Geology and Natural Hazards along Kaligandaki and Highways Kathmandu-Pokhara-Butwal-Mugling

-Guidebook for Student Himalayan Exercise Tour in Nepal-

Second Edition

Edited by

M. Yoshida, P.D. Ulak and B.N. Upreti

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Preface

The Himalaya attracts people by its beautiful mountain views and having the world highest peaks of over 8000 meters above sea level. People come to know, viewing the yellow band near the peak of Mt. Everest, that the summit is made up of strata with marine fossils and so the summit was once under the sea. Thus people naturally realize the mountain building power of the earth, that is the central of the geological processes.

Thus, we have believed that publishing easy geoscience guidebook of the Himalaya should be useful to people world wide who are interested in geosciences, including the mountain building processes of the earth, and to those who visit Nepal as well as the Himalaya.

The Student Himalayan Exercise Program (SHET) started in 2012 and since then has been conducted in March every year. The present guidebook is prepared for the tour of the above program. From Muktinath, trekking along the upper reaches of the Kaligandaki Valley to Pokhara and then Pokhara to Butwal crossing from the Tethys Himalayan, the Higher Himalayan, the Lesser Himalayan and the Sub-Himalayan zones covers a full section of the Himalayan Orogen (Fig. I-1). The present guidebook will not only be useful for the students of SHET program mentioned above but also will encourage people to understand science behind the mountain building process and enjoy studying geosciences of the Himalaya.

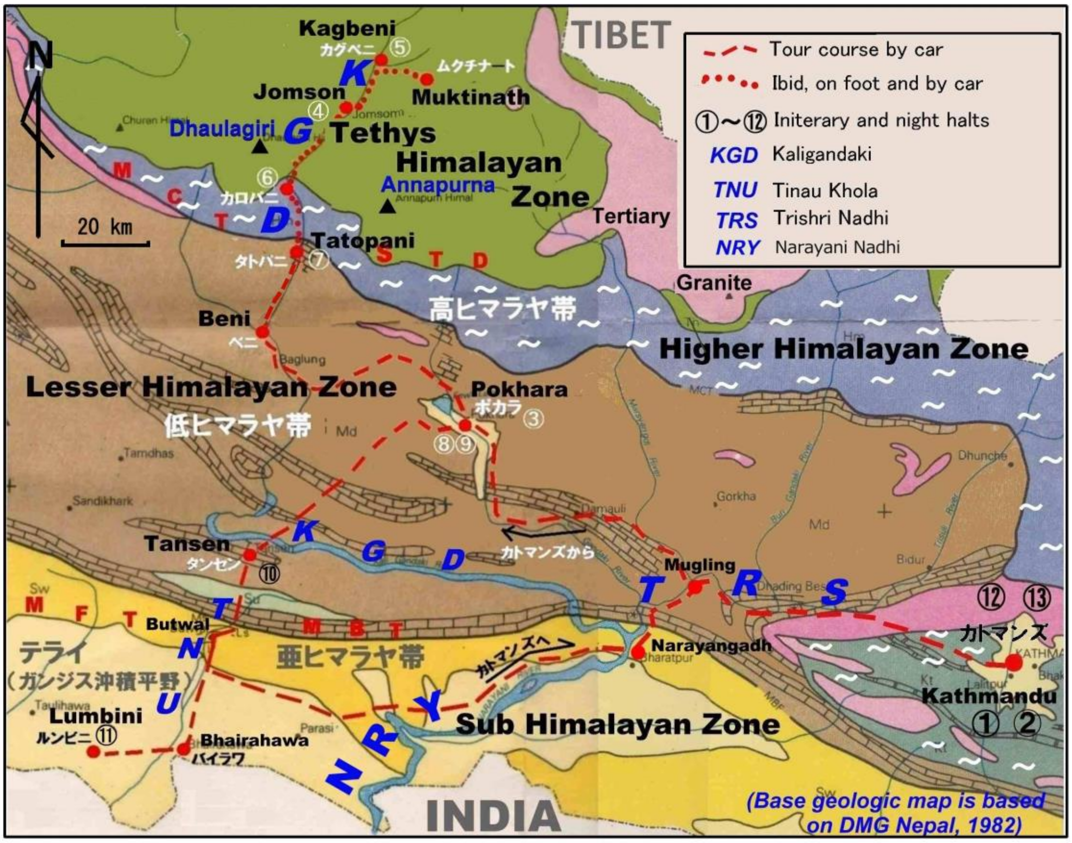


Fig. I-1. Geologic outline (DMG, 1982) and geo-excursion course (red broken line). STD: South Tibetan Detachment System, MCT: Main Central Thrust, MBT: Main Boundary Thrust, MFT: Main Frontal Thrust, MT: Mahabharat Thrust, TG: Tansen Group, AG: Augen Gneiss, MG: Miocene Granite, LS: Limestone/Dolomite-rich zone, TRS: Trishuli River, KGD: Kaligandaki River, TNU: Tinau River.

Contents

I. THE HIMALAYA

Origin of the Himalaya

The Himalaya is the highest as well as the youngest mountain range on Earth. It was formed by the most recent mountain building process (orogeny/tectonic activity) in the earth's history. The origin of this nearly 2500 km long mountain range began around 55 million years ago when the northward moving Indian plate collided with the southern edge of Asia (Tibet) closing the intervening Tethys Sea that was lying between them **(Fig. I-2).** India continued moving northward against Asia even after this continent-continent collisional event. During the above process India's leading northern edge covered with predominantly marine sedimentary rock sequence ranging in age from at least Paleoproterozoic (earlier than 1800 million years ago) to as young as early Miocene (22 million years ago) was folded, sliced and uplifted to form the Himalayan mountain range (**Fig. I-2, Table I-1**). Later, the succeeding effect of the same process also created the Tibetan Plateau, the largest plateaus on earth **(Fig. I-2).**

Today, India is still moving northward bulldozing Asia at the rate of 50mm annually and part of Indian crust is pushed underneath the Tibetan Plateau. The mountain is still active and continues to rise today. The frequent earthquakes in and around the Himalaya manifest the still on-going present-day mountain building activity in the Himalayan region. The recent Global Positioning System (GPS) data obtained in Nepal show that some parts of the Himalaya are rising at the rate of as much as nearly one cm per year. At the same time the Himalayan terrain is being squeezed horizontally by about 20mm annually. The present boundary between the Indian and Eurasian plates lies in Tibet and is marked by the Indus-Tsangpo Suture Zone approximately running parallel to the Indus and Tsangpo rivers in a east–west direction **(Fig. I-3).**

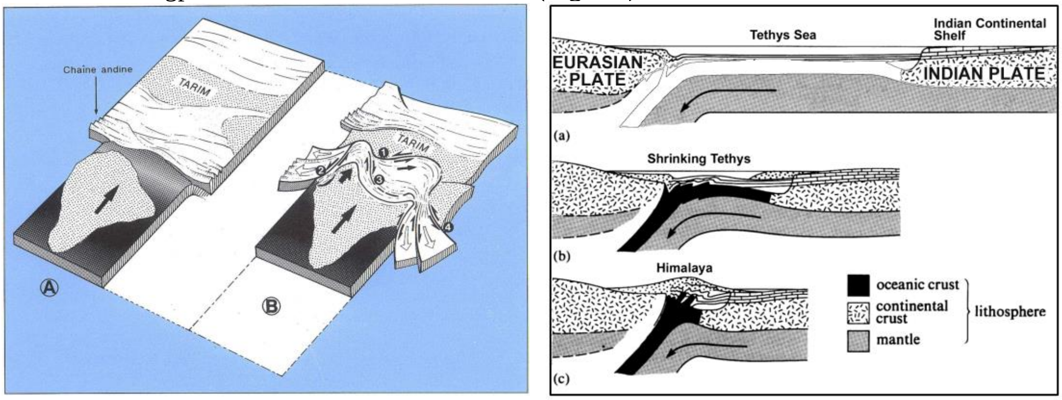


Fig. I-2. Schematic diagram showing the northward movement of Indian plate and collision with Asia producing the Himalaya and Tibetan Plateau (Left: Modified after Mattauer, 1989、Right: Dewey and Bird, 1970).

The Himalaya exhibits one of the most spectacular sections of the earth's crust where nearly 40 km thick cross section, from the mountain root to the mountain top can be observed along a single N-S traverse such as along the Kaligandaki or Marsyangdi valleys in Nepal. Excellent exposures of rocks from deep-seated metamorphic environment at the bottom to the unmetamorphosed fossiliferous sedimentary rocks at the top (in the orogenic structure) are exposed. Thus, the Himalaya is a natural laboratory where the on-going mountain building process in a continent-continent collision setup can be studied.

Table I-1. Major events of the evolutional history of Himalaya (modified after Valdiya,1998).

Era		Age (Ma)	Major Event	Sedimentation History
Cenozoic	Qnry	0.01	Uplift along active faults	IGS
			Upheaval of the Siwalik followed by the activity the HFT, evolution of the Indo-Gangetic Basin (1.7-1.5 Ma)	
	Tertiary	2.59	Formation of MBT, upheaval of Mahabharat Range, Beginning of Indo-Gangetic Foreland Basin 2.5-2.0 Ma)	SG
		23	Widespread emplacement of granite, upheaval of Higher Himalaya, metamorhism and nappe formation Intense activity of MCT, formation of STDS, initiation of Siwalik Foreland Basin (25-20 Ma)	
			Embryonic movement of the MCT (35-30 Ma)	
		53	Collision and welding of India with Asia (55 Ma)	TG
		65		
Mesozoic		135	Starting of break up of India from Antarctica (Gondwanaland break up)	
		250		
Palaeozoic		290	Widespread glaciation. Interruption of sedimentation in Tethys domain (310-280 Ma)	TTS
		510	Deformation and metamorphism (HHCS) associated with widespread emplacement of granite. Assembly of Gondwanaland (540-470 Ma)	HHCS
		570		
Proterozoic		1000	Start of sedimentation of the Protolith of the HHCS	NG
			Start of sedimentation of the LH metasediments (e.g., Nawakot Group)	
		2050		

Time span not to scale
HFT-Himalayan Frontal Thrust; MBT-Main Boundary Thrust; MCT-Main Central Thrust; HHCS-Higher Himalayan Crystalline Sequence; IGS- Indo-Gangetic Sediments, SG- Siwalik Group,TG- Tansen Group,TTS- Tibetan-Tethys Sedimentary Series, NG-Nawakot Group; Qnry-Quarternary

Geologic (Tectonic) Zones of the Himalaya

The major architectural framework (Tectonic zones) of the Himalaya is very uniform (Gansser 1964; Le Fort, 1975; Hodges 2000) with major geologic zones running throughout its length. The basic framework of the Himalaya is controlled by four northerly inclined master faults that extend all along the Himalayan range: viz., the South Tibetan Detachment System (STDS), the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT) from north to south, respectively **(Fig. I-3).**

The STDS is a normal fault and has played an important role in the development of the Himalaya (Burg and Chen, 1984; Pecher, 1991: Burchfield et al., 1991; Hodges et al., 1992, Figs. I-3). This fault separating the Higher Himalayan Zone to the south and the Tethys Himalayan Zone to the north is considered to be nearly contemporaneous in age with the MCT. It is interpreted that the STDS was initiated when the Himalaya attained a significant height by the thrusting along the MCT, resulting in the northward gravitational collapse of the Tethys Group rocks that overlie the Higher Himalayan rocks.

The thrust faults viz., MCT, MBT, MFT) get younger in age from north to south; MCT being the oldest and the MFT the youngest. During the movement along the MCT, a 25-30 km thick pile of rocks on the hanging wall moved southward for over 200 km (Parrish and Hodges 1996; Harrison and others 1999) overriding a different set of rocks in the south (the Lesser Himalayan rocks). In central Nepal, the southward movement of the rocks above the MCT resulted in forming a large nappe structure which was named as the Kathmandu Nappe (Hargen. 1969, Stocklin 1980). The hanging wall rocks of the MBT and MFT also moved southward in a similar manner at different times (cf**. Table I-1**). At present, significant movement occurs only along the MFT which forms the most active structure of the Himalaya. Broadly speaking the MCT was initiated around 25 Ma before present and was active until 15 Ma (Harrison and others, 1998).

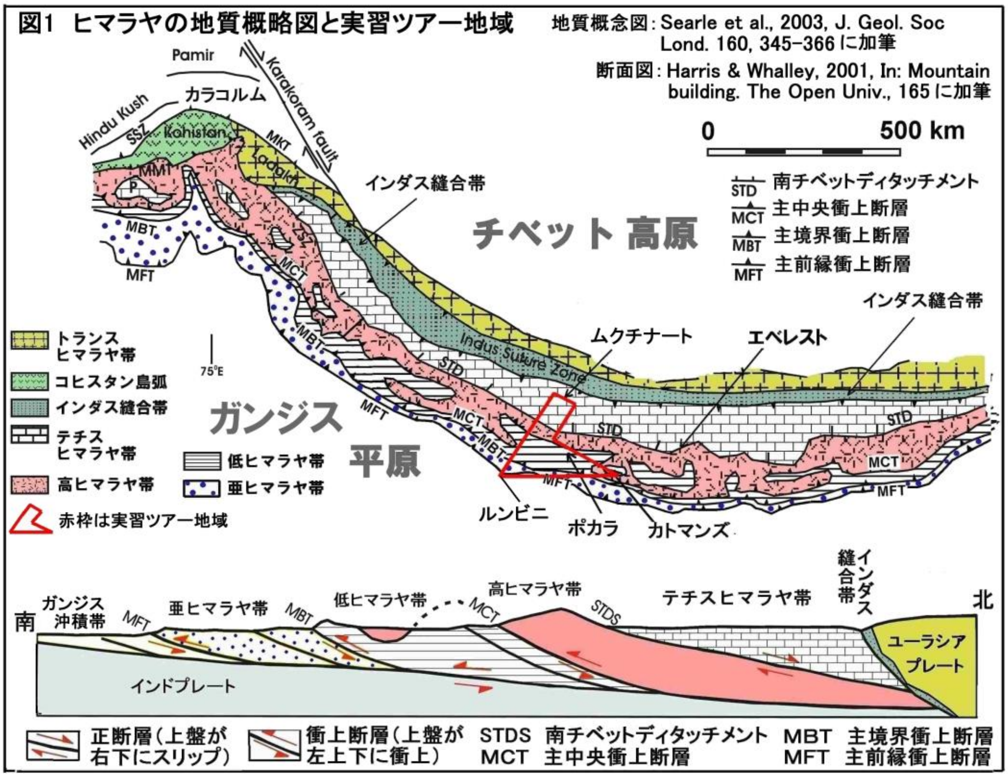


Fig. I-3. Regional geologic map (modified after Searle et al., 2003) and cross section (modified after Harris and Whalley, 2001) of the Himalayan range.

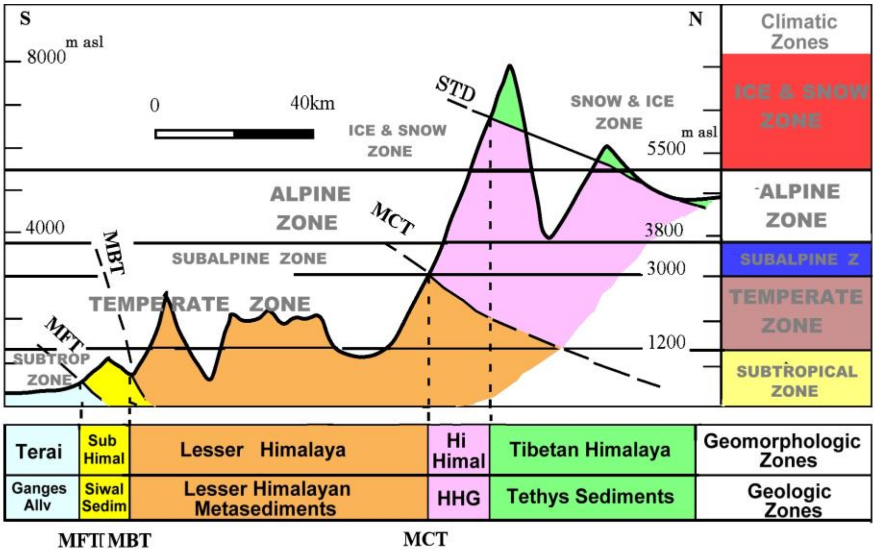


Fig. I-4. Simplified physiographic and geological cross-section of the Himalaya (Kizaki, 1994). STDS: South Tibetan Detachment System, MCT: Main Central Thrust, MBT: Main Boundary Thrust, MFT: Main Frontal Thrust.

Divided by the above-mentioned four boundary faults, five major geologic zones are recognized in the Himalayan Orogen **(Figs. I-3, I-4**). From south to north they are (1) the Indo-Gangetic Alluvial Zone (Terai), (2) the Sub Himalayan Zone, (3) the Lesser Himalayan Zone, (4) the Higher (or Greater) Himalayan Zone, and (5) the Tethys Himalayan (or Tibetan Tethys) Zone.

The Indo-Gangetic Alluvial Zone is the present day foreland basin of the Himalaya, mostly composed of fluvial sediments of mostly late Cenozoic age derived from the Himalayan mountains. The Bengal Bay sediments also form a part of this zone. The Sub Himalayan Zone is composed of the Siwalik Group (also called the Churia Group), which is the Cenozoic foreland basin sediments. The Lesser Himalayan Zone is composed of the Lesser Himalayan Metasediments, which is named as the Nawakot Complex in Central Nepal and the Kaligandaki Super Group in Western Nepal, and the Tansen Group, which is mostly distributed in Western Nepal. The Lesser Himalayan Metasediments are mostly the continental shelf sediments of early to middle Proterozoic, and the Tansen Group is mostly the terrestrial sediments of late Paleozoic to Mesozoic age. The Higher Himalayan Zone is composed of the Higher Himalayan Gneisses, which are composed of high-grade metamorphic rocks. The Tethys Himalayan Zone is composed of the Tethys Group (also called the Tibetan Tethys Sedimentary Sequence), which is mostly the continental shelf sediments of Paleozoic to Mesozoic in age.

The above subdivision is applicable throughout the length of the mountains (Gansser, 1964) and is generally parallel to the physiographic zones of the Himalaya (Fig. 1-4, Kizaki, 1994). A generalized geologic map of Nepal (Upreti, 1999) is presented in Fig. 1-5. From south to north, a short description of these tectonic zones as recognized in Nepal is presented below. In Table 1-1, a general time range of deposition of all major geologic units is shown for readers' conveniences.

(1) The Indo-Gangetic Alluvial Zone

This area forming the southernmost part of Nepal is a part of the northern end of the Indo-Gangetic Alluvial plain, called Terai in Nepal range in elevation from 100 to 200 m above MSL. The Terai region is generally with very low relief. The sediments of this zone are brought by the rivers originating in the Himalaya and Tibet and represent the foreland basin deposit. It extends from the Nepal-India border in the south to the base of the Churia hills in the north. The width of Terai

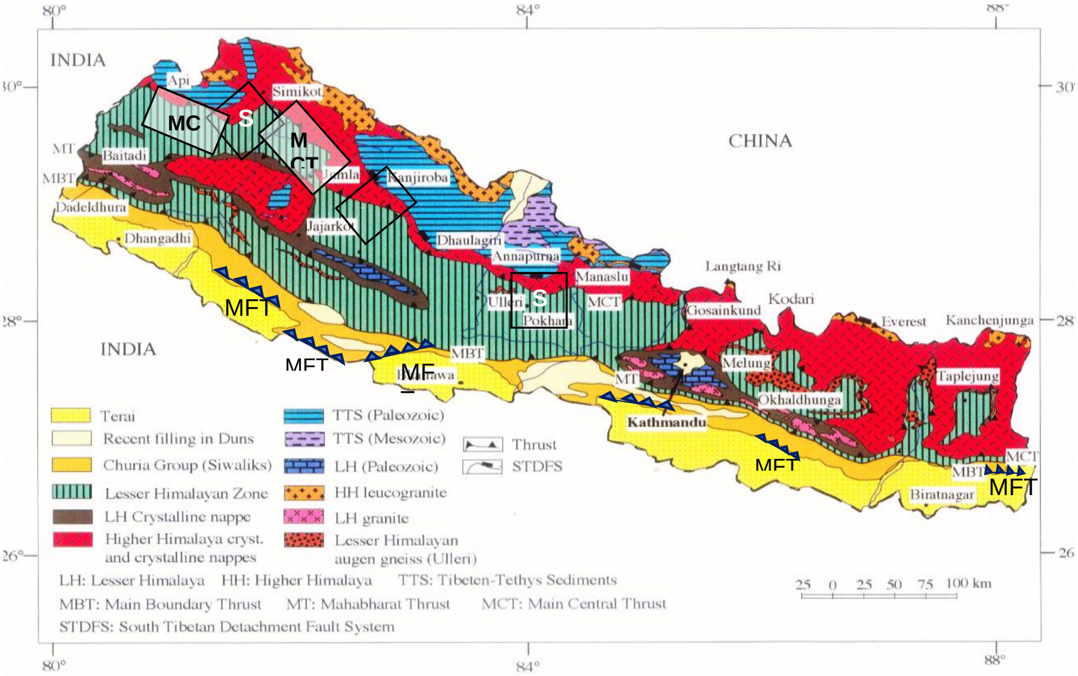


Fig. I-5. Geological map of Nepal (Upreti, 1999).

varies between 10 to 50 km and forms a nearly continuous belt from east to west,

The study of surface geology as well as the recent subsurface geological investigation from a large number of drillings made for the groundwater investigation has led to the further subdivisions of Terai from north to south as Northern, (Bhabhar zone), Middle and Southern zones.

Northern Terai Zone (Bhabhar Zone): The Northern Terai or Bhabhar Zone lies adjacent to the foothills of Churia and extends southward to a maximum width of about 12 km. This zone is mainly covered by dense subtropical forest and is composed of a thick sediment zone characterized by boulders, pebbles, cobbles and coarse sands derived from the rocks of the Himalayas and beyond to the north.

Middle Terai Zone: This is an intermediate zone between the Bhabhar and the Southern Terai Zone. It is about 10-12 km wide. This zone is resulted due to the interfingering of two distinctly different facies of sediments. Differences in porosity and permeability between the sediments of Bhabhar Zone and Southern Terai has caused the development of spring line, natural ponds, and marshy land. This zone is characterized by pebbly and sandy sediments with few clay layers.

Southern Terai Zone: This zone extends southward to the India-Nepal border and continues further into India. It represents the typical featureless Indo-Gangetic plain. It is mainly composed of the fine sediments consisting of sand, silt and clay.

(2) The Sub-Himalayan Zone (Siwalik Zone)

The Sub-Himalayan or the Siwalik Zone is bounded in the north by the Main Boundary Thrust (MBT) and in the south by the Main Frontal Thrust (MFT) (**Figs. 1-3,4, 5**). The rocks of this Zone is known as the Siwalik Group (also known as the Churia Group in Nepal) which is thrusted over by the Lesser Himalayan Metasediments along the MBT. Along the MFT, the Siwalik Group itself, thrusts over the Indo-Gangetic Alluvial Zone (known as Terai in Nepal). The Siwalik Group belonging to the Mid Miocene to late Pleistcene age is 6-10 km thick and essentially made up of fluvial sedimentary rocks that form the southernmost hill range of Nepal known as the Siwalik (Churia) Hills.

The Stratigraphy of the Siwalik Group in Western Nepal (Ulak and Nakayama, 2001a) is shown in Table I-2. This Group is broadly dived into three units (Tokuoka et al, 1988): (i) The Lower Siwalik (Arung Khola Formation) consists of finely-laminated sandstones, siltstones, and mudstones, (ii) the Middle Siwalik (Binai Khola Formation) is made up of medium- to coarse-grained salt-and-pepper type sandstones, and (iii) the Upper Siwalik (Chitwan Formation) comprises predominantly of conglomerate and boulder beds with minor proportion of course sandsotnes and mudstones. The Dun valleys within the Sub Himalayan Zone (iwalik Hills) are covered by the Quaternary fluvial sediments.

These rocks also contain vertebrate and plant fossils and fresh- water molluscs. Based on paleomagnetic studies, the age of the exposed Churia Group in Nepal ranges from ~14 Ma to <2 Ma (Tokuoka et al., 1986; DeCelles et al., 1998; Ojha et al., 1999; Gautam and Rosler, 1999).

Table I-2 . Stratigraphy of the Siwalik Group (Ulak and Nakayama, 2001a).

Formation	Age	Thickness (m)	Lithological characteristics
Deorali Formation (D)*	Middle Miocene to Early Pleistocene	450+	Poorly sorted, matrix supported boulder-sized, loose conglomerates and lenses of sands. Sandsone boulders are derived from the lower part of the Siwalik Group.
Chitwan Formation (C)		200+	Well sorted, clast supported, moderately indurated cobble-pebble conglomerates. The clasts of conglomerate are from the Lesser Himalayan terrain.
Binai Khola Formation (B)			
Upper Member (Bu)		260	Thick bedded, coarse- to very coarse-grained, "pepper and salt" sandstone with pebbly sandstone. Sandstones are less indurated.
Middle Member (Bm)		1220	Thick bedded, coarse- to very coarse-grained, "pepper and salt" sandstone with dark gray mudstone. Sandstones are moderately indurated. (sst>>ms)
Lower Member (Bl)		340	Medium- to coarse-grained, sandstone with dark mudstone. Psudo"pepper and salt" sandstone are found in which the amount of biotote flakes are less. (sst>ms)
Arung Khola Formation (A)			
Upper Member (Au)		1350	Medium- to coarse-grained, gray sandstone alternates with variagated mudstone. Gray mudstone and "pepper and salt" texture sandstone are rarely found. (sst>ms)
Middle Member (Am)		250+	Fine-grained, calcareous, gray sandstone interbeds with variegated mudstone. Pseudoconglomerates are rare. (ms=sst)
Lower Member (Al)		500+	Fine-grained, calcareous, greenish gray sandstone interbeds with variegated mud-stone and siltsone (35:65). Psudoconglomenrates are commonly found. (ms>>ss).

*indicates not exposed in the Tinau Khola section, west Nepal

(3)The Lesser Himalayan Zone

The Lesser Himalayan Zone lies between the Main Boundary Thrust (MBT) to the south and the Main Central Thrust (MCT) to the north and covers a large area of the Nepal Himalaya **(Fig. I-5).** It is mostly composed of early to middle ***Proterozoic*** unfossiliferous[1] ***low-grade*** **metasedimentary** rocks, which are called the Lesser Himalayan Metasediments (LHM). The LHM is ***unconformably/disconformably*** covered by the younger rocks of ***Permo-Carboniferous*** to

[1] Carrying no fossil

Miocene (the Tansen Group) and Cenozoic (Bainskathi and Dumri formations) strata. The MBT is essentially a continuous east-west extending structure all along the Himalayan range. This large fault can be very well recognized in the field and also clearly identifiable in air-photos. Along the MBT, The LHM tectonically overlies the Neogene to Quaternary Siwalik Group.

The Lesser Himalayan Zone displays a relatively subdued and matured topography. At many places these ***low-grade metasedimentary rock*** units are tectonically overlain by higher-grade metamorphic rocks (the Higher Himalayan ***gneisses***) that traveled from their root zones in the north along the MCT and the Mahabarat Thrust, and form narrow and isolated relict bodies called **nappe** and **klippe** resting over the Lesser Himalayan rocks (Upreti, 1999).

In central Nepal, Stöcklin and Bhattarai (1977) and Stöcklin (1980) have used the term **Nawakot Complex** to include all the older Lesser Himalayan rocks (mostly low-grade metamorphic rocks of Precambrian age), and **Kathmandu Complex** for all the medium-grade metamorphic rocks and younger sedimentary rocks (**Table I-3**). The Kathmandu complex lies tectonically above the Nawakot Complex. The boundary is the Mahabarat Thrust and the Kathmandu Complex is thought to have travelled several hundred kilometers southward and formed the Kathmandu Nappe (Hagen, 1969).

In western Nepal, on the other hand, Sakai (1983, 1985, 1991) called the older Lesser Himalayan rocks (of mostly Paleoproterozoic to Mesoproterozoic**)** as the ***Kali Gandaki Supergroup*** and the overlying younger Lesser Himalayan rocks of the upper Paleozoic to Mesozoic ***Tansen Group*** and the Cenozoic **Bhainskati and Dumri formations (Table I-4**). The rocks of the Tansen Group and the younger two formations overlie the Kali Gandaki Supergroup with a disconformity..

For convenience[2], in this guidebook we use the stratigraphic subdivisions given by Stöcklin and Bhattarai (1977) and Stöcklin (1980) that is shown in Table I-3. However, because the Robang Formation has been found to belong the lower Nawakot Group as mentioned below, and the unconformity between the Dhading Dolomite and the Benighat Slate is not well recognized, in this guidebook, the subdivision between the Lower and Upper Nawakot Complex is not followed. Instead, the entire lower and younger Nawakot Complex is described as simply the Nawakot Complex.

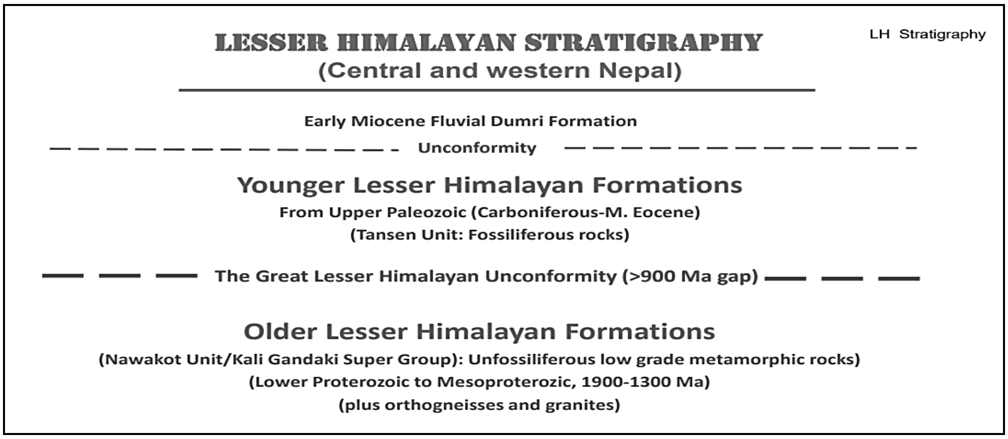


Fig. I-6: Broad subdivision of the Lesser Himalayan rocks of Nepal Himalaya (Upreti, 1999).

For readers' conveniences, the comparison of stratigraphic sequences in Central (Stocklin, 1980) and Western (Sakai, 1985, 1991) Nepal for the areas of Lesser Himalayan Zone and further south is shown in Table I-4, although the upper part of these stratigraphies are problematic as mentioned

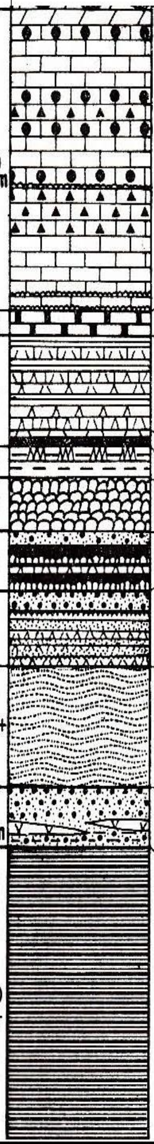
[2] This is because we are familiar with the Nawakot Group of central Nepal, and also because Sakai's stratigraphy has been proposed in the area further south and did not cover the present section.

above. Upreti,1999 has proposed a broad subdivision of the Lesser Himalayan formations into the Older and Younger Lesser Himalayan Formations separated by a very prominent unconformity which he named as The Great Lesser Himalayan Unconformity **(Fig. I-6).**

Table I-3. Stratigraphy of the Lesser Himalayan metasediments (central Nepal, modified after Stöcklin 1980). Details of the stratigraphy of the Kathmandu Complex is given in Table I-7.

<table>
<tr><td rowspan="2">Kathmandu Complex</td><td colspan="5">Phulchauki Group</td></tr>
<tr><td colspan="5">Bhinphedi Group</td></tr>
<tr><td colspan="6">---Mahabharat Thrust -----------------------------------</td></tr>
<tr><td>Complex</td><td>Group</td><td>Formations</td><td>Thickness</td><td>Main Lithology</td><td>Age after Martin (2011)</td></tr>
<tr><td rowspan="9">Nawakot Complex</td><td rowspan="3">Upper Nawakot Group</td><td>Robang Formation with Dunga Quartzite</td><td>200-1000</td><td>Phyllite, quartzite</td><td>Paleoproterozoic (probably equivalent to Kuncha Formation and this formation does not represent the youngest formation of the Nawakot Complex) as proposed by Stöcklin 1980</td></tr>
<tr><td>Malekhu Limestone</td><td>800</td><td>Limestone, dolomite</td><td>Paleo - Mesoproterozoic?</td></tr>
<tr><td>Benighat Slate with Jhiku Carbponate beds</td><td>500-3000</td><td>Slates, argillites, dolomite</td><td>Paleo-or Meso-Proterozoic?</td></tr>
<tr><td colspan="5">-----------------------------------Unconformity--------------------------</td></tr>
<tr><td rowspan="5">Lower Nawakot Group</td><td>Dhading Dolomite</td><td>500-1000</td><td>Stromatolitic dolomite</td><td>Paleo-or Meso-Proterozoic?</td></tr>
<tr><td>Nourpul Formation</td><td>800</td><td>Phyllite, meta-sandstone,dolomite</td><td>Paleo-or Meso-Proterozoic?</td></tr>
<tr><td>Dandagaon Phyllite</td><td>1000</td><td>Phyllite</td><td>Paleoproterozoic</td></tr>
<tr><td>Fagfog Quartzite</td><td>400</td><td>White quartzite</td><td>Paleoproterozoic</td></tr>
<tr><td>Kuncha Formation</td><td>3000+</td><td>Phyllite, quartzite, gritstone, conglomerate</td><td>Paleoproterozoic</td></tr>
</table>

Table I-4. Generallized lithostratigraphic section of the Kaligandaki Supergroup In Western Nepal (Sakai, 1985).



Geol. Age	Supergroup	Group	Formation	Thickness	Lithofacies (Western Central Nepal (Sakai, 1985))	Formation (Central Nepal (Stocklin 1980))
Cenozoic-Late Paleozoic	TANSEN GROUP					
early Palaeozoic	KALI GANDAKI SUPERGROUP	UPPER GROUP	(Robang F) Kerabari (Maleku Ls)	-7 2000 m -6	upper; bedded gray dolomicrite with red-purple sh, thin ss, oolitic dolomite, chert beds middle; bedded gray dolomicrite with chert beds and lenses lower; sheet-form algal ls, intraformational dolomicrite pebble cgl, bedded dolomicrite with ripple mark and flute cast	Robang Formation Maleku Limestone
			Riri Memb	150	black laminated ls~limy slate	
			Ramdighat (Benighat Sl)	-5 750	light brown laminated slate varicoloured calcareous slate with thin ls	Benighat Slate
late Precambrian		MIDDLE GROUP	Saidi Khola (Sorek F)	180	black & green slate bioturbated rhythmite of ss & sh	Dhading Dolomite
			Khoraidi (Dhading Do)	350	dolomitic stromatolite of various types, oolite, quartzite, rhythmite	
			Chappani (Dhading Do)	-4 400	quartzite with sun cracks, gray clay slate with stromatolite	
			Virkot (Nourpul F)	510	white pink quartzite and red-purple sh with ripple mark, sun crack and stromatolite	Nourpur
			Heklang (Dandagaon Qt)	-3 800+	green~light brown phyllitic slate with fine laminae and marl bed	Dandagaon Phyllite
			Thrust			
		LOWER GROUP	Naudanda (Fagfog Qt)	400 m -2	strongly rippled white quartzite with metabasite	Fagfog Quartzite
			Andhi (Kuncha F)	-1 2000 +	gray~light green phyllite with fine laminae and gritty phyllite	Kuncha

Table I-5. Correlation chart of the Lesser Himalaya, Nepal (Modified after Sakai, 1985).

Western Nepal			Central Nepal		
Indo-Gangetic Alluvial sediments and Bengal Bay sediments					
Shiwalik Group (Churia Group)					
Tansen Group (Sakai 1983)					
Kali Gandaki Supergroup (Sakai 1983)	Upper	Kerabari Formation	Nuwakot Complex (Stöcklin 1980)	Upper Nuwakot Group	Robang Formation Malekhu Limestone
		Riri Limestone Ramdighat Formation			Benighat Slate
		Conformity			Unconformity
	Middle	Saidi Khola Formation		Lower Nuwakot Group	Hushdi Beds
		Khoraidi Formation			Dhading Dolomite
		Chhappani Formation			Nourpul Formation
		Virkot Formation			
		Heklang Formation			Dandagaon Phyllite
		Fault			
	Lower	Naudanda Quartzite			Fagfog Quartzite
		Andhi (Kuncha) Formation			Kuncha Formation

Stratigraphy of the Nawakot Complex

The low-grade metasedimentary rocks outcropping in the north, west and southwest of Kathmandu Nappe has been grouped into the Nawakot Complex by Stocklin & Bhattarai, 1977 and Stocklin, 1980. They have worked out a detailed stratigraphy of Nawakot Complex in the surroundings of the Kathmandu Nappe which has been widely used as reference for the stratigraphic investigations farther away to west and east of the nappe. The stratigraphy proposed by them is presented in **Table I-2.**

The oldest formation of the Nawakot unit and perhaps in the entire Lesser Himalaya of Nepal is the **Kuncha Formation**, the base of which is not exposed anywhere. The Lower part of the formation consists of a monotonous sequence of flysch-like alternation of phyllites, phyllitic quartzites and phyllitic gritstones with some highly deformed lenticular and thin conglomeratic horizons. The phyllites have silky luster and are yellowish, blue-gray and green-gray in colour. This formation covers the widest area in the western part of Nepal extending to Gorkha - Pokhara and further west to Bheri river. Lenticular bodies of basic metavolcanics (amphibolites) are commonly found interlayered with this formation.

The Fagfog Quartzite rests above the Kuncha Formation with a sharp contact. It is a coarse to fine grained white quartzite with frequently developed ripple marks and current beddings. Thin phyllitic intercalations are not uncommon. The overlying **Dandagaon phyllite** is green-gray phyllite and darker than Kuncha Formation. Thin layers of dolomite and calc-phyllite appear first time in this sequence. It passes upward to the **Nourpul Formation** which has a mixed lithology of thinly banded purple slate-calcareous metasandstone and frequently intercalates thicker quartzites.

The overlying Dhading Dolomite is massive to thick bedded sequence which is finely crystalline to micritic in texture. It is characterized by bluish-gray colour and with splintery fractures. Black slates are commonly interbedded in it. Columnar stromatolites are profusely developed in this formation.

The Benighat Slate overlies the Dhading Dolomite with a possible erosional unconformity (?). It consists of dark, soft-weathering slates and phyllites. The carbonaceous slates contain much graphitic matter. Carbonate rocks are frequently intercalated. The **Malekhu limestone** which is a thin to thick bedded platy dolomite and siliceous limestones of light gray colour conformably lies over the Benighat Slate.

The **Robang Formation** consisting of the sericite-chlorite phyllites of green-gray colour and interbedded quartzites and amphibolites (found along the Malekhu Khola) was considered as the youngest formation of the Nawakot unit by Stocklin & Bhattarai (1977) and Stocklin (1980). However, recent works have shown that the Robang Formation belongs to the Lower Nawakot Group (probably a part of the Kuncha formation) and not the youngest formation of the Upper Nawakot Group. Robang Plyllite rests above the Malekhu Limestone by a thrust known as the **Ramgarh Thrust** (Pearson and DeCelles, 2005). According to these authors, the stratigraphy of the upper Nawakot Group in Table I-5 does not stand any more.

Age of the older Lesser Himalayan Rocks (Kuncha Formation, Fagfog Quartzites and Malekhu Limestone)

In central Nepal, uncertainty of the absolute depositional ages and the relative stratigraphic positions of several formations in the Proterozoic part of the Lesser Himalayan series existed for long. Recently, Martin et al. (2011) attempted a stratigraphic and geochronolgic work at the stratigraphic base of the Lesser Himalayan series in central Nepal which has provided a good foundation in establishing the stratigraphy and ages of these older rock sequences.

Martin et al. (2011) found the detrital zircon U/Pb isotopic ages that constrains the maximum possible depositional ages for the previously defined Kuncha Formation, Kushma Formation and Fagfog Wuartzite at their type localities in central Nepal as 1900, 1770, and 1810 Ma, respectively. According to him, because the 1770 Ma constraint on the maximum possible depositional age comes from the lower part of the Fagfog Quartzite, the entire formation must have been deposited after 1770 Ma. Granites (Ulleri Augen gneiss) intruded the Kuncha Formation at 1878±22 and 1780±29 Ma. The former age, combined with the constraints from detrital zircon ages of the Kuncha Formation, constrains the deposition to the Kuncha Formation to 1900–1856 Ma, considering uncertainties. The zircon U/Pb isotopic ages thus suggest an unconformity/disconformity of a minimum duration of 86 million years between the Kuncha Formation and the Fagfog Quartzite.

Martin et al. (2011) also concluded that Carbon isotopes of carbonate from the Malekhu Limestone suggest deposition prior to c. 1300 Ma. The Malekhu Limestone (considered to be equivalent of Kerabari Formation of Tansen area, Sakai, 1983) is stratigraphically younger than the Fagfog Quartzite overlain with a disconformity by the younger than ~300 Ma (late Carboniferous-Permian) Sisne Formation (Gondwanas) in Tansen area. In central Nepal this disconformity is not present and the Malekhu Limestone is overlain by the older Lesser Himalayan rocks along a thrust (Ramgarh Thrust). Thus the unconformity between the youngest Lesser Himalayan） unit and the Gondwana sequence spans at least 1000 million years and rules out the presence of any Neoproterozoic or lower Paleozoic strata in the Lesser Himalayan series in central Nepal.

Younger Lesser Himalayan Rocks (Tansen Group)

In Central Nepal, the deposition of older Lesser Himalayan rocks started with the Kuncha Formation at round 1900 Ma and ended before 1300 Ma with the deposition of Malekhu Limestone （Martin et al., 2011）. There is a very long period of nondeposition after Malekhu Limestone, forming a most important unconformity in Nepal named as the Great Lesser Himalayan unconformity by Upreti (1999) that spans at least 1000 million years. Laying above this unconformity is the Younger Lesser Himalayan rocks represented by the **Tansen Group** (Gondwana sequence) and younger 2 formations (post Gondwana sequence) defined by Sakai

(1983, 1991) . The rocks of the Tansen Group with a total thickness of about 1200 m rest above the older Lesser Himalayan rocks (Nawakot Complex of Stocklin, 1980 and Kali Gandaki Supergroup of Sakai, 1983). These fossiliferous rocks are well exposed in Tansen, Piuthan, Tosh, Sallyan, and Jajarkot-Rukum areas in western Nepal and some outcrops are found in eastern Nepal along the Koshi River section. Sakai (1983) described in detail those younger Lesser Himalayan rocks **(Table. I-6).**

The Gondwana Sequence

The Gondwana Sequence unconformably/disconformably overlying the older unfossiliferous Lesser Himalayan rocks is largely a non-marine sequence. Sakai (1983, 1991) studied this sequence in detail and termed the Tansen Group, which consists of 3 formations.

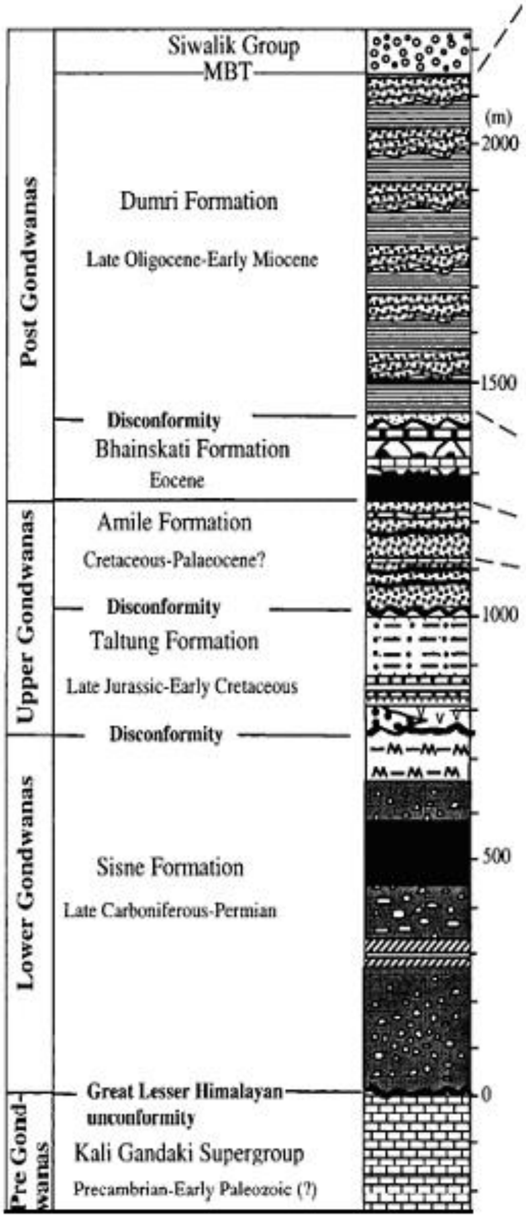
The Sisne Formation represents the oldest rocks of the Tansen Group and well exposed in the Tansen Synclinorim. This formation rests disconformably on the Kerabari Formation of the Kali Gandaki Super Group (Sakai, 1985) with a basal conglomerate derived from the underlying Kerabari Formation. Sisne formation is mainly composed of **glacial diamictite** and claystone or mudstone (converted into slates) with some beds of sandstones and conglomerates. They are unstratified and consists of scattered clasts of various sizes and shapes embedded in the structureless clayey to silty matrix. When the proportion of the clasts increases, the rocks become a true conglomerate. The clasts vary in size from pebble-cobble to sand size but sometimes exceed 2 m in diameter. The uppermost part of the Sisne Formation consists of mudstone with rhythmically interlayered fine-grained sandstone. The depositional age of the Sisne Formation is defined as Late Carboniferous to Permian.

The Taltung Formation: It disconformably rests on an eroded surface of the Sisne Formation, and includes fluvial shale, conglomerate and sandstone. Some basalt lava flows named the Aulis Basalt are intercalated near the base of this formation giving it an olive green colour. The basal conglomerate **(the Charchare Conglomerate)** of the Taltung Formation forms an important marker bed.

The Taltung Formation yields abundant plant fossils at many horizons and these floral assemblages indicate the affinity to the Upper Gondwana Plants of late Jurassic to early Cretaceous age

The Amile Formation: This formation is

Table. I-6 Lithostratigraphy of the Tansen Group (Sakai, 1991).



largely composed of nonmarine sediments, and exhibits a diverse sequence of rocks that consists dominantly of sandstone with subordinate alternating sandstone and shale, and shale and limestone. Feruginous white quartzite characteristically occurs in the Formation. The basal bed consists of an about 10 m thick white conglomeratic quartz arenite that rests on a distinctly and irregularly eroded surface of the red-purplish shale of the Taltung Formation. Many of the sandstones of the Lower member are thoroughly mottled by ferruginous matter. The Middle Member is characterized by the presence of fossiliferous siltstone and limestone. The fossiliferous siltstone beds form a distinct unit up to 20 m in thickness with thin, 1enticular interbeds of argillaceous limestone that abundantly yield marine bivalves, gastropods, echinoids, corals and some others. They are overlain by a pink-coloured limestone which also contains marine fossils. The Upper Member of the Amile Formation comprise a bioturbated, carbonaceous muddy sandstone containing coalified wood fragments. The Amile Formation is assigned to Cretaceous to earliest Tertiary in age (Sakai, 1983.

The Post Gondwana sequence (Paleogene - Early Neogene)

Restricted occurrences of these post Gondwana rocks are well documented all along the Himalaya. In Nepal, Eocene rocks were known to occur from Tansen, northern Dang and Surkhet from quite early dates. Later, it was also mapped westward in areas in western Nepal across Karnali, Seti rivers and beyond. In Tansen area, Sakai (1983) has mapped these rocks and divided them into two formations - the lower Bhainskati Formation and the upper Dumri Formation.

The Bhainskati Formation is a nummulit[illegible]ring formation which was the first known Eocene locality in the Lesser Himalaya of Nepal (Sharma 1973). This formation is well exposed around the Tansen Synclinorium (Sakai, 1983). In this area, the formation conformably overlies the Amile formation with an abrupt change of lithofacies. Bhainskati Formation is a marine formation made up of black shale with many thin fossiliferous dark muddy limestones. The upper part of this formation mostly consists of green and reddish-purple shale with subordinate hematite beds and hematite ooids. In the lower middle part of this formation occurs a large number of fossils of bivalves, gastropods and larger foraminiferas.

The **Dumri Formation** from the Tansen area rests disconformably over the eroded surface of the Bhainskati Formation (Sakai, 1983). It comp[illegible] a thick series of medium-grained, bluish-gray to greenish gray quartzose sandstone interbedd[illegible]ith red-purple and green shales. Vertebrate bone fragments, carbonized plant remains includi[illegible]aves, trunks and branches are reported. however, no fossils for age determination are found.[illegible] this formation unconformably lies over the late Eocene Bhainskati Formation the age assign[illegible] these rocks are from Oligocene to early Miocene. Dumri Formation is a fluvial deposit and represents the earliest foreland basin deposits in the Himalaya.

(4) The Kathmandu Nappe

The Kathmandu Nappe is one of a series of klippen and half-klippen in the southern Himalaya which are collectively referred to as the Lesser Himalayan Crystalline Nappes or the Outer Crystalline Klippen. The Kathmandu Nappe was first recognized by Hagen (1969) and later mapped in detail by Stöcklin and Bhattarai (1977) and Stöcklin (1980) **(Fig. I-5).**

The base of the Kathmandu Nappe is defined by the Mahabharat thrust (a name proposed by Stöcklin and Bhattarai, 1977, Stöcklin, 1980), which is widely interpreted as the southern branch trace of the Main Central Thrust. The Paleo- to Mesoproterozoic older Lesser Himalayan rocks (the LHM) occur in the footwall of the Mahabharat Thrust, whereas the hanging wall is named as the **Kathmandu Complex** (e.g., Stöcklin, 1980) (Table I-7), which is divided into two groups, viz., the approximately 10 km thick (i) **Bhimphedi Group** of Late Precambrian age with amphibolite facies metamorphic rocks, and the unconformably overlying 3.5-4 km thick, and (ii) the **Phulchauki Group** of unmetamorphosed to weakly metamorphosed sediments containing fossils of Lower-Middle Paleozoic age (Table I-7, Stöcklin and Bhattarai, 1977 and Stöcklin, 1980). Stöcklin and

Bhattarai, (1977) and Stöcklin, (1980) have described the lithstratigraphy of the BhimPhedi and Phulchauki groups in detail as follows.

Table I-7. Stratigraphy of the Kathmandu Complex (modifield after Stöcklin and Bhattarai, 1977 and Stöcklin, 1980).

<table>
<tr><th>Complex</th><th>Group</th><th>Formations</th><th>Thickness (m)</th><th>Main Lithology</th><th colspan="2">Age</th></tr>
<tr><td rowspan="12">Kathmandu Complex</td><td rowspan="5">Phulchauki Group</td><td>Top Limestone</td><td>300</td><td>Limestone, dolomite</td><td colspan="2">Devonian (?)</td></tr>
<tr><td>Chitlang Formation</td><td>1000</td><td>Slate</td><td colspan="2">Silurian</td></tr>
<tr><td>Chandragiri Limestone</td><td>2000</td><td>Limestone</td><td colspan="2">Cambro-Ordovocian</td></tr>
<tr><td>Sopyang Formation</td><td>200</td><td>Slate, calc-phyllite</td><td colspan="2"></td></tr>
<tr><td>Tistung Formation</td><td>3000</td><td>Metasandstone, phyllite</td><td colspan="2"></td></tr>
<tr><td colspan="6">--Transition--</td></tr>
<tr><td rowspan="6">Bhimphedi Group</td><td>Markhu Formation</td><td>1000</td><td>Marble, schist</td><td colspan="2"></td></tr>
<tr><td>Kulekhani Formation</td><td>2000</td><td>Quartzite, schist</td><td></td><td rowspan="5">Precambrian</td></tr>
<tr><td>Chisapani Quartzite</td><td>400</td><td>White quartzite</td><td>480-500 Ma</td></tr>
<tr><td>Kalitar Formation</td><td>2000</td><td>Schist, quartzite</td><td></td></tr>
<tr><td>Bhainsedobhan Marble</td><td>800</td><td>Marble, garnet-schist</td><td></td></tr>
<tr><td>Raduwa Formation</td><td>1000</td><td>Garnetiferous schist, quartzite</td><td></td></tr>
</table>

The Bhimphedi Group

The lithology of the Bhimphedi Group consists of pelites, quartzites and carbonates which are locally intruded by a number of Cambro-Ordovician granitoids named as the Palung Granite, Agra Granite, Narayanthan Granite etc (Stöcklin, 1980; Gehrels et al., 2006) ranging in age from 470 to 490±11 Ma. The metasedimentary rocks of the Bhimphedi Group show a steady decrease in grade of metamorphism from the garnet-amphibole grade at the bottom to a sericite-chlorite grade on the top (Johnson et al., 2001). The total thickness of the Bhimphedi Group is about 10 km, and consists of 6 formations (Stocklin and Bhattarai, 1977; Stocklin, 1980).

The lowest formation of the Bhimphedi Group is the **Raduwa Formation** consisting of a coarsely crystalline garnetiferous two mica-schists with minor quartzite intercalations. With a transitional contact, this formation gives way to the overlying **Bhainsedobhan Marble**. It is a coarse crystalline, well-bedded to massive white marble. Above the Marble, the characteristically dark coloured **Kalitar Formation** occurs. It is composed of dark-green-gray biotite or biotite-muscovite schists with intercalations of thin impure micaceous quartzite.

The C**hisapani Quartzite** overlies the Kalitar Formation. It is a white or pale-green clean quartzite. It is a fine-grained thin to thick-bedded quartzite showing strong crossbedding and ripple marks. The contact with the overlying **Kulekhani Formation** is a rapid transition.

The Kulikhani Formation is essentially made up of fine-grained biotite-schist, and impure, strongly micaceous quartzite of dark and light-green-gray colour. The youngest formation of the Bhimphedi Group is the **Markhu Formation** of a mixed lithology, consisting of schists, quartzites and carbonates (marble) in varying proportions.

The Phulchauki Group

The Phulchauki Group is generally dominated by unmetamorphosed limestone, shale, and sandstone, with a conglomeratic horizon and associated unconformity at or near the base. These rocks are generally accepted as correlative to the age-equivalent Tethys Group rocks exposed to the north (e.g., Upreti, 1999). The Bhimphedi Group passes into the Phulchauki Group without a significant break in sedimentation, however, a minor unconformity has been recently recognized (Gehrels et al, 2006). The Phulchauki Group has a total thickness of 5-6 km and includes 5 formations.

The lowest **Tistung Formation** marks a change in lithofacies from the unfossiliferous Bhimphedi Group to the fossiliferous Tistung. This formation is made up of fine clastic sequence of metasandstones, siltstones, phyllite, slates and calc-phyllites. The overlying **Sopyang Formation** is a transitional phase between the fine-grained clastic Tistung and the thick younger The **Chandragiri Limestone** is a distinct formation of the Phulchauki Group due to its thick limestone sequence and wider distribution forming the Phulchauki-Chandragiri hill range to the south and west slopes of the Kathmandu Valley. The main rock type is a yellow or brown well bedded to massive weathered limestone containing abundant crinoids, cystoids and echinoderms of the Upper-Middle Ordovician age.

The Chitlang Formation consists of dark purplish soft weathered slates with white quartzite interbedded in the lower part and argillaceous limestones in its upper part. In these rocks of the Phulchauki Group, a rich assemblage of Silurian fauna of trilobites, brachiopods, echinoderms, etc. (Bordet ***et** al.* 1959) have been identified. The **Devonian Top Limestone** (Stöcklin, 1980) is a revised name for the earlier Godavari Limestone of Stöcklin and Bhattarai (1977). This is the youngest formation of the Phulchauki Group and, in fact, the youngest formation in the entire Kathmandu Nappe itself. It occupies the core of the Phulchauki syncline. The lower part consists of well bedded green and purple argillaceous limestones crowded with crinoidal fragments. The main part of the formation above the crinoidal limestone is the medium to coarse grained massive crystalline limestone and dolomite of grayish blue, pale brown to purple colour. The age of the Devonian Top Limestone is yet to be established.

(5) The Higher (Greater) Himalayan Zone

The Higher (or Greater) Himalayan Zone has been mapped and traced along the entire Himalayan region and has been named differently at different places. Geologically, the Higher Himalayan Zone includes the rocks lying to the north of the Main Central Thrust (MCT) and below the fossiliferous Tethys Himalayan Zone. The northern or the upper limit of this zone is generally marked by a normal fault known as the South Tibetan Detachment System (STDS).

This zone consists of about 10 km thick succession of crystalline rocks and also known as the Tibetan Slab (Le Fort 1975). The crystalline rocks which are collectively called the Higher Himalayan Gneisses in this guidebook extend continuously along the entire length of the country. Le Fort (1975) and Le Fort et al. (1986) studied the rocks of the Higher Himalayan Zone in detail in Central Nepal and found that they are composed of mostly pelitic and psammitic gneisses in the lowest, calcareous gneisses in the middle, and the granitic gneisses in the uppermost, forming the Formation I, Formation II, and Formation III from the bottom to the top (Table I-8). Tertiary tourmaline granites occur at the upper part of the unit intruding the Formation III rocks as well as the overlying Tethys Sediments. The existence of 0.8–1.0 Ga detrital zircons in Greater Himalayan gneisses in the Langtang area and the occurrence of ca 0.5 Ga granite intrusions in the Gneisses demonstrate that the sedimentary precursors of these rocks are no older than 0.8 Ga and probably deposited over the Late Proterozoic~~–Middle~~ Late Cambrian interval.

.Table 1-8, Stratigraphy of the Higher Himalayan Gneisses (Le Fort, 1975)

Formation III	Granitic gneisses, Gneissose granite, Augen gneiss
Formation II	Calcareous gneiss, Marble
Formation I	Biotite gneiss, Garnet-Biotite gneiss, Sillimanite-garnet-biotite gneiss, Kyanite-garnet-biotite gneiss, Two mica gneiss.

(6) The Tethys Himalayan Zone (Tibetan-Tethys Zone)

The Tethys Himalayan Zone lies above the Higher Himalayan Zone separated by the South Tibetan Detachment System (STDS), a normal fault, continues to the north in Tibet. In Nepal, the fossiliferous rocks of the Tethys Himalayan Zone are well developed in Thakkhola, Manang, and Dolpa areas and are called the Tethys Group in this guidebook. These rocks are collectively known as the Tethys Group or the Tibetan-Tethys Sedimetary Sequence (also called the Tethys sediments). The general stratigraphy of the Tethys Group formed in the Kaligandaki area by Colchen et al (1980) is given in **Table I-9.** Rocks of the Tethys Group are distributed on the most of the Great Himalayan peaks of Nepal including Mt. Everest, Manaslu, Annapurna, Dhaulagiri and so on (Fig. 5). The Tethys Group is composed of sedimentary rocks such as shale, limestones, and sandstones, ranging in age from Lower Palaeozoic to Palaeogene. The rocks exposed at the basal part of the zone shows a medium to higher-grade, mostly thermal metamorphism which gradually decreases upward and almost disappears at a higher level. The rocks of this zone are generally rich in fossils content. The lithostratigraphy of the Tethys Group described in Western Nepal (Colchen et al., 1986) is shown in Table I-9 and detailed description by them are given in Chapter II.

Natural Hazards in the Nepal Himalaya

Nepal is known to be highly vulnerable to natural disasters; a recent study puts it as a very high-risk country in the world. It is estimated that over 90% of the Nepalese population are constantly exposed to two or more types of natural disasters. Every year in average over 300 people die due to natural disasters and the cost due to loss and damage to property runs into hundreds of millions of rupees. Numbers of natural disaster events occur in Nepal due to natural as well as man-made causes. Very fragile geologic condition, steep topography and strong monsoon climate are major reasons of natural hazards in this country. The condition is further deteriorated due to increasing population, unplanned settlement, and weak economic condition which make the mitigation of natural disaster very difficult in Nepal.

Nepal is found vulnerable to various types of natural disasters such as landslide, debris flow, flood, avalanche, Glacial Lake Outburst Flood (GLOF), and earthquake. Each geologic and physiographic zones of Nepal suffers form various types of natural hazards. The Indo-Gangetic Alluvial plaine in the south is prone to frequent floods where as the mountain areas are vulnerable to landslide, debris flow, GLOF, and avalanche (Upreti and Dhital, 1996; Chalise and Khanal, 2001; Upreti, 2001). The Siwalik Range (the Sub Himalayan Zone) has very rugged topography with steep slopes and contains soft sedimentary rocks. The area also receives heavy rainfall during the monsoon period. These factors make the Siwalik Range area a highly prone area to heavy soil erosion, landslide and debris flow. The Lesser Himalaya is mostly made up of soft rocks such as phyllites and slates and

Table I-9. The stratigraphy of the Tethys Group in the Kaligandaki Valley (after Colchen et al., 1986).

Formation	Thickness (m)	Main Rock type	Important fossils	Age	
Muding Formation	300	Thin bedded, fine-grained, grey sandstone and grey to dark grey shale	*Hedbergella infracretacea*	Middle Cretaceous	
Chukh Formation	900	Thick bedded, pebble bearing greenish grey sandstone and dark grey shale.	*Ptillophyllum, Nepalensis (Plant), Tropaeum australe*	Lower Cretaceous	
Spiti Formation	500	Laminated grey shale interbeds with grey limestone and sandstone.	*Kranosphinctes Blanfordicera, Paraboliceras*	Upper Jurassic	
Lumachelle	300	Alternation of grey limestone with shale sandstone and marl.	*Oyster, Bellemnopsis*	Middle Jurassic	
Jomsom Formation	400	Dark grey micritic and Oolitic limestone interbeds with grey sandstone and black shale.	*Vidalina martana, Haurania,Belemnites, Formosus Oxycerites*	Lower Jurassic	Mesozoic
Quartzite Formation	300	Thick bedded quartzite interbeds with shale	*Trychyceras, Joannites, Arcestus, Arpodites, Juvavites,*	Upper Triassic	
Thinigaon	800	Alternating of light brown limestone and light grey shale. Shale is greater proportion than limestone	*Meekoceras Clypeoceras, Flemingites, Episageceras, Trachyceras*	Lower Triassic	
Thini Chu Formation	700	White colored, coarse-grained quartzite interbeds with grey slate.	*Spiriferella rajah, Fenestella polyseptata*	Permo-Carboniferous	
Tilicho Lake Formation	300	Grey, bluish grey to black limestone, calcschist and black shale.	*Attenuatus, Septopora ct.*	Permo-Carboniferous	
Tilicho Pass Formation	600	Black slate, phyllite, medium-grained sandstone and slate.	*Monograptides, Tentaculites Favosites*	Devonian	
Sombre Formation	600	Interbedding of black shale and sandstone with gritty dolomite.	*Monograptus Orthograptus Glyptograptus*	Silurian.	
North Face Quartzite Formation	700	Detrital sandstone, quartzite and white to pink schist.	*Orthambonites Glyptocystidae, Cheirocrinus*	Ordovician	Palaeozoic
Nilgiri Formation	1500	Thick bedded, blue limestone intercalated with schist.	Brachiopoda Nautiloidae	Ordovician	
Pi Formation	450	Interbedding of black schist and calcschist.	Crinoids	Ordovician	
Annapurna Yellow Formtion	2000	Bluish grey, limestone with quartzite and schist.	Worm traces, bilobites, Trilobites,	Cambrian	
Sanctuaire Formation	350	Alternating of greywacke, dolomite and phyllite.		Cambrian	

some other low-grade metamorphic rocks. These rocks are highly susceptible for weathering and erosion and prone to landslide and debris flow. The extremely high relief and steep slopes of the area of the Higher Himalayan Zone with heavy rainfall in its southern front make this area also highly vulnerable to landslide, debris flow, and rock fall. River damming by landslide is common in this zone which causes flash floods in the downstream by the breach of the landslide dams. The Trans Himalaya (Tethys Himalayan Zone) which lies in the rain shadow zone of the Himalaya and receive less than 250mm annual precipitation suffer very little from water induced disasters compared to the south. However, debris flow is common in some areas due to the development of either glacier-related sediments or steep slopes. Snow avalanches and rock falls are the major threats in the snow covered high altitude areas of the Himalaya. Earthquake is a constant threat to any part of Nepal because of its being on the active orogenic zone.

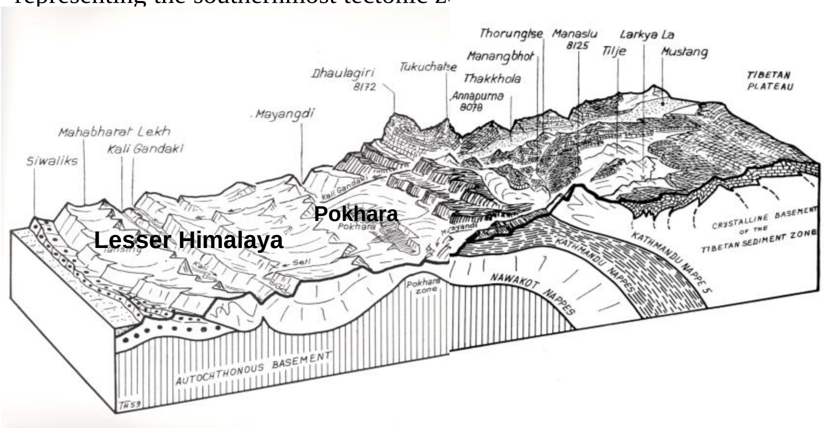
II. GEOLOGY AND NATURAL HAZARDS ALONG THE POKHALA-MUKTINATH COURSE

As this chapter is primarily aimed at providing geologic and natural hazard information along the Kaligandaki valley between Beni and Muktinath via Jomsom and Kagbeni, description of only the northern part of the Lesser Himalayan Zone from Beni and the Tethys Himalayan Zone up to Kagbeni-Muktinath, and the Higher Himalayan Zone between the two are included.

Geology of the Kaligandaki Valley

The Kaligandaki River in Western Nepal offers an excellent section for the study of the Lesser, Higher and Tethys Himalayan zones. Geology of the Kaligandaki River section between Beni and Muktinath is one of the most extensively studied areas of the Himalaya.

This part of the guidebook contains a zone-wise description of the geological characteristics of the Kaligandaki River section. The Indo-Gangetic Alluvial and Sub Himalayan (Siwalik) zones representing the southernmost tectonic zones of the Himalaya, is exposed only in the far south (**Figs.**



Chapters IV and V. For
a block diagram drawn
es of the geologic units
The geologic map and
along the Kaligandaki
we modified this map
m south to north, the
d below.

Fig. II-1: A general three-dimensional geologic outline of the western Nepal Himalaya.

(1) The Lesser Himalayan Zone

A wide area of western Nepal is covered by the Lesser Himalayan metasediments as explained in Chapter I (**Figs. I-1, I-3**). The geologic map of about 30km length along the Kaligandaki valley north from Beni to Dana is presented in **Fig. II-2**. The Lesser Himalayan rocks continue northward from Beni up to the MCT near Dana **(Fig. II-4).** The MCT is placed at the northern end of the Dana village**.** Stratigraphically, the rocks around Beni belong to the lowest section of the Lesser Himalayan Metasediments (the Nawakot Complex of Stöcklin 1980 or the Kali Gandaki Supergroup of Sakai 1985) known as the Kuncha (Andhi) Formation **(Table. I-3 in Chapter 1)** unger sections of the Lesser Himalayan rocks crop out. They are represented by some thin beds of purple rocks (purple slate and calcareous sandstone) with mud cracks and ripple marks of the Dhandagaon Phyllite, followed by a few hundred meters thick carbonate rocks, (essentially dolomitic limestone with subordinate amount of phyllite) of the Dading Dolomite.

The above-mentioned Lesser Himalayan stratigraphy of the area is well comparable with the well established stratigraphy of the Nawakot Complex in Central Nepal (Stöcklin 1980, **Table I-3**) and the Kali Gandaki Supergroup in Western Nepal (Sakai, 1985), though the thickness of rocks in this northern section is much reduced compared to their southern counterpart. As mentioned elsewhere, we provisionally follow the stratigraphy of Stöcklin (1980) throughout the present chapter. A geological cross section and a stratigraphic column between Beni and Kokhethati including the Lesser and Higher Himalayan Zones are given in **figs. II-5** and **II-6.**

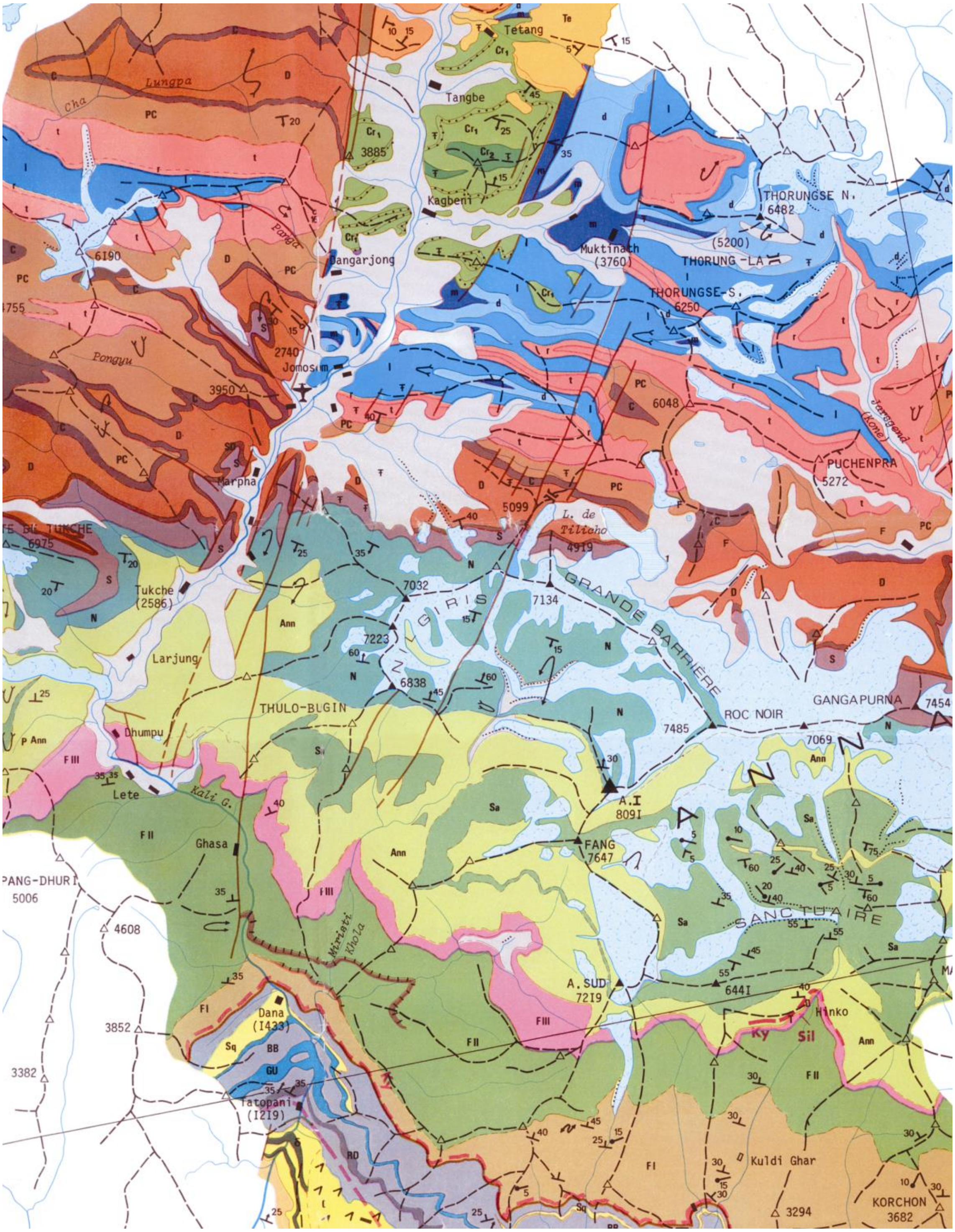


Fig. II-2. Geological map of central-west Nepal (after Colchen et al., 1980). The key is given in Fig. II-3. Note that our geologic maps along the trekking route do not strictly same as this map.

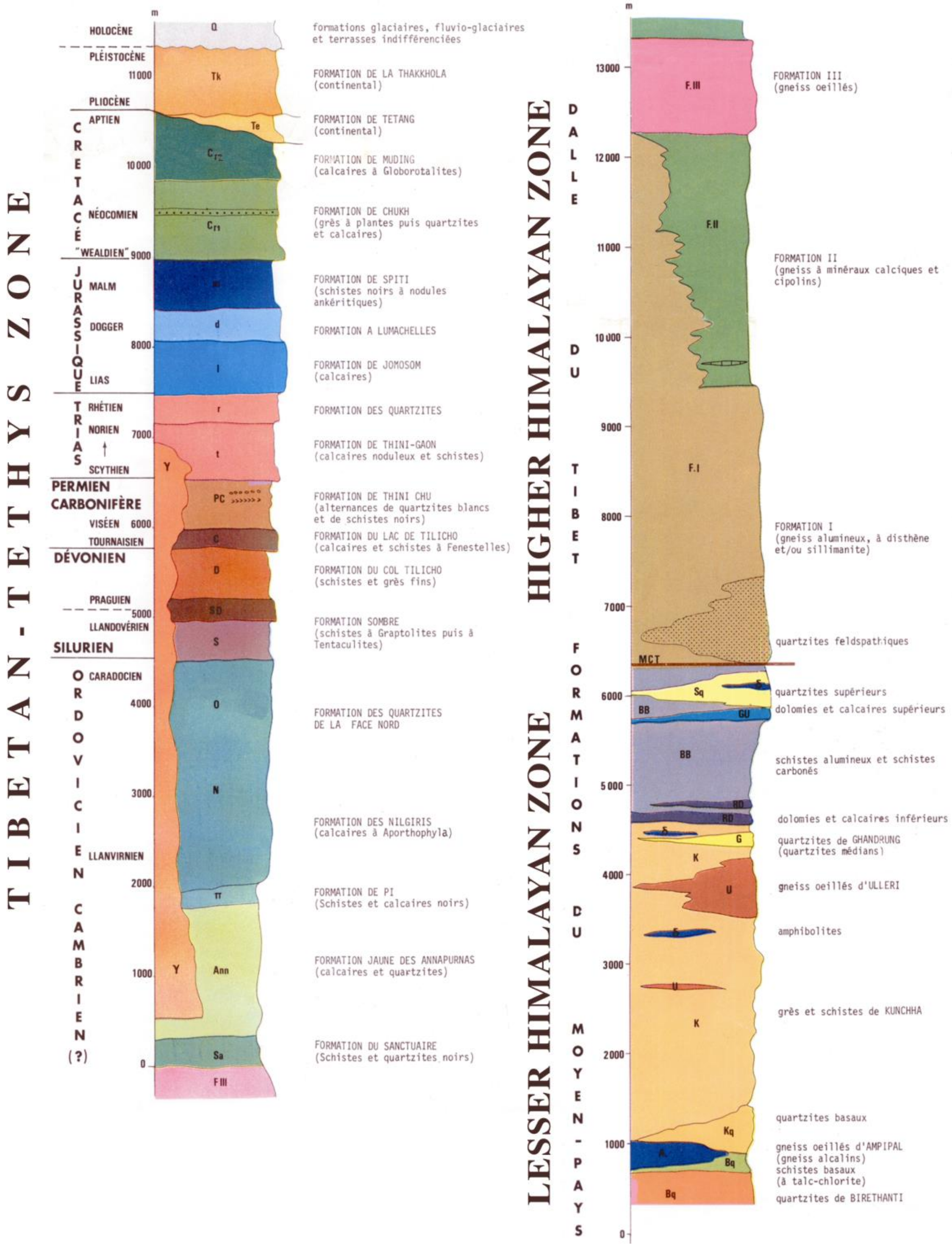


Fig. II-3. Stratigraphic sequence of the Tibetan-Tethys (A) and Lesser and Higher Himalayan (B) zones of central-west Nepal Himalaya (key to Fig. 17, Colchen et al., 1980).

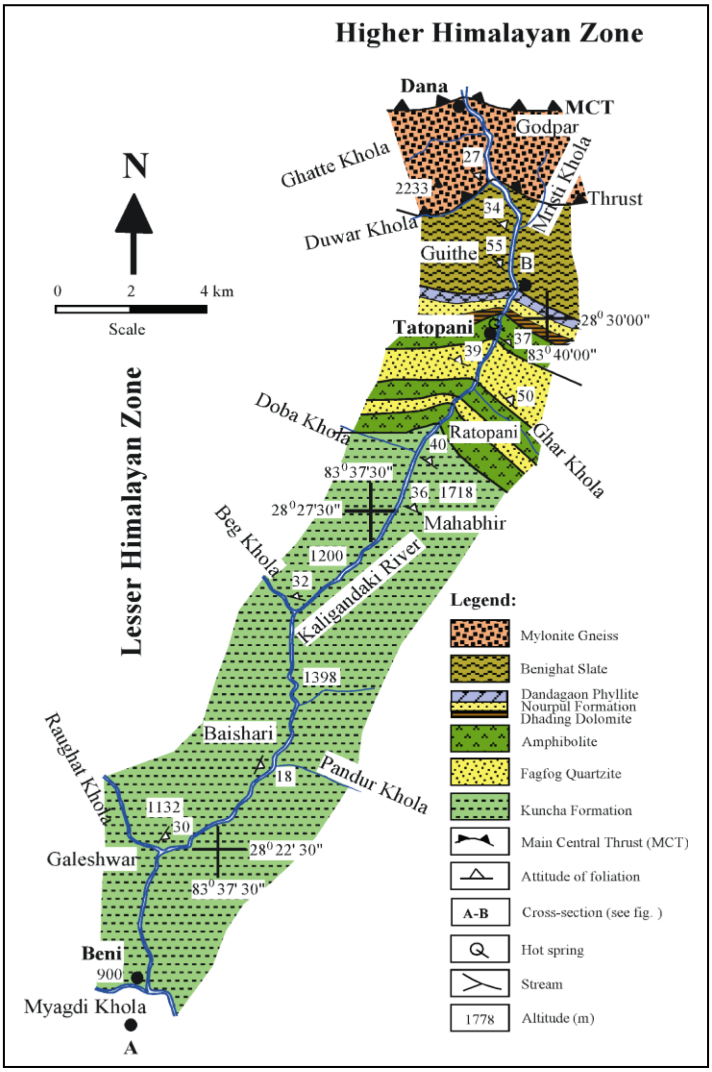


Fig. II-4. Geologic map of the Lesser Himalayan Zone along the Kaligandaki valley north of Beni (present study).

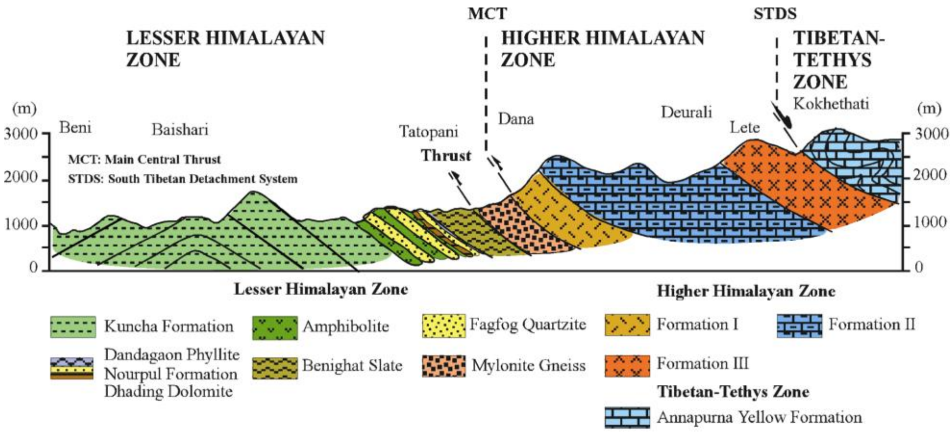


Fig. II-5. Geologic cross section between Beni and Kokhethati showing the major structures of the Lesser, Higher and Tibetan-Tethys zones.

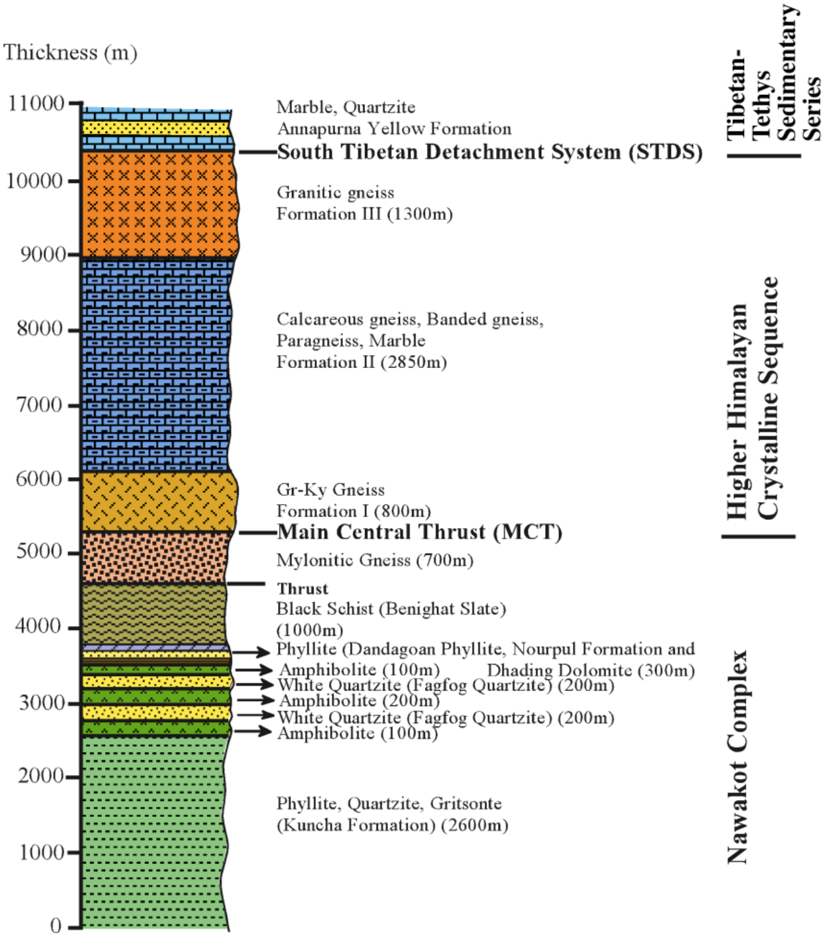


Fig. II-6. Stratigraphic column of the Lesser Himalayan and Higher Himalayan formation of the Kaligandaki valley between Beni and Kokhethati.

North of the black phyllites and carbonates, while approaching to the MCT, a series of various mylonites including phyllite-origin phyllonite, granite-origin mylonite, granitic gneiss-orogin mylonite, and various cataclasite of all the above rocks occur for about 4km N-S section of the Dana village. The field observation clearly shows a sudden change in both lithology and metamorphic grade of these rocks compared with the uppermost Lesser Himalayan units described above. We consider the area where the mylonitic rocks occur as the MCT zone and placed a fault at the southern margin and northern margin of the mylonite zone. The southern marginal fault forms the contact of the mylonitic rocks and the black schist of the upper Lesser Himalayan rocks. We consider this fault to form the lower major thrust of the MCT Zone. This thrust is comparable to the Ramgarh Thrust recognized by De Celles and others (1998) in other parts of the Nepal Himalaya. We consider the fault of the northern margin of the mylonite zone as the upper major thrust of the MCT Zone. We delineated this thrust fault to run along the Ghatte Khola flowing in the northern end of the Dana village.

All along the Himalaya including Nepal, the nature and position of the MCT and the characteristics of the rocks occurring in its vicinity has been a theme of serious discussions and controversy for long and a great deal of present-day research is focused on this zone. There is no general agreement among geologists on the issue of MCT. Therefore, the interpretation made by the authors of this guidebook may vary with interpretations by many other authors.

(2) ***The Higher Himalayan Zone***

Rocks of the Higher Himalayan Zone of Nepal have been studied in detail along the deep gorges of the major rivers including the Kaligandaki and Marsyangdi valleys in central-west Nepal that cut through the Higher Himalaya. These gorges expose over 12km thick Higher Himalayan crystalline rocks as well as rocks of the Lesser Himalayan and the Tethys Himalayan zones. The exposure of this deep-seated core of the mountain belt is one of the most distinctive characteristics of the Himalayan Orogen.

Le Fort (1975) grouped the Higher Himalayan crystalline rocks into three formations: Formation I, II and III (structurally from bottom to top). The Higher Himalayan rocks are well exposed along the Kaligandaki valley between Dana and Kokhethati **(Fig. II-7).**

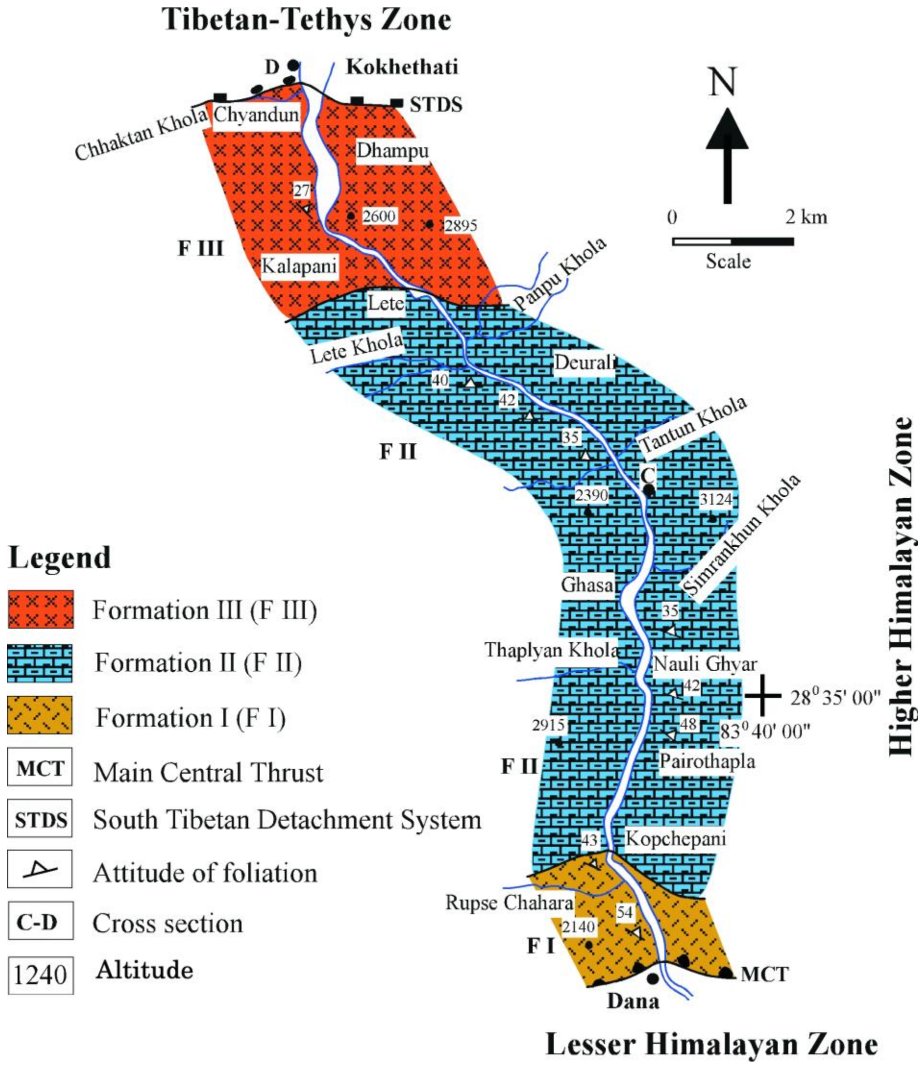


Fig. II-7. Geologic map of the Higher Himalayan Zone along the Kaligandaki valley (present study).

The total thickness of rocks in this section is about 5000m. The Formation I (800m thick) is the lowest unit and occurs in the southernmost section of the zone. This unit having pelitic to arenaceous composition consists of two-mica banded gneisses locally containing kyanite and garnet. The Formation II occurs in the middle part of the Higher Himalayan Zone and is mainly composed of an alternation of pyroxene and/or amphibole-bearing calc-gneisses, marbles and some pelitic gneiss. The total thickness of the Formation II is 2850m. The contact between the Formation I and II is not well defined due to gradual change of lithology between the two formations. The Formation III occurs in the northernmost section of the Higher Himalayan Zone. This unit is essentially made up of 1300m thick coarse-grained augen gneiss. The boundary between the Formation III and the calcareous rocks of the overlying Tethys Himalayan Zone (Annapurna Yellow Formation) is marked by the South Tibetan Detachment System (STDS) (Pechêr 1991; Godin et al., 1999).

The South Tibetan Detachment System (STDS) is located around the Kokhethati village at about the half distance between Beni and Jomsom. A good outcrop of this detachment is seen along a small stream called the Chhaktan Khola (just opposite Kokhethati) on the right bank of the Kaligandaki River (cf. **Fig. III-73)** as well as at the road crossing of the river on its right bank slope. This stream forms a waterfall and a large fan on the Kaligandaki flood plain. The Detachment is marked by a sharp contact between the augen gneiss of the Formation III of the Higher Himalayan Zone and the calcareous schist and dolomitic marble of the Tethyan-Tethys Zone. Leucogranite occurs at the boundary zone intruding into both the metasediments and granitic gneiss, and therefore the detachment fault itself is difficult to identify (Yoshida and others 2004).

(3) The Tethys Himalayan Zone (Tibetan-Tethys Zone)

The rocks of the Tethys Himalayan Zone known as the Tibetan-Tethyan Sedimentary Series (abbreviated as the Tethys Group or the Tethys Sediments in this guidebook) is very well preserved in the upper reaches of the Kaligandaki valley (Thakhola valley) (**Figs. I-I, II-9**). The geologic map between Kokhethati and Muktinath is presented in **fig. II-8** and is also seen in **fig. II-2**. The Thakkhola valley is a graben bounded by two N-S trending normal faults developed in the Paleozoic-Mesozoic rocks of the Tethys Himalayan Zone. A generalized tectonic map and a cross section by Hagen (1968, 1969) and Garzione et al. (2000) showing major rock groups and structures of the upper reaches of the Kaligandaki valley including the Thakola area are shown in **figs. II-10, II-11 and II-12.** The Tethyan sediments show very large-size folds (mega folds) particularly seen in the Nilgiri and Dhaulagiri ranges. A sketch showing large scale folds are shown above in **fig. II-9** (Colchen and others 1980) and in Figs. **III-14** and **III-60 of Chapter III**.

Following Colchen and others (1980), from the bottom to top the Tethys sediments are divided (T**able I-9, Chapter I**): (1) Sanctuaire Formation, (2) Annapurna Yellow Formation, (3) Pi Formation, (4) Nilgiri Formation, (5) North Face Quartzite, (6) Sombre Formation, (7) Tilicho Pass Formation, (8) Tilicho Lake Formation, (9) Thini Chu Formation, (10) Thinigaon Formation, (11) Quartzite Formation, (12) Jomsom Formation, (13) Lumachelle Formation, (14) Spiti Formation, (15) Chukh Formation, and (16) Muding Formation. The Cenozoic sedimentary sequence and the younger sediments rest on the Tethyan sequence. They include (17) Tetang Formation (18) Thakkhola Formation, and (18) Glacial, lacustrine, fluvioglacial , fluvial and terraces.

The Palaeozoic rocks mainly consist of limestone, dolomitic limestone and calcareous shale with some minor quartzite. The fossiliferous Mesozoic rocks are well exposed in Jomsom and northward. They are mainly composed of limestone and calcareous shale. Details of lithology, description, thickness, fossil content etc of each formation of the Tethys sediments are given in Table I-9 in Chapter I.

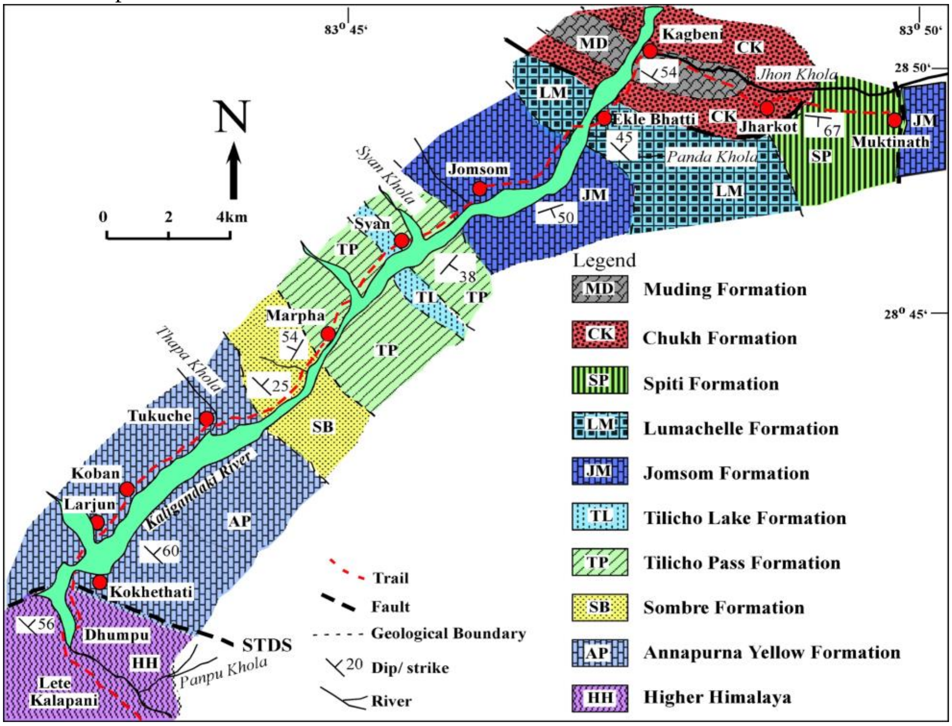


Fig. II-8. Geologic map of the Tibetan-Tethys Zone along the Kaligandaki valley (present study)

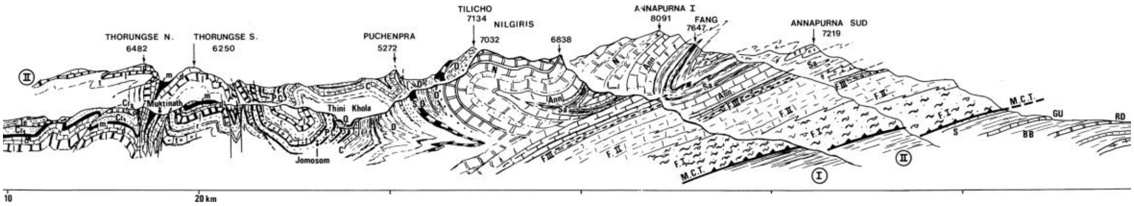


Fig. II-9. Geologic structures of the Annapurna-Nilgiri area showing well folded Tethys sediments (Colchen et al., 1980).

(4) *The Tatang and Thakkhola Formations (Thakkhola Graben-fill sediments)*

The Thakkhola Graben is bounded by Paleozoic Tethyan Series rocks in its western and Mesozoic Tethyan Series rocks in eastern sides. Cenozoic sedimentary sequence composed of lacustrine (lake origin) and fluvial (river origin) extensively develop within the graben (Hagen, 1968, 1969). All these sediments are distributed in the Mustang area north of Kagbeni and do not occur in the area of the present trekking route. The locally occurring older Tetang Formation is up to 240m thick and rests unconformably on Mesozoic Tethyan rocks. The age of the rocks range from 11 to 9.6 Ma (Garzione and others 2000). The younger Thakkhola Formation is up to 1000m thick and occurs throughout the graben. The basal part of this formation is estimated to be younger than 7 Ma in age. The map showing the distribution of the Tetang and Thakkhola formations along with the older basement rocks are shown in **figs. II-10** and **II-12**.

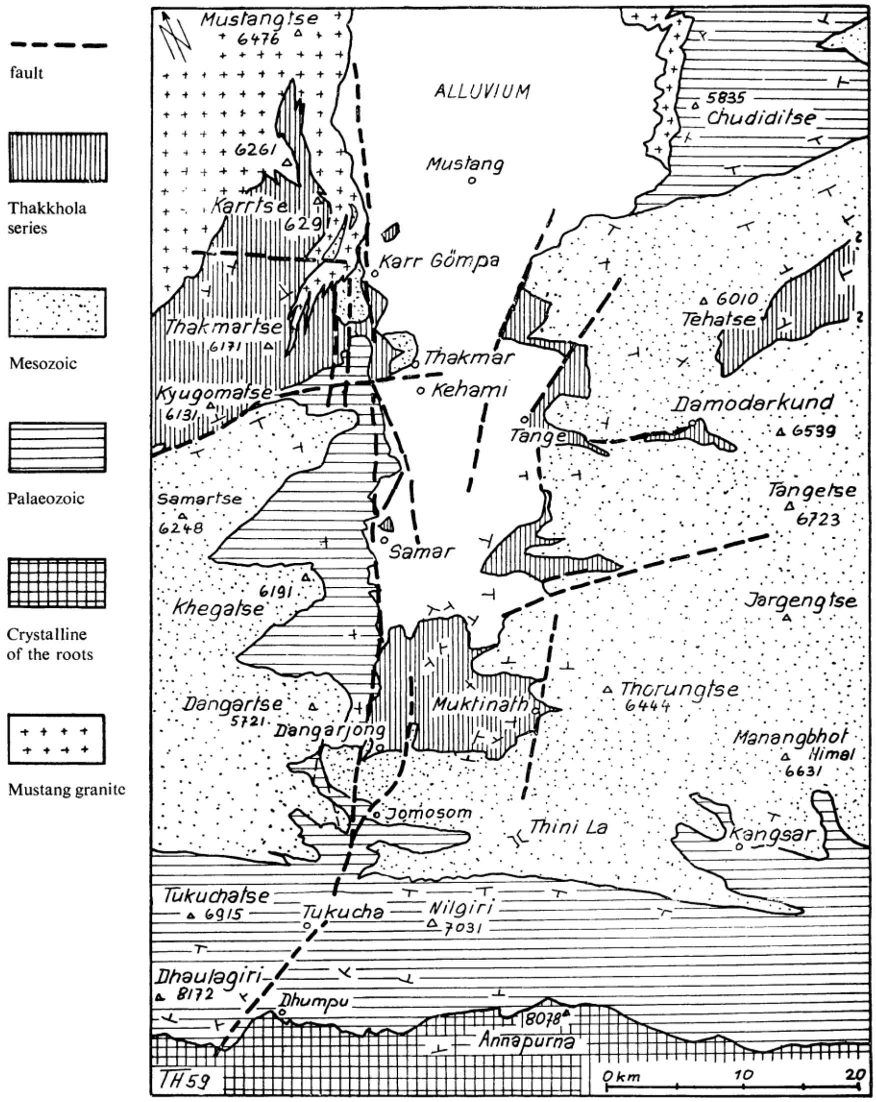


Fig. II-10. Tectonic map of the Thakkhola area (Hagen, 1969).

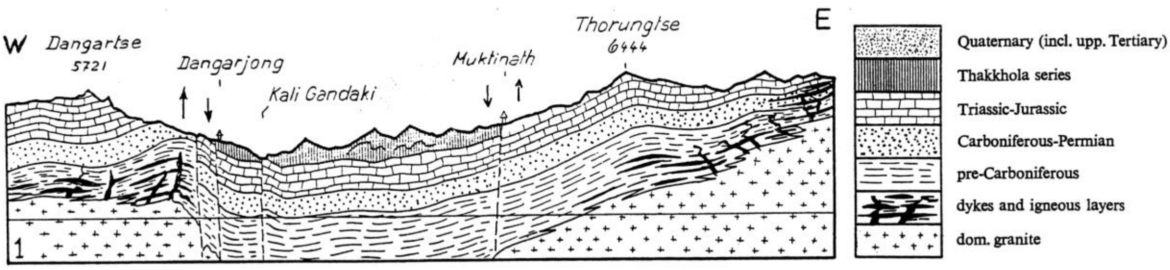


Fig. II-11. Geological cross section across the Thakkhola Graben between Dangartse and Thorungtse (Hagen, 1968).

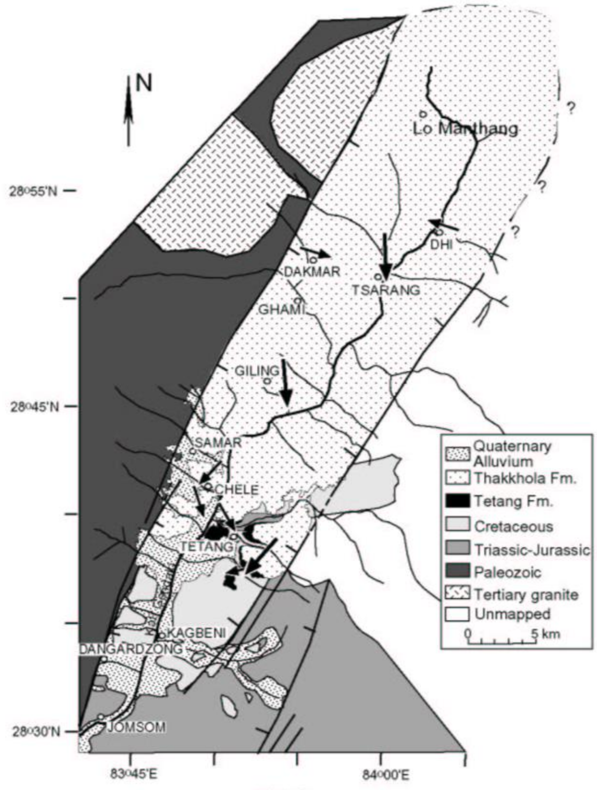


Fig. II-12. Distribution of Tetang and Thakkhola formations in theThakkhola Graben. Arrows indicate the palaeocurrent directions in the Tetang and Thakkhola formations (Garzione et al., 2000).

(5) Late Cenozoic Deposits and Terraces along the Kali Gandaki Valley

A wide variety of Neogene-Quaternary sediments of various origins such as lacustrine, glaciofluvial, glaciolacustrine, fluvial and debris flow develop along the Kaligandaki valley (**Fig. II-13**, Iwata, 1984; Adhikari and Wagreich, 2011). These sediments locally form several levels of river terraces along the valley. In addition thick glacial moraine deposits occur locally (**Fig. II-14**). Thick deposits of lacustrine, glaciolacustrine and glacial deposits extensively occur in the upper section of the trekking route mostly from Muktinath to Ghasa (Iwata et al., 1982; Iwata, 1984).

Thick Neogene glaciolacustrine sediments develop extensively along the Kaligandaki Valley from Kagbeni to Larjung (Iwata, 1984; Adhikari and Wagreich, 2011). These sediments are though to have deposited in the Paleo Marpha Lake (Fort, 1980) which is thought to have formed by a glacial damming at around Largung (Iwata, 1984). Iwata (1984) termed these sediments the Marpha Formation and suggested the time of the beginning of its deposition during the pre-last interglacial of middle Pleistocene citing data by Yoshida et al. (1984).

In Marpha, a thick deposit of glacier origin also occurs below the Marpha Formation (cf. **Fig. III-62**). Iwata (1984) identified this deposit to be the till. Yoshida et al. (1994) pointed out that the accumulation of the formation was during the Brunhes Normal Epock and ended before the Laschamp Event (possibly about 140000 to 50000 years BP). Yoshida and others (2023), however, described that the dark gray diamictite occurring at the right bank cliff of Pharam Khola backside (to the west) of the lower Marpha village is identified as the landslide debris. They considered a possibility that the above rocks form at least a part of the diamictite below the Marpha Formation.

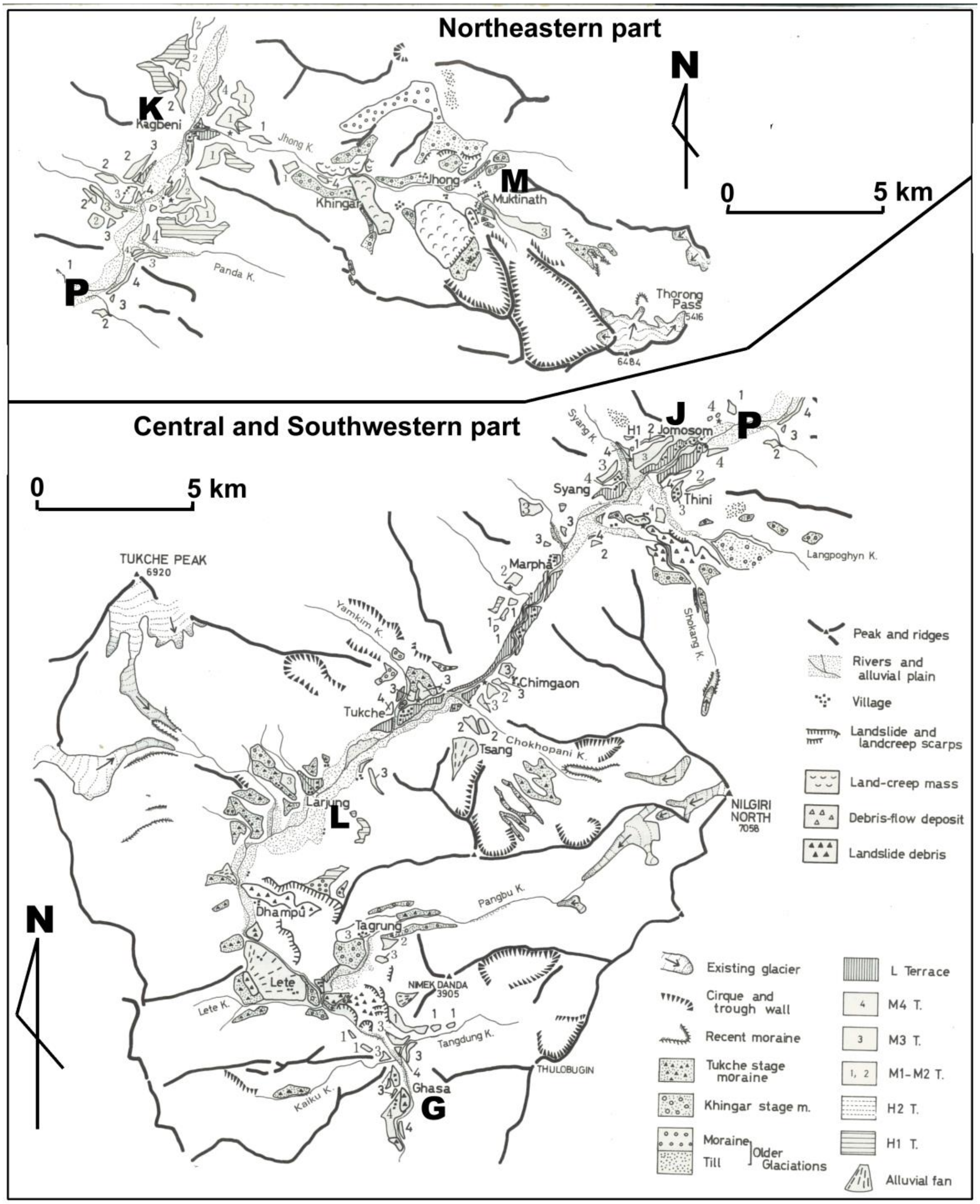


Fig. II-13 Distribution of Cenozoic sediments in the tributary of the upper reaches of Kaligandaki on the section from Muktinath (M) to Ghasa (G) (Modified after Iwata, 1984). Original one sheet map is divided into two parts, to be connected at the point P. P: Confluence of the Puchchhardhon Khola and Kaligandaki, K: Kagbeni, J: Jomsom, L: Larjung.

Various steps of river terraces develop extensively along the Kaligandaki River, especially surrounding confluences of larger tributaries (**Fig. II-13**). A typical development of four levels of terrace is observed in the middle and upper sections of the trekking route. Around Jomsom, these terraces are formed on the glaciofluvial deposits (terrace, T1 at an elevation more than 3,000m), fluvial (terrace, T2 at elevations between 3,000- 2,900 m), lacustrine (terrace, T3 at an elevation less than 2,900m) and recent alluvial deposits (terrace, T4) (cf. Fig. III-53). Iwata (1984) identified 7 steps of terraces along the Kagbeni-Ghassa section and reported that the highest terrace (his H1 terrace) is situated maximum 400 m higher than the present river bed. According to him, the highest terrace forms over the Marpha Formation and is considered generally formed nearly during the same age.

Fig. II-14**. A **moraine hill (the low smooth hill in the fore front east of Lete). The Lete village is seen in the center of the valley.

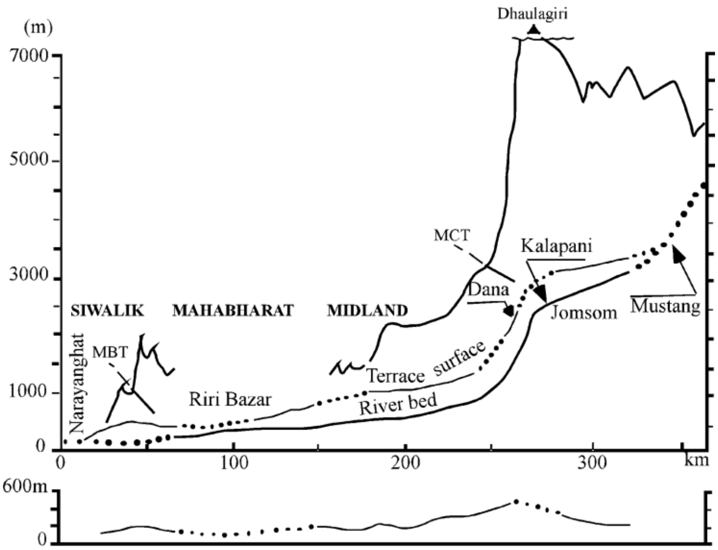


Fig. II-15 North-South profile of the Himalaya showing the relative height of high terrace along Kaligandaki River (Iwata et al., 1982).

According to Yamanaka and Iwata. (1982) and Iwata (1984), the age of the deposition of the higher terrace is established to be pre-last interglacial period (could be around 150,000 years BP), and the middle terrace in the Kaligandaki valley was formed during the early substage while the lower terrace was interpreted to be in the later substage of the last Glacial period. **Figure II-15** (Iwata and others 1982) shows the longitudinal profile of the Kaligandaki River covering further south from the guidebook section up to Terai. The figure shows the relative height of the highest terrace surface above the present riverbeds. The largest relative height represents the largest upheaval part within the section and it is found around the Dana village near the MCT in the Higher Himalayan Zone. The differential uplift of the terrace along the Kaligandaki valley shows that the upheaval of the Higher Himalaya, Mahabharat and Siwalik ranges must have been going on since the late quaternary.

Natural Hazards Along the Kaligandaki Valley

Originating from the southern slope of the Tibetan Marginal Range that lies to the south of the Tibetan Plateau, the Kaligandaki River passes through all the geological zones of Nepal, namely the Tibetan- Tethys, Higher Himalayan, Lesser Himalayan, and Siwalik zones and finally draining out to the Gangetic Plain. Since it is an antecedent river (the river existed and flowed to the south even before the rise of the Himalaya), it has witnessed the entire history of the Himalayan uplift. A longitudinal profile along the Kaligandaki valley form Beni to Kagbeni is given in **fig. II-16.** The sudden changes in the riverbed gradient reflect the effect of tectonic activities in the area. A nearly horizontal longitudinal profile of the riverbed in the Tibetan Tethys Zone north of the Kalopani village suddenly becomes steeper as soon as it enters into the Higher Himalayan Zone. This sudden increase in riverbed gradient just after entering the Higher Himalayan Zone may be due to the high rate of present uplift in the Higher Himalayan Zone. The riverbed gradient again becomes gentler in the Lesser Himalayan Zone indicating that the rate of uplift in this zone is also low.

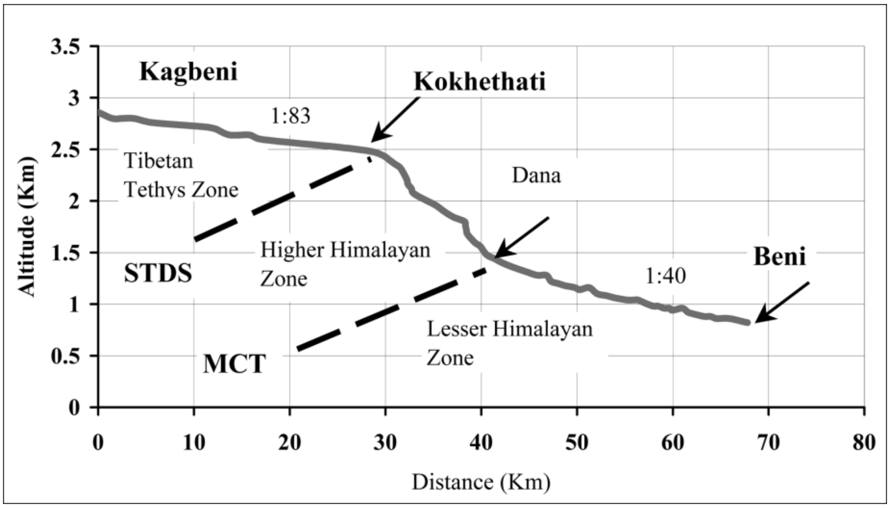


Fig. II-16. Longitudinal profile along the Kaligandaki River from Beni to Kagbeni.

It is very likely that the Kaligandaki River must have been blocked several times at different locations by landslides and glaciers in the geological past. Accordingly, throughout its journey from north to south, the river has developed several lake terraces and wide flood plains. The world-famous deep gorge along the Kaligandaki valley is a witness of the erosional power of the river (**Fig. II-17**). Like a chain saw this antecedent river maintained its downward flow to the south by continuously vertically cutting over 60 km of the rising Himalaya.

The Kaligandaki River section is prone to various types of mass movement hazards. A brief account of the geologic zone-wise mass movement hazard is presented below.

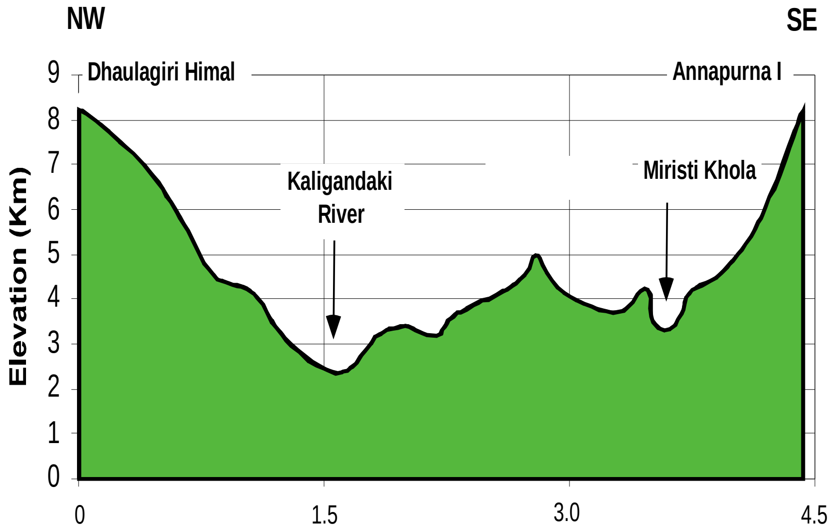


Fig. II-17. Topographic profile between Dhulagiri and Annapurna peaks forming the deepest gorge of the world along the Kaligandaki valley.

Lesser Himalayan Zone:

The first high mountain range situated just to the north of the MBT is known as the Mahabharat Range **(Figs. I-4, II-1).** Since the Mahabharat Range acts as an effective monsoon cloud barrier, the northern and southern slopes of the range receive heavy precipitation during summer seasons. The frequency of high intensity rainfall (cloudburst) is also very high in this area.

Low-grade metamorphic rocks such as slates, phyllites, schists quartzites, dolomites and amphibolite are exposed along the trail. Stronger rocks like quartzites, dolomites, sandstones, and amphibolite are resistant to weathering and have developed steep slopes. On the other hand, softer rocks such as phyllites and schists are easily weathered and thus form gentle slopes on which most farmlands are developed. The rocks are highly jointed and locally faulted and folded as well. The climatic factors in combination with the steep topography, intense differential weathering, inappropriate land use practices and inherently weak geological conditions have made the Lesser Himalayan Zone prone to landslides, river bank cuttings and debris flows.

Higher Himalayan zone

The Higher Himalayan Zone lying between the Main Central Thrust (MCT) and the South Tibetan Detachment System (STDS) consists of only high-grade metamorphic rocks such as gneiss and migmatite, marble etc. These rocks are comparatively stronger and can support very steep slopes. Near-vertical cliffs of several hundred meters high are not uncommon. Since the monsoon cloud cannot cross these high mountains, heavy rainfall occurs to the southern slopes of the Higher Himalayan range.

The Higher Himalayan rocks such as gneiss and quartzite are strong, but discontinuities such as rock joints and layering planes cut the rock mass into big blocks. The orientation, spacing and persistence of these discontinuities are arranged in such a way that they create large rock blocks that may fail along discontinuity planes. These geological conditions in combination with the climatic factors have made the Higher Himalayan Zone subject to landslides of various sizes. In addition, at many localities, the river passes through the moraine deposits that are loosely compacted. Since the riverbed gradient is also comparatively higher here, riverbank erosion is very intensive particularly where the riverbank is composed of moraine materials.

Tethys Himalayan Zone

Tibetan Tethys Zone is mainly composed of hard sedimentary rocks including limestone, dolomite, shale, sandstone etc. All the high snow peaks situated on either side of the Kaligandaki River are composed of these rocks. Since these very high snow peaks ranging in height from 5000 m and above are barrier to the monsoon cloud they do not allow the clouds to pass to the north. This has resulted the northern face of these mountain ranges to lie under rain shadow zone that receives very low annual precipitation normally below 250mm. Besides rock exposures, thick lake deposits are also well exposed along the trail. These lake deposits are well cemented by calcareous materials and can support steep slope of several meters high. Very low annual precipitation has also contributed for the stability of the soil slopes. These factors have collectively made the Tibetan-Tethys Zone less prone to landslides.

However, since most rocks are dipping to the north, the north facing slopes of the valleys are susceptible for plane failure. The stream banks at several places are composed of fluviolacustrine deposits, which are easily eroded or slided down once the riverbank cutting process is initiated during glacier melting season. Landslides on banks of the tributaries may also create landslide dam temporally and result in accidental flooding to the lower reaches. In the higher areas, i.e., the Jharkot-Muktinath area, moraine deposits intermixed with colluviums form slopes. Since the surface water is not well managed and therefore percolates inside the soil, slope creep and large rotational slides are common.

III. FIELD OBSERVATION ALONG THE POKHARA-MUKTINATH COURSE

Pokhara Valley

Physiography and Geology

The Pokhara town is the headquarter of the Kaski District of western Nepal, and the second most favoured destination of tourists in Nepal. The town is famous as a base station to Himalayan trekking in mid-west Nepal such as Annapurna-Machhapuchhre base camp and the Kaligandaki Valley. All visitors are greatly impressed by the dominating view of the Machhapuchhre and Annapurna Range, and Phewa and Begnas lakes surrounded by dense forests that add the beauty to the valley. The Pokhara Valley extends along NW-SE direction, having about 5 km width and 20 km length **(Fig. III-1).** The valley-fill sediments are presently cut very deeply by the Seti River, and also form wide terraces at different levels.

The Pokhara Valley is an intermountain basin similar to the Kathmandu Valley, characteristically developed in the Midlands of the Himalaya. The valley floor is believed to have formed along the old Seti River valley by the deposits from repeated debris flows and associated Glacial Lake Outburst Flood (GLOF) deposits originating from the high mountain areas in the north. The age of the sediments is very young (Quaternary even including Holocene).

The Pokhara Valley is principally underlain by very old (early Proterozoic) Lesser Himalayan metasediments called the Kuncha Formation. The formation includes shale, tuffacious shale with minor sandstone and volcanigenic rocks. All these rocks have undergone weak metamorphism and are now represented by phyllite, meta-sandstone and meta-igneous rocks. These rocks are exposed mostly in the hilly areas around the valley, and partly at lower part of the riverbank slopes.

Directly resting over the basement rocks are the Quaternary sediments ranging some meters to some hundreds meters thick. The Quaternary sediments include both consolidated (debris flow formations) and unconsolidated (soft) sediments. The debris flow sediments covering almost all the Pokhara Valley (Koirala 1998) are the most characteristic Quaternary deposits. The Ghachok Formation (about 12000 years old) and the Pokhara Formation (about 700 years old), both having concreted due to the calcareous nature of their matrix form the major portion of the debris flow deposits. Some other older debris flow deposits develop sporadically in the Pokhara Valley, but their ages are yet to be confirmed.

The Phewa Lake first appeared when the Harpan Khola was dammed, which now flows into the Phewa Lake from the west. The damming was caused by the debris flow sediments deposited along the main stream of the Seti River. The oldest age obtained from the Phewa Lake sediments is BC 12640 – 12025. Thus, the birth of the Phewa Lake is regarded to be about 13000 - 1500 years ago or even older.

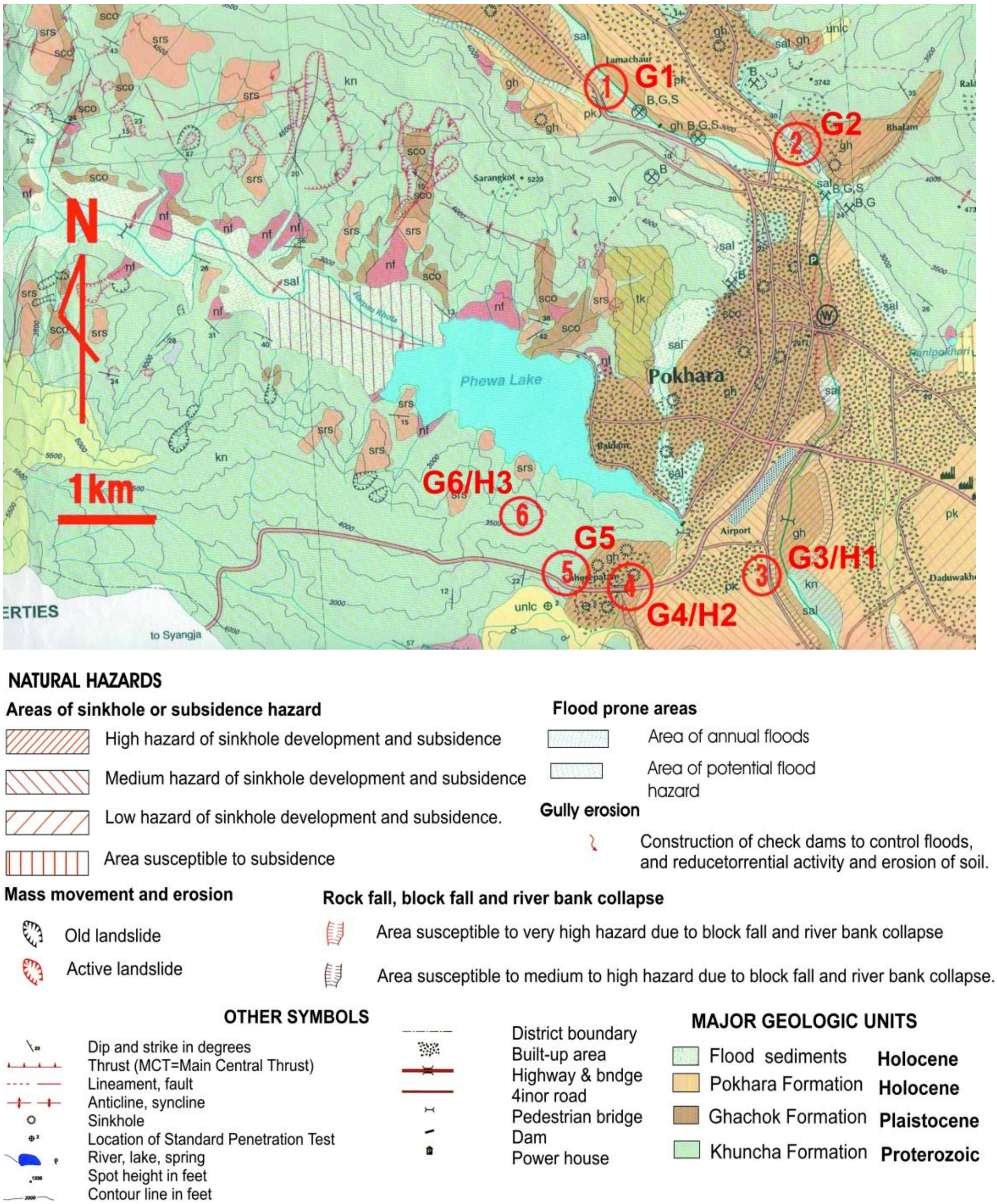


Fig. III-1. Geologic and environmental map of Pokhara and surrounding area (Koirala, 1998). G/H numbers are observation points explained in the text. srs: Residual soil, sco: Colluvial soil, af and nf: (active and non-active) alluvial fan deposit, sal: Flood plain and lower alluvial terrace deposit, unlc: Undifferentiated lake deposit, pk: Debris flow (Pokhara Formation), Gh: Debris flow (Ghachok Formation), kn: Kuncha Formation.
①～⑥ : Observation stops.

Natural Hazards and Environmental Problems

Natural hazards in the Pokhara Valley are mainly related to the nature of the sediments that fill the valley. In may places badlands are developed on the debris flow deposits. Land subsidence is the most common hazard in the valley. The debris flow deposits are slightly to moderately cemented conglomerate composed of limestone, schist, gneiss and granite with silty and sandy matrix. Due to high lime content in the deposit, groundwater makes intricate network of caves and caverns within the sediments at various depth, resulting in a high difficulty of underground survey of the caves. It is highly prone to subsidence when thickness of the overlying sediment is small. The risk of bank collapse along escarpment and riverbanks are also common, along with the risk of underground karstification with sinkhole development. It has also a high potential for deep groundwater resource in the karstified formations. Further, landslide and rock fall hazards are common on mountain slopes. There are also flood prone areas along the riverbanks and lakes.

One-day Excursion in the Pokhara Valley

The excursion begins at the Stop No. 1 on the Seti River bank near the Yandir Khola bridge crossing on the Pokhara-Baglung road. The location is about 5 km north from the Pokhara City center just lying upstream of the Seti River dam site. **(Fig. III-1).**

G-1: Gravels on the Seti River floor

On the gravel floor of the Seti River on the right bank **(Fig. III-2),** very large boulders to small pebbles of various rock types of the Lesser, Higher and Tethys Himalayan rocks are observed. The large boulders of the Higher Himalayan gneisses include garnet-kyanite gneiss garnet gneiss, biotite gneiss and gneissose granite. Beautiful crystals of gem quality kyanite and garnet are observed easily on surface of many boulders of gneiss. Boulders of limestone belonging to the lower part of the Tethys metasediments also occur widely. Boulders of phyllite and quartzite belonging to the Lesser Himalayan metasediments can also be found.

G-2: Kali Khola suspension bridge and debris flow sediments

A large suspension bridge over the deep and wide Kali Khola valley provides fantastic view of both the valley itself and the debris flow deposits on both sides of the valley (Fig. III-3). Lithological succession and horizontal structure of the deposits are clearly observed, appearing to show that the deposits include both the Ghachok and Pokhara formations.

G-3/H-1: Mountain Museum and unconformity at the Seti River bank

The museum (Fig. III-4) is located on the right bank terrace of the Seti River, which is composed of the Quaternary (12000-700 years ago) debris flow deposits covered by a thin (2 m thick) Recent terrace gravel bed. On a road just 100 m north of the museum, a good trail descends down to the Seti riverbed. A large cliff of about 30 m high extensively develops; it is composed of Quaternary debris flow deposits (the Ghachok and Pokhara formations), which is facing a high danger of slope collapse. The bank slope on which the trail is located is totally composed of huge

Fig. III-2. Gravel floor of the Seti River (G-1).

Fig. III-3. Kali River suspension bridge and debris flow deposits of both banks (G-2).

collapsed blocks (up to over ten meters diameter) from the cliff. Below the Quaternary formations, exposes phyllite of the Kuncha Formation, the lowest formation of the Nawakot Complex for about 50m downwards to the riverbed. A beautiful unconformity is viewed on the opposite bank of the river.

The mountain museum exhibits not only items related to mountaineering, but also those related to Himalayan geology, environment, ethnic people and culture etc.

Fig. III-4. Mountain Museum front view with its wide garden. Leftmost peak is a miniture Himalaya.

G-4/H-2: David's Fall and Gupteshwar Mahadev Cave

Just southwest of the Phewa dam where the Siddhartha Highway crosses the Pardi Khola, a beautiful waterfall occurs cutting through the Pokhara and Ghachok formations (Figs. III-5, III-6). The deep calving is due to the loose as well as calcareous signature of the debris flow sediments. Deep, steep and overhanging signature of the David's Fall suggests that the deposits are prone to be affected by caving and the areas underlain by these deposits are prone to meet land subsidence. The Gupteshwar Cave lies on the opposite side of the highway near the David's Fall and provides a good exposure of the Ghachok Formation.

G-5: Kuncha Formation on the way to the World Peace Monastery

At about 700m west from the bridge near the David's Fall, a trail veers away from the highway to the north and start climbing a hill for about 300m in height where the World Peace Monastery (Nippon-san Myohoji) is built. Just after entering the trail branching from the highway, good outcrops of phyllite of the Kuncha Formation occur on road cuts and along the trail (Fig. III-7). At an altitude of about 950m, coarse-grained sandstone and micro-conglomerate are also observed.

G-6/H-3: View from World Peace Monastery

Further climb of about one and half hours from the G-5 point, the World Peace Monastery is situated at a hilltop. From the top one can enjoy a very wide and beautiful view of the Pokhara Valley below, and the Annapurna Range far ahead in front (Figs. III-8, III-9, III-10). The commanding view of the Pokhara town along with the Phewa Lake, a large part of the Pokhara Valley and several geologic hazard sites including floods and landslide can be observed. Landslide topography is very characteristic on the southern slope of Sarankot Hill (Fig. III-11).

Fig. III-5. David's Fall, showing good outcrop of the Pokhara Formation (G-4/H-2).

Fig. III-6. Conglomerate of the Pokhara Formation at the David's Fall (G-4/H-2).

Fig. III-7. Phyllite of the Kunchha Formation on the road surface (G-5).

Fig. III-8. Pokhara City viewed from near the World Peace Monastery (G-6).

From the World Peace Monastery, a trail descends down the northern steep slope to the Phewa Lake with about a one-hour walking distance. There are few outcrops of the Kuncha Formation along the trail, although a long trail with stone steps provides a good variety of lithology of the Kuncha Formation. A boat is generally available to carry people to the north bank of the lake. On the boat people again can enjoy the famous view of Machhapuchhre and Annapurna peaks.

Fig. III-9. Annapurna Range and Machhapuchhre view from the World Peace Monastery (G-6).

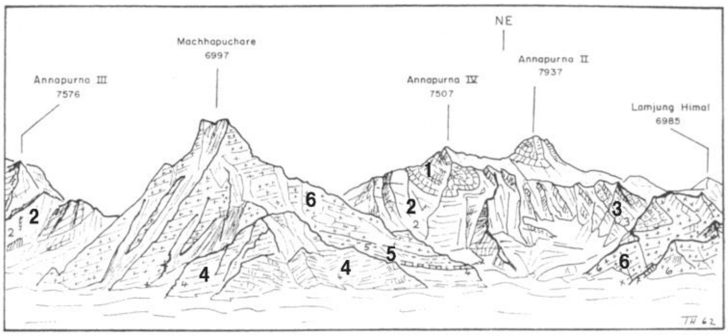


Fig. III-10. The Annapurna Range seen from the south (from airplane, Hagen, 1968). *1-2: Tethys sediments (1: Devonian, 2: Silurian-Ordovician-Cambrian), 3-6: Higher Himalayan gneisses, (3: Calcsilicate rocks, 4: Paragneisses, 5: Mixed gneisses and migmatites, 6: Granite-gneisses) .*

Fig. III-11. South slope of the Sarankot hill where several landslide scarps well develop.

Jomsom - Muktinath Section

Physiography and Geology

The. The distance between Jomsom (2,740m) and Muktinath (3,800m) is about 15 km (**Fig. III-13**). Geologically, this section belongs to the Tethys Himalayan Zone (Tibetan-Tethys Zone) and meteorologically lies in a dry rain-shadow part of the Himalaya with only about 250 mm of annual rain. Almost all the area is barren with only sparse vegetation (shrubs) very similar to Tibet.

This section of the Kaligandaki valley is generally very wide ranging from few hundreds of meters to one kilometer in width **(Fig. III-12a).** High peaks and major ridges are often well viewed from the riverbed where most of the trekking trail is located, and 6000m to 7000m high peaks including the Nilgiri Range to the southeast and Sandachhe Himal to the southwest can be viewed from the valley. The topography of the surrounding hills between Jomsom to Kagbeni is steep appearing to reflect the past V-shaped valley, which is half buried by fluvial sediment (Fig. III-12a). Further north from Panda, the topography becomes less steep.

From the topographic features of the Kaligandaki valley and surrounding slopes, it is assumed that the present wide river bed of the Kaligandaki valley was originated from the past glacial U valley which was completely filled by later fluvial sediments **(Fig. III-12b)**. Thus the surface of the present riverbed composed of fluvial sediments is considered to be nearly the same height level with, i.e., the same surface, of the past main glacier flowing along the Kaligandaki valley at those times.

Fig. III-12a Kaligandaki valley north of Jaomsom looking toward north. It shows braded streams over a wide river bed. A large U-valley is estimated to lie below the river bed which is presently filled with alluvial sediments (cf. Fig. III-12b).

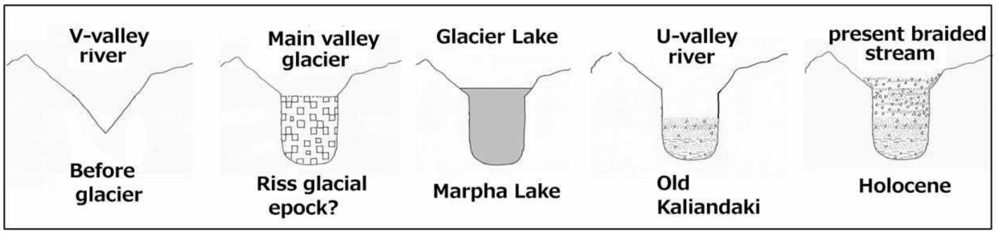


Fig. III-12b. A model of the topographic development of the Kligandaki valley.

The Jhon Khola which originates in the east from the Muktinath and Purkhung ranges flows westward on this mildly ragged areas, possibly the relic topography of the ancient wide glacial valley. The Kagbeni village (2,800m) is located at the confluence of the Kaligandaki River and the Jhon Khola. The main river coming from the upper Mustang near Tibet is called the Thakkhola (meaning red river in local language) and only downstream of the confluence with the Jhon Khola is called the Kaligandaki River in this guidebook, although the Kaligandaki River north of Kalapani is also called the Thakkhola.

This section of the valley is occupied by the upper formations (Mesozoic rocks) of the Tethys sediments, which are steeply to moderately inclined. The Tethys sediments generally show open to close type of folds with mostly gentle to horizontal axial planes giving rise to recumbent folds. These bedrocks are unconformably covered by Cenozoic (late Tertiary and Quaternary) sediments with mostly horizontal attitude.

Natural Hazards

The river terraces are nearly horizontal whereas the colluvial slopes formed at the lower part of the hills are very steep with as much as 65^0. Nearly vertical slopes develop on the edges of the fluviolacustrine deposits.

Debris flows are the main type of mass movement in this section followed by landslides and riverbank erosion. The major tributaries of the Kaligandaki River bring a large amount of debris and form extensive fans at the confluence with the main river. Instabilities of rock slopes resulted due to road cuts can be found at some places along the trail. At higher areas creeps in moraine deposits are also common.

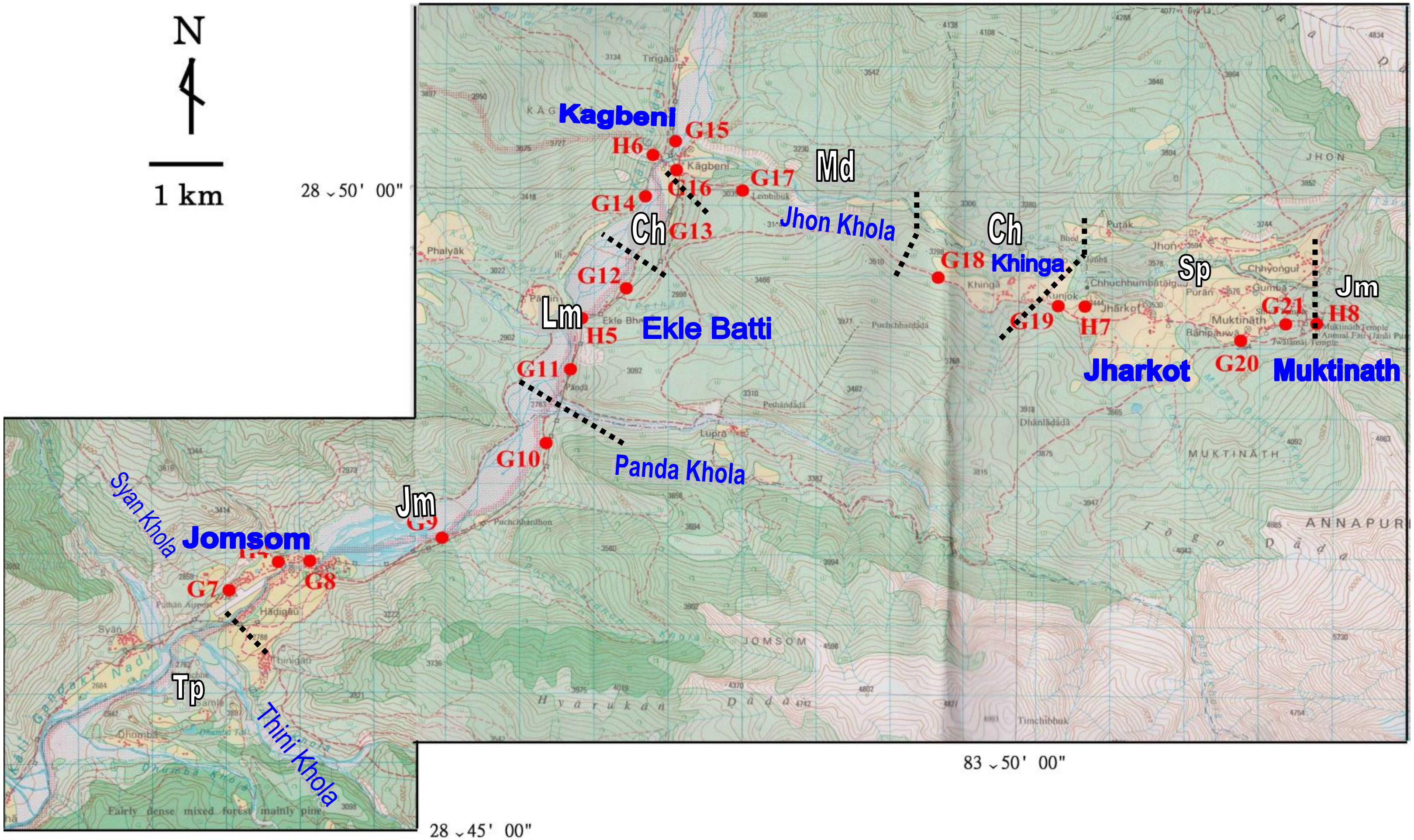


Fig. III-13. Trekking route and locations of observation points between Jomson and Muktinath (G: Geology, H: Natural Hazard).

The Tour Course

The total length of the tour course between Jomsom (2740 m) and Muktinath (3800 m) is about 15 km out of which the distance between Jomsom and Kagbeni (2800 m) is about 7 km and between Kagbeni and Muktinath (3800m) is about 8 km (**Fig. III-13**). The first part of the road between Jomsom and Kagbeni is quite gentle, where as the route between Kagbeni and Muktinath is much steeper and covers most of the altitude difference of about 1000 m. The road from Jomsom to Kagbeni entirely follows the ***left bank*** [1]of the Kaligandaki river and passes through the riverbed or the lowest terrace less than 1-2 m high. On this sector the trail has very low relief and is easy walk.

At Kagbeni, the trekking route (car road) to Muktinath branches from the Kaligandaki valley and follows parallel to the Jhon Khola that flows into the Kaligandaki valley from the east. The road runs along the hill slope on the southern side of the Jhon Khola (left bank), passing through either terraces or hill slopes mostly with glaciofluvial deposits and only rarely encounters basement rocks. Along this route, Ekle Bhatti, Kagbeni, Khinga, Kunjok, Jharkot and Muktinath (from SW to NE) are the main settlements.

Observations along the Trekking Route

Jomsom Village

Jomsom village (2700m high above mean sea level) is the headquarter of the Mustang District. It is relatively a new settlement which gradually developed after the construction of the Jomsom airport. This village is situated partly on the glacial deposits and partly on the lacustrine deposits on both banks of the Kaligandaki River **(Fig. III-14).** The basement rock in the area is limestone of the Jomsom Formation belonging to the Tibetan-Tethys Sedimentary Series (Tethys Group). The glacial deposits are composed of angular to subangular big boulders, cobbles and pebbles with sandy matrix. Above the glacial sediments are more than 30m thick yellowish brown to yellowish gray lacustrine deposits, exposed along the roadside of the main trai**l (Figs. III-16, 17).** Different levels of river terraces have developed around Jomsom. To the southeast the serene early morning view of the beautiful snow covered Nilgiri Range will be sure to leave a memorable impression on anybody (Fig. III-15).

G-7A: Recumbent fold of Tethys sediments on the north face of Nilgiri North

People arriving in Jomsom are all astonished by the brilliant Nilgiri North peak (7061 m) with beautiful Himalayan gathers, standing 10 km to the south of Jomsom. If one amazes the northeast cliff of the peak, a large-scale inclined recumbent fold will be found (**Fig. III-15**). The folded sequence is the Nilgiri Formation according to Colchen et al (1986), mostly composed of limestone including Brachiopod fossil which lived in shallow sea.

[1] Left side bank of the river seen from the upper stream to the lower stream

Fig. III-14. Jomsom village looking down towards north. Note on the good development of river terraces. The Jomsom airport is seen on the middle of the photograph.

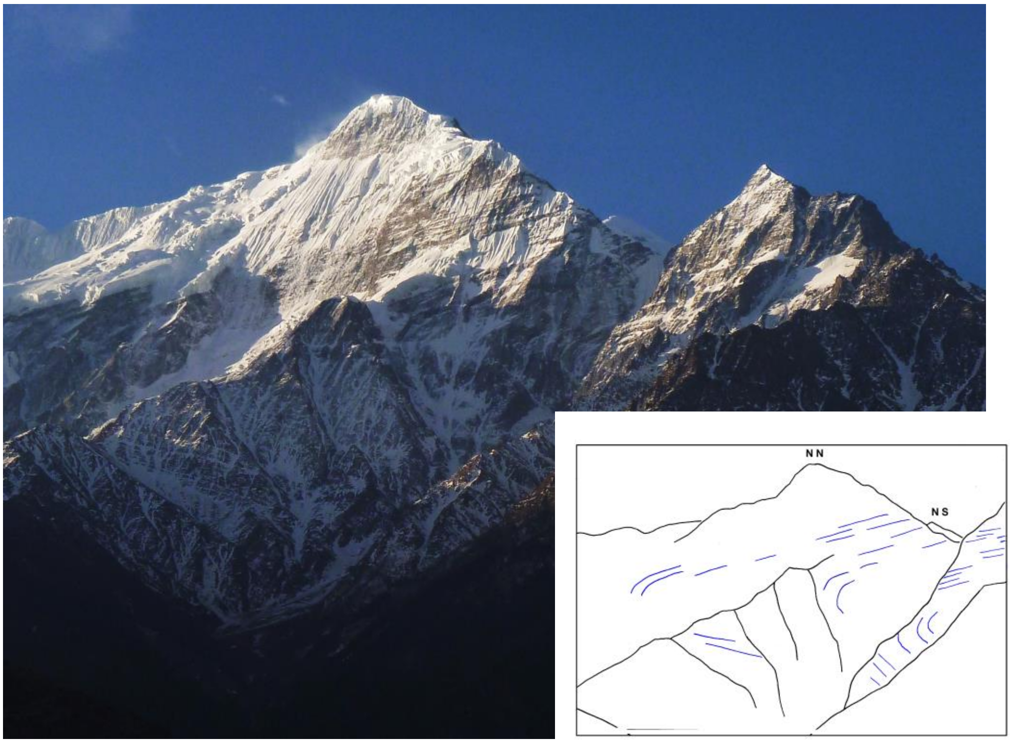


Fig. III-15. Nilgiri North peak with its north cliff showing a large scale recumbent fold (G-7A).

G-7B: Jomsom Formation and Lake sediments in Jomsom

Soon after getting out of the Jomsom airport, we can see beautiful cliff on the western mountain slope **(Fig. III-16).** The lower Jurassic Jomsom Formation (199-175 million years ago) is **well stratified**[1] and dipping steeply **as if showing a monoclinal structure**[2]. On the lower slope, thick horizontal deposit of light yellowish brown **lake sediments**[3] can be observed. The lake (lacustrine) deposit is comprised of fine-grained sand and silt **(Fig. III-17)**. These sediments are considered to be the Quaternary lake deposits which are called the Marpha Formation (Hagen, 1968: Iwata, 1984). The thickness of the lake deposit is more than 50m. The lake sediments are resting unconformably on the Jomsom Formation. Similar kinds of lake deposits can be seen along the trekking route from Jomsom to Kokhethati mainly around Marpha and the Chimangau village along the Chiman Khola. According to Iwata, the Marpha Formation was formed before the latest interglacial age (before about 150000 years BP).

Fig. III-16. Basement rocks (Tethys sediments, upper part of the slope) and lake deposit (lower one-fourth of the slope) around Jomsom (G-7B).

Fig. III-17. Close view of the lake deposit in Jomsom (G-7B).

H-4: Jomsom river bank cutting

The Jomsom village is located on a river terrace bounded by mountain slopes on both sides. The Kaligandaki River makes a narrow course calving the terrace deposits. The river has caused intense bank/toe cuttings destroying cultivated land on the terrace. This process is more pronounced near the military camp, downstream from the old suspended bridge over the Kaligandaki River. On the riverside, a sign of instability such as tension crack can be observed.

The military camp itself is located on a fan of a seasonal stream. The stream may bring debris under a worse weather condition in such ways as over melting of snow and occurrence of landslide on its bank. If such incidence occurs, it may cause loss of lives and properties in this area.

[1] Showing good stratified (forming alternation of strata) structure.

[2] Should be a fold wing (limb). Due to too large size of the fold, only its half limb is observable and as a consequence, exhibit and apparent monoclinic structure.

[3] Due to the past development of glacial lake in this area.

G-8: Structures of the Tethys sediments on the eastern mountain slope along the Kaligandaki River

At the northern margin of Jomsom around the old suspended bridge over the Kaligandaki River, viewing to northeast, a series of the Tethys sediments are well observed on the eastern mountain slope (Figs. III-18a,b). A large-scale recumbent fold with the axial plane gently dipping east is also discernible.

Fig. III-18a. Tethys sediments overviewed northward from Jomsom (G-8).

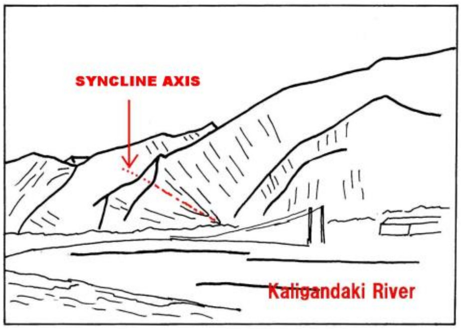


Fig. III-18b. Sketch of Fig. 18a, showing a recumbent fold with the trace of its axial surface shown by a red chain (G-8).

G-9 (Optional stop): View of sandstone-shale alternations and limestone beds of the Jomsom Formation

Just after getting out of old Jomsom village, the first outcrop occurs on the right side of the trail. At this first outcrop of the Jomsom Formation, sandstone and shale alternations with a mild to gentle dip crop out, which are unconformably overlain by the Quaternary lake sediment. Dark gray limestone also occurs some tens of meters north.

Further northwards along the Kaligandaki valley, steeply to moderately dipping monoclinal or folded rocks of the Jomsom Formation is observed extensively on both mountain slopes of the Kaligandaki valley (cf. Figs. III-14, 16, 18a,b, 19). The limestone contains a lot of fossils (Crinoids, Bivalves, Brachiopoda). Well-bedded micritic limestone interbedded with shale having the traces of bioturbation (Chondrites) is found.

To further north we can observe the upper horizon of the Jomsom Formation, which exhibits thinly bedded, fine- to medium-grained and light yellow to light brown sandstone interbedded with limestone. A recumbent fold is observed at about 2 km north of Jomsom on the left bank of the Kaligandaki River as viewed at G-8 (Figs. III-18a,b).

G-10 (Optional): Limestone of the Jomsom Formation

Dark gray and well-banded limestone forms a large outcrop south of the confluence of the Panda Khola with the Kaligandaki River.

Fig. III-19. Folding in the Jomsom Formation to the north of Jomsom along the Kaligandaki River (G-9).

G-11: The Lumachelle Formation with fossils

At about 800m south of the Ekle Bhatti village, on the left bank of the Kaligandaki River, an exposure of dark gray, fine-grained micritic limestone intercalated with shale is observed (Fig. III-20a). This is the type lithology of the Lumachalle Formation. Dark colored coarse-grained sandstone is also interbedded. Limestone interbedded with gray shale contains abundant fossils of bivalves rarely including belemnite **(Figs. III-20a,b)**, which provide the time of sedimentation to be of the middle Jurassic (175-161 million years ago).

Thinly spaced steep cleavage inclined from the bedding develops in this outcrop, indicating the existence of a large fold with its axial plane to the south.

Fig. III-20a. (Left) Interbedded dark gray shale and limestone of the Lumachelle Formation south of Ekle Bhatti (G-11). Fig. III-20b. (Right) Bivalve fossils from the Lumachelle Formation, south of Ekle Bhatti (G-11).

A good exposure of the Lumachelle Formation is also observed on the right bank of the Kaligandaki River, at the west edge of the suspended bridge near the Ekle Bhatti village. In this outcrop, limestone interbedded with gray shale contains abundant fossils of bivalves including belemnite **(Fig. III-21a,b)**. A folded structure can be seen on the left bank of the Kaligandaki River within the Lumachelle Formation.

Fig. III-21a. (Left) Bivalve fossils preserved in the dark gray limestone of the Lumachelle Formation, at an outcrop south of Eklebhatti (G-11). Fig. III-21b. (Right) Belemnite fossils from the Lumachelle Formation (G-11).

On the short cut way to Muktinath near the Ekle Bhatti village on the left bank of the Kaligandaki River, a huge outcrop of the lake deposits covering the glacial deposits is observed **(Figs. III-22, III-23).**

Fig. III-22. (Left photo) Glaciofluvial and lake deposits forming different levels of terrace of the Kaligandaki River between Jomsom and Kagbeni (G-11). Fig. III-23. (Right) Lake deposits (light yellowish non-vegetated part) on the way to Ekle Bhatti from Jomsom (G-11).

H-5: Ekle Bhatti wedge failure

On the left bank of the Kaligandaki River, about 200m downstream from the Ekle Bhatti village, typical example of ***fault-controlled slope instability***[1] can be observed **(Fig. III-24).** The bedding dips about 45° towards south. A fault dips about 60° towards southeast. One of the prominent joint sets dips about 70° towards north-northwest. The joint has smooth surface, widely open and is

[1] The slope may collapse due to the development of fault

extended all along the slope. The joint and the fault form a large wedge block on the steep cliff. Due to excavation for the construction of the trail, some parts of the slope are overhanging. It is likely that the wedge block may fail during further widening of the trail.

Fig. III-24. Large wedge block formed by the intersection of a joint and a fault, south of Ekle Bhatti (H-5).

G-12A. Recumbent folds viewed on the eastern slope of Daputon Dada

Beautiful recumbent folds of Tethys formations are clearly viewed while trekking in the wide river floor of Kaligandaki near Eklebati **(Fig. III-25).** It is found that the folded strata include almost all the Mesozoic formations.

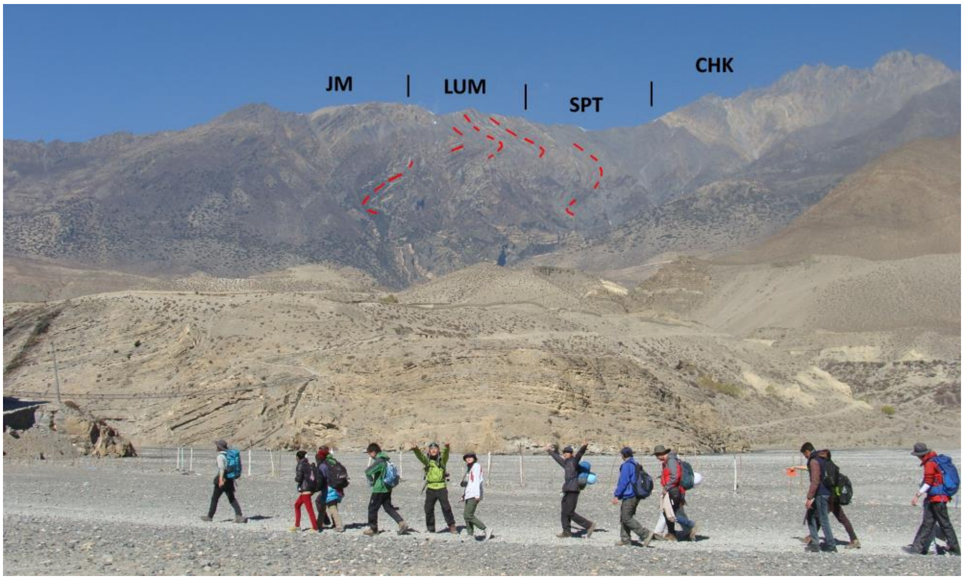


Fig. III-25. Recumbent folds of Mesozoic Tethys formations viewed on the eastern slope of Daputon Dada. JM: Jomsom Formation, LUM: Lumachare Fm, PST: Spiti Fm,CHK: Chukh Fm..

G-12B: Quaternary sediments north of Ekle Bhatti

On the left bank of the Kaligandaki River about 500m north of Ekle Bhatti at around the confluence of Pethan Khola, a thick pile of Quaternary glaciofluvial sediments (presently the majority of them are soft sandstone) occurs **(Fig. III-26a)**. It is over 10m in thickness and is composed of very coarse-grained sand stone partly with pebbles. The sediments represents yellowish brown color and well solidified. The pebbles are comprised of limestone and sandstone, and are angular to subangular in shape. **Micro conglomerate**[2] also occurs in minor amount. The sandstone shows a very gentle dip towards west and therefore is considered to have formed the fan of the Pethan Khola.

On some part of surface of the outcrop, imprints of scripts are found **(Fig. III-26b)** and a concrete protection was set up recently by the local government.

Fig. III-26a. Soft sandstone probably of pre-Marpha Formation near Ekle Bhatti (G-12B).

Fig. III-26b Scripts on the Quaternary sandstone (G-12B). Protecting concrete wall is also shown on the top of the photo picture.

G-13: Chukh Formation

At about a half way between Ekle Bhatti and Kagbeni, there is a good exposure of the Chukh Formation (lower Cretaceous, about 145-100 million years ago) on the left bank of the Kaligandaki River (Fig. III-27a). Thick beds of pebbly sandstone show the fining upward sequence. They are ill-sorted with cross bedding. Plant fossils (Fig, III-27b) and ripple marks are also preserved in the sandstone.

Fig. III-27a. Sandstone of the Chukh Formation, exposed on the way to Kagbeni from Ekle Bhatti (G-13).

Fig. III-27b. Plant fossil (dark and elongate) preserved in the sandstone of the Chukh Formation (G-13).

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[2] Conglomerate with small clasts

G-14. Repeated folding of Muding and Chukh formations

On the right bank slope of the Kaligandaki River just south of Kagbeni, a repetition of foldings possibly associated with a thrust fault is observed (Figs. III-28a). On this outcrop, the Chukh (alternation of light colored sandstone and dark colored shale) and the Muding (black and dark colored sandstone and shale) appear. One possible idea of folding-faulting structure of this outcrop is shown on Fig. III-28b.

Fig. III-28a. Tethys formations showing repeated folding south of Kagbeni (G-14).

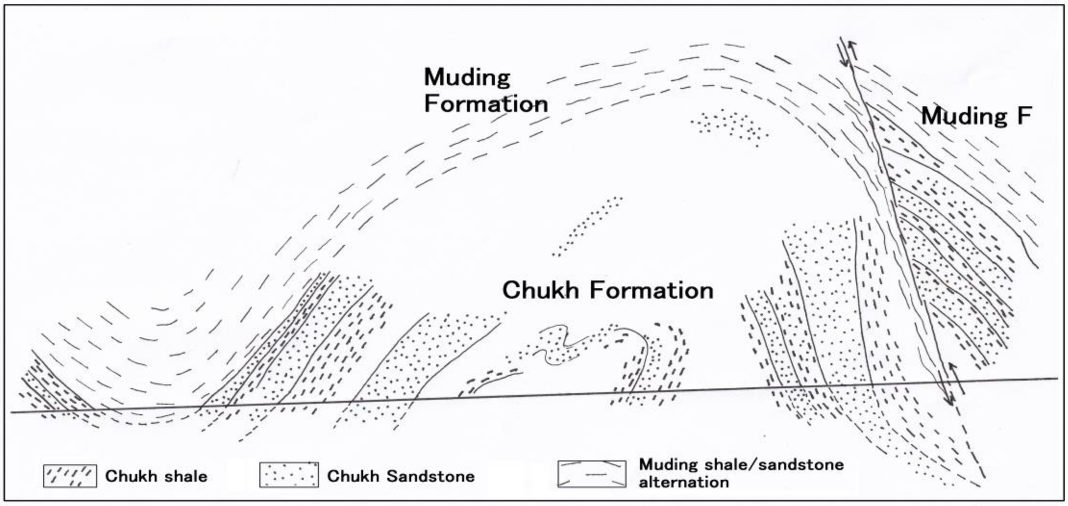

Fig. III-28b. A possible geologic structure of the cliff. A gently inclined straight line is the present river surface.

Kagbeni village

The Kagbeni village (2900m above sea level) is situated at the confluence of the Kaligandaki River and Jhon Khola (locally called the Kag Khola). This village lies on the lower river terrace of the Kaligandaki River **(Fig. III-29, see also Fig. III-33)**. This village is the entry point to the upper Mustang and has preserved a more than 300 years old monastery famous for the wall painting. The monastery is located on the alluvial deposits of the Kaligandaki River. On the eastern part of the Kagbeni village along the Jhon Khola, fluvioglacial sediments up to 200m thick are exposed (see **Fig. III-32)**. Pebbles including ammonite fossils are rarely found in the riverbeds that are brought by the Jhon Khola eroding the Spiti Formation, which is a good ammonite horizon.

Fig. III-29. The Kagbeni village, view toward south, with the Nilgiri Range on the back view.

H-6: Kagbeni rockslide

On the right bank of the Kaligandaki River, opposite to the Kagbeni village, a huge rockslide is found **(Fig. III-30).** The site is ideal to understand the role of geologic structures resulting in various types of failure. Bedding dips about 50^{o} towards north-northeast, whereas other two prominent sets of joint steeply incline southwest and southeast respectively. These joints intersect and form wedge blocks. Just upslope of the right abutment of the suspended bridge over the Kaligandaki River, process of wedge development[1] and wedge and toppling failure can be observed **(Fig. III-30)**. ***Riverbank cutting process***[2] is also active on the left bank of the river, which threatens some residential buildings of Kagbeni.

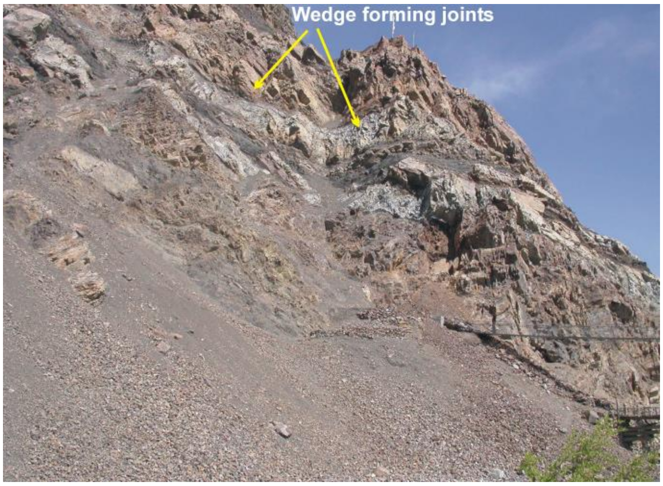

Fig. III-30. A typical wedge failure, at the right bank of the Kaligandaki River, near the Kagbeni village (H-6).

[1] Rock blocks formed by the intersection of joints.
[2] Wash out of banks' materials by the river water.
3 Bedding structure is well developed

G-15: Chukh and Muding formations in the Kagbeni village

On the right bank of the Kaligandaki River, opposite the Kagbeni village, a large exposure consists of **well-bedded**[3], medium- to coarse-grained, gray quartzite and sandstone interbedded with gray and dark gray shale (Fig. III-31a). Cross beds, cross laminations and wind and water ripple marks (Figs. III-31b,c) are well preserved in the sandstone. Pebbly sandstone is found sporadically. The whole rock succession shows the fining upward sequence. This rock succession suggests that these rocks are probably of fluvial origin. Fossils of plant remains and bivalves are well preserved.

To the north and south of the Chukh sandstone beds, occur dark gray fine sandstone and shale beds (cf**. Figs. III-28a,b, 31a)** appearing to be disturbed by shearing associated with a boundary fault with the Chukh Formation. These beds are thought to belong the Muding Formation, the youngest strata in this region.

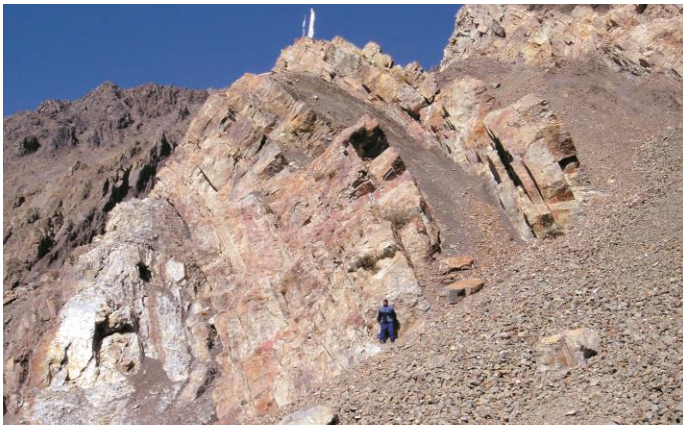

Fig. III-31a. Sandstone (light gray) and shale (dark gray) of the Chukh Formation (G-15).

Fig. III-31b. (Left photo) Wave ripple mark in sandstone of the Chukh Formation (G-15)
Fig. III-31c. Wind-ripple marks preserved in sandstone of the Chukh Formation (G-15).

G-16: Glaciofluvial sediments and different levels of terraces around Kagbeni

Soon after departing from Kagbeni towards Muktinath, a thick pile of subangular to angular clast-supported gravel beds of the glaciofluvial origin is found **(Fig. III-32).** The trekking route starts climbing steep slope and reaches to the two steps of the higher terrace of about 200～250m above Kagbeni from where beautiful views of geology around Kagbeni including the highly dipping Tethys sediments, horizontal late Cenozoic lake deposits and varieties of terraces composed of glaciofluvial sediments are observed **(Figs. III-33, 34a,b).** During the climb on the route to the Khinga village, thick piles of the glaciofluvial sediments are also viewed from the trekking route on the northern bank of the Jhon Khola. The right bank slope of the Jhon Khola is composed of the glaciofluvial deposits mentioned above and show steep topography. The surface of the terrace is gently inclined to the west, and thus these huge amounts of sediments are considered to have been transported by the Jhon Khola.

Fig. III-32. Glaciofluvial sediment in Kagbeni (G-16).

G-17: Geologic and geomorphologic view from the east terraces of Kagbeni

These terraces (3035～3100m) provide a beautiful view of the Tethys Himalayan zone. To the north, upper reaches of the Kaligandaki River, which are called the Thakkhola valley where the upper Mustang district extends, are well exposed on its full desert scenery with 5000m-6000m peaks of the Tibetan Marginal Mountains on the skyline that carry few snow and ice on their main ridges **(Figs. III-34b,c,d).** Geologically these areas are mostly composed of younger formations of the Tibetan-Tethys Sedimentary Series (Tethys Sediments), which are covered by the late Neogene (Plio-Pleistocene) Thakkhola Formation along the upper reaches of the Thakkhola valley.

Fig. III-33. View of the Kagbeni village and surrounding area with the Mesozoic Tethys sediments (highly inclined) and late Cenozoic strata (horizontal light layer seen just above people). High mountains on the right back are the Tibetan Marginal range (G-17).

Fig. III-34a. Northward topographic scenery viewed from east terrace of Kagbeni. The valley ahead is the Kaligandaki River and a river below is the Jhon Khola. The Mustang area and the Tibetan Marginal range are on the back. T1 and T2: Higher terraces; T3 and T4: Low terraces. The higher terrace is about 200m high from the riverbed of the Jhon Khola. (G-17).

Fig. III-34b. Northward view from the east terrace of Kagbeni. The Tibetan Marginal Mountains (back) and the Thakkhola Graben filled by the Cenozoic glaciolacustrine and glaciofluvial sediments (middle). (G-17).

To the west, steep slopes of 6000m peaks including the Sandachhe Himal with little snow on major ridges are mostly barren, showing a good geologic structure of the middle formations (middle to lower Mesozoic) of the Tethys Sediments **(Fig. III-34c).**

To the south a beautiful and completely white Dhaulagiri and Tukuche peaks stand above the barren eastern slopes of the Sandachhe Himal (**Fig. III-34d)**; these are the Higher Himalaya, but geologically the far-most Dhaulagiri peaks are composed of the lower formations of the Tethys Sediments (early to late Palaeozoic, about 500-350 Ma). Below the snowy Dhaulagiri, runs the South Tibetan Detachment System (STDS) and the Higher Himalayan Gneisses starts to occur. However, these are not viewable from here.

Further climbing towards east, reaching around the Khinga village on the trail, thick lake sediments composed of yellowish gray to light yellow sands and silts are observed. Thin lamination of the silty clay is seen in the sediments.

Fig. III-34c. West view from the east terrace of Kagbeni. Middle formations of the Tethys Sediments show steep to moderate (apparent) monoclinic structure. Skyline is the Sandachhe Himal (G-17).

Fig. III-34d. Southern view from the east terrace of Kagbeni. Dhaulagiri and Tukuche peaks are beautiful (G-17).

G-18: View of geology and geomorphology of upper reaches of the Jhon Khola

On the trekking route from Kunjok to Jharkot, beautiful scenery of upper reaches of the Jhon Khola extends ahead **(Fig. III-35).** High peaks including the Yakwakan (also called the Thoron peak, 6482m) and Khatunkan (also called Deriatse, 6484m) and their western and northwestern slopes are composed of **upper formations**[1] of the Tethys Sediments showing beautiful structures **(cf. Fig. III-39)**. Below the steep slope are developed characteristic gentle but complex topography of

[1] Younger formations that are generally lying over the older formations.

colluvium and landslide deposits made up mostly of moraines and glaciofluvial sediments surrounding Muktinath.

Viewing further east and northeast, characteristically gentle and wide slope extends with a very gentle dip towards west. This slope is considered to have been formed as a lacustrine fan on a very wide horizontal plain of glaciolacustrine sediments developed long back when a large glacial lake was there.

G-19: Spiti Formation with ammonite fossils

The rocks of the Spiti Formation are exposed between Kunjok and Jharkot villages **(Fig. III-36a)**. Here, the **pencil-cleavaged[2]** black shale with thin layers of dark gray limestone is well exposed. Spherical to flatten spherule-shaped light yellow to dark brown calcareous **concretions[3]**, which sometimes carry good ammonite fossils, occur sparsely within the layers of shale and limestone. This locality is well known for the collection of ammonite fossils (Saligram in the Nepali language, **Figs. III-36a,b).**

Fig. III-35. Eastward view from the trekking route west of Khinga. The gap between the Yakwakan (Thoron peak, 6482m) at the centre and Khatunkan (Deriatse, 6484m) on the right is the Thoron La (pass). The Jharkot village on the middle below, and Muktinath is just below the slope of Khatunkan (G-18).

Just about 300m down from the route along the Jhamiunda Khola, which flows between Jharkot and Kunjok, a lot of ammonite fossils and concretions up to 2m in diameter can be found. Around the Jharkot village, a thick deposit of glaciolacustrine (glacier-lake) sediments are seen along the trekking route up to Muktinath. These sediments are characterized by light gray color and composed of fine-grained sands and silts. Angular to subangular clasts of sandstone and limestone are sparsely distributed within the thick piles of sand and silt.

[2] Due to the development of two sets of micro joints (cleavages), the rock is easily fragmented in a small columnar shape often like a pencil.

[3] The concretion is formed by the segregation of $CaCO_3$. This starts from some nuclei within the rock, and fossils work as able nuclei for the concretion. It is also called nodule, especially for smaller ones.

Fig. III-36a. (Left photo) Outcrop of the Spiti Formation with the calcareous concretions (G-19). Fig. III-36b. (Right photo) Ammonite fossils from Jharkot collected by local people and sold in the village (March 2014) (G-19).

H-7: Kunjok soil slide

Both sides of the trekking trail connecting the villages of Kunjok and Jharkot are cultivated land. Active tension cracks and landslide scars are common on the down slope of the trail. It seems that the whole lands lying between the hill slope and the riverbed of the Jhon Khola are creeping down slowly. Near the riverbed, cultivated land is severely affected by the landslide **(Fig. III-37).** Old landslide scars are also seen on the upslope of the trail.

The area consists of glacial deposit of various grain sizes. In general, coarser sediments (moraine boulders) are found at the foothill whereas the finer sediments (fluviolacustrine silt and clay) are observed down slope, near the riverbed. Gravel-mixed silty clay constitutes the middle portion of the slope. Generally, groundwater seepages are found along the boundary between these soils.

Fig. III-37. Multiple landslide scars near the Jhon Khola, down slope of the Jharkot village (H-7).

The reason of the soil slide in the above area is considered to be something like that described below. The melting of the glacier and snow accumulated on the nearby mountains produces a huge amount of water that flows through slopes. Besides flowing on the surface, a considerable amount of water is also percolating down the glaciofluvial sediments particularly around the upper slope composed of coarser sediments. But the middle and lower portion of the slope have finer sediments that reduce the hydraulic conductivity of the sediment. As a result, ***pore water pressure***[1] is created pushing the slope downwards.

Muktinath Village

The Muktinath village is situated at the height of around 3760m. The village is named after the holy temple of Muktinath situated on the highest part of the village. Around the Muktinath temple thick moraines deposit develops, which is composed of big boulders of limestone derived from the Jomsom and the Spiti formations. Above the Muktinath temple, the limestone cliff of the Jomsom Formation is juxtaposed with the Spiti Formation by a fault (Colchen and others 1986).

The Muktinath temple lies on the colluvium deposit derived from the southeastern mountain slope, which is composed of limestone boulders of the Jomsom Formation. One of the most interesting aspects in the Muktinath area is the seepage of methane gas from the moraine sediments below the temple, which feeds the flame in the Muktinath temple.

G-20: View of the western slope of Yakwakan (Thoron peak)

On the western slopes of Yakwakan and Khatunkan **(Fig. III-39)** are developed upper formations of the Tethys sediments showing good alternations of Mesozoic formations, which are demonstrated in the Hagen's (1968) sketch **(Figs. III-38, 39)**.

Fig. III-38 Tethys sediments and moraine field in the upper reaches of Jhon Khola. The left peak is 5270 m peak and the right-most peak is 5413 m peak west of Yakwakan (Thoron Peak) (G-20).

G-21: Moraine deposit in Muktinath

Along the trekking route from Jharkot to Muktinath, before crossing the gate of the Muktinath village, a huge deposit of big boulders of limestone on the gentle hill slope represent the moraine deposits (Figs. III-40a,b). The flat area below the Muktinath temple is also composed of angular-shaped moraine boulders of limestone.

[1] Pores of the sediments are going to be filled with water and further, the water pressure increases in time. This facilitates the sediments easy to creep down the gentle slope.

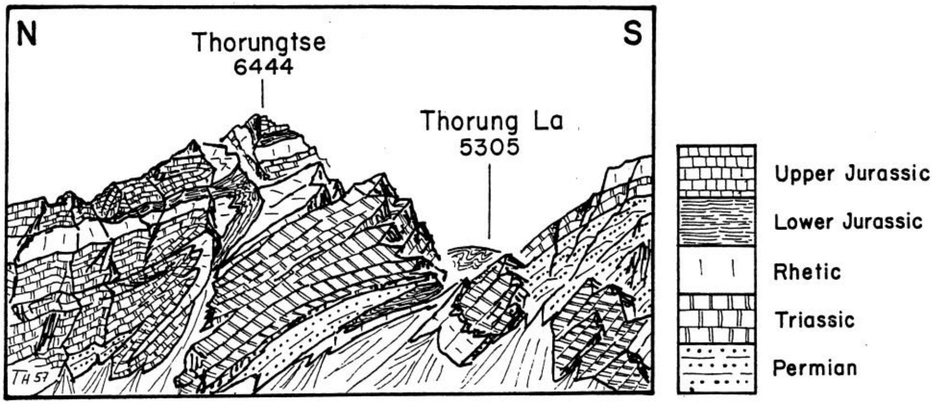

Fig. III-39. Tethys sediments with clearly banded and folded structures on the western slope of Yakwakan (Thoron Peak, 6482m) seen from Muktinath (sketch after Hagen, 1968)(G-20).

Fig. III-40a. (Left photo) Moraine deposit in Muktinath (G-21). Fig. III-40b. (Right photo) Close view of moraine deposits (G-21).

H-8: Muktinath creep

The Muktinath temple area consists of moraine material intermixed with colluvium derived from the failure of nearby cliff composed of limestone. Besides bedding, two prominent joint sets are clearly developed in the rock mass in the cliff. The orientations of the discontinuities are such that they favor both plane and toppling types of failures. Previous failures seem to be dictated by the arrangement of these joints. Since these joints are gentler than the natural hill slope, rock blocks lying on the slope will easily slide down along the plane of the slope forming joints in the future.

The Muktinath Temple is founded on the moraine deposit intermixed with colluvium. The ground is gently inclined northwest. The terrain is slightly undulating, making small depressions at a few places. These depressions are filled up with rain, fluvial and underground water. One of such depressions can be observed just behind the temple (southeast side of the temple). Some of the trees grown up around the temple have their trunk bended downwards the slope **(Fig. III-41a).** Towards the southwest corner of the temple, wide open cracks develop in the compound wall. Near the front gate, the wall of the temple has also a diagonal set of cracks (Fig. III-41b). These signs clearly indicate that the area is creeping down slowly endangering the temple. The problem of slope stability seems to be caused by the pore water pressure formed in the glacial material. A huge amount of water is flowing in and the temple.

Fig. III-41a. (Left) Bent tree trunks around the Muktinath temple (H-8). Fig. III-41b. (Right) A diagonal crack in the wall of the Muktinath temple (H-8).

Besides flowing on the surface of the ground, the water is also infiltrating down the moraine at the foothill, near the temple. The moraine is composed of boulders intermixed with considerable amount of gravel, sand, silt and clay. Most probably, the amount of finer materials increases at depths and also towards down slope. Consequently, hydraulic conductivity of the soil reduces and pore water pressure increases in the glacial material considerably. This situation seems to be responsible in causing the creep in and around the temple, the situation being similar to that observed near Kunjok (H-7).

Jomsom-Kokhethati Section

Physiography and Geology

This section covers an about 23 km distance from Jomsom (2800m) to Kokhethati (2420m) (**Fig. III-42a,b**). Physiographically it lies within the Tibetan and Higher Himalayan zones, and meteorologically belongs mostly to the cold temperate zone. The area north of Marpha belongs to the Tibetan dry zone. Sparse and tiny pine trees are common in the central part and they gradually become larger and form dense forest southward. The valley is mostly very wide about 0.5 to 1km, and ridges on both sides of the valley are very high as much as 8000m (Dhaulagiri Range to the west) to 7000m (Nilgiri Range to the east) in the southern to central sector, while 5000m to 6000m in the northern sector. At the southern end of the present section near Kokhethati, dense vegetation becomes common.

The rocks of this section are composed of the Palaeozoic to Mesozoic sedimentary sequence of the Tibetan-Tethys Sedimentary Series (Tethys sediments) and Quaternary sediments of fluviolacustrine, fluvial and colluvial origin~~s~~. The Tethys sediments are older southward, with mostly north dipping beds, although various large-scale folding structures develop extensively. Basement rocks are, however, only poorly exposed along the trekking route, being mostly concealed by Quaternary sediments, since the trail is situated along the valley. The Quaternary sediments of various origin form low to high terraces on both sides of the valley. Extensive development of wide terraces of various heights, and landslide/slope collapse deposits, Quaternary lake sediment and glacier-related sediments are well developed along the valley. The lake sediments are known as the Marpha Formation (Hagen, 1968; Iwata, 1984). The fluviolacustrine sediments develop only on the southern part.

Natural Hazards

Along this section, the river terraces form gentle slopes whereas the talus deposits exhibit slopes as steep as 35 degrees. Nearly vertical slopes of riverbank cutting on fluviolacustrine sediments can also be observed along the trail. Rock exposures generally form slopes of about 45^o except for a few steep rock cliffs.

Debris flow, riverbank cutting, rock fall and landslide are the main types of mass movement in this section. Major tributaries of the Kaligandaki River have deposited debris in their channel. Slope collapses on large and steep cliffs of middle and lower terraces are found occasionally. At some places, landslides may occur in future. Old plane failure and wedge failure scars can also be observed near the Kali Odar village. At some places where the Kaligandaki River makes a narrow course, the process of bank cutting is very intensive. Remains of thick moraine deposits at places having caused damming of tributaries/main stream of the Kaligandaki River in the past are observed. These may cause debris flow in the downstream during flooding events.

The Tour Course

The tour course is on the rough gravel road and occasionally directly on the river floor. The road mostly follows the right bank of the Kaligandaki river, connecting lower terraces, riverbed and riverside slopes, generally not very high from the river (**Fig. III-42a,b**), and bedrocks occur only sporadically.

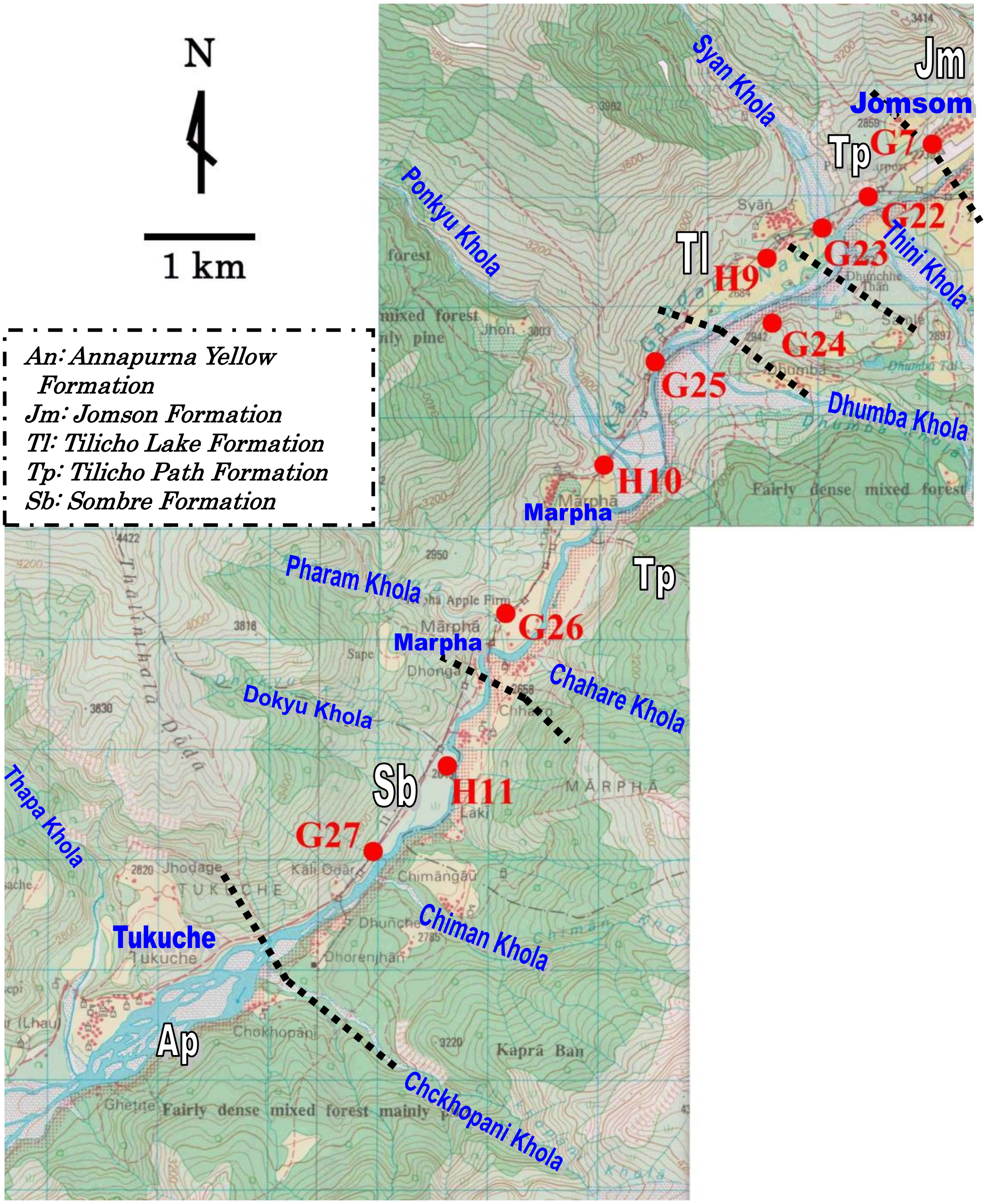

Fig. III-42a. Trekking route and locations of observation points between Jomsom and Tukche (G: Geology, H: Natural Hazard).

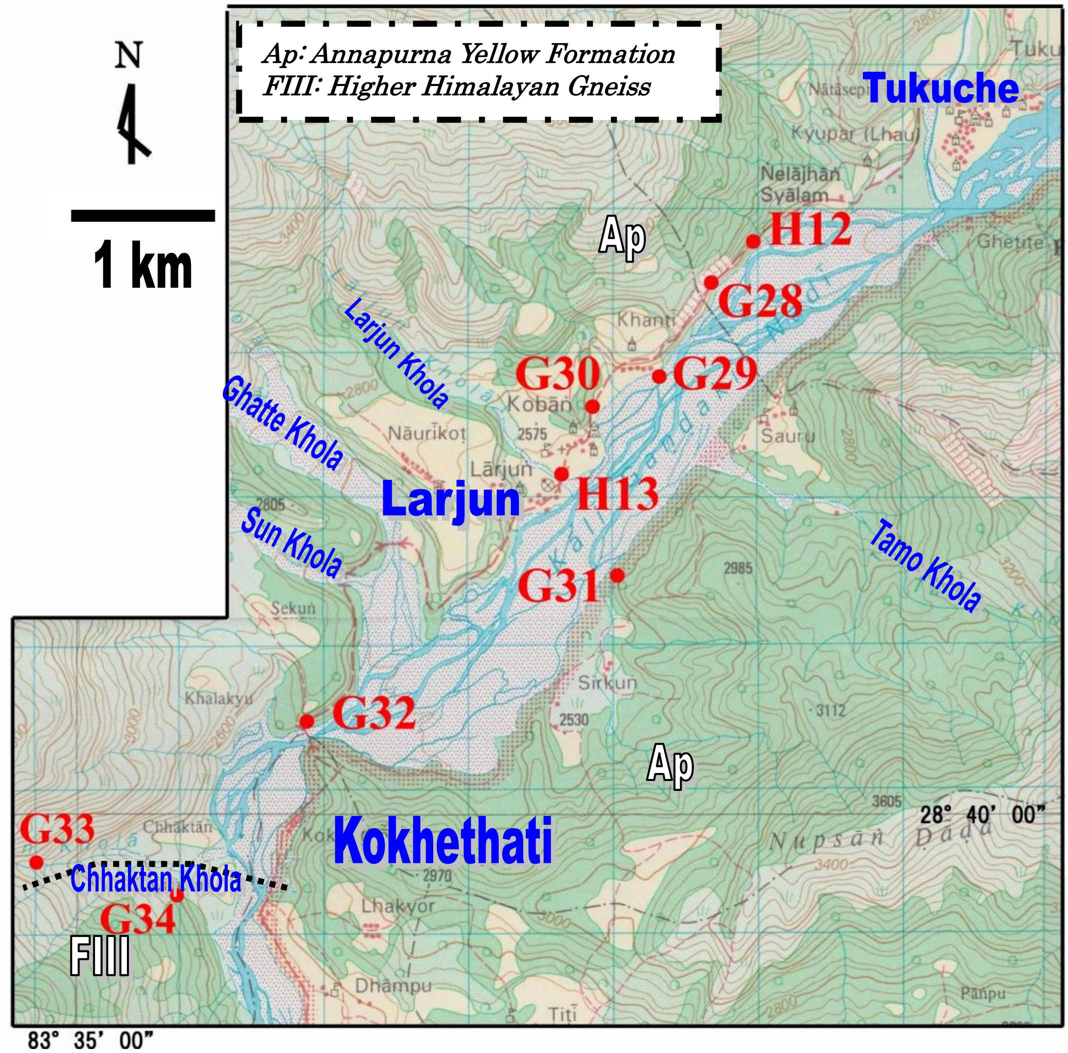

Fig. III-42b. Trekking route and locations of observation points between Tukche and Kokhethati (G: Geology, H: Natural Hazard).

The road mostly passes through a gentle profile with very low relief and walking is less strenuous. During the dry season, local people prefer to walk on the riverbed. Along the road, basement rocks are often covered by quaternary sediments, although on higher mountain slopes, extensive exposures of bedrock with beautiful structures are often well observed.

Observations along the Tour Course

G-22: Several levels of terraces at the mouth of the Thini Khola

On the right bank near the Syan village and on both sides of the Thini Khola (just opposite to the Syan Khola), 3 to 4 *levels of terraces* can be observed **(Fig. III-43a,b)**. These *terraces* are formed by *fluvial*, g*laciofluvial*, *lacustrine* and *Holocene alluvial* deposits. The middle and higher terrace deposits are more than 50m thick.

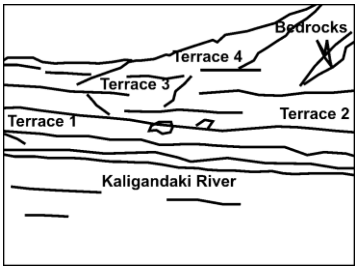

Fig. III-43a (Left) Different levels of terraces on the left bank of the Kaligandaki River (opposite to the Syan Khola) (G-22). Fig. III-43b (Right) Sketch showing the terrace development on the photo left.

H-9: Syan Khola debris flow

As reported by the villagers, about 4.5m thick debris was deposited on the river channel by the Syan Khola debris flow that occurred in 1999. During the event, maximum flood level was reported to be as high as 1.5 m above the present riverbed. The maximum size of the boulder brought by the debris measures 0.85m x 0.6m x 0.6m ($0.3m^3$). In general, the debris flow constitutes about 30 % boulders intermixed with clayey silt and sandy gravel. The debris flow deposits have maintained a slope of about 10 degrees near its confluence with the Kaligandaki River. The recurrence period of the debris flow is not known.

At the confluence of the Syan Khola with the Kaligandaki River, at the lower part of the Syan village, some residential buildings including the Technical Training Center are constructed on an alluvial plain. As the alluvium is only about 1.5m high from the existing Kaligandaki River channel, the buildings are in danger during high flood in the Kaligandaki River. On the other hand, the spur constructed to control the debris flow in the Syan Khola is just 1.5m high which may not be sufficient to control flood or debris flow on the river.

G-23: View of the Sandachhe Himal from the Syan Khola

At the mouth of the Syan Khola, a beautiful view of the folded sequence of the Tethys sediments is well observed **(Figs. III-44a,b)**. According to Colchen et al's. (1996) map, the Tethys sediments belong the Thini Chu, Thini Gaon, Quartzite, and Jomson formations from bottom to the top. If so, the folded white layer could be the Quartzite Formation (shown by a letter Q in Fig.III-55), and the dark layer above (top-most) could be the Jomson Formation (letter J).

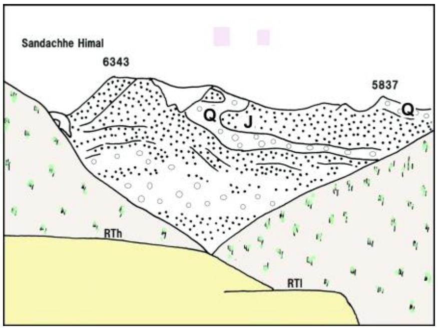

Fig. III-44a. (Left) Southeast slope of the Sandachhe Himal, view from the mouth of the Syan Khola (G-23). Fig. III-44b. (Right) Recumbent fold on southeast slope of the Sandachhe Himal. Q: Quartzite Formation, J: Jomson Formation.

G-24 (Optional): Exposure of banded green schist

To the south of the Syan village and on the left bank of the Kaligandaki River, an exposure of well banded greenschist, pelitic schist, psamitic schist and quartzite occurs forming a large, high and steep cliff **(Fig. III-45)**. These rocks are metamorphosed supracrustal rocks under greenschist facies conditions and contain albite, chlorite, sericite, epidote, and possibly pumpellyite, and are considered to belong to the Thilicho Pass Formation. A sudden change of the metamorphic grade compared with rocks occurring to the north is noticeable.

Fig. III-45 Well banded greenschist, pelitic schist, quartzite alternation of the Tilicho Path Formation south of the Syan village (G-24).

G-25: Rocks of the Tilicho Pass Formation

At about 1km southwest of the Syan village, on the right bank of the Kaligandaki River, the colluvium from the mountain slope contains clasts of various sizes entirely made up of sericite semischist sometimes with crenulation cleavage. ***Schistosity* inclined from the bedding**[1] is also observed. Further south within 500m, some exposures of well-laminated (some millimeters to centimeters thick, **Fig. III-46)**, thick bedded (over 1m), gray limestone with calcareous shale belonging to the Tilicho Pass Formation is observed. A beautiful recumbent fold with a small fold core head is observed with a white marble layer **(Figs. III-47)**.

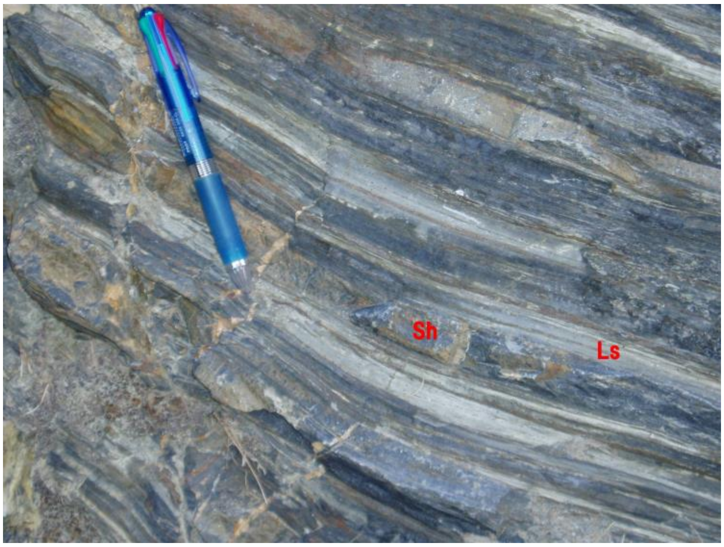

Fig. III-46. Thinly laminated structure of the calcareous shale (Sh) and limestone (Ls) (G-25).

Fig. III-47 Alternation of limestone (Ls) and calcareous shale (Sc), exhibiting a recumbent fold with limestone at the core (delineated by a dashed line (G25).

H-10: Ponkyu Khola debris flow

The debris flow, which occurred in 1999, deposited about 2m thick sediments on the Ponkyu Khola channel as reported by the villagers. The maximum size of the boulders brought by the debris flow was 2.41m x 1.25m x 0.65m (1.96m^3). The debris flow deposit constitutes about 20 % boulder,

[1] Schistosity develops either parallel to or inclined from the bedding. Orientation relationship between the schistosity and bedding is important to study the geologic structure of the area.

20 % gravel and 60 % clayey silt and sand. The debris flow deposit has maintained a slope of about 17^o at the confluence with the Kaligandaki River **(Fig. III-48)**. The recurrence period of the debris flow is not known. The Dhumba Khola that flows west into the Kaligandaki River just south of the Syan village also brought debris.

Fig. III-48 Debris flow deposit brought by the Ponkyu Khola (H-10).

To prevent the debris flow entering into the Marpha village, a spur was constructed along the left bank of the Ponkyu Khola. But the spur is just 1m high and at places it is only 30cm high from the present riverbed. Further improvement of the spur seems to be urgently needed to prevent hazard from debris flows in the future.

Marpha

The Marpha village (2750m above sea level) is well known and beautiful village among the villages along the trekking route. This village is situated on the alluvial deposits of the Kaligandaki River. Thick debris deposited from the Pharam Khola at the southern part of the village. A large amount of lake and glacial deposits of some hundreds of meters thick is seen backside (north) of this village (see **Fig. III-50**). The Ekai Kawaguchi museum and stupa also add the attraction in this village for the tourists. The Japanese monk Ekai Kawaguchi lived here for a short period before going to Tibet more than 100 years ago. The brandy made from apple is famous as well as tasty apple itself. The village is a centre of the ethnic group of Thakali.

G-26-A: Recumbent fold of the Paleozoic Tethys formations and glacial sediments backside (south) of the Malpha village

To the south of Marpha, at the mouth of the Phayan Khola, a beautiful large recumbent fold with a white layer at the core is observed on the eastern slope of the Kaligandaki River (**Figs. III-49a,b).** A possible family of this recumbent fold also develops on the right bank cliff of the river, with an apparently opposite **vergence**[1]. According to the map of Colchen et al (1986), the white layer in the

[1] These structures are considered to form the couple of a large antiform and a synform with their fold axes nearly parallel to the Kaligandaki valley (NE-SW). Thus, they do not have opposite vergencies, but are considered to have a common NW vergence.

core of the fold is the North Col Quartzite and Sombre formations, and the outer beds are the Tilicho Col Formation.

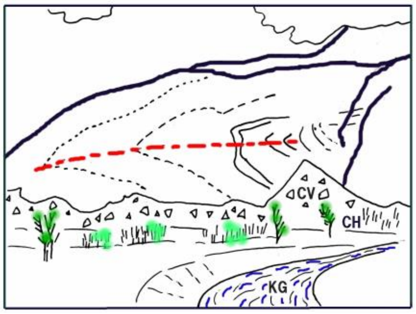

Fig. III-49a. (Left) A large recumbent fold observed on the left bank slope of the Kaligandaki River at Marpha (G-26A). Fig. III-49b.. (Right) Sketch showing the axis of the recumbent fold. Red dashed line shows the axis of the fold. CV: Colluvium, CH: Chilallo village, KG: Kaligandaki River.

G-26B. Marpha Formation and morainic sedimentss

The Marpha Formation (Iwata, 1984) composed of yellowish-light gray fine sediments with angular boulders and gravels occurs surrounding Marpha up to Kagbeni. The distribution of these sediments led Fort (1980) to propose the past development of the Paleo Marpha Lake extending from Kagbeni to Larjung.

On the backside (to the west) of Marpha, on the right bank of the Pharam Khola, a thick layer of light gray Marpha Formation occurs, covering dark gray glacial diamictite and landslide debris, both covering bedrocks composed of the Tilicho Path Formation **(Figs. III-50, 51)**. A thin fluvial or glaciofluvial sediments are found covering the Marpha Formation.

Fig. III-50. Lake (white) and landslide debris (dark gray) exposed on the backside the Marpha village (G-26B).

Fig. III-51. The glaciofluvial deposit (left top) covers the lake deposit (white), which again covers the dark gray glacial deposit.(G-26B).

H-11*: Kali Odar riverbank cutting*

On the right bank of the Kaligandaki River, between Dhonga and Kali Odar, a different state of mass movements can be observed. Along this narrow stretch the river flows with flat terraces on both sides. Near the Dhonga village, intense bank / toe cutting on the left bank of the river is observed. The slumping process at this location has extended up to 20m far from the river bank **(Fig. III-52**). Further downstream, the right bank of the river has suffered intense landslides. As many as five landslide scars are observed by successive landslides within a narrow zone of about 30m. Each landslide scar dips toward the river and also exhibits about 50cm wide opening. The terrace height at this location is about 40m.

Fig. III-52. Multiple scars developed on the terrace between the Dhonga and Kali Odar villages due to the slumping process (H-11).

The glaciofluvial sediments at the failure sites consist of about 5 % boulder, 25 % gravel and 70 % clayey to silty sand. The stretch between the riverbank and the nearby foothill forms a flat terrain that does not dip toward the river. Consequently, rainwater or snowmelt will get more time to percolate down into the soil instead of directly flowing to the river. This situation creates high pore water pressure in the soil of the glaciofluvial sediments that pushes the riverbank outward. This situation in combination with the toe cutting by the river resulted into many landslides above.

G-27: Thinly laminated limestone of the Sombre Formation

On the large cliff just north of the Kali Odar village, calcareous shale/limestone alternations occur. Limestone carries thinly laminated structure. Proportion of the limestone appears to increase southward. Argillaceous facies carries sericite and biotite and changed to semischist. Further towards southwest, the Kaligandaki valley floor becomes wider and a part of Dhaulagiri range appears in front of us (**Fig. III-53**).

Fig. III-53. Wide Kaligandaki valley floor with the Dhaulagiri and Tukuche ranges on the back (right highest peak is the Tukuche Peak) (G-27).

Tukuche village

The Tukuche village (2650 m) lies on the alluvial deposits of the Kaligandaki River on the right bank and situated on the confluence of the Thapa Khola and the Kaligandaki River. Tukuche is also a well-known village as Marpha along the trekking route. This village is also known for producing the apple brandy. According to local people, Ekai Kawaguchi had lived sometime long in this village during his travel to Tibet.

H-12: Nelajhan Syalam rock fall

Downstream from Tukuche, at the Nelajhan Syalam village, on the right bank of the Kaligandaki River, cultivated area extends on the toe part of a landslide deposit. Toe cuttings by the river have further accelerated the slope failure further accelerated the slope failure process. To the northwest corner of the landslide deposit, a thick pile of colluvium

Fig. III-54. Steep rock cliff near the village of Nelajhan Syalam (H-12).

derived from an old plane failure is found. Further downstream, the main trail passes through the foot of a steep cliff (**Fig. III-54**).

The cliff shows three sets of prominent discontinuous planes. Bedding dips about 30° towards north-northeast. Other two discontinuities (75°S and 84°ESE) are slope-forming joints. At some places rock falls may take place in future because of overhanging part of the cliff with wide-open joint.

G-28: Small folds in the Annapurna Yellow Formation

At about 500m south of Nelajhan Syalam, on the right bank of the Kaligandaki River, a large cliff with good exposures of thinly laminated, calcareous, medium-grained gray sandstone with fine-grained gray shale of the Annapurna Yellow Formation is observed. In some places, sericite-muscovite schist interbedded within meta-pelitic and meta-psamitic rocks is also found. Small-scale folding of thin laminae as well as calcite veins shows ***the south-verging thrusting sense of movement***[1] **(Figs. III-55a,b**).

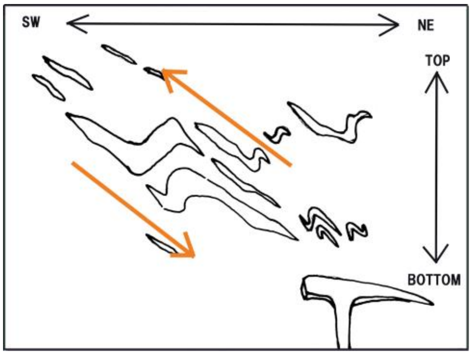

Fig. III-55a (Left). Reverse-sense small folds of calcite veins in the calcareous shale of the Annapurna Yellow Formation (G-28). Fig. III-55b (Right) Sketch showing the reverse fold with southward vergence. Allows indicate sense of the shear.

G-29: View of Dhaulagiri and Nilgiri peaks

There are only few basement outcrops along the trail between Tukuche and Larjun. However, we can enjoy the beautiful view of both sides of the Kaligandaki valley, the Dhaulagiri Range to the west and the Nilgiri Range to the east **(Figs. III-56, 57a).**

The mountain section between the Dhaulagiri and Ruwachaur Himal (some 15km south of Dhaulagiri) shows large-scale geologic structures **(Fig. III-57a,b)**. Along the ridge, southeastward from the Dhaulagiri peak to the 5263m peak (1:50,000 map), the Tethys sediments are exposed, while all the Ruwachaur Himal further south (left in **Fig. III-57a)** consists of the Higher Himalayan gneisses. The north dip of mountain surfaces surrounding the 5263m peak reflects a general northward dipping of the geologic structures of both the Tethys sediments and the Higher

[1] This sense of movement is same as that of the MCT, but in contradiction to most of large-scale folds within the Tethys sediments, the latter being generally correlated with the normal-sense movement of STDS.

Himalayan gneisses. Also, the extensive development of Cenozoic sediments including lake deposits, talus, terrace and fan deposits is very characteristic along the Kaligandaki valley of this sector.

Fig. III-56. Wide gravel riverbed of the Kaligandaki River, looking northeast from Khanti. The Nilgiri Range lies on the back, which is composed of the lower formations of the Tethys sediment (G-29).

Fig. III-57a. Dhaulagiri -Ruwachaur ranges observed from the Kaligandaki valley near Khanti. North (rightward) dipping structure of the Higher Himalayan gneisses and Tethys sediments is reflected in the topography (G-29).

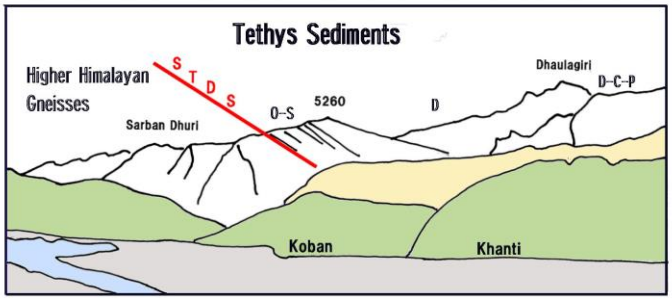

Fig. III-57b. Dhaulagiri and Ruwachaur ranges with geologic structures. STDS (South Tibetan Detachment System), O-S: Ordovician-Silurian sediments, D: Devonian sediments, C-P: Carboniferous to Permian sediments (G-29).

G-30: (Optional): Main characteristics of the Annapurna Yellow Formation

At about 200m north of the Koban village, on the right bank of the Kaligandaki River, a good outcrop of the Annapurna Yellow Formation occurs. The main constituents of the Annapurna Yellow Formation are light gray and dark gray limestone often with many fossils and oolitic structure **(Fig. III-58).** The limestone is interbedded with thin layers of schist and meta-sandstone.

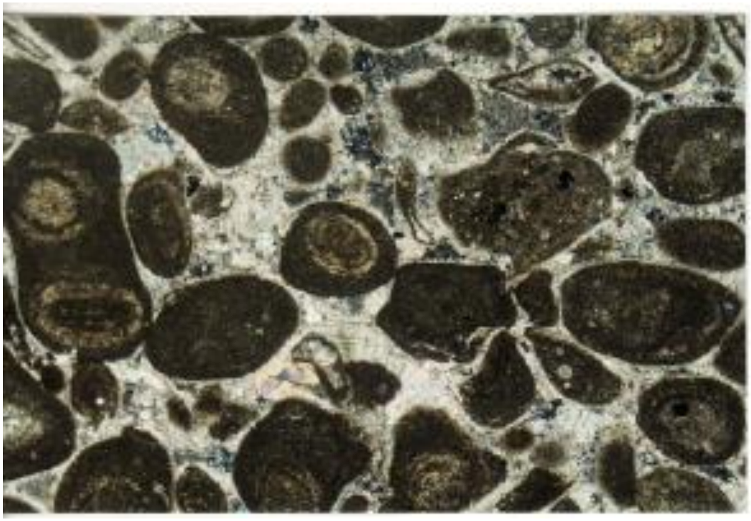

Fig. III-58. Oolitic limestone of the Annapurna Yellow Formation (G-30).

H-13: Larjun Khola debris flow

About two meters thick sediment was deposited on its channel and nearby areas by the Larjun Khola debris flow in 2002. The maximum size of the boulder brought by the debris flow is 1.5m x 1.0m x 0.6m. The debris flow deposit forms a slope of about 15 degrees near the confluence with the Kaligandaki River. Residential buildings situated nearby the river channel were heavily damaged due to the debris flow event. Ground floors of some buildings were filled up with the debris. Similarly, the apple garden near the river channel was also filled up with a thick pile of debris **(Fig. III-59a)**. The source of the debris flow was reported to be a landslide dam created at a few kilometers upstream from the village.

Villagers have constructed gabion wall (height: 1 – 1.5m and width: 1.5m) to control the river

(Fig. III-59b). This has limited the river to flow in a narrow channel of about 20m wide. Considering the intensity of the last debris flow, the height of the gabion seems to be insufficient to control the similar incident in future. Similarly, the suspended bridge over the river is too low to be sustainable from debris flow in future.

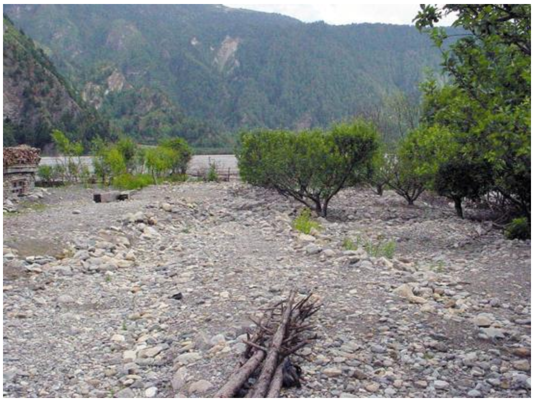

Fig. III-59a. (Left photo) Gabion of the Larjun Khola (H-13). Fig. III-59b. (Right photo) An apple garden covered up by the debris flow brought by the Larjun Khola (H-13).

G-31 (Optional): Cataclasite/breccia zone in the Annapurna Yellow Formation

Remarkable cataclasite/brecciated limestone of the Annapurna Yellow Formation **(Fig. III-60)** develops for about 3km along the left bank cliff of the Kaligandaki River centering the G-30 point. Since there is no outcrop on the right bank of the river, this cataclastic zone of 3km wide possibly continues to the right bank, running nearly east-west. There is a possibility that this cataclastic zone is correlated with the activity of the ***South Tibetan Detachment System (STDS)***[1] identified in the Everest area.

Fig. III-60. Cataclastic limestone on the left bank of the Kaligandaki River SE of Larjun (G-31).

[1] The boundary between the Higher Himalayan gneisses and the Tethys sediments is not the fault but intrusive at Chhacktan Khola (see G-33) as reported in this guidebook. The detachment, if it is, may be located further north than the G-33 point, possibly surrounding G-31.

G-32: Lower part of the Annapurna Yellow Formation

On both sides of the suspension bridge over the Kaligandaki River north of Kokhethati, coarse-grained arenaceous gray marble with the schistosity shown by biotite flakes occurs. The marble ***belongs to the Annapurna Yellow Formation***[1] which is the basal litho unit of the Tethys sediments. The grade of metamorphism obviously increases here compared to the upper part of the Annapurna Yellow Formation occurring to the north. The marble is overlain by the thick Quaternary deposit composed of yellowish brown silty sand with scattered angular clasts of limestone and sandstone. This deposit was most probably formed through the glaciofluvial process. This deposit occurs extensively along the Kaligandaki River northward up to Larjun.

G-33: Boundary between the Tethys sediments and the Higher Himalayan gneisses

On the valley bed of Chaktan Khola at the top of the fan[1], good exposures of marking the boundary ***(comparable with STDS)***[2] between the Tethys sediments ***(the Annapurna Yellow Formation)***[1] to the north and the Higher Himalayan gneisses to the south is found (Figs. III-61, 62). The basal part of the Annapurna Yellow Formation consists of calcareous meta-sandstone with quartz, feldspar, biotite, and calcite (Fig. III-63). Some coarse-grained white marble layers were also observed. The tourmaline-bearing leucogranite intruded into the marble**.** The augen gneiss of the Higher Himalayan gneisses also appears to be intrusive to the marble. Thus obvious fault relationship to be correlated with the South Tibetan Detatchment System (STDS) is not ascertained at this critical outcrop, or regarded to be the intrusive relationship (Yoshida and others 2004).

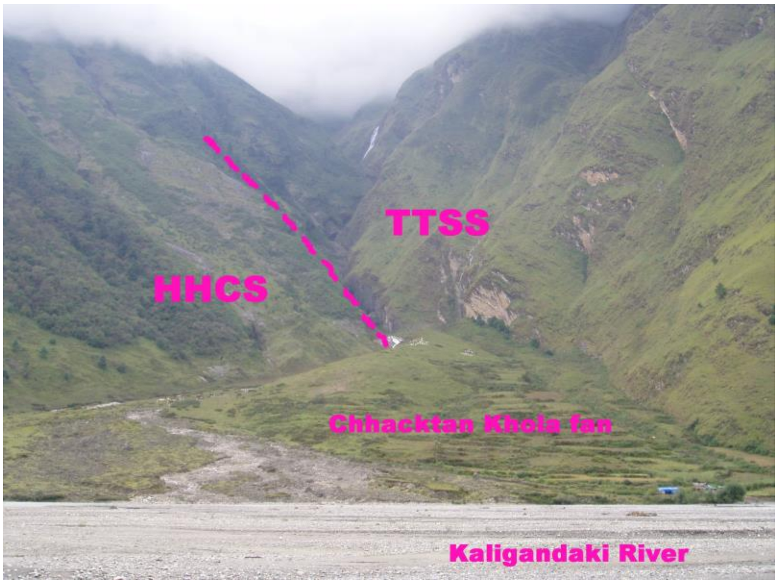

Fig. III-61. The Chhoktan Khola along which the boundary (South Tibetan Detachment System) (Dashed line) between the Higher Himalayan Zone (HHCS) to the south and the Tibetan-Tethys Zone (TTSS) to the north runs. (G-33).

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[1] Some authors (e.g., Bodenhausen and others 1964) consider this part of the Tethys sediments to be the Larjun Formation, which underlies the Annapurna Yellow Formation.

[2] See footnote 1 of page 63

[1] This location is very dangerous due to the possibility of avalanche. Because of the danger, the Student exercise tors used to abandon to visit this critical location.

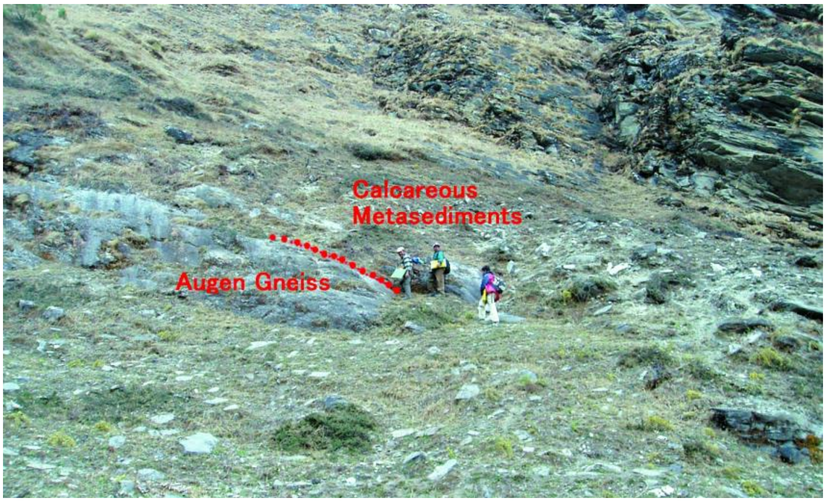

Fig. III-62. Boundary between the marble of the Tibetan-Tethys Zone and the augen gneiss of the Higher Himalayan Zone on the right bank slope of the Chhaktan Khola (G-33). The G-33 point is very dangerous prone to suffer avalanche in any season.

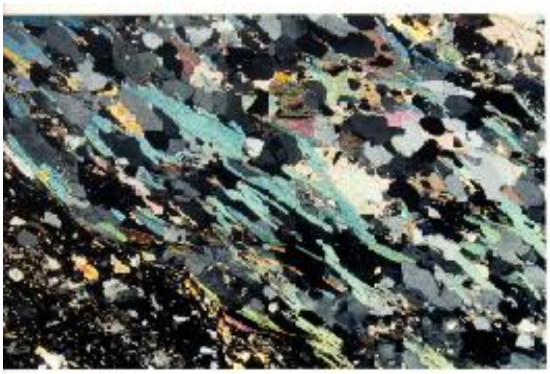

Fig. III-63. (Left) Photomicrograph of the metamorphosed limestone (two mica marble) of the Annapurna Yellow Formation, just above the STDS (G-33).   Fig. III-64. (Right) An outcrop of STDS on the roadside near Chhaktan Khola. TS: Calcareous meta- sediment, TG: Tourmaline leuco granite, HHG: Granitic gneiss (G34) .

G-34: Critical boundary of the Tethys sediments and the Higher Himalayan Gneisses

Just at the right bank cliff that forms the west road side wall of the road, there was a good exposure of the boundary of the Tethys sediments and the Higher Himalayan Gneisses. A small body of tourmaline leuco granite is situated between the two rocks. The granite shows intrusive relationship to the gneiss and the Tethys sediments, and the boundary between the granite and the sediments is planer and appears to be tectonic (Fig. III-64), although it does not appear to be an important fault such as STDS. The Tethys Sediments are severely affected by thermal metamorphism and carry metamorphic minerals including garnet and diopside etc. Thus this outcrop shows that the leuco granite intruded along the boundary of the Tethys sediments and the Augen Ggneiss. The outcrop of Fig. III-64 disappeared due to road construction and instead, a new good fresh outcrop of the analogous signature appeared in 2019, which, however again disappeared by road construction in March 2022.