Quartzite
Lesser Himalaya	Nawakot Complex		Khekuwa Phyllite
Lesser Himalaya	Nawakot Complex		Lower Hokse Quartzite
Lesser Himalaya	Nawakot Complex		Hinuwan Phyllite

Tribeni-Dharan-Dhankuta section (after Dhital, 2015)

Higher Himalayan Crystallines	
--MCT--	
Phongsawa Group	Guthitar Formation
Phongsawa Group	Okhre Formation
Phongsawa Group	Mulghat Formation
--Chimra Thrust--	
Bhedetar Group	Karkichhap Formation
Bhedetar Group	Sanguri Quartzite
Leoti Group	Chiuribas Formation
Leoti Group	Phalametar Quartzite
Leoti Group	Raguwa FOrmation
--Dharapani Thrust--	
Barahakshetr a Group	Tamrang Formation
Barahakshetr a Group	Sapt Koshi Formation
Barahakshetr a Group	Kokaha Diamictite
Unconfirmity	
Lukwa Formation	
--MBT--	
Siwalik	Middle Siwalik
Siwalik	Lower Siwalik

The Higher Himalayan Crystalline thrust sheet has undergone three phases of deformation. The Eo-Himalayan Phase is characterized by the prograde metamorphism up to the kyanite grade. In the syn-MCT phase, there occurred the sillimanite retrograde metamorphic event, and the post-MCT event comprises retrograde metamorphism as the replacement of garnet and biotite by chlorite. Similarly, the Lesser Himalayan Sequence has undergone a syn-MCT and a post-MCT metamorphic event in which they suffered the inverted and the retrogressive metamorphism, respectively.

Upreti *et al.* (2003) focused their studies on the granitic intrusive bodies in between the metasedimentary sequence of the Taplejung Window. The window is an east-plunging domal anticline. The authors divide the Lesser Himalayan Sequence into the Taplejung Formation, the Mitlung Augen Gneiss and the Linkhim Schist from bottom to top, respectively. The granite bodies intrude the Taplejung Formation and are composed of quartz, alkali feldspar, plagioclase, muscovite, biotite and tourmaline as primary constituents. These granites show gneissified S-C mylonitic texture at the marginal part, related to the movement of the MCT. The crystallization age of the granite of the Kabeli Khola is more than 1.6 Ga determined based on the Ar^{40}/Ar^{39} muscovite dating.

Iwano *et al.* (2004) conducted the $^{40}Ar/^{39}Ar$ and fission track dating on the granitic rocks in the Lesser Himalaya and underlying the Dumri Formation of Miocene fluvial sediments in far eastern and eastern Nepal in order to delineate the time series of the metamorphic nappe cover on the Lesser Himalaya. Inverted metamorphism in the case of the Dumri Formation just beneath the nappe was reported on the basis of the resetting of the fission track of the detrital zircon. The authors concluded the time to be 14 Ma in which the Higher Himalayan Crystalline nappe covered the Lesser Himalayan autochthon. This cover thermally (350±50ºC) affected the upper part of the Lesser Himalaya. The mid-section of the Lesser Himalaya was experiencing a 240∼300ºC temperature until 5 Ma, which later cooled down to 130±30ºC by 2.5∼2 Ma. The cooling rate of the frontal part of the Lesser Himalaya is higher than the middle as it was already cooled to 130±30ºC by 8∼7 Ma.

Ulak (2004) conducted a study on the primary structure and sedimentary facies of the Siwalik of Chatara-Barahakshetra section, eastern Nepal in order to delineate the depositional setting of the area. The Siwalik of the Chatara-Barahakshetra area is classified into the Lower Siwalik and the Middle Siwalik, which are further subdivided into lower and upper members. The presence of the Central Churia Thrust (CCT) is marked by the reappearance of the Lower Siwalik in the northern section of the area. From facies analysis, the lower and upper members of the Lower Siwalik are inferred to be deposited by fine-grained, and flood flow dominated meandering river systems, respectively. The lower and upper members of the Middle Siwalik of the Chatara-Barahakshetra section is interpreted to be the work of sandy meandering and sandy braided rivers, respectively.

Pearson and DeCellas (2005) worked around the Tribeni village of Dhankuta and stated the presence of the Ramgarh Thrust at the Tribeni village, near the confluence of the Sunkoshi, Arun and Tamor River. The literature adopted the Ranimatta-Kuncha stratigraphic nomenclature and stated that the Tribeni area is comprised of the rock sequence of the Greater Himalaya, the Ranimatta Formation, the Ulleri Gneiss, the Kushma Formation, and the Syangja and Galyang Formations from north to south, respectively. The MCT separates the Greater Himalaya from the Ranimatta Formation, and the Ramgarh Thrust marks the boundary between the Kushma Formation (hanging wall) and the Syangja and Galyang Formations.

Goscombe *et al.* (2006) discussed the crustal architecture of the Himalayan Metamorphic Front (HMF) of eastern Nepal on the basis of stratigraphic, kinematic, strain and metamorphic profiles. The authors postulated that, in the case of eastern Nepal, the unconformity that separates the Mesoproterozoic Lesser Himalayan Sequence and the Neoproterozoic-Cambrian Greater Himalayan Sequence does not coincide with discrete structural or metamorphic discontinuity or the MCT. The High Himal Thrust (HHT), a 100 – 400 m thick mylonitic zone, lies within the Greater Himalayan Sequence and controls the orogenic architecture in eastern Nepal. The HHT separates the HMF into the Upper-Plate and the Lower Plate, in which the former constitutes high temperature and moderate pressure metamorphic sequence metamorphosed between 20-24 Ma and the latter has a moderate temperature and high pressure inverted metamorphic schistose zone metamorphosed between 18-6 Ma.

Searle *et al.* (2008) defined the MCT on the basis of strain criteria at the basal section of the ductile shear zone and inverted metamorphic sequence. In their paper, they show a shortened northward extension of the Arun Tectonic window and they presented the MCT just north of Tumlingtar. Further, the authors expressed the Arun Window as southwardly open and the Tamar Tectonic Window as a closed window.

Groppo *et al.* (2009) worked on the P-T evolution across the MCTZ of the eastern flank of the Arun Tectonic Window using pseudosection modelling for thermobarometric evaluation and ICP-MS and SEM-EDS methods for the determination of bulk rock composition. The research encrypted the area into lower (the Lesser Himalaya) to higher (High Himalayan Crystallines) structural levels across the MCTZ and reported the inverted metamorphism around the area. The authors illustrated three different evolutionary stages of pressure and temperature for different structural levels on the basis of analysis of metapelites. The lower structural levels show a prograde thermobarometric path with 550ºC and 0.65 GPa as the peak of metamorphism. The intermediate structural level shows evidence of heating and decompression and reaches 600-650º C and 0.85-0.95 GPa. The highest structural level is interpreted as chemically equilibrated with peak metamorphic conditions of 655ºC and 0.754 GPa.

Sitaula (2009) established the modal composition of sandstone present in the Gondwana sequence of Lesser Himalaya of the Barahakshetra area. The Permo-Carboniferous sandstone of Barahakshetra Group bears sandstone of arkosic composition, whereas quartz arenitic to litharenitic (Eocene-Early Miocene) sandstone model has also been classified. The author urges that the Tamrang Formation was deposited on the juvenile foreland basin between the Indian craton and Tibet. From the cooling ages of the detrital muscovite, the author concluded that the sediments could be related to the magmatism in the Indian craton. The author further suggested to reevaluate the stratigraphy of the Gondwana Sequence of eastern Nepal as the supposed Permo-Carboniferous Sapt Koshi Formation is considered as late Cretaceous, and the Tamrang Formation is correlated with the Eocene Bhainskati Formation of western Nepal (Sakai, 1983).

Ulak (2009) divided the Siwalik of the Kankai section into the Lower, Middle, and Upper Siwalik in ascending order. The Lower Siwalik and the Upper Siwalik are further subdivided into the lower and upper members, and the Middle Siwalik is further subdivided into the lower, middle and upper members. The lower and upper members of the Lower Siwalik are inferred to be deposited by fine-grained, and flood flow dominated meandering river systems, respectively. The lower, middle and upper members of the Middle Siwalik of the Kankai section are interpreted to have formed from the deposition of sandy meandering, deep sandy braided and shallow braided river systems, respectively. The Upper Siwalik are the result of gravelly braided to debris flow dominated braided systems. The latter on the basis of grain diameter and thickness of fining upward successions, he estimated that there is an increase in flow velocity, channel slope gradient and discharge of the fluvial system (Ulak, 2016b).

Sakai *et al.* (2013) carried out geological investigations focusing on the multichronological analysis in the Taplejung Window of eastern Nepal. The authors constructed the tectonostratigraphy to include the Higher Himalayan Crystalline, the Linkhim Schist, the Mitlung Augen Gneiss, the Kuncha Formation from bottom to top, respectively. The Higher Himalayan Crystallines is comprised of gneiss and a minor amount of schist and quartzite. The Linkhim Schist and the Mitlung Augen Gneiss are considered to be lithologies of the MCTZ. The Kuncha Formation forms the nappe structure and consists of chlorite-sericite grade phyllite, schist and metasandstone. The deposition of the Kuncha Formation was from a rift system and aulacogen environment and started around 1900 Ma, which was later intruded by two mica tourmaline granite, the Taplejung Granite, around 1850 Ma. The Kaligandaki Supergroup of the Taplejung region has been correlated with the Coronation Supergroup of the Slave craton, Canada and deposition was proposed to be the rifting and subsiding of a passive continental margin (Hou *et al.*, 2008). The cooling ages of the Kuncha Formation and the Higher Himalayan Crystallines were determined from the fission track ages of zircon and apatite and found to have cooled below 240°C at 6-5 Ma and below 100°C at 3-2 Ma.

Ambrose *et al.* (2015) applied the pseudosection modeling and monazite petrochronology of paragneiss from the Kanchenjunga region and projected the presence of a series of mystifying tectonic and metamorphic discontinuities with the Himalayan metamorphic core. The authors established five geological units based on the lithology and metamorphic observations. The rocks that formed part of the Himalayan metamorphic core reached garnet grade depths by middle Eocene. The metamorphism in the metamorphic core was prolonged and lasted more than 30 Ma. The evolution of the Himalayan metamorphic core was enhanced and assembled by the lateral extrusion, underplating and formation of the High Himal Thrust, an out of sequence thrust, which was active between 20 to 18 Ma.

Dhital (2015) made a review of the work on the stratigraphy of the Taplejung area and proposed a lithological subdivision. The region is divided into the Higher Himalayan Crystallines and the Lesser Himalaya, separated by the MCT. The litho-classes comprising the Lesser Himalaya are the phyllite and metasandstone, the granite, the quartzite and phyllite, the biotite-chlorite schist, the gneiss, the garnet schist and the hornblende-actinolite schist from bottom to top, respectively. A similar kind of work has been carried around the Dhudhe Khola and the Sidhdhi Khola of the Mechi Transect. The area is comprised of rock sequences of the Higher Himalayan Crystalline, the Lesser Himalaya and the Siwalik separated by the MCT and the MBT, respectively. The Lesser Himalaya is further subdivided into the phyllite and quartzite, the major quartzite band and the garnet schist in ascending order, respectively.

Rai *et al.* (2016) worked around the Dharan-Mulghat area and stated the presence of the Higher Himalaya, the Lesser Himalaya and the Siwalik tectonic units separated by the MCT and the MBT, respectively. The author divided the Lesser Himalaya sequence into ten formations, grouped into two groups and one individual lithounit. The Bhedetar Group includes the Raguwa Formation, the Phalametar Quartzite, the Chiuribas Formation, the Sangure Quartzite and the Karkichhap Formation. Similarly, the Dada Bajar Group is comprised of the Ukhudanda Formation, the Mulghat Formation, the Okhre Formation, and the Patigau Formation. The Bhorleni Formation is described as the individual lithounit, equivalent to the Gondwana Group of rocks. The Dadabazar Group and the Raguwa Formation is correlated with the Kuncha Formation (Stöcklin & Bhattarai, 1977; Stöcklin, 1980). Similarly, the Phalametar Quartzite is correlated with the Fagfog Quartzite, the Chiuribas Formation with the Dandagaon Phyllite, the Sangure Quartzite with the Purebesi Quartzite and the Karkichhap Formation with the Benighat Slate of central Nepal. The Chimra Thrust, the Chhotimorang Thrust, the Malbase Syncline and the Leutiphedi Anticline are other regional structures of the area.

Ulak (2016a) has followed the two group division system of Valdiya (1995) for the age determination of the Lesser Himalayan Sequence of eastern Nepal. The author divided the Lesser Himalaya into the Older Lesser Himalayan Formation and the Younger Lesser Himalayan Formation. These two groups are separated from each other through an unconformity named as the Greater Lesser Himalayan Unconformity. The Older Formation beneath the unconformity are of Paleoproterozoic to upper Precambrian age and the Younger Formations above it, are the Permo-Carboniferous as Gondwana. The author also argued that the rugged topography and the intense distribution of the crystalline rock sequences of Higher Himalaya in eastern Nepal in comparison to that of central and western Nepal are indicating the earlier initiation of the thrust tectonics and exhumation in western Nepal compared to eastern Nepal. Hence, the majority of thrust sheets of the Higher Himalaya in the west have suffered intensive erosional processes.

Adhikari (2017) and Shrestha (2017) prepared a geological map of the Chatara-Machuwatar section during their dissertation work of Master's Degree. The researchers stated the presence of some overturned beds of the Gondwana. Shrestha (2017) correlated the Lesser Himalayan section with that of central Nepal as the Lukwa Formation with the Dhading Dolomite, the Chiuribas Formation with the Nourpul Formation and the Mulghat Formation with the Dadagaon Phyllite. Later on, Adhikari *et al.* (2018) published the geological map of the Siwalik of the Chatara-Barahakshetra section, in which the authors stated the zone as a highly deformed area as it contains several folded structures. Further, the rock sequence near the CCT suggested it as an overturned structure.

Bhandari *et al.* (2018) compared the detrital zircon U-Pb age analysis from sandstone and tuff samples of the sedimentary succession of eastern and western Nepal and proposed a new stratigraphic framework in the case of eastern Nepal. The authors argue that the youngest part of the Tamrang Formation to be equivalent to the Permian Sisne Formation, and the Saptakoshi Formation is correlated with the Amile Formation of western Nepal. Further, the authors concluded that the Baraha Volcanics is not equivalent to the Aulis Volcanics of western Nepal. The authors suggest the Gondwana and post-Gondwana sequences be the Greater Himalaya and the Tethys Himalaya or the similar source which must had provided the sediments for the Greater Himalaya and the Tethys Himalaya, unlike the previously stated source by Sitaula (2009) as the Malani Igneous Suites, the Erinpura Granite, the Munger Orogeny, and alkali syenite intrusion in Chotanagpur terrain.

Lamichhane (2018) mapped the eastern section of the Taplejung Window and its surrounding regions giving emphasis on the petrography and metamorphism. The study section is comprised of lithological sequences of the Lesser Himalaya and the Higher Himalayan Crystallines separated by the MCT. The Lesser Himalaya is composed of the Kuncha Formation, the Chilindin Formation, the Phyame Formation and the Phidim Formation from bottom to top. The Higher Himalayan Crystallines is named as the Prangbung Formation. The petrographic study reveals the green schist facies rocks formations are composed of the Lesser Himalaya while the Higher Himalaya is comprised of the amphibolite facies rock sequences. The author tried to explain the metamorphic events in different time periods as Eo-Himalayan and the Neo-Himalayan but urges that only the petrographic data are insufficient for reliable reasoning.

Present understanding of the geology of the Arun-Tamor region

As other sections of Nepal Himalaya, the eastern Nepal Himalaya can also be subdivided into four east-west stretching tectonic units as the Siwalik, the Lesser Himalaya, the Higher Himalaya, and the Tibetan-Tethys Himalaya. The MFT is the southernmost tectonic thrust that separates the Indo-Gangetic Plain and the Siwalik (hanging wall). Similarly, the MBT separates the Siwalik and the Lesser Himalaya (hanging wall), the MCT separates the Lesser Himalaya and the Higher Himalayan Crystallines (hanging wall) and these thrusts are distributed gradually northward, respectively. The STDS is a normal shear zone that separates the Tibetan-Tethys

Himalaya (hanging wall) and the Higher Himalayan Crystallines and is the northernmost tectonic boundary.

The Tibetan-Tethys Himalaya is composed of thick piles of sedimentary rocks like limestone, sandstone, shales and is very well distributed in the Manang-Mustang-Dolpo area of western Nepal and in the Saipal-Api area far-western Nepal, where complete sections can be studied within the Nepal Borders (Heim & Gansser, 1939; Bordet *et al.*, 1971; Fuchs, 1977; Ulak, 2016a). In the case of eastern Nepal, only the basal section of the Tibetan-Tethys sediments are exposed at the highly elevated regions and are comprised of biotite to garnet grade greenschist, calc-silicate marble, limestones and black shale (Searle *et al.*, 2008). They are underlain by the migmatite and gneiss of the Higher Himalaya (Lombard, 1958; Bordet, 1961; Lombardo *et al.*, 1993).

The Higher Himalayan Crystallines consists of high-grade crystalline rocks as various kinds of gneiss, schists, and migmatites. Its extension in western Nepal is confined to a root zone, and the width is restricted to a few km (Ulak, 2016a). The extension of thrust sheets accompanied by nappes and klippes in central and far-western Nepal has added width to the extent of exposure (Stöcklin, 1980; Upreti, 1990; Yoneshiro & Kizaki, 1996; Dhital, 2015). In eastern Nepal, the Higher Himalayan Crystallines have a larger areal extent which almost reaches to the MBT and is composed of migmatite, gneiss and schist, which are of upper amphibolite to granulite facies (Bordet, 1961; Akiba *et al.*, 1973; Andrews, 1985; Schelling, 1992; Chamlagain *et al.*, 2003; Dhital, 2015).

The Lesser Himalaya is composed of sedimentary and metasedimentary successions and is widely distributed in the west and becomes narrow in the east (Dhital, 2015; Sah, 2015; Ulak, 2016a). In central and far-western Nepal, the crystalline cover has narrower exposures (Stöcklin, 1980; Yoneshiro & Kizaki, 1996; Upreti, 1990; Dhital, 2015). The lithological sequence is well developed in the case of western Nepal, which is devoid of the crystalline nappe covers (Sakai, 1983, 1985; Dhital *et al.*, 2002; Dhital, 2015; Ulak, 2016a). The Arun-Tamor region of eastern Nepal contains very narrow stretches, north of MBT as frontal part, and large tectonic windows, beneath the crystalline covers at the deep gorges of the Arun and Tamor rivers of the Lesser Himalaya (Bordet, 1961; Akiba *et al.*, 1973; Upreti *et al.*, 2000, 2003; Dhital, 2015; Ulak, 2016a). The Lesser Himalaya, east of Dharan, nearly comes in direct contact with the Siwalik and is slightly broadened west of Dharan (Dhital, 2015; Rai *et al.*, 2016; Ulak, 2016a). The frontal region is comprised of both sedimentary succession and metasedimentary succession. The sedimentary succession has very limited exposure and is subdivided as the Kokaha Diamictite, the Sapt Koshi Formation and the Tamrang Formation (Dhital, 2015). They are comprised of diamictite, quartzite, shale and sandstone. The Arun and Taplejung Tectonic Windows consist of metasedimentary sequences of thickness about 5000 m (Andrews, 1985) and 6000 m, respectively (Upreti *et al.*, 2003; Sakai *et al.*, 2013). These tectonic windows are domal anticlines, with the Arun Window having an N-S axial trend and the Taplejung Window plunging to the east (Bordet, 1961; Akiba *et al.*, 1973; Upreti *et al.*, 2000, 2003). The metasedimentary succession consists of limestone, slate, phyllite, schist, and gneiss (Bordet, 1961; Akiba *et al.*, 1973; Andrews, 1985; Schelling, 1992; Dhital, 2015). The metamorphic section of the Tribeni-Dharan-Dhankuta region exhibits prograde metamorphism (Akiba *et al.*, 1973; Maruo *et al.*, 1979; Sunuwar, 1993), whereas the Arun and Tamor Tectonic Window section exhibit inverted metamorphism (Bordet, 1961; Meier & Hiltner, 1993; Upreti *et al.*, 2000, 2003; Ghimire, 2001). The metamorphism grade ranges from green schist to almandine-amphibolite facies (Andrews, 1985; Meier & Hiltner, 1993; Sakai *et al.*, 2013).

In Nepal, the Siwalik succession is 4-6 km thick and represents a coarsening upward sequence of rocks, i.e. shale, mudstone, siltstone, fine sandstone at basal part, followed by a medium to coarse salt-pepper sandstone, pebbly-sandstone at middle section, while pebble-cobble to boulder conglomerate at the upper section, with fining up cycles (Tokuoka *et al.*, 1990; Dhital *et al.*, 1995; Ulak, 2004, 2009; Sigdel *et al.*, 2011; Adhikari & Sakai, 2016). The distribution of these sedimentary successions is comparatively narrow in the Arun-Tamor section, in comparison with the western regions where wide distribution is accompanied by the presence of dun valleys. In the Arun-Tamor region, the Siwalik has been sub-divided as Lower, Middle and Upper Subgroups on the basis of composition, sediment size and depositional environment (Ulak, 2004, 2009; Dhital, 2015). The sediments of Lower Siwalik depositions are the result of fine-grained to flood flow meandering systems (Ulak, 2004, 2009). The Middle Siwalik were deposited by a sandy meandering river at the basal section followed by a deep sandy to a shallow braided river system. The Upper Siwalik are the result of deposition of gravelly braided to debris flow-dominated braided rivers.

Besides major thrusts such as the MFT, MBT, MCT and STDS, there are a number of imbricate faults and thrusts within the Lesser and the Higher Himalaya (Bordet, 1961; Akiba *et al.*, 1973; Maruo *et al.*, 1979; Andrews, 1985; Schelling & Arita, 1991; Dhital, 1992, 2015; Rai *et al.*, 2016). The Tamor Granite, the Khandbari Gneiss, and the Baraha Volcanics are the major igneous units in eastern Nepal (Lombard, 1958; Bordet, 1961; Andrews, 1985; Schelling, 1992; Upreti *et al.*, 2000, 2003; Sakai *et al.*, 2013).

Controversies

Murphy and Salvador (1999) revised the International Stratigraphic Guide and stated the procedures for establishing and revising stratigraphic units, and provided the guidance for the name, stratotypes, correlation while establishing the stratigraphy. The guide clearly states that the name of stratigraphic units should consist of geographic name combined with the kind and rank of the unit. The work of Andrew (1985), Dhital (2015), and Upreti *et al.* (2000; 2003) in some sections matched or have followed these norms presented by the guide (Tumlingtar-Milkedanda section, Tribeni-Dharan-Dhankuta section, Taplejung section, respectively). But, in some of the works, the lithological classification of eastern Nepal has no standard pattern. The researchers have established individual classification schemes without taking care of standard stratigraphic classification (Goscombe & Hand, 2000; Ghimire, 2001; Sakai *et al.*, 2013; Dhital, 2015; Rai *et al.*, 2016 (Dharan-Mulghat section); Lamichhane, 2018 (Taplejung section)). Many important previous works seem unfit for a modern stratigraphic protocol (Bordet, 1961; Akiba *et al.*, 1973; Maruo *et al.*, 1979; Schelling, 1992), and some later works have also not followed the international stratigraphic guide (Meier & Hiltner, 1993, Arun Tectonic Window; Chamlagain *et al.*, 2003, Ilam section; Dhital, 2015, Taplejung and Mechi Transects). The correlations of these units are difficult due to the differences in the scale of work and due to the discrepancy in the nomenclature adopted (Maskey, 1987; Meier & Hiltner, 1993; Dhital, 2015; Rai *et al.,* 2016; Shrestha, 2017; Bhandari *et al.,* 2018).

There are diverse concepts on structural interpretation in the case of the Arun-Tamor region. As the definition and the position or placement of the MCT is highly debated (metamorphic and strain criteria by Searle *et al.* (2008); the age of the motion criteria by Yin (2006); protolith boundary criteria by Martin (2016)), many researchers in case of Arun-Tamor region has followed the metamorphic rheological conception of the MCT, but also have presented a varied view on the position and form of the MCT. Many authors have thought of it as a broad shear zone, but some authors have cited the MCT as a single shear thrust (Andrew, 1985; Meier & Hiltner, 1993; Groppo *et al.*, 2009; Sakai *et al.*, 2013; Dhital, 2015). Maruo *et al.* (1979) stated it as the shear zone comprising two thrusts, and there is a view of the MCT consisting of more than two thrusts (Akiba *et al.*, 1973). The known conception of the MCT, the basal section of the ductile shear zone and the inverted metamorphic zone (Searle *et al.*, 2008), is debated in the case of the frontal section of the Lesser Himalaya at Arun-Tamor section. The proposed stratigraphic classification of Tribeni-Dharan-Dhankuta does not exhibit the inverted metamorphism of the Lesser Himalaya near the MCT (Dhital, 2015; Rai *et al.*, 2016). Pearson and DeCellas (2005) mapped the Ramgarh Thrust in the Tribeni area, which has not been traced during the latter works of Dhital (2015). The number and positions of thrusts, faults and other structural units vary along with the researchers (Bordet, 1961; Akiba *et al.*, 1973; Maruo *et al.*, 1979; Andrews, 1985). In the case of the MBT, the discussion also varies from a single thrust to a zone of multiple faults (Maruo *et al.*, 1979; Dhital, 2015).

There are common concepts regarding deformation and related metamorphism of the Higher Himalayan Crystallines and the Lesser Himalaya. During the Pre-MCT period, the Higher Himalayan Crystallines suffered prograde metamorphism with temperatures of more than 600°C and pressures ~7 kbar and the units are comprised of upper amphibolite to granulite facies metamorphic rocks (Meier & Hiltner, 1993; Goscombe & Hand, 2000; Chamlagain *et al.*, 2003). The metamorphic evolution was accompanied by crustal thickening and partial melting (Goscombe & Hand, 2000). The leucogranite intrusions and the overriding of these hot rocks of the Higher Himalayan Crystallines during the formation of the MCT caused the Lesser Himalaya to undergo prograde metamorphism, which resulted in inverted metamorphism characterized by high pressures and moderate temperatures (more than 10 kbar P and 500ºC T) (Meier & Hiltner, 1993; Goscombe & Hand, 2000; Ghimire, 2001; Chamlagain *et al.*, 2003; Groppo *et al.*, 2009). Emplacement of this nappe cover of the Higher Himalayan Crystallines rocks over the Lesser Himalayan autochthon continued up to 14 Ma (Iwano *et al.*, 2004). The beginning of the retrograde metamorphism of the Higher Himalayan Crystallines, the beginning of the reverse shearing along the MCT and the normal shearing along the STDS at the Arun-Tamor region was a coeval process that occurred around 18 Ma (Chamlagain *et al.*, 2003). However, the petrochronological studies conducted in western and central Nepal have indicated a much older initiation of motion along the STDS. The western Nepal klippe experienced the motion about 30-29 Ma (Soucy La Roche *et al.*, 2016), the main range of western Nepal shows the movement initiated to be >24 Ma (Carosi *et al.*, 2013) and the age determined for central Nepal is 25 Ma (Leloup *et al.*, 2015). Furthermore, the cooling of the Lesser Himalayan sequence rocks commenced before the crustal shortening at the MBT (Meier & Hiltner, 1993; Goscombe & Hand, 2000; Chamlagain *et al.*, 2003). The formation of domal anticlines and denudations along the deep valleys of the Arun and Tamor was the later deformational event which resulted in the formation of large tectonic windows (Meier & Hiltner, 1993).

These concepts of tectonometamorphic history were based on the understanding that an unconformity separating the two basinal sequences, the Higher Himalayan Crystallines and the Lesser Himalaya, coincides with the MCT that has controlled the architecture of the Himalaya (Goscombe *et al.*, 2006). Unlike in central and western Nepal, this unconformity, the Himalayan Unconformity, is not represented by the MCT, and it coincides with the HHT which lies structurally within the Higher Himalayan Crystallines (Goscombe *et al.*, 2006). The HHT controls the orogenic architecture of eastern Nepal (Goscombe *et al.*, 2006). Ambrose *et al.* (2015) also agree on the presence of the out of sequence thrust, the High Himal Thrust, within the Higher Himalayan Crystallines but argues that it was not active for long. The authors have concluded that the prograde metamorphism of the Higher Himalayan Crystallines is protracted and lasted more than 30 Ma. This period of metamorphism was accompanied by the lateral extrusions, underplating, and the formation of the HHT (Ambrose *et al.*, 2015). These results have established the contradictions on the previous conceptualization on the position and the role of the MCT and the whole understanding of the tectonometamorphic history of the area.

Research gaps

Modern day geology has built up a focus on intensified laboratory work in order to get greater details of geological information on microscopic level. These kinds of studies ultimately lead to in-depth knowledge about tectonics and the metamorphic history of a region. There has been a very limited approach to microstructural analysis in eastern Nepal (Meier & Hiltner, 1993; Sakai *et al.*, 2013) which has limited the knowledge of structural aspects of the region. The major focus of the previous studies was on the petrography in order to delineate the assemblages of metamorphic minerals (Akiba *et al.*, 1973; Maruo *et al.*, 1979; Andrews, 1985; Schelling, 1992; Sunuwar, 1993). The modern analytical techniques of geochemistry have been applied to the very selective situations and locations of limited areas (Goscombe & Hand, 2000; Upreti *et al.*, 2003; Groppo *et al.*, 2009; Sitaula, 2009; Sakai *et al.*, 2013; Bhandari *et al.*, 2018). These have enlightened interesting knowledge of the metamorphic paths and depositional settings of such areas. These developments of thermobarometric analysis are the need of other untouched sections also to unveil the time, heat and pressure path the section has experienced.

The depositional environment of the Siwalik sections, the Chatara-Barahakshetra section and the Kankai section has been interpreted on the basis of primary structures and sedimentary facies analysis (Ulak, 2004, 2009). Since it is a fluvial deposit, there are lateral variations in many aspects, such as lithology and fauna (Dhital, 2015). The lateral variations make it difficult for most of the classification systems to fit perfectly for all the sections. Hence, the remaining larger portions of Siwalik should be addressed with a proper classification system and depositional environment analysis, which will be very much informative for determining hinterland exhumation history. In the case of the Lesser Himalaya, the sedimentary section of the Barahakshetra region with sedimentary petrography, heavy mineral analysis of Sitaula (2009), and detrital zircon U-Th age analysis of Bhandari *et al.* (2018) has different sorts of conclusions related to stratigraphy and provenance analysis. Sitaula (2009) relates the provenance with the magmatism on the Indian Craton, but Bhandari *et al.* (2018) argue the source should be similar to that of the Higher Himalayan Crystallines and the Tibetan-Tethys Himalaya. Further, the metasedimentary section of the Taplejung Tectonic Window has got some attention (Sakai *et al.*, 2013), but the remaining metasedimentary section lacks its depositional environmental analysis.

Future directions of research

Future research on the Arun-Tamor region should focus on the basic and foremost geological information in order to determine the geological evolution of the area. The primary factor should be the establishment of the lithostratigraphy of each section with detailed work on appropriate scales (1:25000 or less). For constancy of stratigraphic nomenclature, unit names should be synthesized and correlated to existing units where possible. The adopted and revised stratigraphy should be correlated with other sections of Nepal Himalaya. All the aspects of structural evaluation, the mega-, meso- and microstructural analysis, should be carried out with the help of intense field data as well as microscopic study. The elaboration of petrographic study for metamorphic state evaluation to geochemical analysis with modern techniques for determination of metamorphic path, the pressure-temperature-time path, for delineation of overall metamorphic history of the region is essential. The petrographic data, primary structural analysis, geochemical analysis as well as sedimentary facies analysis should be conducted to determine the depositional history of sedimentary and metasedimentary sections. The studies related to the determination of geochronological ages (deposition of sediments, metamorphic ages, age of thrusting, age of crystallization of intrusive bodies) are very essentials to interpret the tectonic and metamorphic, as well as depositional evolution of the region. These are very vital works which will clarify the picture of the overall geological status and will enlighten with geological proceedings of the area through the past.

CONCLUSIONS

The present understanding, controversies and research gaps of the Arun-Tamor region of eastern Nepal has been summarized as below:

a) The Tibetan-Tethys sedimentary successions, the Higher Himalayan metamorphic sequence, the Lesser Himalayan metamorphic and sedimentary sequences, and Siwalik sedimentary successions are the major tectonic units that made up the Arun-Tamor section of the eastern Nepal Himalaya.

b) There are diverse views among researchers regarding the stratigraphic classification and nomenclature, and the structural set up of the area.
c) The controversies exist in case of interpretations of deformational and related metamorphic evolution history as well as depositional ages and provenance analysis of the sedimentary sequence of the Lesser Himalaya.
d) Further, area still lacks a detailed investigation on depositional environment, microtectonics, P-T measurements and geochronology.

These studies are essential for deep understanding of the geological evolution of the area and to clarify the existing controversies.

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AUTHOR CONTRIBUTIONS

Conceptualization, LPP and DA; methodology, LPP and DA; software and digitization, CBS; formal analysis, LPP and DA; writing original draft, DA; writing review and editing, DA and CBS; supervision, LPP.

CONFLICTS OF INTEREST

The authors declare no conflict of interest pertinent to this work.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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