Geological and Petrological Evolution of the Lesser Himalaya between Mugling and Damauli, central Nepal

A Dissertation for the Award of
Doctor of Philosophy (Ph. D.) Degree in Geology

By
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RECOMMENDATION

Mr. Kabiraj Paudyal has completed his dissertation work entitled "**Geological and Petrological Evolution of the Lesser Himalaya between Mugling and Damauli, Central Nepal**" under my supervision. I recommend the dissertation for the award of Doctor of Philosophy in geology. To my knowledge this work embodies the candidate's own work and it has not been submitted for any other degree.

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LETTER OF APPROVAL

On the recommendation of the Central Department Research Committee (CDRC), this dissertation work of Mr. Kabiraj Paudyal is approved and forwarded for the examination to the Institute of Science and Technology (IOST), Tribhuvan University for the award of doctor of philosophy in geology.

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DECLARATION

I hereby declare that the work presented in this dissertation for the award of Doctor of Philosophy in geology has been done by myself and has not been submitted for the award of any other degree. All the sources of information have been specially acknowledged by reference to the authors or institutions.

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ABSTRACT

The Himalaya is divided into four tectonic zones as the Sub-Himalaya, the Lesser Himalaya, the Higher Himalaya, and the Tethys Himalaya from south to north, respectively. The Lesser Himalaya is a fold-and-thrust belt bounded by the Main Central Thrust (MCT) in the north and the Main Boundary Thrust (MBT) in the south and comprises autochthonous unit made up of Late-Precambrian to Early Paleozoic (?) low- to medium-grade metasedimentary rocks discordantly overlain by Proterozoic metamorphic crystalline rocks transported by thrusts. Although many authors have worked in central Nepal Lesser Himalaya, many parts still lacks large scale geological map and there are a number of problems and controversies on stratigraphic classification, tectonic interpretation and metamorphism.

Present study was carried out in the central Nepal Lesser Himalaya between Mugling in the east and Damauli in the west covering both the autochthonous and allochthonous units. Main objectives of the study were to clarify the stratigraphic classification proposed by the previous authors, to prepare geological map and its cross-sections, to use magnetic susceptibility for stratigraphic comparison, and to unravel the tectono-metamorphic history of the area.

In the present study about 1000 square km area of the Lesser Himalaya between Mugling and Damauli was mapped in 1:25,000 scale. Lithostratigrpahy of the area was established and compared with the type-section by detailed route-mapping and preparation of columnar sections. Magnetic susceptibility was measured and analyzed in the autochthonous rocks along three sections in the Mugling-Damauli area and one section in the Malekhu area. Regional geological structures were measured and traced throughout the study area. Mesoscopic and microscopic structures were studied and analyzed both in the field and in thin sections. Metamorphic study was carried out using conventional petrographic microscope in thin sections. Illite and graphite crystallinities were measured

by X-ray diffractometer and Raman Spectrocopy of Carbonaceous Materials was carried out using Raman Spectroscope.

The study shows that the stratigraphic classification of the Lesser Himalayan autochthon proposed by Stöcklin and Bhattarai (1977) and Stöcklin (1980) need some modificaton. Possibly there exists no disconformity between the Dhading Dolomite and the Benighat Slate. Therefore, whole autochthonous rocks should be named as the Nuwakot Group (not the Nawakot Complex). The Anpu Quartzite, the Labdi Phyllite and the Banspani Quartzite are found to be lateral extensions of the same units as the Fagfog Quartzite, the Dandagaon Phyllite and the Purebensi Quartzite, respectively. Therefore, the former units do not exit as separate members. The Nourpul Formation is very extensive and is divisible into four members and two beds in the present study area.

Magnetic susceptibility (MS) measurement in the Nuwakot Group rocks shows that each stratigraphic unit has its own MS pattern and range of MS values. This pattern is uniform in all sections of the present study area as well as in the type locality of the Nuwakot Group (i.e., Malekhu section). Therefore, it supports the present lithostratigraphic correlation made by field mapping in the Lesser Himalaya.

The rocks of the allochthonous unit (Kahun Klippe) are named as the Tanahun Group and can be divided into three formations as the Gwaslung Formation, the Musimarang Formation and the Shivapur Schist, from bottom to top, respectively. The lithology of the Shivapur Schist is similar to that of the Raduwa Formation of the Kathmandu Nappe and Chaurijhari Formation of the Jajarkot Klippe. Therefore, the Gwaslung and the Musimarang Formations should be units older than the Raduwa Formation. It indicates that the Kathmandu Nappe, Kahun Klippe and Jajarkot Klippe are a part of a single crystalline thrust sheet and the basal thrust of the Kahun Klippe (the Dubung Thrust) is equivalent to the Mahabharat Thrust (MT). There is no lithological similarity between the rocks of the Kahun Klipe and that of the MCT zone and Higher

Himalaya. Therefore, the rocks of the klippe are probably units older than the Kunchha Formation deposited on top of the Higher Himalayan basement.

The Mugling-Damauli area forms a part of a large duplex structure. The Dubung Thrust is the roof thrust, the MBT is the floor thrust, the Dewachuli Thrust is the imbricate fault and the Bhangeri Thrust is a back-thrust. The origin of the Lesser Himalayan crystalline nappes can be explained on the basis of single thrust model, i.e., the southward extension of the MCT.

The area shows polyphase deformation (D_1-D_5) and metamorphism (M_0-M_3) as in the other parts of the Lesser Himalaya. At least two deformation events (D_1 and D_2) and one metamorphic event (M_0) are pre-Himalayan. The M_0 is normal burial metamorphism with grade increasing stratigraphically downwards and peak temperature reaching up to 370°C. The area suffered three deformation events (D_3, D_4 and D_5) and three metamorphic events (M_1, M_2 and M_3) after India-Eurasia collision. The second event (M_1) is Eohimalayan event causing garnet-grade prograde metamorphism in the Tanahun Group. This is pre-MCT event. The MCT-related Neohimalayan metamorphism (M_2) is inverted also in the low-grade zone of the Lesser Himalaya just below the Kahun Klippe. It is shown by both the illite and graphite crystallinity values.

Key words: Lithostratigraphy, metamorphism, deformation, Kahun Klippe, root zone, central Nepal, Lesser Himalaya.

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ACRONYMS

BT	=	Bhangeri Thrust
CDG	=	Central Department of Geology
CDRC	=	Central Department Research Committee
CM	=	Carbonaceous Material
Cm	=	centimeter
DCT	=	Dewachuli Thrust
DMG	=	Department of Mines and Geology
DT	=	Dubung Thrust
GC	=	Graphite Crystallinity
HHC	=	Higher Himalayan Crystalline
IC	=	Illite Crystallinity
ITS	=	Indus-Tsangpo Suture
KI	=	Kübler Index
MBT	=	Main Boundary Thrust
MCT	=	Main Central Thrust
MFT	=	Main Frontal Thrust
MS	=	Magnetic Susceptibility
MT	=	Mahabharat Thrust
RSCM	=	Raman Spectroscopy of Carbonaceous Materials
STDS	=	South Tibetan Detachment Fault System
XRD	=	X-ray Diffractrometry

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

The Himalaya is the highest and the largest mountain range in the world. It consists of 10 of the world's 14 peaks over 8,000 m and more than 40 peaks over 7,000 m.The Himalaya is believed to be originated as a result of continent-continent collision between Indian and Eurasia Plates (Dewey and Bird 1970; Powell and Conaghan 1973). Present Himalayan region was occupied by a large sea known as the Neo-Tethys in the Mesozoic-Lower Tertiary. The northward drift of the Indian Plate in the Late Cretaceous and subduction of ocean floor under the Eurasian Plate narrowed the Neo-Tethys progressively (Molnar and Tapponnier 1975; Patriat and Achache 1984). The closing of the Tethys Ocean and opening of the Indian Ocean is considered side by side as a close tectonic link.

By about 55 Ma ago the Tethys Ocean was vanished, the oceanic lithosphere of the Indian continent laid beneath the Eurasian continent and the continental lithosphere of the Indian Plate was juxtaposed against the Eurasian continent. Around 50 Ma ago the Indian continent was completely lodged against the Eurasian continent resulting in collision tectonics (Coward et al. 1988) and the last remains of the marine condition of the Tethys Ocean disappeared. As the continental crust of India could not sink to the great depths needed (>100 km) to be consumed (unlike oceanic crust), resistance developed against the northward movement of India. Then the rate of northward movement of Indian continent decreased from 15 cm to 5 cm per year.

After collision, as a result of continuous movement of Indian continent northward against Eurasia (Tibet), the Indian crust thickened producing metamorphism and transforming the deep seated rocks of the Higher Himalayan Zone at temperatures ranging from 500 to 700°C and at pressures of about 5 to 12 Kbar (Pêcher 1989). The collision is further characterized by crustal-scale thrusting and widespread nappe emplacement (Molnar 1984; Butler and Coward 1989). Consequently, the Himalayan province was overtaken by a severe convulsion of tectonic movements. These were accompanied by widespread invasion of granitic magma and attendant metamorphism leading to reconstitution of rocks under elevated temperature and pressures in the presence of chemically active fluids. Orogeny shifted progressively from the suture zone in the north to the Main Frontal Thrust in the south. About 1000 km of continental shortening has occurred in the northern Indian continent since its collision with the Eurasian continent (Allègre et al. 1984). In totality of the phenomena entailing folding, faulting, and thrusting accompanied by metamorphism and intrusion of granites that gave rise to the building of the mighty Himalaya is known as the Himalayan Orogeny (Le Fort 1986).

India-Eurasia collision not only produced crustal shortening but also caused slicing of the northern margin of the Indian continent into slivers along three principle thrusts: the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Main (or Himalayan) Frontal Thrust (MFT) from north to south, respectively. These major intra-crustal thrusts divide the Himalaya into four tectonic zones as the Sub-Himalaya, the Lesser Himalaya, the Higher Himalaya, and the Tethys Himalaya from south to north, respectively (Gansser 1964).

The Lesser Himalaya stretching over 1500 km from Himachal Pradesh to Bhutan and lying between the Great Himalayas and the Sub-Himalaya is made up of a highly deformed, thick pile of partly metamorphosed clastic and carbonate rocks. One of the problems of geological mapping and stratigraphic correlation in the Lesser Himalaya is that the stratigraphic units have been defined on the basis of lithology only, most of the units are unfossiliferous, and radiometric data are rare and lithological characteristics extensively varies laterally. It is a fold-and-thrust belt with complex geological structures. Moreover, a number of nappes and klippes having crystalline to non-crystalline rocks are widespread within the Lesser Himalaya. The origin and evolution of these tectonic structures has a great debate among the Himalayan geo-scientists till the date. To avoid the aggravation of such sort of confusion as mentioned above, it is fundamentally necessary to make systematic and detailed large-scale mapping and to establish the lithostratigraphic sequence with appropriate descriptions of the defined rock units.

Systematic geological investigations had a very late start in Nepal when compared with the adjoining countries. However, a number of foreign and Nepalese geologists have made their contribution on geological researches on Nepal Himalaya. There are a large number of published and unpublished literatures by these scientists. Himalaya has been a heaven for geological researchers in the last few decades.

Geological mapping is the first step to understand the mineral resources of the country. Geological mapping together with petrological studies help to recover the tectonic history of the region; which can be ultimately tied-up to assess the natural hazards like landslide, earthquake, volcanism, flood, etc. Geological condition judges the suitability of the site for infrastructural development. Geological structures and stratigraphy of the region control the location of natural gas, petroleum and groundwater reservoirs. Therefore, the geological mapping and petrological studies can be considered as the backbone for the development of a country.

Out of the four tectonic zones of the Himalaya, a large middle tract of the Nepal Himalaya is covered by the Lesser Himalayan rocks. It is exposed continuously from east to west (Gansser 1964; Hashimoto et al. 1973). The Nepal Lesser Himalaya as in the other parts of the Himalayan region is a fold-and-thrust belt with complex stratigraphy and structures (Stöcklin 1980; Sakai 1985; Hirayama et al. 1988; Dhital et al. 2002). There are several thrust sheets, stacked one over the other and folded and faulted on a large scale. Tectonically, it is made up of the autochthonous-paraautochthonous units, with various nappes, klippe and tectonic windows.

Many parts of the Lesser Himalaya in central Nepal still lack detailed geological maps. Wherever geological mapping has been done, there are several discrepancies and controversies on the adopted stratigraphy and tectonics among different researchers. This had created a great problem not only for accurate correlation of the sequences in contiguous region but also for structural interpretation and tectonic evolution of the Lesser Himalaya as a whole. Due to the lack of detailed geological mapping and petrological analysis of rocks, deformation and metamorphic histories of the low-grade metamorphic terrain in the Mahabharat Zone is still uncertain. Keeping these views in mind, with the aim to overcome these geological issues, the geological and petrological study was started in the Mugling-Damauli area of central Nepal Lesser Himalaya.

In the present study, a detail geological mapping of Mugling-Damauli region was carried out in 1:25,000 scale. The lithostratigraphic classification of the area was revised based on new observations. Deformation history of the area was interpreted by analyzing large-scale, small-scale and micro-structures. Metmaorphic evolution of the area was established on the basis of petrographic study of rocks in thin sections, illite crystallinity study, graphite crystallinity study and measurement of Raman Spectroscopy of carbonaceous materials. Finally, a tectono-metamorphic evolution model has been presented for the Lesser Himalaya in the study area. Parts of the results have been already published in Paudyal and Paudel (2011a), Paudyal et al. (2011), Paudyal and Paudel (2011b), Paudyal et al. (2012), Paudyal (2012) and Paudyal and Paudel (2013).

1.2 GEOLOGICAL SETTING OF THE NEPAL HIMALAYA

Like the entire 24000 km long Himalayan Range, the Nepal Himalaya is also divided into five major tectonic units as Indo-Gangatic Plain (in Nepal: the Terai Zone), the Sub-Himalayan Zone, the Lesser Himalayan Zone, the Higher Himalayan Zone and the Tethys Himalayan Zone from south to north, respectively (Gansser 1964; Hagen 1969, Fig. 1.1). These zones extend approximately parallel to each other throughout the country. Each zone is characterized by its own lithology, tectonics, structures and geological history. The Indus-Tsangpo Suture Zone and Lhasa Block do not fall in the Nepal Himalaya.

1.2.1 Indo-GangaticPlain

It forms the southernmost tectonic division of Nepal. Physiographically, this zone does not belong to Himalayan system. It is a foreland basin and its origin is directly linked with the rise of the Himalaya and it is thus genetically inseparable. In the north, it is bounded by the MFT. Pleistocene to recent alluvial deposits cover the Terai plain, which rest on the Sub-Himalaya (or Siwaliks) which in turn rest on the post-Gondwana rocks of the Eocene-Oligocene age (Sharma 1990). Within the lithological succession of Terai plain, there exists lateral facies variation. Mostly, the coarser sediments (gravels-sands) are distributed in the northern part, near the Churiya foot hills and the finer sediments (sands and clays) in the southern part of the Terai. The recent alluvium in Terai is brought in by the rivers coming from the northern hills. The average thickness of deposit is about 1500 m. The Terai Zone shares a significant proportion of current Himalayan stress accumulation which is evidenced by presence of thrusts and thrust-propagated folds beneath the sediments.

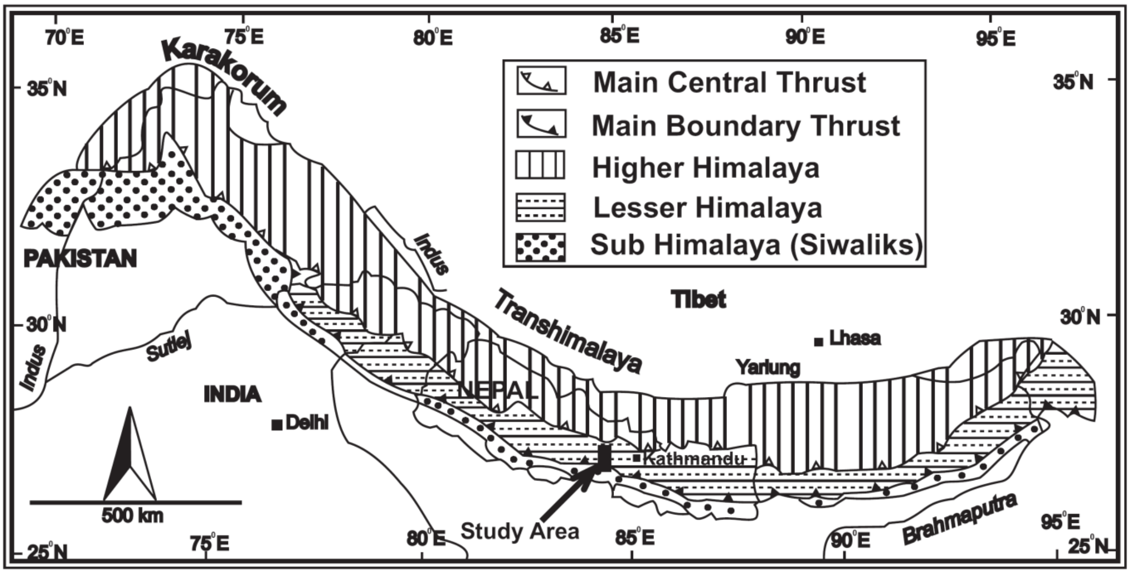


Fig. 1.1. Simplified Geological Map of the Himalaya showing major litho-tectonic division (Modified after Gansser 1964).

1.2.2 Sub-Himalayan (Siwalik) Zone

The foothill ranges of the Himalaya are called the Sub-Himalayan Zone or Siwaliks. In Nepal, this range is often referred to as the Churiya, and in some part of the Himalaya it is also known as the Outer Himalayan Zone. The Sub-Himalayan rocks represent the Late Tertiary (Middle Miocene to Early Pleistocene) continental mollasic sediments deposited within the southern foredeep basin of the Himalaya. The Siwalik succession is 4-6 km thick in Nepal Himalaya and in general represents a coarsening upwards sequence with individual fining up cycles which reflects the rising history of the Himalaya (Gansser 1964). The rock formations of the Siwalik Group include thick-bedded mudstone, sandstone and shale in the lower and middle parts, and conglomerate in the upper part. The Siwalik strata consist of rich assemblages of vertebrate fossils (Corvinus 1988) in addition to the fossils of invertebrates, plant leaves and locally fresh water molluscs. Based on palaeo-magnetic studies, the age of the Siwalik Group in Nepal ranges from about 17 Ma to less than 2 Ma (Tokuoka et al. 1986; DeCelles et al. 1998). The altitude ranges from 200 to 1,000 m from the sea level. It is bounded to the south by the MFT while in the north it is separated by the MBT.

1.2.3 Lesser Himalayan Zone

The Lesser Himalaya lies between the Sub-Himalaya and Higher Himalaya. Both the southern and northern boundaries are represented by thrust-faults, i. e., the MBT and the MCT respectively. It comprises mainly sedimentary to low-grade meta-sedimentary rocks of Late Precambrian to Oligocene (Hashimoto et al. 1973; Stöcklin and Bhattarai 1977; Sakai 1983). The Lesser Himalaya of Nepal shows lateral variation in stratigraphy, structure, and magmatism. In the eastern part, it consists of many windows consisting of low grade meta-sedimentary rocks around the crystalline rocks of the thrust sheets while in the central and far western parts it has a number of nappes and klippen of both crystalline and non-crystalline rocks. The rocks of the Lesser Himalaya belong to the greenschist and lower facies. In the northern part, however, they are extremely sheared and metamorphosed up to garnet and sometimes kyanite grade. The sheared and mylonitized zone is known as the Main Central Thrust zone (MCT zone). The unfossiliferous nature of the low-grade meta-sedimentary rocks and the complicated structures of the zone in Nepal have contributed many problems related to the age, stratigraphy, tectonics and correlation of the rocks with the other parts of the region. The low-grade meta-sedimentary rocks are unconformably overlain by the Gondwana type, marine as well as continental sediments in the southern part of the Lesser Himalaya.

1.2.4 Higher Himalayan Zone

The Higher Himalaya includes the rocks lying north of the MCT and south of the fossiliferous Tibetan-Tethys Zone. The zone is also called the Tibetan Slab and is composed of about 10 km thick pelitic, psammitic and calcareous paragneisses, granitic ortho-gneisses and migmatites of amphibolites facies containing kyanite and sillimanite (Le Fort 1975; Arita 1983; Colchen et al. 1986). The MCT has transported the high- grade Higher Himalayan rocks over the low-grade meta-sedimentary rocks of the Lesser Himalaya. The Higher Himalayan rocks form nappes and klippe at different places. The Higher Himalaya can be divided into four main units. From bottom to top these units are: Kyanite-Sillimanite Gneiss, Pyroxene Marble and Gneiss, Banded Gneiss, and Augean Gneiss (Bordet et al. 1972). Le Fort (1975) revised this classification and divided into three formations as Formation I, Formation II and Formation III in the ascending order. Formation I consists of kyanite-sillimanite-garnet two-mica banded gneisses of pelitic to arenaceous composition. Formation II commonly begins with a coarse quartzite beds with several tens of meters thick. It is mainly composed of an alteration of pyroxene and amphibole bearing calc-gneisses and marbles. Similarly, the formation III is characterized by a thick succession of coarse-grained augen gneiss.

1.2.5 Tethys Himalayan Zone

The Tethys Himalayan Zone lies between the South Tibetan Detachment Fault System (STDS), a north dipping normal fault system and the Indus-Tsangpo Suture (ITS) Zone in the north. This zone is composed of sedimentary rocks such as shales, limestones, and sandstones, ranging in age from Cambrian to Cretaceous from shelf-sediments deposited on the northern margin of the Indian Continent (Hagen 1968; Bodenhausen and Egeler 1971; Bordet et al. 1971; Colchen et al. 1980). It has undergone very little metamorphism except at its base where it is in contact with the high-grade metamorphic rocks of the Higher Himalaya. Except Cambrian, all systems of Palaeozoic and Mesozoic Erathems with several Stages have been well established by fossil content. In Nepal, these fossiliferous rocks are well developed in Thank Khola (Mustang), Manang, Dolpa and

Nyi-Shang regions. Most of the High-Himalayan peaks of Nepal, including Everest, Manaslu, Annapurna and Dhaulagiri are made up of these fossil rich Tethys Himalayan rocks.

1.3 STUDY LOCATION AND ACCESSIBILITY

The present study area is a part of the Lesser Himalaya in western-central Nepal (Fig. 1.2). It is about 150 km west of Kathmandu and covers mainly Tanahun and parts of the Chitwan, Gorkha, and Nawalparasi districts. It lies between 27°45'00"N-28°10'00"N lattitudes and 83°50'00"E-84°10'00"E longitudes. It extends from Mugling in the east to Ramjakot in the west and Chhoprak of the Gorkha district in the north to the Dewachuli area of Napalparasi in the south. The study area covers about 1000 sq.km area.

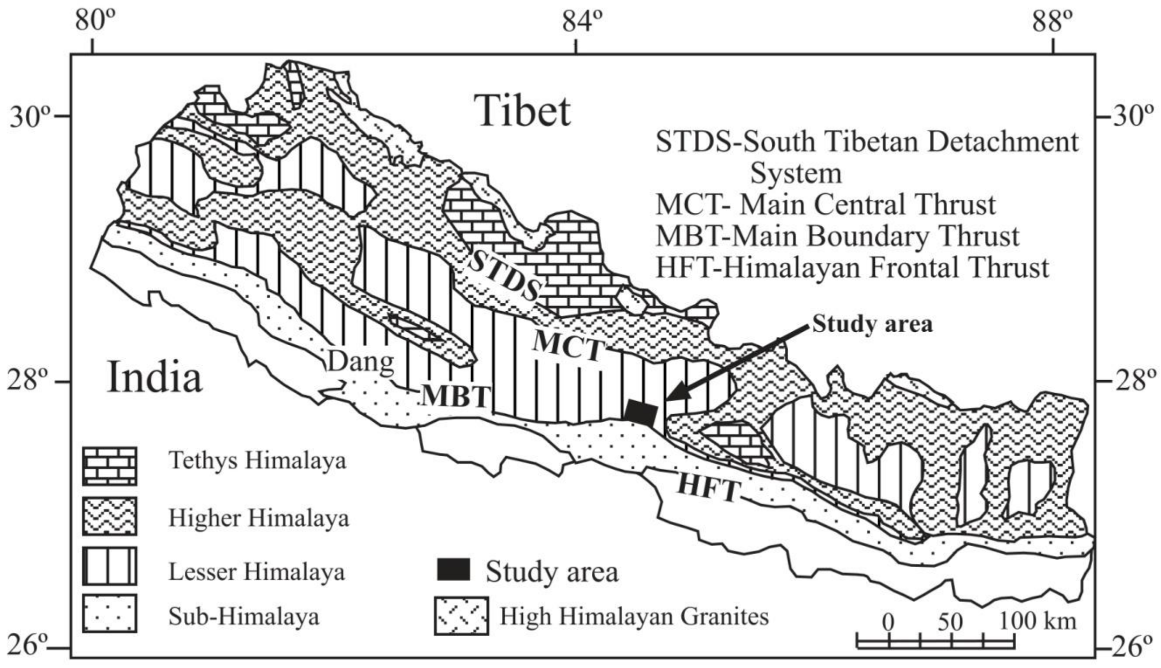


Fig.1.2. Simplified geological map of the Nepal Himalaya showing major tectonic units (modified after Upreti and Le Fort 1999).

The Mugling-Damauli sector of the Prithvi Highway and the Mugling-Narayangarh road pass across the study area. Other main earthen motor roads are the

Ghumaune-Damauli road (along Seti River valley), Damauli-Shivapur road (ridge road) and Dhodeni-Khalte road (along Kali Gandaki River valley) that pass the main parts of the study area.

Geologically, the area occupies the southern part of the outer Lesser Himalaya bounded in the south by the MBT and in the north by the MCT (Fig.1.3).

1.4 PHYSIOGRAPHY OF THE STUDY AREA

Present study area dominantly belongs to the Mahabharat Range and partly in the Churia Range. It forms the semi-matured, rugged terrain with sharp crests and moderate to steep slopes with several semi-wet gulleys and steep streams (Fig.1.4). The southern slopes are generally steeper than the northern ones. The elevation of the area ranges from 251 m (Sisara valley located at the Kali Gandaki River bank) to the highest peak 2120 m (the Chhimkeswori Danda, southwest of Mugling). Some other prominent peaks are the 2068 m peak (no name) at SE of Hilekharka; Dewachuli Lake (1980 m), Labdi Hill (1503 m), Chhipchhipe Danda (1296 m), the Solighopte Danda (1288 m), Naram (1266 m), Chanduli Danda (1238 m), Loprang (1198 m), Ransing (1195 m), Dihi (1170 m) etc. Similarly, some of the populated and lowest elevated lands of the area are: Mugling (266 m; Trishuli Valley), Damauli (320 m; Seti Valley), Khalte (255 m; Kali Gandaki Valley), Singuwa (166 m; Kali Gandaki Valley) etc. Mahabharat hills are higher than the Siwalik Hills in the south and the Midlands in the north. These hills form the first effective barrier to the monsoon clouds entering the Himalaya, and exert considerable influence on the country's rainfall distribution. The climate of the area is sub-tropical. The peak temperature in the area reach up to 38°C in the river valleys in Jun/July and the lowest temperature drops to 5°C in December/January.

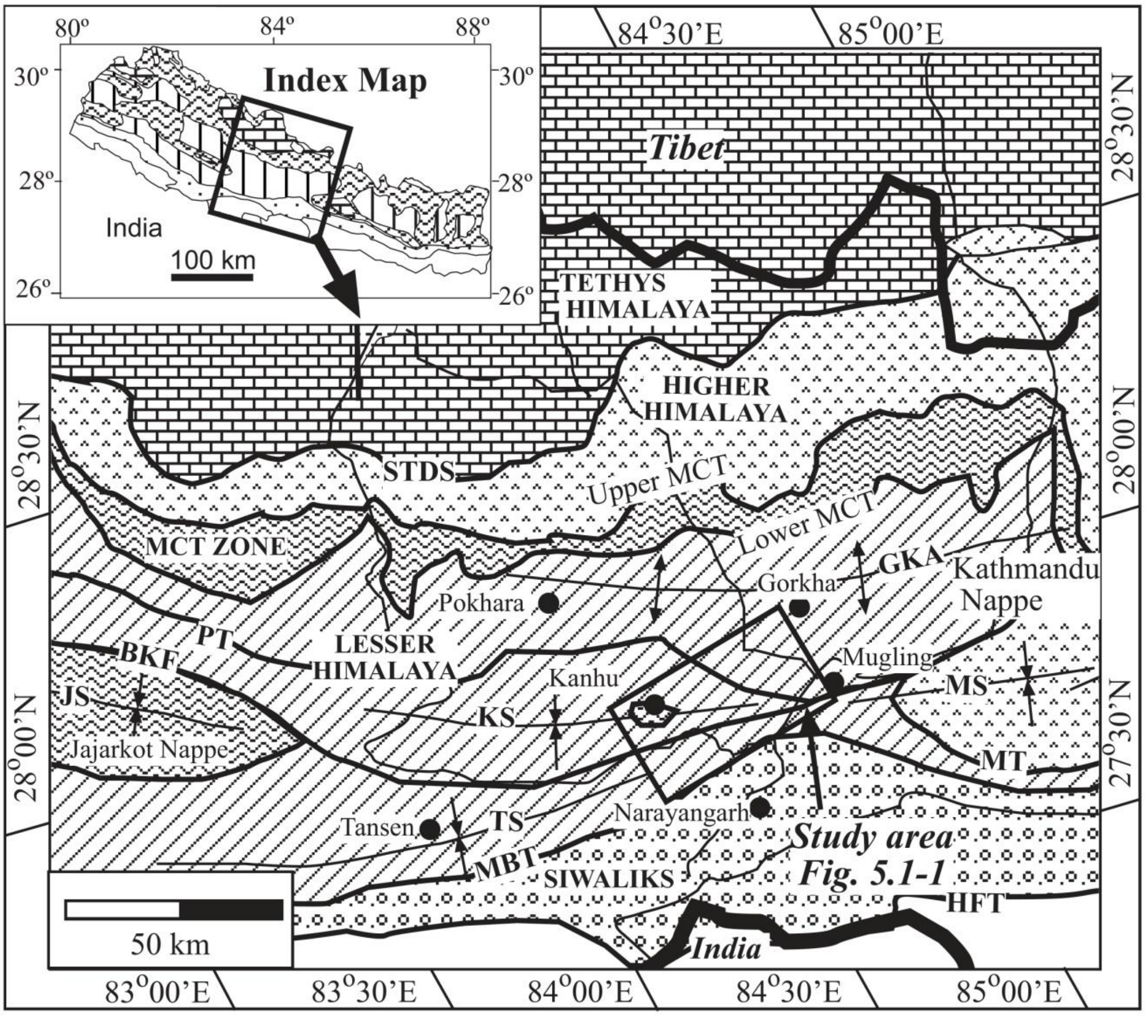


Fig.1.3. Simplified tectonic map of central Nepal, Lesser Himalaya (Paudel and Arita 2000) showing the location of the study area. STDS: South Tibetan Detachment System, MCT: Main Central Thrust, MBT: Main Boundary Thrust, HFT: Himalayan Frontal Thrust, MT: Mahabharat Thrust, BKF: Bari Gad-Kali Gandaki Fault, PT: Phalebas Thrust, MS: Mahabharat Synclinorium, GKA: Gorkha-Kunchha Anticlinorium, TS: Tansen Synclinorium, KS: Kahun Syncline, JS: Jalbire Syncline.

Soil erosion and mass movement activities are very severe cases of natural hazards in monsoon periods. This is ultimately link with the genetically weak geological setting in conjunction with the high rate of deforestation and intense rainfall within 3 months of monsoon period. The physiography and river systems of central Nepal are controlled by the lithology and structure of bedrocks. The major rivers flowing in the study area are the Trishuli, Seti, Marshyangdi, Madi and the Kali Gandaki (Fig. 1.4). Among

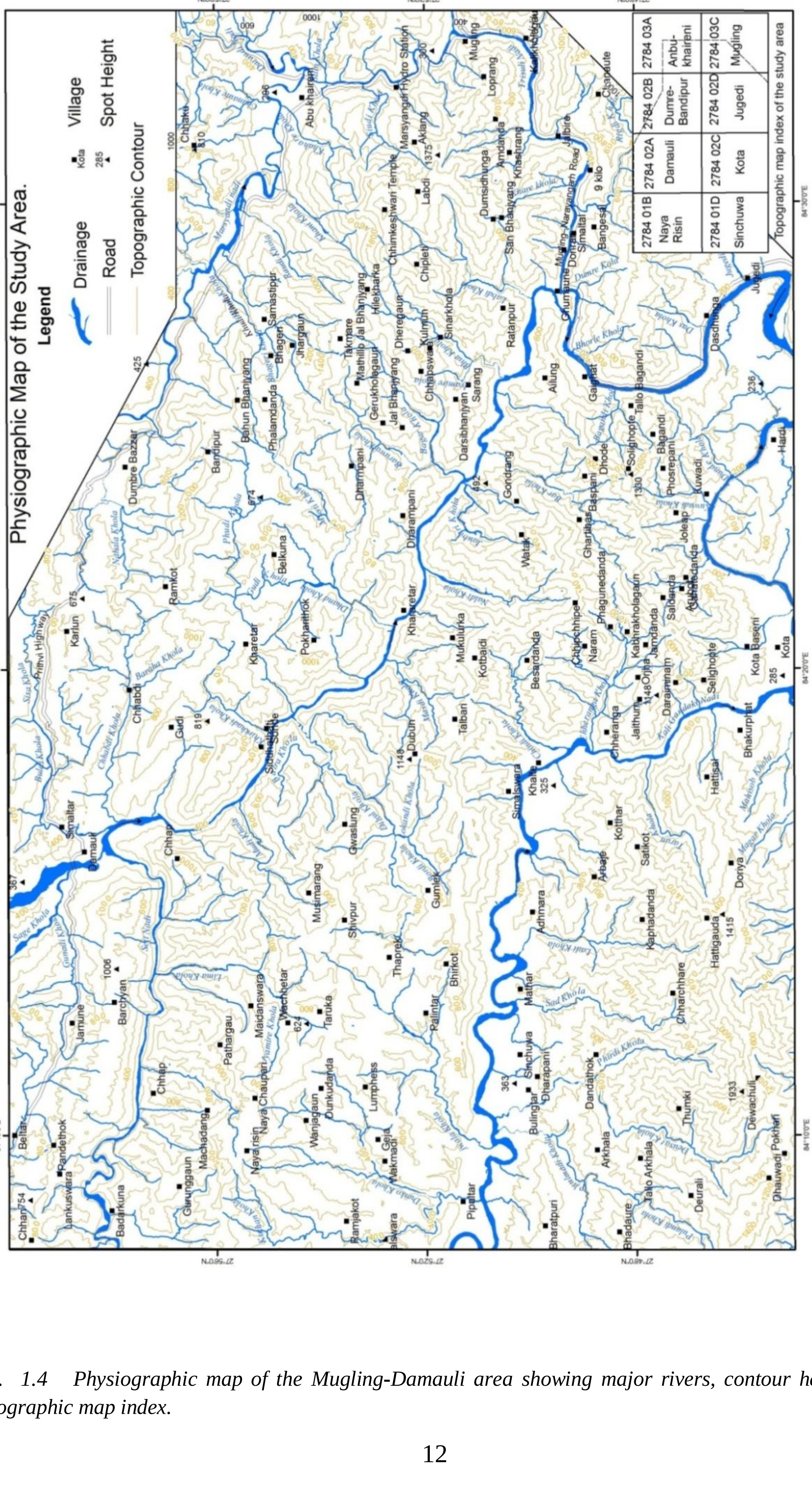


Fig. 1.4 Physiographic map of the Mugling-Damauli area showing major rivers, contour heights and topographic map index.

these rivers, the Trishuli and the Kali Gandaki are the master rivers of the area. The Marshyandgi, Seti, and the Madi Rivers join with the Trishuli River and finally the Trishuli and the Kali Gandaki Rivers join at Deughat where it is known by Narayani. These all are antecedent rivers originated from the glaciated peaks in the north and following to the south. There are several small to medium sized streams joining to these major rivers originated from the Mahabharat Range. Overall river system is dendritic with deep valley cut and steep gradients.

Genetically, the soil type of the area can be classified into three groups: residual soil (~ thickness 1 cm- 2.5 m) at the top parts of the weathered hills; colluvium soils (~ thickness few cm to few meters) at the mid part to base of the slopes and the alluvial soil (~ thickness few meters to some tens of meters) at the river side or in the palaeo-fluvial deposits. In average, the forest and cultivated land are in the proportion of 4:1. Rice, maize and millet are the main types of corns locally available in the area. Potatoes, onion, cabbage, cauli-flower, seasonal vegetables, garlic, zinger, runner beans are the main vegetable items grown there. Mostly, rice is cultivated in the open lands attached to the river valleys while the maize and millet are grown in the elevated gentle slopes where water is scarce and temperature is low. The area is well populated especially along the ridge and the gently dipping northern slopes and is fairly cultivated. The main casts of people living in the area belong to the Gurung and Magar, the ethnic community of Nepalese hills. Their main occupation is security force, labour work and agriculture. They are proved to be pure-hearted and innocent community having their own culture and tradition.

1.5 MAIN GEOLOGICAL PROBLEMS

There are a number of problems and controversies on stratigraphy, tectonics and metamorphism of central Nepal. Some of the major problems associated to the present research in the proposed study area are described below:

1.5.1 Lack of large scale geological maps

Many parts of the Lesser Himalaya in central Nepal still lack large-scale (1:25,000) geological maps. The stratigraphy of the Lesser Himalaya of central Nepal (around Kathmandu region) including that of the overlying crystalline nappe has been established and mapped continuously for about 250 km along the strike from the Sindhuli Garhi in the east to the Mugling area in the west (Stöcklin and Bhattarai 1977; Stöcklin 1980). A considerable part of the Lesser Himalaya between Trishuli and Kali Gandaki rivers has been already mapped by various authors (Sakai 1983; 1985; Hirayama et al. 1988; Dhital 1995; Paudel and Arita 1998; Shretha et al. 1999; Dhital et al. 2002). However, a considerable part of the area west of Mugling still lacks detailed geological map. Among the published maps also, there is no similarity (see Fig. 1.5a and b).

1.5.2 Controversies on stratigraphic classification

Different researchers have given different stratigraphic classification and nomenclature for the Lesser Himalayan rocks in central Nepal (see the stratigraphic classification by Fuchs and Frank 1970; Ohta et al. 1973; Stöcklin and Bhattarai 1977; Sakai 1985; Shrestha et al. 1987; Hirayama et al. 1988; Dhital et al. 2002). It is very difficult to correlate the stratigraphic units by one author with that of others' (Fig. 1.5a and b). Geological maps published by the Department of Mines and Geology at different time have used different classification for the same area (Figs. 1.5b and Figs. 1.6a and b) (Shretha et al. 1987; Jnawali and Tuladhar 1996; 1999).

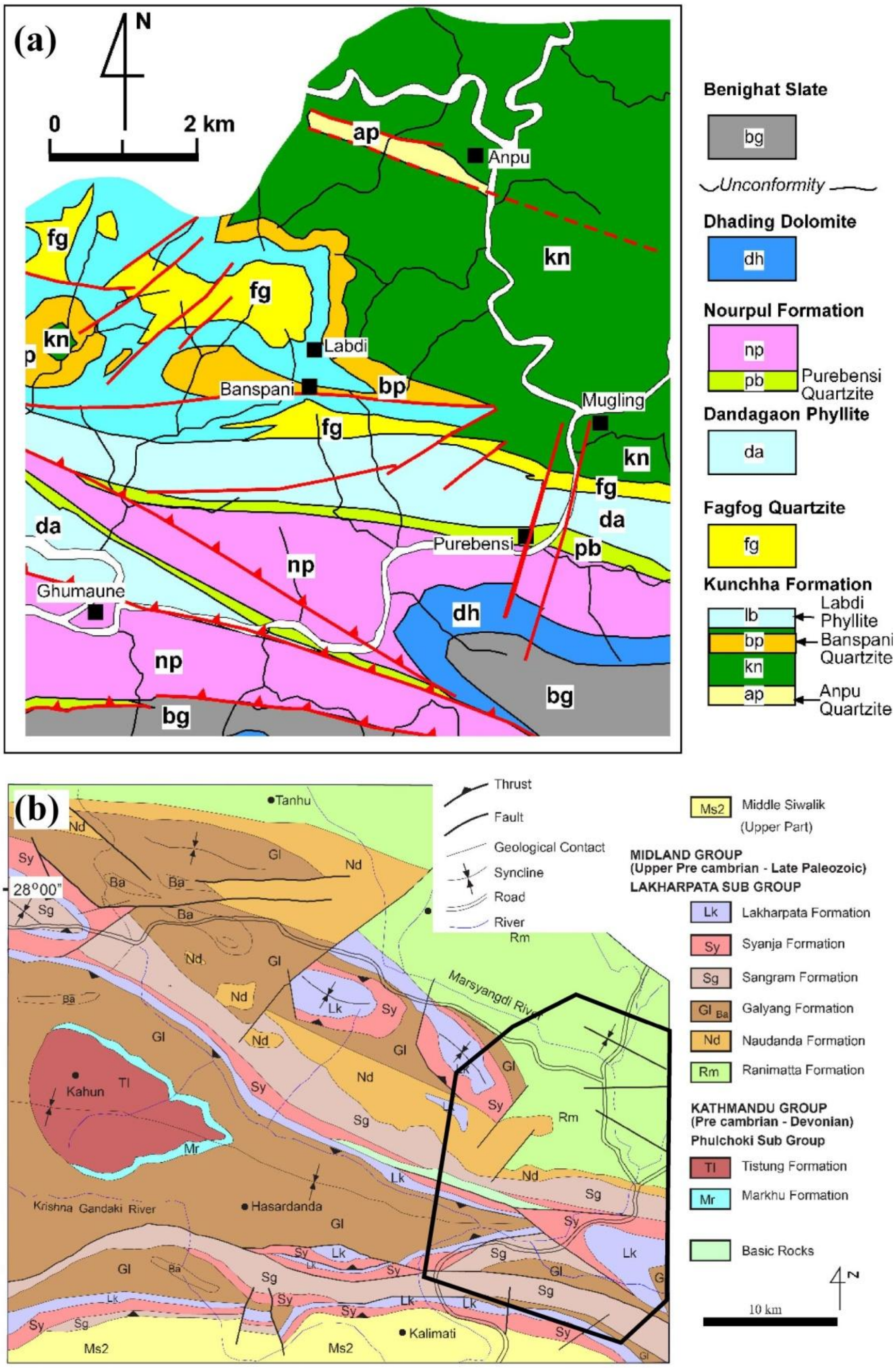


Fig 1.5 (a) Geological maps of the Mugling-Banspani-Anbu Khaireni area of the central Nepal Lesser Himalaya after Stöcklin and Bhattarai (1977). (b) Geological map of the Mugling-Bandipur area of the central Nepal Lesser Himalaya after Shrestha et al. (1987). The area within the box expresents the same area as in the upper map (a). Notice the difference in stratigraphic classification and geological maps. Rm-Ranimatta Formation, Nd-Naudanda Formation, Gp-Ghanpokhara Formation, Gl-Galyan Formation, Sg-Syangja Formation, Lk-Lokharpata Formation, Mr-Markhu Formation, Ti-Tistung Formation.

1.5.3 Problems in structural and tectonic interpretations

Variations in stratigraphic classification of the Lesser Himalaya in the Mugling-Damauli area have created confusion on interpretation of geological structures of the area. For example, Stöcklin and Bhattarai (1977) have shown several thrust faults in the area (Fig. 1.5a). However, Shrestha et al. (1987) have shown a number of klippe and transverse faults in the same area.

The area consists of a crystalline klippe (Kahun Klippe) (Figs. 1.5b and 1.6). Similar crystalline nappe and klippe have been mapped throughout the Himalaya (Auden 1935; Heim and Gansser 1939; Gansser 1964; Hagen 1969; Valdiya 1980 etc.). The origin and root zone of these crystalline thrust sheets is still controversial (see Stöcklin 1980; Rai et al. 1998; Upreti and Le Fort 1999; Johnson et al. 2001) (see §6.4).

1.5.4 Lack of metamorphic study in the low-grade zone

The Lesser Himalaya in the southern part (Mahabharat Zone) is composed of very-low to low-grade metamorphic rocks (chlorite zone). Very little work has been done on the low-grade rocks of the entire Lesser Himalaya. For example, Johnson and Oliver (1990) carried out illite crystallinity measurements in the Kumaun Lesser Himalaya whreas Paudel and Arita (2000; 2006a; 2006b) carried out illite crystallinity and b-spacing studies in the Tansen-Pokhara section of central Nepal. However, the metamorphic evolution of the low-grade rocks in other area of the Lesser Himalaya is still lacking.

1.6 RESEARCH QUESTIONS

To address the above problems, the following research questions are set up for the present research.

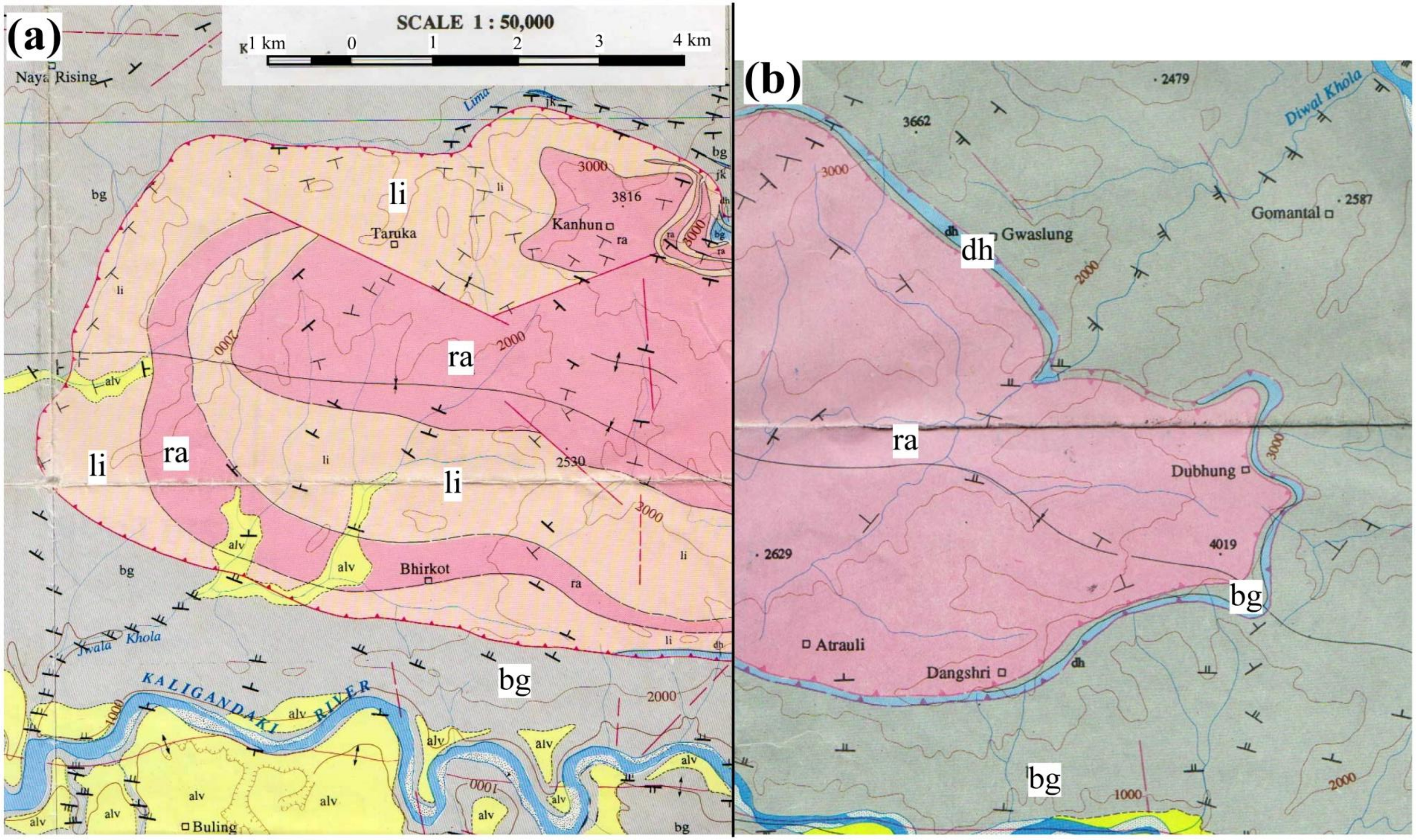


Fig. 1.6 (a) Geological map of the Kahun area after Jnawali and Tuladhar (1999), toposheet no 71A/l. (b) Geological map of the Kahun area after Jnawali and Tuladhar (1996), toposheen no. 72A/5. Notice the geological boundaries of the adjacent area published by the same authors do not match. Their Lima Khola Quartzite in the eastern side (a) has been abruptly truncated along the toposheet boundaries. They have shown tow parallel thrust sheet on the right side while there is only one thrust on the left side. ra-Raduwa Formation, li-Lima Khola Quartzite, bg-Benighat Slate, dh-Dhading Dolomite.

1. Is the stratigraphic classification of Stöcklin and Bhattarai (1977) valid throughout the Lesser Himalaya in central Nepal? Or should it be modified?
2. Is it possible to compare the rocks of the Lesser Himalaya at two different locations based on their physical properties (such Magnetic Susceptibility)?
3. Is the Kahun Klippe the westward extension of the Kahtmandu Nappe?
4. What is the possible root zone of the Kahun Klippe?
5. What is the thin-skinned structural architecture of the area?
6. Does the area express polyphase deformation and metamorphism as in other parts of the Lesser Himalaya?
7. Does the area also show inverted metamorphic zonation?

1.7 LIMITATIONS OF THE RESEARCH

There were several constraints during the research.

1. The research was conducted with very limited laboratory facilities in Nepal. The Central Department of Geology had facility of making thin-sections and X-ray diffraction analysis. Several hours of electricity cut down hampered works in the laboratory.
2. It was very hard to conduct field work due to security problem, frequent transport strike and political agitations.
3. Only the 20% of total cost was supported from research grant. Rest of the cost had to be managed personally.
4. Chemical analysis of rocks and minerals could not be performed due to the lack of such facilities in Nepal and lack of funds to send the samples abroad.
5. Although quite dense traverses were made during the geological mapping, still

there exist many gaps. In such places boundaries were inferred.

1.8 LAYOUT OF THE DISSERTATION

The overall design of the dissertation is based on the format developed and implemented by Dean Office of Science and Technology of Tribhuvan University. The layout of the dissertation is given below.

CHAPTER 1. INTRODUCTION
CHAPTER 2. OBJECTIVES OF THE STUDY
CHAPTER 3. LITERATURE REVIEW
CHAPTER 4. MATERIALS AND METHODS
CAHPTER 5. RESULTS
CHAPTER 6. DISCUSSIONS AND CONCLUSIONS
CHAPTER 7. SUMMARY AND RECOMMENDATION

CHAPTER TWO

OBJECTIVES OF THE STUDY

The following are the major objectives of the present study:

1. To assess the stratigraphic classification of the Mugling-Damauli area by the previous authors and to modify the lithostratigraphic classification if necessary.
2. To measure the magnetic susceptibility of the autochthonous sequence and to judge whether it can be used as a supporting tool for lithostratigraphic correlation.
3. To make a clear understanding on the structural set up, thin-skinned tectonics and deformation history of the study area.
4. To interpret the root zone of the Kahun Klippe and other Lesser Himalayan crystalline nappes and klippes.
5. To establish the metamorphic evolution of the study area.
6. To propose a model for tectono-metamorphic evolution of the study area.

The following are the specific objectives of the present study:

1. To carry out detailed route mapping along different sections of the study area and type locality of Stocklin and Bhattarai (1977), i. e., Malekhu section.
2. To prepare columnar sections of different stratigraphic units in the study area.
3. To compare the rocks of the Kahun Klippe with that of the Kathmandu Nappe, MCT zone and Higher Himalaya.

4. To measure magnetic susceptibility of different rock types of the autochthonous zone.
5. To work out the magnetic susceptibility pattern of the stratigraphic sequence of the autochthnous zone at different sections and compare them.
6. To prepare a detailed geological map and cross-section of the Mugling-Damauli area at 1: 25,000 scale.
7. To trace the major thrusts, faults and folds in the study area and study their characteristics.
8. To study the meso- and micro-structures in the rocks from the study area and establish deformation history.
9. To carry out the petrographic study of the rocks from the study area and to find-out grade of metamorphism and metamorphic zonation.
10. To study the low-grade metamorphism of the area.
11. To evaluate the paleo-temperature of the low-grade zone.

CHAPTER THREE

LITERATURE REVIEW

A large number of research papers have been published on the geological studies of central Nepal till the date with its long history. Based on the nature of geological studies carried in Nepal Himalaya, the total time from the beginning to the date can be tentatively divided into the following periods:

1. Period before 1950 A.D.
2. Period between 1950-1980 A.D.
3. Period between 1981- 2000 A.D.
4. Period after 2001 A. D.

A brief overview of geological studies in these periods is given below. The previous works before 1980 covers all the regional geological works in the Nepal Himalaya. After 1980, there are vast numbers of works in the Nepal Himalaya and it is not possible to review all the works. Therefore, only the works related to the Lesser Himalaya in central Nepal have been reviewed for the period after 1980.

3.1 BEFORE BEFORE 1950 A.D.

Prior to 1950 border of Nepal was closed to foreigners. In this period, only a few geologists could visit the Nepal Himalaya either in their personal relation or in some especial circumstances. Those were reconnaissance type of investigations across some transects of the Nepal Himalaya. Research publications of this time are dispersed and poorly linked to each other. Only a very few publications are available of this period.

Hooker was the earliest geologist visiting eastern Nepal up to the Tamur Valley in

1848 (Gansser 1964). Subsequently Medlicott took a traverse from Amlekhgunj to Kathmandu and Trishuli river section (Medlicott 1875). This was followed by brief visits by a number of other officers of the Geological Survey of India during the period of British rule; *viz.* Jones (1889), Oldham (1899), Diener (1912), Heron (1922) and Sutton (1933). Auden visited Nepal in 1934 for geological investigations in connection with the Great Bihar-Nepal earthquake of 1934 (Auden 1935). He presented several cross-sections across the Himalaya supporting the nappe concept earlier proposed by Argand (1924), who never visited the Himalaya. Auden noticed the superposition of high-grade metamorphic rocks on the top of low-grade metamorphic rocks in the Mahabharat Range. Heim and Gansser (1939) mapped one of the intra-crustal thrusts of the Himalaya, the Main Central Thrust (MCT). They reported the Norian faunas from northeastern Nepal.

3.2 PERIOD BETWEEN 1950 -1980 A. D.

Systematic geological studies in Nepal Himalaya were started from 1950 when Nepal opened its borders to foreigners. In this time period, most of the geological studies were concentrated for regional geological mapping (mainly in 1:50,000, 1:63,000 and 1:253,400 scales), for the establishment of stratigraphy and the regional geological structures for large scale tectonic interpretation. Tony Hagen, a Swiss geologist, started his field investigation of the Nepal Himalaya in 1950 under the United Nations Programme of Technical Assistance and covered most part of the country. After more than 10 years of field survey, he published his findings in two volumes (Hagen 1969). He recognized more than 20 nappes in the Nepal Himalaya. Based on lithology, these nappes can be categorized into two types: one type consists of crystalline rocks while other type consists of meta-sediments. Three of his higher nappes from bottom to top are the Kangchendozonga-Lumbasumba Nappe, the Khumbu Nappe and the Kathmandu Nappe consisting predominantly of crystalline rocks and the rest of the nappes were mainly composed of meta-sediments. Hagen (1969) divided the geology of the Kathmandu area into two nappes, the Kathmandu Nappe and Nawakot Nappe (Fig. 3.1). The distinction of these nappes was based on differences in composition and metamorphic grade and on an assumed difference in age. Based on lithological comparisons with the Alps, Hagen (1969) placed the Nawakot Nappe (or in more recent terminology the Nawakot Complex and in the present study the Nuwakot Group) in the Palaeozoic-Mesozoic and thus considered it to be younger than the overlying Kathmandu Nappe (=Kathmandu Complex) of Precambrian-Early Paleozoic age. This apparently abnormal superposition was explained by tectonic emplacement. Further, the Kathmandu Complex was interpreted as an erosion relict of a once extensive thrust sheet, rooted in the central crystalline and today still linked with it by a ‘tectonic bridge’ formed of the Gosaikund gneisses north of Kathmandu.

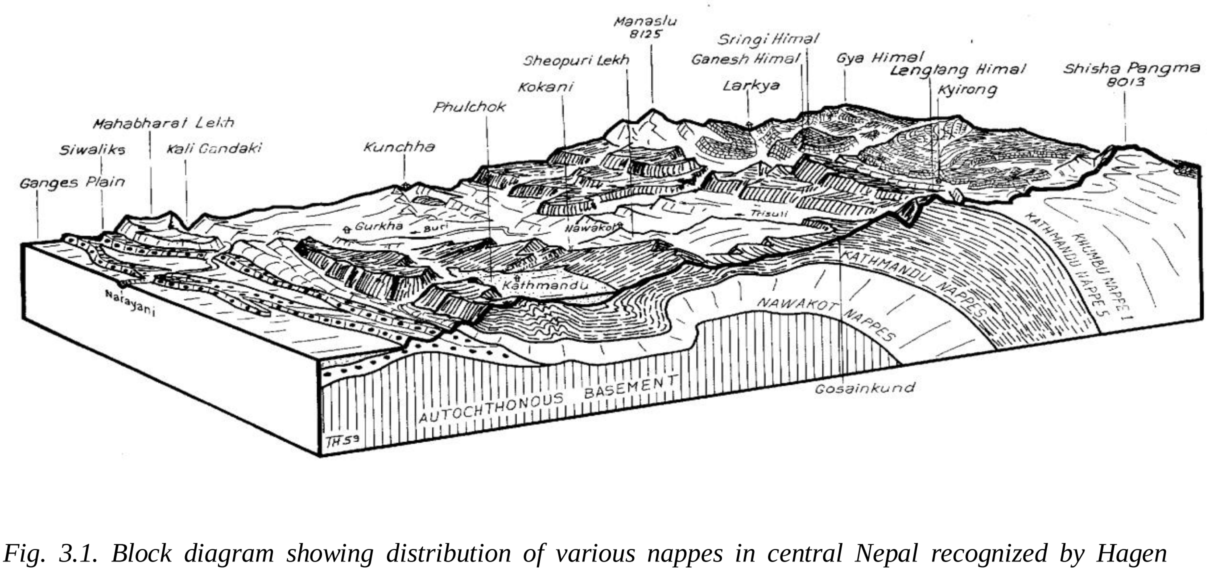


Fig. 3.1. Block diagram showing distribution of various nappes in central Nepal recognized by Hagen (1969).

Lombard (1958) carried out studies in the Everest region. Bordet et al. (1961) visited Phulchoki area south of Kathmandu and noticed the trilobite fossils of Silurian age. Bordet (1961) carried out studies in the Everest and Makalu-Arun regions, and published the first geological report from the Nepalese Himalaya. Gansser (1964) gave a broader framework and geological summary of the Himalaya including the Nepal Himalaya. He divided the Himalaya into four tectonic zones separated by major thrusts.

Nanda (1973) carried out more detailed (1:253,400) field mapping in the region east of the Kali Gandaki River and west of the Marsyangdi River. He separated the following formations from bottom to top respectively: the Bhimphedis, Grits, Quartzites, Grey Phyllites, Purples, Grey Dolomites, Carbonaceous Shales, Tansens (Khakis), and Siwaliks.

Fuchs (1967), Fuchs and Frank (1970) and Frank and Fuchs (1970), carried out geological investigation in western Nepal including some parts of central Nepal and correlated the stratigraphic units with that of the Garwal Himalaya in India. Fuchs considered that some Lesser Himalayan nappes (similar to his Chail Nappe) are represented throughout the Himalaya (Fuchs 1977). A team of geological researchers from the Hokkaido University, Japan conducted several geological expeditions in the Nepal Himalaya from 1955 to 1970 and published their results in 1973 (Hashimoto et al. 1973). It gives the first detailed account of geology, stratigraphy, tectonics and metamorphism covering almost all of the Nepal Himalaya. They recognized a number of block faults in central Nepal. Present study area lies in the Mahabharat, Kekmi-Bandipur and Kunchha-Gorkha Anticlinorium Zones in their geological map (Fig. 3.2). They suggested that the essential structures of the Nepalese mountain range resulted from longitudinal block movements with several vertical displacements and not from the Alpine folding as described by Hagen (1969).

After 1970, a group of French researchers including P. Bordet, P. Le Fort, A. Pêcher, and M. Colchen started geological investigations in central Nepal. They have published a detailed geological map and a number of papers related to the tectonics, metamorphism and magmatism in central Nepal (e.g. Bordet et al. 1972; Le Fort 1975; Pêcher 1975; 1977; Colchen et al. 1980). They investigated inverted metamorphism along several sections of central Nepal and explained it as due to the over thrusting of hot Higher Himalaya over the cold Lesser Himalaya (Le Fort 1975).

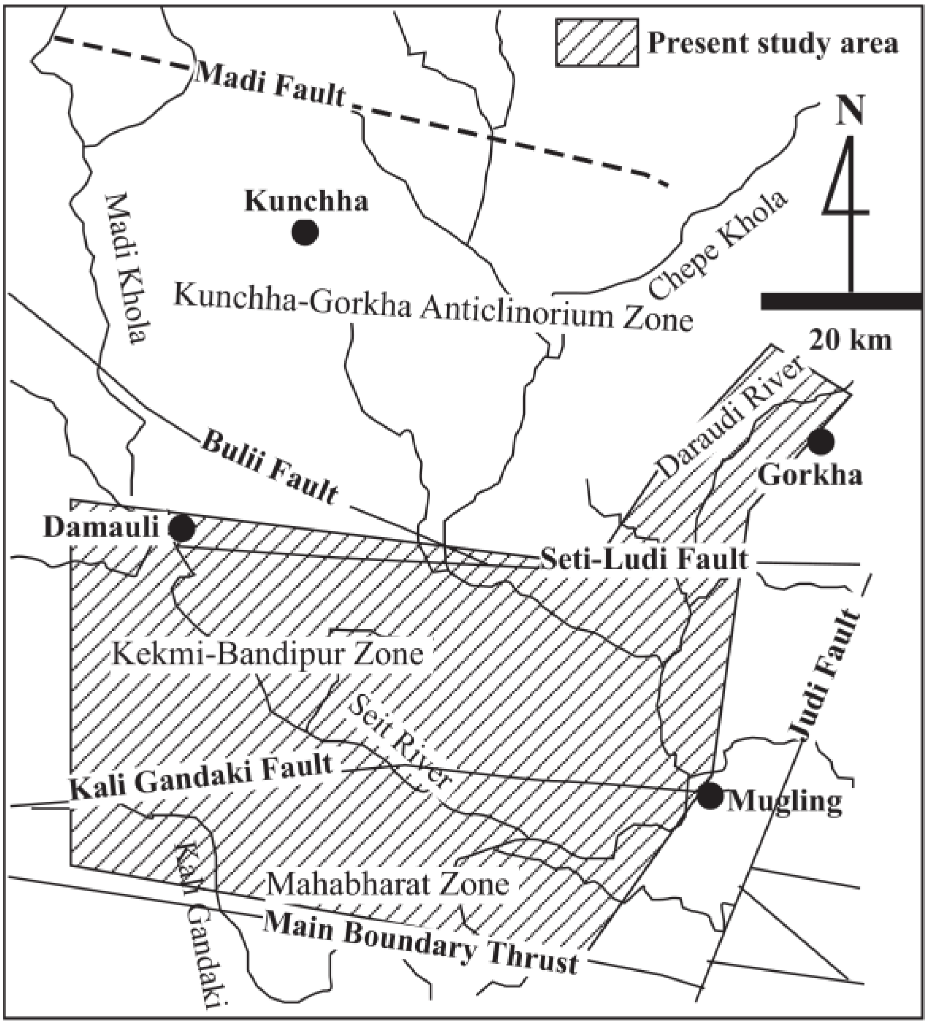


Fig. 3.2. Geological division of the Mugling-Damauli area after Ohta et al. (1973).

Nadgir et al. (1968-1973) rejected the nappe structure and believed in a stratigraphically continuous Nawakot-Kathamandu sequence; ending with Palaeozoic fossiliferous beds at top. The discovery of stromatolites of presumed Precambrian age in Nawakot Nappe rocks seemed to support this view. The higher metamorphic grade of the

Kathmandu Nappe rocks was considered to have been caused by heating from the granites that form a part of the Kathmandu Nappe.

Sharma (1977) studied the geo-tectonics of the Kathmandu block on the basis of lithology, stratigraphy and structure. According to him, there exists an anticlinorium to the north and a synclinorium to the south of the valley which itself is a faulted anticline.

Brunel et. al. (1979) studied the tectonic evolution of the central Himalaya of Nepal in terms of structural analysis. They found that the tectonic activity during the Himalayan orogenesis was migrating southward. First and second phase of deformation were related to the MCT movements. The MCT shear zone was active during upper Oligocene-Lower Miocene but the tectonic movements were initiated as early as Eocene and were responsible for metamorphism, granitization and formation of major cleavage in rocks of the area. Afterwards, the MCT zone witnessed deformation of third, fourth and fifth phases. They also interpreted the MBT as a superficial equivalent of a shear zone similar at depth to the MCT on the basis of seismicity.

Stöcklin and Bhattarai (1977) and Stöcklin (1980) carried out a comprehensive geological mapping of the central Nepal Lesser Himalaya and Kathmandu Nappe. Their stratigraphic classification for central Nepal Lesser Himalaya and Kathmandu Nappe has been still widely adopted as a pioneer work of the region. They divided the rocks of this region into two complexes-medium grade crystalline rocks with fossiliferous sedimentary cover at the top named as the Kathmandu Complex (the Kathmandu Nappe) and beneath it the non-crystalline, low-grade meta-sedimentary rocks as the Nawakot Complex. Their stratigraphic classification is given in Table 3.1. The frontal part of the Kathmandu Complex is separated from the Nawakot Complex by a thrust known as the Mahabharat Thrust (MT) (Stöcklin 1980) and is shown to be a direct continuation of the MCT

(Stöcklin 1980; Fuchs 1981).

Tribhuvan University started B. Sc. in Geology (in 1967) and M. Sc. and PhD in Geology (in 1976) for the first time in Nepal. MSc and PhD students were involved in geological research of the Himalaya for their dissertation. Department of Mines and Geology (DMG) was also established in the same time (1967) by the Government of Nepal. The DMG started systematic mapping and mineral exploration of whole Nepal.

Table 3.1: Stratigraphic sub-division of central Nepal Lesser Himalaya (After Stöcklin and Bhattarai 1977; Stöcklin 1980).

Complex	**Group**	**Formation**	**Main lithology**	**Thickness**	**Age**
Kathmandu Complex	**Phulchauki Group**	Godavari Limestone	Limestone	300–400 m	Devonian
		Chitlang Formation	Slate, quartzite	1000 m	Silurian
		Chandragiri Limestone	Limestone	2000 m	Cambrian
		Sopyang Formation	Slate, calc. Phyllite	200 m	Cambrian (?)
		Tistung Formation	Metasandstone, Phyllite	300 m	Early Cambrian or Late-Precambrian
	Bhimphedi Group	Markhu Formation	Marble, schist	1000 m	Late Pre-Cambrian
		Kulikhani Formation	Quartzite, Schist	2000 m	Pre-Cambrian
		Chisapani Quartzite	White quartzite	400 m	Pre-Cambrian
		Kalitar Formation	Quartzite, schist	2000 m	Pre-Cambrian
		Bhainsedobhan Marble	Marble	800 m	Pre-Cambrian
		Raduwa Formation	Garinitiferous schist	1000 m	Pre-Cambrian
Mahabharat Thrust					
Nawakot Complex	**Upper Nawakot Group**	Robang formation	Phyllite, quartzite	200–1000 m	Early Paleozoic
		Malekhu Limestone	Limestone, dolomite	800 m	Early Paleozoic
		Benighat Slates (Jhiku Carbonates)	Slate, argillaceous dolomite	500–3000 m	Early Paleozoic
	?Erosional Unconformity				
	Lower Nawakot Group	Dhading Dolomite (with Husdi Beds)	Stromatolitic Dolomite	500–1000 m	Pre-Cambrian
		Nourpul Formation (with Purebensi Quartzite)	Phyllite, Meta-sandstone	800 m	Pre-Cambrian
		Dandagaun Phyllites	Phyllite	1000 m	Pre-Cambrian
		Fagfog Quartzite	White Quartzite	400 m	Pre-Cambrian
		Kunchha Formation (with Anpu Quartzite, Labdi Phyllite and Banspani Quartzite)	Phyllite, Quartzite	3000 m	Pre-Cambrian

3.3 PERIOD BETWEEN 1981-2000 A. D.

In this period many foreign and Nepalese researchers worked in the Nepal Himalaya and published a number of papers on geology, stratigraphy, sedimentology, paleontology, structure, metamorphism, magmatism, thermobarometry and geochronology.

Upreti et al. (1980) identified stromatolites of the Dhading Dolomite as *collenia* and *conophytons* and assigned the Middle to Upper Riphean age for them.

A team of Japanese geologists in collaboration with the Nepalese geologists carried out geological research from 1980 to 1984 under the project "Crustal Movements in the Nepal Himalaya". The results were published in special issues 2 in 1982 and 4 in 1984 of the Journal of Nepal Geological Society.

Many Japanese and Nepalese geologists have carried out individual researches in central Nepal. For example, Arita (1983) studied the inverted metamorphism in the Modi Khola section and explained the phenomenon of shear heating along the MCT zone. Sakai (1983, 1985) carried out geological mapping in the Tansen area, immediately western part of the presently studied area. He divided the rock units of the area into the Kaligandaki Supergroup (Late Precambrian-Early Palaeozoic) and the Tansen Group (Late-Carboniferous-Permian to Oligocene-Early Miocene).

Tater et al. (1984) compiled a geological map of western Nepal by different authors and indentified six stratigraphic units in the Kusma-Galyang area. They showed two quartzite units in the area namely the Kusma Formation and the Naudanda Formation above and below the Seti Formation.

Pêcher and Le Fort (1986) mentioned that crystalline rocks of the Lesser Himalaya, such as the Almora and Kathmandu Nappes are the thrust outliers of the Higher Himalayan Crystalline (HHC).

Department of Mines and Geology (Shrestha et al. 1987) has published a geological map of central Nepal by compiling the geological maps prepared by several geologists of DMG and other previous researchers in 1:250,000 scale. In this map, the Lesser Himalayan rocks of central Nepal including the present study area has been divided into three groups as the Kathmandu Group (Pre-Cambrian to Devonian) with Bhimphedi and Phulchoki Sub-groups, Midland Group (Upper Precambrian to Late Palaeozoic) with Lakharpata and Dailekh Sub-groups and Surkhet Group (Cretaceous to Eocene). They have used different stratigraphic classification than that of Stöcklin and Bhattarai (1977) and Sakai (1985). Their map shows a small klippe around the Kahun area, southwest of Mugling (Fig. 1.5b). The lithological units of this klippe are represented by the rocks of the Markhu Formation and the Tistung Formation of the Kathmandu Group.

Hirayama et al. (1988) carried out a detailed geological mapping in the Tansen-Syangja, Khaireni-Basini, and Syangja-Khaireni areas and published several colored geological maps. They distinguished the following formations in the Naudanda-Galayang area from bottom to top respectively: the Kuncha Formation, the Naudanda Quartzite, the Uniayachaur Slate, the Syangja Formation, the Darsing Dolomite, the Galyang Slate and the AnghaKhola Formation. They interpreted the structure of the area in terms of vertical faults and thrusts.

Pêcher (1989) found that the metamorphic grade increases from low-(chlorite+biotite+zeolite) to medium-grade (biotite+garnet+kyanite±staurolite) over a north-south distance of ~20 km towards the MCT, with the highest-grade Lesser Himalaya rocks found within the shear zone.

Arita et al. (1990) studied the K-Ar ages on biotite from a pelitic gneiss and on hornblende from a calcareous gneiss both from the Higher Himalaya of Nepal. The ages reflected two major cooling histories: the old one of late Cretaceous to Eocene, and the young one of late Eocene-Oligocene to the present.

Morrison and Oliver (1993) studied the illite crystallinity and fluid inclusions in the rocks of the Kathmandu Nappe and the MCT zone in central Nepal. They suggested that the Kathmandu Klippe was not significantly heated during more than 100 km of Tertiary thrusting.

Dhital (1995) carried out geological mapping in the Gorkha-Ampipal area, north of the present study area. According to his map, the area from Anpu Khaireni to Gorkha is covered by low-grade metamorphic rocks of the Kuncha Formation. A noteworthy feature in the area is the presence of several intrusive bodies of nepheline syenites within the Kunchha Formation as already noted by Colchen et al. (1980).

Paudel and Dhital (1996) carried out geological mapping in the Pokhara-Kusma area, western Nepal. Paudel and Arita (2000) also carried out the geological studies on the Lesser Himalayan rocks between Palpa and Pokhara area. They divided the area into four tectonic units namely the Parautochthonous Unit, Thrust Sheet I, Thrust Sheet II and the MCT Zone. The Bari Gad-Kali Gandaki Thrust is regarded as the out-of-sequence thrust like the Sun Koshi Thrust in eastern Nepal. These out-of-sequence thrusts played an important role in the rapid uplift of the Higher Himalaya (similar to the MCT) since the Late Pliocene. They recognized five deformational and three metamorphic events in the area.

Kaneko (1995, 1997) studied the metamorphism in the MCT zone along the Modi Khola valley. He carried out thermobarometry of the zone and found an inverted thermal profile across the MCT.

Parrish and Hodges (1996) reported U-Pb ages of 1870-2600 Ma for detrital zircons from Kunchha Formation in the Trisuli Valley of central Nepal.

Jnawali and Tuladhar (1996; 1999) carried out more detailed mapping (1:50,000 scale) of the Kahun Klippe and they correlated the rocks of the Klippe with the Raduwa Formation of the Bhimphedi Group (Fig. 1.6). A quartzite member (Lima Khola Orthoquartzite) is shown to exist at the base of the klippe. They divided the Lesser Himalayan autochthonous successions as the Lower and Upper Nawakot Groups. They have adopted the stratigraphic classification of Stöcklin and Bhattarai (1977) for the autochthonous succession. In their work, the Nourpul Formation is divided into three members as np_1, np_2 and np_3.

Rai et al. (1998) mentioned that the Kathmandu-Gosainkunda region can be divided into a Gosainkunda Crystalline Nappe (GCN), corresponding to the continuous HHC of Langtang and a Kathmandu Crystalline Nappe (KCN) representing an out-of-sequence thrust sheet in the Lesser Himalaya. The boundary between the two nappes corresponds to their definition of the MCT.

Dhital et al. (1998) carried out geological mapping in the Kusma-Syanga-Galyan area and published geological map in 1:50,000 scale. He found many overturned folds and back-thrusts in the area.

Upreti and Le Fort (1999) interpreted the crystalline nappes/klippes of the Lesser Himalaya as exotic slices. They highlighted the problem of origin of the crystalline thrust sheets in the Lesser Himalaya. They proposed two thrusts models to explain the origin of the thrusts. Upreti (1999) gave an overview of the stratigraphy and tectonics of the Nepal Himalaya.

Guillot (1999) gave an overview of the metamorphic evolution in central Nepal. He suggest that the overall metamorphic history in central Nepal from Oligocene to Pliocene, reflects the thermal reequilibration of rocks after thickening by conductive and advective heating and partial melting of the middle crust.

3.4 Period after 2000 A. D.

Recent works in the Lesser Himalaya of central Nepal are more concentrated on geothermometry, geochronology, microstructures and uplift and erosion. Most of the geological studies are based on the laboratory investigation of samples. Some of the authors have also provided review of previous works in the region.

Robinson et al. (2001, 2003) interpreted the kinematic history of the MCT zone in central Nepal. They presented a kinematic model for the Himalayan thrust belt in the MCT zone in Nepal and showed that, the MCT juxtaposes a hanging-wall flat in Higher Himalayan rocks with a footwall flat in Lesser Himalayan rocks. Few kilometres below the MCT, within the Lesser Himalaya, they proposed that a major thrust occurred, the Ramgarh Thrust, essentially along the whole orogen, forming the Ramgarh Thrust Sheet. The Ramgarh Thrust is the roof thrust to a large Lesser Himalayan duplex. Sequential emplacement of the Main Central (early Miocene) and Ramgarh (middle Miocene) thrust sheets was followed by insertion of thrust sheets within the Lesser Himalayan duplex and folding of the MCT and Ramgarh Thrust during late Miocene–Pliocene times.

Johnson et al. (2001) carried out metamorphic and geo-chronological studies of the Kathmandu Complex rocks. They studied the MCT/ MT exposed at the Malekhu Khola and Trishuli Ganga and at the Rapti Khola north of Hetaunda and refused the concepts of Rai et al (1998) and Upreti and Le Fort (1999).

Pearson (2002) mapped several parts of central Nepal and showed that, with few exceptions, the Ramgarh Thrust, which accommodated >120 km of tectonic shortening, carries rocks of the Robang Formation, Kushma and Ranimata Formations, or their equivalents. They also noted that after movement on the MCT ended, in the middle Miocene, and before displacement on the MBT began in the Pliocene, tectonic shortening was accommodated by structures contained within Lesser Himalaya. The Ramgarh Thrust was active during the middle Miocene in western Nepal, between 15 and 11 Ma but in central Nepal the thrust may have been active somewhat later.

Gehrels et al. (2003) argued that the Himalayan orogenic belt was initiated as an Early Paleozoic thin-skinned thrust belt. They presented a number of evidence to show early Paleozoic tectonism in the Kathmandu Complex rocks.

Beyssac et al. (2004) measured thermal structure of the Nawakot Complex rocks along the Kathmandu-Pokhara road using Raman Spectroscopy of Carbonaceous Materials (RSCM). This study revealed that the Lesser Himalaya has undergone a large-scale thermal metamorphism, with temperature decreasing progressively from about 540^0C at the top to less than 330^0C within the deepest exhumed structural levels.

Johnson (2005) carried out critical evaluation of the thrust sheets in Nepal and ruled out the existence of two crystalline thrust sheets in central Nepal.

Wobus et al. (2005) found an active out-of-sequence thrust fault in central Nepal Himalaya and interpreted that the Quaternary accelerated uplift in the Higher Himalaya was caused by the out-of-sequence fault.

Cameron et al. (2006) carried out neo-tectonics of the central Nepalese Himalaya from geomorphology, detrital $^{40}Ar/^{39}Ar$ thermo-chronology, and thermal modeling. They observed the sharp physiographic transition between the Lower and the Higher Himalaya in central Nepal as a suggestive of spatial gradients in rock uplift rates over relatively short (10 km) length scales. The general coincidence between this physiographic transition and a change from reset to unreset detrital $^{40}Ar/^{39}Ar$ dates in the Burhi Gandaki, Trisuli, and Bhote Kosi valleys suggests that these gradients in rock uplift have persisted at least long enough to preserve a prominent discontinuity in cooling history within the Lesser Himalayan sequence.

Paudel and Arita (2006a) studied the compositional variation on K-white micas and interpreted the thermal evolution of the Lesser Himalaya in central Nepal. The K-white micas show at least two prograde thermal events in the LH.

Sah (2007) critically reviewed the stratigraphic schemes of the Nepal Lesser Himalaya by different authors and tried to develop an integrated workable stratigraphic scheme (Table 3.2).

Acharya (2008) carried out the geological, structural, geochemical and geo-chronological studies of central Nepal in the vicinity of the Kathmandu valley. He interpreted the MCT as a stretching thrust fault, where wall rocks lengthen parallel to the shear direction.

Paudel (2008) studied the metabasites of the Lesser Himalaya along the Modi Khola valley in central Nepal. He found that the metabasites also record at least two prograde metamorphic events in the Lesser Himalaya.

Kohn et al. (2010) discussed several lines of evidence to argue that the Paleoproterozoic assemblage at the base of Lesser Himalayan sequence represents a continental arc, rather than a passive margin, a collision belt, or a plume- or rift-related environment.

Alexander et al (2011) proposed a new model to resolve the Lesser Himalayan crystalline nappe problems. They discovered southern extension of the South Tibetan Detachment along the northern margin of the Kathmandu Nappe. They interpreted that the right-way-up metamorphic sequence of the Lesser Himalayan Crystalline Nappe is continuous across the South Tibet Detachment and the MCT hanging walls.

Sapkota (2011) carried out the study of structures, metamorphism and tectonics of the Kathmandu Nappes and its adjacent areas. He noted five generations of foliation preserved in the matrix and shear sense associated with them formed as a result of the motion on the MCT followed by folding at a regional scale by the Gorkha-Kathmandu fold couplet plus other deformation events.

Rai (2011) reviewed the lithostratigraphy of the Nawakot Complex from Malekhu to Syabrubensi area along the Trishuli River. He reported the transitional contact between the Dhading Dolomite (Lower Nawakot Group) and the Benighat Slate (Upper Nawakot Group) in the Galchi-Kaljeri section.

Thapaliya and Paudel (2011) carried out geological study along the road from Kathmandu to Trishuli Bazar covering both the Lesser Himalayan autochthonous unit and the Kathmandu Nappe. They reported clear evidence of inverted metamorphism at the footwall of the Lesser Himalayan crystalline nappe.

Paudel (2011) carried out the K-Ar dating of white mica from the Lesser Himalaya, Tansen-Pokhara section, central Nepal. He found that the K-Ar dates also support the concept of pre-Himalayan metamorphism in the Lesser Himalaya.

Khanal and Robinson (2013) prepared a balanced cross-section along the Budhi-

Gandaki River in central Nepal. They estimated crustal shortening of about 400 km in the region. They also explained the existence of the Ramgarh Thrust in Malekhu area.

In the context of Nepal Lesser Himalaya, still there is vast room for research on stratigraphy, structure and metamorphism. Keeping these views in mind, the present study was aimed to clarify the stratigraphy, locating geological structures and carry out metamorphic studies of the Muglin-Damauli area as this is the core part of the Lesser Himalaya in central Nepal. Presence of both autochthonous and allochthonous crystalline rocks in this area have made the study more integrated and problem orientated.

Table 3.2-1: Stratigraphic Classification Schemes Developed by Researchers for Precambrian Metasedimentary Succession of Nepal Lesser Himalaya (after Sah 2006).

Scheme	Group	Subgroup	Formations (top to bottom)
Hashimoto et.al. 1973	Midland Metasedimentary Group	Upper Subgroup (Calareous Succession)	
		Middle Subgroup (Silliceous Succession)	
		Lower Subgroup (Arenaceous Succession)	
		Lowermost Subgroup (Argillaceous Subccession)	
Stöcklin 1980	Upper Nawakot Group		Robang Fm; Malekhu Limestone; Benighat Slate; Dhading Dolomite
	Lower Nawakot Group		Nourpul Fm; Dandagaon Phyllite; Fagfog Quartzite; Kuncha Fm
Tater et.al. 1983	Midland Group	Lakharpata Subgroup	Lakharpata Fm; Syangja Fm; Sangram Fm; Galyang Fm
		Pokhara Subgroup	Ghan Pokhara Fm; Naudanda Fm; Seti Fm; Kusma Fm; Ulleri Fm
		Dailekh Subgroup	Ranimatta Fm
		Jaljala Subgroup	Surbang Fm; Siuri Fm
Arita et al. 1984	Midland Mesediment Group		Black Slate; Dolomite Fm; Varigated Fm; Phyllite Fm; Quartzite Fm; Quatrzose Sandstone Fm
T. Sharma et al. 1984	Nawakot Group		Surtibang Dolomite; Variegated Fm; Harichour Fm
	Kunchha Group		Hatiya Fm; Kunchha Fm
Sakai 1983, 1985		Kaligandaki Subgroup	Kerabari with Riri member; Ramdighat Fm; Saidi Fm; Khoraidi Fm
			Chappani Fm; Virkot Fm; Heklang Fm; Naudanda; Andhi (Kuncha)
Dhital & Kizaki 1987	Gwar Group		Ranibas Fm; Sirchaur Fm; Dharbang Fm; Hapurkot Fm; Khamari Fm; Ranagaon Fm
	Sharada Group		Balle Quartzite; Dangri Fm
Hirayama et al. 1988	Nawakot Group		Ramdighat Fm; Anghakola Fm; Galyang Slate; Darsing Dolomite; Syangja Fm; Uniyachaur Slate; Naudanda Quartzite; Kuncha Fm
Poudel & Dhital 1996	Upper Nawakot Group		Benighat Slate
	Lower Nawakot Group		Dhading Dolomite; Nourpul Fm
	Kaski Group		Balewa Fm; Naudanda Quartzite; Seti Fm
Dhital et al. 2002			Dhanpure Limestone; Sorek Fm; Benighat Slate; Dhading Dolomite; Nourpul Fm; Nayagaun Fm; Naudanda Quartzite; Kunchha Fm

CHAPTER FOUR

METHODS AND MATERIALS

A wide variety of methods and materials were used to collect the primary and secondary data to complete the present research. The methods used in the present research are presented in seven broad topics namely (i) desk study, (ii) field study, (iii) laboratory analysis, (iv) data analysis, (v) data synthesis and interpretation, (vi) presentation and publication of data and (vii) dissertation writing. Each step has been elaborated and discussed in the following sections. The methodology used in the present study has been summarized in Fig. 4.1.

4.1 DESK STUDY

This includes study of any relevant research already undertaken and other sources of information about the geology of the study area. Preliminary geological informations about the study area were gathered through review of the published and unpublished geological reports, books, PhD theses and research articles. Materials were collected from libraries, online-journals and different websites. Many e-copies of articles were provided by friends living abroad. Extensive discussions were made with members of Central Department Research Committee (CDRC) and other experts.

Similarly, informations were collected also from the study of the topographic maps, aerial photographs and satellite images in the google map (https:// maps.google.com/). The topographic sheet of Mugling (2784 03C), Jugedi Bazzar (2784 02D), Kota (2784 02C), Sinchuwa (2784 01D), Anbu Khaireni (2784 03A), Dumre-Bandipur (2784 02B), Damauli (2784 02A) and Naya Risin (2784 01B) in 1:25,000 scale were used for the study.

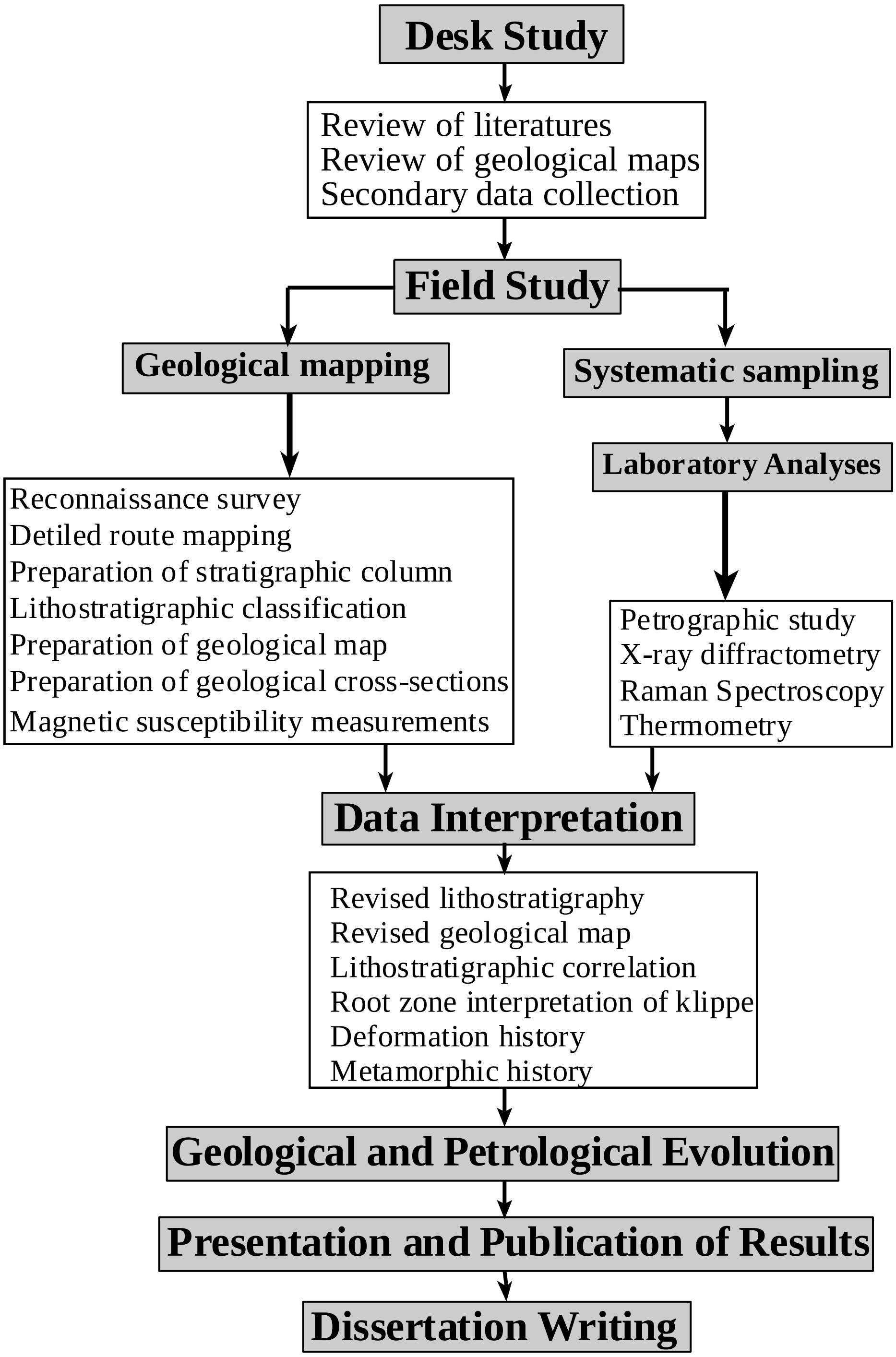


Fig. 4.1. Methodological flow chart.

Main geological problems, controversies and issues in central Nepal, particularly in the Mugling-Damauli area were identified through the desk study. This helped in the identifying main geological problems and formulation of research objectives, methodology and planning of the field and laboratory works.

4.2 FIELD STUDY

This research is mainly based on the field study of the area. Therefore, most of the research period (80%) was spent in the field. Field work was started from January, 2009 and was continued till April, 2013. A total of 9 month time was spent in the field survey with one or two assistant geologists or with some helpers in each field visit. During this period 17 field trips were organized. The duration of the trips varied between one week to one and half months. The main purpose of the field work was to assess the lithology, stratigraphy and geological structures of the area and to prepare a geological map in 1:25,000 scale. The other purpose was to collect samples for the laboratory analysis.

The field study was carried out with the help of Brunton compass, geological hammer, measuring tape; 1:25000 scale topographic base maps, GPS, altimeter, digital camera, hand lens and 10% dilute Hydrochloric Acid.

The field work can be divided into seven topics based on the nature of the work in the field.

4.2.1 Reconnaissance surveys

The first step in geological mapping is to identify the mappable lithological units in the area. For this reconnaissance surveys were carried out across different sections in the study area and adjacent regions. Straitgraphic classification of Stöcklin and Bhattarai

(1997) and Stöcklin (1980) is the most adopted classification for the central Nepal Lesser Himalaya in Nepal. Therefore, first reconnaissance field survey was performed along the Malekhu-Thople Khola and Kulekhani-Hetauda sections in central Nepal to assess the stratigraphic units of Stöcklin and Bhattarai (1977). These sections were selected because most of the type localities of the rocks units proposed by Stöcklin and Bhattarai (1977) lie along these sections. These surveys provided information about the lithological characteristics of each unit defined by Stöcklin and Bhattarai (1977).

It was followed by reconnaissance surveys in the present study area along the Mugling-Narayangarh road and Trishuli River section, Mugling-Bandipur road section, Anpu-Khaireni-Gorkha Bazzar road section, Ghumaune-Damuli road section, Damauli-Kahun road section and Gwaslung-Sonde foot trail. Major mappable lithological units were identified from the survey. These surveys also gave an idea about the overall orientation of the strata, major structure and metamorphic condition. Reconnaissance surveys helped in developing detailed field study plan. Sections for detailed route maps were selected, possible traverse routes for mapping were fixed and possible camp sites were selected.

4.2.2 Detailed route mapping

Two major routes (i) Mugling-Narayangarh section and the (ii) Gwaslung-Kahun-Shivapur sections were selected for detail route mapping. The first route covered many of the rock units of the Lesser Himalayan autochthon. The second route covered all rock units of the crystalline klippe at Kahun-Dubun area. Route mapping was also carried out along the Malekhu-Thople Khola section of Dhading District and also along the Kulekhani-Markhu road of Makawanpur districts for comparison.

Route maps were prepared mostly in 1:1000 scale. Wherever more detailed information was needed, mapping was carried out in 1:100 or 1:10 scales. The length was measured with the help of 30 m measuring tape, bearings were taken with the help of Brunton compass, thickness of each bed were measured with tape. All the data were plotted on the A4 size graph papers to produce the geological route map. Attitudes of the beds, lithology, sedimentary structures and fossil contents were also shown by standard symbols.

4.2.3 Preparation of stratigraphic columns

Stratigraphic columns showing the rock succession of the area were prepared on the A4 graph from the route maps. Younging direction of the strata were identified with the help sedimentary structures such as ripple marks, mud cracks, graded beddings, cross-laminations and stromatolites. True thickness of the strata was calculated using trigonometry. In some places, detailed stratigraphic columns were prepared by directly measuring the true thickness of the strata on the outcrop. Detailed columns were prepared for each mappable rock units and important lithological and tectonic boundaries.

4.2.4 Lithostratigraphic classification

Before starting the aerial geological mapping of the area, the strata were classified into different stratigraphic units. For this “International Stratigraphic Code” (Murphy and Salvador 1999) was followed. The strata were first classified into formations. Attempts were made to retain the definition, classification and name of the units proposed by the previous authors such as Stöcklin and Bhattarai (1977) and Stöcklin (1980) as far as possible. Wherever entirely different stratigraphy was observed, new formations and members were established. Names of the new units were given from the geographic name of the area where the unit is best exposed.

4.2.5 Preparation of geological map

The main task of the field study was to prepare the geological map in 1:25,000 scales. After clarifying the stratigraphy of the area, geological mapping was started from most accessible and well-understood part of the area, i.e., the Mugling-Narayangarh section. Attempts were made to extend the boundaries westward from the road section. Camps were set for 3 to 4 days at one place and traverse routes were fixed around the camp. And the camps were gradually shifted westwards. Most of the traverse lines were selected across the strike of the strata so that boundaries of many units could be traced along the route. The field data were transferred to a base map kept at the camp every evening to produce a fair copy. Data collection method was as in the route mapping. The traverse routes used in the present mapping are shown in Fig. 4.2.

Eight topographic maps of 1:25,000 scale covering about 1000 square km area was mapped in the present study. It covers mainly the Tanahu district and parts of the Chitwan, Nawalparasi and Lamjung districts. Final fare copy of the map was prepared using the software ArcGIS9.3.

4.2.6 Preparation of geological cross-sections

Geological cross-sections were made across two parallel sections, one along Jugedi-Anbu Khaireni and the other across Kota-Kahun-Damauli. It was prepared manually on the graph paper. The boundaries of different formations were projected on the

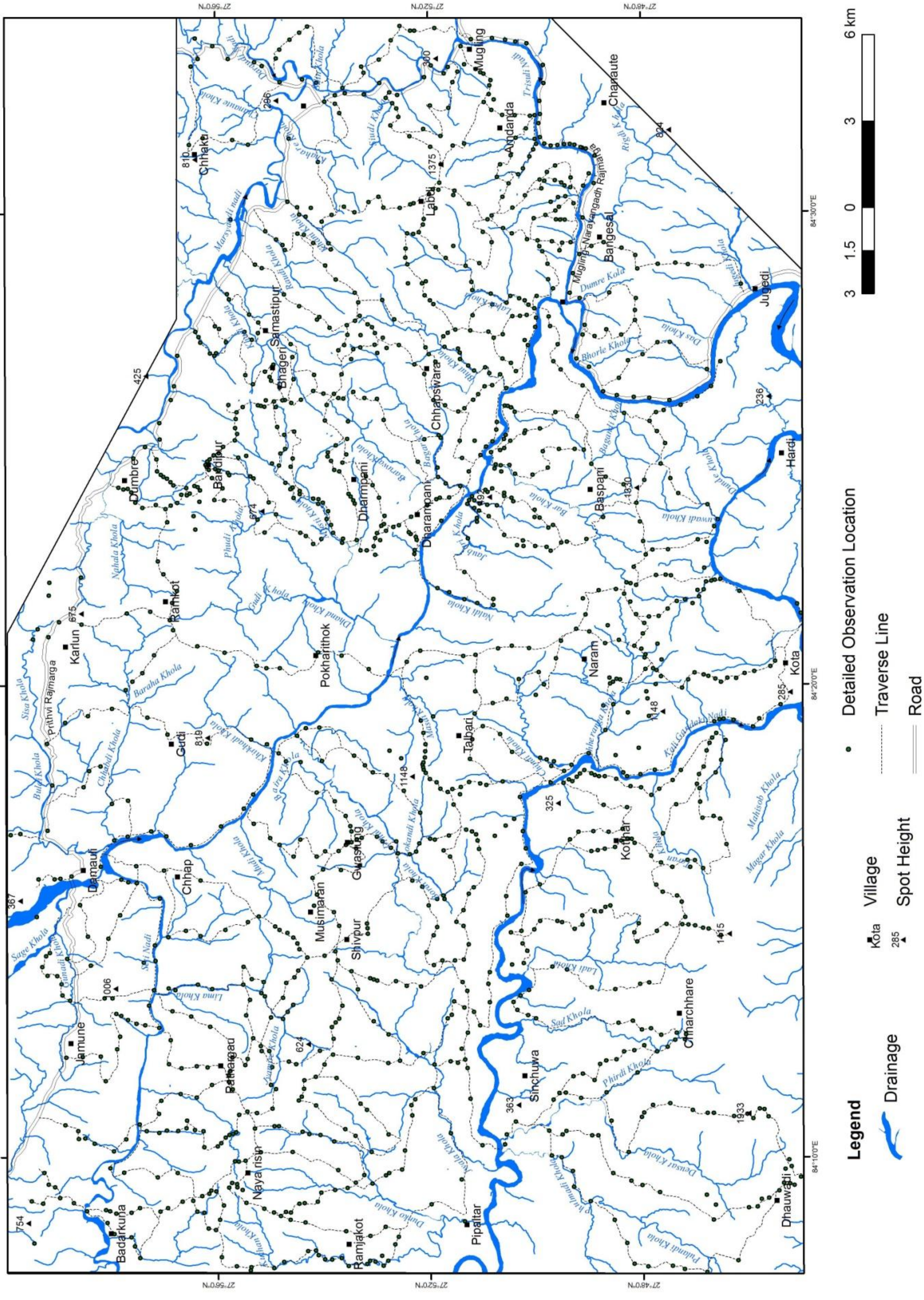


Fig. 4.2. Topographic map of the study area showing the observation points and traverse routes.

vertical plane considering the apparent dip of the beds along the line of cross-section. The boundaries were extrapolated to the depth to fit the geological structures observed on the surface. Efforts were made to balance the length and area of units as far as possible. Final fare copy of the cross section was prepared using the software ArcGIS9.3.

4.2.7 Magnetic susceptibility measurements

The intensity of magnetization is related to the strength of inducing magnetic field 'H' through a constant of proportionality, K is known as magnetic succeptibility. It is given by the following equation:

$$M=KH$$

Where, K is proportionality constant called magnetic susceptibility. H is inducing magnetic field and M is intensity of magnetization. The magnetic susceptibility is a physical parameter that can be used to characterize and differentiate the rocks, that widely used in mineral and oil exploration also. It has been commonly used recently for assessment of quality and quantity of material in land, water and air system in natural media or even for assessment of the degree of pollution or contamination by pollutants or heavy metals due to anthropogenic activities.

Magnetic susceptibility of rocks of the autochthonous units was measured to characterize each unit and use it as a tool for lithostratigrahic comparison and mapping. Magnetic susceptibility is the most easily measurable petrophysical parameter of rocks. The magnetic susceptibility is the indicator of the concentration of magnetic minerals in the rocks. Magnetic behavior of the strata is sometimes useful in comparing rock successions of two distant places.

In the present study, an attempt was made to measure the magnetic susceptibility of the succession in the Malekhu, Mugling-Jugedi, Mugling-Bandipur and Ghumaune-Damauli sections. A portable Kappa Meter of the KT series (ZH Instruments SM 30, Czech Republic) was used to measure the susceptibility. The instrument was very sensitive (1 x 10-6 [SI] in the KT-10 model), measured the susceptibility very rapidly (one measurement takes a few seconds), contained memory for storing large amounts of measured data (up to 500 measurements), and possess blue tooth connectivity (for combining susceptibility data with GPS measurements) and USB connectivity (for transferring the measured data into computer).

For the susceptibility measurement, at first plane and fresh surfaces of rocks (e.g., bedding, foliation or joint) were selected. The MS meter was opened at air and then put on the outcrop and again moved to the air which gives the MS value of the outcrop with respect to the air. In this process, final value on air among three values (first air, then outcrop and again air) was taken. At each site, at least 10-15 spot readings were measured on rock surfaces of macroscopically identical lithology distributed over an area of several square meters. In case of intercalated succession of outcrop, MS reading was taken separately for contrast lithology. MS measurement at each site was accompanied with the outcrop characteristics such as rock type, structure, texture, color, degree of uniformity and degree of weathering clearly in field diary. MS measurement was carried out for each litho-type of each formation separately. If any anomalous values of MS in any rock type is obtained an attempt was made to find its cause. For those contributing factors of rocks to change of MS was evaluated. For example, if MS value of quartzite was obtained more than its standard value, then its cause to be higher value was evaluated either in terms of its texture and weathering or associated minerals inside the rocks. Weathering and texture are evaluated in the field. Mineral paragenesis was checked in thin sections.

4.2.8 Sampling

Rock samples were collected for petrographic study, illite and graphite crystallinity measurements and measurement of Raman Spectroscopy of Carbonaceous Materials (RSCM). Representative and fresh samples of average 4x2x2inch size were collected for the thin section preparation. For illite crystallinity measurements, samples were selected such that they were phyllosilicate-rich, having shining surfaces, fresh and devoid of detrital grains. For the graphite crystallinity and Raman Spectroscopy of carbonaceous materials, black slates and phyllite were collected. The sampling spacing was varied depending upon the accessibility of outcrop and appropriate lithology. All the samples were numbered, wrapped with newspaper and kept in a plastic or cloth bags to protect them from abrasion. Oriented samples were also collected for the study of foliation, lineation, deformation and shear-sense indicators.

4.3 LABORATORY ANALYSES

4.3.1 Preparation of thin sections

Thin sections of the rock samples were prepared at the Central Department of Geology, TU. Rock cutters, hot plates, polishing discs, petropoxy, and abrasive powders were used in making thin-section. Thin sections were made parallel to the lineation and across the foliation. In total, about 250 thin sections of representing rock types were prepared.

4.3.2 Petrographic study and photomicrography

The thin sections were studied under high resolution petrological microscope. Study was focused on the mineral paragenesis, texture, identification of metamorphic index minerals and micro-structures related to deformation. Photomicrographs were taken from digital eye-piece camera with Motic Image Plus software. Altogether 250 thin-sections (meta-sedimentary rocks = 200 and crystalline rocks of thrust sheet =50) were prepared. Among them 51 good quality and representative thin sections were used for detail petrographic study.

4.3.3 Illite crystallinity measurement

Crystallinity usually signifies the degree of ordering in a white mica crystalline lattice (Kübler 1967) or the size of the diffracting crystallites in white mica as measured by the Scherrer equation (Annex I) (Merriman and Roberts 1985). Any mineral that changes its crystallinity continuously with increasing metamorphic grade provides significant information about a metamorphic terrain. Illite abundantly presents in low-grade meta-pellites. The Illite Crystallinity (IC) in meta-pellites increases with metamorphic grade and saturates around biotite grade. Therefore, IC serves as an useful proxy to evaluate the pattern of low-grade metamorphism in metapelites. Although IC is affected by many factors (Kisch 1983; Frey 1970), systematic changes in the shape of (001) illite peak on X-ray Diffractrograms serve as an indirect measure of the change in IC (Weaver 1960; Paudel 2001). Several methods are used to quantify the shape of the 10Ǻ illite peak (Frey 1987), the most commonly used one is Kübler Index (KI). The KI is measured as the peak width at half height of the 10Ǻ X-ray diffraction peak above the background (Kübler 1967; Dunoyer de Segonzac et.al 1968) (Fig. 4.3). The KI decreases with increasing IC (Kübler 1967). Therefore, the IC should be regarded as an empirical approach and several pitfalls should be avoided during its measurement. Statistically significant numbers of samples should be analyzed to get any inference from the IC data. If a large sample population is analyzed, IC can be used as qualitative geo-thermometer in very low-and low-grade metamorphic rocks. On the basis of IC, low-grade metamorphism can be divided into the diagenetic zone (>0.42Δ°2θ), anchizone (0.25–0.42Δ°2θ) and epizone (<0.25Δ°2θ), which are roughly equivalent to the zeolite facies, prehnite-pumpellyite facies and greenschist facies of metamorphism in metabasites, respectively (Warr 1996).

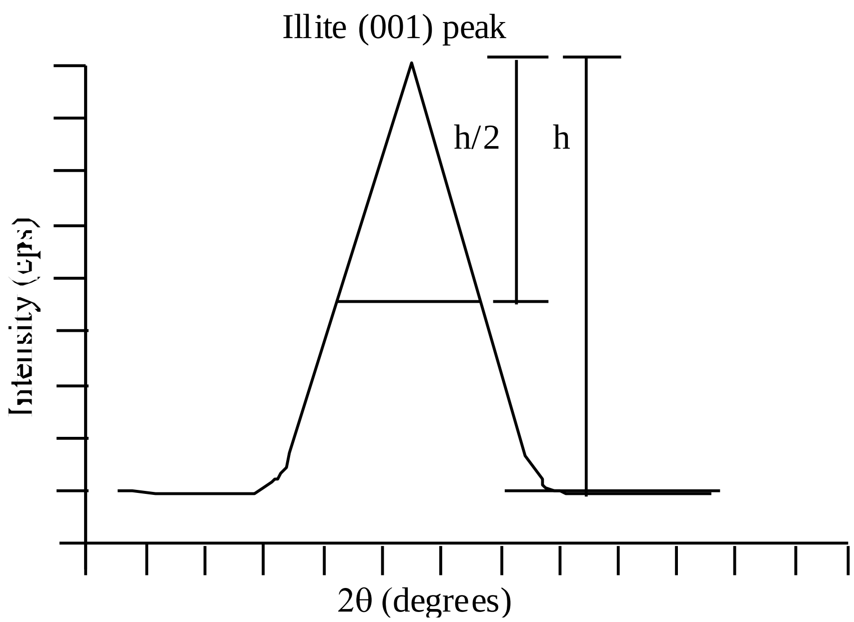


Fig. 4.3. Schematic diagram showing the measurement method of Kübler Index.

In the present study IC was measured using the D8 Advance X-ray Diffractometer at the Central Department of Geology (CDG), Tribhuvan University. Sample preparation methods and diffractometer settings and measurement methods are given in Annex I. Diffractograms were acquired using DiffracPlus Software. The IC was measured manually on the hard copies. Each sample was scanned three times and an average value was calculated.

4.3.4 Graphite crystallinity measurement

Carbon is an important constituent in most of the black pelitic rocks of sedimentary origin. The crystallinity of carbon is denoted by degree of graphitization. In carbon, width at half height of (002) peak is widely used to quantify the degree of graphitization. The graphite crystallinity also increases with metamorphic grade in low-grade metamorphic rocks (Landis 1971). The value of crystallinity decreases with the increasing degree of graphitization and the peak becomes more sharp and narrow. In low-grade carbonaceous rocks, there usually exist two peaks of carbon, the sharp and tall one representing the well-ordered detrital graphite and the next one a diffuse peak occurs at a somewhat lower 2θ that represents the metamorphic carbon (Itaya 1981). With increasing metamorphic grade, the intensity of the diffuse peak gradually increases, its width decreases, and its position shifts towards higher 2θ and approaches the sharp graphite peak. In biotite zone, graphitization gets saturated and only one peak appears as metamorphic carbonaceous material approaches well ordered graphite and the metamorphic and detrital graphites become indistinguishable. Since graphitization is a rate process, the temperature of complete graphitization differs from one metamorphic terrain to another as a function of the duration of metamorphism. In an individual metamorphic terrain, however, the degree of graphitization is a useful indicator of relative metamorphic temperature in lower grade rocks.

In the present study, carbonaceous material was separated from the pelitic rocks using the methods described in Tagiri (1981) (Annex II). Measurement method was similar to that in illite crystallinity (§4.3.3).

4.3.5 Measurement of Raman Spectroscopy of Carbonaceous Materials

The progressive graphitization of Carbonaceous Material (CM) with increasing temperature forms the basis of a metamorphic thermometer for metasedimentary rocks (Beyssac et al. 2002; 2004; Rantitsch et al. 2004). Sedimentary rocks generally contain trace amounts of initially poorly ordered CM, which transforms into well-ordered graphite with increasing metamorphic grade (Pasteris and Wopenka 1991). Laser Raman Spectroscopy is a tool to directly measure the degree of ordering of CM (Beyssac et al. 2002). Beyssac et al. (2002) were the first to formulate an empirical metamorphic thermometer using Raman Spectroscopy of CM (RSCM). They demonstrated that CM crystallinity is strongly correlated with peak metamorphic temperature. The thermometer is based on an observed linear relation between metamorphic temperature and the R^2 parameter, which is the ratio of the peak areas for the disordered and ordered bands as measured in the CM Raman spectra. Their RSCM thermometer works best for samples with metamorphic temperatures between 330 and 650ºC.

A micro-Raman system (Thermo Scientific, Nicolet Almega XR) with a 532 nm laser that was housed at Nagoya University, Japan was used for measurements. Acquisition time was set as 6 s x 5 times. Analytical setting in the present measurement was after Aoya et al. (2010). Peak position and band area (integrated area) were determined by using the Peak Fit 4.12ver. (SeaSolves Software) after Aoya et al. (2010).

4.4 DATA ANALYSES

4.4.1 Analysis of structural data

Orientations of bedding, foliation and lineations were statistically analyzed using the software DIPS 5.1. Mean values of bedding, foliation and lineation orientations were calculated from the stereograph.

4.4.2 Analysis of illite crystallinity, graphite crystallinity and RSCM data

Average values and standard deviations of illite and graphite crystallinity and RSCM were calculated using Microsoft Excel.

4.4.3 Semi-quantitative Geothermometry

Semi-quantitative peak paleotemperatures were estimated from IC and RSCM. The following calibration proposed by Underwood et al. (1993) was used to calculate temperature from IC.

$KI = 1.197 - 0.0029T°C$

Where KI= Kubler Index, T= peak paleo-temperature

The following calibration equation provided by Beyssac et al. (2002) was used for the calculation of temperature from RSCM.

$T(°C) = -445\ R^2 + 641$, and $R^2 = D1/(G+D1+D2)_{Area}$

Where G is area of G band centered at about 1580 cm^{-1}, defect band D1 located at about 1350 cm^{-1}, and defect band D2 located at about 1620 cm^{-1}.

4.4 DATA SYNTHESIS AND INTERPRETATION

All the field and laboratory data were combined together to interpret the overall geological history of the area. The stratigraphy of the area was revised based on the present data. Depositional sedimentary environment of the area was interpreted based on lithology, primary structures and fossils. A structural and tectonic map of the area was prepared and deformation events were established. The metamorphic condition of the area was judged based on the petrographic data, IC, graphite crystallinity and RSCM. Metamorphic events were identified and paleotemperature of metamorphism was semi-quantitatively measured. Finally a model was proposed for the tectono-metamorphic evolution of the area.

4.5 PRESENTATION AND PUBLICATION OF RESULTS

In the course of research, results were presented at several national and international conferences. In total, 5 progress reports were presented in the research committee of the Central Department of Geology, Tribhuvan University, Kirtipur. Five research papers were published in peer-reviewed national geo-science related journals and one paper was published in peer-reviewed international journal (Annex XI).

4.6 DISSERTATION WRITING

Finally, the dissertation was prepared by compiling all the maps, figures, photographs, photomicrographs and table. Fair copy maps and figures were prepared using ArcGIS9.3 and Aldus Freehand. Photographs were processed in Adobe Photoshop. Text was prepared in Microsoft Word.

CHAPTER FIVE

RESULTS

5.1 LITHOSTRATIGRAPHY

The study area comprises an autochthonous succession of low-grade metasedimentary rocks tectonically overlain by an allochthonous sequence of metamorphic crystalline rocks.

The autochthonous succession is similar to the Nawakot Series or Nawakot Nappe of Hagen (1969), Midland Group of the Hashimoto et al. (1973), the Nawakot Complex of Stöcklin and Bhattarai (1977), Kaligandaki Supergroup of Sakai (1985) and Nawakot Group of Hirayama et al. (1988) and Daban Supergroup of Dhital and Kizaki (1987). The most adopted name for these rocks of the Lesser Himalaya is the Nawakot Complex. Stöcklin and Bhattarai (1977) and Stöcklin (1980) suggested that there is an unconformity between the stromatolitic dolomite (Dhading Dolomite) and black carbonaceous slates (Benighat Slate) on the basis of presence of a "50-100 cm thick rusty, laterite-like zone". In this context they divided the autochthonous rocks into the Lower and Upper Nawakot Groups and referred the autochthonous rocks as the Nawakot Complex.

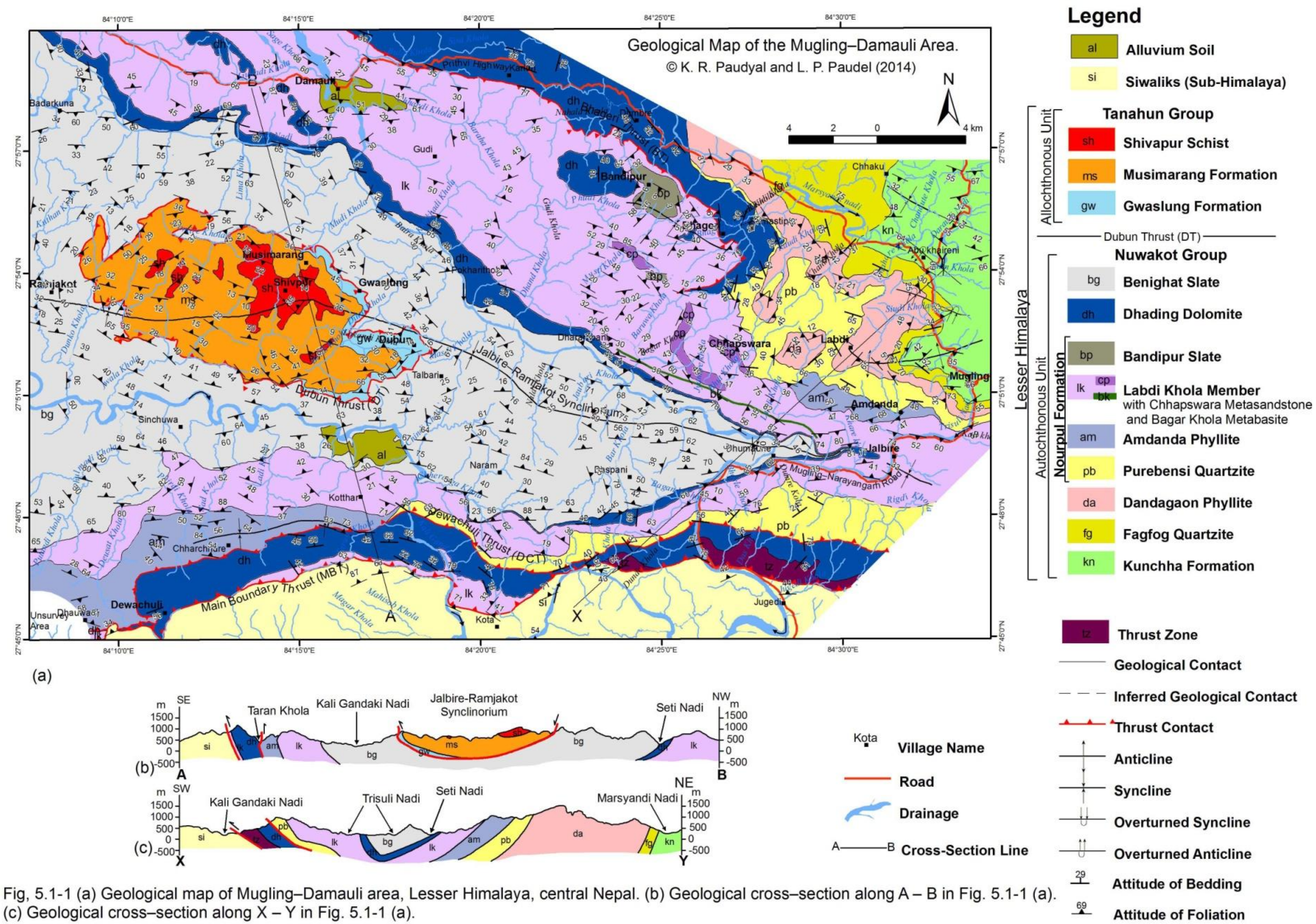
However, none of the previous (Hashimoto et al., 1973) and subsequent researchers (Sakai 1985; Hirayama et al. 1988; Dhital and Kizaki 1987; Upreti 1997; Dhital et al. 2002) have found evidence of such an unconformity in the Lesser Himalaya. In the present area also the contact between the stromatolitic dolomite and carbonaceous slates is conformable and sharp in some places and transitional in other places. There is no evidence of erosion along this boundary. Therefore, we think that the division of the autochthonous rocks into two groups on the basis of an unconformity is not appropriate.

The Benighat Slate frequently shows rust-like weathering. Probably the ‘laterite-like’ zone observed by Stöcklin and Bhattarai (1977) is the weathering product of slate. Division of Nuwakot Group into calcareous and non-calcareous sequences as suggested by Upreti (1996) is also not appropriate for the present study area because calcareous rocks are found throughout the autochthonous sequence including the Kunchha Formation. We think that the Nuwakot Group (=Nawakot Group) is the most appropriate name for the autochthonous rocks as suggested by Hirayama et al. (1988). Therefore, in the present work, we have adopted the name Nuwakot Group for the autochthonous rocks.

Further classification of the Nuwakot Group is based on Stöcklin and Bhattarai (1977) and Stöcklin (1980) as far as possible. This is because most of the formations defined by them are laterally continuous to the present study area from the type locality in central Nepal. However, several discrepancies were found in their classification in the present area and the lithostratigraphy has been partly revised based on the new observations.

The allochthonous rocks of the area form a klippe in the area and was referred as the Damauli Klippe by Bollinger et at. (2004). However, the klippe is about 25 km south of Damauli in the Kahun area. Therefore, it is referred as the Kahun Klippe in the present study. The crystalline rocks of the Kahun Klippe are named as the Tanahun Group in the present study.

Detailed route mapping was carried out along the Mugling-Jugedi section of the autochthonous zone and Gwaslung-Shivapur section of the allochthonous zone in the present study to define the mappable lithostratigraphic unit (Annex III and IV).



Fig, 5.1-1 (a) Geological map of Mugling–Damauli area, Lesser Himalaya, central Nepal. (b) Geological cross–section along A – B in Fig. 5.1-1 (a). (c) Geological cross–section along X – Y in Fig. 5.1-1 (a).

The Mugling Damauli area was mapped based on the revised lithostratigraphy in 1:25000. The geological map and cross sections of the area are given in Fig. 5.1-1. Detailed lithological characteristics of each formation has been described in the following sections.

5.1.1 Lithostratigrpahy of the Nuwakot Group

A generalized lithostratigraphic column for the Nuwakot Group prepared from the route maps is given (Fig. 5.1-2). The Nuwakot Group is divided into six formations as the Kunchha Formation, Fagfog Quartzite, Dandagaon Phyllite, Nourpul Formation, Dhading Dolomite and the Benighat Slate from bottom to top, respectively. Lithological and sedimentary characteristics of each formation are given in the following sections. Detailed description of each formation is also given in Paudyal and Paudel (2011a; 2011b; 2013) and Paudyal et al. (2011; 2012).

(a) Kunchha Formation (kn)

The name Kunchha is derived from a village of Gorkha District, immediately north to the present study area (Fig. 3.2).

Synonymy: Se'rie de Kunchha (Bordet 1961 in central Nepal), Daram Suite (Talalov 1972), Gritty Phyllites (Nanda 1973 in central and western Nepal), Andhi Formation (Sakai 1985 in western Nepal), Ranimatta Formation (Shrestha et al. 1987), Kunchha Formation (Stöcklin and Bhattarai 1977; Hirayama et al. 1988; Sharma et al. 1984 and Dhital et al. 2002 in central and western Nepal), Lower Arenaceous Subgroup (Hashimoto et al. 1973 in whole Nepal Himalaya), Hinuwa Phyllite (Andrews 1985 in eastern Nepal), Dangri Formation (Dhital and Kizaki 1987 in western Nepal), Seti Formation (Paudel and Dhital 1996) of central west

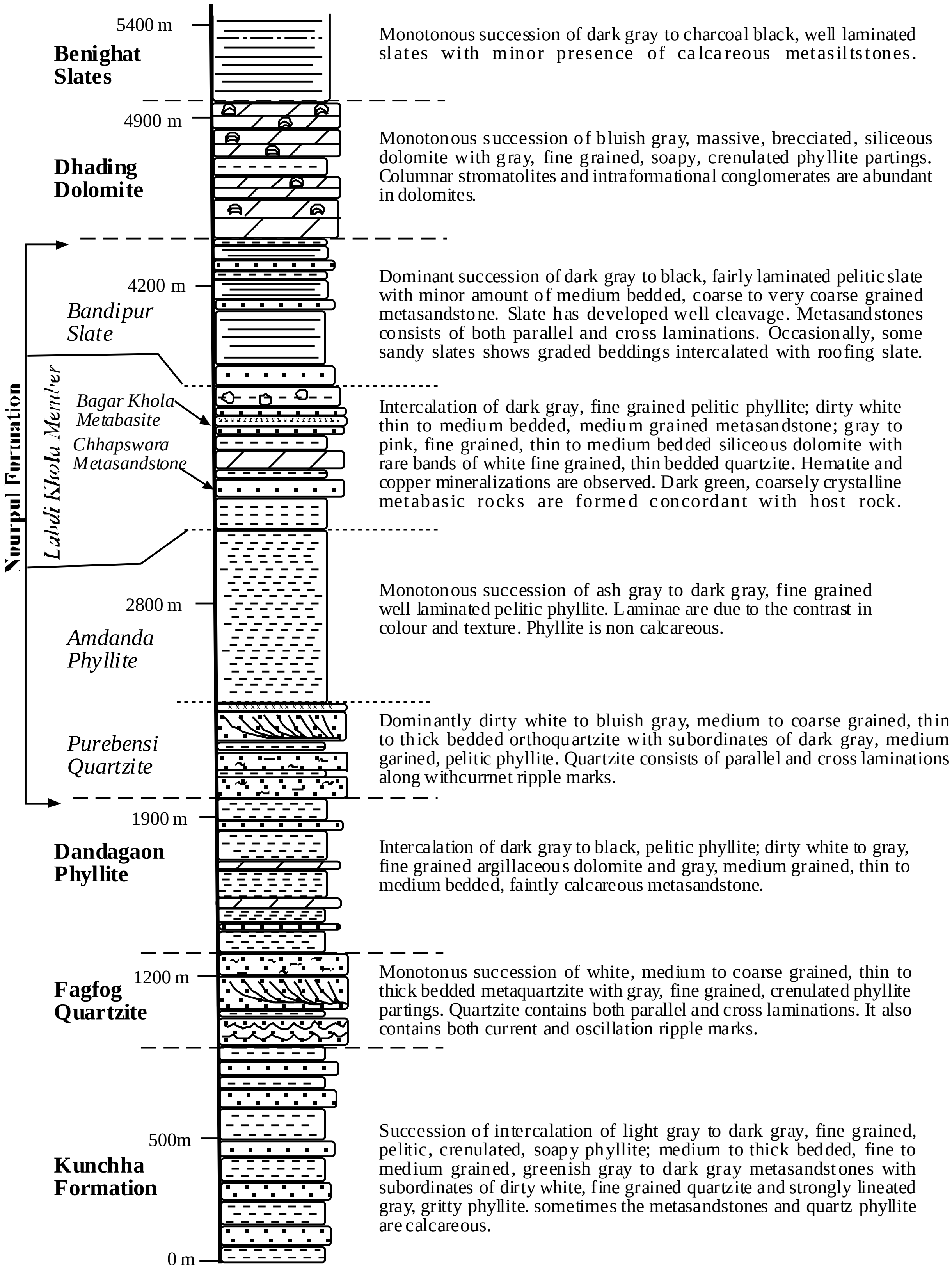


Fig. 5.1-2.Generalized columnar section of rocks of the Nuwakot Group exposed in Mugling-Damauli area.

Nepal). The Kunchha Formation is well-distributed in and around the Mugling-Anbu Khaireni area (Fig. 5.1-1). It forms comparatively smooth ridges with gentle spurs and valley slopes. In the study area, only the uppermost part of the Kunchha Formation is exposed along the Mugling-Anbu Khaireni motor road and Marshayandi river section. It is also exposed along the Mugling-Narayangarh road and Trishuli river sections. Detailed lithology of the upper part of the Kunchha Formation is shown in Fig. 5.1-3. The formation consists of green-grey, medium- to coarse-grained metasandstones, blue-green to grey phyllite, grey to yellowish-grey, sometime dirty white, fine- to medium-grained quartzite and green-grey to light grey gritty phyllite in various proportions. The metasandstones are medium- to very thick-bedded (50 cm to 2 m) with faint laminations. When weathered, the Kunchha Formation yields yellowish-brown to orange, red and greenish grey colored soil.

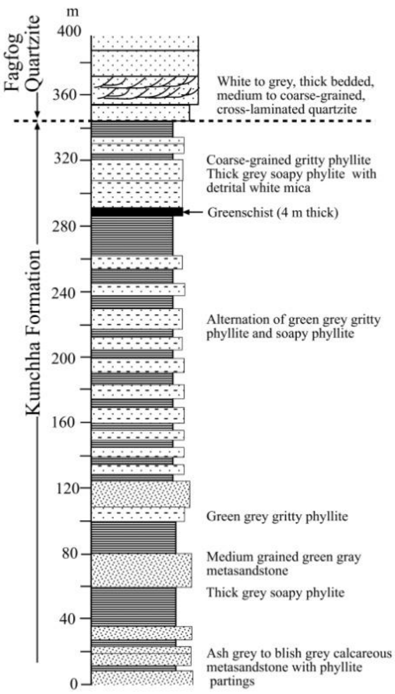


Fig. 5.1-3.Detailed columnar section of the upper part of the Kunchha Formation along Mugling-Narayangarh road near Mugling.

The Kunchha Formation also comprises a sporadic inter-banding of coarse-grained meta-conglomerate and thick (up to 10 m) grey psammitic phyllite with some intercalations of amphibolites. Phyllite is very fine-grained, thinly foliated and fairly crenulated. Calcareous metasandstone with phyllite partings of about 15 m thickness was observed in the upper part of the Kunchha Formation about 2.5 km southward from Mugling along the Mugling-Narayangarh road (Fig.5.1-4a). Opposite to Marsyangdi Hydropower station, the Kunchha Formation also consists of calcareous meta-conglomerates with rounded to semi-rounded, strongly deformed (stretched) pebbles of dolomite, quartzite, slate and rock fragments (Fig. 5.1-4b). The pebbles are up to 10 cm in diameter. The succession is found strongly lineated, predominantly in NNE to SSW direction. The most prominent is the intersection lineation and sometimes stretching lineation as defined by deformed quartz and feldspar clasts. Occasionally, brillent crystals of detrital mica are observed along the foliation planes in the phyllites and metasandstones.

Stöcklin and Bhattarai (1977) and Stöcklin (1980) have shown two quartzite (the Anpu Quartzite and the Banspani Quartzite) and one phyllite (the Labdi Phyllite) members in the in the Kunchha Formation (Fig. 1.5a). However, present mapping shows that the Anpu Quartzite is the westward continuations of the Fagfog Quartzite and the Banspani Quartzite is the westerward extension of the Purebensi Quartzite observed in the Mugling-Narayangarh road, respectively. Similarly, the Labdi Phyllite is the westward continuation of the Dandagaong Phyllite. There the three members of the Kunchha Formation do not exist in the field.

The contact between the Kunchha Formation and the overlying Fagfog Quartzite is very sharp in the observed section. However, the lower contact of Kunchha Formation is

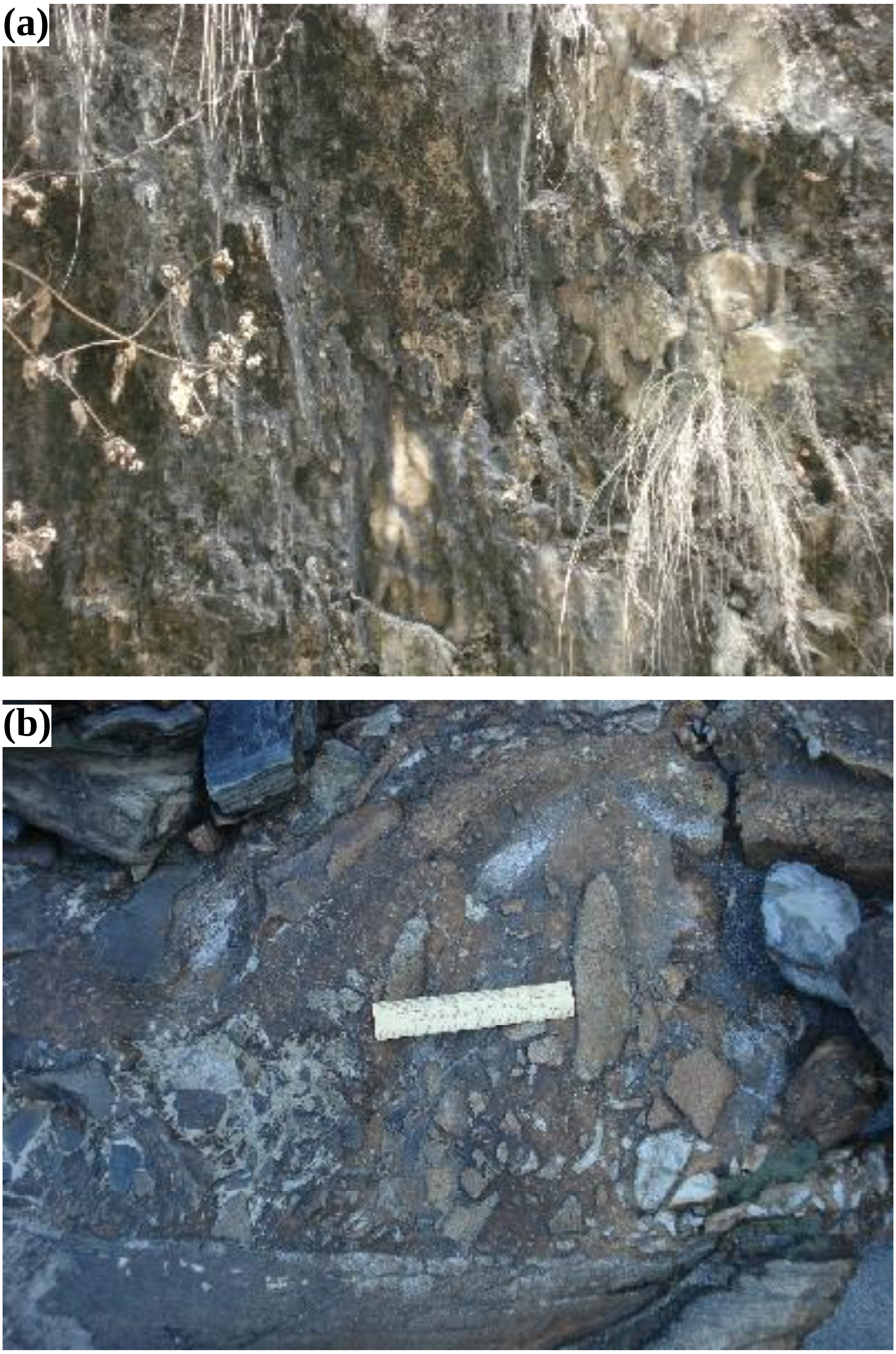


Fig. 5.1-4. (a) Photograph of calcareous crust on outcrop of the Kunchha Formation exposed about 2 Km south of Muglin Bazzar along Muglin-Narayangarh road.(b) Outcrop view of meta-conglomerate observed at the top part of the Khuncha Formation at the right bank of the Marshyandi River in between Mugling and Anpu Khaireni.

not exposed anywhere and the thickness of the Kunchha Formation is more than 1000 m.

(b) Fagfog Quartzite (fg)

The name Fagfog Quartzite was first used by Hashimoto et al. (1973) and it is derived from a village of Fagfog of Dhading district (outside of the present study area) in central Nepal.

Synonymy: Birethanti Quartzite (Le Fort 1975), Naudanda Quartzite (Sakai 1985; Hirayama et al. 1988; Paudel and Dhital 1996 described from the western Nepal); Balle Quartzite (Dhital and Kizaki 1987 described from the northern Dang); Hokse Quartzite (Andrews 1985 described from eastern Nepal).

A complete succession of the Fagfog Quartzite is observed along the road section about 2 km south of Mugling and is a marker unit in the area. It consists of thin- to thick-bedded (5 cm to 1.5 m), medium- to coarse-grained, white quartzite with thin (~1 cm) partings of grey, fine-grained pelitic phyllite. In the lower and middle parts of the succession it consists of medium- to thick-bedded white quartzite with rare partings of grey, pelitic phyllite (Fig. 5.1-5). However, in the upper part the proportion of phyllite increases. In the lower succession, sedimentary structures like parallel and cross-laminations (Fig. 5.1-6a), wave ripple marks (Fig. 5.1-6b) are abundant. In the upper part, sedimentary structures are rare. In weathered outcrops, the quartzite shows reddish, yellowish or pale orange color. The beds are usually parallel and continuous to several meters. Coatings of malachite and azurite are observed on the outcrops of white quartzite near the Marsyangdi Hydropower station and south of Anpu Khaireni indicating possible copper mineralization in this formation. The phyllite shows silky luster and soapy weathering surface due to the presence of chlorite and sericite.

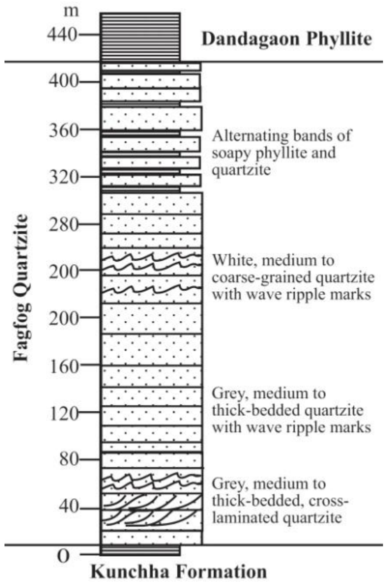


Fig. 5.1-5.Detailed columnar section of the Fagfog Quartzite along the Mugling-Narayangarh road south of Mugling.

The Fagfog Quartzite uninterruptedly extends westwards from Mugling to Loprang, Marsyangdi Hydropower station and Anbu Khaireni. It forms a broad anticline in between Mugling and Anbu Khaireni and an overturned syncline north of the Hydropower station (Fig. 5.1-1). The Fagfog Quartzite is followed up section by the Dandagaon Phyllite and the contact is very sharp and conformable. The thickness of the unit is about 400 m in the studied areas.

(c) Dandagaon Phyllites (da)

The unit is named after the village Dandagaon, east of Dhading Bensi by Stöcklin and Bhattarai (1977).

Synonymy:"Grey Phyllites" (Nanda 1973), "Daram Suite" (Talalov 1972), Galyang Formation (Shrestha et al. 1987), Balewa Formation (Paudel and Dhital 1996), Nayagaon Formation (Dhital et al. 2002), Ranagaon Formation (Dhital and Kizaki 1987), Heklang Formation (Sakai 1985), Phyllite Formation (Arita et al. 1984 in western Nepal), Maksuwa

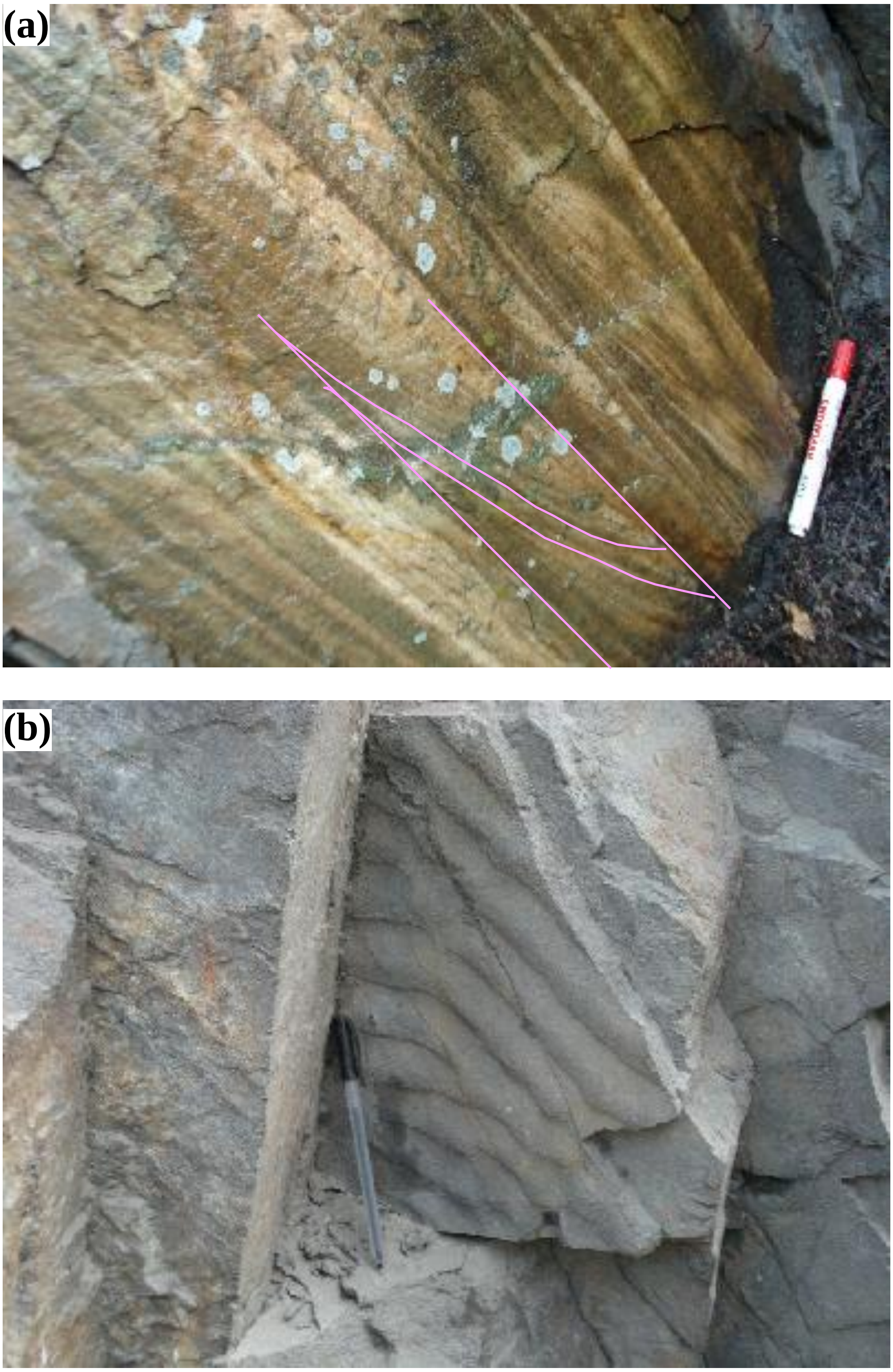


Fig. 5.1-6.(a) Cross-laminations in the Fagfog Quartzite approximately 3 km south of Mugling showing right-side up sequence. (b) Wave ripples in the Fagog Quartzite observed at Mugling-Narayangarh road, about 3.5 km south of Mugling.

Phyllite (Andrews 1985 in eastern Nepal).

The Dandagaon Phyllite is extensively distributed south and southwest of Mugling along the Mugling-Narayangarh road section and around the villages Loprang, Labdi, Chipleti and Aklang areas (Fig. 5.1-1). It comprises the succession of black pelitic phyllite and dark grey psammitic phyllite intercalated with calcareous grey phyllite, dark grey fine-grained and thin-bedded metasandstone and grey to dirty white, thin-bedded quartzite. The thickness of phyllite varies from 1 to 25 cm and that of quartzite and metasandstone with 1 to 30 cm. Occasionally, thin layers of grey dolomites are found within the succession. The lithology as a whole reflects darker tone in outcrop and do not contain gritty phyllite as in the Kunchha Formation which makes the main difference between these two formations. The dark grey phyllite of Dandagaon Phyllite is often strongly deformed and exhibit crenulations.

The lower part of the Dandagaon Phyllite comprises black pelitic phyllite, calcareous psammitic phyllite and dirty grey quartzite. This is followed by a thick sequence (100 m) of non-calcareous grey, bluish grey and dark grey laminated soapy phyllite with some intercalations of sandy phyllite and dark grey metasandstones. The upper part of the Dandagaon Phyllite consists of alternating bands of finely foliated black phyllite and ferruginous metasandstones (Fig. 5.1-7).

The Labdi area is extensively covered by light grey laminated phyllite with cleavage developed oblique to the laminations. Stöcklin and Bhattarai (1977) have mapped this phyllite as a member of Kunchha Formation (Labdi Phyllite member). However, present mapping shows that the Labdi Phyllite is the continuation of the Dandagaon Phyllite observed in the Mugling-Narayangarh road section.

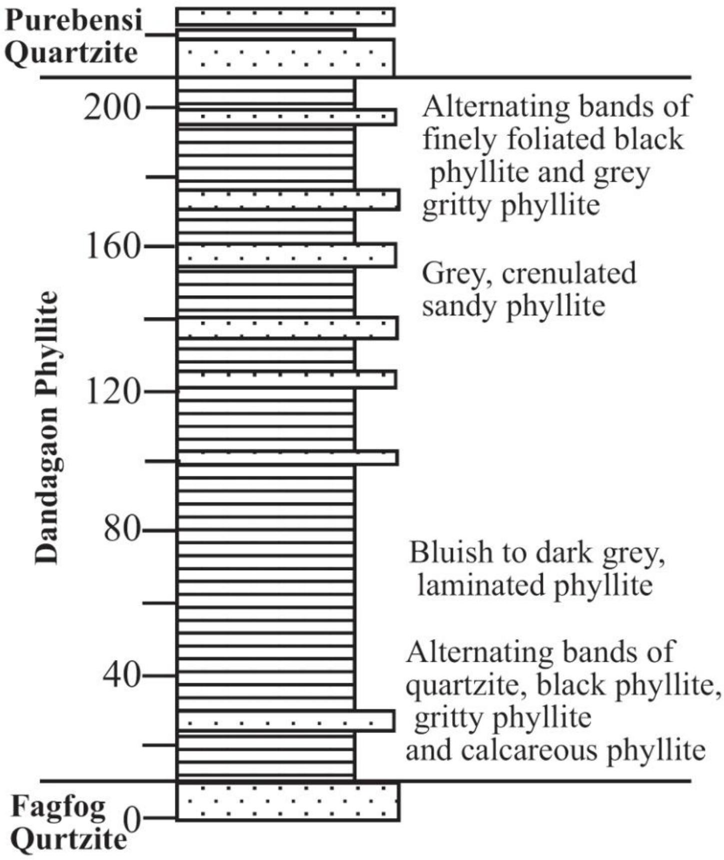


Fig. 5.1-7. Detailed columnar section of the Dandagaon Phyllite along the Mugling-Narayangarh road south of Mugling.

An extensive inlier of Dandagaon Phyllite is mapped around Chipleti area where younger rocks of the Purebesi Quartzite has surrounded the rocks of the Dandagaon Phyllite. The lithology of Dandagaun Phyllite of the inlier consists of grey, compact, laminated, soapy phyllite in alternation with greenish grey, medium- to coarse-grained, medium- to thick-bedded (>60 cm) metasandstone/ortho-quartzite. In weathering outcrops, phyllite shows grey coloration whereas metasandstone is brown, purple and greenish-grey in color. Metasandstones are fairly lineated.

The Dandagaon Phyllite is followed up section by the Purebensi Quartzite with a sharp and conformable contact. The thickness of the Dandagaon Phyllite is about 200 m.

(d) Nourpul Formation (np)

This formation was named after the village of Nourpul south of Dhading by Stöcklin and Bhattarai (1977).

Synonymy:"Purple Phyllite" or "Purple Member" (Pawde 1973; Nanda 1973), "Galang Suite" and "Khabre Suite" (Talalov 1973), (Harichour + Varigated) Formations (Sharma et al. 1984), Heklang and Virkot Formations (Sakai 1985), (Uniyachaur Slates and Syangja Formation (Hirayama et al. 1988).

The Nourpul Formation is exposed extensively in the study area. It is a succession of varied type of lithology like grey phyllite, grey-green slate, green-purple-red shale, grey metasandstone, pink dolomite, pink, grey, dirty white quartzite etc. Stöcklin and Bhattarai (1977) have shown a quartzite unit at the base of the Nourpul Formation and is named as the Purebensi Quartzite. However, in the present study area, the Nourpul Formation is divisible into for members. They are the Purebensi Quartzite, Amdanda Phyllite, Labdi Khola Member and the Bandipur Slate successively from bottom to top (Fig. 5.1-2). These all members are lithologically distinct and easily mappable in 1:25,000 scales. Moreover, the Purebensi Quartzite is lithologically distinct and acts as a marker succession in the area. The Labdi Khola Member and the Bandipur Slate are well-recognized by their mineral resources like hematite and roofing slate, respectively. The laminated phyllite intervening between the Purebensi Quartzite and the Labdi Khola Member is mapped as the Amdanda Phyllite. Detail description of these rock units are given below.

(i) Purebensi Quartzite Member (pb)

It is named after a village Purebensi located at the right bank of the Trishuli River about 6 km south of Mugling by Stöcklin and Bhattarai (1977) (Fig. 5.1-1). It lies conformably above the Dandagaon Phyllite.

Purebensi Quartzite is well distributed in the Bhoteswara, Dhonde, east of Hillekharka, north of Dumsidhunga, Banspani, Chhimkeswori, Khasrang areas where it lies above the Dandagaon Phyllite. It is repeated in Bagandi, Phosrepani, Joleap, Gahatedada and Daraiminam areas by the Dewachuli Thrust (DCT). It forms a very steep topography (about 70-80 degree inclination) in the study area. A faint weathering on quartzite shows the yellow and iron rusting coloration. This unit is dominated by dirty white to ash grey, parallel- and cross-laminated quartzite (80%) intercalated with grey, green-grey, crenulated, and coarse-grained pelitic phyllite (20%)(Fig. 5.1-8).The quartzite is coarse-grained, medium- to thick-bedded (50 cm to 1.2 m) with abundant wave and current ripples (Fig.5.1-9a). Lower part of the succession consists of medium- to thick-bedded quartzite with phyllite partings. It consists of abundant current and oscillation ripples and occasionally the cross-beddings. Parallel beddings are very common in these rocks. From its basal contact to about 100 m up section, dark green bodies of meta-basites are found concordant to the quartzite and phyllite in several levels. In the middle part, the proportion of phyllite increases and the thickness of quartzite beds decrease. In the upper part the proportion of the phyllite rather increases and quartzite becomes thinner and fine-grained. In Banspani area, the succession of the Purebensi Quartzite is distributed extensively. Stöcklin and Bhattarai (1977) have mapped this quartzite as a member of the Kunchha Formation (the Banspani Quartzite). However, present mapping shows that the Banspani Quartzite is a direct continuation of the Purebensi Quartzite observed in the Mugling-Narayangarh road section. In the Banspani-Chhimkeshowri area, the dip becomes gentle and quartzite covers an extensive area. A famous Chhimkeswori temple is located above the succession of the Purebensi Quartzite and it is the highest peak (2134 m) of the present study area.

In the southern part, it is continuously mapped from the Bagandi to the Selighopte.

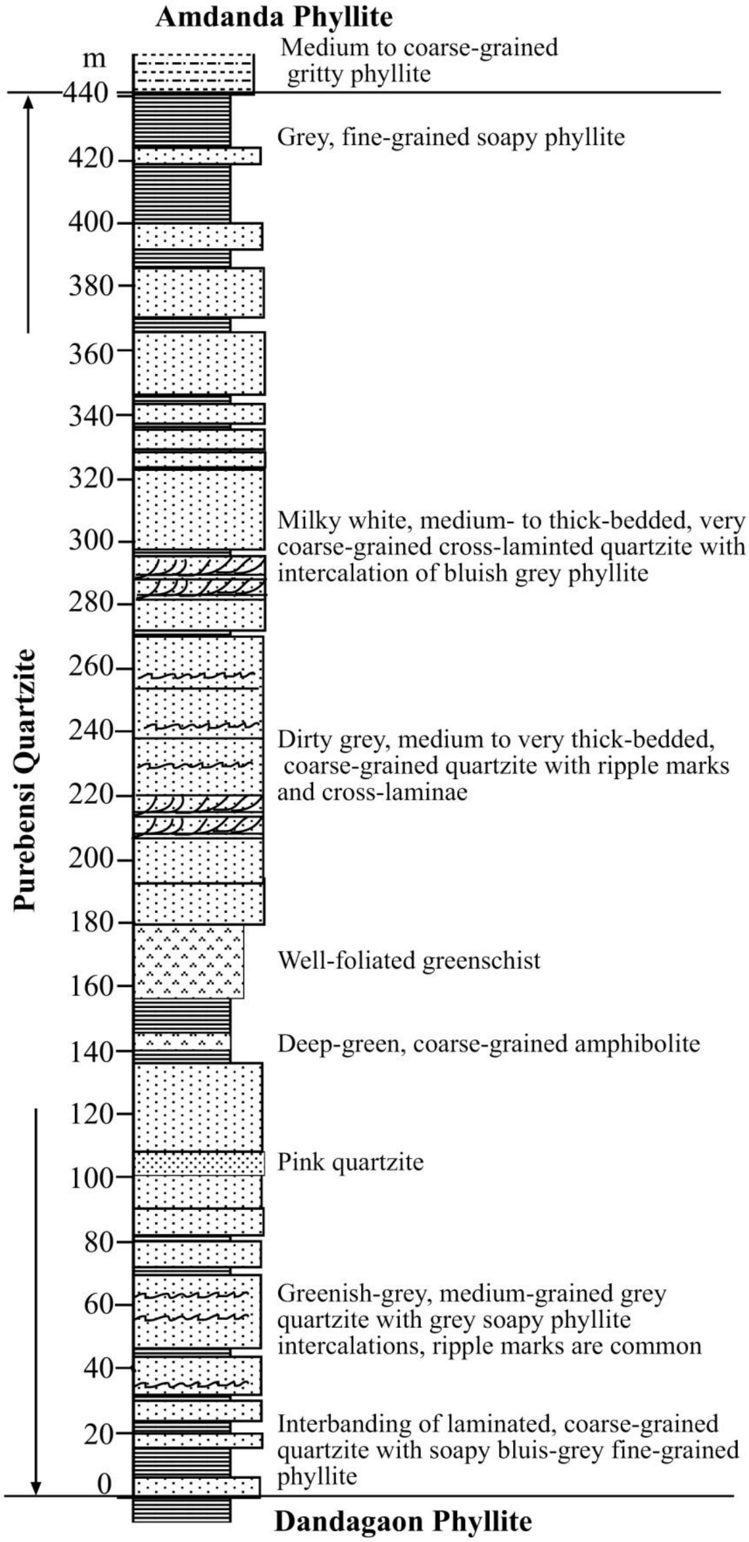


Fig. 5.1-8. Detailed columnar section of the Purebensi Quartzite along the Mugling-Narayangarh road near Purebensi.

It lies above the Dhading Dolomite along the Dewachuli Thrust (DCT). The main lithology of this unit consists of light grey, greenish-grey to dirty white, medium- to coarse-grained, medium- to very thick-bedded ortho-quartzite (85%) and grey to greenish grey, thinly foliated, fine-grained pelitic phyllite (15%). Both parallel- and cross-laminations as well as oscillation ripple marks are observed in ortho-quartzite. Occasionally, the succession consists of minor amount of grey, fine-grained, medium-bedded metasandstone and white, medium- to thick-bedded siliceous dolomite. Several bodies of metabasic rocks (greenschists and amphibolites) concordant to the host rocks are also observed in many locations. Due to the presence of several bodies of metabasic rocks, the succession makes confusion whether it belongs to the Purebensi Quartzite or other units of the Lesser Himalaya.

Succession of phyllite, quartzite, and dolomite with several bodies of metabasic rocks is observed near Bagandi Khola. Phyllite is purple in color and shows several boudins of pink dolomite in purple phyllite which is 1 cm to 6 cm in length. Greenschists/phyllites are abundantly observed in the ridge between Tallo Bagandi and Bagandi village. Even the cultivated land is covered by the greenschist boulders in the Tallo Bagandi. Finely foliated soapy violet-colored phyllite is observed in the Phroshrepani area in equal proportion with the dirty white to pink quartzites.

At Gahatedada, the Purebensi Quartzite consists of a succession of grey to white, medium-bedded ortho-quartzite intercalated with greenish-grey to grey, psammitic, and crenulated phyllite in 2:1 ratio. Occasionally, subordinates of white, medium- to thick-bedded dolomite are also observed within the succession.

The Purebensi Quartzite is followed by the middle member of the Nourpul Formation (the Amdanda Phyllite) in some places and in others it is directly followed by the upper member of the Nourpul Formation (the Labdi Khola Member).

The contact of the Purebensi Quartzite with the overlying Amdada Phyllite is sharp and conformable which is easily identified in the field by vegetation and relief (Fig.5.1-9b). The thickness of the Purebensi Quartzite is more than 400 m in Mugling-Amdanda section and it is about 250 m in the Khani Khola section.

(ii) Amdanda Phyllite (am)

The Amdanda Phyllite represents the middle part of the Nourpul Formation and is well-exposed in the Amdanda village about 9 km southwest of Mugling (Fig. 5.1-1). It is distributed in northeast and southwest parts of the study area. In eastern part, the Amdanda Phyllite extends westward to the Labdi Khola, Khasran, upper reaches of Khare Khola, San Bhanjyag, Dumsidhunga areas. It is suddenly interrupted by the Bhangeri Thrust (BT) around the Hillekharka and Bandipur areas. It consists of finely-laminated (2 mm to 1 cm), grey, sandy phyllite (Fig. 5.1-10). In many exposures, phyllite alternates with greenish grey, laminated, thin- to medium-bedded (5 to 50 cm) metasandstone. Some beds of dirty white to dark grey ortho-quartzite are common within the succession. The color of phyllite is bluish green in places with vivid yellow, pink, purple and violet variations in weathered condition. Quartz veins are frequent and show the cross-cutting relation with the primary sedimentary lamina. Total thickness of this unit is about 450 m in this section and it passes transitionally into Labdi Khola Member.

In the south-west of the study area, it is repeated above the Dhading Dolomite (younger unit) through the Dewachuli Thrust (DCT) and it is distributed in Satikot-Kaphaldada-Chharchhare-Thumki-Pokhari areas (Figs. 5.1-1). It is characterized by greenish-grey, light to dark grey, well-laminated, thin-bedded, faintly calcareous phyllite

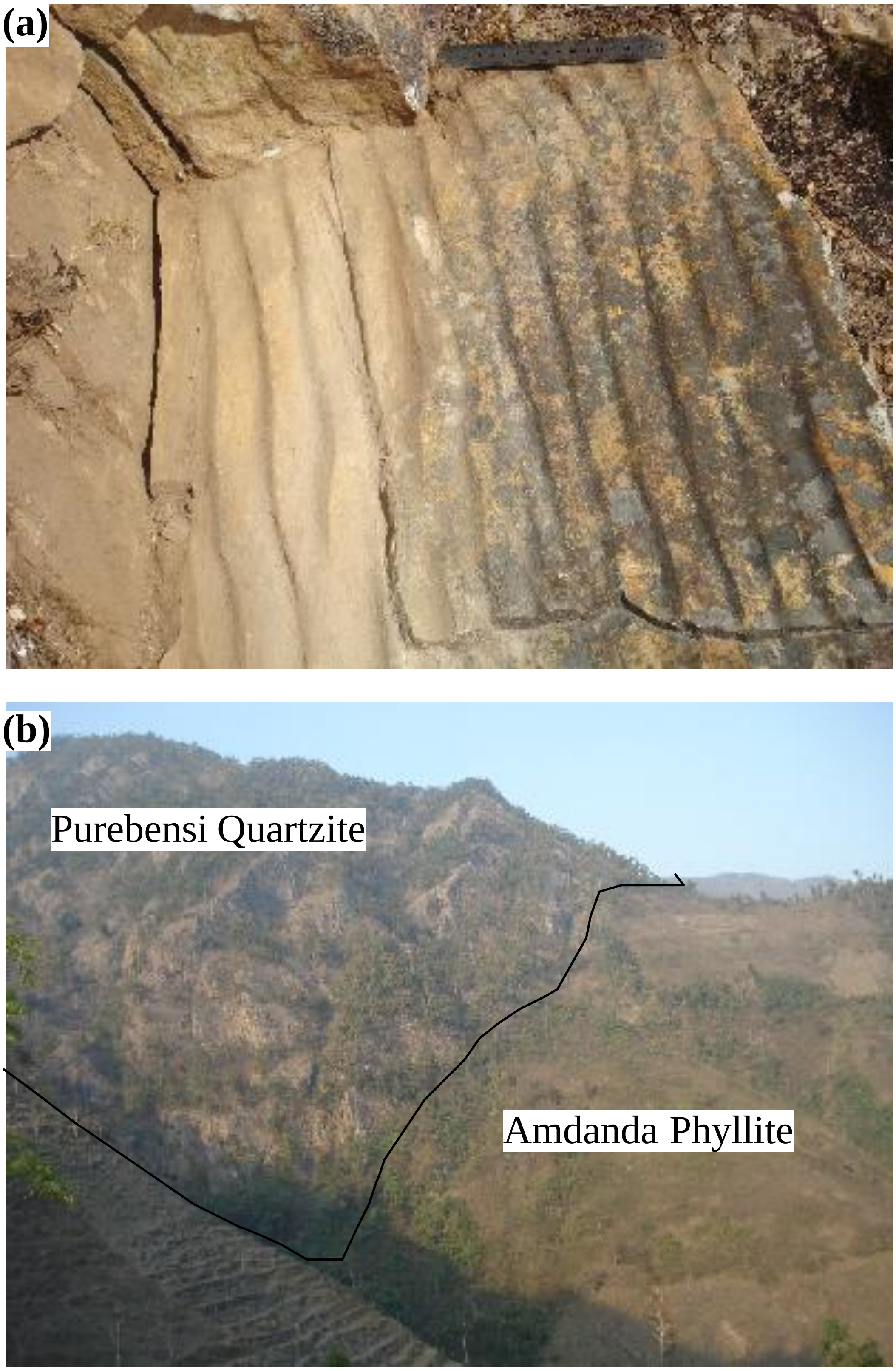


Fig. 5.1-9.(a) Wave ripples in the Purebensi Quartzite observed at Chimkeswori (facing towards E). (b) Geological contact between the Purebensi Quartzite (left) and the Amdanda Phyllite (right), viewed east from Dumsidhunga. Beds are dipping to the south (bottom right).

Fig. 5.1-10. Parallel-laminated succession of the Amdanda Phyllite observed at Dumsidhunga village, facing N.

(85%), grey, and medium- to thick-bedded metasandstone (10%) and white, coarse-grained, medium- to thick-bedded quartzite (5%) with rare intercalations of grey limestone. This unit is moderate to highly weathered in the study area with yellowish to reddish brown as well as silver white color and forms the gentle to moderate slope with thickly vegetated and cultivated lands.

At Satikot, the succession of the Amdanda Phyllite consists of intercalation of dark grey to black, strongly laminated, calcareous shale; lead grey to charcoal black, laminated slate and dark grey, laminated, argillaceous limestone with abundant pyrite crystals.

At Kaphaldada, this unit is composed of monotonous succession of dark grey to black, well-laminated, carbonaceous slate. At Chharchhare, the unit consists of monotonous succession of bluish-grey, greenish-grey to dark grey, finely-laminated shale;

bluish-grey to purple-grey, laminated and compacted slate and greenish-white, coarse-grained, thick bedded quartzite (2:2:1 ratio). At Thumki, the same succession is found as the light to dark grey, laminated, monotonous shale with black, finely laminated slate with subordinates of dirty white, coarse-grained metasandstone.

In Pokhari, north of the MBT, the Amdanda Phyllite consists of dominantly red, purple, greenish-grey, light to dark grey, thinly-bedded, finely-laminated shale; dark grey, thinly bedded, strongly laminated slate and dirty white, coarse-grained, thick-bedded ortho-quartzite (1:1:1 ratio) with a few bands of lead grey dolomite and hematite beds (maximum 2 m thick). The lamina is 1 mm to 1 cm thick and is oblique to the foliation. Mud-crack is well observed on the way south from Pokhari. The thickness of the Amdanda Phyllite in this area varies from 300 m at Dumsidhunga area to more than 1000 m in Chharchhare area.

(iii) Labdi Khola Member (lk)

The name of this member has been derived from the Labdi Khola, a small tributary of Seti Nadi, 3 km southwest of Ghumaune (Fig. 5.1-1). It is widely distributed in the study area and the exposure can be viewed into three places, in the northern and southern limbs of the Jalbire-Ramjakot Synclinorium and to the north of the MBT.

The Labdi Khola Member comprises the succession of intercalation of slate, phyllite and metasandstone with frequent interlayers of silicious, pink to cream colored dolomite and faintly calcareous quartzite. Lower part of the succession consists of greenish grey metasandstone, grey, greenish grey, brown pelitic phyllite, grey psammitic phyllite with rare bands of thin-bedded, grey, silicious dolomite and thin-bedded dirty white quartzite (Fig. 5.1-11a). The middle part consists of grey, greenish grey, green, pelitic phyllite and grey to greenish grey metasandstone in about equal proportion. Some bands of greenschist (up to 17 m thick in Labdi Khola-Bhut Khola section) or metabasites are observed in several sections at the middle part of the member. The upper part of the succession consists of sandy phyllite with abundant current, sinus and linguid ripples (Fig. 5.1-12a) and mud-cracks (Fig. 5.1-12b) with sub-ordinates of pink dolomite, pink calcareous quartzite with current ripple marks. A cyclic deposit of grey phyllite, dirty grey metasandstone, pink dolomite and quartzite is found at the very top of the Labdi Khola Member (Fig. 5.1-11b) which Stöcklin and Bhattarai (1977) termed the typical Nourpul Formation.

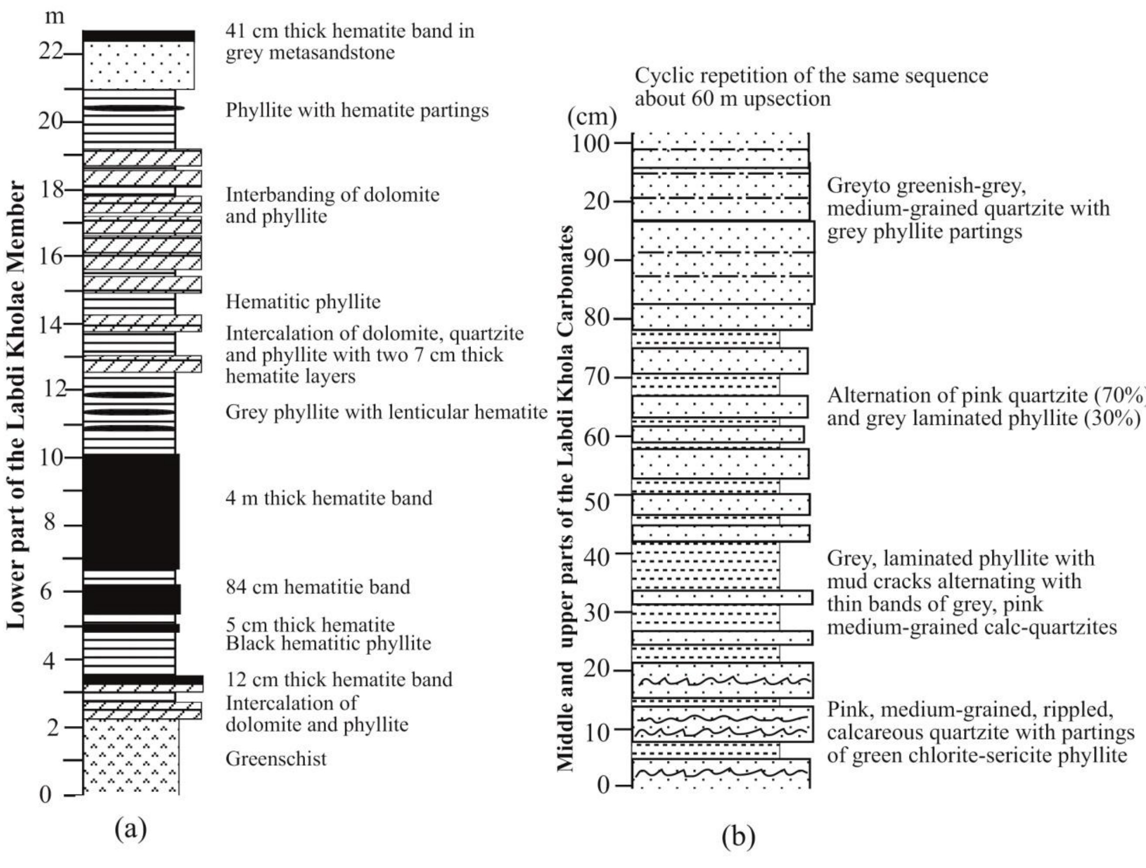


Fig. 5.1-11.(a) Columnar section of the lower part of the Labdi Khola Member observed in Labdi Khola, about 2.5 km upstream from the confluence of the Seti Nadi and the Labdi Khola.(b) Cyclic deposits of upper part of the Labdi Khola Member observed at the right bank of Trishuli river, below suspension bridge at 9 Kilo from Mugling to Narayangarh.

Fig. 5.1-12.(a) Linguid ripple marks in the Labdi Khola Member observed at the right bank of the Trishuli River at Jalbire, south of Mugling, facing toward south. (b) Mud-cracks in grey phyllite of the upper part of the Labdi Khola Member observed at the right bank of the Trishuli River at Jalbire, south of Mugling, facing toward south.

In Kali Khola-Amdanda section, the lower part of the Labdi Khola Member, above the Amdada Phyllite is predominantly phyllitic with variable amounts of quartzite and calcareous intercalations. The phyllite is dark green and grey in fresh outcrop whereas in weathered condition it often shows intense red and purple colors. The quartzite is impure, micaceous, grey and greenish-grey to pink in color. At Jalbire, about 6 km south from Mugling, the middle part of the Labdi Khola Member consists of grey, greenish grey phyllite with well preserved mud-cracks and sandstone and psammitic phyllite with ripple marks. Both phyllite and sandstone are faintly calcareous. Poorly preserved ripple marks are also recorded in some pink quartzite of this succession. A characteristic pink/orange color bandings can often be observed, caused by regular alterations of dolomite, phyllite and quartzite. The thickness of alternate bands is in the range of centimeter to tens of centimeters. Quartz veins oblique to foliation and boudinage of calcareous quartzite within phyllite are frequently observed. At 9 km from Mugling towards Narayangarh (9 kilo in Nepali), at the left bank of river Trishuli, just below the suspension bridge, the uppermost part of the Labdi Khola Member is well observed. It is a cyclic succession of pelitic and psammitic beds (Fig. 5.1-11b).

A good exposure of upper part of the Labdi Khola Member is observed in the Bhut Khola section, about 7 km south west from the Ghumaune to Damauli earthern road. It consists of cyclic deposit of thinly-foliated black phyllite and thin- to medium-bedded white, yellow, pink dolomite with sub-ordinates of grey metasandstones and grey, pink, flesh colored ortho-quartzite. Such cycle repeats up to ten times in the outcrops (Fig. 5.1-13a). Large boudinage of quartzite within the pelitic phyllites are observed along the Bhut Khola-Labdi Khola sections with copper mineralization (azurite, malachite and chalcopyrite) (Fig. 5.1-13b). There is the presence of metabasite (greenschist/amphibolite)

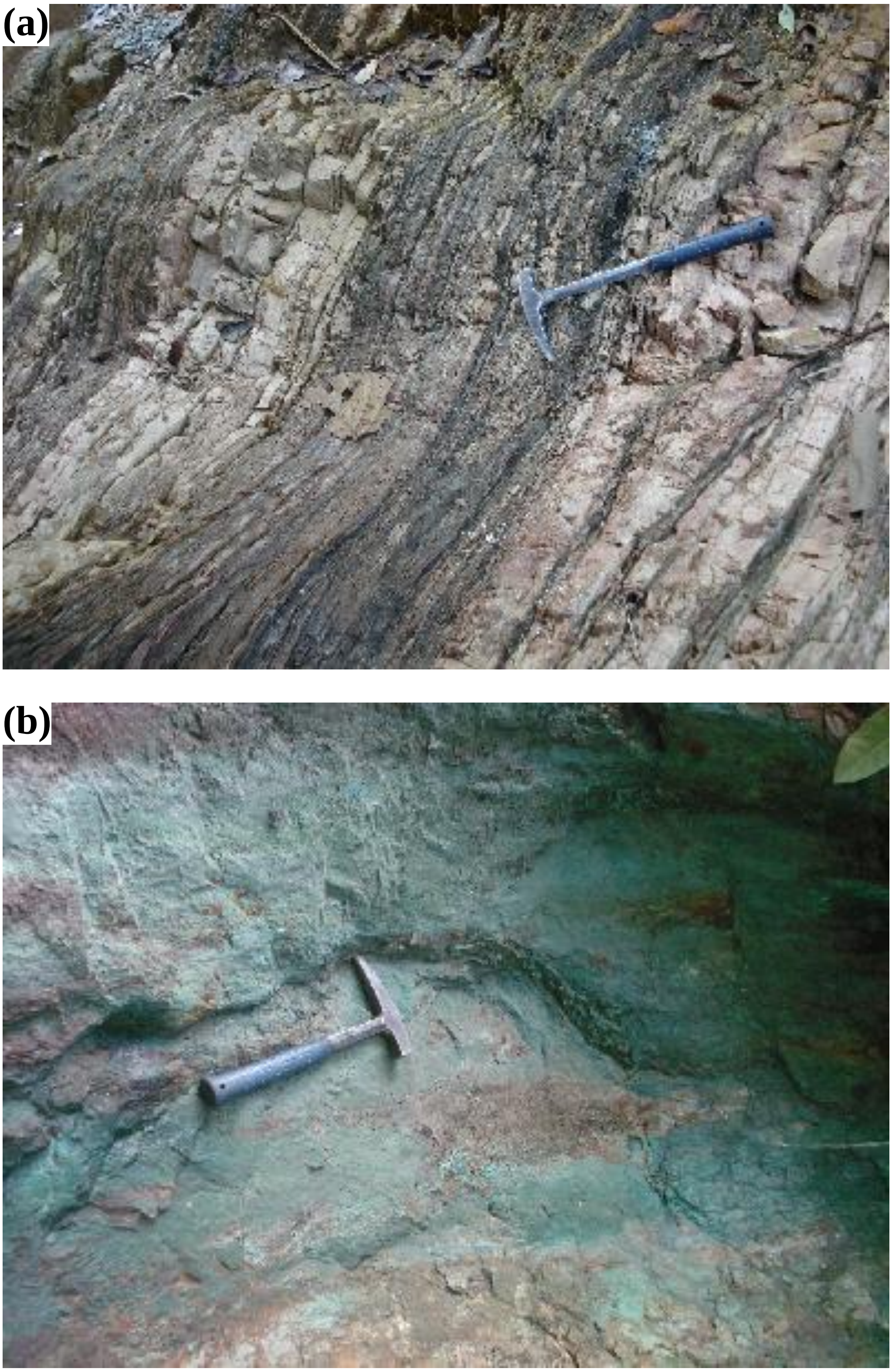


Fig. 5.1-13.(a) Cyclic deposits of the pink quartzite, pink dolomite, black phyllite and grey metasandstone of the upper part of the Labdi Khola Member, observed in the Bhut Khola, facing N. (b) Malachite coatings in quartzite of the upper part of the Labdi Khola Member, observed in Bhut Khola area.

extensively distributed from the Labdi Khola, Bhut Khola to Bagar Khola areas along the strike. Radiating crystals of secondary gypsum are also found in the faintly calcareous quartzite and siliceous dolomite. In the middle part of this member there is alternation of metasandstone and calcareous phyllites. After easy weathering and dissolution of calcareous phyllite in comparison to metasandstone, alternate sequence of pot holes and waterfalls are developed along the Bhut Khola.

In Khare Khola section, the succession consists of bluish grey, purple, pelitic phyllite intercalation with grey psammitic phyllite and grey metasandstone. Phyllite is well-foliated and consists of detrital mica and it is well intercalated with pink siliceous dolomite. The transitional contact with lineated pelitic and psammitic shale and phyllite of Amdada Phyllite is also exposed in this section.

In Ghumaune, it consists of intercalation of pink quartzites and green phyllites in the ratio of 1:1. Faintly preserved current ripples are usually found in the beds of grey quartzite and sandy phyllites. Hematite band is noted within the succession. About 30 m thick metabasite is observed concordant to the phyllite and metasandstone in the Mugling-Ghumaune road, near Ghumaune.

A noteworthy feature of the metasandstones (quartz arenite) of the Labdi Khola Member observed in the Jalbhanjyang, Geru Khola Gaon, and upper reaches of Hilekharka areas is the presence of very coarse-grained smoky quartz crystals (>90%). Surprisingly, dark grey to smoky ortho-quartzites in Jalbhanjyang and Geru Khola area has developed orange colored soil (*Geru* in Nepali) (Fig. 5.1-14). In Jhargaon and Bahun Bhanjyang areas, north of Bandipur, the metasandstones and ortho-quartzites consist of well-developed rock crystals. Most of the rock crystals are colorless while some varieties consist of pink and flesh colored. At Bahun Bhanjyang and in the lower reaches of the

Phalamdada area, phyllite is well-laminated (thickness of lamina= 1 to 7 mm) and lamina are oblique to the foliation. In the Bhangeri Khola, near Bhangeri Gaon, vein type polymetallic deposits are observed in the locally exposed charcoal black phyllite/slate. At the lower reaches of Jhargaon, meta-congolomerates are also found within this succession.

Fig. 5.1-14. Weathering of ortho-quartzite of the Labdi Khola Member. Geru (red soil) is developed as a weathering product. Photograph is taken from the Geru Khola Gaon, facing NW.

The Labdi Khola Member exposed in the southern limb, just northern part of the Dewachuli Thrust (DCT), is found almost similar to the succession exposed in the northern part of the Synclinorium. At Kota Baseni, the Labdi Khola Member consists of greenish-grey to dark grey, soapy phyllite and grey, medium-grained, thick-bedded metasandstone in 2:1. The similar type of lithology is found in the northern parts of the Hattisal area. In Hattigauda area, this unit is composed of purple, green to grey, laminated phyllite and dirty white, fine-grained, calcareous metasandstone. Mud-cracks and linguid ripple marks are recorded in purple phyllite in this area.

At Bagandi, Saldada and Jamdada areas, the Labdi Khola Member shows almost similar type of lithology. It is represented by the purple, greenish-grey, ash grey to dark grey, soapy, well-foliated phyllite intercalated with greenish grey, medium-grained metasandstone and ortho-quartzite. Northern part of Bagandi, green phyllite and green schist is found abundantly. At Jamdada, abundant mud-cracks are observed in purple-grey, psammitic phyllite. At Chheranga, purple, greenish-grey, bluish-grey to dark grey, thin bedded, well-foliated phyllite is intercalated with greenish-grey, medium-grained, thick-bedded metasandstone. Phyllite shows faintly calcareous in fresh outcrops. While moving westward, (around Kotthar and Arbaje areas) phyllite becomes more laminated and strongly crenulated or deformed.

In Kota Baseni, Hattisal and Hattigauda areas, the Labdi Khola Member is exposed immediately above the MBT. In Bagandi, Phosrepani and Gahatedada areas, it is exposed directly above the Purebensi Quartzite where the middle member the Amdanda Phyllite is missing. Westward, in Kotthar, Arbaje, Dandathok and Deurali areas, the Labdi Khola Member is exposed immediately above the Amdanda Phyllite. In Chherenga and Jaithum areas, the Labdi Khola Member directly comes above the Dhading Dolomite along the DCT. In Pokhari area, the Labdi Khola Member is exposed immediately north of the Siwalik succession by the MBT. In this section, a thin band (30 m) of ortho-quartzite is exposed north of MBT and it is successively followed by the variegated shale with mud-cracks and ripple marks and sub-ordinates of argillaceous dolomite with columnar stromatolites. The lithological succession of this area is not very similar to the succession exposed in the eastern part of the area. Dolomite bands with stromatolites and purple shale with green and red shale is also new appearance. In Deurali area, NW of Pokhari, the lithology of this unit is composed of greenish grey to ash grey, medium to coarse-grained, thick-bedded metasandstone/quartzite intercalated with purple to grey, fine-grained phyllite in about equal proportion. Mud-cracks are well exposed on the way, south from Pokhari village. The weathering of the Labdi Khola Member is moderate to high with moderate to gentle topography. Most of the settlements and the cultivated lands lie in this unit.

Chhapswara Metasandstone Beds (cp)

In Chhapswara area, metasandstone beds within the Labdi Khola Member is thick enough to be mapped and has been mapped as the Chhapswara Metasandstone Beds (Fig. 5.1-1).It is well distributed in the Chhapswara, Dheregaon, upper reaches of the Sinarkhola (a tributary of the Bhut Khola), Mathillo Jalbhanjyang, upper reaches of the Musti Khola and Kulmun areas. Lithology of this unit is dominantly composed of fine- to medium-grained, grey, metasanstone with subordinates of grey phyllite. In Dheregaon, it consists of lead grey to ash grey, fine- to coarse grained, and medium -to thick-bedded (40 cm to 1.5 m) metasandstone with minor intercalation of grey, purple, fine-grained phyllite. The Metasandstone beds occasionally consist of faint laminations whereas the intercalated phyllite is rich in detrital muscovite. The lower part of the Bed consists of light grey, medium-bedded, fine-grained metasandstones with sub-ordinates of light grey, psammitic phyllite (Fig. 5.1-15a). In middle section, the proportion of metasandstone increases where it contains the faintly preserved parallel laminations. The top part is composed of greenish grey, fine- grained, medium-bedded metasandstone and purple pelitic phyllite in equal proportion. The lower and upper contact of this unit with the Labdi Khola Member is transitional everywhere. The total thickness of this unit is about 300 m (max. thickness) in the Jalbhanjyang-Chhapswara area. It has been mapped in three pathches in the adjacent areas and its extension pinches out near to the Labdi Khola in the east and Dhanda Khola in the west (Fig. 5.1-1).

Bagar Khola Metabasite (bk)

In the Bagar Khola area the metabasites can be mapped as a separate unit and has been named as the Bagar Khola Metabsite (Fig. 5.1-15b). The exposure is about 1 km upstream from the confluence of Seti River and Bagar Khola. The metabasite is dark green due to chlorite, epidote and amphiboles. It is massive and granoblastic with distinct mineral lineation. The lineation is due to the preferred orientation of actinolites. It is massive in fresh outcrops and foliation is weakly developed. It is uninterruptly exposed in Dharampani, Sarang, Bhut Khola section, Ratanpur, Labdi Khola section, Donran and Khasran areas (Fig. 5.1-1). The contact of amphibolite with adjacent rocks of the upper part of the Nourpul Formation is sharp and conformable. The thickness of the metabasite is not uniform and it varies from 25 m to 100 m in the study area. In Labdi Khola section (located about 1.5 km upstream from the confluence of Seti River and Labdi Khola), the metabasite is altered to greenschist with well-developed foliation. The maximum thickness of this succession is about 80 m in this section. The Bagar Khola Metabasite appears like weathered pelitic phyllite in the ridges.

The average thickness of the Labdi Khola Member is about 1000 m. It sharply passes into the Dhading Dolomite or the Benighat Slate in some places. In Bandipur area, it transitionally passes to the Bandipur Slate.

(iv) Bandipur Slate (bp)

It is well-developed at Bandipur and its adjacent areas locally (Fig. 5.1-1). The rock succession consists of the monotonous succession of grey, faintly-laminated slates with subordinates of grey, coarse- to very coarse-grained, medium-bedded metasandstones. The thickness of individual sheets of the slates is measured in the range of millimeter to few

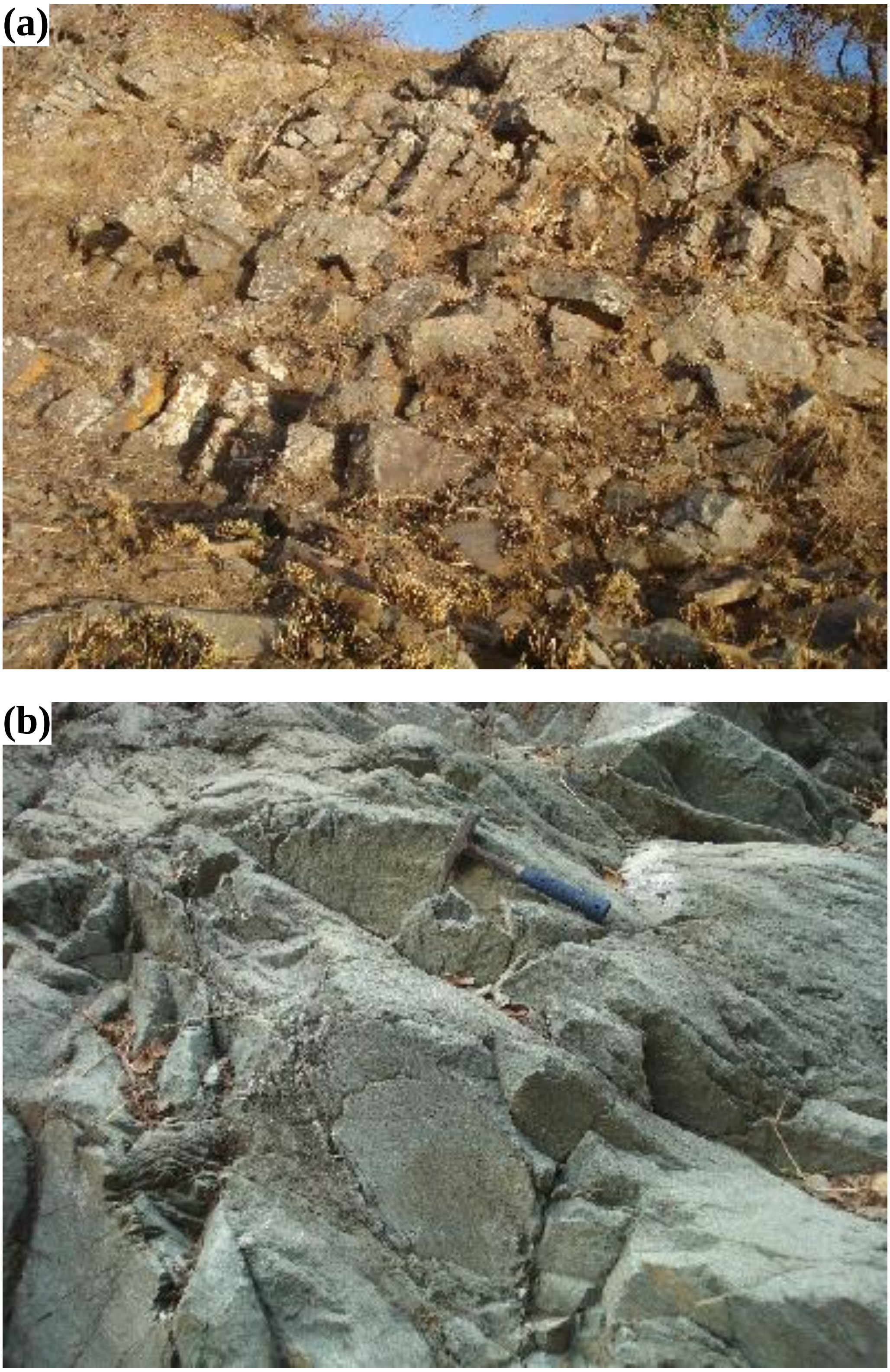


Fig. 5.1-15. (a) Outcrop view of the Chhapswara Metasandstone beds observed at the Dheregaon, facing N. (b) Outcrop of metabasite at Bagar Khola. The metabasite band is more than 80 m in the area and extends to the whole stretch of the mapped area.

centimeters. It has been used as a good quality roofing stone for a long time (Fig. 5.1-16a). In most of cases the bedding is found parallel to the foliation or cleavages. The metasandstones are laminated with distinct cross-beddings(Fig. 5.1-16b).The metasandstones in some palaces show the growth of small well-developed rock crystals (max observed size=6 cm x 3 cm x 2 cm). It is mapped as the top most unit of the Nourpul Formation. The total thickness of the unit is >200 m and its contact with overlying Dhading Dolomite is sharp and conformable.

(e) Dhading Dolomite (dh)

The name Dhading Dolomite was first used by Stöcklin and Bhattarai(1977) from the place Dhading Bensi of central Nepal.

Synonymy: "Grey Dolomite" (Indian geologists, particularly, Pawde 1973; and Talalov 1972), "Hilang Suite" (part) (Talalov 1972) and Dhading Limestone by Arita et al. (1973); "Surtibang Dolomite" (Sharma et al. 1984); (Chhapani+Khoraidi+Saidi) Formations in Kaligandaki area (Sakai 1985) and "Darsing Dolomite" (Hirayama et al. 1988).

The Dhading Dolomite is a conspicuous ridge-forming unit all over the study area. It is widely distributed in the study area and is exposed in four places: above the Dandagaon Phyllite as unconformable contact (NE part of study area), in isolated pockets as outliers in north-central part of the study area, on both limbs (core part) of Jalbire-Ramjakot Synclinorium and in the southern part immediately north to the MBT (Fig. 5.1-1).

Dhading Dolomite is a monotonous succession of bluish grey, thin to massive, siliceous dolomite with grey, fine-grained, crenulated pelitic phyllite partings (Fig. 5.1-

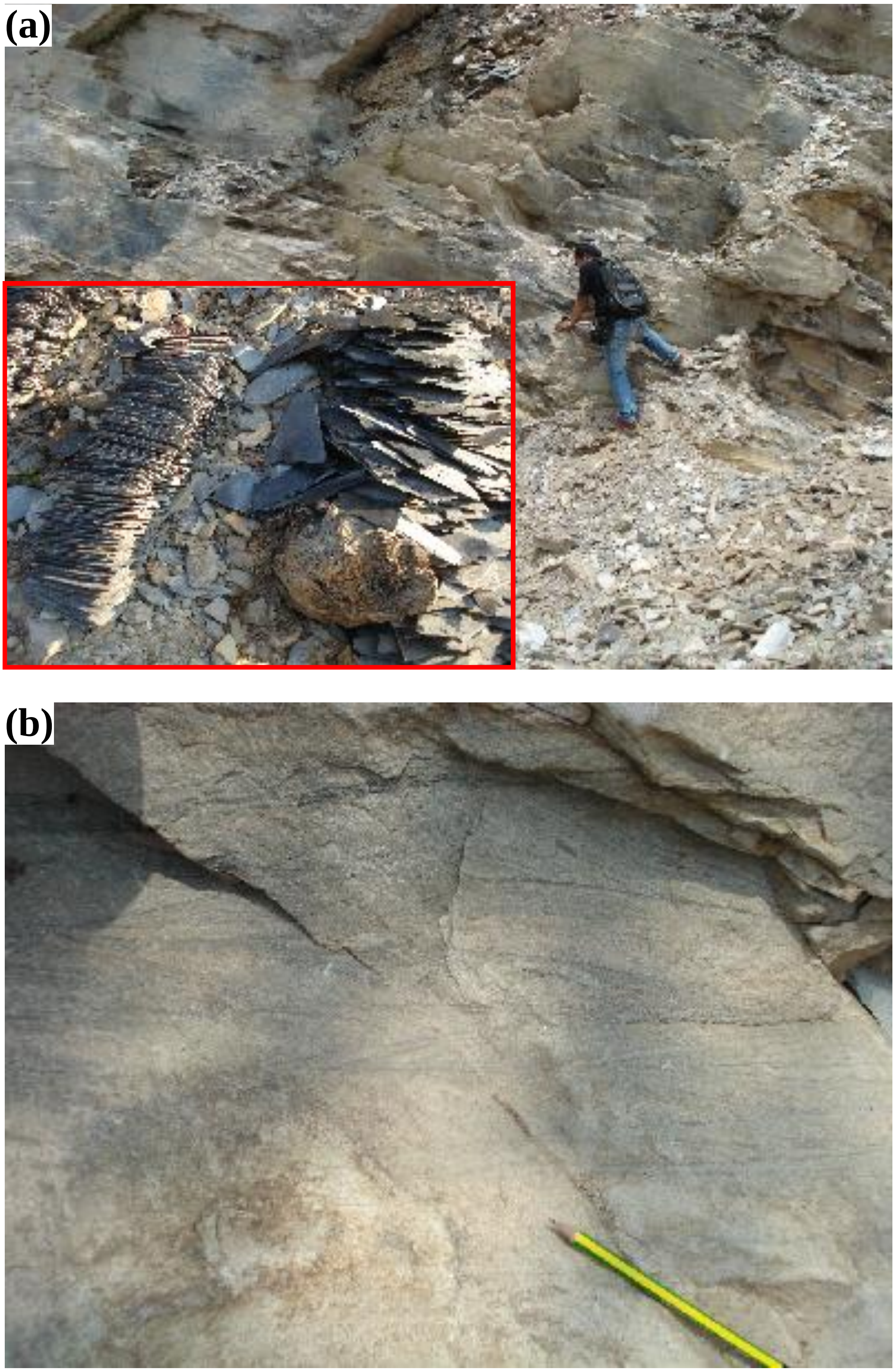


Fig. 5.1-16. (a) Outcrop of the Bandipur Slate at a quarry site near Jhapri, south of Bandipur. The photo in the inset (lower left corner) shows roofing slates mined from the Bandipur Slate. (b) Cross-laminations showing locally overturned bed of metasandstone in the Bandipur Slate.

17). Dolomite consists of poorly preserved algal mats and well-developed columnar stromatolites. Grey to dirty white quartzite is occasionally associated within the succession. Sometimes, the occurrences of phyllite/slate become 20% or more within this unit. In general, the lower part of the unit consists of medium- to thick-bedded cherty dolomite (95%) with rare imprints of algal mats. Grey, fine-grained pelitic phyllite appears as partings within the dolomites. Occasionally, some thin beds of dirty white quartzite are found. In the middle part, the thickness of dolomite beds increases and it contains abundant and well preserved columnar stromatolites(Fig. 5.1-18a) with sub-ordinates of quartzite and phyllite. At the top part, the beds of dolomite decreases, the stromatolites become rare. However, intra-formational conglomeratic beds become abundant(Fig. 5.1-18b). The quartzite beds disappear thereby increasing the pelitic rocks up to 10%.

Thickness of the Dhading Dolomite is not uniform in the area; it is about 20 m thick in Ghumaune and it increases to 300 m and more in Khara, Sonde, Damauli and Dewachuli areas. Weathered outcrops display elephant skin appearance, honey-comb-structures and some leaching features like stalactites and stalagmites with many cavernous surfaces. Mostly, the dolomite beds are strongly deformed and disintegrated into blocks, which make it often difficult to distinguish bedrock and boulders. This is the case especially in the deep weathered ridges and spurs.

In the NE part of the study area, around the Dumre Bazzar and lower reaches of Bandipur area, Bhangeri area, Khudi Khola section and Takmare, the succession is exposed immediately above the Dandagaon Phyllite (the Nourpul Formation is missing). It is a monotonous succession of bluish grey to cream white; well-laminated to platy to massive beds of siliceous dolomite with columnar stromatolites and intra-formational clasts containing dolomites with grey, fine grained pelitic phyllite partings. On the way to

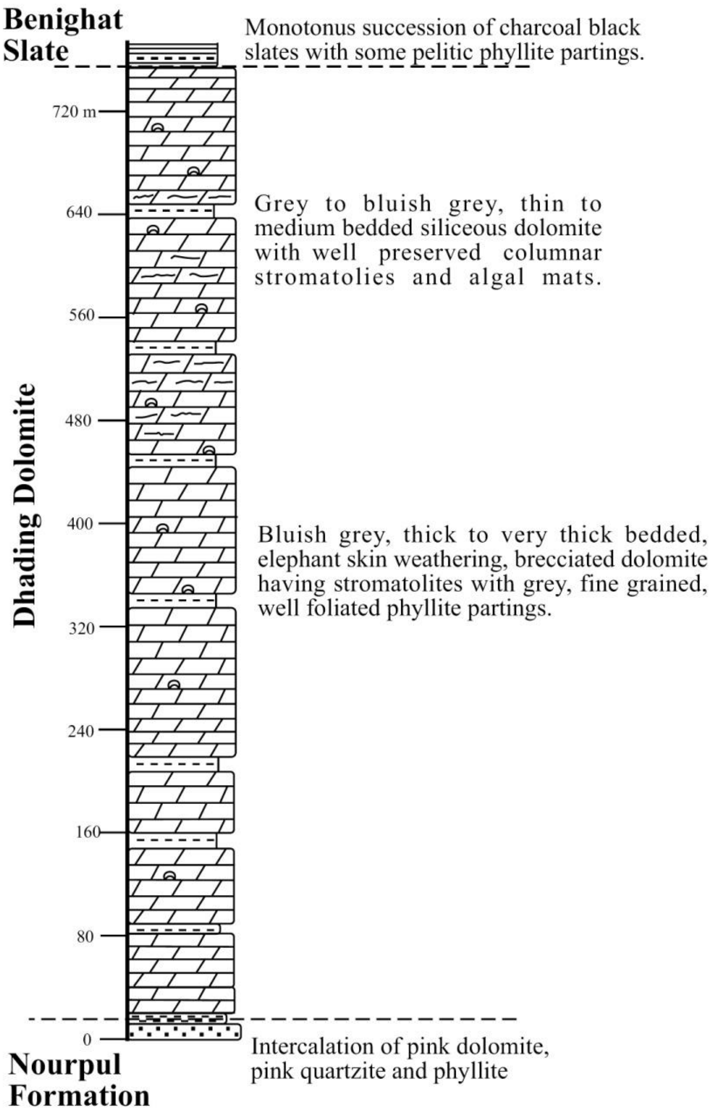


Fig. 5.1-17. Detailed columnar section of the Dhading Dolomite at Jugedi, along the Mugling-Narayangarh road.

Bandipur from Dumre Bazzar, dolomite is found highly deformed, folded and differentially weathered. Abundant intra-formational clasts (size= 4.5 cm long and 1.5 cm thick) are observed in this section. In the Bhangeri area, it is creamy white in color and beds exhibit slaby in nature (flooring quality) due the presence of chlorite/talk rich thin to very thin phyllite partings. Columnar stromatolites show the beds in right side up position.

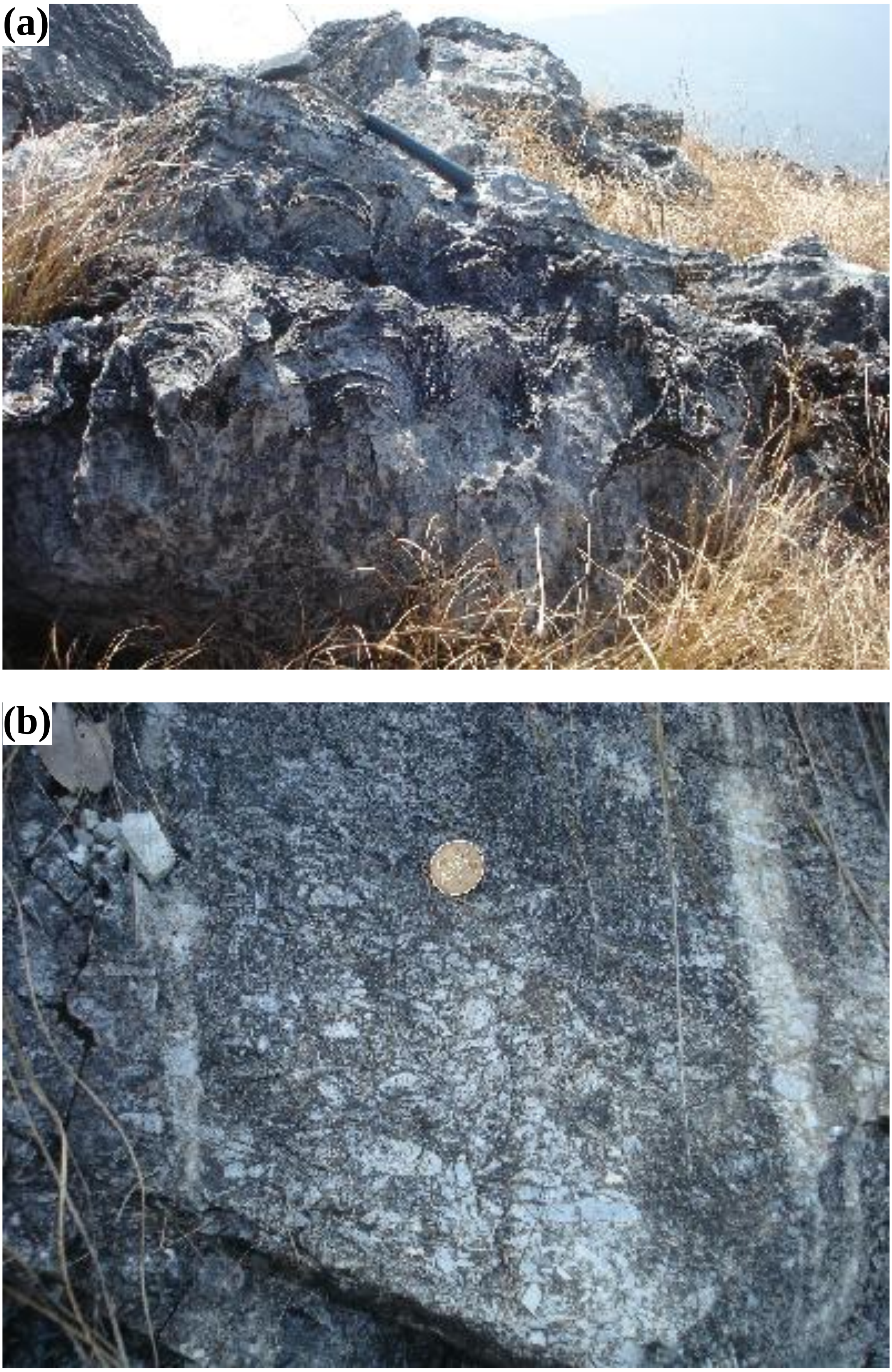


Fig. 5.1-18. (a) Columnar stromatolites in the Dhading Dolomite at Dewachuli Peak showing normal stratigraphic position of the beds. (b) Intraformational clasts in the Dhadig Dolomite at Taran Khola.

A prominent Bhangeri Thrust (BT) carries the older Labdi Khola Member of the Nourpul Formation on its stratigraphic top position.

There are two isolated outliers of Dhading Dolomite mapped around the Bandipur area; one immediately NW of Bandipur Bazzar (Fig.5.1-19a) and other SE of the Bandipur at Phalamdanda area. Two outliers are also mapped at the SW and NW of Damauli area around the Chhabdi area. All these exposures consist of monotonous succession of bluish grey, siliceous dolomite with grey, fine-grained phyllite partings. The percentage of phyllite is sometimes reached to 20% in Chhabdi section. Algal mats and columnar stromatolites are commonly observed in the dolomites. Some cherty beds are also found within the successions. Occasionally, intra-formational clasts are also observed.

An extensive exposure of the Dhading Dolomite is mapped in the northern limb of the Jalbire-Synclinorium while in the southern limb it has limited extension and disappears with decreasing thickness slowly at Jaithum-Chherenga Khola. At the core part of this fold the thickness of the dolomite is very thin (up to 15 m only in Ghumaune area) while it is extensive forming prominent peaks westward. For example, in Khare and Sonde areas, dolomite forms the great thickness with the inaccessible terrain. Vertical cliffs of the dolomite can be viewed up hills while moving along Ghumaune-Damauli road. The lithology consists of bluish grey, medium-to-thick, siliceous dolomite. In contrast to other positions, the dolomite consists of poorly preserved algal mats and stromatolites in this section.

The Dhading Dolomite is relatively thicker (~ 900 m) to immediately to the north of the MBT at Dashdhunga area along Muglin-Narayangarh. The main lithology of this unit comprises the monotonous succession of bluish grey, mostly massive, sometime medium to thick bedded, rarely platy, brecciaed, siliceous dolomite with partings of grey, fine-grained, pelitic phyllite. Occasionally, cherty beds are also found inter-bedded within the succession. The most noteworthy feature of dolomite in this section is the presence of abundant algal mats and columnar stromatolites. Intra-formational conglomerates within the dolomites are abundantly observed in the upper parts.

In the lower reaches of the Bagandi, right bank of the Trishuli River, immediately north to the MBT (north of Siwalik), a great succession of dolomite is observed. It consists of bluish grey, thin-to-thick-bedded, siliceous dolomite with partings of purple, dark grey, pelitic phyllite. Well-preserved columnar stromatolites and remarkable intra-formational conglomerates are observed. In the lower part of this unit, some beds of white, fine-grained ortho-quartzites (max. 10 m thick) are found. On the way to Phoshrepani from Kuwadi Khola, a monotonous succession of dolomite with abundant columnar stromatolites is found. In these ridge sections, rocks are moderate to highly weathered forming significant karst topography. SE of the Gahatedada similar type of lithology is encountered.

In Selighopte section, massive beds of siliceous dolomite is found rarely intercalated with cherty dolomite and charcoal black slates. In Besardada area, dolomite on its deep weathering has given red soil development with karst topography. The lithology is almost similar to the general lithology of the Dhading Dolomite observed in other adjacent sections. The most remarkable is the well-preserved stromatolites in moderately weathered outcrops. At Taran Khola section, laminated siliceous dolomite (about 85%) is intercalated with grey and purple slate (15%). In this section, the most remarkable is the increase of argillaceous material (slate) within the succession. South of Satikot, the most remarkable feature is the abundant intra-formational clasts and columnar stromatolites in the dolomite.

In Dewachuli areas, the Dhading Dolomite forms the highest peak (1910 m) of Nawalparasi District. It comprises the monotonous succession of ash grey to bluish grey, laminated to massive, brecciaed, siliceous dolomite with beautiful exposure of columnar stromatolites (Fig. 5.1-18a). Partings of grey, pelitic phyllite and beds of intra-formational conglomerates (dimension of clasts: max. length=15 cm and max. thickness=4 cm) are also noted within this section.

The Dhading Dolomite shows irregular thickness in the area. It forms a prominent inverted funnel like hill (Solighopte peak in Nepali) in the northern limb of this fold. In this area, it is well developed and its thickness increases suddenly. This unit consists of monotonous succession of bluish grey, massive, siliceous dolomite with abundant partings of grey, pelitic phyllite. Faintly preserved columnar stromatolites are found in some beds of dolomites. Intra-formational clasts of dolomite are found commonly. In the upper part of the succession, dirty white, coarse-grained, thick bedded, non-calcareous ortho-quartzite (~ 50 m) is found locally.

The thickness of the Dhading Dolomite decreases westward from the Solighopte and completely disappears at Jaithum-Orjha areas. The Dhading Dolomite sharply passes to the Benighat Slates in stratigraphic up section (Fig. 5.1-19b).

(e)Benighat Slate (bg)

The name was first used by Stöcklin and Bhattarai in (1977), and it is derived from the village of Benighat at the confluence of Burhi Gandaki and Trushuli River in central Nepal; eastern part of the present study.

Synonymy:"Carbonaceous Phyllites" and "Carbonaceous Slates" (Indian geologists, particularly, Nanda 1973; and Pawde 1973); "Tara Suite" (part) (Talalov

Fig. 5.1-19. (a) The Dhading Dolomite forming cliffs south of Bandipur Bazar. It occupies the core of a syncline extending NNW-SSE. (b) Sharp and conformable contact between the Dhading Dolomite and overlying Benighat Slate along the Labdi Khola.

1972); Riri Slate (Fuchs and Frank 1970); Hatiya Formation (Sharma et al. 1984); Black Slate (Arita et al. 1984); Ramdighat Formation (Sakai 1985) and Galyang Slate (Hirayama et al. 1988).

It is widely distributed in the present study area. About 35% of the area is covered by the monotonous succession of slates/phyllites occupying the core of the Jalbire-Ramjakot Synclinorium (Fig. 5.1-1). The great thickness is due to the repetition of rocks due to multiple folds as it occupies the core of the regional fold. It is the youngest unit of the area. The younger units like the Malekhu Limestone and the Robang Formation as found in Malekhu area are missing in this area.

Benighat Slate consists of monotonous succession of dark grey to charcoal black, finely-laminated slate with minor amount of meta-siltstones and dolomites (Fig. 5.1-20). In fresh outcrops it displays the dark grey to charcoal black slates/phyllites with well developed laminations (Fig. 5.1-21a and b). However, in weathered condition, slates are ash grey to silver white and brown to dark grey in color(Fig. 5.1-21b). The color of soil formed by these rocks reflects lead grey to brown. It forms a subdued and gentle topography with thick vegetation, crop lands and suitable lands for settlements. However, in counter dip slopes especially on the scars of the landslides it formed a very steep and inaccessible terrain.

Rocks of this formation are exposed in both sides of Seti River and Kali Gandaki River valleys and ridges. In Gaighat, Ghumaune-Labdi Khola-Bhut Khola sections the slate is dark grey to charcoal black, finely-laminated and internally folded. The outcrop consists of 90% phyllite/slate and 10% calcareous metasiltstone. The characteristic dark slate is usually observed in fresh outcrop along the river banks but in weathered exposures of the hill slopes rocks show much lighter color like lead-grey, silver-grey, pink-pale-green etc. Some charcoal black graphitic layers are observed within the succession.

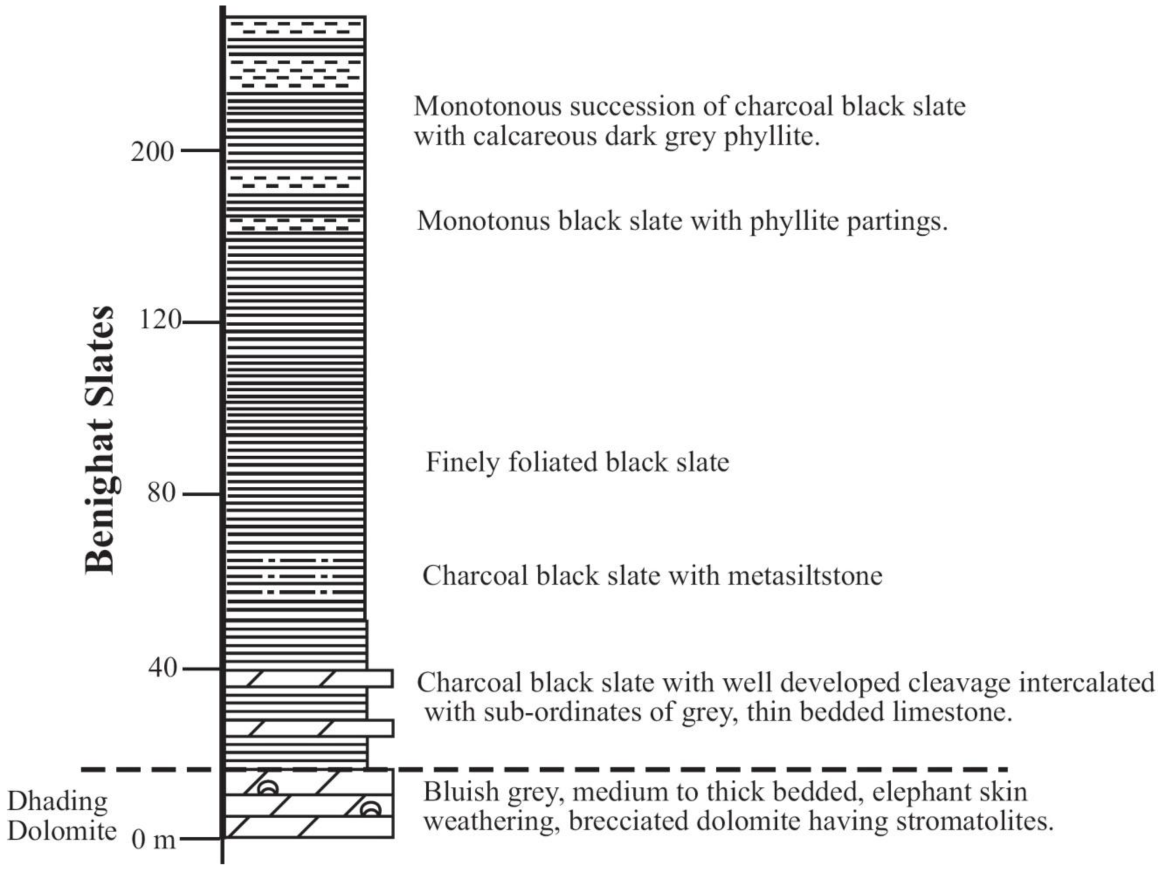


Fig. 5.1-20. Detailed columnar section of the lower part of the Benighat Slate along the Muling-Narayangarh road at Gaighat. The contact is transitional in some sections.

In Bar Khola section, the Benighat Slate contains finely laminated (lamina=1 mm to 5 mm) slates with sub-ordinates of thin to medium bedded grey metasandstones. Rare bands of carbonates and coarse-grained metasandstones are also reported. Randomly oriented quartz and gypsum veins are found in slate. Few bands of poly-metallic ore (thickness=10 cm) are also observed. The same type of band is also observed in Jaubari Khola and Khare Khola along-strike extension from Bar Khola. A large area of Watak, Gondran and Ailung is covered by the laminated succession of the Benighat Slate.

Fig. 5.1-21.(a) Finely laminated black carbonaceous slate of the Benighat Slate along the Masti Khola. (b) The Benighat Slate looks dark black in the fresh outcrops (right side of the photo) and grey in weathered outcrops (left side of the photo).

In Kot Baidi area, the succession consists of large boudinages of quartz (diameter= 22 cm).

At Ghartibas area, the proportion of grey, medium bedded, fine-grained metasandstone is found relatively more (20%) within the succession of slates. In Jamune area within the Benighat Slate, about 50 m thick band of grey ortho-quartzite is found in addition to several thin bands of white ortho-quartzites. In Naram and Chippchhipe areas, there is intercalation of pelitic and psammitic slates/phyllites in 1:1 ratio with frequent grey, medium-bedded, medium-grained metasandstone. The monotonous succession of the Benighat Slate is well distributed in the Watak and Gondrang areas forming rounded hills where the slate on weathering has produced dark grey to black soil and is quite fertile for the crops and fruits. In Kabhrekholagau thin bands of grey dolomites are observed within the dark grey, well-foliated slates. In these areas the slate and phyllite is highly deformed and folded. Roofing slates are found in Phagunedada.

At Khalte, the succession of Benighat Slate consists of intercalation of dark grey pelitic slate/phyllite and psammitic calcareous slate with minor amounts of grey, medium-bedded dolomite. At Mathar-Adhmara there is similar type of lithology as observed in the Khalte. Crenulation cleavages and quartz veins parallel to foliation are the remarkable features of this area.

In Buling-Dharapani area, the succession of this unit is dominantly composed of strongly laminated slate with occasional bands of grey, thin-bedded dolomite. In Phildi Khola, upper reaches of Bullintar, this unit consists of significant amount of grey, calcareous, medium bedded metasandstone with grey, green and purple slate. In Arkhala area, monotonous succession of moderate to highly weathered slates is observed. Several bands of metasandstone, limestone and dolomite are frequently inter-bedded with slate. Limestone bands are also faintly laminated.

The Benighat Slate is overlain by crystalline rocks of the Tanahun Group forming the Kahun Klippe in west-central part. It is extensively distributed all around the klippe in the form of syncline and covers enormous area. It consists of dark grey to charcoal black, finely laminated slate and phyllite. In weathered condition, it shows ash grey to brown color. Within the succession, there are several calcareous horizons within the slates, sometime in the basal part and somewhere towards the top. Grey limestone beds are not uncommon anywhere within the succession. In some outcrops, it consists of psammitic phyllite, coarse-grained quartzite (up to 1.5 m thick) and calcareous pellitic phyllite. Usually the quartzites are lenticular and even form boudinage. Such feature is best studied in Gwaslung and Machadang where it is prominently folded. Very well developed laminations and frequent quartz veins that are folded and parallel to the lamination are two characteristic features of the phyllite and slate. The Thickness of lamina varies from 0.25 mm to 4 m.

A highly undulated, greenish-grey phyllite is exposed at Wakmadi. In Lima Khola section monotonous black calcareous phyllite forms a thick succession. Towards the top of the formation, about 60 m thick succession of laminated, bluish-grey, siliceous dolomite with phyllite partings (9:1) is exposed in Maidanswara equivalent to the Jhiku carbonate and extends a short distance from Lima Khola to Pathargau village. Near to the thrust contact with the crystalline succession, admixture of pelitic and psammitic rock forms a rod and mullion structure.

A succession of greenish-grey to brown and black, calcareous to non-calcareous, thin- to medium-bedded, thinly-laminated, pellitic and psammitic phyllite with subordinates of medium-bedded, grey, slightly calcareous quartzite is well-exposed in Jyamire Khola. Similar lithology exists in Gurungau-Lankuswara section and in Naya

Risin-Ramjakot-Pipalswara areas. Towards the south of klippe, the lithology is primarily grey to black, sandy phyllite and bluish-grey, soapy phyllite with abundant, deformed quartz veins parallel to the foliation and sub-ordinates of dirty-grey limestone as intercalations.

The observed minimum thickness of this formation is 2600 m. crystalline rocks of the Gwaslung Formation overlie the Benighat Slate along the Dubung Thrust (DT) (Fig. 5.1-22).

Fig. 5.1-22. Contact between the underlying Nuwakot Group and the overlying Tanahun Group observed at Gwaslung. The boundary is a tectonic contact named as the Dubung Thrust. Photo facing SE.

5.1.2 Lithostratigraphy of the Tanahun Group

The name of this group is derived from the district Tanahun. It overlies the Nuwakot Group along the Dubung Thrust (DT). It consists of metamorphic crystalline rocks (up to garnet grade) like schist, quartzite and marble of the Kahun Klippe. The rocks of the Kahun Klippe are distributed in the Gwaslung, Gumlek, Kahun, Shivapur, Dubung and Wangja Gaun areas about 25 km south of Damauli. A complete section of the Tanahun Group exposed along the road section from Gwaslung to Shivapur is shown in the route map (Annex IV). It occupies the core of the Jalbire-Ramjakot Synclinorium. The Tanahun Group can be divided into three units as the Gwaslung Formation, Musimarang Formation and the Shivapur Schist from bottom to top, respectively. A generalized columnar section of the Tanahun Group is given in Fig. 5.1-23.

(a) Gwaslung Formation (gw)

The name of this formation is derived from the village Gwaslung (Fig. 5.1-1).The Gwaslung Formation sharply overlies the Benighat Slate along the thrust contact (the DT) (Fig. 5.1-23). It is widely distributed to the NE of Gwaslung and southern parts of Dubung area. The succession is missing towards the western part of the klippe. The formation is dominated by the calcareous rocks. The basal part of the formation consists of a band of bluish grey saccroidal dolomite marble (0.5 to 2.5 m thick) intercalated with chlorite-biotite pelitic schist. It is followed up by dirty white, well-laminated, fine- to medium-grained, medium- to thick-bedded impure marble (90%) (Fig. 5.1-24a) with subordinates of white faintly calcareous quartzite and bluish grey, medium-grained pelitic schist (10%).

In the upper part, milky white calcareous quartzite becomes dominant over dolomite-marble and biotite-schist. The dolomitic marble is siliceous whereas the quartzite

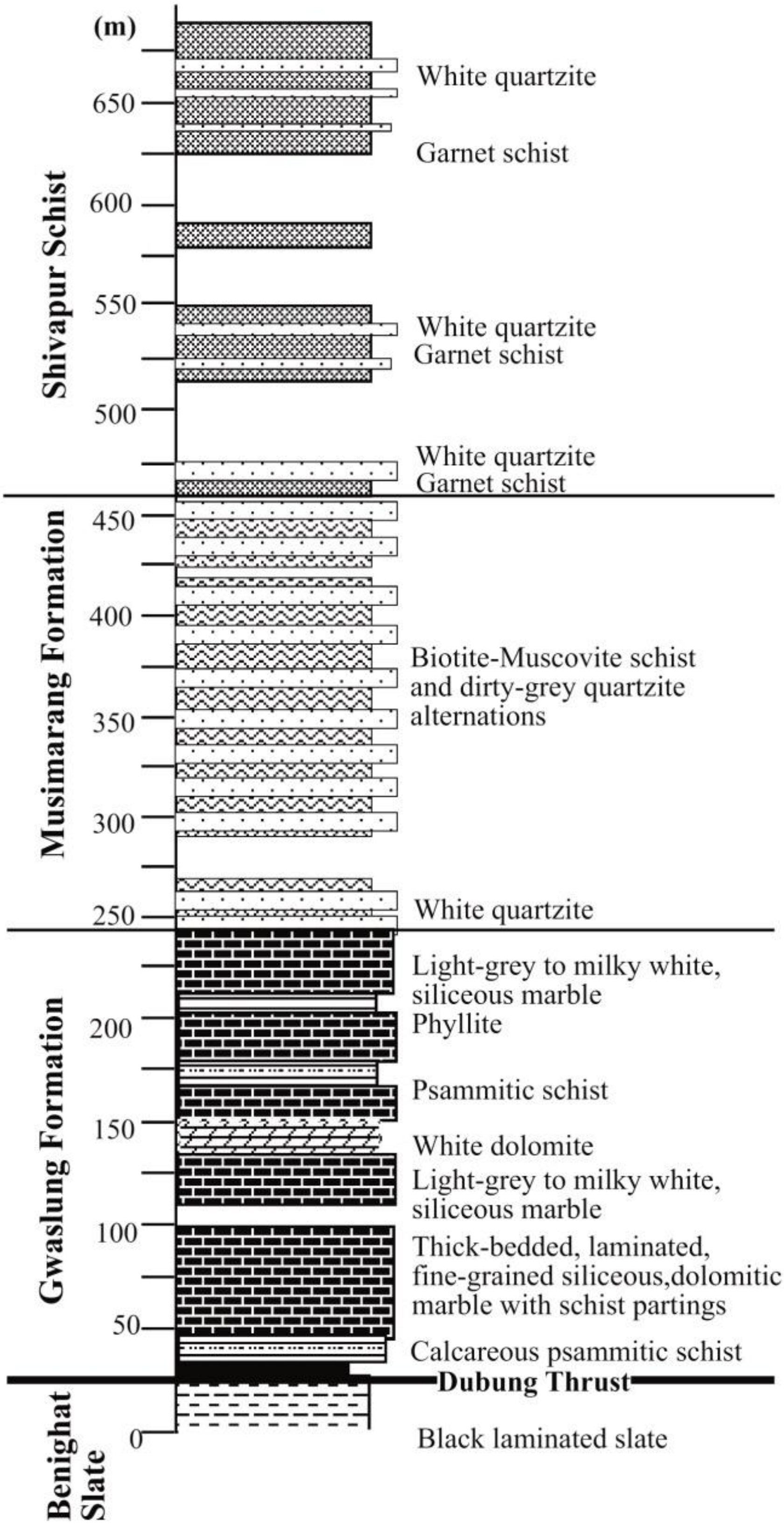


Fig. 5.1-23.Generalized columnar section of the Tanahun Group along the Gwaslung-Shivapur section.

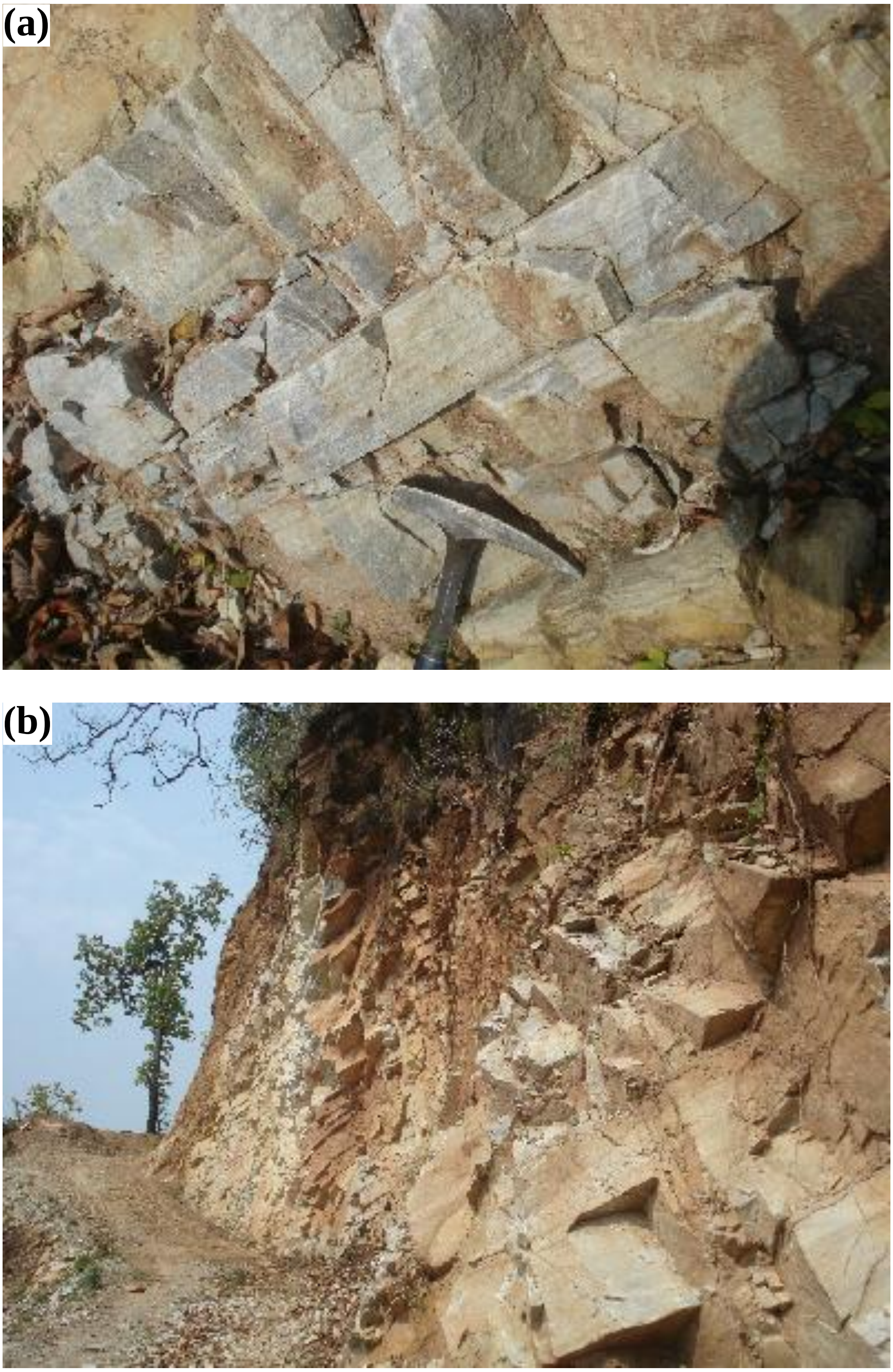


Fig. 5.1-24.(a) Outcrop view of the well-laminated dolomitic marble of the Gwaslung Formation observed at the Gwaslung section, photo facing SE. (b) Outcrop view of pinkly weathered, fine-grained white calcareous quartzite of the middle part of the Gwaslung Formation exposed in Gwaslung section, photo facing SE.

is faintly calcareous and strongly lineated. Pinkly weathered color is the remarkable characteristics of the white quartzite (Fig. 5.1-24b). The thickness of the Formation is not uniform. It is absent in the Wangja Khola section and its maximum thickness is about 300 m at Dubung. This is followed up section transitionally by Musimarang Formation.

(b) Musimarang Formation (ms)

This is the most extensive of all three formations and is distributed around Kahun, Musimarang, Palintar and Wangja Khola areas (Fig. 5.1-1). The lithology includes the non-calcareous succession of white to dirty-white, thin- to thick-bedded, lineated quartzite with intercalation of well-foliated, grey, psammitic and two-mica pellitic schists (Fig. 5.1-25a).

It is well-observed at the Musimarang area, on the road cut section from Kahun-Shivpur to Gwaslung. It is the succession of intercalation of quartzite and schist in about equal proportion. Towards the western and northern part, lower reaches of Naya Rising, this formation lies immediately above the Dubung Thrust. It is exposed along the road and stream sections, generally in weathered form. The fresh outcrops can only be observed in fresh road cuts and in some draining streams. The deep weathering is probably due to the excessive fracturing and the presence of fine mica partings. In some places the deeply weathered white quartzite shows the nature of weathered white sandstone (Fig. 5.1-25b). At the lower reaches of Naya Rising, due to its peculiar white appearance the place is named as Goredada (in Nepali: Gore means white). In Wangja Khola section, the rock succession, representing the western part of the formation, consists of non-calcareous, platy and laminated beds of grey to dirty-white quartzite (80%) intercalated with chlorite schist (20%). Quartzite shows yellowish brown, pink to reddish brown weathering color. The thickness of the Musimarang Formation is about 200 m in the Musimarang area. It is followed stratigraphically up-section by the Shivapur Schist with conformable and

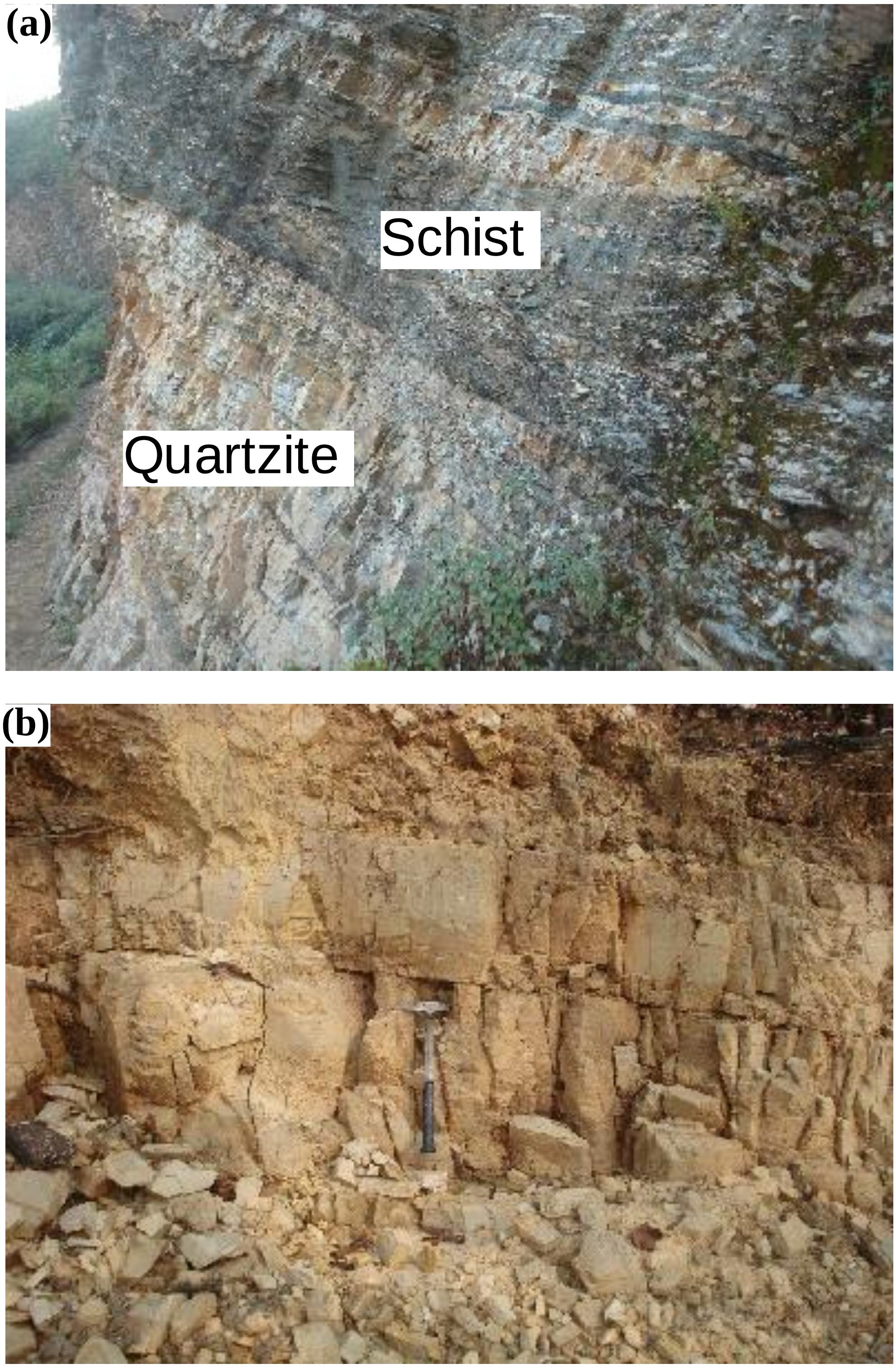


Fig. 5.1-25.(a) Alternation of micaceous quartzite and two-mica schist of the Mushimarang Formation observed in Gwaslung section, facing SW. (b) Deeply weathered micaceous quartzite of the Musimarang Formation observed in the Goredanda, at the lower reaches of the Naya Rising, facing N.

transitional contact.

(c) Shivapur Schist (sh)

The unit is named after the village Shivapur, south-west of Damauli where it is widely distributed. It has also been mapped in Taruka, Thaprek, Dunkudada, Lumphes and Gumlek as isolated outliers (Fig. 5.1-1) and is the youngest unit of the Kahun Klippe. Rocks of this formation occupy the top of the rounded hills which is mostly populated and cultivated.

The formation dominantly consists of grey, medium-grained, garnet-schist and/or phyllite with seldom occurrence of thin beds of quartzite and metasandstone. Garnets are pink and variable in size. The maximum size of the garnet observed in these rocks is about 3 mm diameter in Shivpur (Fig. 5.1-26a and b) and Lumphes areas while it is very tiny in other several sections. In some places, a note worthy feature is that the garnets are developed in fine grained phyllite containing sedimentary laminations (Fig. 5.1-26b). The garnet in this schist is often altered to biotite and chlorite. It is very seldom to get fresh sample from this formation. A noteworthy feature of the Shivapur Schist is its deep weathering with the development of thick lateritic soli. The rocks are often horizontal to very gently dipping. The exposed thickness of this unit is about 250 m.

5.2.3 Depositional environment of the Nuwakot Group

The depositional environment of the Nuwakot Group has been interpreted based on the lithological characteristics and sedimentary structures. The details of the environmental interpretation are given in Paudyal (2012). It has been described in brief here.

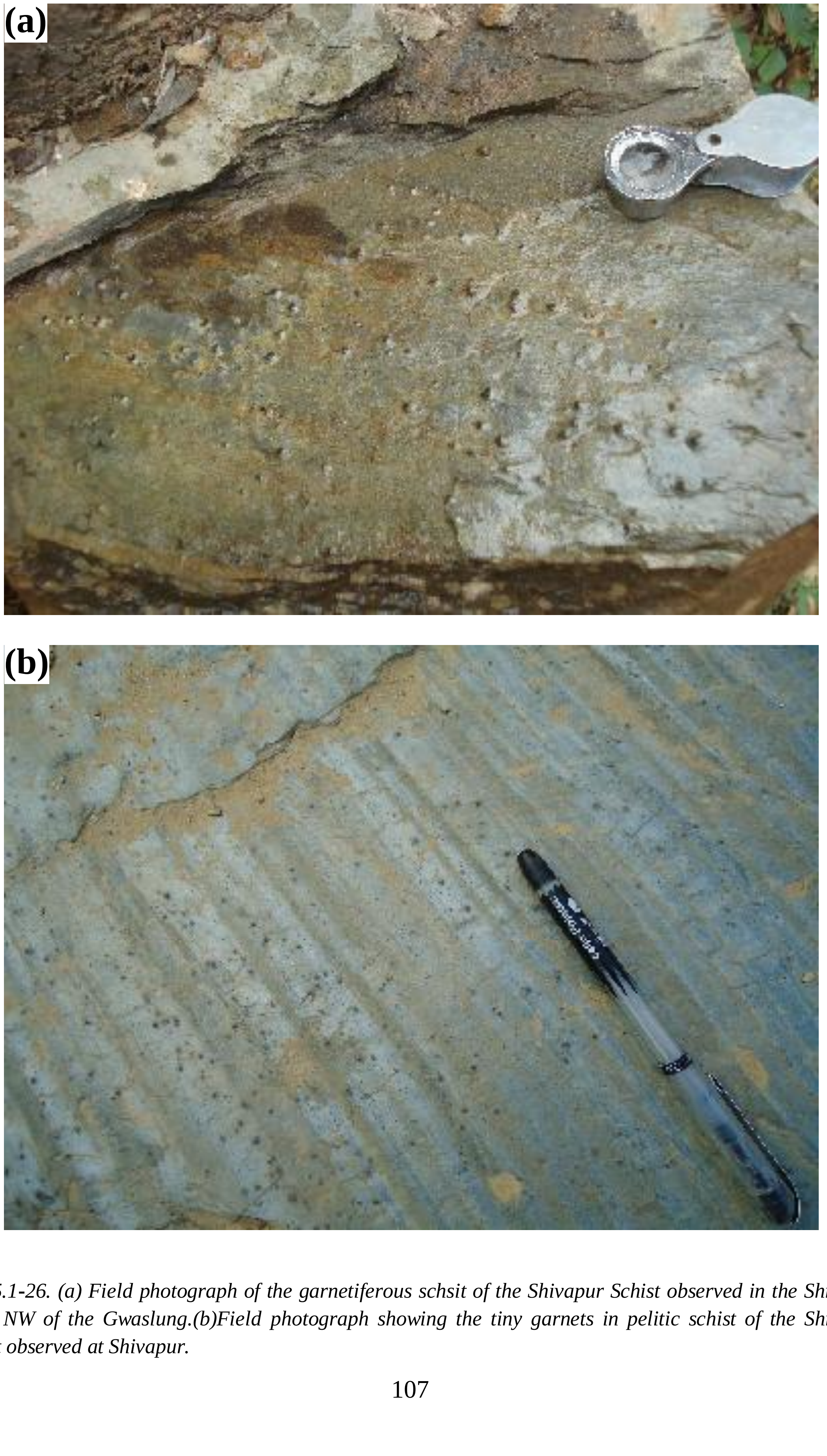


Fig. 5.1-26. (a) Field photograph of the garnetiferous schsit of the Shivapur Schist observed in the Shivpur area, NW of the Gwaslung.(b)Field photograph showing the tiny garnets in pelitic schist of the Shivpur Schist observed at Shivapur.

The thick succession of the Kunchha Formation represents the marine environment of deposition. Flysch type rocks show deeper and calm environment. However, the presence of calcareous meta-sandstones with psammitic phyllite indicates a transitional environment between the off-shore and the shore face. The Fagfog Quartzite is considered to be deposited on the fluvial dominated deltaic environment. The argillaceous sediments and lime-mud of the Dandagaon Phyllite is supposed to be deposited in deeper to neritic environment below the active current zone. The palaeo-environment of deposition of Nourpul Formation is not found uniform. The basal part (quartzite succession) could be deposited under fluvial dominated submarine deltaic environment which can be inferred by the presence of cross-beddings and current ripples. The middle part (Amdanda Phyllite) is considered to be deposited under some locally controlled deeper parts or lagoons. Similarly, the succession of Labdi Khola Member is considered to be deposited in intermediate depth to shallow depth and short term aerial exposure as well. Presence of rhythmic deposits on its topmost part clearly indicates the transgression stage of ocean which is also supported by the presence of mud-cracks in the sandy shale. However, locally distributed Bandipur Slate on the top of the Nourpul Formation might have been deposited on locally wave-controlled area within the deeper basin. Intra-formational conglomerates of dolomite fragments and presence of columnar stromatolites in the Dhading Dolomite indicates its deposition on very shallow depths like beach lagoons, bays or tidal flats. Probably, the intra-formational fragment of the dolomite within the dolomite beds was deposited in the supra-tidal and intertidal flats associated with the coastal lagoons. The Benighat Slates can be considered as the deposition on the deeper oceanic environment below the active wave with some episodic shallow environment as indicated by the presence of carbonates within the monotonous succession of finely laminated carbonaceous slates. The deposition of argillaceous material from the suspended load was probably in reducing environment as indicated by the black color of slates with pyrite crystals.

The overall succession seems to be deposited in a quite fluctuating depositional basin from deep and calm to fluvial dominated submarine deltaic to aerial exposures. It shows that in the past the depositional basin was unstable and there were the cycles of regression and transgression of the sea basin while depositing the Precambrian sediments of the Lesser Himalaya. Change in depositional basin is also indicated by tectonic environment as shown by the several basic intrusions concordant to the host rocks.

5.2 MAGNETIC SUSCEPTIBILITY OF THE NUWAKOT GROUP

Correlation of the metasedimentary succession of the Lesser Himalaya from adjacent regions has been always a problem for geologists. This is mainly because the rocks are devoid of fossils, marker beds are not always present, rocks are complexly deformed and same lithology has been repeated many times by folds and thrusts. Lithology-based correlation has also problems because many formations have mixed lithology of similar rock types in varying proportions.

Present work on magnetic susceptibility (MS) measurements is an effort to check whether it can be used as a proxy for identification of geological formations by comparing their MS trends with that in type localities.

In present study, MS was measured at first in Malekhu area where most of the type localities of the geological units of the Nuwakot Group defined by Stöcklin and Bhattarai (1977) are exposed. In the present study area, MS of the Nuwakot Group were measured along the Malekhu, Mugling-Jugedi, Ghumaune-Damaluli and Mugling- Bandipur road sections (Fig. 5.2-1).

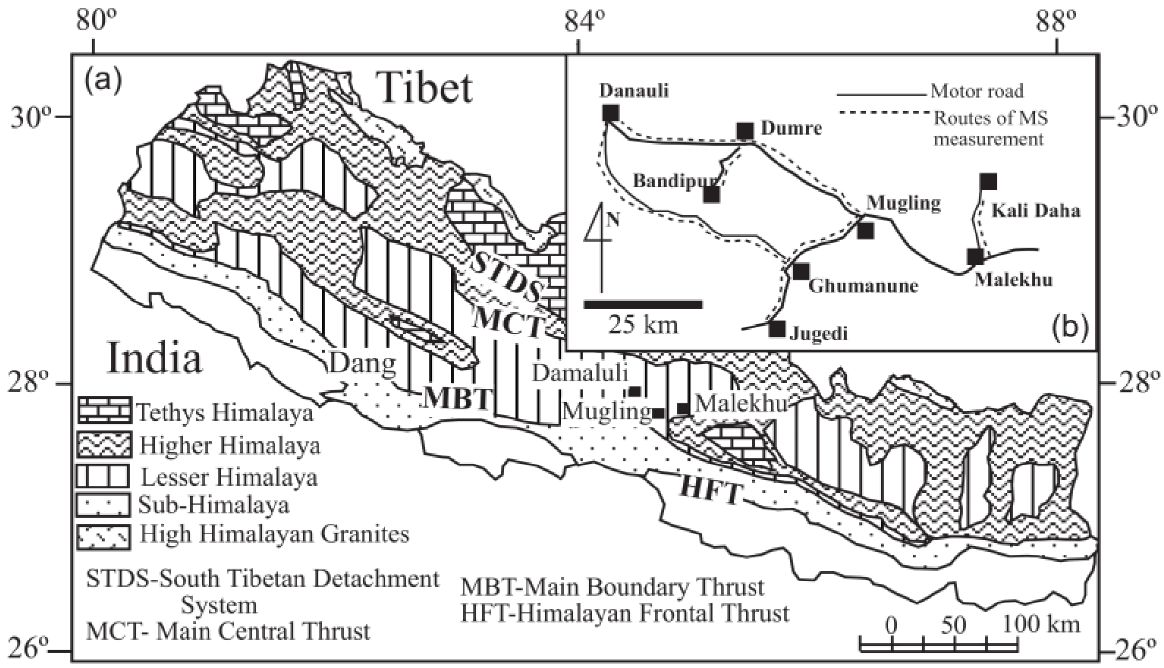


Fig. 5.2-1. (a) Geological map of the Nepal Himalaya (modified after Upreti and Le Fort 1999) showing the location of the routes of present magnetic susceptibility measurements. (b) Sketch of map showing the routes of MS measurement.

Along each section, MS of each rock type from each formation was measured systematically in the field. The rock types in which MS was measured include (i) phyllite and metasdandstone of the Kunchha Formation, (ii) quartzite of the Fagfog Quartzite, (iii) phyllite of the Dandagaon Phyllite, (iv) quartzite, phyllite, shale, metasandstone and dolomite of the Nourpul Formation, (v) dolomite of the Dhading Dolomite and (vi) black slate of the Benighat Slate. MS was measured along the Malekhu-Thople Khola section, Mugling-Jugedi section, Ghumaune-Damauli section and Mugling-Bandipur section covering major rock types of each formation. All the measured data are given in Annex V and average data are given in Table 5.2-1.

Table 5.2-1: Average magnetic susceptibility data of the Nuwakot Group rocks from the Malekhu, Mugling-Jugedi, Mugling-Bandipur and Ghumaune-Damauli sections of central Nepal.

Unit	Rock type	Average MS value (SI)			
		Malekhu Section	Mugling-Jugedi	Mugling-Bandipur	Ghumaune - Damauli
Kunchha Formation	Phyllite	0.267	0.241	0.168	NM
	Metasandstone	0.137	0.116	0.075	NM
Fagfog Quartzite	Quartzite	-0.007	-0.006	NM	NM
	Phyllite	0.081	NM	NM	NM
Dandagaon Phyllite	Phyllite	0.163	0.249	0.161	NM
Purebesi Quartzite	Quartzite	0.030	0.054	NM	NM
Nourpul Formation	Shale	0.211	0.185	NM	NM
	Phyllite	NM	0.760	NM	0.300
	Quartzite	NM	0.064	-0.010	0.017
	Metasandstone	0.829	NM	0.306	NM
	Dolomite	NM	0.065	NM	0.092
	Amphibolite	NM	0.694	NM	0.662
Dhading Dolomite	Dolomite	0.025	0.036	0.016	0.020
Benighat Slate	Slate	0.125	0.115	NM	0.062

NM- Not Measured

5.2.1 Average MS data for different rocks

The average MS value was found to be smaller for quartzites (-0.007 to 0.064) of all formations and larger for amphibolite (0.662-0.694), phyllite (0.76) and metasandstones (up to 0.829) of the Nourpul Formation. The average Ms data range for 0.081 to 0.760 for phyllite, 0.016-0.092 for dolomite, 0.062-0.125 for slate, 0.075-0.829 for metasandstone and 0.185-0.211 for shale (Table 5.2-1, Fig. 5.2-1). The MS values measured for different lithologies in the present sections are similar to that of the data presented by Gautam et al. (2011) for the Malekhu-Mugling-Jugedi and Butwal-Pokhara sections of central Nepal.

The rocks of the Mugling-Jugedi sections show higher MS values compared to those in the Malekhu section. Higher MS values can be attributed to the presence of Ferich minerals such as magnetite, hematite, pyrite, chalcopyrite and amphibolites etc. in the rock successions of the Mugling Jugedi area. These rocks show higher concentrations of opaque minerals also in thin-sections. Metasandstone of the Kunchha Formation in the Malekhu section also shows higher values of MS (Table 5.2-1) because those rocks also contain abundant iron oxides such as magnetite both in hand specimens and thin sections.

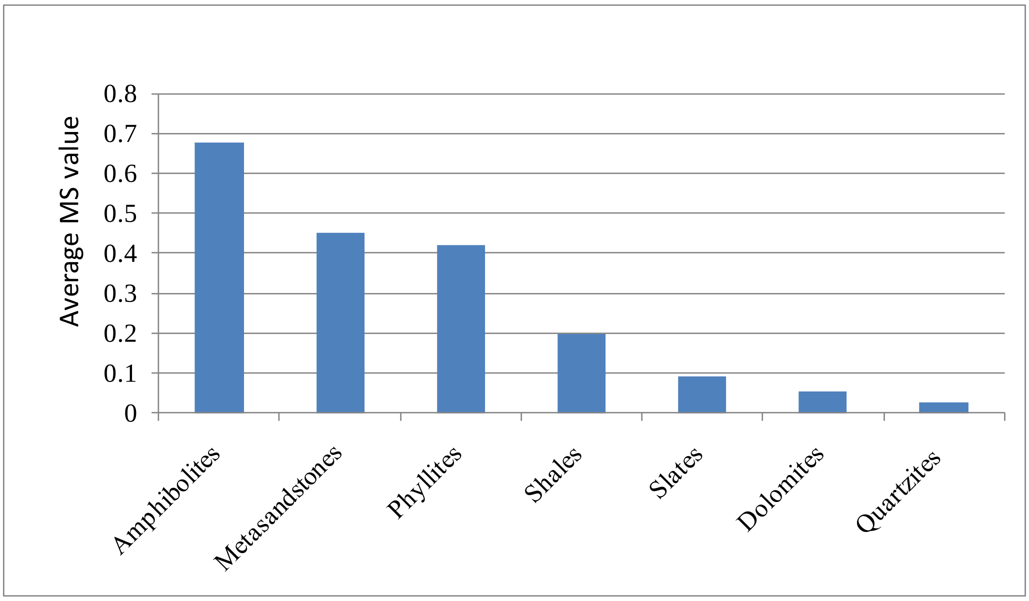


Fig. 5.2-2. Average MS values of different rock types in the Nuwakot Group, Lesser Himalaya, central Nepal.

5.2.2 MS pattern in the Nuwakot Group

The MS pattern in different formations of the Nuwakot Group was assessed by plotting the average MS of different rock types for each formation against their relative stratigraphic positions in the studied routes (Fig. 5.2-3). Interestingly, all the Nuwakot Group successions show similar patterns in Malekhu, Mugling-Jugedi, Ghumaune-Damauli and Mugling-Bandipur routes. The MS values tend to decrease from Kunchha to the base of Nourpul Formation (the Purebensi Quartzite). And then it increases suddenly in the Nourpul Formation in all the studied sections. Above the Nourpul Formation the

MS values again decrease. Such a uniform trend in all the sections can be explained by the variation in magnetic minerals in the rocks. Most probably the concentration of magnetic minerals decreases from the Kunchha Formation to the base of the Nourpul Formation (the Purebensi Quartzite). In the middle and upper part of the Nourpul Formation, concentration of magnetic minerals increases suddenly. It is justified by the presence of many metallic deposits (hematite and chalcopyrite) and amphibolite layers in the Nourpul Formation. Above the Nourpul Formation, the Dhading Dolomite is mainly made up of dolomite. It contains very few amounts of magnetic minerals. The Benighat Slate is mostly carbonaceous. Carbonaceous materials have usually very low MS (Annex V).

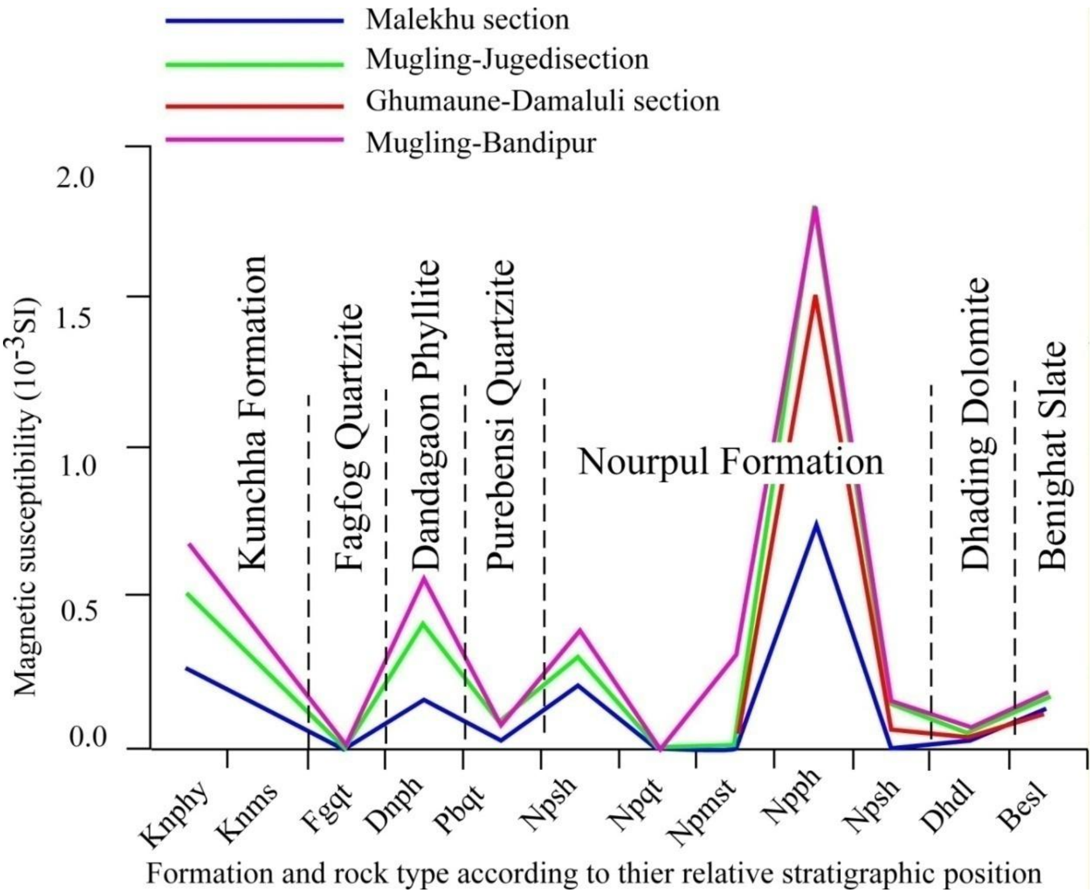


Fig. 5.2-3. Magnetic susceptibility pattern along the Malekhu, Mugling-Jugedi, Ghumaune-Damaluli and Mugling- Bandipur road sections. Knphy: Phyllites of Kunchha Fm.; Knms: Metasandstones of Kunchha Fm.; Fgqt: Fagfog Quartzite; Dnph: Dandagaon Phyllite; Pbqt: Purebensi Quartzite; Npsh: Shale of Nourpul Formation; Npqt: Quartzite of Nourpul Formation; Npmst: Metasandstone of Nourpul Fm; Dhdl: Dhading Dolomite; Besl: Benighat Slate.

5.3 GEOLOGICAL STRUCTURES

The study area is a fold-and-thrust belt exhibiting a number of large-scale as well as small-scale geological structures. Important geological structures observed in the area are thrusts, folds, foliation and lineation. In present study, the large scales structures were mapped and their basic characteristics were identified. Orientation of a number of small-scale structures were measured in the field and analyzed statistically. The structures have been described in the following sections.

5.3.1 Major Thrusts

(a) Main Boundary Thrust (MBT)

The boundary between the Tertiary Siwaliks and Precambrian Lesser Himalaya is named as the Main Boundary Thrust (MBT). It was first identified by Medlicott (1864) in the Indian Himalayas. The MBT is one of the well-recognized and less-disputed intra-crustal thrust extending through the length of the Himalaya (Gansser 1964; Valdiya 1980). It is sharply defined in the field both by geologic and geomorphic features. It is topographically well-expressed as a continuous depression throughout the study area.

In the study area, the MBT extends from Jugedi in the east to Dewachuli in the west (Fig. 5.1-1a). The MBT is very discordant in the field and cross-cuts rocks of the hanging wall. It brings the Labdi Khola Member and Dhading Dolomite on the top of the Siwaliks in the western part of the study area. In the Kota and Tarang Khola sections (west-central part of the present study), the MBT is very sharp where the Labdi Khola Member of the Nourpul Formation (in some places the Dhading Dolomite) abruptly rides over the pebbly salt-and-pepper sandstone and mudstone of the Middle Siwalik (Fig. 5.1-

1a). In the eastern part around Jugedi and north of Deughat, it forms a very thick (~600 m) shear zone of mixed rocks of both the Middle Siwalik and Labdi Khola Member. Both the hanging wall and footwall rocks have gone intense deformation and cataclasis. Black fault gauge and breccias are widely observed along the fault.

The MBT is steep (60-70°) to very steep (>80°) at the surface in most of the places of the study area (Fig. 5.1-1a and b). In most cases it dips to the north. In some places it is overturned to the south.

(b) Dewachuli Thrust (DCT)

The Dewachuli Thrust (DCT) trends east-west throughout the present study area (Fig. 5.1-1a). The DCT is very discordant in the field and cross-cuts rocks of the hanging wall. It brings the older Purebensi Quartzite member of the Nourpul Formation on top of the younger Dhading Dolomite in the eastern part of the study area while in the western part it brings the Amdanda Phyllite member of the Nourpul Formation on top of the Dhading Dolomite. At the Tarang Khola section, the DCT is well-expressed by a zone of fault breccias (~60 cm wide) and fault gauge (~am wide). The DCT sharply bends to the south to the west of Charchhare and merges with the MBT at Dhawadi.

The average dip of the thrust is 40-70° towards NNW.

(c) Dubung Thrust (DT)

The metamorphic crystalline rocks of the Tanahun Group (Kahun Klippe) overlie the rocks of the Nuwakot Group (Benighat Slate) along the Dubung Thrust (DT) and it forms a klippe (Kahun Klippe) in the western part of the study area. The DT is very discordant in the field. It is well-observed at Gwaslung and Dubung Villages where crystalline marble of the Gwaslung Formation (garnet zone) sharply overlies the low-grade rocks (chlorite zone slate/phyllite) of the Benighat Slate (Fig. 5.3-1). The boundary is marked by the presence of a shear zone of about 10 m defined by crumbled slates and breccia. At the Wangja Khola section, well-foliated and recrystallized micaceous quartzite of the Musimarang Formation lies on top of the Benighat Slate where the Gwaslung Formation is missing. At the thrust contact the rocks are highly deformed, crumbled, folded and deeply weathered. The thrust is folded along with the foliation showing folding after the thrust sheet emplacement (Fig. 5.1-1). The thrust is very gently to moderately dipping. In the north it dips 15-25°SW and in the south it dips 20-60°NE.

(d) Bhangeri Thrust (BT)

The Bhangeri Thrust (BT) carries the Labdi Khola Member (the upper most unit of the Nourpul Formation) over the younger Dhading Dolomite in the north-east part of the study area (Fig. 5.1-1a and c). It is well-marked in the Bhangeri Village and the lower reaches of the Bhangeri Khola (Fig. 5.3-2). In the tributaries of the Bagar Khola, it is marked by a shear zone with fault breccia (~1 m wide) and fault gauge of about 10 m width. In the northern part of Chhapswara and Dheregaon villages, on the way to Jal Bhanjyang and Hillekharka areas, along the freshly cut road sections, the Bhangeri Thrust is represented by a 20 m wide, strongly sheared zone containing dolomite blocks mixed with metasandstone and phyllite of the Labdi Khola Member. It is topographically distinct and landslides have occurred along it at several places. Adjacent to the fault area, outcrops consist of densely distributed quartz veins in different orientations. This fault seems to die out in the Dheregaon and upper reaches of the Baruwa Khola areas. Interestingly, both the Purebensi Quartzite and the Dhading Dolomite disappears suddenly very near to the region (Fig. 5.1-1a).

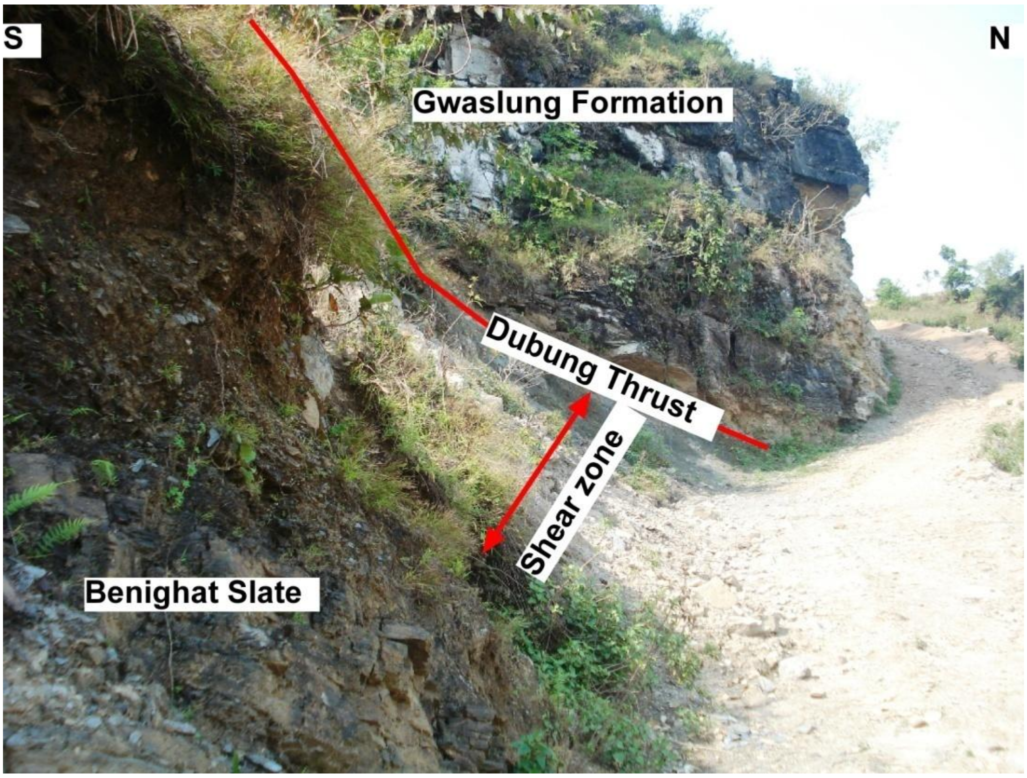


Fig. 5.3-1. Field photograph showing the outcrop of the Dubung Thrust (basal thrust of the Kahun Klippe). A shear zone of about 5 m is observed below the thrust. Facing towards west.

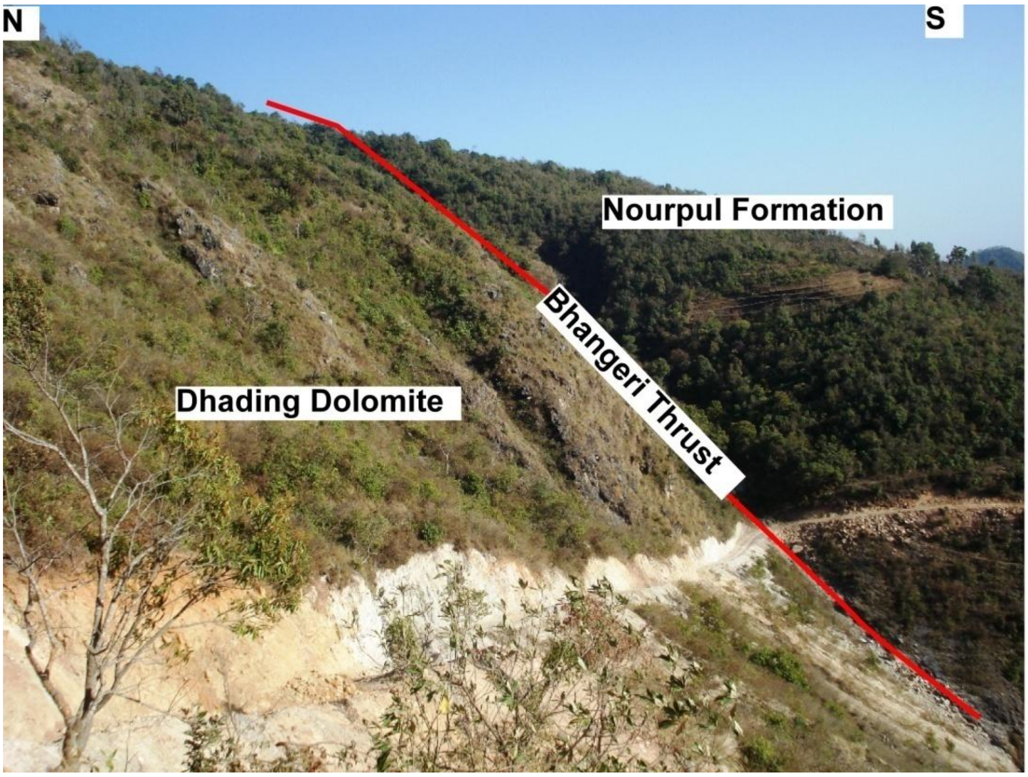


Fig. 5.3-2. Field photograph showing the outcrop of the Bhangeri Thrust. The thrust is south dipping and is a back-thrust. Facing towards east.

(e) Direction of thrust movement

Small scale structures found in the outcrop scale and microstructures in thin sections were observed at various places to identify the direction of thrust movement in the area. Stretching and mineral lineations are trending NNE to SSW in the study area indicating NNE-SSW transport of the thrust sheets. Small-scale structures such as z-type folds and asymmetric boudins show that the movement of the Dubung Thrust was from northeast to southwest (Fig. 5.3-3). In thin section, a number of shear sense indicators such as asymmetric pressure shadow, crenulation cleavage and S-type inclusions in garnet consistently show top to the south sense of shearing (see §5.4).

5.3.2 Large-scale folds

(a) Jalbire-Ramjakot Synclinorium

The area forms a major synclinorium named as the Jalbire-Ramjakot Synclinorium (Fig. 5.1-1). The Mahabharat Synclinorium of the Kathmandu area (Stöcklin and Bhattarai 1977) terminates at the eastern part of the study area around Jalbire. The western closure of the Mahabharat Synclinorium (locally also known as Jalbire Syncline) plunges to the ESE with about 7 ° angles. The Jalbire-Ramjakot Synclinorium plunges to the WNW. The two oppositely plunging synclinal folds form tight neck near Jalbire.

The Jalbire-Ramjakot Synclinourium extends to the whole study area. The core of the synclinorium is occupied by the metamorphic crystalline rocks of the Tanahun Group in the western part and the Benighat Slate of the Nuwakot Group in the eastern part.

The axial trace of the synclinorium passes from Jalbire to Ghumaune, Kota-Baidi, Shivapur and Ramjakot. It extends from ESE to WNW. The axial trace is wavy. The synclinorium is relatively open with asymmetric limbs in the western part of the study area

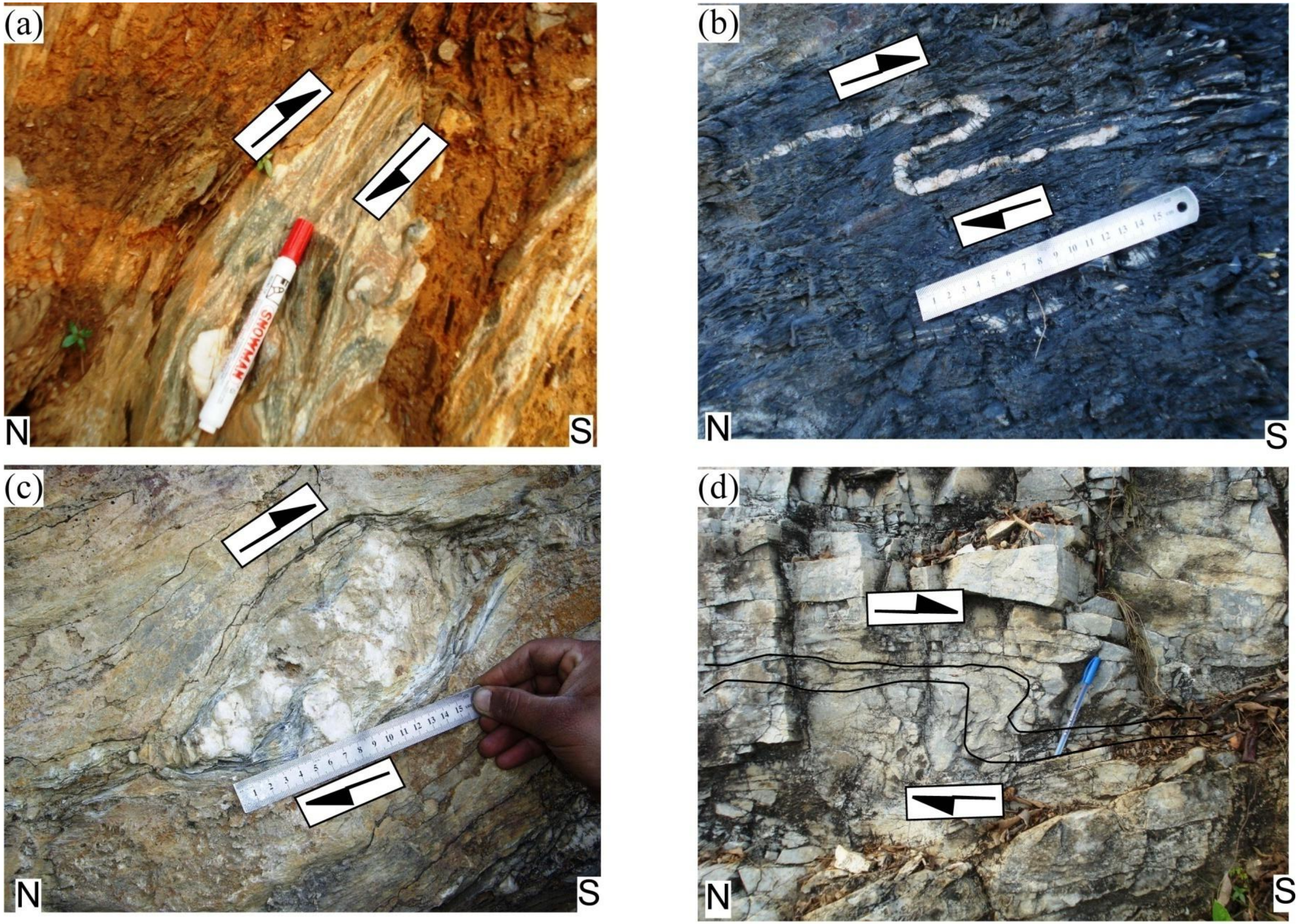


Fig. 5.3-3. (a) Z-type drag fold in the marble of the Guwaslung Formation near the Dubung Thrust showing southward sense of shearing. (b) Z-type folded quartz vein in the Benighat Slate below the Dubung Thrust at Kot Baidi area. (c) Asymmetric quartz boudin in the Benighat Slate showing top-to-south sense of shearing observed in Kot Baidi area. (d) Z-type drag fold in the Gwaslung Formation showing top-to-south sense of thrust movement.

in the Shivapur-Ramjakot area. The northern limb is gently dipping (~20-25°) to SSW whereas the southern limb is relatively steeply dipping (~60-80°) to NNE. In the eastern part in the Jalbire-Ghumaune area, the synclinorum is very tight and the limbs are almost vertical.

The poles to the foliation measured in the whole study area representing both the limbs of the synclinorium has been plotted on Schmidt's equal area net and shown in Fig. 5.3-7. The poles have been contoured to find the best fit plane and mean orientation of the synclinorium axis. The data clearly show different nature of the fold in the western and eastern part. In the western part it is nearly cylindrical in nature. The contour diagram of the poles shows that the poles nearly fit to a great circle. It shows gentle plunge to the ESE (<10°). In the eastern part, the poles are very much scattered, and shows non-cylindrical nature of the fold.

(b) Other folds

There are several ESE-WNW conjugate anticlines and synclines at both the limbs of the Jalbire-Ramjakot Synclinorium (Fig. 5.1-1). Among them, most prominent folds are observed along the road from Mugling to Anbu Khaireni. The Fagfog Quartzite forms a jig-jag shape in this area due to multiple folding. The axis of an anticline passes from about 4 km north of Mugling. The anticlinal bend is observed in the rocks of the Kunchha Formation and the Fagfog Quartzite. The anticline plunges to the 6º with trend of 260º (SW). It is followed in the north by the a syncline. It is an overturned fold with both of its limbs dipping towards north. The axis of the fold passes from north of the Marsyangdi Hydropower station. The axis of the fold is trending WNW-ESE. Another anticline passes from north of Anbu Khaireni. This is also an overturned syncline both of its limbs dipping to the north.

Another prominent synclinal fold is observed in Bandipur area. The core of the syncline is occupied by two small outliers of the Dhading Dolomite (Fig. 5.1-1). The axial trace of the syncline is curved and roughly trends from WNW to ESE. The average trend/plunge of the syncline is 297°/9°.

5.3.3 Mesoscopic structures

Besides the large-scale structures described in the above sections, there are a number of outcrop-scale structures such as folds, lineation, foliation, veins and shear zones.

(a) Mesoscopic folds

A number of mesoscopic folds are observed at the limbs of the Jalbire-Ramjakot-Synclinorium in the study area. The folds range from tight isoclinal folds (Fig. 5.3-4a and b) to parasitic drag folds (Fig. 5.3-4c and d). The isoclinal folds (F_1) trend NNE or NNW to SSE or SSW with gentle to steep (Fig. 5.4-5). The parasitic drag folds (F_2) trend NNW to SSE and have their axis parallel to the axial trend of the major large-scale folds. It shows two generations of folds in the study area. The N-S trending isoclinals folds were probably pre-Himalayan formed by the east-west compression. The E-W trending drag folds are related to the Himalayan event.

(b) Stretching and mineral lineations

Stretching and mineral lineations are observed in the Kunchha Formation and Tanahu Group in the study area. Stretching lineations are found in the competent beds like quartzite, metasandstone and gritty phyllites or psammitic phyllites (Fig. 5.3-5a). Mineral lineation is defined by preferred orientation of biotite flakes on the foliation.

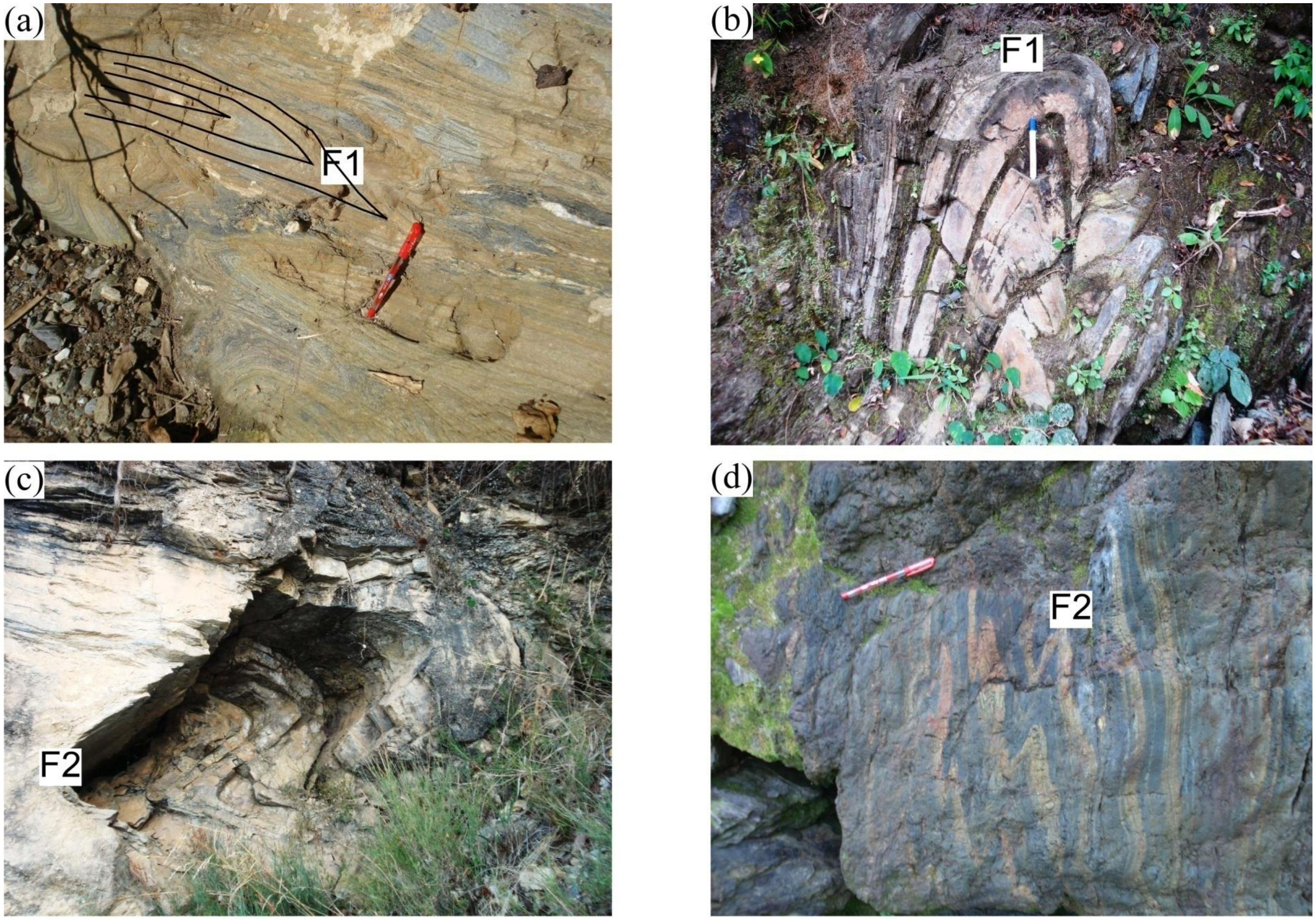


Fig. 5.3-4. (d) Mesoscopic isoclinals plunging fold in the Benighat Slate at Kota area. (b) Tight isoclinals fold in the Benighat Slate observed at the right bank of the Chherenga Khola. (c) Z-type drag fold in the Labdi Khola Member of the Nourpul Formation. (d) Mesoscopic S-type folds in the Benighat Slate in Bar Khola section at the northern limb of the Jalbire-Ramjakot Synclinorium. Facing to the west.

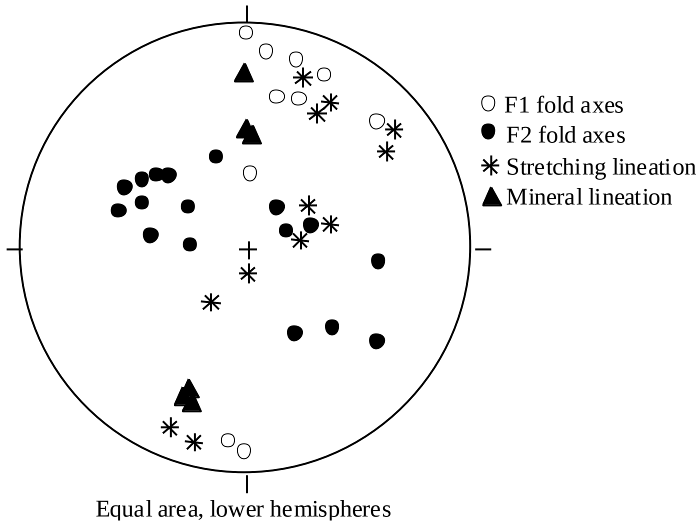


Fig. 5.3-5. Plot of fold axes, stretching lineation and mineral lineation from the study area.

(c) Foliation

Different types of foliations are observed in the area. Most of the rocks show strong foliation (S_1) developed parallel to sub-parallel with the sedimentary layering (S_0) (Fig. 5.3-6a). The second foliation (S_2) is either crenulation cleavage or slaty cleavage (Fig. 5.3-6b-d). Poles to S_1 (=S_0) from the area are shown in the Fig. 5.3-6. Poles to foliation are well distributed along NNE-SSW trending great circle in the western part of the study area showing nearly cylindrical folding (Fig. 5.3-7b, c and d). In the eastern part of the study area, the poles to S_1 are scattered and show non-cylindrical folding (Fig. 5.3-7e and f).

(d) Brittle shear zones and fractures

The latest deformational structures observed in the field are brittle shear zones and fractures. Shear zones cross-cutting all the previous structures are found throughout the area. The shear zones are characterized by 5-10 cm thick zone of intense shearing and presence of black gauge (Fig. 5.3-8a). Similarly, fractures and veins (quartz and calcite veins) cross-cutting all the previous structures are common in the study area (Fig. 5.3-8b).

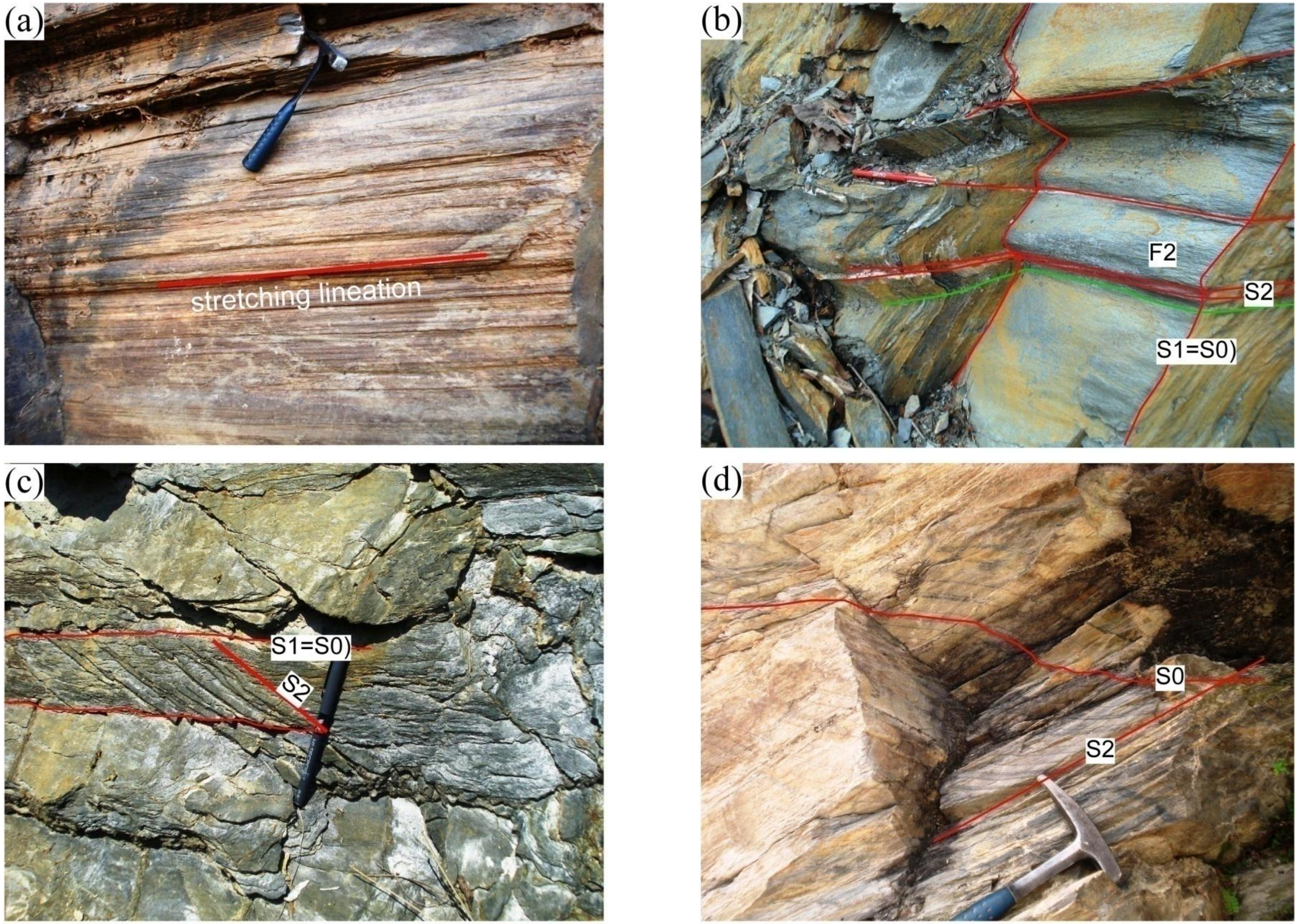


Fig. 5.3-6.(a) Stretching lineation observed in the metasandstone of the Kunchha Formation at Mugling-Narayangar section. (b) Crenulation cleavage (S2) in the Benighat Slate at Naram area. (c) Crenulation cleavage (S2) in the phyllite of the Kunchha Formation, lefte bank of the Marsyangdi River, Anpu Khaireni. (d) Slaty cleavage (S2) developed oblique to bedding (S0) in the Amdanda Phyllite, Pokhari in area.

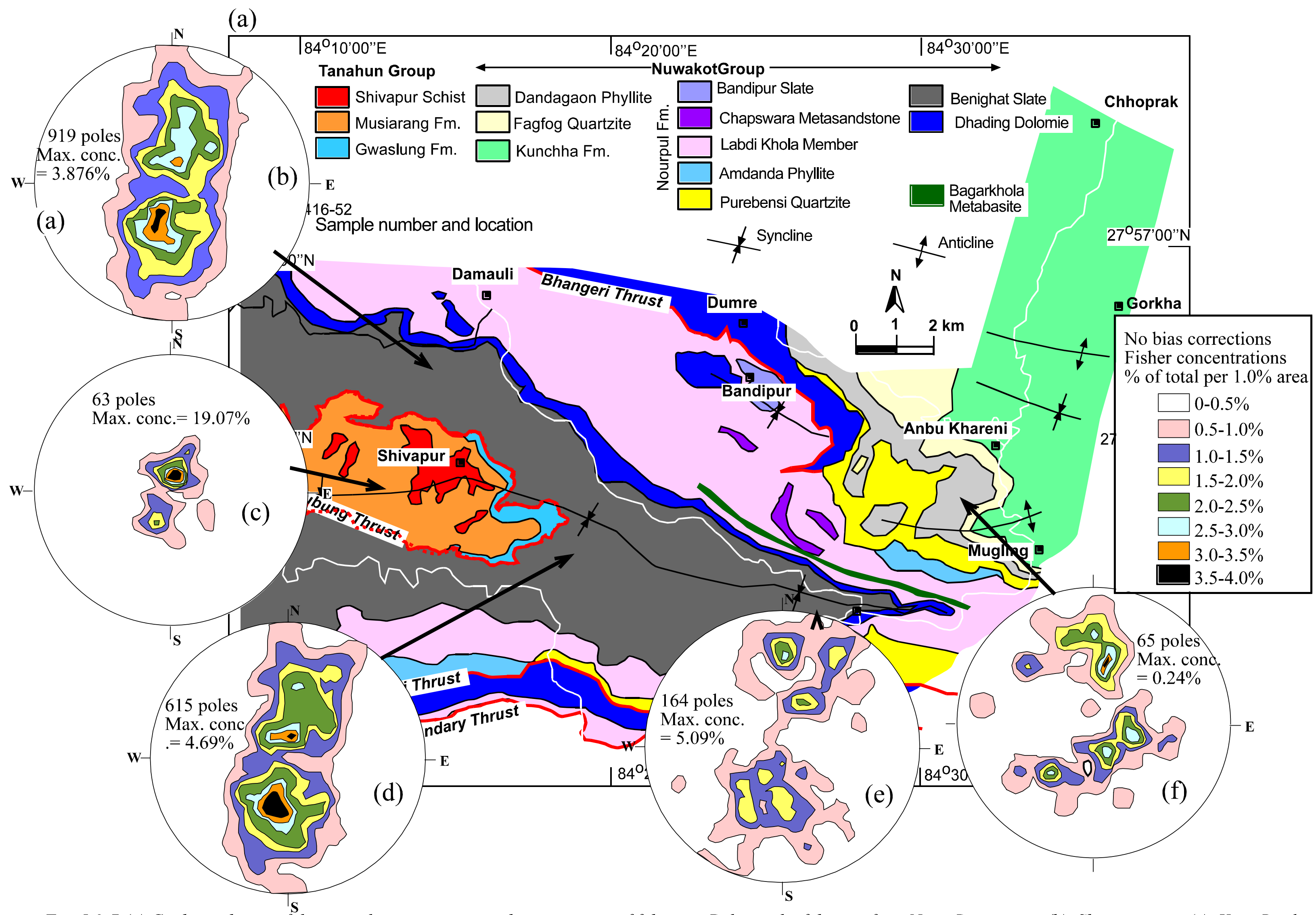


Fig. 5.3-7.(a) Geological map of the area showing stereographic projection of foliation. Poles to the foliation from Naya-Rising area (b), Shivapur area (c), Kota-Baidi area (d) Ghumaune area and (e) and Mugling area (f). Equal area projection.

5.4 PETROGRAPHY AND METAMORPHIC ZONATION

During the field observation, oriented samples were collected systematically representing all the stratigraphic units and rock types. Oriented thin sections were prepared from 51 (33 from Nuwakot Group and 18 from Thahun Group) selected samples representing all formations and lithology. Petrographic study was carried out under the polarizing microscope at the Central Department of Geology. Photomicrographs were taken from digital eye-piece camera with Motic Image Plus software. Special attention was given to study the mineral assemblage, texture and microstructure of the rock. Detail petrographic description of each studied thin section is given below and the location of the samples is given at the end of the section in Fig. 5.4-29.

5.4.1 Petrography of Nuwakot Group

It consists of low-grade meta-sedimentary rocks like slate, phyllite, metasandstone, ortho-quartzite/meta-quartzite and metabasites. The rocks exposed in the Gorkha-Jugedi section represent almost all units of the Nuwakot Group. Most of the studied samples are from this section.

(a) Kunchha Formation

(i) Metasandstone

Sample L13-13

Sample L13-13 was taken from approximately 2 km north from the confluence of the Daraudi and the Marsyandi Rivers. It is grey, medium-grained, thick-bedded metasandstone in hand sample. The sample belongs to the middle part of the Kunhha Formation.

In thin section the modal composition is quartz (~60%), mica and chlorite (~35%), albite (~3%), tourmaline (~1%) and opques (~1%). It contains both recrystallized matrix (~70%) and detrital porphyroclasts (~30%). The mineral assemblage in the recrystallized matrix is sericite+chlorite+albite+quartz. The recrystallized matrix quart is up to 0.15 mm in diameter whereas mica and chlorite is <0.10 mm.

The detrital grains are composed of rock fragments, quartz, albite, muscovite and tourmaline. The size of the quartz clasts reaches up to 0.3 mm in diameter. Detrital muscovite flakes are up to 1.5 mm in length. The quartz clasts are rounded to sub-rounded and some are ellipsoidal with long axes oriented sub-parallel to the foliation. Most quartz grains show indented contacts (Fig. 5.4-1), and deformational bands are significant. Recrystallized quartz grains are mostly surrounded by sericite and chlorite. Recrystallized white micas occur as small tabular flakes with preferred orientation defining one set foliation. Rock fragments are made up of quartzite.

It contains well-developed foliation (S_1) parallel to the bedding (S_0). Foliation is defined by the preferred orientation of phyllosilicates and elongated quartz grains.

Sample DM38-45

Sample DM38-45 was taken from approximately 500 m southeast of Mugling. This is blue-grey and weakly foliated in hand specimen. This sample belongs to the upper part of the Kunchha Formation.

In thin section the modal composition is quartz (~65%), calcite (~30%), mica and chlorite (~5%). It contains both recrystallized matrix (~30%) and detrital porphyroclasts (~70%). The mineral assemblage in the recrystallized matrix is sericite+ chlorite+albite+quartz+calcite. The recrystallized matrix quartz is up to 0.10 mm in diameter whereas mica and chlorite is <0.10 mm.

The detrital grains are composed of quartz, muscovite and rock fragments (quartzite). The size of the quartz clasts reaches up to 0.2 mm in diameter. Detrital muscovite flakes are up to 1.0 mm in length and show resorbed grain boundaries. The quartz clasts are rounded to sub-rounded and are weakly deformed. They show wavy extinction and deformation lamellae.

Foliation is very weak. The rock contains abundant calcite veins with sparry calcite most probably filled up in late stage fractures.

(ii) Meta-greywacke

Sample L18-16

Sample L18-16 was taken from about 6 km north of Anbu Khaireni (at Abuwa). It is grey, green-grey, and medium-grained and show strong stretching lineation and crenulation cleavage in hand specimen. This sample belongs to the middle part of the Kunchha Formation.

In thin section the modal composition is quartz (~55%), biotite (~20%), muscovite (~10%), albite (10%) and others (K-feldspar, tourmaline, opaques etc. ~5%). It contains both recrystallized matrix (~60%) and detrital porphyroclasts (~40%). The mineral assemblage in the recrystallized matrix is biotite+muscovite+chlorite+albite+quartz. The biotite grains are up to 0.15 mm and are preferably oriented parallel to the foliation. Most of the grains are altered to chlorite.

The detrital grains are composed of quartz, muscovite, plagioclase and K-feldspar. The quartz grains are mostly rounded and range in size from 0.1 to 0.25 mm. Some quartz clasts are sheared to form asymmetric pressure shadows (Fig. 5.4-2). They show top to the south sense of shearing. The plagioclase grains show very well polysynthetic twinning, are lath-shaped and reach up to 0.2 mm in length. The detrital muscovite grains show very good pigeon-like interference colour. Some grains are bent and show resorbed grain

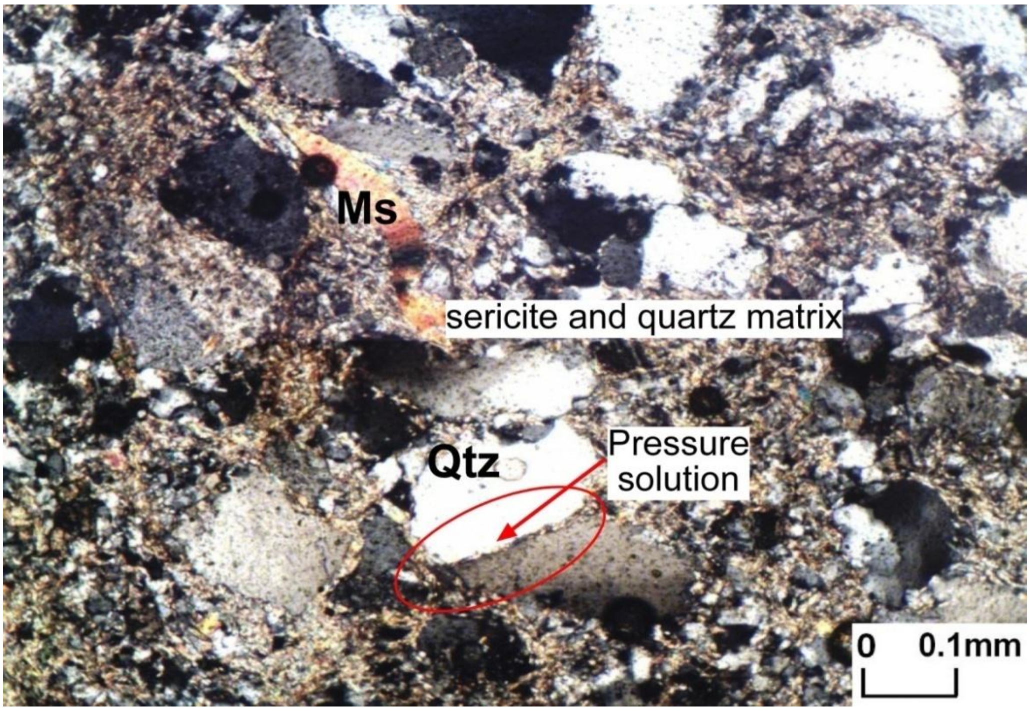


Fig. 5.4-1: Photomicrograph of metasandstone of the Kunchha Formation (Sample L13-13) showing recrystallized matrix and deformed clasts. The sample shows pressure solution features along the adjacent quartz clasts. Under XPL. Location: Confluence of the Daraudi and the Marsyandi Rivers. Qtz: Quartz, Ms: Muscovite.

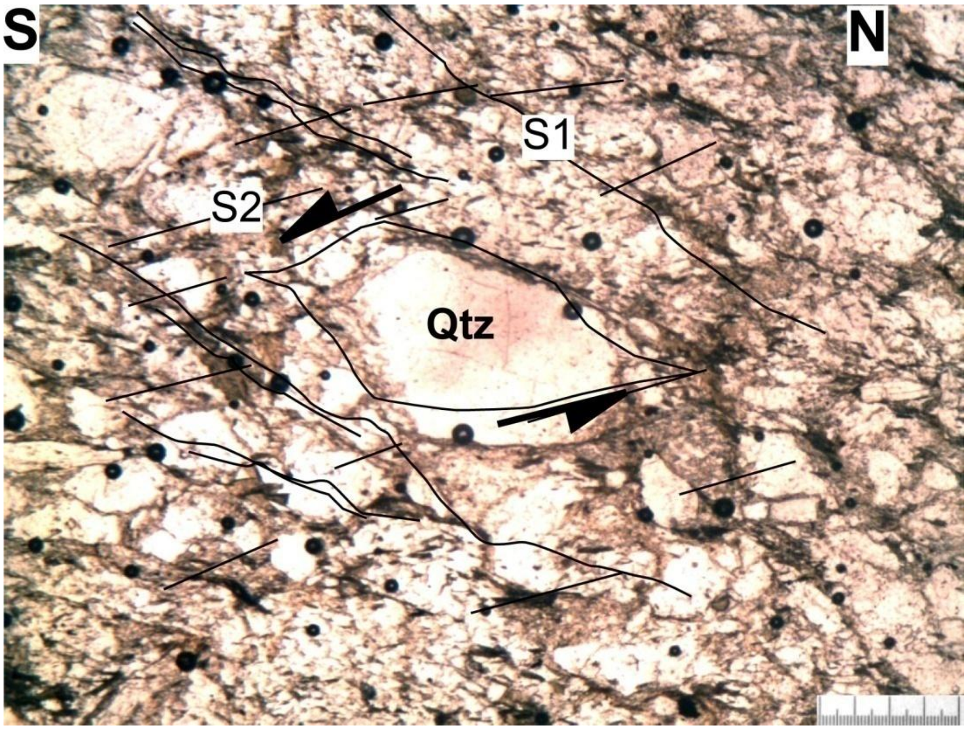


Fig. 5.4-2: Photomicrograph of meta-greywacke of the Kunchha Formation (Sample L18-16) showing sheared quartz clast with asymmetric shadows. The asymmetric clast shows top to south sense of shearing. Under PPL. Location: Anbu Khaireni. Scale: 0.4 mm.

boundaries. The detrital muscovite reach up to 0.4 mm. K-feldspar grains are rounded and highly altered to muscovite and quartz.

The sample shows two foliations oblique to each other. The S1 is prominent and S2 is weakly developed (Fig. 5.4-3).

Sample DM416-52

This sample was taken from the right bank of Bhusundi Khola, SE of Gorkha. In hand specimen, this sample is grey, lineated and crenulated phyllite. This sample belongs to the lower part of the Kunchha Formation.

In thin section it is composed of ~60% quartz, ~20% biotite, ~10% muscovite and chlorite, ~5% orthoclase, ~2% albite and 3% others. This sample also contains both recrystallized matrix (~60%) and detrital porphyroclasts (~40%). The mineral assemblage in the recrystallized matrix is biotite+muscovite+chlorite+albite+quartz. The matrix is relatively coarse-grained compared to the previous samples. The biotite grains are up to 0.5 mm and are preferably oriented parallel to the foliation. Most of the grains are altered to chlorite.

The detrital grains are mostly composed of quartz, muscovite, K-feldspar, albite and tourmaline. The quartz clasts are elongated parallel to foliation and polygonized. Asymmetric pressure shadows developed around the grains show top to south sense of shearing as in other rock samples. Quartz clasts are up to 0.7 mm in diameter. K-feldspar clasts are rounded and reach up to 0.5 mm in diameter. Detrital muscovite grains are smaller than 0.25 mm.

Two sets of foliation (S_1 and S_2) are well-developed in this sample.

Sample DM406-51A

This sample was taken from Ludi Khola, north of Anbu Khaireni. It belongs to the lower part of the Kunchha Formation. This is grey, medium-grained phyllite in hand specimen. This sample has also characteristics similar to that of DM416-52. Mineral assemblages in recrystallized matrix is biotite+muscovite+chlorite+albite+quartz. Grain size ranges from 0.5 to 1.5 mm. Quartz shows strong wavy extinction and faint deformation lamellae. Asymmetric pressure shadows are developed around quartz porphyroclasts. Some quartz clasts show core-and-mantle structure. Some quartz grains are re-crystallized into polygonal aggregates (Fig. 5.4-4). Re-crystallization of silica matrix into sub-polygonal quartz is also observed. Biotite occurs as fine-grained platy matrix oriented parallel to the foliation. Muscovite occurs both as large detrital grains (up to 0.6 mm length) as well as re-crystallized matrix. Orthoclase has gone severe alteration to sericite and chlorite. Albite shows its diagnostic twinning with some unidentified inclusions. This sample also contains two sets of foliation.

(iii) Chlorite Phyllite

Sample L7-6

Sample *L7-6* was taken from approximately 1 km from Mugling towards Anbu Khaireni along the Gorkha–Narayangarh road section. It is grey, thinly foliated soapy phyllite. It belongs to the upper part of the Kunchha Formation.

In thin section it is composed of ~60% quartz, ~30%, sericite and chlorite, ~5% feldspar and 5% others. This sample also contains both recrystallized matrix (~60%) and detrital porphyroclasts (~40%). The mineral assemblage in the recrystallized matrix is muscovite+chlorite+albite+quartz. The matrix is very fine-grained (<0.1 mm). Recrystallized chlorite occurs as bunches aligned parallel to the foliation.

The detrital grains are mostly composed of quartz, muscovite and albite. The quartz clasts are rounded to sub-rounded. They are of up to 0.1 mm in diameter.

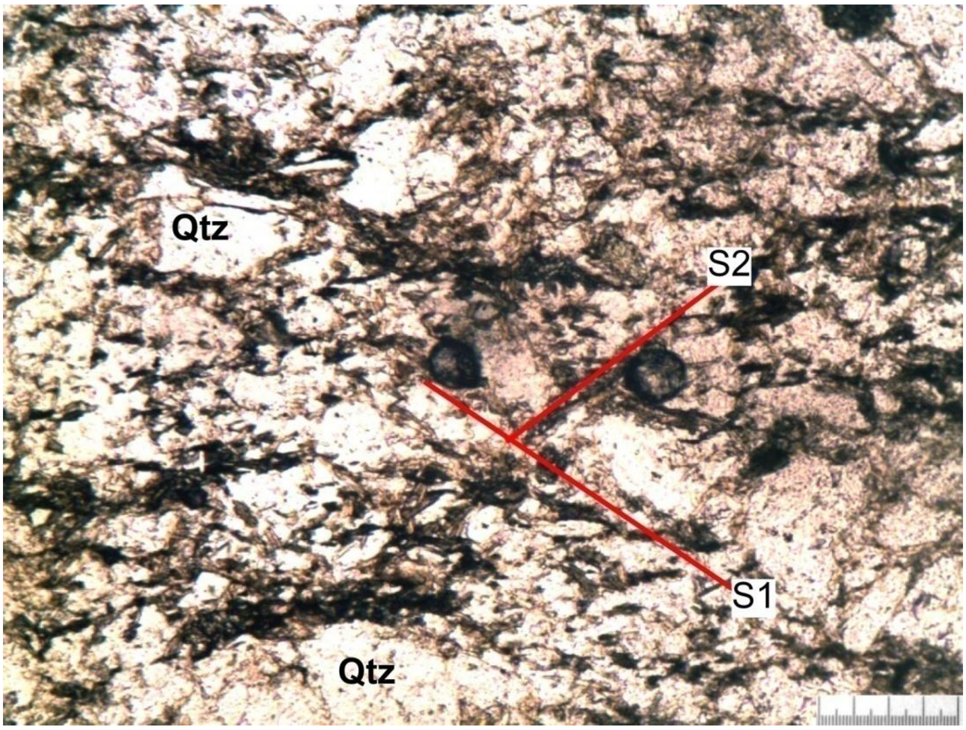


Fig. 5.4-3: Photomicrograph showing two sets of foliation (S_1 and S_2) in the meta-greywacke of the Kunchha Formation (Sample L18-16). Ms: Muscovie. Under PPL. Location: Anbu Khaireni.Scale=0.4 mm. Scale: 0.4 mm.

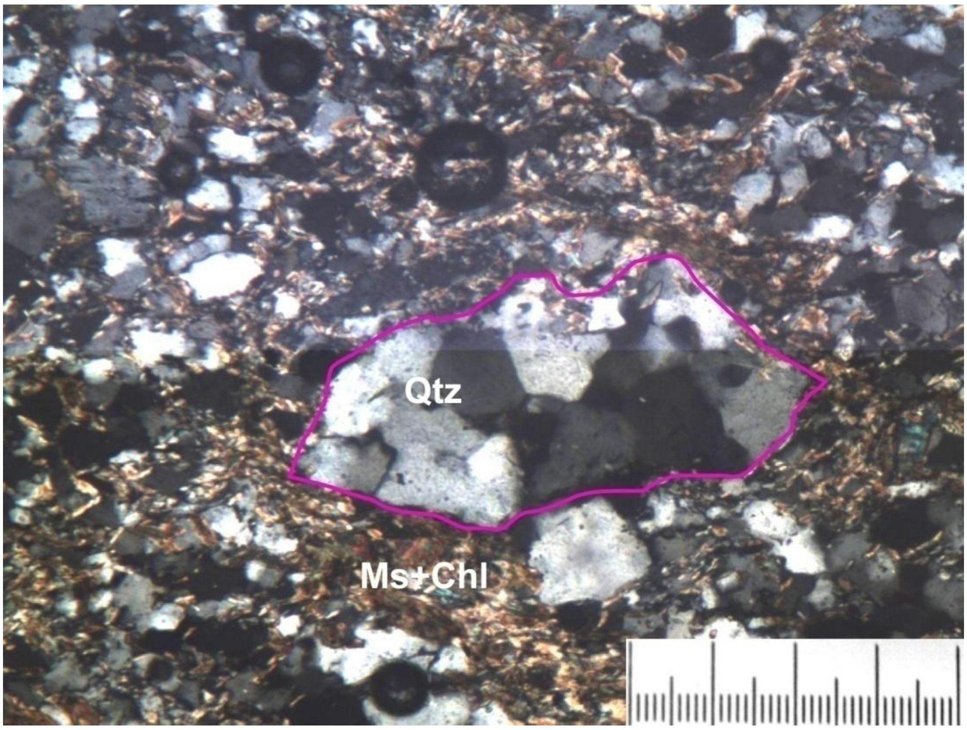


Fig. 5.4-4: Photomicrograph of the meta-greywacke of the Kunchha Formation (Sample DM406-51A) showing polygonized quartz clasts. Under XPL. Location: Ludi Khola.Scale= 0.4 mm.

It shows two sets of foliation (S_1 and S_2). The S_1 is subparallel to the sedimentary layering.

(iv) Garnet Schist

Sample DM419-55

Sample DM419-55 was taken from Chhoprak, near the Lower MCT. It is coarse-grained garnetiferous schist belonging to the lower part of the Kunchha Formation.

In thin section it is composed of ~70% phyllosilicates (biotite, muscovite and chlorite), ~25% quartz, and 5% others (albite and opaques). This sample is completely recrystallized and does not contain any detrital mineral. It contains the mineral assemblage garnet+biotite+muscovite+chlorite+albite+quartz. Garnet porphyroblasts reach in size up to 5 mm. Garnet shows poikiloblastic texture with inclusions of quartz and opaques. The inclusions are preferrly oriented parallel to the S1 foliation (Fig. 5.4-5). Garnets occur in different shapes (skeletal, elongated, s-shaped and equidimensional) and sizes (0.1-5 mm). The garnet porphyroblasts display post-tectonic rim overgrowth across the main foliation (Fig. 5.4-6). The garnet is highly fractured and altered to biotite and chlorite along the cracks.

Biotite, muscovite and chlorite define well-developed foliation in the schists. Biotite shows pale yellow to brown pleochroism. Quartz is main component in all the schists. Quartz occurs as coarse-grained (0.1-0.3 mm) and as elongated polygonal aggregates. Continuous as well as discontinuous quartz lenses wrapped by mica and chlorite are common. The grain boundary between the quartz grains is usually straight and show clear triple junctions.

The samples show strongly developed S_1 foliation and crenulation cleavage (S_2) (Fig. 5.4-7). The S_1 also occurs as inclusions in garnet. It shows that the garnet growth occurred after the development of S_1.

(b) Fagfog Quartzite

The sample DM80-96 was taken from the Mugling–Anbu Khaireni road section of the Gorkha–Narayangarh road. The outcrop consists of medium to thick-bedded, white quartzite with abundant ripple marks and cross-laminations.

Under the microscope the sample consists of dominantly clasts of quartz (98%) with subsequent amount of lithic fragments, muscovite, tourmaline and opaques (2%). The quartz clasts are rounded to sub-rounded and range in size from 0.1 to 0.3 mm. Adjacent grains show indented to sutured contacts (Fig. 5.4-8). Some quartz grains show sub-grain development along the rim. The quartz cement is completely recrystallized to polygonal mosaic grains.

(c) Dandagaon Phyllite

Rock sample MN-5 was taken from about 3 km south of Mugling along the Mugling-Narayangarh road section. It is dark grey, thinly foliated and pelitic in composition. It is very fine-grained in thin sections and consists of alternating layers of quartz-rich and phyllosilicate-rich layers. The mineral assemblage is sericite+chlorite+quartz. The modal composition is estimated as phyllosilicates (sericite and muscovite)~55%; quartz~40%; feldspar~2% and opaque~3% Sericite and chlorite are aligned parallel to the foliation. The maximum length of sericite and chlorite is 0.1 mm and 0.15 mm, respectively. Bimodal quartz grains are distributed unevenly in the rock mass.

(d) Nourpul Formation

(i) Quartzite of the Purbensi Quartzite member

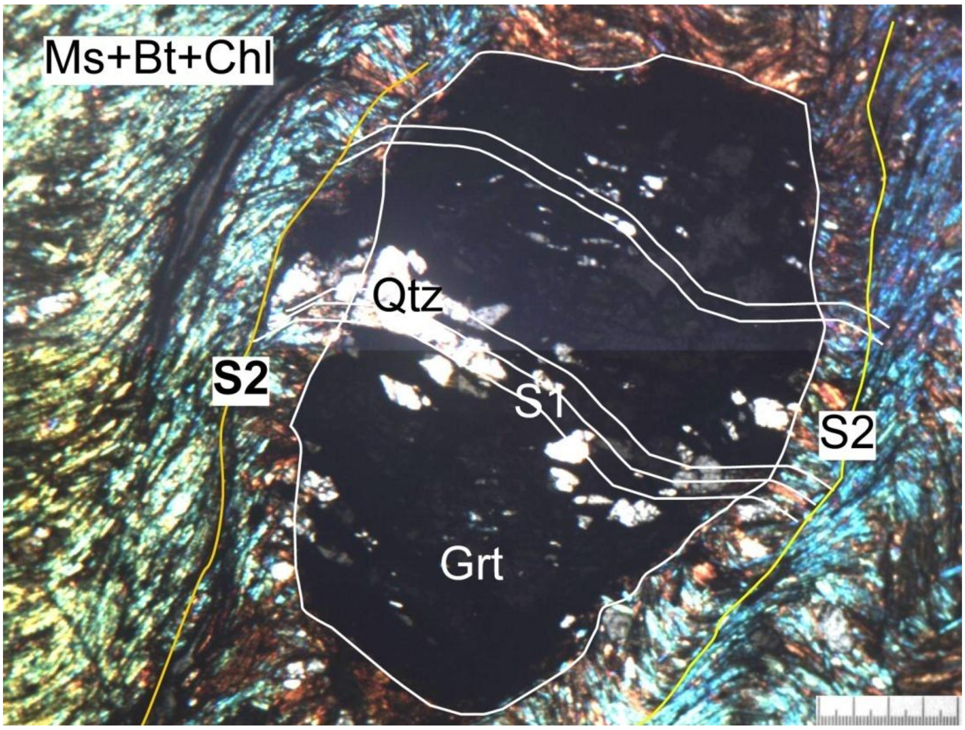


Fig. 5.4-5: Photomicrograph of schist from the Kunchha Formation near the MCT zone (Sample DM419-55). The garnet has grown across the S1 foliaiton and relics of S_1 is preserved within garnet as inclusions of quartz and opaques. Under XPL. Location: Chhoprak, Gorkha.Scale=0.4 mm.Grt-Garnet, Ms-Muscovite,Bt-Biotite, Chl-Chlorite.

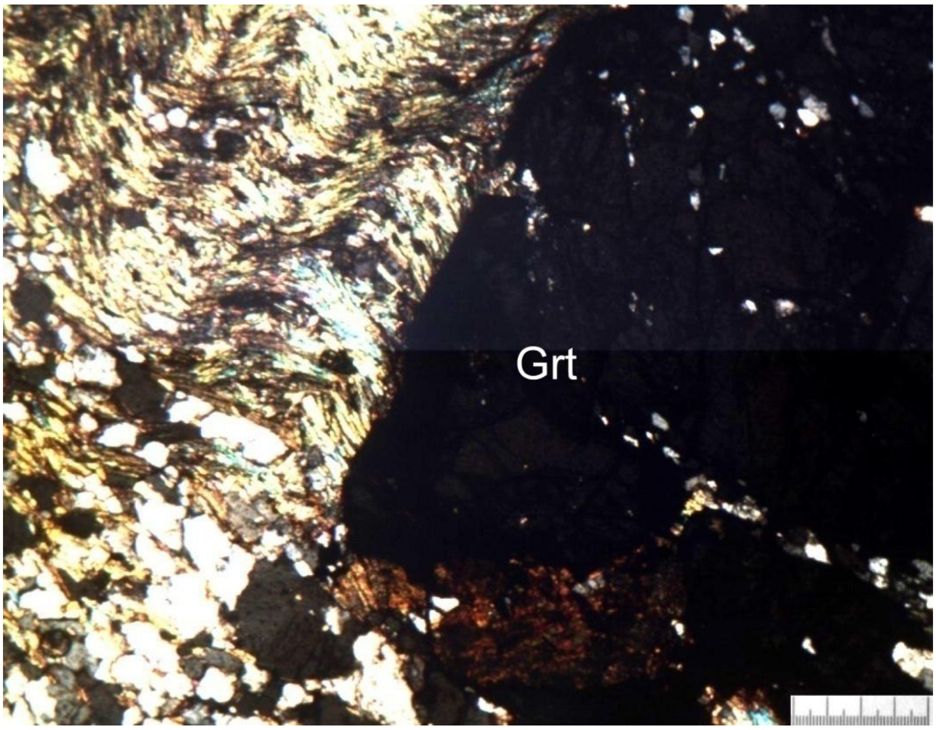


Fig. 5.4-6: Photomicrograph of schist from the Kunchha Formation near the MCT zone (Sample DM419-55). The garnet shows post-tectonic rim overgrowth across the foliation. Under XPL. Location: Chhoprak, Gorkha.Scale=0.4 mm.

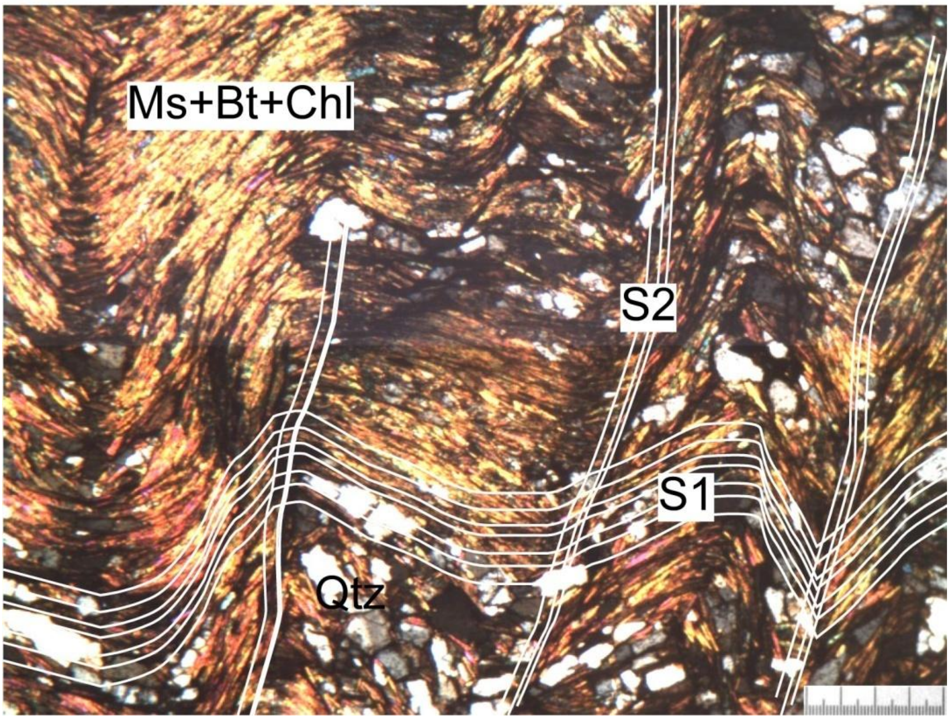


Fig. 5.4-7: Photomicrograph of schist from the Kunchha Formation near the MCT zone (Sample DM419-55) showing well-developed crenulaiton cleavage. Under XPL. Location: Chhoprak, Gorkha.Scale=0.4 mm.Grt-Garnet, Ms-Muscovite,Bt-Biotite, Chl-Chlorite.

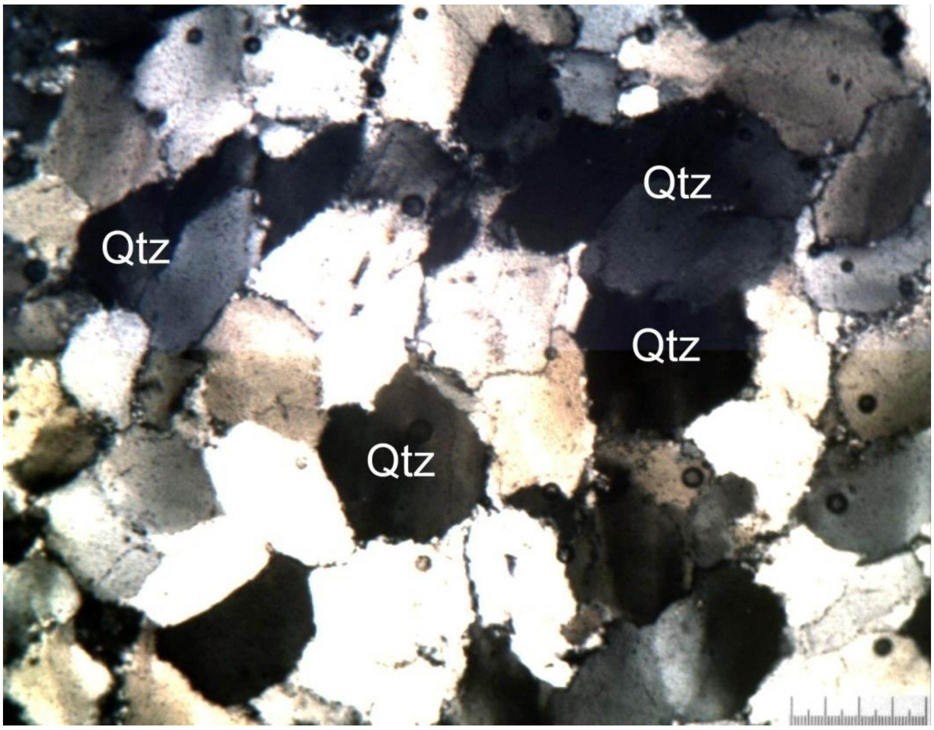


Fig. 5.4-8: Photomicrograph of quartzite from the Fagfog Quartzite (Sample DM80-96). The rock is clast-supported, weakly deformed and shows indented and sutured contact among the adjacent grains. Quartz grains mostly show wavy extinction. Under XPL. Location: Mugling-Anbu Khaireni road. Qtz-Quartz.

It shows bimodal grain distribution with coarse-grained clasts and fine-grained matrix (Fig. 5.4-9). The recrystallized mineral assemblage is sericite+chlorite+quartz. The modal composition of whole rock has been estimated as quartz~95%, sericite~2%, chlorite~2% and opaques~1%. The matrix quartz is partly recrystallized to polygonal aggregate. The clasts are rounded to sub-rounded and range in size from 0.2 mm to 0.5 mm. They are weakly deformed and show pressure solution features along the contacts with other grains. The clasts exhibit strong undulose extinction. Foliation is very weak to absent.

(ii) Phyllite of the Amdanda Phyllite member

Samples MN-21 was taken from the Amdanda Village (type locality of Amdanda Phyllite member). It is grey, fine-grained, thinly foliated and well-laminated, soapy phyllite in outcrop. It is very fine-grained in thin section and consists of the assemblage sericite+chlorite+quartz. The proportion of phyllosilicates and quartz is equal. Sericite and chlorite flakes define foliation.

The sample shows two sets of foliations, strongly developed S_1 parallel to the sedimentary layering (S_0) and weakly developed crenulation cleavage (S_2) (Fig. 5.4-10).

(iii) Labdi Khola Member

Phyllite (Sample DM 8-14)

The sample was taken from approximately 1 km southeast from Ghumaune. It consists of the assemblage sericite+chlorite+quartz+calcite. A modal composition has been estimated as quartz~60%, chlorite ~20%, sericite ~10% and others (opaques) ~10%. The grain size of minerals is usually less than 0.075 mm. However, detrital muscovite grains sometimes reach up to 0.19 mm along long axis.

The sample shows strong S1 foliation parallel to the sedimentary layering. S_1 is folded to form crenulation folds. S_2 is weakly developed along the axial planes of S_2 (Fig. 5.4-11).

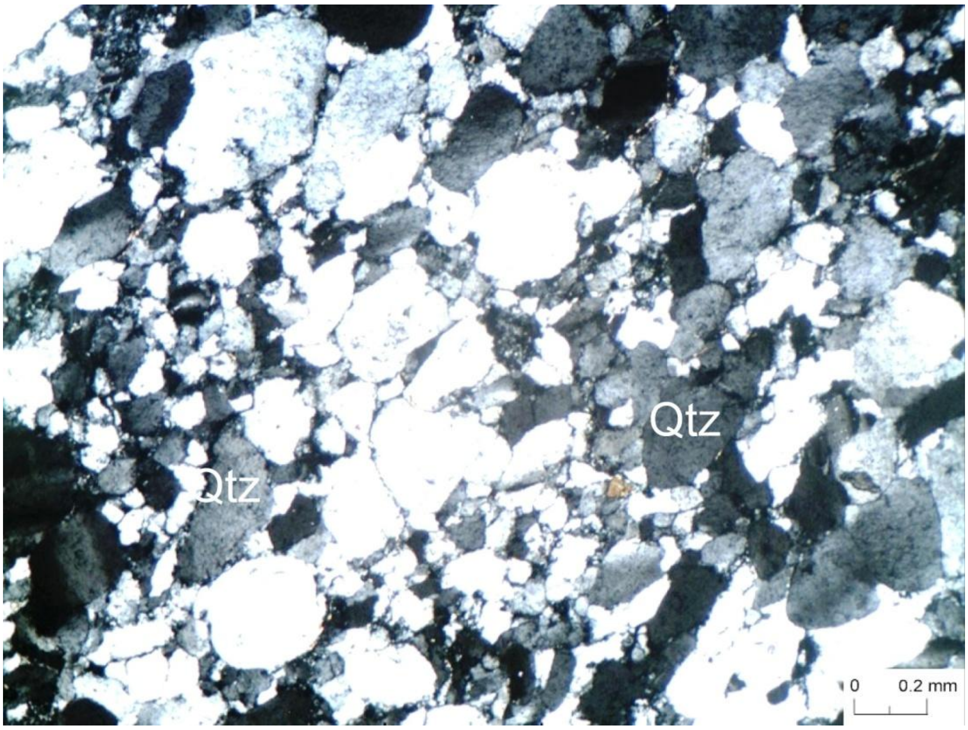


Fig. 5.4-9: Photomicrograph of quartzite from the Purebensi Quartzite (Sample GE6-18showing bimodal grain distribution. The rock is weakly deformed and shows weak foliation defined by elongated quartz grains. Under XPL. Location: Purebensi, along Mugling-Narayangarh road.. Qtz-Quartz.

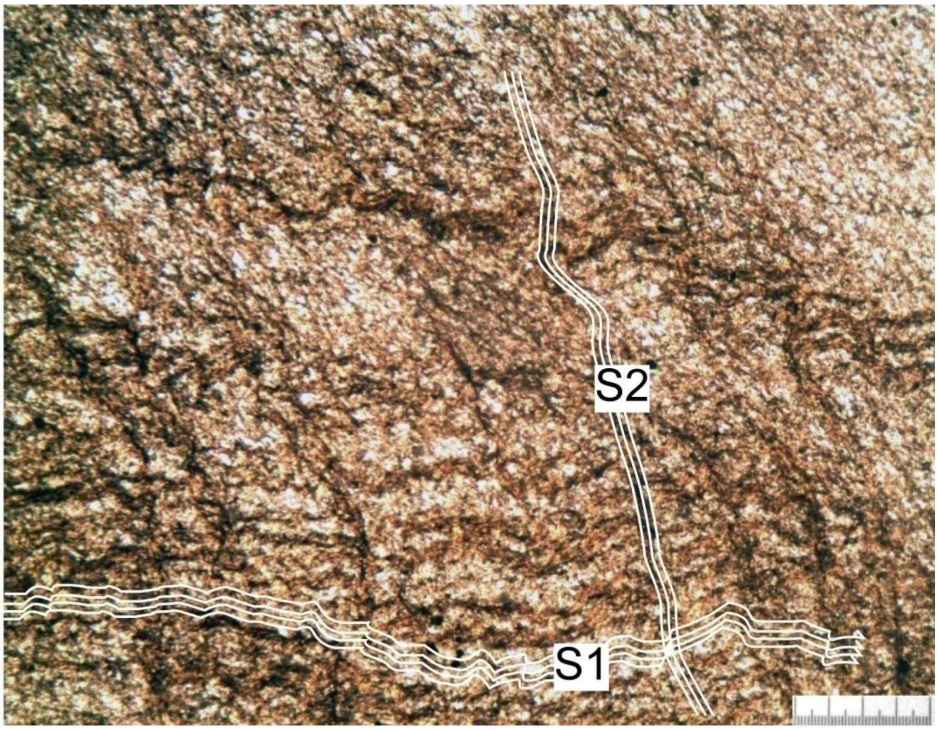


Fig. 5.4-10: Photomicrograph of phyllite from Amdanda Phllite (Sample MN-21) showing well-developed two sets of foliation. The S1 is parallel to the sedimentary layering (S0). The S2 is crenulation cleavage formed across S1. Under PPL. Location: Amdanda.

Calcareous Metasandstone (KL22-2)

Sample KL22-2 was taken from Baralungbesi. The sample belongs to the uppermost part of the Labdi Khola Member. The metasandstone is matrix-supported and contains detrital grains (~40%) embedded in fine-grained matrix (~60%) (Fig. 5.4-12). The modal composition is quartz~65%, calcite~20%, albite~5% and others (muscovite and opaques) ~10%.

Porphyroclasts are made up of quartz, albite and muscovite. Quartz porphyroclasts range in size from 0.3 to 0.5 mm. They are rounded to sub-rounded. Grain boundaries of quartz clasts are mostly corroded and irregular due to pressure solution (Fig. 5.4-13). They show strong wavy extinction. The matrix is made up of calcite, quartz and sericite. It is well-recrystallized. The sample shows no foliation.

Quartzite (JK-50)

The sample JK-50 was taken from an outcrop, about 600 m west from Jamdada village. It is dark grey, medium- to coarse-grained, thick-bedded ortho-quartzite. It is composed of ~95% quartz and ~5% other minerals (tourmaline, muscovite and opaques). The rock is clast-supported (Fig. 5.4-14). Quartz clasts are relatively large (up to 0.7 mm), rounded to sub-rounded and the contacts between adjacent grains is mostly irregular due to pressure solution (Fig. 5.4-15). Quartz grains show strong undulose extinction. Foliation is absent

Metasandstone (KL-73)

This sample was taken from approximately 3 km north of Jalbire. In thin section the sample is composed of 80% clasts and 20% matrix. The clast is mostly (90-95%) made up of rounded to sub-rounded quartz and minor amount of muscovite and tourmaline. Grain size of clasts range from 0.2 to 0.4 mm. Quartz clasts show very good wavy extinction. Pressure solution features is shown by straight and indented contacts among adjacent grains (Fig. 5.4-16). The matrix is made up of quartz (80%) and sericite and chlorite (20%). The sample does not show any foliation.

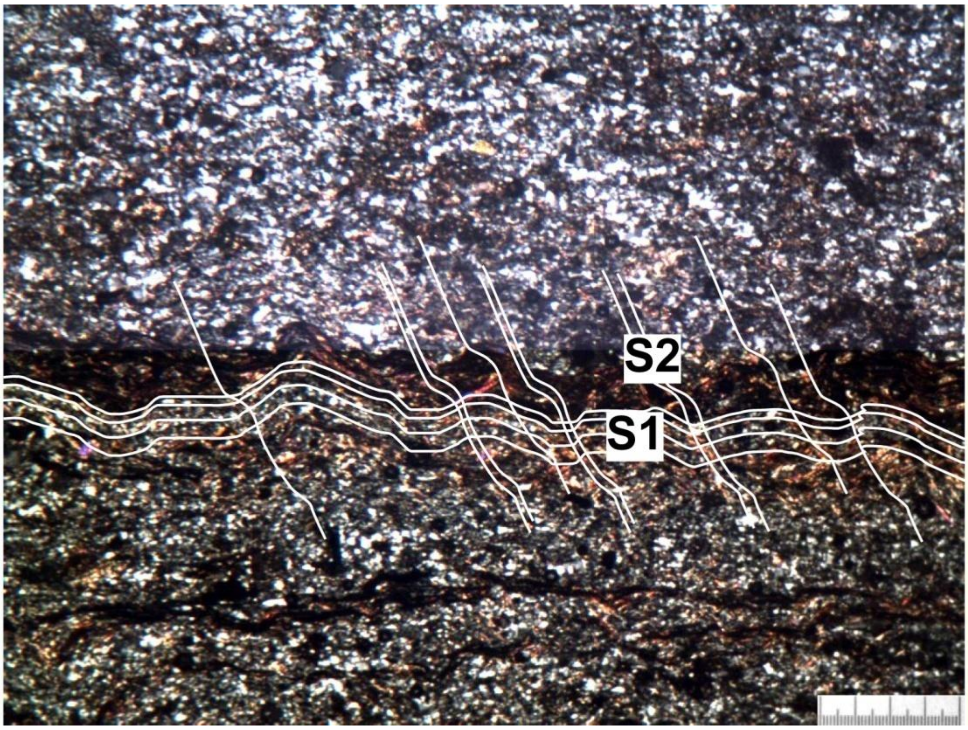


Fig. 5.4-11: Photomicrograph of phyllite from Labdi Khola Member of Nourpul Formation (Sample DM8-14) showing crenulation folds. The S1 is parallel to the sedimentary layering (S0). The S2 is weakly developed across S1. Under XPL. Location: Ghumaune.

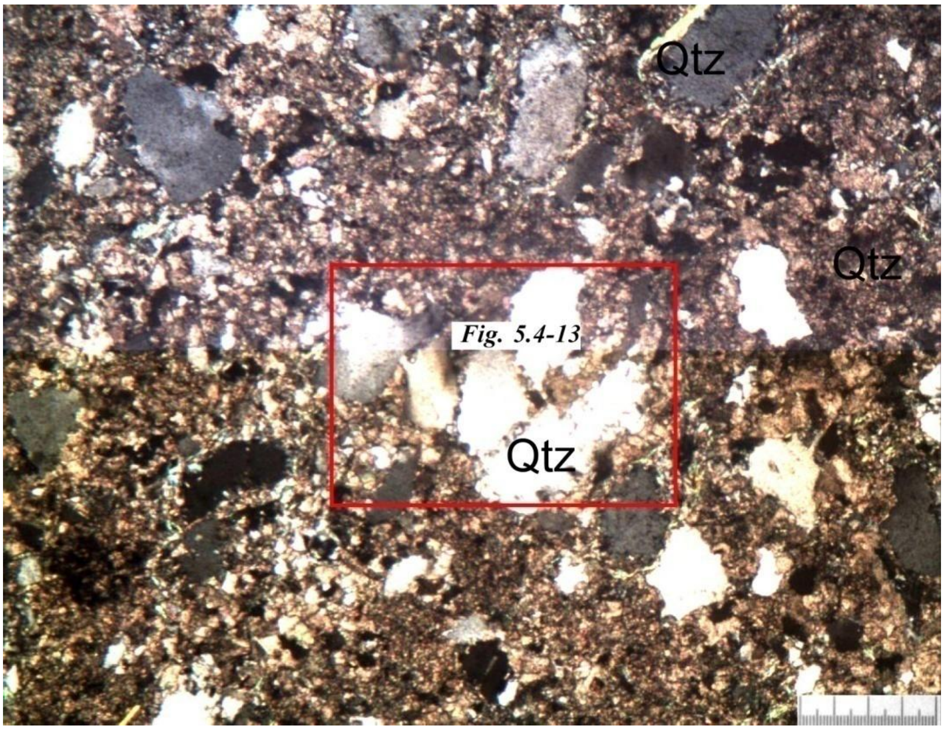


Fig. 5.4-12: Photomicrograph of calcareous metasandstone from Labdi Khola Member of Nourpul Formation (Sample KL22-2) showing clasts of quartz embedded in siliceous and calcareous matrix. Under XPL. Location: Baralungbesi. The area in the box has been enlarged in Fig. 5.4-13. Scale=0.4 mm.

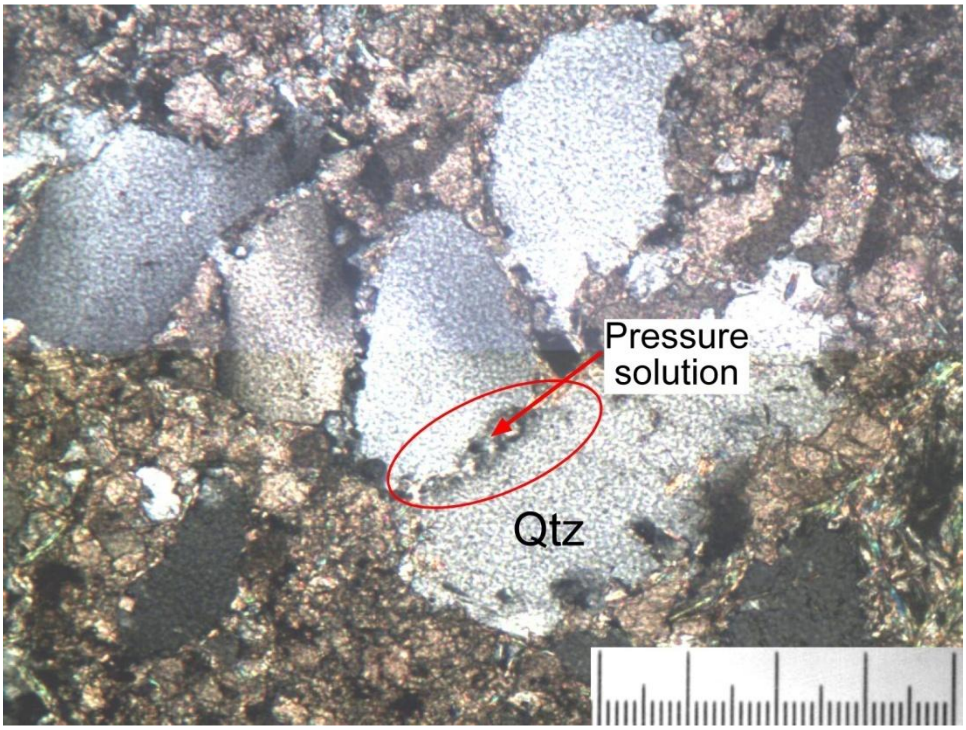


Fig. 5.4-13: Photomicrograph of calcareous metasandstone from Labdi Khola Member of Nourpul Formation (Sample KL22-2) showing corroded boundaries of quartz due to pressure solution. Under XPL. Location: Baralungbesi. Scale=0.4 mm. Qtz-quartz.

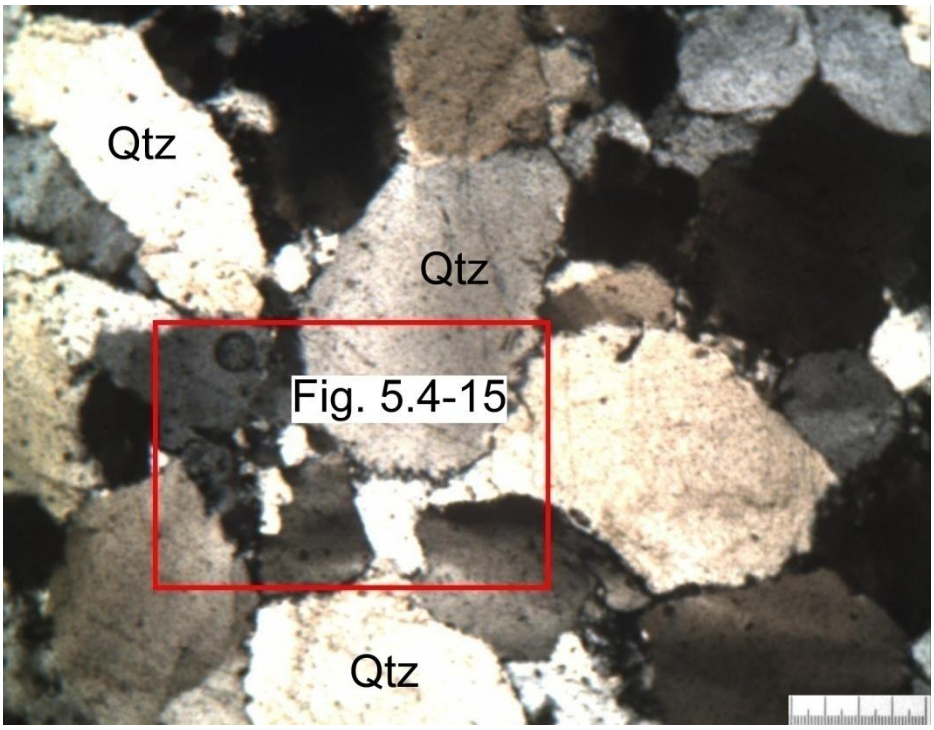


Fig. 5.4-14: Photomicrograph of quartzite from Labdi Khola Member of Nourpul Formation (Sample JK-50) showing closely-packed clasts of quartz. Under XPL. Location: Jamdada Village. Scale=0.4 mm. Qtz-Quartz. The area in the box has been enlarged in Fig. 5.4-15.

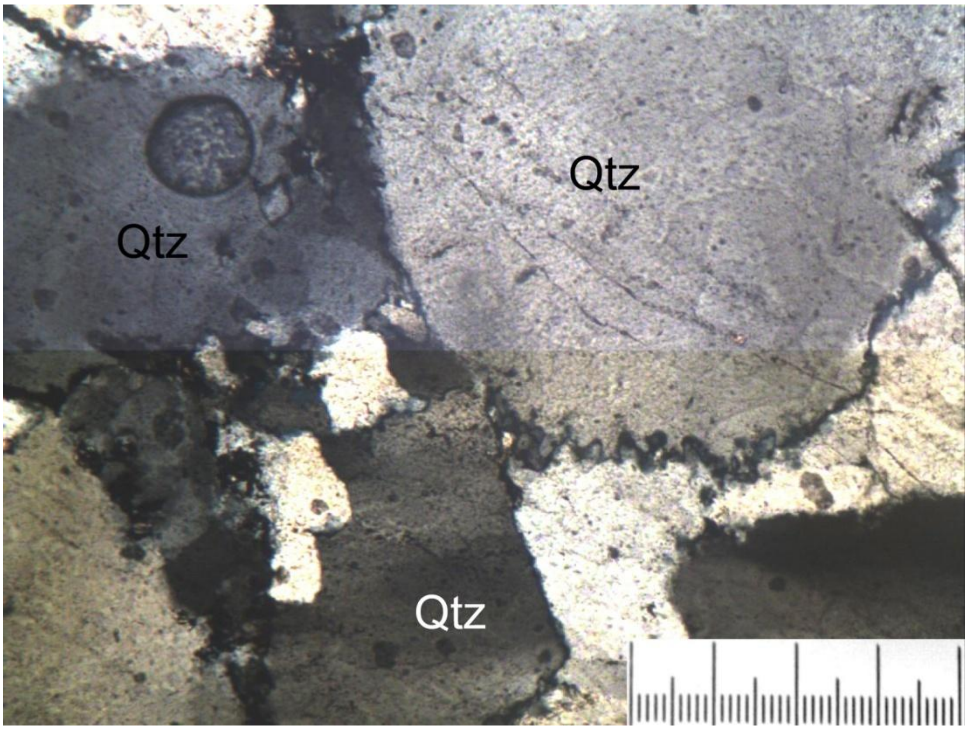


Fig. 5.4-15: Photomicrograph of quartzite from Labdi Khola Member of Nourpul Formation (Sample JK-50) showing irregular and corroded contacts of quartz due to pressure solution. Under XPL. Location: Jamdada Village. Scale=0.4 mm. Qtz-Quartz.

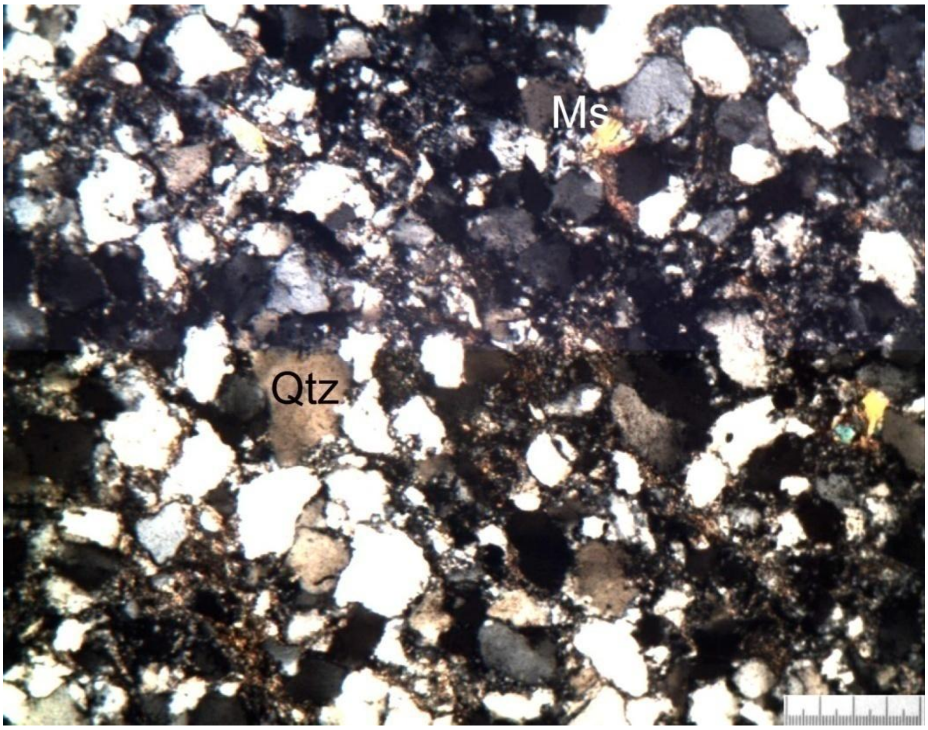


Fig. 5.4-16: Photomicrograph of metasandstone from Labdi Khola Member of Nourpul Formation (Sample KL-73) showing randomly oriented clasts of quartz embedded in phyllosilicate matrix. The sample does not exhibit any foliation. Undex XPL. Location: Jalbire. Scale=0.4 mm. Qtz-Quartz, Ms-Muscovite.

Chhapswara Metasandstone Beds

Sample KL-56

KL-56 was collected from middle part of the Nourpul Formation (lower part of Chhapswara Metasandstone at Darsibhanjyang). The outcrop consists of light gray, fine-grained, medium-bedded metasandstone with phyllite partings. In thin section, the rock is

a matrix-supported metasandstone with 70% clasts and 30% matrix. The clasts are mainly composed of quartz (90%), alkali feldspar (7%), and muscovite and tourmaline (3%). Quartz clasts are rounded to sub-rounded and are of up to 0.3 mm in diameter. They show pressure solution features along the contacts with adjacent grains. Alkali feldspar grains (0.2-0.3 mm in size) are mostly altered to an aggregate of sericite and quartz (Fig. 5.4-17). Most of them occur only as pseudomorphs. Muscovite clasts are measured <0.1 mm in size. They show resorbed and corroded boundaries.

The sample shows no foliation.

(e) Dhading Dolomite

Thin sections were made from four samples, i.e., KL-67 (Mathillo Jalbhanjyang), JK-9 (Tallo Bagandi Village), NR-65 (Kaphaldada Village) and DD-19 (Dewachuli Dada) from different places.

Almost all the samples show similar characteristics in thin section except that one sample (JK-9) has intraformational clasts (Fig. 5.4-18). The samples are dominantly very fine-grained (<0.1 mm) and is composed of dolomite/calcite (~90%), quartz (~8%) and opaques (~2%). Dolomite/calcite is very fine-grained (<0.1 mm). The sample is faintly laminated and lamina is due to clay minerals.

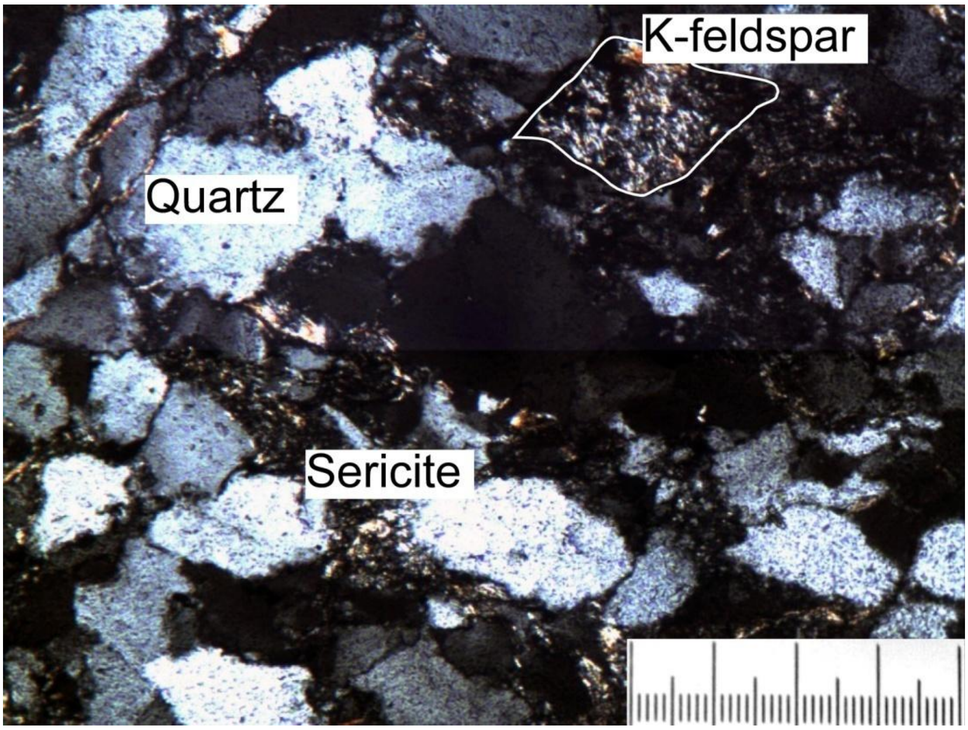


Fig. 5.4-17: Photomicrograph of metasandstone from Chhapswara Metasandstone member (KL-56) showing pseudomorph of alkali feldspar. The metasandstone also shows no foliation. Undex XPL. Location: Darsibhanjyang. Scale=0.4 mm.

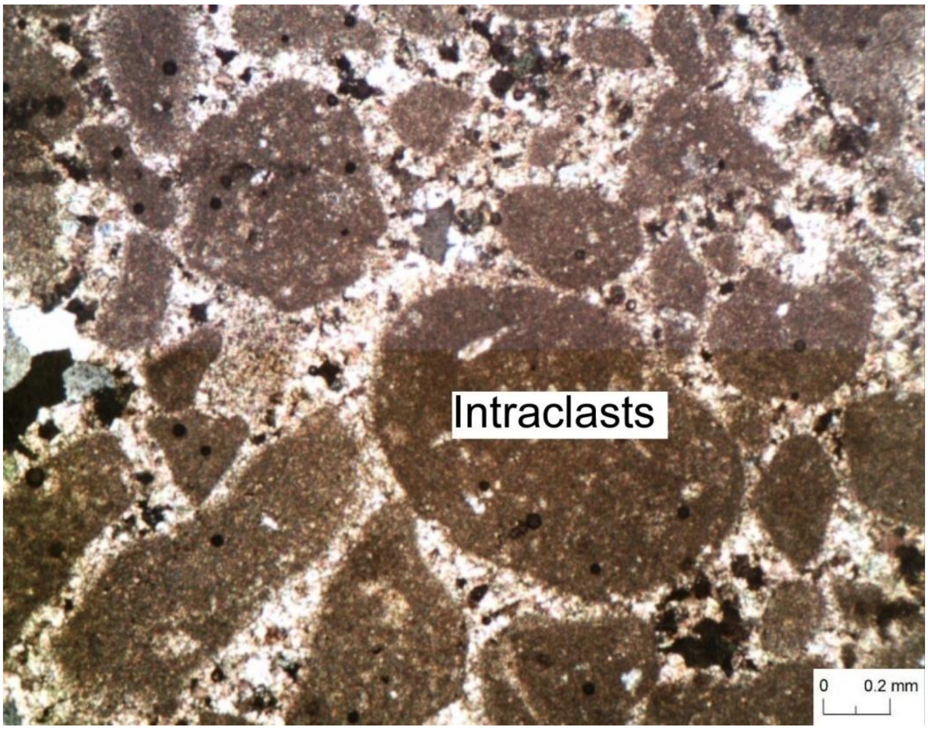


Fig. 5.4-18: Photomicrograph of intraclastic dolomite from the Dhading Dolomite (Sample JK-9) showing rounded intraclasts. The clasts show random orientation. Undex XPL. Location: Tallo Bagandi Village. Scale=0.4 mm.

The sample JK-9 contains sub-rounded to rounded intra-formational clasts (up to 1 mm in size). Few oblique veins of dolomite and calcite (very fine-grained) are also present. Most of the dolomite samples are highly fractured and contain criss-cross veins filled with sparry calcite and quartz (Fig. 5.4-19).

The dolomite samples do not show any foliation.

(f) Benighat Slate

The Benighat Slate is dominantly composed of well-laminated black carbonaceous slates with sub-ordinate amount of dolomite.

(i) Slate

Sample DM22-29

Sample DM22-29 was brought from approximately 3 km south of Ghumaune and represents the lower part of the Benighat Slate. Tectonically it is away from the basal thrust of the Kahun Klippe. It is black, fine-grained and folded in hand specimen.

In thin sections, the slate is made up of very fine-grained (<0.1 mm) white mica, chlorite, and quartz. It contains alternating layers of quartz and phyllosilicate domains (Fig. 5.4-20). The minerals show strongly preferred orientation parallel to the foliation.

The sample shows two sets of foliation (Fig. 5.4-20). The S1 is parallel to the sedimentary layering (S_0). It is folded and S_2 foliation is weakly developed along the axial planes of fold.

Sample LKR-1

The sample was taken from Naya Chaupari representing the upper part of the Benighat Slate and tectonically immediately below the Kahun Klippe. It is greenish-grey in outcrop.

The sample is relatively coarse-grained and well recrystallized compared to the

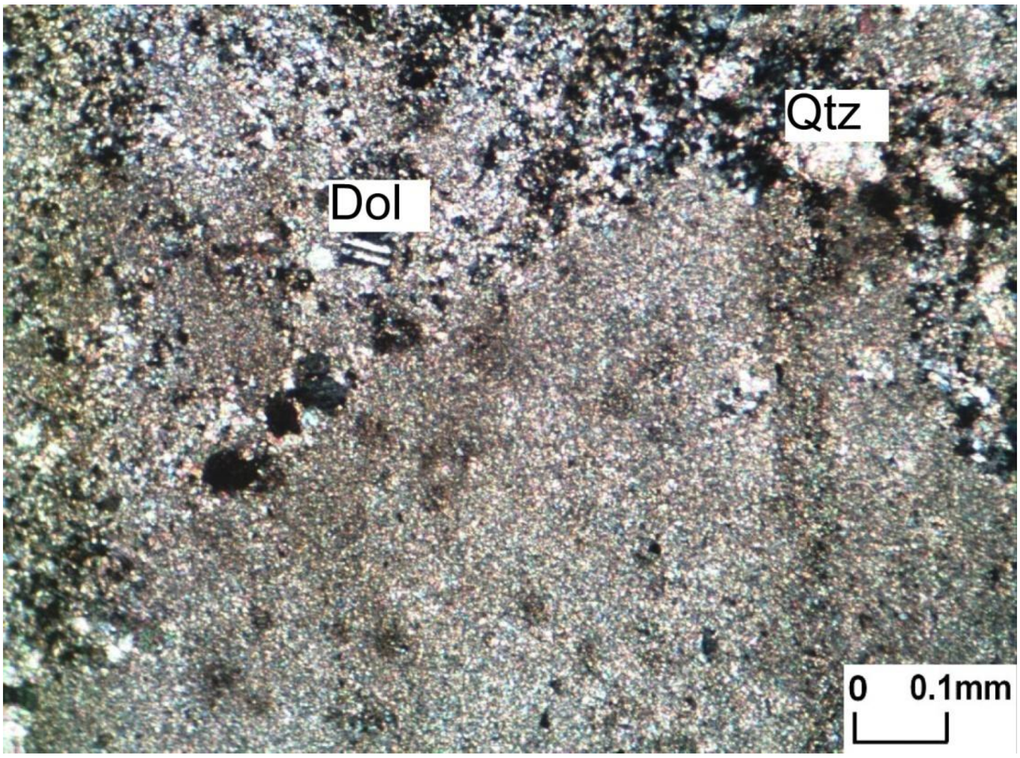


Fig.5.4-19: Photomicrograph of the siliceous dolomite from the Dhading Dolomite (Sample Kl-67). The sample does not show any foliation. Undex XPL. Location: Mathillo-Jalbhanjyang. Scale=0.4 mm. Dol-dolomite, Qtz-quartz.

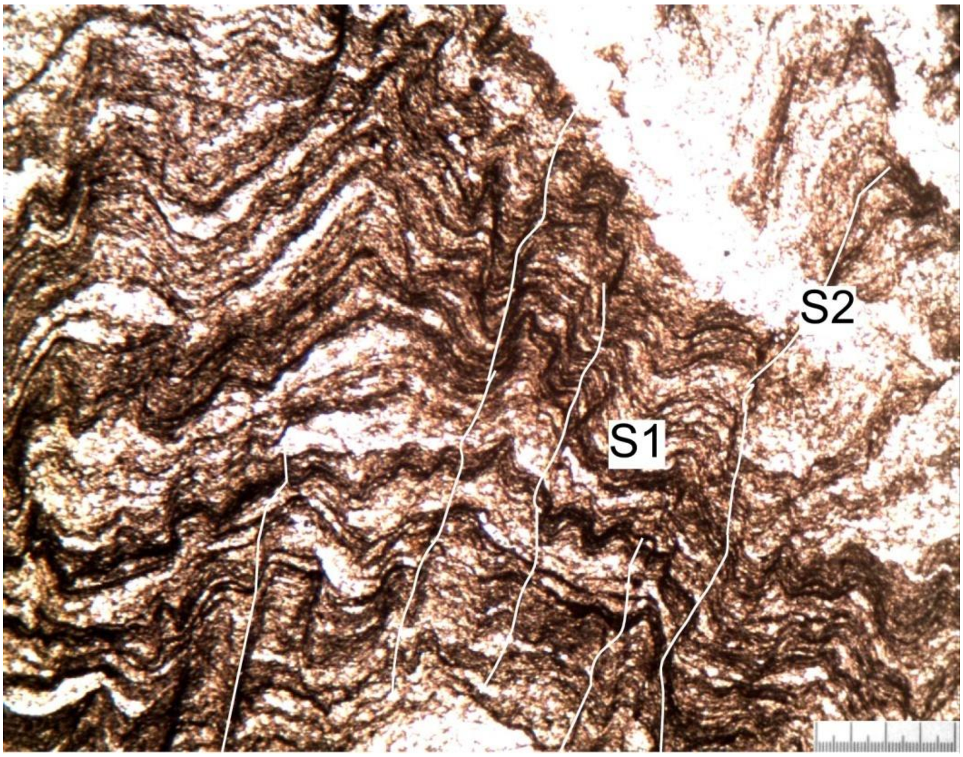


Fig. 5.4-20: Photomicrograph of black carbonaceous slate from the lower part of the Benighat Slate (Sample DM22-27) showing crenulation folds and two sets of foliations. Undex PPL. Location: Ghumaune. Scale=0.4 mm.

Quartz is strongly deformed and aligned parallel to the foliation. Preferred orientation of chlorite and muscovite define the foliation in the rock.

The foliation is cross-cut by several quartz and calcite veins. Ptygmatic folds are common in the sample (Fig. 5.4-21).

(ii) Dolomite

Sample KSY-5 was taken from Pathargau, north of Purano Rising. In thin section it is made up of dolomite/calcite (~80%), quartz (~10%), muscovite (~8%) and opaques (~2%). Dolomite/calcite and phyllosilicate (chlorite and sericite) grains are very fine-grained (<0.1 mm). Quartz veins are common in the rock and are strongly sheared.

In contrast from other dolomite (Dhading Dolomite), this sample is strongly sheared and shows well-developed shear foliation. Quartz veins are sheared parallel to the foliation. Quartz grains in the vein are well-recrystallized, comparatively larger in size (0.1-0.2 mm) and some are in ribbon form (Fig. 5.4-22).

5.4.2 Petrography of Tanahun Group

The rocks of the Tanahun Group are divided into three units: the Gwaslung Formation, the Musimarang Formation and the Shivapur Schist from bottom to top, respectively. Petrographic description of representative rocks from each unit is described in the following sections.

(a) Gwaslung Formation

The Gwaslung formation comprises predominantly of fine- to coarse-grained, thin- to thick-bedded, bluish-grey, milky-white to dirty-white, laminated to non-laminated siliceous dolomite- marble with occasional to regular schist partings.

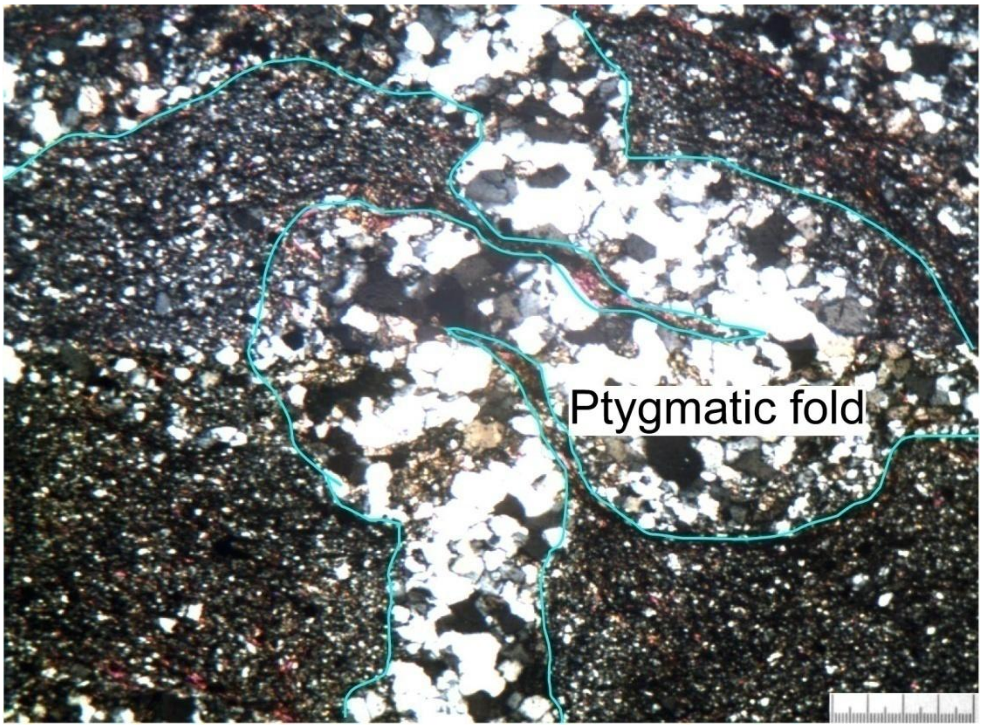


Fig. 5.4-21: Photomicrograph of grey slate from the upper part of the Benighat Slate (Sample LKR-1) showing recrystallized quartz and sericite. It contains abundant ptygmatic folds of quartz and calcite. Undex XPL. Location: Naya Chaupari. Scale=0.4 mm.

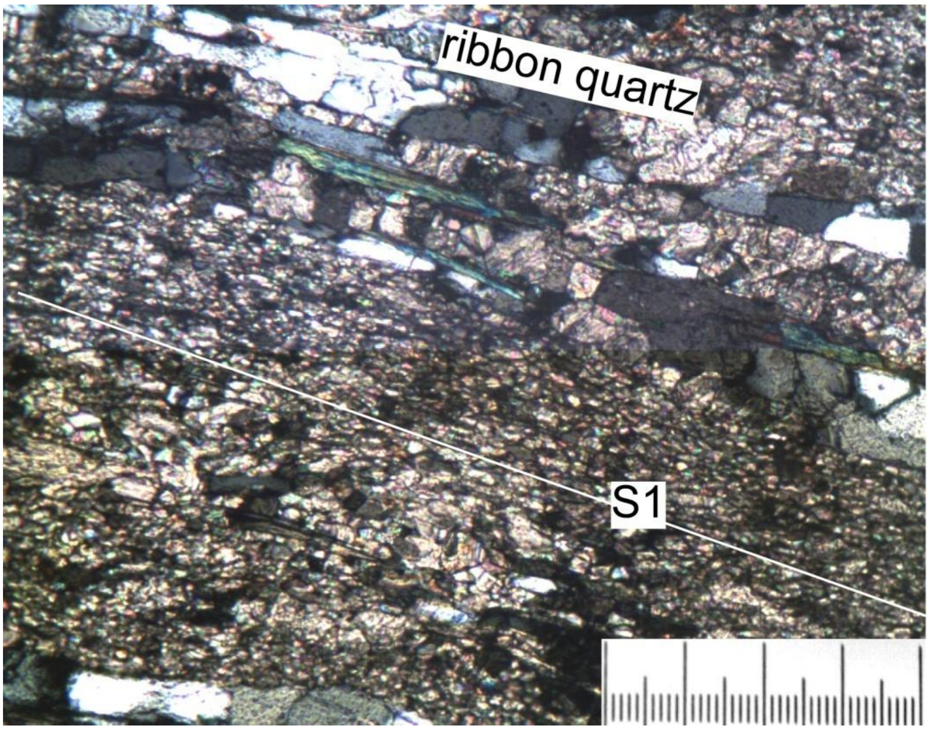


Fig. 5.4-22: Photomicrograph of dolomite from the upper part of the Benighat Slate (Sample KR-65). Dolomite and quartz are strongly sheared to define foliation. Quartz is in ribbon form. Undex XPL. Location: Pathargau, north of Purano Rising. Scale=0.4 mm.

(i) Marble/Schistose Marble

Sample KR-44

Sample KR-44 was taken from 300 m north-west of the Gwaslung Village. It is blue-grey, well-laminated and medium bedded marble in outcrop.

The mineral assemblage found in the sample is biotite+chlorite+calcite/dolomite+quartz. It contains about 70% calcite, 15% quartz, 10% chlorite and 5% biotite. The mineral grains are medium- to coarse-grained, (maximum size of calcite: 1 mm, quartz: 0.9 mm, biotite: 2.0 mm, chlorite: 0.2 mm) and mineral grains are euhedral to anhedral. Preferred orientation of mica and elongated grains of quartz and calcite/dolomite defines very good foliation. In some parts it is folded and deformed with adjacent quartz and calcite grains elongated parallel to the foliation. Most of the quartz grains have sutured contact with the adjacent grains. Under the crossed polars, the interference color is of very high order and the surface is mottled. Calcite twinning is seen in some larger grains which is diagnostic to differentiate from dolomite.

The sample contains only one set of foliation (S_1) defined by chlorite, biotite and elongated calcite and quartz.

Sample KR-47

This sample represents the lowermost part of the Gwaslung Formation. It was taken from an outcrop on the road section, near the thrust zone, about 1 km north-west of Gwaslung School. The marble is blue-grey, medium-grained and medium-bedded in hand specimen.

The mineral assemblage is biotite+chlorite+calcite/dolomite+quartz. The modal composition is ~ 70% calcite, ~ 15% quartz, ~10% chlorite and ~5% biotite. The maximum size of quartz, calcite and biotite are found to be 0.5 mm, 0.8 mm and 1.0 mm, respectively. Foliation is marked by platy minerals and inequent grains (quartz and calcite). The large grains of calcite, surrounded by fine matrix of quartz and calcite display a characteristic prophyroblastic fabric in some part of the rock. The subhedral and anhedral grains of quartz are mostly fractured and elongated.

This sample also shows one set of foliation.

Sample KR-65

This sample was taken from an outcrop on the road section, about 500 m south of Bhirkot School. The sample is blue-grey, coarse-grained and thin-to medium-bedded in outcrop.

Under the thin section, the rock shows mineral assemblage as biotite+muscovite+chlorite+calcite/dolomite+quartz+epidote. The modal composition is calcite~55%, quartz~30%, biotite~5%, muscovite~5%, epidote~2% and others~3%. Calcite/dolomite is very coarse-grained (0.5-1.2 mm) and elongated along the foliation (Fig. 5.4-23). The size of quart grains range from 0.1 to 0.3 mm. Quartz shows sutured contact among the adjacent grains. Muscovite and biotite are relatively fine-grained (0.1-0.2 mm). Epidote is sparsely distributed along the foliation. It is mostly fine-grained (<0.1 mm).

The sample also shows one set of foliation.

(b) Musimarang Formation

The Musimarang Formation comprises the non-calcareous succession of white to dirty-white, thin- to thick-bedded, lineated quartzite with intercalation of thin bands of pelitic-phyllite; well-foliated, grey, psammitic and pelitic schist and occasionally thinly-banded metasandstone. Petrography of representative samples is given below.

(i) Metaquartzite

Sample KSY-17

Sample KSY-17 represents quartzite of the Musimarang Formation in northern part. The sample was taken from 750 m southeast of the Laire village. It is greenish-grey and thin- to medium-bedded in outcrop.

It contains the mineral assemblage of biotite+muscovite+chlorite+quartz. The modal composition is visually estimated as quartz~85%, biotite~5%, muscovite~5%, chlorite~2% and opaque minerals~3%. Quartz is completely recrystallized and show polygonized. Strong undulose extinction in polygonized quartz grain is remarkable. The size of quartz ranges from 0.2 to 0.3 mm. It is elongated and defines foliation. Biotite is oriented parallel to foliation. It is mostly altered to chlorite.

The sample shows only one set of well-developed foliation as defined by elongated quartz, biotite and chlorite.

Sample KR-27

Sample KR-27 was taken from 250 m northeast of the confluence between Wanja and Dunku Khola. It is white and thin- to medium-bedded and shows pink weathering in outcrop.

It contains the same mineral assemblage biotite+muscovite+chlorite+quartz. The modal composition is quartz~95%, biotite and chlorite~3% and tourmaline and opqaques~2%. The most remarkable feature is that quartz shows presence of polygonal sub-grain boundaries with mosaic texture (Fig. 5.4-24).

In general, the meta-quartzite shows a well-developed foliation (S_1).

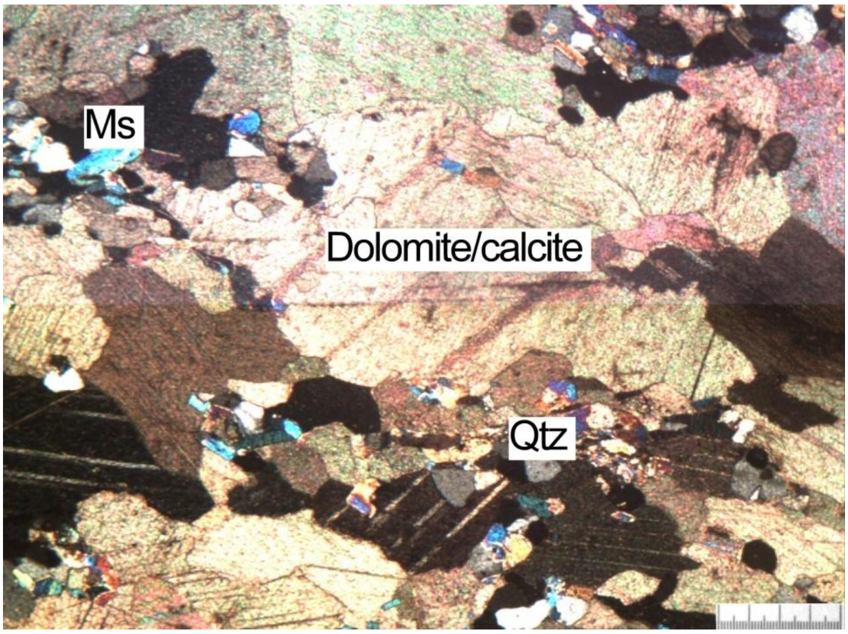


Fig. 5.4-23: Photomicrograph of marble from the Gwaslung Formation (Sample KR-65) sparry calcite/dolomite and quartz. Calcite/dolomite and qurtz are prferrably oriented to define foliation. Under XPL. Location: Gwaslung Village. Scale=0.4 mm.Qtz-quartz, Ms-muscovite.

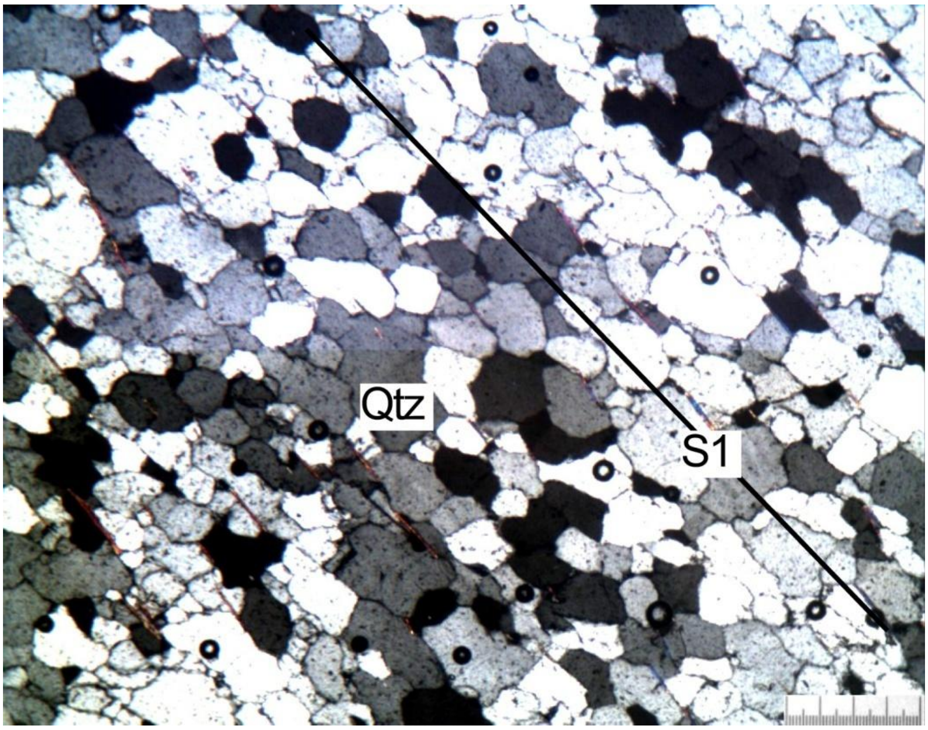


Fig. 5.4-24: Photomicrograph of quartzite from the Musimarang Formation (Sample KR-27) showing polygonal mosaic texture. Quartz grains are elongated to form foliation. Under XPL. Location: Confluence of Wanja Khola and Dunku Khola. Scale=0.4 mm.Qtz-quartz.

(ii) Schist

Sample LKR-7

Sample LKR-7 was collected from Wanja Khola at about 500 m north of the confluence between Wanja and Dunku Khola. It is yellowish-white, laminated, platy and thin- to medium-bedded in outcrop.

It is composed of the mineral assemblage biotite+muscovite+chlorite+quartz. The modal composition is quartz~50% and ~50% others (phyllosilicates). The maximum grain size of quartz grain is 0.3. It is completely recrystallized.

The sample shows strong crenulation folding and well-developed crenulation cleavage (Fig. 5.4-25). Two sets of foliation (S_1 and S_2) are clearly visible in the thin section. There is strong shearing along S_2 which shows top to south sense of shear (Fig. 5.4-26). Quartz is strongly stretched parallel to the foliation to form ribbon structure (Fig. 5.4-27).

(c) Shivapur Schist

The Shivapur Schist is entirely made up of garnetiferous schist. The petrographic description of two representative samples is given below.

Sample GER-15 of schist was taken from Gairathok, Kahun. It is dark-grey and strongly foliated in outcrop. The mineral assemblage is garnet+biotite+muscovite+chlorite+quartz. The modal composition has been estimated as quartz~45%, phyllosiliates (biotite, muscovite and chlorite)~45%, garnet~5%, and opaque minerals~5%. Size of quartz grain range from 0.2 to 0.3 m and are completely recrystallized showing polygonal mosaic texture. Some quartz grains show ribbon structure indicating very strong shearing.

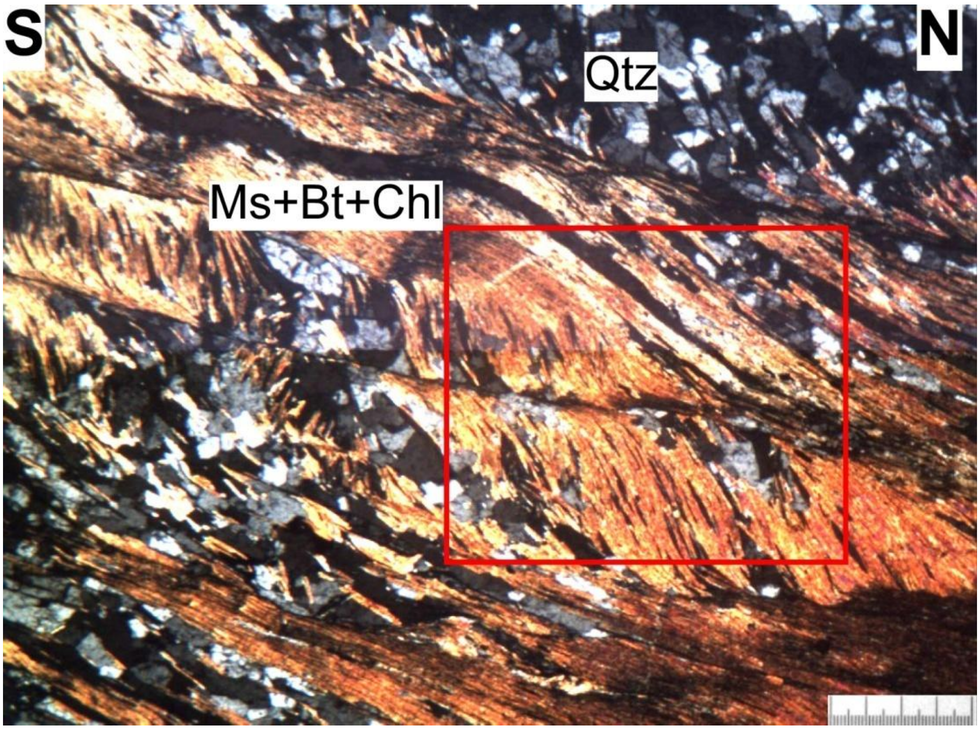


Fig. 5.4-25: Photomicrograph of schist from the Musimarang Formation (Sample LKR-7) showing well-developed crenulation cleavage. Under XPL. Location: Wanja Khola. Scale=0.4 mm. Ms-muscovite, Bt-biotite, Chl-chlorite, Qutz-quartz.

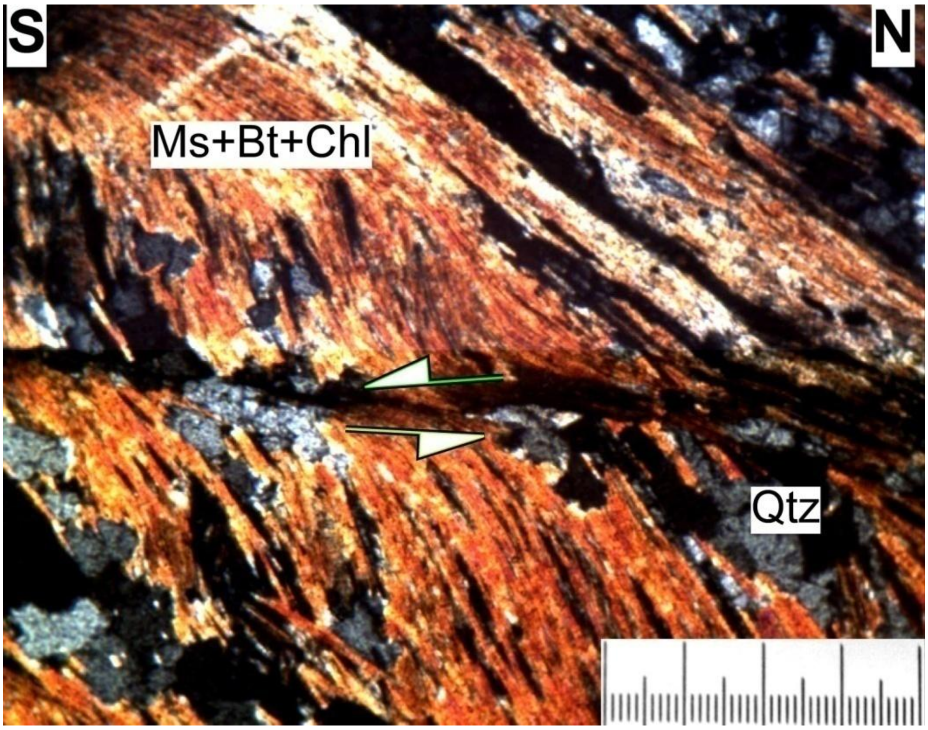


Fig. 5.4-26: Photomicrograph of schist from the Musimarang Formation (Sample LKR-7) showing shearing along the crenulation cleavage. The shearing has top-to-south sense of shearing. Under XPL. Location: Wanja Khola. Scale=0.4 mm. Ms-muscovite, Bt-biotite, Chl-chlorite, Qtz-quartz.

Biotite, muscovite and chlorite are fine-grained (0.1-0.2 mm) and are aligned parallel to the foliation. Garnet porphyroblasts are of up to 1.5 mm. They are strongly altered to quartz, biotite, chlorite and opaque. The S_1 foliation is preserved as S-shaped inclusion in the grain (Fig. 5.4-28). The S_1 inside the grain is continuous to the foliation in matrix. The garnet is itself sheared forming asymmetric pressure shadows and tails of recrystallized quartz (Fig. 5.4-28). The S-shaped inclusions and asymmetric pressure shadows show top-to-south sense of shearing.

5.4.3 Metamorphic zonation

The Lesser Himalaya shows metamorphic assemblages that belong to the Barrovian-type metamorphic sequence of regional metamorphism. The area can be assigned to three metamorphic zones on the basis of index minerals. They are chlorite, biotite and garnet zones. These isograds are shown on Fig. 5.4-29. Summary of mineral mineral assemblage found in the rocks of present study area is given in Table 5.4-1.

(a) Chlorite Zone

A vast area of the present study, south and southwest from Mugling belong to the chlorite zone. The unique metamorphic mineral assemblage in most of the metapelites and metapsammites of the chlorite zone is ‘chlorite+sericite+albie+quartz’.

(b) Biotite Zone

First biotite appears in the Marsyangdi Khola section, north of Anbu Khaireni (Fig. 5.4-29) in the Kunchha Formation. Common mineral assemblages observed in the metapelites and metapsammites of the biotite zone are 'biotite+muscovite+chlorite+quartz'. The biotite zone discordantly cuts across the sedimentary layering and folds.

Table. 5.4-1: Summary of mineral paragenesis in the rocks of the Nuwakot and Tanahu Groups in Mugling–Damauli area.

Minerals (Authigenic)	Nuwakot Group			Tanahun Group
Garnet	■	- - -	- - -	■
Biotite	■	■		■
Muscovite/ sericite	■	■	■	■
Chlorite	■	■	■	■
Albite	■	■	■	
Quartz	■	■	■	■
Calcite/ dolomite	■	■	■	■
Opaques	■	■	■	■
Alteration Product				
Chlorite	■	■	■	■
Sericite	■	■	■	■
Biotite	■			■
Detrital/ Relict				
Quartz		■	■	
K-feldspar		■	■	
Albite	■	■	■	
Muscovite	□■	■	■	
Tourmaline	■	■	■	
Zircon	■	■	■	
Mineral zone	Garnet	Biotite	Chlorite	Garnet
Metamorphic facies	Greenschist		Prehnite-pumpellyite	Greenschist

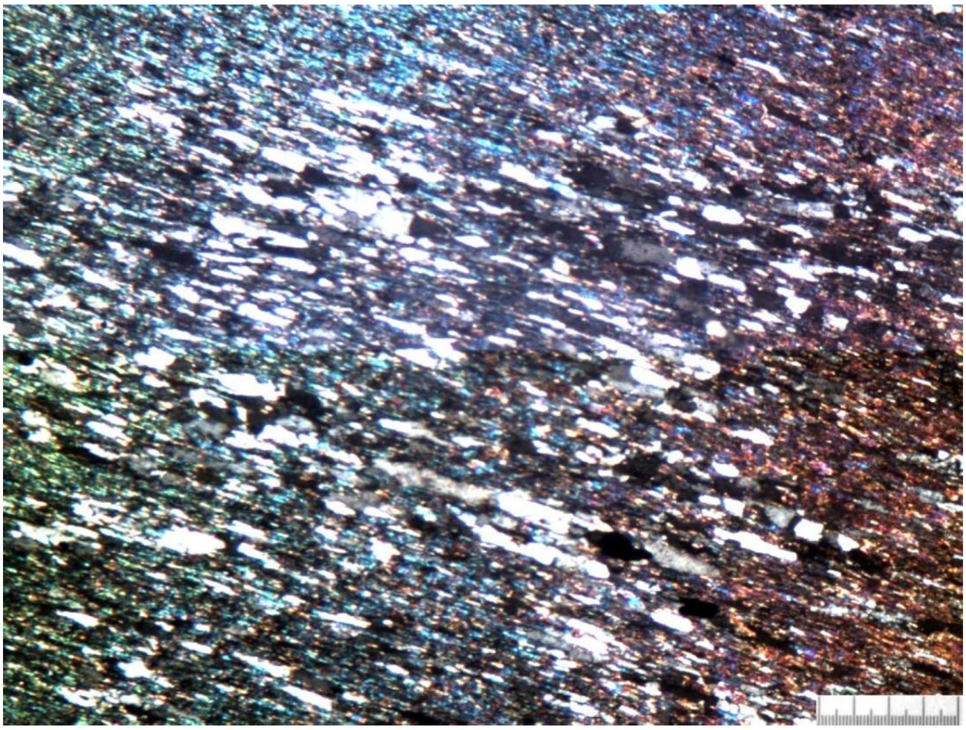


Fig. 5.4-27: Photomicrograph of schist from the Musimarang Formation (Sample LKR-7) showing strong foliation and riboon quartz. Undex PPL. Location: Wanja Khola. Scale=0.4 mm.

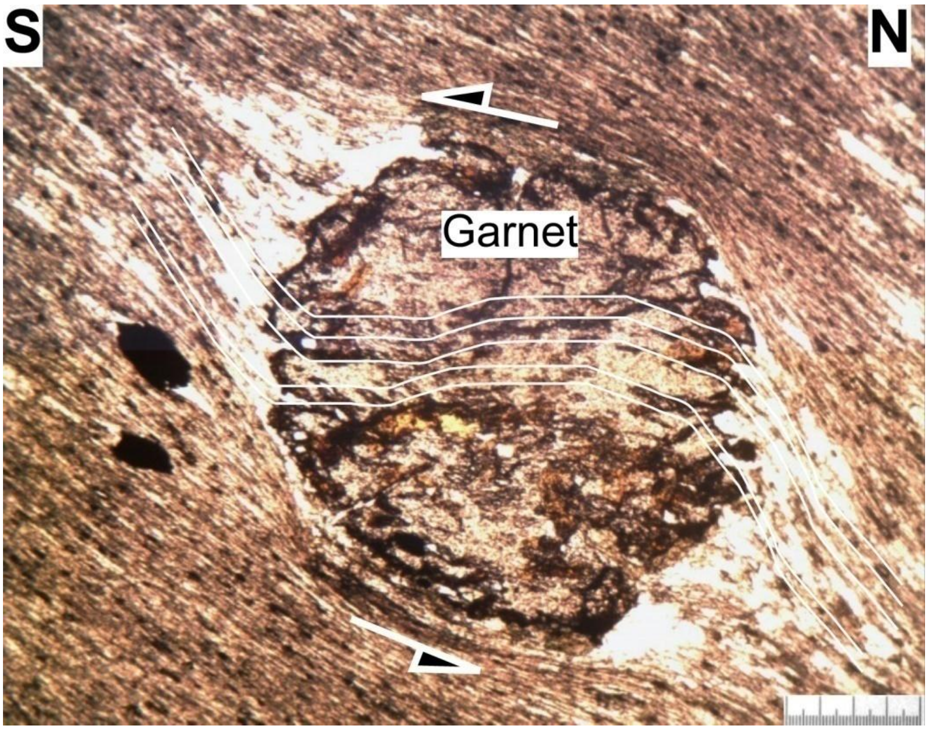


Fig. 5.4-28: Photomicrograph of schist from the Shivapur Schist (Sample GER-15) showing garnet porphyroblasts. The porphyroblasts reserves S1 as S-shped inclusions of quartz and opaques. The shape of inclusion and asymmetric tails show top to south sense of shearing. Undex PPL. Location: Gairathok, Kahun. Scale=0.4 mm.

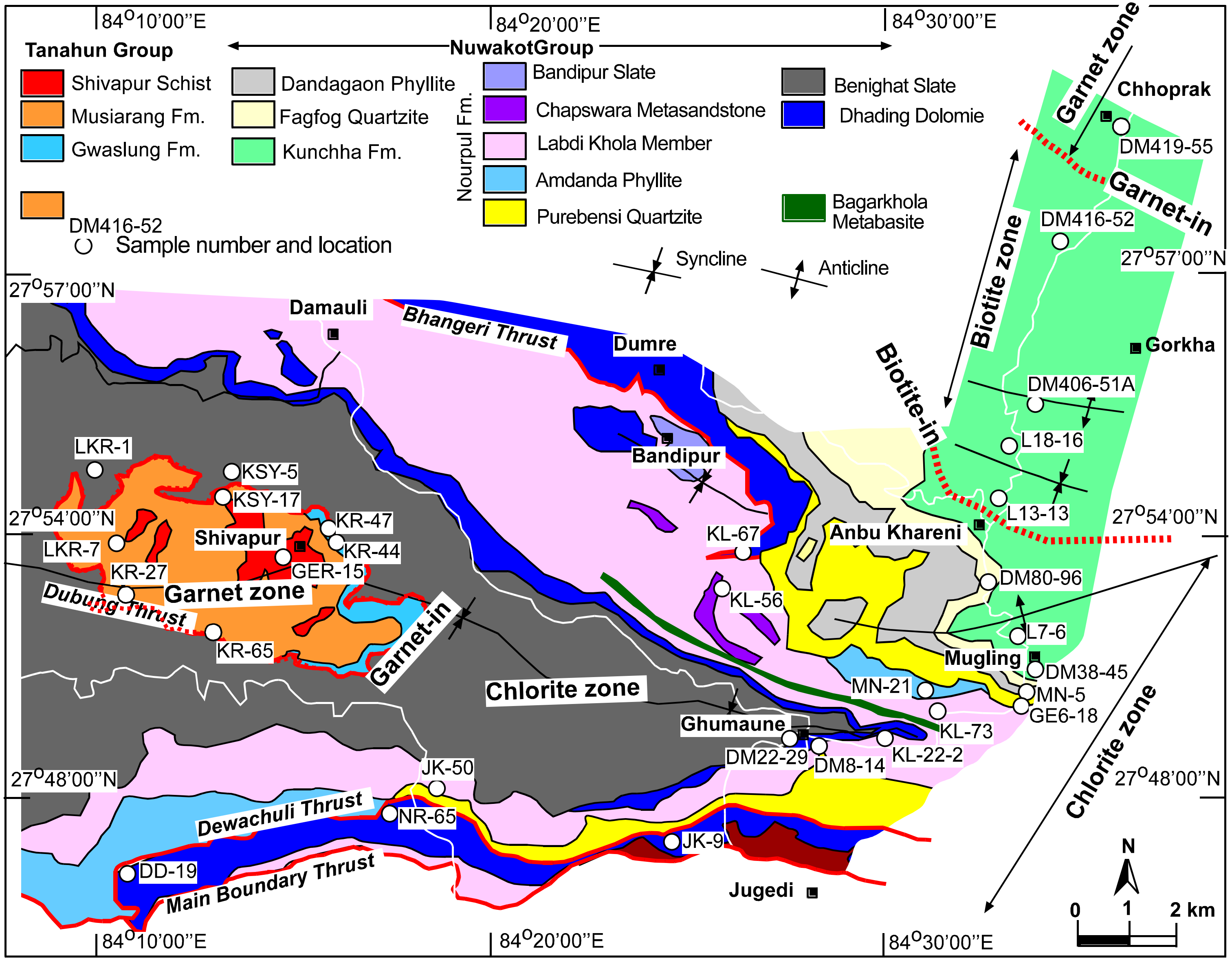


Fig. 5.4-29: Geological map of the study area showing the location of samples used for petrographic study. The metamorphic isograds are shown on the map.

(c) Garnet zone

The garnet isograd appears at two different places in the study area. One is at the base of the Kahun Klippe and the other in the Kunchha Formation (Fig. 5.4-29). In the Kahun Klippe the garnet isograd follows the basal thrust of the klippe (Dubung Thrust). The mineral assemblage is 'garnet+ biotite+ muscovite+chlorite+quartz' in pelitic rocks. In the Kunchha Formation, tiny garnet porphyroblasts visible with naked eyes appear in the psammitic and pelitic schist near Chhoprak. It has mineral assemblages 'garnet+biotite+muscotie+chlorite+albite+quartz'. The garnet isograd is also discordant to the sedimentary layering and folds in the area.

5.5 ILLITE CRYSTALLINITY

5.5.1 Sample selection and measurement

Altogether 34 selected samples from the study area were used for Illite Crystallinity or Kubler Index (KI) measurement. Among them 6 are from Kunchha Formation, 4 are from Dandagaon Phyllite, 13 are from Nourpul Formation, 4 are from the Dhading Dolomite, and 7 are from the Benighat Slate. The location of measured samples is given in Fig. 5.5-1.

All the samples used for KI measurement are fine-grained rocks of similar lithology (mainly pelitic rocks) well-developed foliation with shining surfaces. The samples were also studied in thin sections to check the presence of phyllosilicates and detrital white micas. Samples containing detrital white micas were avoided as far as possible. Such selective sampling helped to reduce the inter- and intra-sample variation.

The KI was measured in <2 µm powder fractions of the samples using D8 Advance X-ray Diffractometer at the Central Department of Geology, Tribhuvan University. The

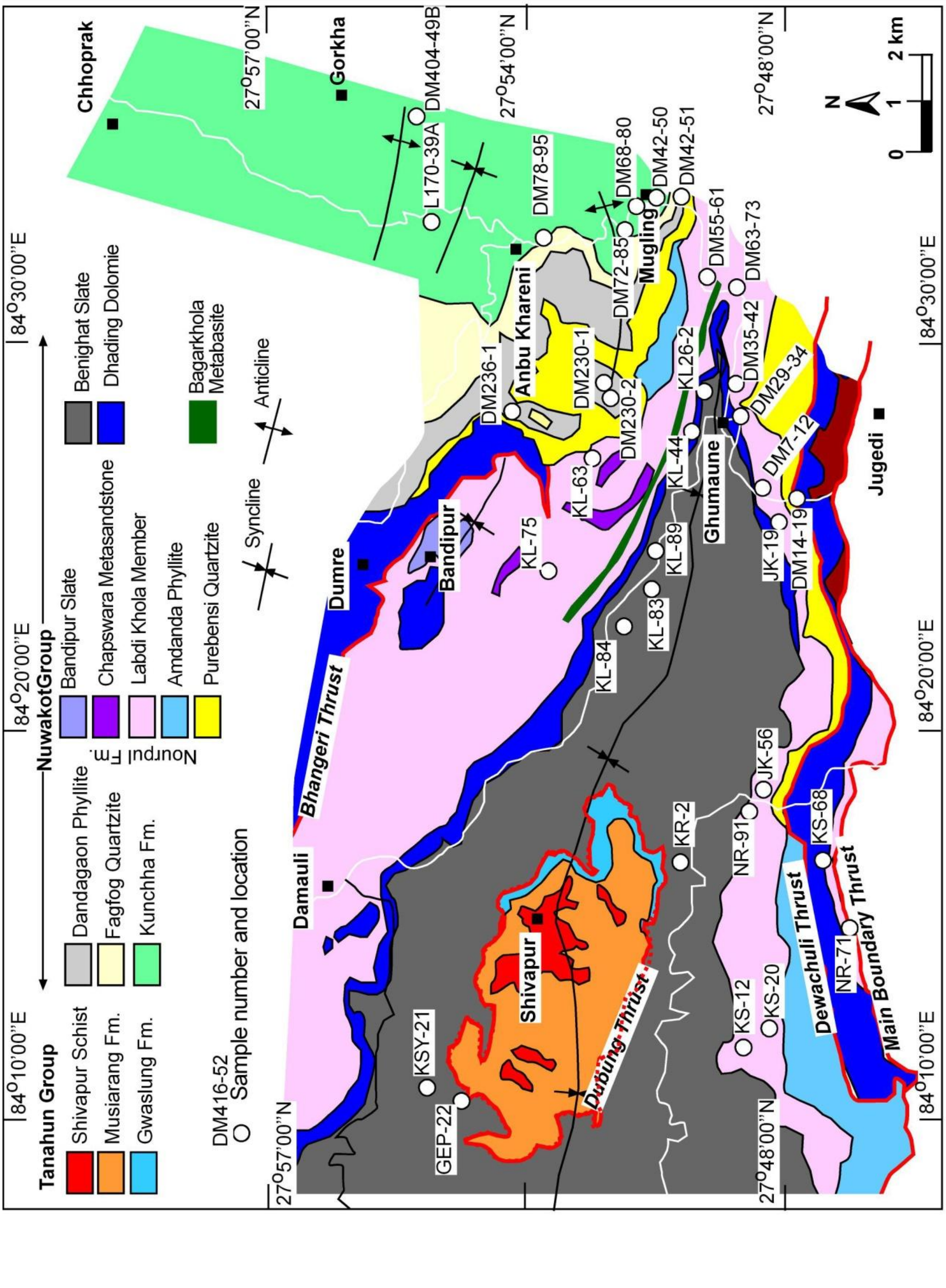


Fig. 5.5-1: Geological map of the study area showing the location of samples used for Illite Crystallinity.

sample preparation methods and measurement conditions are given in Annex I. Each sample was measured 5 times and the average value was determined. The average KI values of the measured samples are given in Table 5.5-1. Representative X-ray diffractograms are given in Annex VI.

5.5.2 Illite crystallinity data

The KI values in the Kunchha Formation range from 0.111 to 0.130 $\Delta^{\circ}2\theta$ in the Kunchha Formation, 0.13 to 0.151 $\Delta^{\circ}2\theta$ in the Dandagaon Phyllite, 0.121 to 0.195 $\Delta^{\circ}2\theta$ in the Nourpul Formation, 0.177 to 210 $\Delta^{\circ}2\theta$ in the Dhading Dolomite, 0.177 to 0.246 $\Delta^{\circ}2\theta$ in the lower part of the Benighat Slate, and 0.180 to 0.190 $\Delta^{\circ}2\theta$ in the upper part of the Benighat Slate.

Finally, the average of KI values and standard deviation for each stratigraphic unit were determined (Table 5.5-1).

Table 5.5-1: Illite crystallinity data (Kubler Index) of the metapelitic samples from the Mugling-Damauli area, central Nepal Lesser Himalaya.

Rock Units	**Illite Crystallinity**								**Average**	**S.D.**	**Meta. Zones**
Benighat Slate (Upper Part)	Sample No.	GEP-22	KSY-21	KR-2							
	KI (Δ°2θ)	0.190	0.190	0.180					**0.187**	**0.006**	
Benighat Slate (Lower Part)	Sample No.	KL-26-2	KL-89	KL-84	KL-83						
	KI (Δ°2θ)	0.246	0.177	0.185	0.192				**0.200**	**0.031**	
Dhading Dolomite	Sample No.	KL-44	KS-68	DM14-19							
	KI (Δ°2θ)	0.177	0.210	0.123	0.210				**0.180**	**0.041**	
Nourpul Formation	Sample No.	KL-75	KL-63	NR-71	JK-19	KS-20	NR-91	KS-12			Epizone
	KI (Δ°2θ)	0.185	0.177	0.182	0.179	0.213	0.180	0.195	**0.164**	**0.030**	
	Sample No.	JK-56	DM7-12	DM63-73	DM55-61	DM35-42	DM29-34				
	KI (Δ°2θ)	0.175	0.127	0.134	0.121	0.143	0.123				
Dandagaon Phyllite	Sample No.	DM42-51	DM230-1	DM230-2	DM236-1						
	KI (Δ°2θ)	0.151	0.143	0.140	0.130				**0.141**	**0.009**	
Kunchha Formation	Sample No.	L170-39A	DM404-49	DM78-95	DM72-85	DM68-80	DM42-50				
	KI (Δ°2θ)	0.111	0.129	0.112	0.122	0.130	0.117		**0.120**	**0.008**	

The average value is $0.120\pm0.008\Delta^{\circ}2\theta$ (n=6) for the Kunchha Formation, $0.141\pm0.009\Delta^{\circ}2\theta$ (n=4) for the Dandagaon Phyllite, $0.164\pm0.03\Delta^{\circ}2\theta$ (n=13) for the Nourpul Formation, $0.180\pm0.041\Delta^{\circ}2\theta$ (n=4) for the Dhading Dolomite, $0.20\pm0.031\Delta^{\circ}2\theta$ (n=4) for the lower part of Benighat Slate and $0.187\pm0.006\Delta^{\circ}2\theta$ (n=4) for the upper part of the Benighat Slate.

5.5.3 The KI pattern and metamorphism

The average data (Table 5.5-1) shows an increasing value of KI (i.e., decrease of illite crystallinity) stratigraphically up section from Kunchha Formation to the lower part of the Benighat Slate. It indicates decrease of metamorphic grade stratigraphically upwards. It probably suggests that the regional metamorphism occurred before folding of strata. It is also supported by the fact that the foliation is parallel or sub-parallel to the bedding and degree of recrystallization of rocks increases down section.

However, in the Benighat Slate, the KI value is reversed, i.e., KI is higher at the lower part and lower in the upper part. It means the grade of metamorphism is higher at the upper part. The Kahun Klippe with crystalline rocks (garnet grade rocks) directly rests on top the Benighat Slate in the study area. Most probably the upper part of the Benighat Slate was affected by thrust (hot iron effect; Le Fort, 1975 and shear heating effect; Arita 1983).

5.2.4 Paleotemperature calculation

Paleotemperature determination is one of the most difficult tasks in the low-and medium-grade metamorphic rocks. The KI values can be used to determine the semi-quantitative peak paleotemperature. Underwood et al. (1993) presented a Temperature versus KI curve for the Shimanto Accretionary Belt in Japan, with combined study of KI and vitritine reflectance studies. He proposed a correlation equation as "KI = 1.197-0.0029T°C".

Peak paleotemperature ranges from 345-370°C in the study area (Table 5.5-2). The average temperature for the Kunchha Formation is 370°C, for the Dandagaon Phyllite is 365 °C, for the Nourpul Formation is 355 °C, for the Dhading Dolomite is 350 °C, for the lower part of the Benighat Slate is 345 °C and for the upper part of the Benighat Slate is 350 °C.

Table 5.5-2: Paleotemperature of peak low-grade metamorphism in the Nuwakot Group rocks of the Mugling-Damauli area, central Nepal Lesser Himalaya. The temperatures were estimated using the calibration of Underwood et al. (1993).

Rock Units	**Average**	Paleotemperature (°C)
Benighat Slate (Upper part)	0.187	348
Benighat Slate (Lower Part)	0.200	344
Dhading Dolomite	0.180	351
Nourpul Formation	0.164	356
Dandagaon Phyllite	0.141	364
Kunchha Formation	0.120	371

5.6 GRAPHITE CRYSTALLINITY

5.6.1 Sample selection and measurement

Graphite Crystallinity (GC) was measured on carbonaceous samples from the study area. Carbonaceous material from the sample was separated using the method described in Annex II. Samples from Kunchha Formation did not contain any carbonaceous material. 3 samples from Dandagaon Phyllite, 9 samples from the Nourpul Formation, 3 samples from Dhading Dolomite, and 10 samples from Benighat Slate were used to determine the graphite crystallinity (see Fig. 5.6-1 for location of the samples).

The GC was measured using D8 Advance X-ray Diffractometer at the Central Department of Geology, Tribhuvan University. Each sample was scanned five times and average value was measured. The GC for flake graphite and pencil graphite were also measured for comparison. Details of the sample preparation methods and measurement conditions are given in Annex II. Average GC values for each sample from the area are given in Table 5.6-1 and representative diffractograms are given in Annex VII.

5.6.2 Graphite crystallinity data

The GC values in the Dandagaon Phyllite range from 0.177-0.18 $\Delta^{\circ}2\theta$, in the Nourpul Formation range from 0.17-0.197 $\Delta^{\circ}2\theta$, in the Dhading Dolomite range from 0.208-0.220 $\Delta^{\circ}2\theta$, in the lower part of the Benighat Slate range from 0.192-0.22 $\Delta^{\circ}2\theta$ and in the upper part of the Benighat Slate range from 0.14 to 0.18 $\Delta^{\circ}2\theta$ (Table 5.6-1).

The average GC value for each geological unit was determined from the measured samples. The average GC value for the Dadagaon Phyllite is $0.179\pm0.001\Delta^{\circ}2\theta$ (n=3), for the Nourpul Formation is $0.184\pm0.012\Delta^{\circ}2\theta$ (n=9), for the Dhading Dolomite is $0.213\pm0.008\Delta^{\circ}2\theta$ (n=3), for the lower part of the Benighat Slate is $0.206\pm0.020\Delta^{\circ}2\theta$ (n=2) and for the upper part of the Benighat Slate is $0.162\pm0.014\Delta^{\circ}2\theta$ (n=8).

5.6.3 The GC pattern and metamorphism

The average data (Table 5.6-1) shows an increasing value of GC (i.e., decrease of crystallinity) stratigraphically up section from Kunchha Formation to the Dhading Dolomite. The average GC value is lower in the Benighat Slate compared to that in the Dhading Dolomite. The GC pattern is reversed also within the Benighat Slate. The GC value is higher in the lower part and lower in the upper part. Therefore, the GC values also indicate decrease of metamorphic grade stratigraphically upwards in the Nawakot Group.

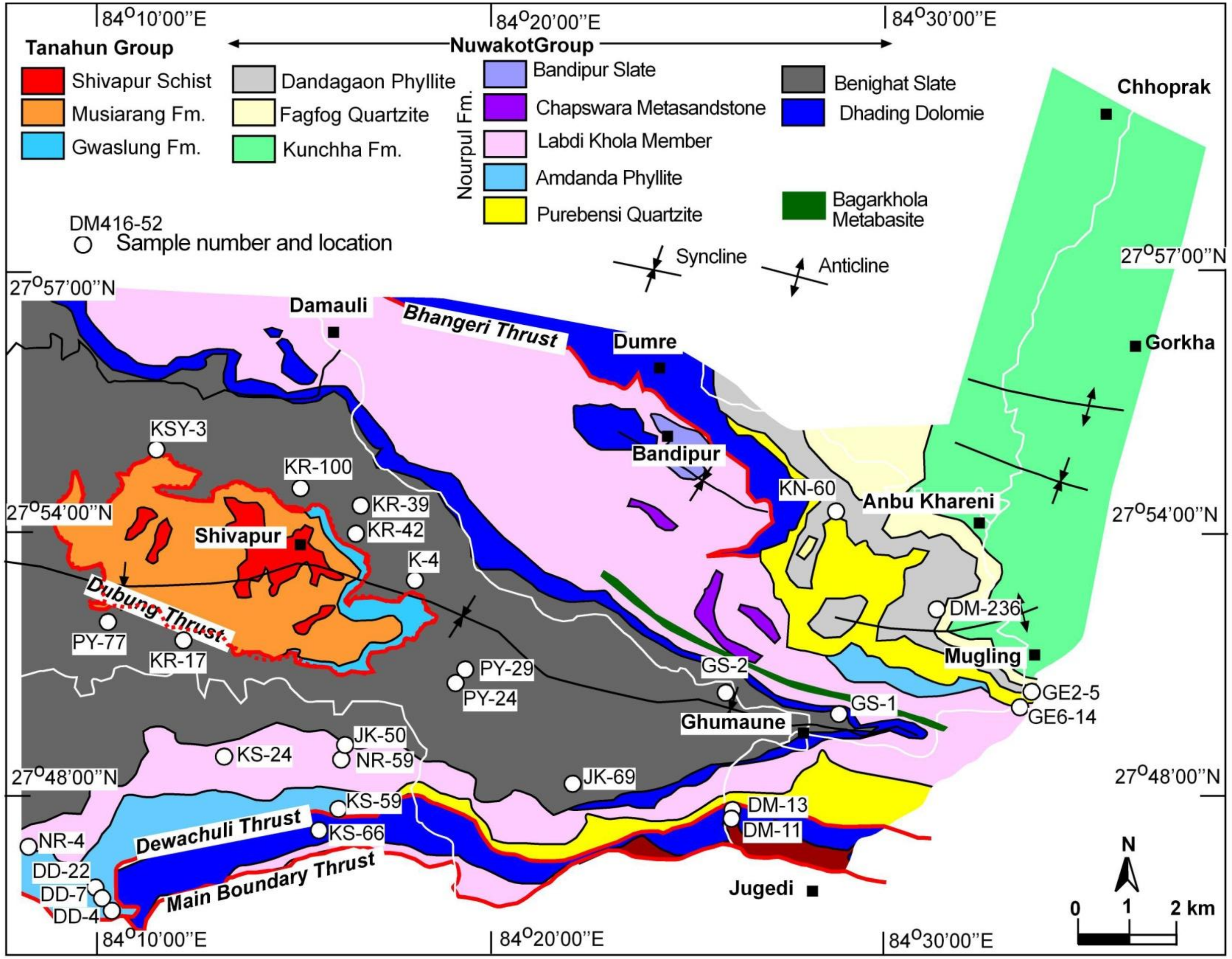


Fig. 5.6-1: Geological map of the study area showing the location of samples used graphite crystallinity measurements.

Table 5.6-1: Graphite crystallinity data from the Nuwakot Group, central Nepal Lesser Himalaya.

Benighat (Upper Part)	Sample No.	KR-42	K-4	KR-100	Py-24	KR-17		
	GC(Δ°2θ)	0.140	0.160	0.150	0.180	0.170		
	Sample No.	KE-39	PY-77	PY-29	KSY-3			
	GC(Δ°2θ)	0.170	0.172	0.179	0.141		0.162	0.014
Benighat (Lower Part)	Sample No.	GS-1	JK-69	GS-2				
	GC(Δ°2θ)	0.192	0.220	0.19			0.202	0.020
Dhading Dolomite	Sample No.	KS-66	DM-11	DM-13				
	GC(Δ°2θ)	0.208	0.220	0.210			0.213	0.008
Nourpul Formation	Sample No.	GE6-14	DD-7	DD-22	LS-59	NR-4		
	GC(Δ°2θ)	0.197	0.180	0.186	0.173	0.170		
	Sample No.	NR-59	KS-24	JK-50	DD-4			
	GC(Δ°2θ)	0.170	0.181	0.213	0.184		0.184	0.012
Dandagaon Phyllite	Sample No.	GE2-5	N-60	DM-236				
	GC(Δ°2θ)	0.179	0.177	0.180			0.179	0.001
Flake Graphite (Standard)	GC(Δ°2θ)	0.150						
Pencil Carbon (Standard)	GC(Δ°2θ)	0.180						

The metamorphic pattern is reversed in the upper part of the Benighat Slate due to the effect of the Thrust. This result is also comparable with the results obtained from the KI measurements (Table 5.6-1).

5.7 RAMAN SPECTROSCOPY OF CARBONACEOUS MATERIALS

Four carbonaceous slate and phyllite samples collected from the Benighat Slate were subjected to Raman Spectroscopic analysis at the laboratory of Nagoya University, Japan. Six spots were analyzed in each thin section for determining Raman Spectra. To avoid the influence that might be caused by polishing thin section, carbonaceous materials that were exposed were not measured in this study. Analytical setting in the present measurement was after Aoya et al. (2010) (Annex VIII). Peak position and band area (integrated area) were determined by using the PeakFit 4.12ver. (SeaSolves Software) after Aoya et al. (2010).

Location of the samples used for present RSCM measurement are given in Fig. 5.7-1. The Raman data are given in Annex IX. The result shows R^2 values of the spectra are similar in all samples and range from 0.61 to 0.69. Paleotemperature calculated from the data using the equation provided by Beyssac et al. (2002) range from 347 to 356 °C. These data are similar to that calculated from Illite Crystallinity (Table 5.5-2).

Table 5.7-1: Paleotemperature calculation from Raman Spectroscopy analysis of carbonaceous materials in the sample from the present study area.

S. No.	Spot no.	R^2	T(°C)	Avr. T(°C)	S.D.(°C)
GE-108	1	0.67417	341	350	7
	2	0.640401	356		
	3	0.637455	357		
	4	0.67155	342		
	5	0.656039	349		
	6	0.64892	352		
PY-93	1	0.632653	359	356	10
	2	0.66834	344		
	3	0.662346	346		
	4	0.641404	356		
	5	0.609909	370		
	6	0.621593	364		
GE-03	1	0.655287	349	356	20
	2	0.641597	355		
	3	0.559618	392		
	4	0.629556	361		
	5	0.684883	336		
	6	0.670213	343		
LD-10	1	0.614358	368	351	10
	2	0.643605	355		
	3	0.66862	343		
	4	0.663557	346		
	5	0.667346	344		
RS-41	1	0.606573	371	347	15
	2	0.688359	335		
	3	0.678213	339		
	4	0.681941	338		
	5	0.650955	351		

T(°C)==-445*R2+641

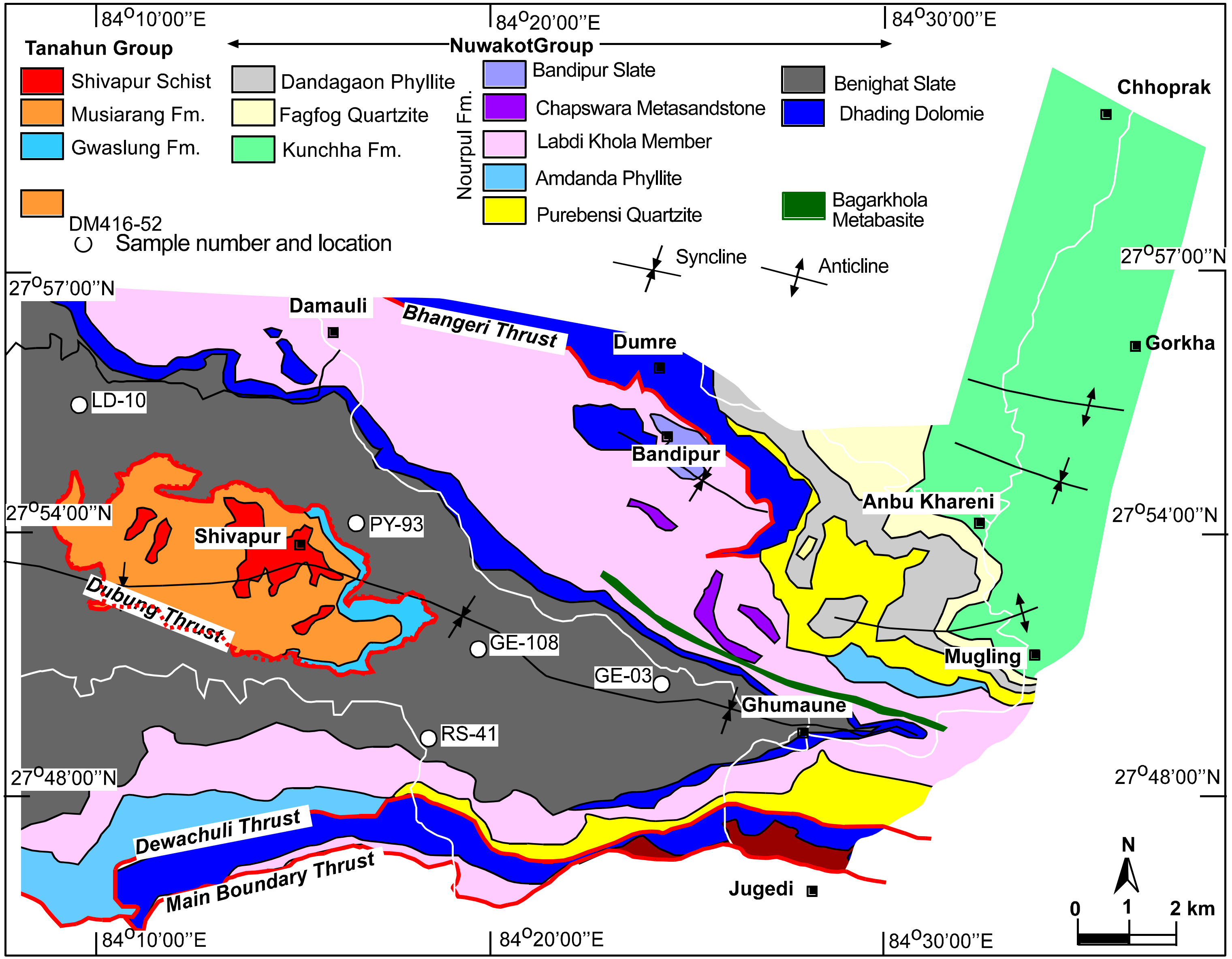


Fig. 5.7-1: Geological map of the study area showing the location of samples used for Raman Spectroscopy of Carbonaceous Materials.

CHAPTER SIX

DISCUSSIONS AND CONCLUSIONS

Present geological and petrological study in the Mugling-Damauli area has following important implications.

1. Modification of the stratigraphic classification of the Lesser Himalayan autochthon.
2. Use of magnetic susceptibility data as a supporting tool for lithostratigraphic comparison.
3. Lithostratigraphic comparison of the Kahun Klippe with adjacent Nappe and Klippe.
4. Possible root zone of the Kahun Klippe
5. Thin-skinned tectonics and deformation history of the Lesser Himalaya.
6. Metamorphic history of the Lesser Himalaya.
7. Geological and petrological evolution of the Lesser Himalaya

Discussions on each of these topics and conclusions of the study have been presented in the following sections.

6.1 MODIFIED LITHOSTRATIGRAPHIC CLASSIFICATION OF THE LESSER HIMALAYAN AUTOCHTHON

Lithostratigraphic classification of the Lesser Himalaya in central has been always a matter of discussion and different authors have presented different classification. Hagen (1969) was probably the first geologist to prepare regional scale map of central Nepal.

Nanda (1966) for the first time prepared detailed (1:253,400) field maping of the study area and attempted to make first lithostratigraphic classification of the area. He proposed the units Bhimphedis, Grits, Quartzites, Grey Phyllites, Purples, Grey Dolomites, Carbonaceous Shales, Tansens (Khakis), and Siwaliks.

Fuchs and Frank (1970) classified the Tansing Unit (south of the Phalebas Thrust) into Simla Slates, Chandpur Formation, Nagthat Formation, Blaini, Infra-Krol and Krol (and Shali). They used the formation names from their work in Indian Himalaya. Ohta et al. (1973) classified the stratigraphy of the Gorkh-Pokhara area as the Kunchha Sandstone-Phyllite Formation, Ginchaar Quartzite Formation, Bhat Khola Slate, Agridanda Limestone Formation, Sandstone-Slate-Phyllite Formation and Gadbhanjyang Limestone.

Stöcklin and Bhattarai (1977) and Stöcklin (1980) while studying the rocks of central Nepal in Kathmandu area, adopted the stratigraphic classification of Nanda with some modifications. They named the autochthonous units as the “Nawakot Complex” and divided it into the Lower Nawakot Group and Upper Nawakot Group separated by disconformity. They were the first to adopt the recommendations of the International Stratigraphic Guide (Hedberg et al. 1978). This classification is the most adapted classification for central Nepal Lesser Himalaya to the date. In their classification, the Lower Nawakot Group consists of the Kunchha Formation, Fagfog Quartzite, Dandagaon Phyllite, Nourpul Formation and Dhading Dolomite. The Upper Nawakot Group consists of the Benighat Slate, Malekhu Limestone and Robang Formation. Stöcklin and Bhattarai (1977) while mapping the Labdi-Anbu Khaireni area introduced several members such as Anpu Quartzite, Labdi Phyllite and Banspani Quartzite in the Kunchha Formation and Purbensi Quartzite in the Nourpul Formation. The Anpu Quartzite has been regarded as the oldest rock of the Kunchha Formation.

Following works in the same area by the Department of Mines and Geology

(Shrestha et al. 1987) adopted entirely different classification from that of Stöcklin and Bhattarai (1977). As a result they produced quite different geological for the area. Department of Mines and Geology in the later works (Jnawali and Tuladhar 1996) adopted the stratigraphic classification of Stöcklin and Bhattarai (1977) and Stöcklin (1980). They tried to differentiate the Nourpul Formation into three members. The later map does not match with the earlier map. Upreti (1996) proposed that the name Nawakot Unit should be used instead of Nawakot Complex. He divides the Nawakot Unit into the Lower Nawakot Unit containing non-calcareus rocks and Upper Nawakot Unit containing calcareous rocks. The boundary is placed at the base of the Nourpul Formation. Sah (1999) highlighted the existing problems on stratigraphic nomenclature and classification of the Lesser Himalayan autochthon. He stressed that the term "Midland" should be used instead of "Nawakot".

Present detailed work in the Mugling-Damauli area warrants for further modification of the stratigraphic classification of the of the Lesser Himalayan autochthonous unit. Stöcklin and Bhattarai (1977, p. 8) realized the need of future modification of their classification and noted "*many of the units are not defined with the desirable precision and may require modifications or redefinition with future, more detailed work*". The following new observations in the autochthonous unit of the Mugling-Damauli area are very important in this context.

1. The Kunchha Formation also contains calcareous beds. Therefore the division of the autochthonous unit into calcareous and non-calcareous as proposed by Upreti (1996) is not possible.
2. The Anpu Quartzite laterally joins with the Fagfog Quartzite. Therefore, the units are the same.

3. The Banspani Quartzite laterally joins with Purebensi Quartzite. Therefore, the units are the same.

4. The Labdi Phyllite member of the Kuncha Formation laterally joins with the Dandagaon Phyllite. Therefore, the units are the same.

5. The Nourpul Formation shows great lateral and vertical variation in lithology and thickness. It is composed of quartzite, metasandstone, various types of phyllite and slates, pink dolomite and frequent intercalations of hematite and amphibolite layers. The thickness of lithotype changes laterally within a short distance. Therefore, one type of lithology thick enough to be mapped as a member in one section pinches out laterally and another lithology appears as a mappable member in other places. For example in the study area, the Amdanda Phyllite member is very thick in the Amdanda area, but it pinches out to the west in Labdi Khola. Similarly, the Bandipur Slate is distributed only in the Bandipur area. Metasandstone bands are mappable only in the Chapswara area. Purebensi Qurartzite is mappable only in the eastern part of the study area. Variable lithology of the Nourpul Formation has created confusion in mapping in central Nepal. This is one of the reasons for variations in stratigraphic classifications, geological maps and structural interpretations in central Nepal among different authors.

6. The contact between the Dhading Dolomite and the Benighat Slate is found to be transitional in some places and sharp in other places. There is no evidence of erosional boundary as mentioned by Stöcklin and Bhattarai (1977). The boundary has been reported as a transional contact in the Sayangja area (Dhital et al. 2002) and Malekhu area (Rai 2011) of central Nepal. Therefore, division

of the autochthonous rock sequence into the Lower and Upper Nawaot Groups based on the presence of unconformity is not justified.

Based on the above observations, a revised stratigraphic classification has been proposed for the Nuwakot Group in central Nepal and recommend for adaptation of new stratigraphic classification scheme as given in Fig. 5.1-2.

6.2 MAGNETIC SUSCEPTIBILITY AS A SUPPORTING TOOL FOR STRATIGRAPHIC COMPARISON

Magnetic susceptibility (MS) has been widely used in mineral, and oil exploration (Petrovsky and Elwood 1999). Magnetic-susceptibility methods have been recently used in stratigraphic correlation and geological mapping (Crick et al. 1997; Crick et al. 2001; Ellwood et al. 1999; Ellwood et al. 2000; Wahlen and Day 2008; Hrouda et al. 2009). Previous works demonstrate that the MS signature of sediments varies with the proportion of detrital-dominated paramagnetic and ferrimagnetic minerals present, and thus each stratigraphic unit expresses unique MS pattern. Although some studies demonstrate that the MS signature may be altered during diagenesis (Katz et al. 1998), primary signature is not destroyed by diagenesis processes.

As discussed in the previous chapters (Chapters 3 and 5.1), published literature reveals that mapping in the Nepal Lesser Himalaya is not unequivocal in terms of assignment of rocks with similar lithologies to the various formations, often with different names, and hence the correlation of the proposed lithostratigraphic schemes with those in adjacent areas is not unique. Therefore, it is quite possible that MS method may be used in the Nepal Lesser Himalaya to identify the lithologic units and correlate them with the adjacent regions. Gautam et al. (2011) for the first time measured MS of the Nuwakot

Group rocks along different sections of central Nepal and highlighted its applicability in stratigraphic comparison. They stressed that MS has high potential for discrimination of lithological units.

Present MS studies in central Nepal demonstrate that each stratigraphic unit of the Nuwakot Group has its own MS pattern and range of MS values (Fig. 5.2-2). The MS values decreases from Kunchha Formation to the lower part of the Nourpul Formation in all the measured sections. The Nourpul Formation shows anomalously higher values of MS compared to that in other formations. The MS value again decreases up section in the Dhading Dolomite and Benighat Slate. This pattern is uniform in all sections of the present study area as well as in the type locality of the Nuwakot Group (i.e., Malekhu section). Therefore we believe that if MS is measured systematically across a geological section, the MS profile can be used to identify the possible stratigraphic unit by comparing the profile with its type locality.

6.3 LITHOSTRATIGRAPHIC COMPARISON OF THE TANAHUN GROUP

There is great variation in the tectonics of the Lesser Himalayan Zone of Nepal from east to west. In eastern Nepal, the tectonics is characterized by the development of an extensive crystalline thrust sheet that has travelled southward for at least 100 km to reach close to the outcrop of the Main Boundary Thrust (MBT) (Schelling and Arita 1991). Almost the entire Lesser Himalayan Zone in eastern area of Nepal Himalaya is occupied by this single thrust sheet. Lesser Himalayan autochthonous sediments are exposed only in a few tectonic windows. However, in central and western Nepal there are several crystalline thrust sheets occupying the cores of major synclines (Fig. 6.3-1). Some of the well-known crystalline nappes and klippe in the Lesser Himalaya of Nepal are the Kathmandu Nappe, Jajarkot Klippe, Karnali Nappe and the Dadeldhura Nappe from central to western Nepal (Upreti 1999).

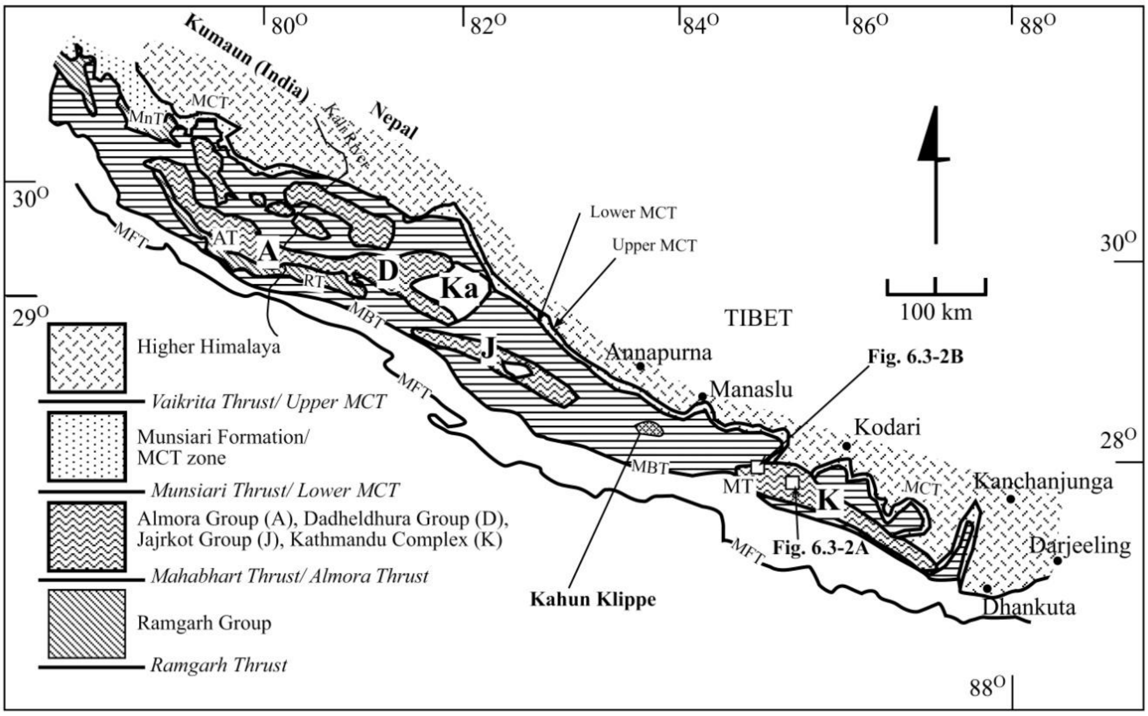


Fig. 6.3-1. Geological map of the central–east Himalaya to show the MCT and Lesser Himalayan crystalline nappes showing the location of the Kahun Klippe. A: Almora Klippe; MnT: Munsiari Thrust; AT: Almora Thrust; MT: Mahabharat Thrust; D: Dadeldhura Klippe; J: Jajarkot Klippe; K: Kathmandu Nappe; Ka: Karnali Nappe; LH: Lesser Himalaya; MBT: Main Boundary Thrust; MCT: Main Central Thrust; MT: Munsiari Thrust; MFT: Main Frontal Thrust; RT: Ramgarh Thrust. Redrawn and modified from (Johnson 2001).

The Lesser Himalayan crystalline napes can be divided into two broad types based on different stratigraphy and metamorphic grade (Upreti 1999): (1) Nappes composed of upper amphibolite to granulite facies rocks and (2) Nappes composed of low- to medium-grade metamorphic rocks with Paleozoic sedimentary cover. The Karnali Klippe with kyanite-sillimanite bearing units (Hayashi et. al. 1984) belongs to the first category. The Kathmandu Nappe, Jajarkot Klippe and Dadeldhura Nappe are composed of low- to medium-grade rocks of the Bhimphedi Group with Paleozoic sedimentary cover of the

Phulchoki Group (Stöcklin 1980; Upreti 1999). The Kahun Klipee belongs to the second category.

6.3.1 Lithostratigraphic comparison with the Kathmandu Nappe

The rocks of the Kathmandu Nappe are lithostratigraphically classified into the Precambrian Bhimphedi Group at the base and Early Paleozoic Phulchoki Group at the top separated by an unconformity (Stöcklin 1980). The Bhimphedi Group is made up of the Raduwa Formation at the base followed successively upwards by the Bhainsedovan Marble, Kalitar Formation, Chisapani Quartzite, Kulikhani Formation, Markhu Formation and Tistung Formation. The Phulchoki Group is made up of the Sopyang Formation at the base followed by the Chandragiri Limestone, Chitlang Formation and Godavari Limestone. In the geological map published by the DMG (Shrestha et al. 1987), the units of the Kahun Klippe have been mapped as the Markhu and Tistung Formations of the uppermost part of the Bhimphedi Group (Fig. 1.5).

A detailed columnar section of the Tistung and part of Markhu Formations of the Bhimphedi Group was prepared at its type locality in central Nepal for the purpose of comparison (Fig. 6.3-2a, see Fig. 6.3-1 for location). It was found that the lithological succession of the Tistung formation is quite different than the lithological units of the Klippe and are not mutually comparable. The Tistung Formation consists of an alternating sequence of metasandstone, mica schist, phyllite and dolomite. It contains abundant trace fossils such as worm trails and bioturbations. Metasandstone is dominant over other lithologies. However, the rocks of the Kahun Klippe consists of dolomitic marble, completely recrystallized and deformed calcareous quartzites and garnetiferous schist.

Another possibility is that the marbles of the Gwaslung Formation is equivalent to the Bhainsedovan Marble of the Bhimphedi Group. In such case, the overlying Musimarang Formation and Shivapur Schists should be equivalent to the Kalitar Formation. However, the the lithology of the Kalitar Formation is not comparable with that of the Musimarang Formation and Shivapur Schists. The Kalitar Formaiton is composed of alternation of psammitic schists, metasandstones, quartzites, dolomites and frequent layers of metaconglomerates. On the other hand the Musimarang Formation is composed of pelitic schist and laminated quartzite and the Shivapur Schist is entirely pelitic garnetiferous schist. Carbonate layers are absent in those formations.

Jnawali and Tuladhar (1996; 1999) (Fig. 1.6) mapped the garnetiferous schists of the Kahun Klippe as the Raduwa Formation. Present observation also shows that the two formations are quite similar in lithology. Both of them comprise monotonous succession of pelitic garnetifeours shcists. Therefore, the Shivapur Schist has been compared with the Raduwa Formation (Fig. 6.3-2). It implies that the Musimarang and the Gwaslung Formations should be units older than the Raduwa Formation. They are missing in the Kathmandu Nappe possibly because the Mahabharat Thrust cut through shallower level in this area.

6.3.2 Lithostratigraphic comparison with the Jajarkot Klippe

The rock succession of the Jajarkot Klippe has been divided into three formations *viz.* (1) Chaurijhari Formation, (2) Thabang Formation and (3) Jaljala Formation from bottom to the top, respectively. Chaurijhari Formation is mainly a schistose sequence consisting of grey to light greenish-grey, muscovite-biotite schist and garnetiferous mica schist with minor intercalations of dark and light colored quartzite (Frank and Fuchs 1970). The Thabang Formation is gradationally overlying Chaurijhari Formation. This is

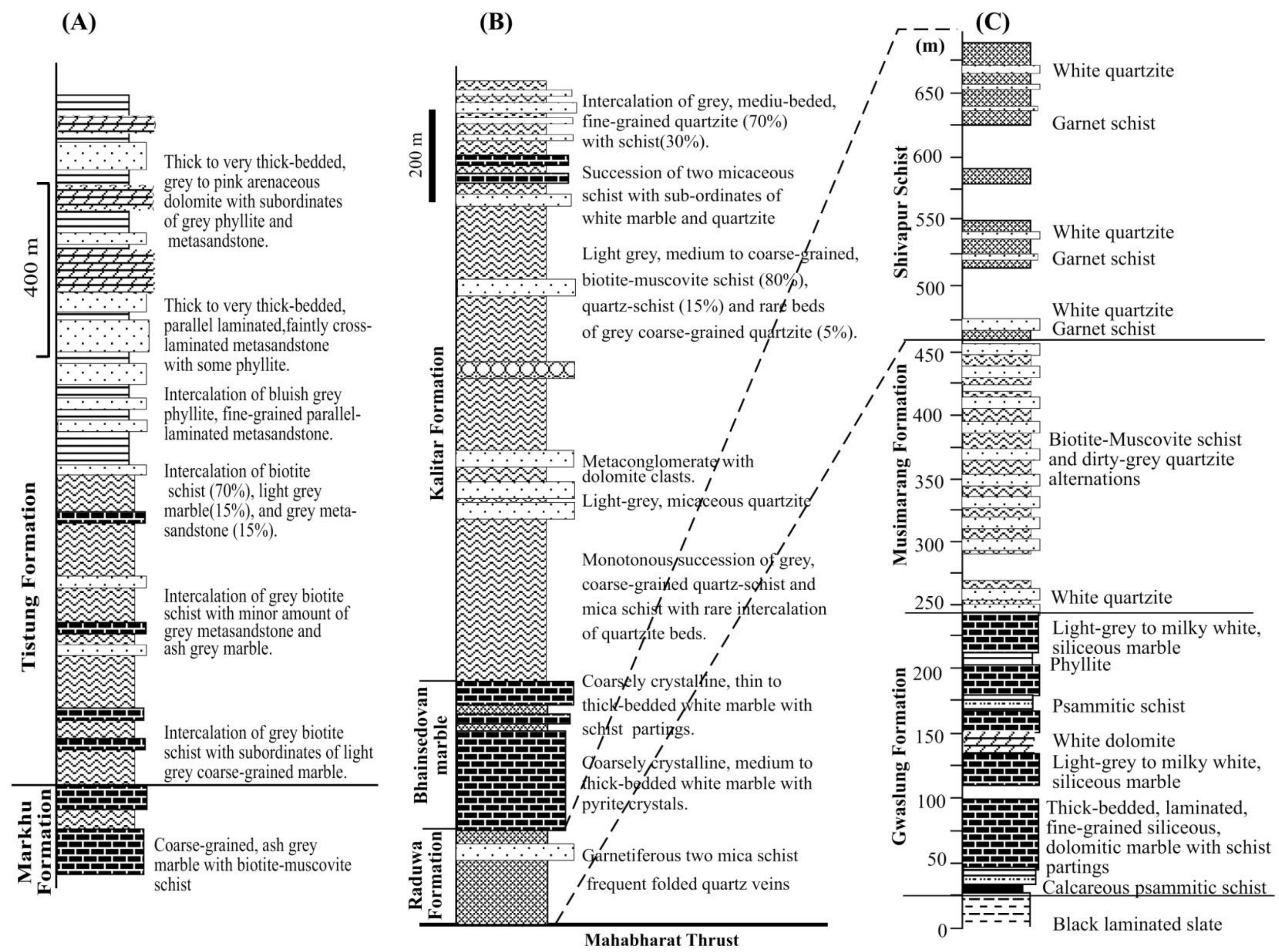


Fig. 6.3-2. (A) Lithostratigraphic column of the Tistung Formation (Bhimphedi Group) along the Kalanki-Dakshinkali road near Kulekhani reservoir, south of Kathmandu. (B) Lithostratigraphic column of the Raduwa Formation, Bhaisedovan Marble and Kalitar schist (Bhimphedi Group) along the Malekhu Khola, west of Kathmandu. (C) Lithostratigraphy of the rocks of the Kahun Klippe exposed at Gwaslung (Present study area).

predominantly coarse-grained crystalline impure marble interbanded with mica schists. The Jaljala Formation overlies the Thabang Formation with an unconformity in between. This youngest formation of the nappe consists of fine- to medium-grained calcareous sandstone and siltstone with some intercalation of gray phyllites. Crinoids have been reported in limestone towards the top of the Formation. Lithological description of the Jajarkot Klippe shows that the Shivapur Schist can be compared with the Chaurjhari Formation.

Structural setting and lithostratigraphic comparison of the Kahun Klippe with that of the Kathmandu Nappe (Fig. 6.3-3) shows that the Kahun Klippe is most probably the westward extension of the Kathmandu Nappe and the basal thrust (Dubung Thrust) of the Kahun Klippe and Mahabharat Thrust are equivalent. Absence of rock units older than the Raduwa Formation (i.e., the Gwaslung and Musimarang Formations of the Kahun Klippe) in the Kathmandu Nappe indicates that the Mahabharat Thrust cuts-off at shallower level in central Nepal. Similar is the case in the Jajarkot Klippe.

Kathmandu Nappe	**Kahun Klippe**	**Jajarkot Klippe**
		Jaljala Fm.
Bhainsedovan Marble		Thabang Fm.
Raduwa Rm.	Shivapur Schsit	Chaurijhari Fm.
	Musimarang Fm.	
	Gwaslung Fm.	

Fig. 6.3-3. Lithostratigraphic comparison of the rock units of Kahun Klippe with those of the Kathmandu Nappe and Jajarkot Klippe.

6.4 ROOT ZONE OF THE KAHUN KLIPPE

The root zone of the crystalline nappe and klippe of the Lesser Himalaya is controversial and different authors have different views on it. Stöcklin (1980) and Johnson et al. (2001) regard them as a part of the Main Central Thrust sheet and believe on "one thrust model". On the other hand, Rai et al. (1998), Upreti (1999) and Upreti and Le Fort (1999) consider that it is a part of a major thrust sheet which occurs below the MCT and believe on two thrusts model.

The nappes consisting of high-grade rocks (Karnali Nappe) are quite similar to the Higher Himalayan rocks. The rock units of this nappe consist of kyanite-sillimanite bearing gneisses, calc-silicate gneiss, migmatitic gneiss and augen gneiss which are similar to the rock units in the Higher Himalaya. Therefore, it is believed that the Karnali Nappe roots to the Higher Himalaya. The Higher Himalayan rocks were transported on to the Lesser Himalaya along the Mai Central Thrust.

However, main controversy lies in the origin of the nappes and klippe with low-grade metamorphic rocks (Bhimphedi Group) with Early Paleozoic cover (Phulchoki Group). The Kathmandu Nappe, Jajarkot Klippe, Dadheldhura Nappe and the Kahun Klippe (presently mapped) belong to this category. The Bhimphedi Group consists of a mixed lithology of marble, schist, phyllite and quartzite with metamorphic grade reaching up to garnet zone. It reaches up to kyanite zone locally only in some places. The boundary with the low-grade metasediments of the Nawakot Complex is sharp and distinct. The Paleozoic cover comprises slates, phyllites and limestones with some fossiliferous beds (Fuchs and Frank 1970; Stöcklin 1980; Sharma et al. 1984; Shrestha et al. 1993; Upreti 1999). The carbonate rocks of the Jajarkot Klippe consist of crinoids and have been correlated with the Chandragiri Limestone of the Phulchoki Group (Fuchs and Frank 1970). The similarity of the rocks of the Kathmandu Nappe, Kahun Klippe, Jajarkot Nappe and Dadheldhura Nappe indicates that they are the same thrust sheets which were disconnected into isolated sheets by erosion. Now the problem lies on where is the root of the thrust sheets?

Shear sense indicators such as z-shaped drag folds (Fig. 5.3-3), asymmetric pressure shadows (Fig. 5.4-2; 5.4-28) and s-shaped inclusions in garnet (Fig. 5.4-28) show that the thrust sheets were transported to the south from the north. Therefore, the root should be somewhere in the north. Looking at the metamorphic grade of the crystalline rocks and the Paleozoic sedimentary cover on it, the MCT zone or Higher Himalayan rocks may be imagined as the likely candidate for the root. However, the lithology and stratigraphic sequence of the crystalline nappes (Kathmandu Complex) cannot be easily compared with that of the MCT zone and the Higher Himalaya as explained by Upreti and Le Fort (1999). It has been discussed in the following sections.

6.4.1 Comparison with the MCT zone

The rocks with similar metamorphic grade to the Bhimphedi Group are found in the MCT zone. The MCT zone rocks, bounded by the Upper MCT in the north and the Lower MCT in the south are named as the Munsiari Formation in India (Fig. 6.3-1). The MCT zone in central Nepal along the Seti River and Modi Khola section consists of garnet schist, quartzite and augen gneiss at the lower part and carbonaceous schists, calc-schists, and calcareous quartzite in the upper part (Paudel and Arita 2000). Amphibolites are found at different levels. Based on the similarity of the rock, some authors interpret the root of the crystalline nappes and klippe as the MCT zone or Munsiari Formation (In India:

Valdiya 1980; Srivastava and Mitra 1994; in Nepal: Fuchs and Frank 1970; Arita et al. 1984).

The lithostratigraphy of the MCT zone rocks along the Modi Khola valley (Le Fort 1975), NW of present study is shown in the Fig. 6.4-1. If we compare the lithology with that of the Kahun Klippe and Bhimphedi Group, there are more dissimilarities than similarities. They have been indicated as follows as already discussed by Upreti and Le Fort (1999).

1. The Bhimphedi Group consists of crystalline marbles at different levels (Bhaisedovan Marble, Bhimsen Dolomite, Markhu Formation etc.). However, the MCT zone rocks do not contain marbles. Only calcareous quartzites are present in the MCT zone.
2. The metamorphism is normal in the Bhimphedi Group, whereas it is inverted in the MCT zone.
3. There are no metabasic rocks in the Bhimphedi Group. On the other hand there are several layers of amphibolites at different levels in the MCT zone.
4. Carbonaceous schists are absent in the Bhimphedi Group. Very thick carbonaceous schist is found in the MCT zone.

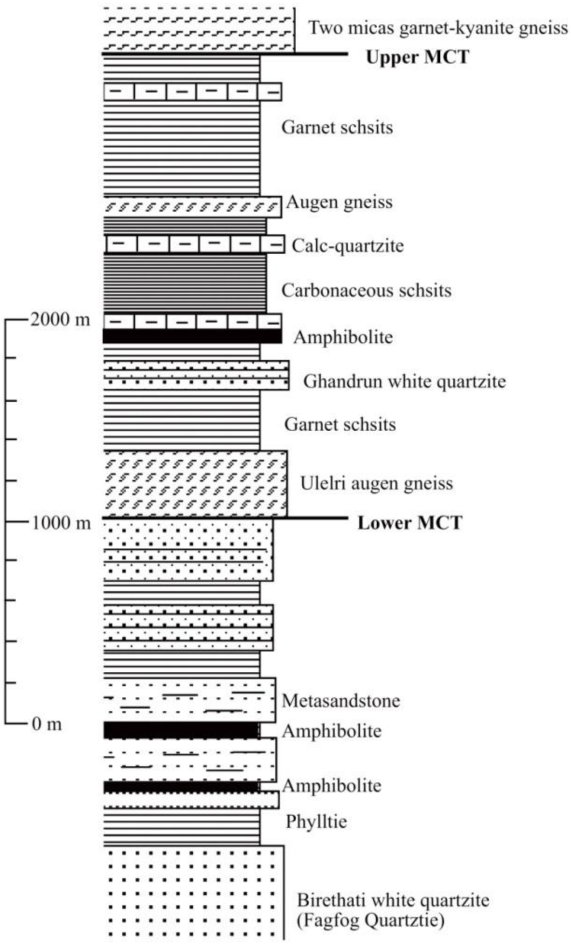


Fig. 6.4-1. Lithostratigrapy of the MCT zone along the Modi Khola valley (modified after Le Fort 1975).

5. The Bhimphedi Group is intruded by porphyritic, weakly or non-deformed, Paleozoic granites. The MCT zone contains no granites.

The lithology of the MCT zone resembles more to the Nawakot Complex than the Bhimphedi Group. MCT zone rocks should be sheared and recrystallized equivalent of the Nawakot Complex rocks as suggested by Paudel and Arita (2000).

6.4.2 Comparison with the Higher Himalaya

The lithostratigraphy of the Higher Himalaya along the Kali Gandaki valley is given in the Fig. 6.4-2. It is very hard to correlate the Bhimphedi Group rocks with that of the Higher Himalayan rocks because of the following points, some of which were already noted by Upreti and Le Fort (1999).

1. The Higher Himalayan rocks are of amphibolites-granulite facies reaching up to sillimanite grade of metamorphism. The Bhimphedi Group mostly at garnet or lower grade.

2. The lithology of the Higher Himalaya is banded kyanite-garnet gneiss at the base (Formation I), followed by a very thick sequence of banded pyroxene-amphibole-garnet calc-gneisses (Formation II) and granitic augen gneisses at the top (Formation III). This lithology is absent in the Bhimphedi Group.

3. Higher Himalayan rocks are intruded by Miocene leucogranites, which is not the case in the Bhimphedi Group.

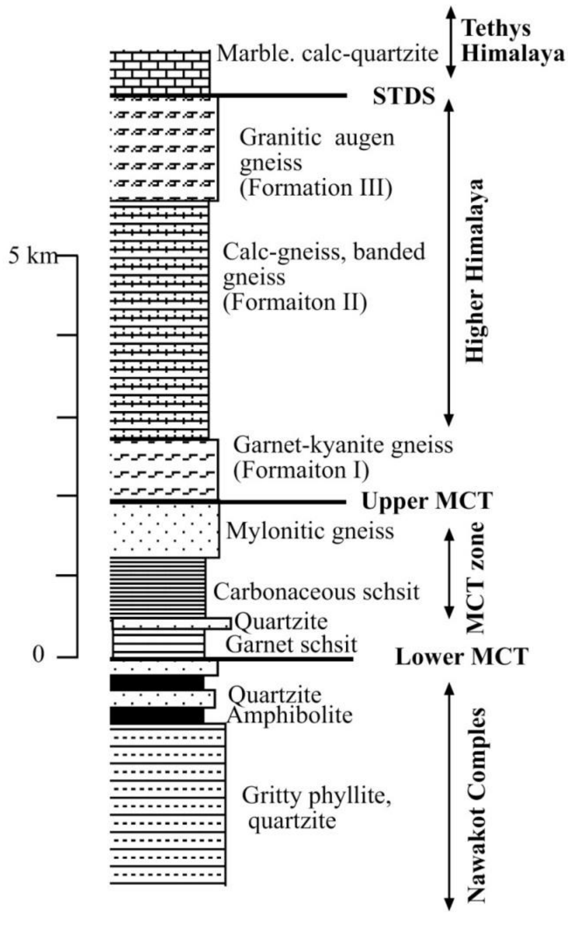


Fig. 6.4-2. Lithostratigrapy of the MCT zone and Higher Himalaya along the Kali Gandaki valley (modified after Upreti and Yoshida 2005).

6.4.3 Possible origin of the Lesser Himalayan crystalline thrust sheets: A conceptual model

There are three explanations proposed for the origin of Lesser Himalayan crystalline thrust sheets.

1. They are the thrust sheets of the Higher Himalaya transported by the MCT (Heim and Gansser 1939; Hagen 1969; Le Fort 1975; Stöcklin, 1980).
2. They are the thrust sheets of the MCT zone carried out by the Lower MCT (or Munsiari Thrust) India: (Valdiya 1980 and Srivastava and Mitra 1994; Fuchs and Frank 1970 and Arita et al. 1984).
3. They are the exotic thrust sheets with lost roots transported by the Mahabharat Thrust (Uptreti and Le Fort 1999). The MT is a branch-off of the MCT. Upreti and Le Fort (1999) interpret the contact between the higher grade Sheopuri Gneiss and the lower grade Bhimphedi Group as the MCT and suggest that the Sheopuri Gneiss override the Kathmandu Complex along the MCT (see Fig. 9b of Upreti 1999). They divided the thrust sheet into two different nappes: the Gosaikund Nappe with Higher Himalayan rocks and the Kathmandu Nappe with the Kathmandu Complex.

The discussions in the previous sections rules out the possibility of correlating the Bhimphedi Group and rocks of the Kahun Klippe with that of the MCT zone and Higher Himalaya. Detailed geological mapping along the Kathmandu-Trishuli road by Silwal and Paudel (2011) shows that the Shivapuri Gneiss clearly underlies the Bhimphedi Group (Fig. 6.4-3). Similar observation is made by Johnson et al. (2001). Therefore, it is very hard to justify that the MT is a sub-MCT thrust branching-off from the MCT.

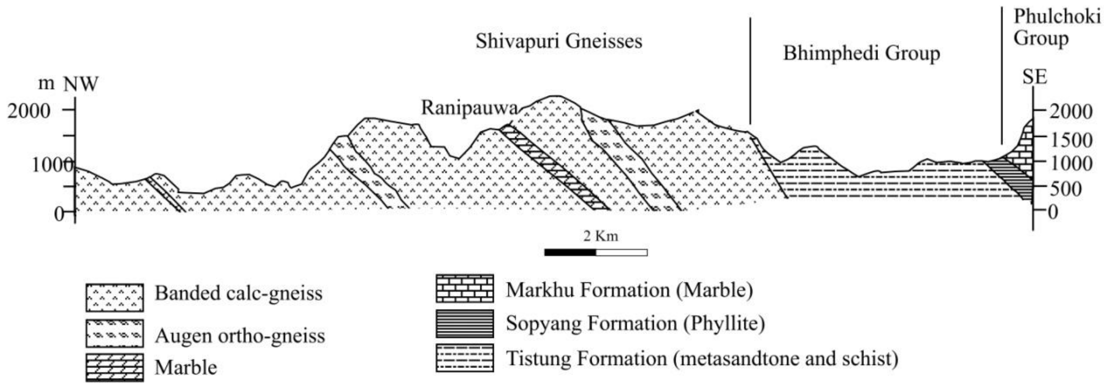


Fig. 6.4-3. Geological cross-section along the Kathmandu-Trishuli road (modified after Silwal and Paudel 2011). Note the Shivapuri Gneisses underlie the Bhimphedi Group.

Here, an attempt is made to explain the origin of the thrust sheets with a single thrust sheet model (Fig. 6.4-4). The model assumes that the Tanahun Group (~Bhinphedi Group) is a sequence stratigraphically lying between the Higher Himalayan crystalline and the Lesser Himalayan autochthonous sequence (Nuwakot Group) (Fig. 6.4-4A). The Tanahun and the Nuwakot Groups were deposited on the Higher Himalayan basement in the northern margin of the Indian Continent in the Paleo-Tethys sea.

Both the sequences were afftectd by a normal metamorphism (grade decreasing up section) before the initiation of the MCT. The timing of metamorphism may be in the Eocene (Eohimlayan) or in the early Paleozoic (Pre-Himalayan) (See discussion in §6.6). The metamorphic grade in the Tanahun Group was intermediate between the Nawakot Complex (chlorite zone) and Higher Himalaya (Kyanite/Sillimanite zone). The MCT transported the Higher Himalaya, a wedge of the Tanahun Group and the Tethys Himalaya over the Nuwakot Group (Fig. 6.4-4b). Inverted metamorphism (Neohimalayan metamorphism) occurred at the MCT zone synchronous to the MCT activity (Le Fort 1975; Arita 1983). The Kathmandu Nappe, Kahun Klippe, Jajarkot Nappe, Dadheldhura Nappe and the Karnali Klippe are the results of different patterns of erosion of the same thrust sheet as shown in the Figs. 6.4-4 c, d, e and f.

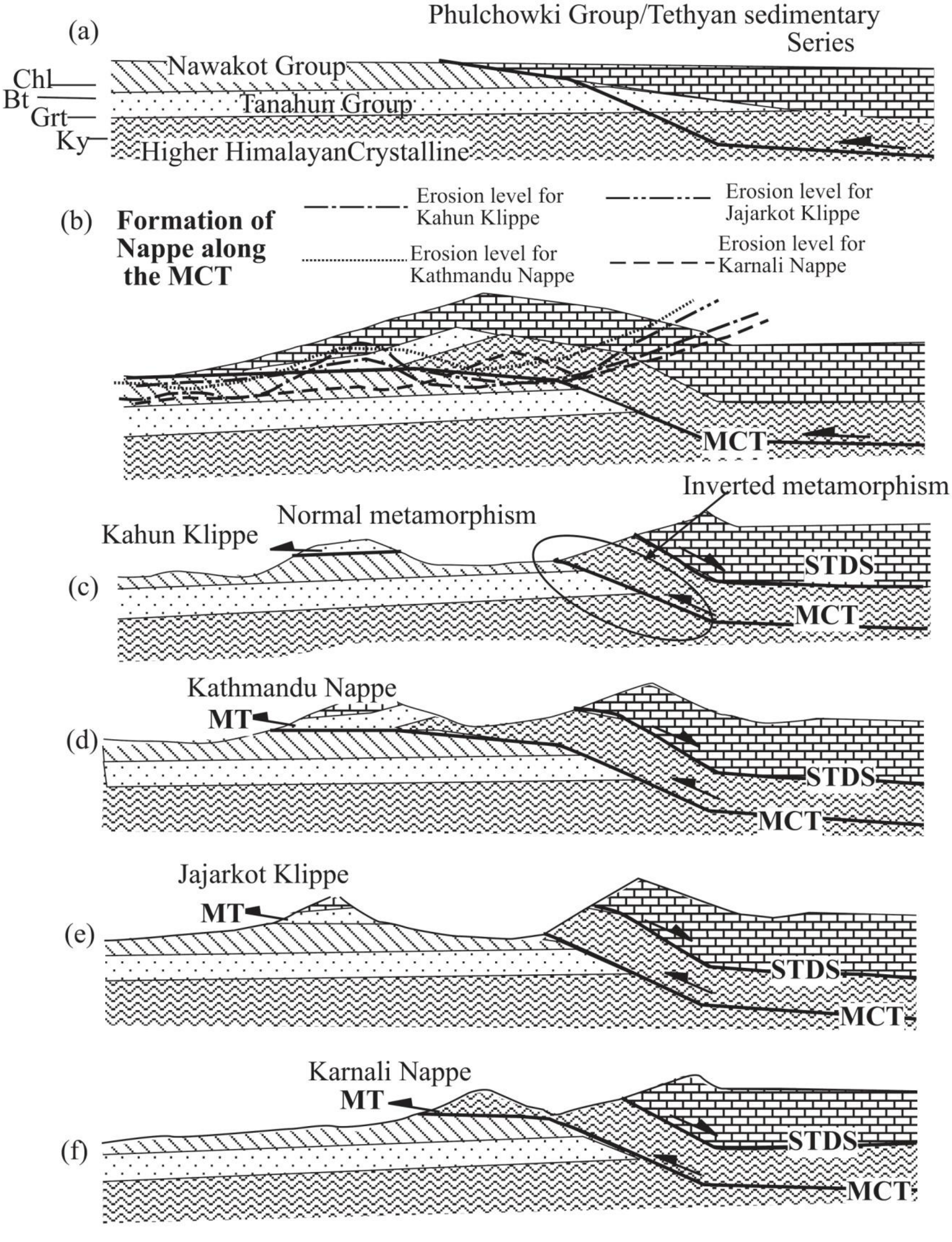


Fig. 6.4-4. A conceptual model (without scale) to show the origin of crystalline nappes in the Lesser Himalaya. A. Stratigraphic set-up of the Higher Himalaya, Bhimphedi Group, Lesser Himalayan sequence (Nawakot Complex) and the Tethys Himalayan sequence. Before the initiation of the MCT, a normal metamorphism occurred due to the thickening of the crust. B. The Higher Himalaya, a wedge of the Bhimphedi Group and the Tethyan sediments were transported on to the Nawakot Complex by the MCT. C-D. Erosion of the thrust sheet gave a present architecture of the crystalline nappes and klippe.

6.4.4 Significance of the Kahun Klippe in relation to the Himalayan tectonics

The central Himalayan fold-and-thrust belt has been long been interpreted as a foreland propagating duplex structure bounded by the MCT roof thrust and the MBT floor thrust (Schelling and Arita 1991; Srivastava and Mitra 1994; DeCelles et al. 1998; Paudel and Arita 2000; DeCelles et al. 2001). The crystalline thrust sheets believed to be the roof thrust of the Lesser Himalayan duplex are distributed all along the cental Himalaya from Sikkim-Bhutan to Kumaun. However, the area between Kathmandu and Jajarkot in the Himalaya is mostly occupied by low-grade metasedimentary rocks of the Nawakot Lesser Complex and a significant thrust sheets are lacking in the area. The Kahun Klippe was poorly explored until now. Present detailed investigation of the klippe and its correlation with the rocks of the Bhimphedi Group rocks supports that the Kathmandu Nappe, Kahun Klippe and the Jajarkot Nappes are a part of continuous thrust sheet and their basal thrust (MT) is the southward extension of the MCT. It furhter supports the view that the Higher Himalayan thrust sheet was extended all over the Lesser Himalaya and acted as the roof thurst of the Lesser Himalayan duplex. The foliation in the Kahun Klippe and the Lesser Himalayan autochthon are parallel everywhere and both are deformed together to form large scale synclinorium. It shows that the MCT roof thrust was initially horizontal and later folded along with the underlying autochthon in the process of propagation of horses.

6.5 THIN-SKINNED TECTONICS AND DEFORMATION HISTORY

6.5.1 Thin-skinned tectonics

Geological structures and tectonic processes associated with the shortening and thickening of the crust or lithosphere is known as the thrust tectonics. Deformation and shortening of crust in the contractional regimes are mainly of two types; thin-skinned and thick-skinned (Hatcher 2007). Thin-skinned deformation refers to shortening that only involves the sedimentary cover. This style is typical of many fold-and-thrust belts developed in the foreland of a collisional zone. The most commonly seen effect of thin-skinned tectonics is the superposition of older rocks on top of younger rocks, just the opposite from what is expected. The usual explanation is that the layers of older rocks were thrust parallel to the bedding planes over the top of the layers of younger rock, sometimes for hundreds of miles. The fold-and-thrust zone that lie along the margins of many orogenic belts constitute one of the most widely recognized and best understood deformation features of the Earth (McClay and Price 1981).

The Lesser Himalaya exhibits thin-skinned style of deformation and has been interpreted as a fold-and-thrust zone forming a foreland-propagating duplex structure (Schelling and Arita, 1991; Srivastava and Mitra 1994; Decelles et al. 1998; Paudel and Arita 2000). The present study area also is a part of the Lesser Himalayan duplex (Fig. 6.5-1). The Dubung Thrust (basal thrust of the Kahun Klippe) is the roof thrust. Most probably it is a southward extension of the Main Central Thrust (MCT) (see discussion in §6.5). The foliations in the Kahun Klippe and the Nuwakot Group are parallel everywhere, and both are deformed together to form the Jalbire-RamjakotSynclinorium. It shows that

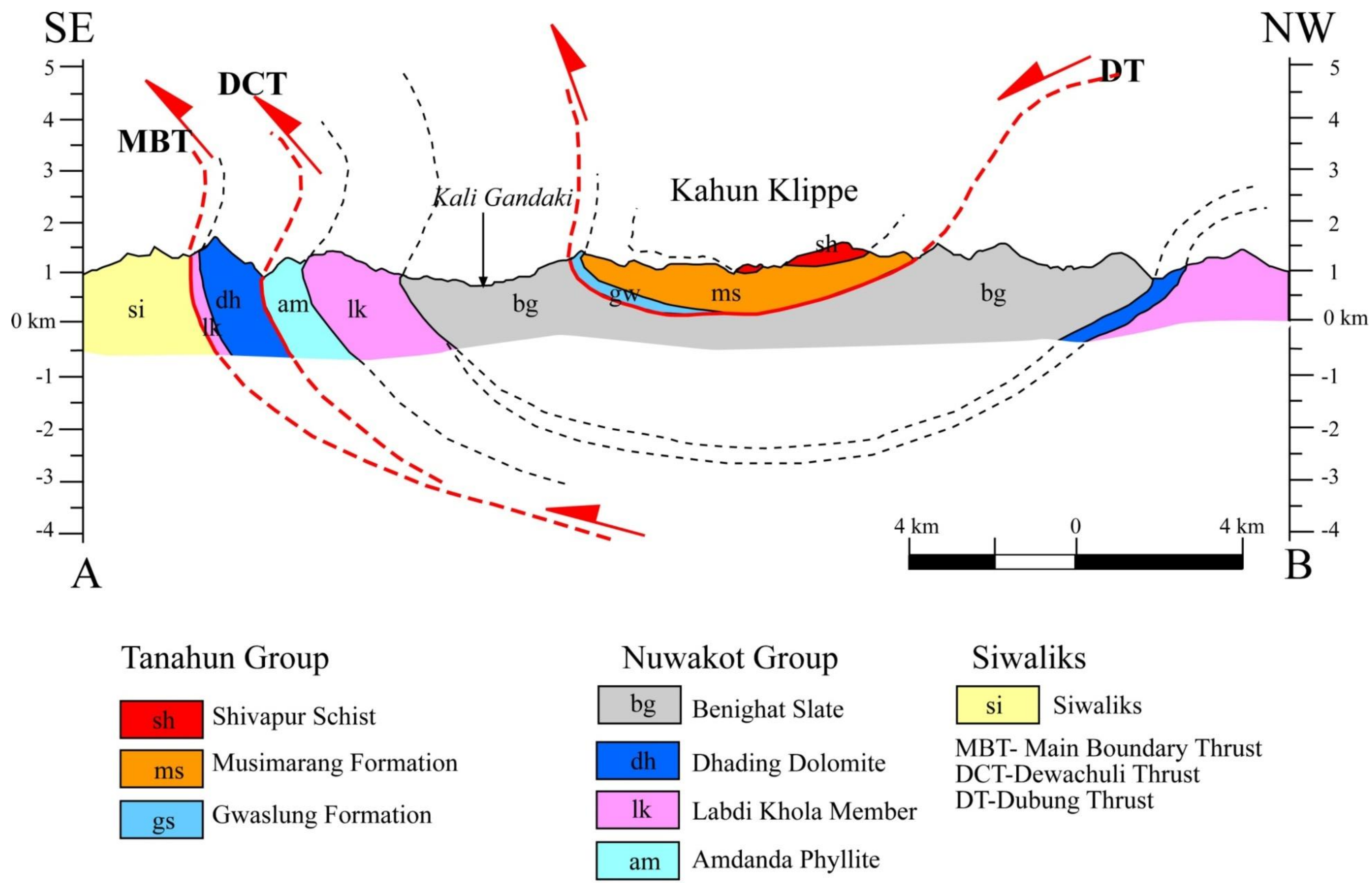


Fig. 6.5-1. Thin-skinned tectonic interpretation of the Mugling-Damauli area, cental Nepal.

the Dubung Thrust was initially horizontal and later folded along with the underlying autochthon in the process of propagation of the horses. The Dewachuli Thrust is the imbricate fault and the Bhangeri Thrust is a back-thrust (Figs. 5.1-1b and c). The MBT acts as the floor thrust for the Lesser Himalayan duplex (Molnar et al. 1973; Seeber and Armbruster 1981; Verma and Kumar 1987).

6.5.2 Polyphase deformation history

Analysis of major and small-scale structures in the area shows that the Lesser Himalaya is characterized by polyphase deformation history as in the other parts of the Lesser Himalaya such as in the Eastern Nepal Himalaya (Schelling 1989), Langtang area (Macfarlane et al. 1992) and Pokhara-Butwal area (Paudel and Arita 2000). The geological structures observed in the area were formed by at least five phases of deformation. Early two events are probably pre-Himalayan and later three events are Himalayan (Table 6.5-1). The structural evolution of the study area has been schematically shown in Fig. 6.5-2.

Table 6.5-1: Summary of deformation history in the Mugling-Damauli area, central Nepal.

Deformation Phases		**Related geological structures**
Himalayan Phases	D_4	Brittle shear zones and fractures
	D_4	WNW-ESE trending folds (F_2), crenulation and slaty cleavage (S_2)
	D_3	Thrusts, stretching lineation, mineral lineation, shear-sense markers such as asymmetric clasts and boudins, drag folds etc.
Pre-Himalayan	D_2	NNE-SSE trending isoclinal folds (F_1)
	D_1	Bedding parallel foliation (S_1)

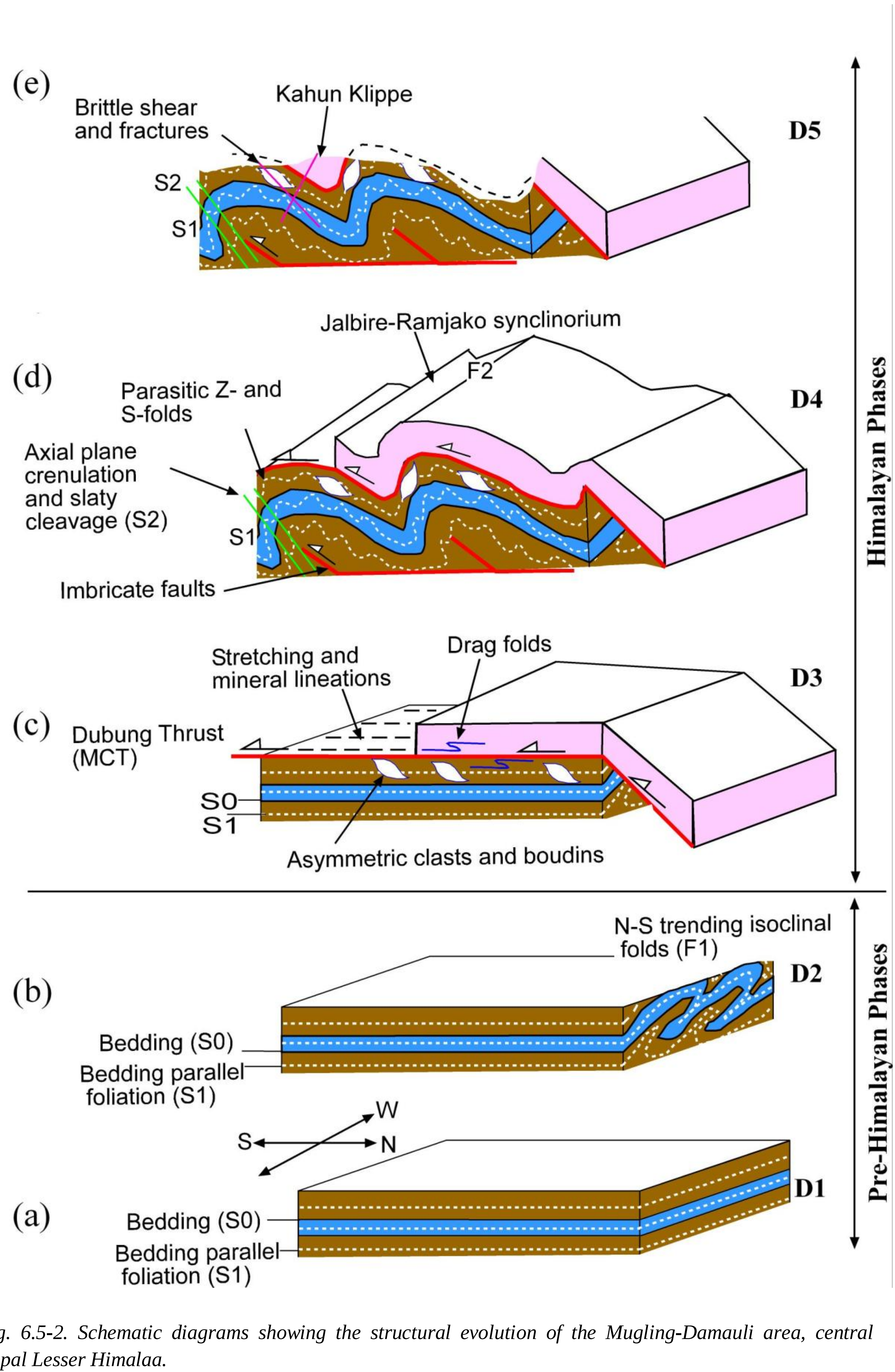


Fig. 6.5-2. Schematic diagrams showing the structural evolution of the Mugling-Damauli area, central Nepal Lesser Himalaa.

(a) Pre-Himalayan Deformations (D_1 and D_2)

Pre-deformational compositional layering (S_0) has been preserved throughout the area both in the Nuwakot and Tanahun Groups. The first deformation event (D_1) is marked by the dominant bedding parallel foliation (S_1) both in the Nuwakot Group and the Tanahun Group. The garnet porphyroblasts in Shivapur Schist preserve S_1 as S-shaped inclusions. The D_1 was most probably due to the flattening of beds due to vertical load. The D_2 event in the study area has been represented by the deformation of the S_0 and S_1 producing drag and isoclinals folds (F_2) with NNE-SSW trending axes. Such folds must have been formed by the ESE-WNW compression before the Himalayan orogeny (Fig. 6.5-2a and b).

Pre-Himalayan deformation in the Himalayan orogen was first reported by Chaudhary and Ghazanfar (1989) and Baig et al. (1988) in the Pakistan Himalaya. Paudel and Arita (2000) reported west-vergent folding in the Lesser Himalaya authochthon. Recent studies in the Kathmandu areas has also shown that the Himalayan orogen was initiated as an Early Paleozoic thin-skinned thrust belt (Gehrels et al. 2003; 2006). Present results in the Mugling-Damauli area are in agreement with the observations in different sections of the Himalaya.

(b) Himalayan Deformations (D_3-D_5)

The Himalayan deformational events can be considered as a single continuous phase of non-coaxial simple-shear progressive deformation related to thrust movements (Schelling 1989). As the thrusts propagated successively from the north to south, deformation progressed accordingly from north to south and from deeper to shallower part with time.

The Himalayan deformation events can be divided into three phases based on the difference in structural style during different stages of progressive deformation. The D_3 is represented by the Dubung Thrust (roof thrust of the duplex structure) and related mesocopic and microscopic structures such as south-vergent drag folds, stretching and mineral lineations (L_1) and top-to-south shear sense markers (asymmetric pressure shadows) (Fig. 6.5-2c). A top-to-the-south sense of shearing has been observed by many previous researchers (Pêcher 1977; Brunel et al. 1979; Kaneko 1997; Paudel and Arita 2000) in central Nepal. The D_3 has been related to the thrusting along the Main Central Thrust in the northern part of the study area.

The D_4 is represented by WNW-ESE trending major folds and axial plane crenulation and slaty cleavages. All the previous planar (S_0, S_1 and S_2, L_1) structures were deformed during the D_4 (Fig. 6.5-2d). The latest deformation (D_5) in the area is the formation of brittle shear zones and fractures cross-cutting all the previous structures.

6.6 METAMORPHIC HISTORY

The petrographic study of the rocks from the area reveals polyphase metamorphic events in the study area both in the Nuwakot and Tanahun Groups. Polymetamorphism in the Lesser Himalaya and Higher Himalaya has been documented in various sections of central Nepal (Le Fort 1975; Arita 1983; Hodges and Silverberg 1988; Pêcher 1989; Arita et al. 1990; Inger and Harris 1992; Hodges et al., 1994; Vannay and Hodges 1996; Rai et al. 1998; Macfarlane 1999; Paudel and Arita 2000; Kohn et al. 2005; Paudel and Arita 2006a; Paudel 2008). They have reported an earlier high P/high T kyanite-grade Barrovian-type metamorphism (Eohimalayan or M_1, Caby et al. 1983) followed by a later lower P/high T sillimanite-grade metamorphism (Neohimalayan or M_2).

Several lines of evidences suggest a pre-Himalayan metamorphic event in the Lesser Himalayan low-grade metasediments, Lesser Himalayan crystalline thrust sheets and Higher Himalaya. Johnson and Oliver (1990) reported pre-collisional (M_0) thermal event in the Lesser Himalayan low-grade metasediments in the Kumaun Himalaya based on illite crystallinity. Similar results were obtained by Paudel and Arita (2000; 2006a) and Paudel (2011) in the Tansen-Pokhara sections central Nepal based on illite crystallinity, white mica compositions and K-Ar white mica ages. Several lines of evidences indicate that rocks of the crystalline thrust sheets were originally metamorphosed during early Paleozoic time. Stöcklin and Bhattarai (1977) and Stöcklin (1980) reported that the Lesser Himalayan granites (Palung granite and other plutons) were emplaced after regional garnet-grade metamorphism. Early Paleozoic metamorphism in the Higher Himalayan rocks of eastern Nepal have been dated at ca. 436-548 Ma (Th-Pb on monazite, Catlos et al. 2002). Ghrels et al (2003) dated monazite inclusions within garnet grains from the Kathmandu Nappe and found 450-500 Ma Pb-Th ages recording early Paleozoic metamorphism. Martina and Ducea (2011) reported pre-Cenozoic peak metamorphism and deformation (~1250 Ma) in the Benighat Slate along the Modi Khola valley in central Nepal.

Present study area also shows polyphase metamorphism both in the autothnous Nuwakot Group and crystalline thrust sheet (Tanahu Group). The rocks show evidences of all the above metamorphic events M_0 (pre-Himalayan), M_1 (Eohimalayan), M_2(Neohimalayan) and M_3 (retrogression).

6.6.1 Pre-Himalayan event (M_0)

The Nuwakot Group exhibits three phases of metamorphism, M_0, M_2 and M_3. The M_1 is very low-grade and reaches up to epizone (chlorite zone) of greenschist facies as indicated by the illite crystallinity. The peak metamorphic assemblages are "muscovite+chlorite+albite+quartz" in pelitic rocks and "actinolite+ chlorite+ epidote+ albite+quartz" in metabasic rocks. The mineral assemblages were formed during the D_1 deformation as the minerals are aligned parallel to S_1.

The M_0 decreases stratigraphically upwards in the Nuwakot Group. It is shown by the illite and graphite crystallinity data (Tables 5.5-1 and 5.6-1). Deformation style of quartz grains also supports this fact. Quartz grain microstructures can be an important proxy to temperature and metamorphism during deformation. The dominant deformation process in quartz changes from intercystalline diffusion (pressure solution) to intracrystalline creep (plasticity) at temperature of about 450°C (Kerrich et al. 1977). Nuwakot Group samples mostly show pressure solution feature. However, the pressure solution activity is intense in the lower part compared to the upper part. The quartzite samples from the lower part of the Nuwakot Group (Kunchha Formation, Fagfog Quartzite and Purebensi Quartzite) show preferred orientation of quartz grains along the foliation, the contacts between adjacent grains is indented to sutured, grains show deformation lamellae and polygonal subgrains are developed around the grain boundaries. On the other hand, quartzite samples from the upper part of the Nuwakot Formation (Nourpul Formation) show little or no preferred orientation of grains, the contact between the adjacent grains is tangential or straight. These features of quartz grains clearly indicate higher grade of metamorphism in the lower part of the Nuwakot Group compared to that in upper part. This result is consistent with the observations by Paudel and Arita (2000) in the Tansen-Pokhara area.

Peak metamorphic temperature of M_0 in the Nuwakot Group of the study area has been estimated to be 345-370°C based on illite crystallinity (Table 5.5-2) and RSCM values (Table 5.7-1). The paleotemperature estimations are consistent with the values obtained by Paudel and Arita (2000). The paleotemperature data from the RSCM values obtained by Beyssac et al. (2004) from the Damauli area show wide variation from 365 to 518°C. This variation may be defined by local heterogeneity in temperature distribution and shearing.

The pre-Himalayan event (M_0) is not clear in the Kahun Klippe (Tanahun Group).

6.6.2 Eohimalayan event (M_1)

The garnet porphyroblasts in the rocks of the Kahun Klippe are sheared and asymmetric pressure shadow is developed around the grains (Fig. 5.4-28). It clearly shows that the garnet growth was before thrusting. It is considered to be the Eohimalayan metamorphic event occurring after the collision and prior to the MCT. It was occurred due to the thickening of the crust in the mid-Eocene (~44 Ma) (Aikman et al. 2008, Zhang et al. 2011).

The M_1 in the possible root zone of the klippe (Higher Himalaya) and adjacent crystalline thrust sheets of the Lesser Himalaya (Kathmandu Nappe and Jajarkot Klippe) reaches up to kyanite/sillimanite grade (Le Fort 1975; Stöcklin and Bhattarai 1977; Arita 1983). However, the peak metamorphic assemblage preserved in the Kahun Klippe is "garnet+biotite+muscovite+chlorite+quartz" in pelitic rocks. It indicates relatively lower grade of metamorphism in the Kahnun Klippe compared to that in other thrust sheets. RSCM measurement from the klippe by Beyssac et al. (2004; sample nos. DM17 and

DM25) range from 496 to 514°C. Quartz grain deformation style also shows relatively higher temperature condition compared to that in the Nuwakot Group. The quatz grains in quartzite are strongly flattened and preferrly orientated parallel to the foliation (Fig. 5.4-24).

6.6.3 Neohimalayan event (M_2)

The M_2 in the Nuwakot Group is represented by chlorite to garnet grade (greenschist facies) dynamo-thermal Barrovian-type metamorphism associated with the movement along the MCT. The peak metamorphic assemblages representing the M_2 are "ganet+biotite+chlorite+albite+quartz" in pelitic rocks. This event is syn- to post-D_3 as indicated by the s-type inclusions in garnet and post-tectonic overgrowth of garnet across the crenulation cleavage (S_3) (Figs 5.4-5 and 6).

The M_2 is inverted in the study area as in other parts of the Lesser Himalaya (Le Fort (1975; Arita 1983; Pêcher 1989; Jain and Manikavasagam 1993; Guillot 1999; Hubbard 1996; Paudel and Arita 2000; 2006a). In the northern part of the study area north of Anbu Khaireni, the Kunchha Formation passes into the biotite zone and to the garnet zone, structurally upwards. The biotite and garnet isograds discordantly cut across the sedimentary layering and structural boundaries. Garnet show post-tectonic overgrowth of boundaries across S1 and S_2. It shows that the metamorphism is syn- to post-tectonic. The metamorphic inversion in the northern part has been related to the MCT activity (Le Fort 1975; Arita 1983).

The M_2 is also inverted in the low-grade rocks of the Nuwakot Complex below the Kahun Klippe. The illite and graphite crystallinity values increase from Kunchha Formation to the lower part of the Benighat Slate and then decrease near the Kahun Klippe in the upper part of the Benighat Slate. The M_2 inverted metamorphism is clearly related to the Dubung Thrust (basal part of the Kahun Klippe). Thrust-related inverted metamorphism beneath the crystalline nappe in the low-grade sediments (pre-Siwalik Tansen Group) has been reported by Sakai et al . (1999) in west Nepal. The origin of the inverted metamorphism below the thrust sheets can be attributed to heat from the hot crystalline nappe (Le Fort 1975) and shearing along the sole thrust (Arita 1983).

6.6.4 Late-stage retrogresion (M_3)

The latest phase of metamorphism (M_3) is widespread in the area both in the Nuwakot Group and the Tanahun Group. It is represented by widespread retrogression of minerals like garnet and biotite into chlorite, quartz and opqaues. This event occurred during the exhumation process and is coeval with D_5.

6.7 GEOLOGICAL AND PETROLOGICAL EVOLUTION

The Mugling-Damauli area has long history of geological evolution from Precambrian to Recent. Sequence of events in its history has been schematically shown in Fig. 6.7-1. The geological history began with the deposition of the Nuwakot Group sediments on the northern margin of the Indian Continent in the Late Precambrian. Most probably the Tanahun Group acted as a basement for the Nuwakot Group. The depositional environment was deep marine calm condition at the beginning where flysch type Kunchha Formation was deposited. The depositional basin became shallower with time and changed to sub-marine deltaic environment. During the time of deposition of the Nourpul Formaiton and higher successions, the basin was quite unstable and several cycles of transgression and regression of sea have been recorded. The environment frequently changed from fluvial-dominated sub-marine deltaic environment to lagoon and tidal flat condition. The environment again changed to shallow marine to deep condition during the deposition of the Dhading Dolomite and Benighat Slate. Sedimentation of the Nuwakot Group ended in the Early Paleozoic (?) due to large-scale crustal disturbance, which Valdiya (1998) relates with the Pan-African diastrophism. The depositional history of the Tanahun Group is unknown because most of the sedimentary features have been erased by later deformation and recrystallization.

The Nuwakot Group experienced first deformation event (D_1) probably in the Early Paleozoic. The D_1 is characterized by the bedding-parallel flattening due to load. First epizonal burial metamorphism (M_0) occurred in the Nawakot Group almost synchronous with the D_1. It was followed by E-W compression and west-vergent folding (D_2 isoclinal folds). The tectono-metamorphic evolution of the Tanahun Group before the India-Eurasia collision is uncertain. Most probably the first foliation (S_1) in the Tanhaun Group was prior to collision.

After the collision and before the formation of the MCT, the crust was enormously thickened and pressure-temperature was increased at depth. It caused at least garnet-grade metamorphism in the Tanahun Group. Events in the Nuwakot Group at this time are unclear.

The period after the initiation of the MCT is the major phase of thin-skinned tectonism, folding and faulting, inverted metamorphism, uplift and exhumation. The Tanhun Group was transported on top of the Nuwakot Group by the MCT (Dubung Thrust) in the Early Miocene. The Dubung Thrust acted as the roof thrust of the Lesser Himalayan Duplex. South-vergent drag folds, NNE-SSW trending stretching and mineral lineations, inverted garnet-grade inverted metamorphism in the footwall of the MCT (Nuwakot Group) occurred during the time of MCT movement.

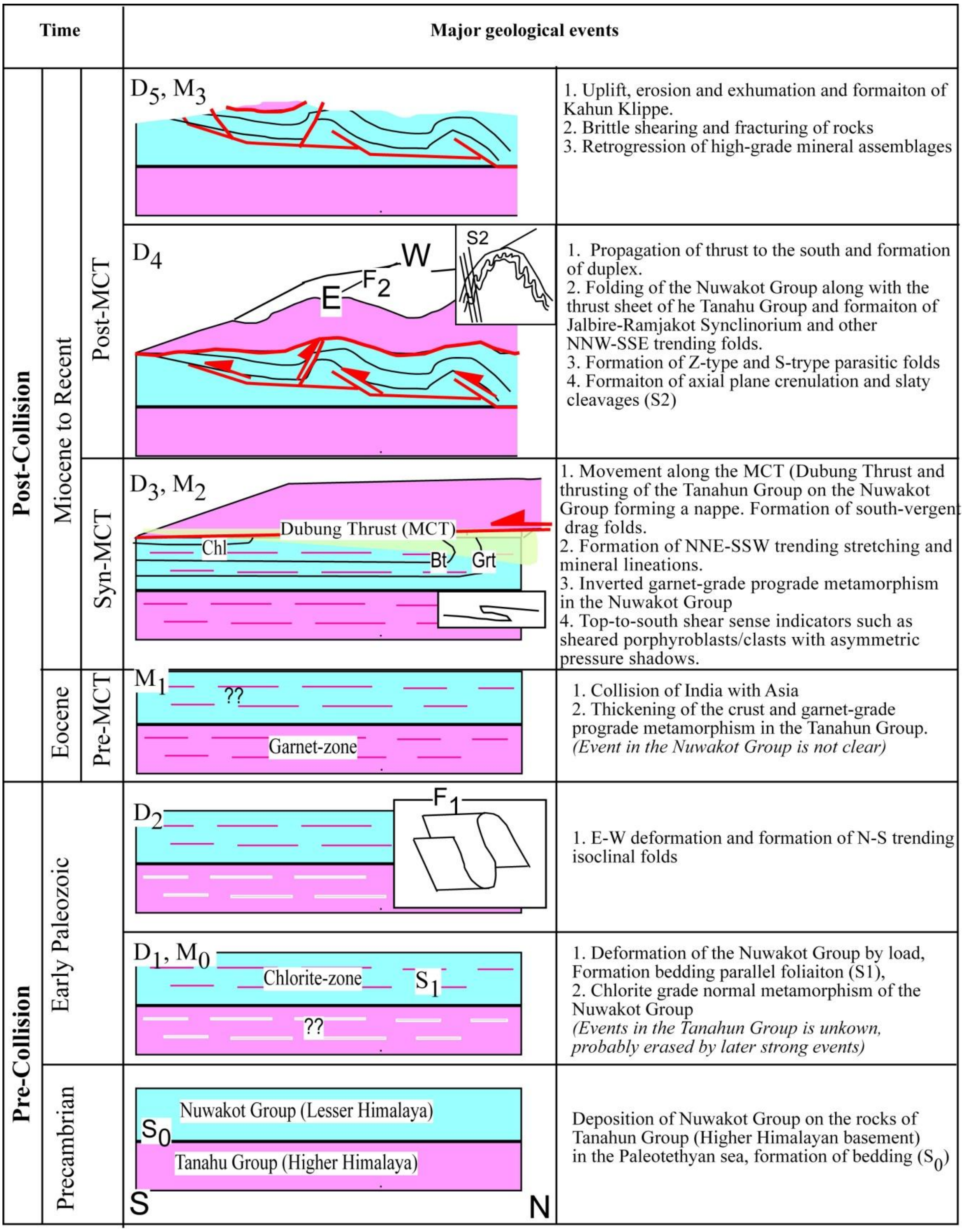


Fig. 6.7-1. Schematic diagram showing the geological and petrological evolution of the Lesser Himalayan in the Mugling-Damauli area, central Nepal.

After the cessation of movement along the MCT, other imbricate thrusts such as the Dewachuli and Bhangeri Thrusts were propagated to the south forming a duplex structure. The MBT acted as the floor thrust for the duplex. The Nuwakot Group along with the Tanahun Group was folded forming NNW-SSE trending folds including the Jalbire-Ramjakot Synclinorium and other folds. The S_1 was refolded to form axial plane crenulation cleavage and slaty cleavage (S_2).

Final phase of evolution in the area was uplift, erosion and exhumation. The Kahun Klippe was formed by erosion of the Higher Himalayan thrust sheet. This phase is characterized by brittle shearing and fracturing of rocks and widespread retrogression and re-equilibration of higher-grade mineral assemblage to lower-grade condition.

6.8 CONCLUSIONS

6.8.1 Lithostratigraphy

(i) The contact between the Dhading Dolomite and Benighat Slate is transitional to sharp and conformable in all exposed sections of the study area. There are no convincing proofs of the presence of an unconformity between them. Therefore, it is suggested to name whole autochthonous rocks as the Nuwakot Group.

(ii) The Anpu Quartzite, Labdi Phyllite and Banspani Quartzite uninterruptly join with Fagfog Quartzite, Dandagaon Phyllite and Purebensi Quartzite, respectively. Therefore, the former units do not exist in the field.

(iii) The Kahun Klippe is westward extension of the Kathmandu Nappe and the Tanahun Group (rocks of the Kahun Klippe) is equivalent to the Bhimphedi Group.

(i) The Tanahun Gorup can be divided into three formations as the Gwaslung Formation, Musimarang Formation and Shivapur Schist, from bottom to top, respectively. The Shivapur Schist can be compared with the Raduwa Formation, and, therefore, the Gwaslung and Musimarang Formations should be units older than the Raduwa Formation.

(iv) The rocks of the Kahun Klippe (Tanahaun Group= Bhimphedi Gorup) cannot be compared with the rocks of the MCT zone and Higher Himalaya. Probably they are rocks lying below the Kunchha Formation and above the Higher Himalaya.

6.8.2 Magnetic Susceptibility (MS)

(ii) The MS value is lowest for quartzites and gradually increases in dolomites, slates, phyllites, metasandstones and amphibolites.

(iii) Each stratigraphic unit of the Nuwakot Group has its own MS pattern and range of MS values. This pattern is uniform in all sections of the present study area as well as in the type locality of the Nuwakot Group (i.e., Malekhu section). Therefore, it is possible to use MS as a supporting tool for lithostratigraphic correlation and mapping in the Lesser Himalaya.

6.8.3 Geological structures and deformation history

(i) The Mugling-Damauli area forms a part of a large duplex structure. The Dubung Thrust (~Mahabharat Thrust) is the roof thrust, MBT is the floor thrust, Dewachuli Thrust is the imbricate fault and the Bhangeri Thrust is a back-thrust.

(ii) The area forms a large synclinorium known as Jalbire-Ramjakot synclinourium. The synclinorium is of cylindrical nature in the west and non-cylindrical nature in the east.

(iii) The area shows 5-phases of deformation. Two deformation events (D_1 and D_2) are pre-Himalayan and three events (D_3-D_5) are Himalayan.

6.8.4 Root zone of the Kahun Klippe

(i) The origin of the Kahun Klippe and other Lesser Himalayan crystalline nappes and klippe can be explained on the basis of single thrust model, i. e., the basal thrust of the klippe and nappe is a southward extension of the MCT.

(ii) The two thrust model by Upreti and Le Fort (1999), i.e., is not supported by the field evidences.

6.8.5. Metamorphism

(i) The area shows four phases of metamorphism. The first metamorphism (M_0) is pre-Himalayan, other three (M_1, M_2 and M_3) are Himalayan.

(ii) The MCT-related Neohimalayan metamorphism (M_2) is inverted also in the low-grade zone of the Lesser Himalaya.

(iii) Peak metamorphic temperature has reached up to 370°C in the low-grade zone of the Lesser Himalaya as shown by illite crystallinity and Raman Spectroscopy of Carbonaceous materials.

CHAPTER SEVEN

SUMMARY AND RECOMMENDATIONS

7.1 SUMMARY

The Nepal Lesser Himalaya as in the other parts of the Himalayan region is a fold-and-thrust belt with complex stratigraphy and structures. Many parts of the Lesser Himalaya in central Nepal still lack large-scale geological maps. Wherever geological mapping has been done, there are several discrepancies and controversies on the stratigraphic classification and tectono-metamorphic interpretations. This had created a great problem not only for accurate correlation of the sequences in contiguous region but also for interpretation of geological evolution of the Lesser Himalaya. With the aim to overcome these geological issues, geological and petrological study was carried out in the Mugling-Damauli area of central Nepal Lesser Himalaya.

In the present study, a geological mapping was carried out in 1:25,000 scales covering about 1000 square km area lying between Mugling and Damauli in central Nepal. Lithostratigrpahy of the area was re-assessed by detailed route-mapping and preparation of columnar sections. Magnetic susceptibility was measured in the autochthonous rocks along four sections and attempt was made to use it as a supporting tool for lithostratigraphic comparison. Regional geological structures were measured and traced throughout the study area. Mesoscopic and microscopic structures were studied and analyzed both in the field and in thin sections. Metamorphic study was carried out using petrological microscope, measurement of illite and graphite crystallinites and measurement of Raman Spectrocopy of Carbonaeous Materials. The results of the present study can be summarized as follows:

1. There are several stratigraphic classification schemes for the central Nepal Lesser Himalaya by different authors and the classification by Stöcklin and Bhattarai (1977) has been widely used to the date. However, the classification has several discrepancies and should be modified. There are no convincing proofs of the presence of an unconformity between the Dhading Dolomite and Benighat Slate and division of the autochthonous rocks into two groups is questionable. Therefore, it is suggested that whole autochthonous rocks should be named as the Nuwakot Group.

   Similarly, the Anpu Quartzite, Labdi Phyllite, Banspani Quartzite are the same units as the Fagfog Quartzite, Dandagaon Phyllite and Purebensi Quartzite, respectively. Therefore, the former units should be removed from the stratigraphic classification. The Nourpul Formation is divisible into four members and two beds in the present study area. However, the same sub-division of the Nourpul Formation may not be valid for the other sections of the Lesser Himalaya as the formation shows great lateral and vertical variation in lithology and thickness.

2. Lithostratigraphic correlation of the Lesser Himalayan rocks is quite difficult due to the lack of fossils, great lateral lithological variation, complex deformation and metamorphism. Magnetic susceptibility (MS) measurement in the Nuwakot Group rocks shows that each stratigraphic unit of the Nuwakot Group has its own MS pattern and range of MS values. This pattern is uniform in all sections of the present study area as well as in the type locality of the Nuwakot Group (i.e., Malekhu section). Therefore, it is possible to use MS as a supporting tool for lithostratigraphic correlation and mapping in the Lesser Himalaya.

3. The rocks of the Kahun Klippe are named as the Tanahun Group and can be

divided into three formations as the Gwaslung Formation, Musimarang Formation and Shivapur Schist, from bottom to top, respectively. The lithology of the Shivapur Schist is similar to that of the Raduwa Formation of the Kathmandu Nappe and Chaurijhari Formation of the Jajarkot Klippe. Therefore, the Gwaslung and Musimarang Formations should be units older than the Raduwa Formation. It indicates that the Kathmandu Nappe, Kahun Klippe and Jajarkot Klippe are a part of a single crystalline thrust sheet and the basal thrust of the Kahun Klippe (Dubung Thrust) is equivalent to the Mahabharat Thrust (MT).

4. Lithology of the Tanahun Group (=Bhimphedi Group) is quite different from that of the MCT zone and Higher Himalaya in central Nepal. Therefore, I believe that the rocks of the Kahun Klippe and other Lesser Himalayan crystalline thrust sheets are units stratigraphically lying between the Nuwakot Group and the Higher Himalaya.

5. The origin of the Kahun Klippe and other Lesser Himalayan crystalline nappes and klippe can be explained on the basis of single thrust model.

6. The Mugling-Damauli area forms a part of a large duplex structure. The Dubung Thrust is the roof thrust, MBT is the floor thrust, Dewachuli Thrust is the imbricate fault and the Bhangeri Thrust is a back-thrust.

7. Analysis of major and small-scale structures shows a polyphase deformation history in the study area. The D_1 forming bedding parallel foliation and D_2 forming isoclinals folds with NNE-SSW trending axes is pre-Himalayan. The D_3 is syn-MCT event resulting in stretching and mineral lineations, south-vergent drag folds and a number of top-to-south shear-sense indicators. The D_4 is post-MCT event related to southward propagation faults and formation of duplex structure,

folding with NNW-SSW trending axes, and formation of S_2 axial plane crenulation and slaty cleavages. The D_5 is the last deformation event related to brittle shearing and fracturing.

8. The area shows polymetamorphism as in other parts of the Lesser Himalaya. M_0 is pre-Himalayan event synchronous with D_1. It is low-grade metamorphism reaching temperature up to 370°C. The M_0 is normal burial metamorphism with grade increasing stratigraphically downwards. The second event (M_2) is Eohimalayan event causing garnet-grade prograde metamorphism in the Tanahun Group. The peak metamorphic temperature reached up to 500°C in the Tanahun Group. The third event (M_3) is syn- to post-MCT inverted metamorphism. It reaches up to garnet-grade in the northern part of the study area near the MCT zone (north of Gorkha). Illite and graphite crystallinity values show that it is inverted also in the low-grade zone of the Nuwakot Group just below the Kahun Klippe.

A schematic model for geological and petrological evolution of the Mugling-Damauli area has been presented.

7.2 RECOMMENDATION

In spite of several limitations, present study unraveled many interesting facts about the stratigraphy, structure and tectono-metamorphic evolution of the Lesser Himalaya. However, there are several things to be still clarified by future research to understand the complete geological history of the Lesser Himalaya.

1. Accurate identification of stratigraphic units is the basis for geological mapping, structural analysis and all other geological researches. Otherwise it may lead to a wrong geological interpretation of data measured in the field and

laboratory. Therefore, any geological investigation should be preceded by stratigraphic work of the area.

2. Present study shows that magnetic susceptibility may be used as supportiv tool for lithostratigraphic correlation where there are not marker beds and fossils. It is quick and indirect method of correlation. Therefore, I recommend for establishing magnetic susceptibility stratigraphy of the Lesser Himalaya and other tectonic units as well.

3. There is no detailed geological information of the area west of the present study and east of the area mapped by Sakai (1985). Therefore, the area should be mapped in future and join the present map with that of Sakai (1985). It will help in more understanding of the stratigraphy and structure of the Lesser Himalaya.

4. The area, especially the Nourpul Formation is rich in mineral resources such as polymetallic deposits (copper, lead, zinc and gold) and hematite etc. The Benighat Slate has prospects of extracting graphite for commercial purposes. Similary the Kahun Klippe comprises good quality marble. The metabasite can be used as a dimension stone. Therefore, detailed mineral exploration should be carried out in the area in future.

5. The timing of M_0 and M_1 events in the Lesser Himalaya has been a long-standing and still-debated problem among the Himalayan geologists. Future works in the Lesser Himalaya should be linked with microtextural and microchemical analysis followed by geochronology.

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