Foemation and Deformation of River Terraces in the Hetauda Dum, Central Nepal A Contribution to the Study of Post Siwalikan Tectonics

著者	KIMURA Kazuo
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Formation and Deformation of River Terraces in the Hetauda Dun, Central Nepal —— A Contribution to the Study of Post Siwalikan Tectonics ——

Kazuo KIMURA

Abstract Situated on the southern fringe of the Nepal Himalayas, the longitudinal "dun" valley consists of polycyclic geomorphological units ; the Highest erosion surface, the Upper, Middle, Lower terraces and flood plains. The following three phases of dun valley development are recognized through geomorphological and sedimentlogical analysis.

Pre-Dun phase : Older geomorphological units (the Highest surface and the Upper terraces) had developed as piedmont alluvial plains at the foot of the Lesser Himalaya. The vertical displacement of the Main Boundary Thrust (MBT) contributed chiefly to the supply of alluvial fan deposits. Until this stage, the study area had faced the Gangetic Plain.

Separation phase : Analysis of the Middle terraces and their deposits reveals evident relation between the upheaval of the Churia Range and palaeogeographic changes of the study area. In contrast to the older surfaces, the Middle terraces generally indicate the trend of development from south to north, and their deposits also show the trace of south-north current. This means that the generation of the Churia Range cut palaeochannels flown from the Lesser Himalaya to the Gangetic Plain, and the Hetauda Dun was closed as an intermontane basin. The separation is caused by the uplift ot the Himalaya Front Fault (HFF) sheet accompanied with the Central Churia Thrust (CCT) and their related tectonics.

Dun phase : The younger units (the Lower terraces, the flood plains and their deposits) demonstrate their origin as pure valley fillings. Unlike the older sediments, which are dominated by fan deposits, the Lower terraces include lacustrine or swamp sediments. Their facies illustrate a typical dun nature, wet lowland. On the other hand, the deposits show younger subordinary tectonic deformation.

Comparison of soil colours, dissection of terrace surfaces, and existing data concerning the Sub-Himalaya provide the following chronology of the phases. The Pre-Dun phase goes back to the Middle Pleistocene. The Separation phase corresponds to the Last Interglacial Stage or the interstadial in the Last Glacial Stage. The Dun phase ranges from the Last Glacial Climax to the Holocene.

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Key words: Quaternary, Sub-Himalaya, intermontane basin, palaeogeography, tectonic geomorphology

1 Introduction

The Nepali word "dun" means wide-opened basins in the Sub-Himalaya. They are typical longitudinal valleys situated in between the Mahabharat Range (Lesser Himalaya) and the Churia Range (Sub-Himalaya). The area is known as a recent uplifting zone that is an active front of the Himalayan orogenic belt. Therefore, geomorphological significance of "dun" must be directly associated with the neotectonics of the Outer Himalaya. This paper aims to clarify the geomorphological development of a dun valley. It is an approach to the neotectonics of the boundary zone between the Himalayas and the Gangetic Plain.

2 Over view

2.1. Physical features

The Hetauda Dun is situated at the central part of Nepal (Fig. 1). It extends 30 km long, WNW-ESE direction, with width of 10 km. Its valley floor ranges from 300 to 600 m above sea level. The Mahabharat Range stands north of the valley, being 1,700-2,500 m. In front of the Mahabharat, the Churia Range develops in height of 700-900 m, and surrounds the dun valley.

The Siwaliks, Himalayan molasses accumulated during the period from the Miocene to the Early Pleistocene, predominate in the Sub-Himalaya (Figs. 2, 3). Forming cuestas and/or hogbacks, they expose around the Hetauda Dun. In dun valleys, younger unconsolidated deposits unconformably overlie the Siwaliks. These coarse deposits are generally termed the Dun Gravel (*e.g.* Sharma 1990).

Three major fault systems develop along the valley. At the Main Boundary Thrust (MBT), the Siwaliks are in fault contact with the Lesser Himalayan Metasediments. The fault line, however, does not accord with the topographic boundary between the Mahabharat Range and the Dun valley. The Central Churia Thrust (CCT) divides the Siwaliks into two parts, the north belt and the south belt. The Upper Siwaliks and the Dun Gravel, the late Neogene sediments, are overthrusted by the Lower Siwaliks. A reverse fault, showing scarplets and pressure ridges, runs intermittently at the south foot of the Churia Range. It must be a part of the Himalayan Front Fault (HFF).

2.2. Previous study

Among geological researches which are mainly focused on Tertiary sediments and

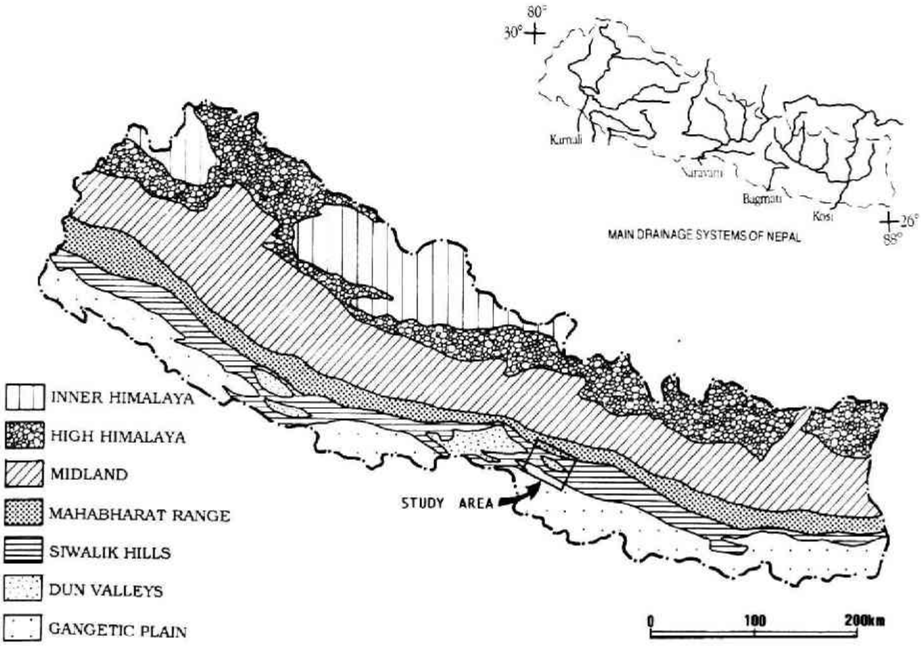


Fig. 1 Topographic province of Nepal (modified after Sharma 1990).

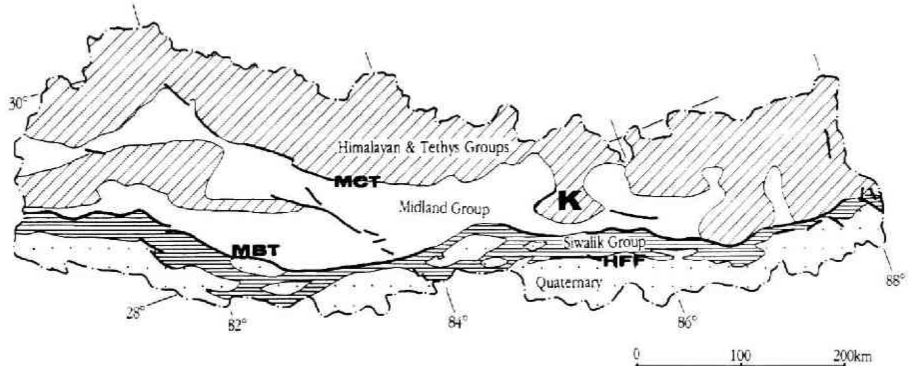


Fig. 2 Simplified geological map of Nepal (modified after Nakata 1989).
K : kathmandu

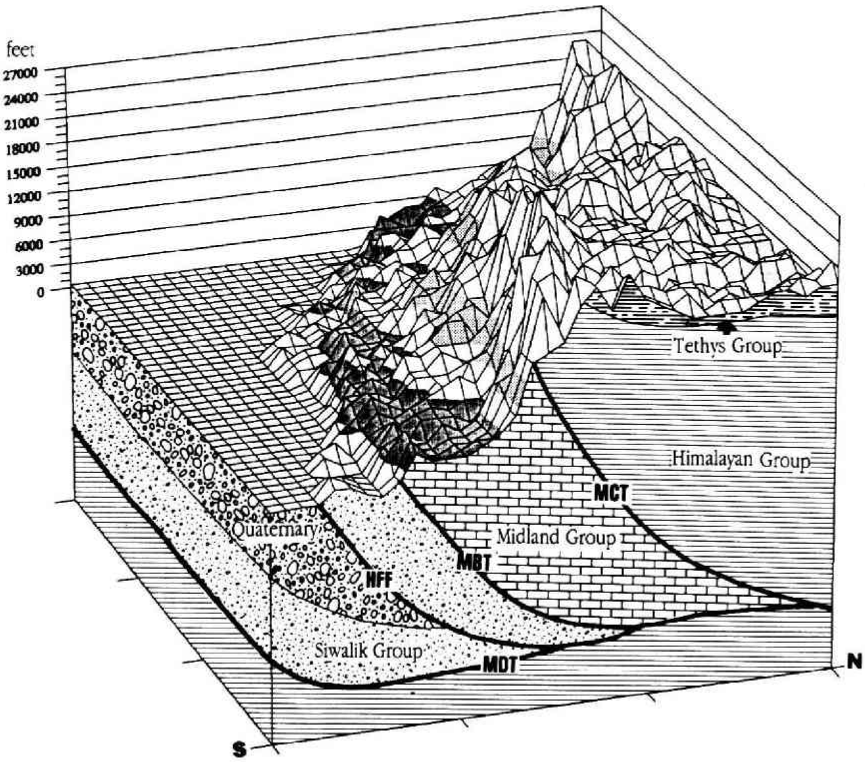


Fig. 3 Cross-section of Central Nepal.

tectonics of the Outer Himalaya, some geomorphological or Quaternary geological studies have been carried out.

Detailed geology of the Chitwan Dun, west of the study area, is described by Tokuoka *et al.* (1994). The area, underlain by the Siwaliks, is divided into the north belt and the south belt by the CCT. The Siwaliks themselves are divided into A, B, C and D units in ascending order. Unit A coincides with the Lower Siwaliks, Unit B is equivalent to the Middle Siwaliks, and the rest corresponds to the Upper Siwaliks (Table 1).

Sah *et al.* (1994) apply the classification of the Siwaliks to the Hetauda Dun. A, B, C and D units of the Siwaliks are respectively named the Rapti Formation dominated by silstone, the Amlekhganj Formation consisting of sandstone, the Churia Khola formation comprising pebble-size conglomerate and the Chriamai Formation of boulders (Table 1).

Schelling *et al.* (1991) discuss tectonic shortening of the Hetauda-Amlekhganj section by the technique of balanced cross-section analysis. According to them, the

Table 1 Correlation of the Siwaliks (after sah et al., 1994)

AGE	Auden 1935	Hegen 1969	Glennie & Ziegler 1964	Itihard *et al.* 1972	Sharma 1977, 90	Kayastha 1978 79	West & Munthe 1981	Yoshida & Arita 1982	Tokuoka & Yoshida 1984	Tokuoka *et al.* 1986	Corvinus 1988	Bashyal *et al.* 1989	Sah *et al.*
EARLY PLEISTOCENE	Upper Siwalik	Upper Siwalik	Conglomerate Facies	Upper Siwalik	Upper Churia Group	Upper Siwalik	Upper Siwalik	Upper Siwalik	Upper Siwalik	Deorali Formation	Dhankh. Beds	Upper Siwalik	Churia Mai Formation
							Gidhnla Fauna			Chitwan Formation	Dobatt Beds		Churia Khola Formation
	Middle Siwalik	Middle Siwalik		Middle Siwalik		Middle (MS_2)		Middle Siwalik	Middle Siwalik	Binai Khola Formation	Surai Khota Beds	Middle Siwalik	Amlekhganj Formation
					Lower Churia Group	Middle Siwalik (MS_1)	Babai Khola Fauna				Chor Khola Beds		
			Sandstone Facies								Water spring Beds		
MIDDLE MIOCENE	Lower Siwalik	Lower Siwalik		Lower Siwalik		Lower Siwalik	Lower Siwalik	Lower Siwalik	Lower Siwalik	Arung Khola Formation	Bankas Beds	Lower Beds	Rapti Formation

three major fault systems, MBT, MDT (the Main Dun Trust coinciding with the CCT) and MFT (the Main Frontal Thrust corresponding to the HFF), are emergent splay thrusts of the Main Detachment Fault, at a depth of about 6 km. Total north-south shortening across the section is estimated about 17 km or 40% during the Neogene period.

According to Itihara *et al.* (1972), three levels of river terraces are distributed in dun valleys in eastern Nepal. They report that the terraces cut the Siwaliks and their deposits are several to 10 m thick.

Geomorphological surfaces of dun valleys and the foothills, which are located in North India, are attributed by Nakata (1972). He classifies the geomorphologial units into five to eight levels in places. He recognizes five types of crustal movements on the basis of geomorphic deformation. Type 1 is the tilted upheaval which is dipping towards the Indo-Gangetic Plain. Type 2 is another type of tilted upheaval that is slanted towards the Himalayas. Type 3 is the fault steps, located at northern boundary of the Sub-Himalaya, subsiding to the South. Type 4 is also the fault steps which has a small narrow rift around the northern boundary of the Sub-Himalaya. Type 5 is the gently undulating upheaval that has occasional fault movements along the major thrust in the Sub-Himalaya. The tectonics of dun valleys is categorized into Type 2, 3 or 4.

Yamanaka and Yagi (1984) clarify geomorphic development of the Dang Dun located in the Middle Western Nepal. They classify fluvio-lacustrine terraces into the following four groups ; the highest terrace, the higher terrace, the middle terrace and the lower terraces. The highest terrace consists of partly cemented gravel that is 15 m thick or more. The age of this oldest terrace deposits are roughly estimated as 400,000 to 500,000 years ago by soil colour. Judging from the facies of the terrace deposits, they were formed as fans at the foot of the Mahabharat Range. The dun commenced to subside after the formation of these older fans. The lower terrace sediments, lacustrine nature and 23 m thick or more, deposited in 16,000 to 26,000 years BP (C-14 dating). Its surface is dipping upstream in the south margin of the Dang Dun. This deformation means that a syncline has continued its development after the formation of the Lower terrace.

Iwata and Nakata (1985) recognize ten levels of geomorphic surfaces in the area around Narayanghat, central part of the Chitwan Dun. They notice the higher surface is tilting northwards against the major trend. The age of the higher surface is presumed 120,000-200,000 years ago in consideration of soil colour. It suggests block movement of the range behind in the Late Pleistocene.

Delcaillau *et al.* (1987) describe the morphostructures of the Siwalik Hills in eastern Nepal. They recognize three levels of fluvial terraces in the narrow longitudinal valleys, and examine their morphostructures. They conclude that these valleys were formed as pull-apart depressions in the post-Siwaliks stage.

Bashayal *et al.* (1989) discuss the Sub-Himalayan neotectonics based on physiographic aspect. In their study, the morphostructural organization in the Himalayan Front is characterized by two types of relief ; the escarped front and the smooth front. The former results from a thrust ramp, and forms high-relieved steep slopes (400-600 m of relative height) due to the greater uplift rate than erosion rate. The latter are regarded to correspond to a flat lying thrust. At the smooth front, erosion and shortening of the crust are balancing each other.

A series of researches by Nakata (1982, 84, 89) reveals some remarkable facts about fault activities in the Sub-Himalaya. He recognizes many active faults along the MBT that is parallel to dun valleys. These faults, along which the Sub-Himalayan side is uplifted, usually show high angle reverse fault feature or that of normal fault. Some of them have been active to recent time. He also notices the deformation of terraces, which are faced towards the Gangetic Plain. The survey estimates that the active faults in the Sub-Himalaya have been slipping in the rate of about 5 mm/y since the Late Pleistocene.

3 Tectonostratigraphic background

The tectonic mechanism of the Sub-Himalayan Zone is characterized by NNE-SSW compression related with the collision between the Indian and Eurasian Plates (*e.g.* Kizaki 1988). Dun valleys develop across the main axis of the stress. Two major fault systems, MBT and the HFF of WNW-ESE strike, run parallel to the valley. By contrast, the CCT is winding through the study area. There are subordinate tectonic structures in the Hetauda Dun (Figs. 4, 5, 6).

3.1. The Main Boundary Thrust

In central Nepal, the Main Boundary Thrust is a medium north dipping (around 45°) reverse fault along which the low grade Lesser Himalayan Metasediments have been thrusted over the Amlekhganj Formation of the Sub-Himalaya. A reverse fault runs a few km north of the Hetauda Dun. It is a part of the MBT and named the Hitaura Fault by Nakata (1982). This paper renames it as the Kiseri Khola Fault after the river name along the fault. Because the name that the Hitaura Fault seems to confuse the Hetauda Fault (Yoshida and Arita 1982), which is resumed to be a part of the MDT. The fault forms saddles or fault line valleys on the south slope of the Mahabharat Range. Its fault line straights about 30 km with WNW-ESE direction. However, there is no evidence of displacement of Quaternary deposits. Neither shutter ridges nor offset channels could be observed. It suggests the Kiseri Khola Fault has not been active since the Late Pleistocene. On the other hand, the summit level shows progressively change at the fault (Fig. 5).

3.2. The Churia Central Thrust

The CCT divides the Siwaliks into two parts, the north belt and the south belt (Tokuoka *et al.* 1994). Huge subangular boulders of the Lower Siwalik origin, the marker deposits of vertical displacement of the CCT, are distributed at the foot wall of the thrust in the Chitwan Dun.

Shelling *et al.* (1991) and Sah *et al.* (1994) delineate a geological fault of NNW-SSE orientation in the southern part of the Hetauda Dun. The fault corresponds to the CCT because the Rapti Formation is overthrusting the Churia Khola Formation, the Churiamai Formation or the Dun Gravel. The angular boulders consisting of huge blocks of the Siwaliks origin, however, could not be observed in the study area. In morphological aspects, the fault stretches intermittently and comprises three parts: the Chakri Khola Fault, the Chure Khola Fault and the Ratmate Fault. Each element of the fault limits the distribution of the Highest and Upper surfaces. However, the lower terraces hide the fault rather than being displaced.

The Chakri Khola Fault is observed as scarplets and depressions of E-W to NW-

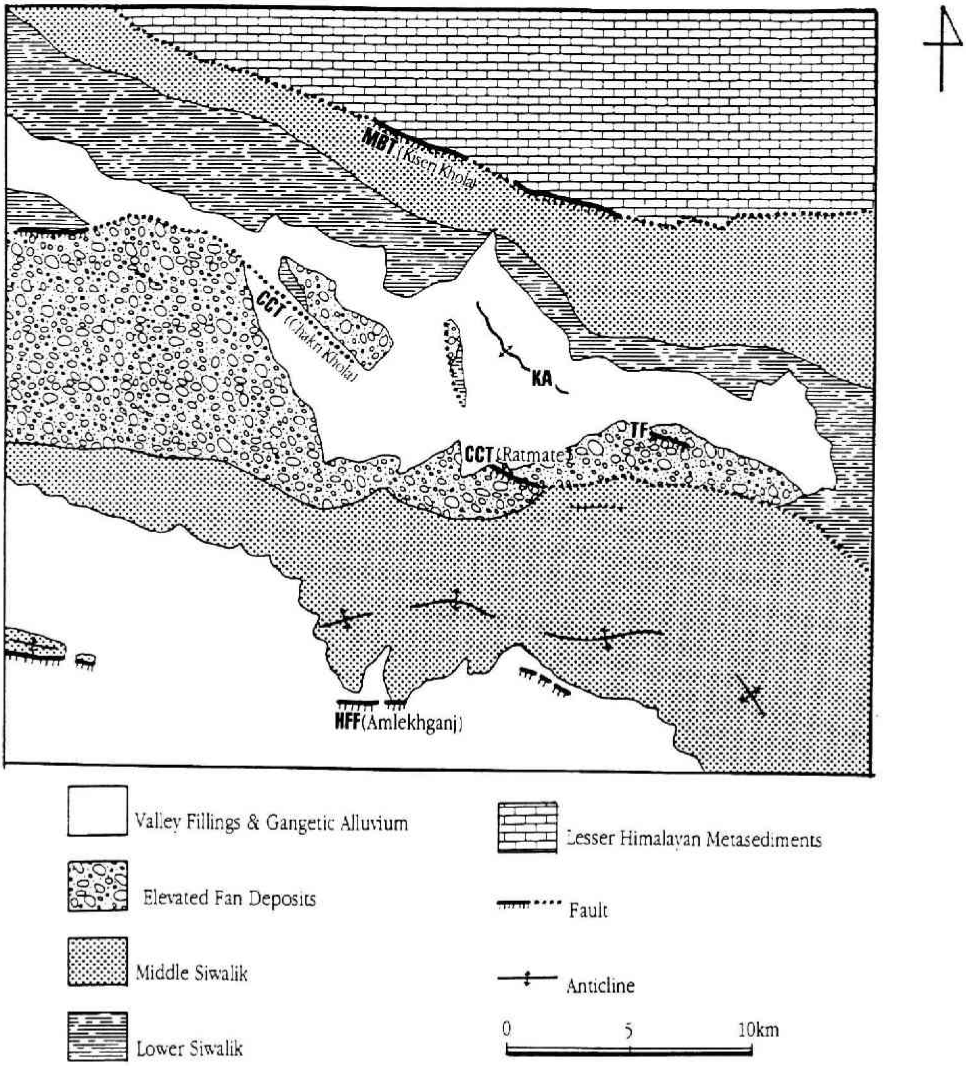


Fig. 4 Tectono-stratigraphic map of the study area.

SE direction at the north foot of the Churia Range (Fig. 4). It stretches about 12 km in length, and forms a clear boundary between the Rapti Formation and the Dun Gravel. The Highest and Upper surfaces are limited by the fault line and their surfaces distributing on the hanging wall of the fault is tilted northeastwards. Large landslide relicts, which are located on the Middle and the Lower terraces, develop along the fault.

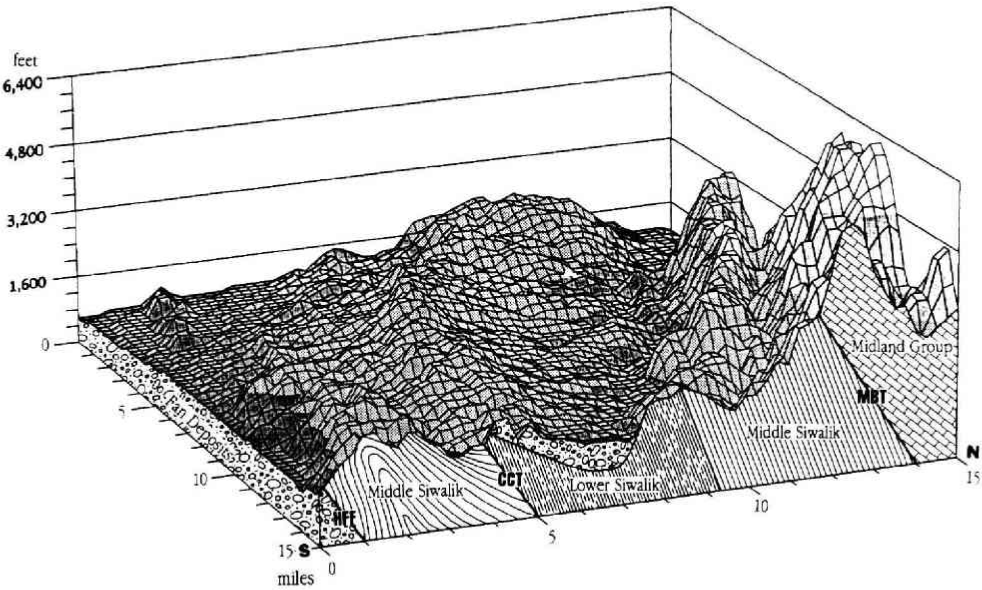


Fig. 5 Cross-section of the study area.

The Chure Khola Fault is NNW-SSE striking photolineament situated on the left bank of the river (Fig. 4). At east of the line, the Rapti Formation exposes on higher level than fluvial terraces. An eastwards dipping gravelly bed, which is intensively weathered, is underlain by the Rapti Formation. This stratigraphic features are similar to those of the CCT, and the Chure Khola Fault is branched from the Ratmate Fault described below.

In the area between the upstream of Chakri Khola and Chure Khola, the CCT is buried by younger terrace deposits. It appears near the divides of the Churia Range, south of Ratmate (Fig. 4). A surface gap of the Ratmate Fault, which displaces the U2 terrace 1.6-8 m vertically, is traceable about 2.5 km long with NW-SE to WNW-ESE orientation, and its photolineament extends more than 6 km towards east. The Rapti Formation and the Upper Terrace deposits are overthrusting the gravelly strata of the Upper Siwalik on the fault (Fig. 7). Terraces on the hanging wall are steeply dipping (greater than 60°) towards northeast. At the place, a few hundred meter north from the fault line, the Upper Terrace deposit is folding anticlinally, and forms pressure ridges rising about 15 m from the surroundings.

3.3. Subordinate structures

On the thrust sheet of the CCT, two parts of structural lines, the Karra Khola Anticline and the Trisuli Fault, are parallel to the CCT.

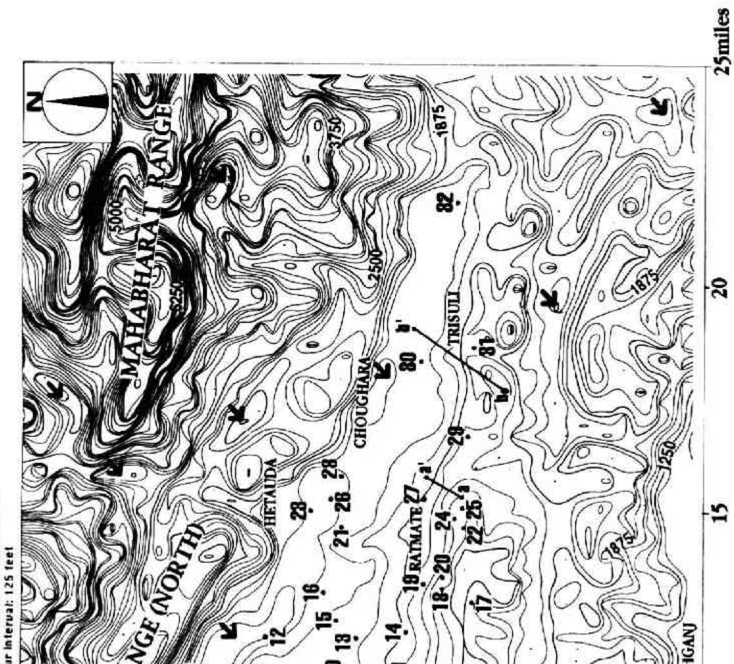


Fig. 6 Locality index map.

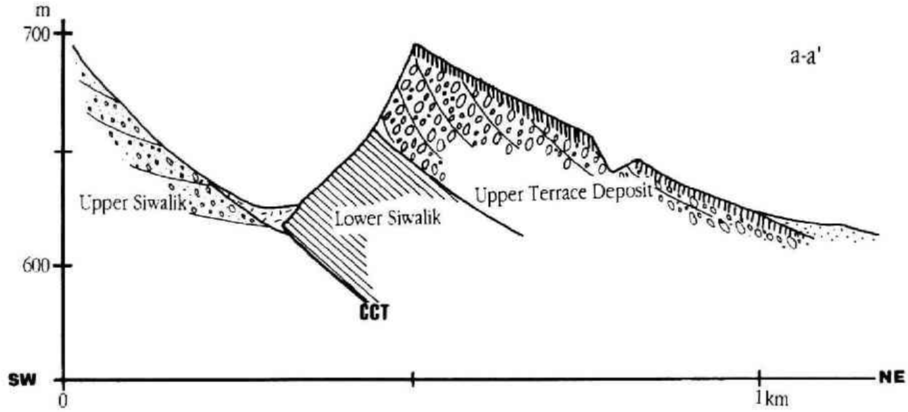


Fig. 7 Cross-section of the Central Churia Thrust (a-a' in Fig. 6).

The Karra Khola Anticline (KA) shows a chain of tectonic bulges. From Hetauda to the left bank of Karra Khola, upstream-inclined terraces and bulges develop intermittently. Though these swells wind in hundred meter length, they generally stretch in NW-SE direction (Fig. 4). On the hinge of the anticline, the L1 Terrace is dipping 1-8° upstream against the talwegs, which is commonly incline 3-5° downstream (Fig. 8). Some tributaries of Karra Khola are cranked by the anticline (paralled to the axis and cross it as antecedent streams). The L1 Terrace bends up more than 15 m on the anticline, and is surrounded by younger terraces without scarplets. Its deposits are also folded, and the deformation increases in descending order. This means that the anticline has been gradually developing since the formation of the L1 terrace.

The Trisuli Fault (TF) is a thrust of 1.8 km long, developing between the divide and Trisuli Village, southwestern part of the study area (Fig. 4). Though the foot wall is buried by younger sediments, the fault vertically displaces the Upper terrace a few metres (Fig. 9). The M1 Terrace deposit is also deformed by the fault. As same as on the Ratmate Fault, the Upper Terrace deposits slant northeastwards, and tectonic

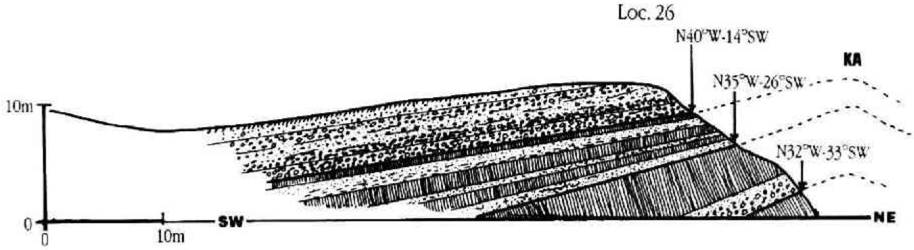


Fig. 8 Sketch of the Karra Khola Anticline (Loc. 26 in Fig. 6).

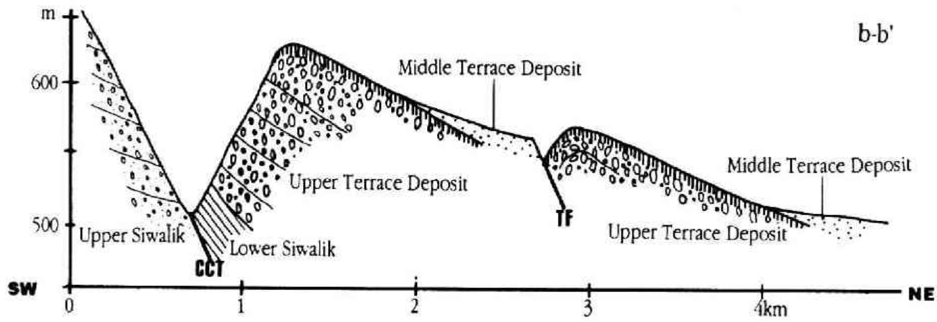


Fig. 9 Cross-section of the Trisuli Fault (b-b′ in Fig. 6).

bulges occur on the hanging wall.

3.4. The Himalayan Front Thrust

The Himalayan Front Fault separates the Churia Range from the Gangetic Plain, the present foreland basin of the Himalayas. The Middle and/or Lower Siwaliks are generally thrust over the recent alluvium (Nakata 1982). Shelling *et al.* (1991) and Sah *et al.* (1994) illustrate a geological fault of WNW-ESE to E-W direction at the southern foot of the Churia Range. On the hanging wall, a range front anticline, along which the Amlekhganj Formation is overturned, develops in parallel with the HFF (Sah *et al.* 1994).

In the area around Amlekhganj, an E-W striking flexure scarp is traceable about 3.5 km in length (Fig. 4). This paper calls it the Amlekhganj Fault. Although the relative height of the scarp ranges from 6 m (on the L3 Terrace) to 21 m (on the L1 Terrace), acutual displacement of terrace surfaces is unknown because both the L1 and L3 Terrace deposits submerge into the Gangetic Alluvium on the foot wall of the HFF.

At westwards extension of the Amlekhganj Fault, there are isolated hills standing about 300 m above the surrounding alluvial plain. The ridges are in accord with an anticline in the Middle Siwalik. At east of Amlekhganj, terraces are displaced a few meter by short scarplets.

4 Geomorphic Units

4.1. Topographic setting

The airphoto interpretation and the field survey of the Hetauda Dun have made it possible to distinguish the following units. Pre-recent gemorphic surfaces would be four groups ; the Highest Erosion Surface group (H1, H2 Surfaces), Upper Terrace group (U1, U2 Terraces), Middle Terrace group (M1, M2 Terraces) and Lower Terrace group (L1, L2, L3, L4 Terraces), considering continuity, litho-facies and lithological

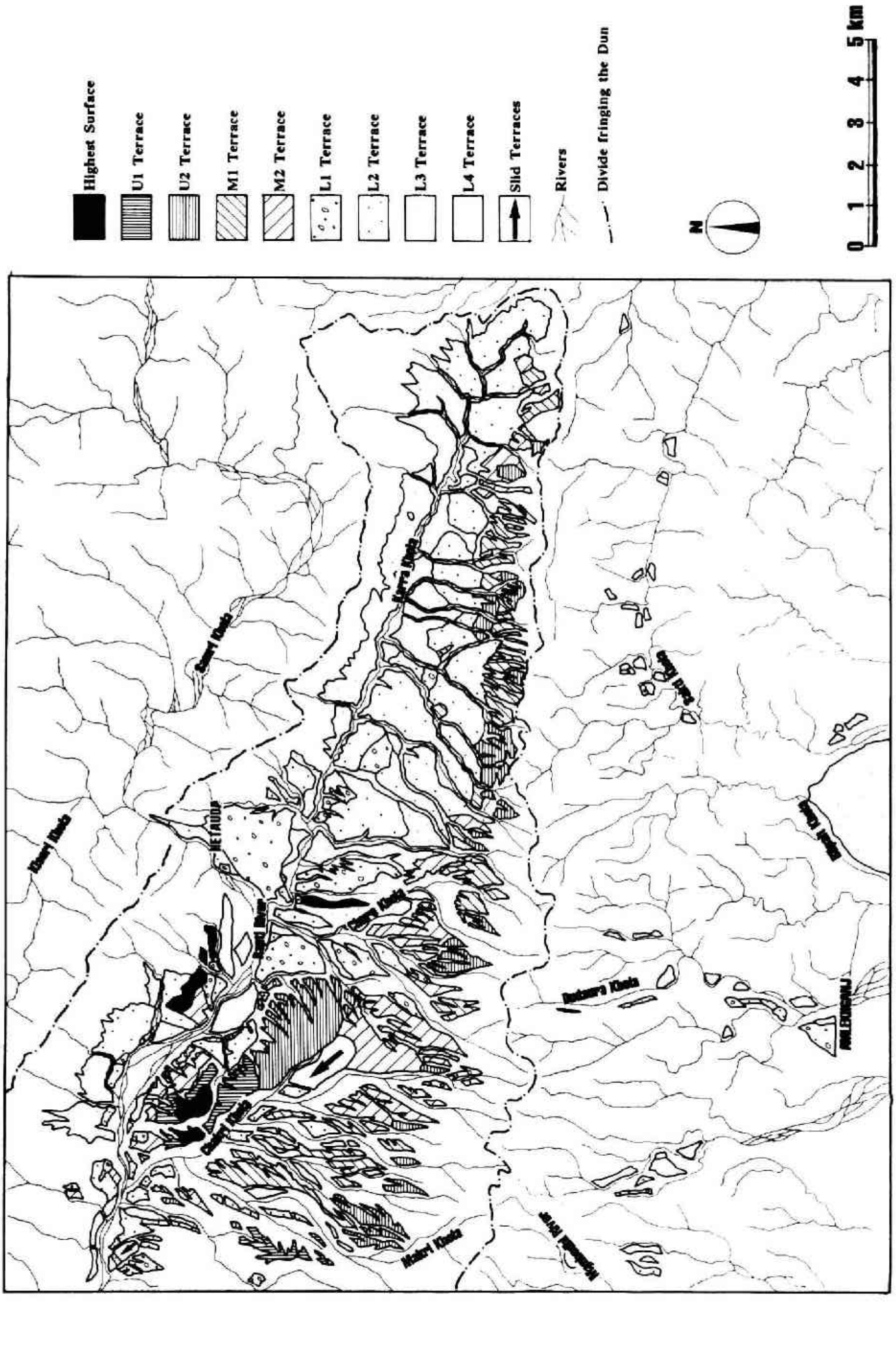


Fig. 10 Geomorphological map of the study area.

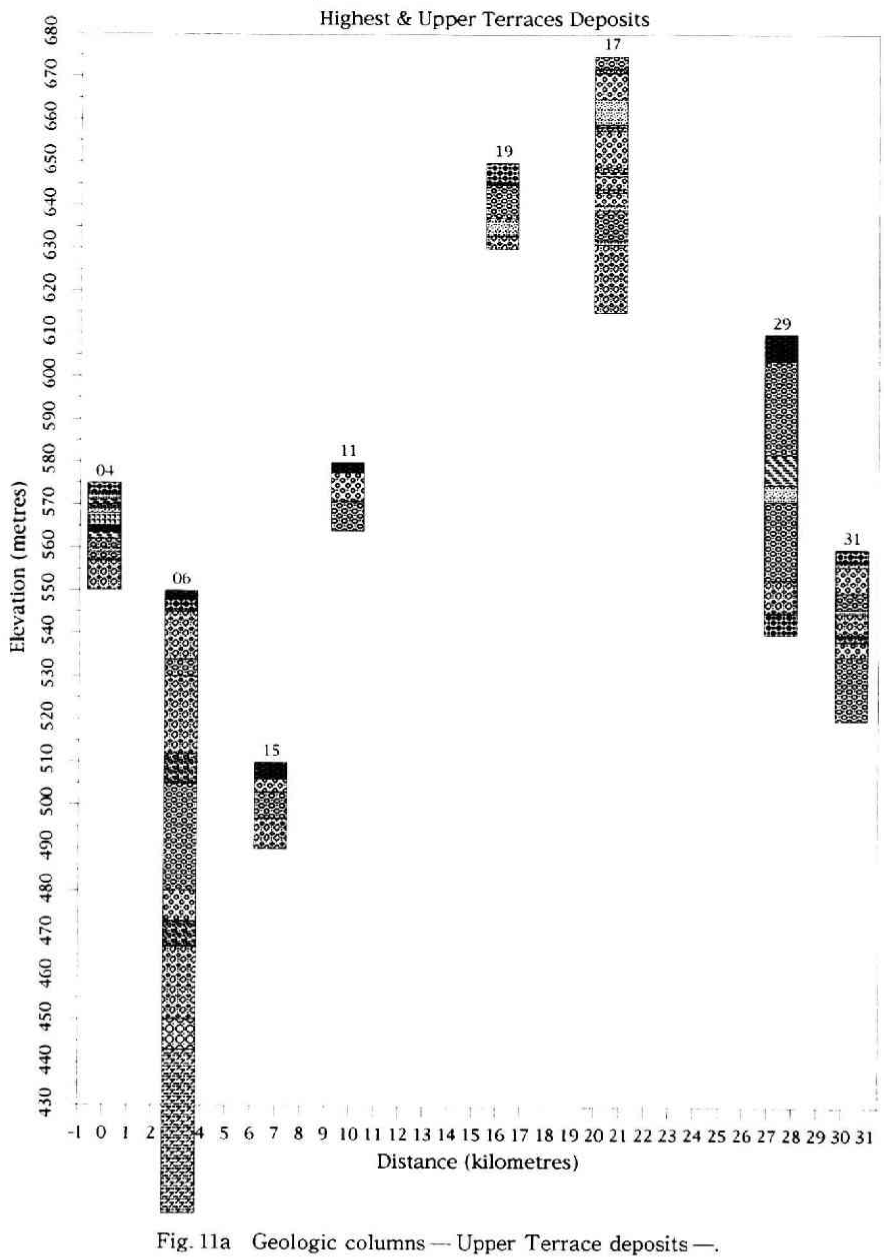


Fig. 11a Geologic columns — Upper Terrace deposits —.

composition of terrace deposits and development of weathering crust. Distribution pattern of terraces leads to the subdivision of the study area into two parts. One of them is the Rapti River area that is bounded by the Chakri Khola Fault and Chure Khola, and the other is northern slope of the Churia Range. In the former area, paired fluvial terraces are lying along the Rapti River. On the northern slope of the Churia Range dissected fan like landforms develop well from the divides to the valley floor (Figs. 6, 10).

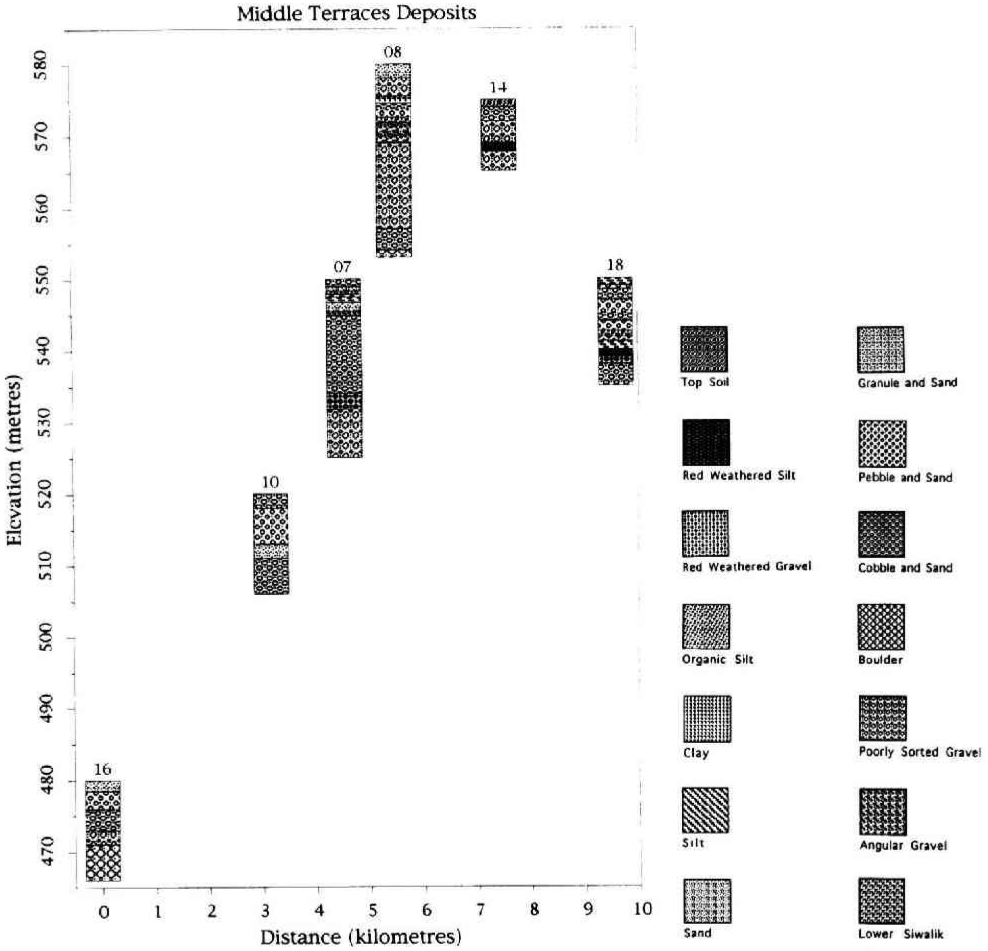


Fig. 11b Geologic columns — Middle Terrace deposits —.

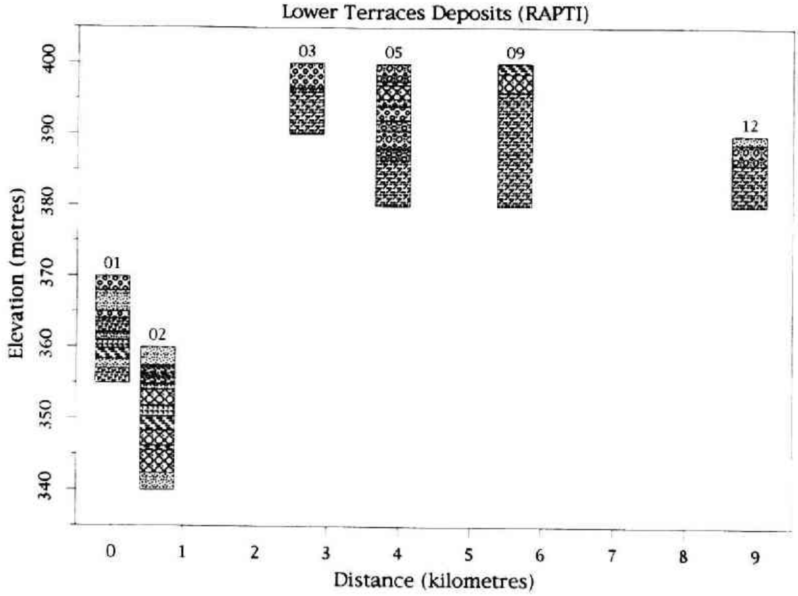


Fig. 11c Geologic Columns — Lower Terrace deposits in the Rapti River Area —.

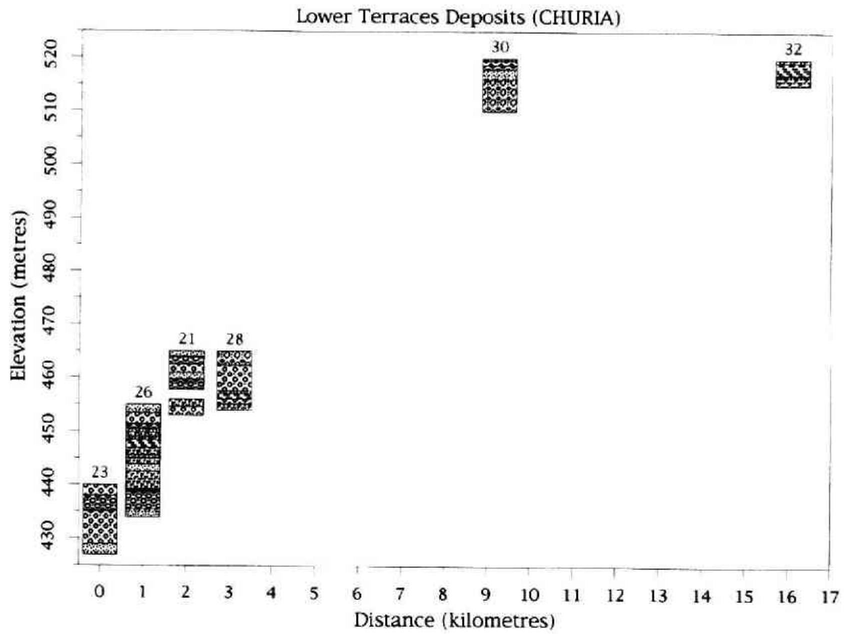


Fig. 11d Geologic Columns — Lower Terrace deposits on the northern slopes of the Churia Range —.

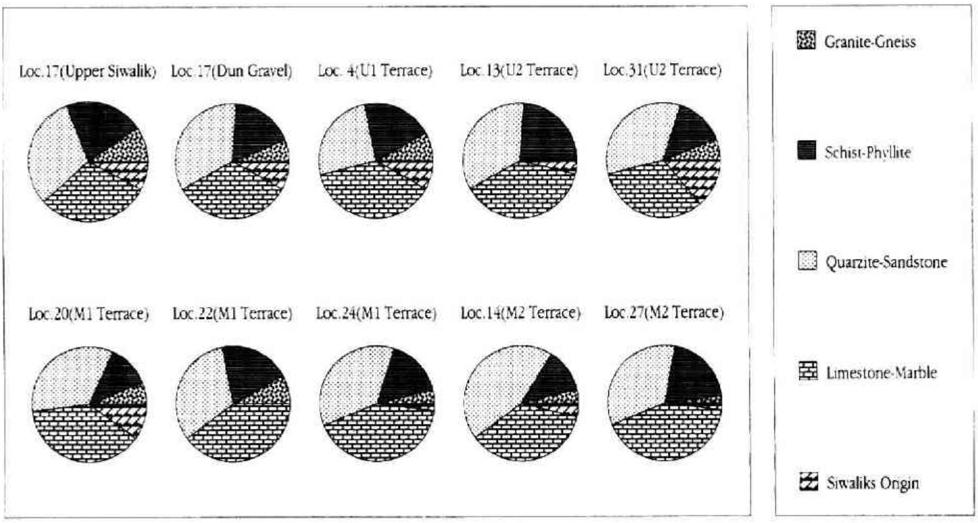


Fig. 12 Lithologic composition of the Upper Siwalik & the Dun Gravel.

4.2. Rapti River area

4.2.1. The Highest Erosion surface

The Highest Surfaces are mainly distributed on the left bank of the Rapti River. They form narrow, undulating hilltops. Though the surface consists of gravelly gentle slopes, it truncates the original sedimentary surface and is reformed as an erosion surface. The Highest Surface stands from 500 to 650 m above sea level. There are two levels of surfaces at the central part of the study area. Relative height of terrace scarps attains about 120 m (H2 Surface) or 150 m (H1 Surface). Terrace deposits consist of loose well-rounded gravel more than 100 m thick, including thin sandy silt beds (Fig. 11-a). Those gravelly beds overlap the Lower Siwalik unconformably, and the gravel varies from pebble size to over 1 metre in diameter. Generally, their facies shows normal grading but stratification is not clear. The gravel is chiefly composed of quartzite, and includes limestone, sandstone, phyllite, schist and few granitic rocks (Fig. 12). The granitic gravel is fully decomposed. Red weathering crust develops from their surface to 5-20 m depth. Its rubification indicates 10R 5/8 to 2.5YR 5/8.

4.2.2. The Upper Terrace group

The U1 Terrace is a fill-top surface distributing on the left bank of the Rapti River only. Relative height from talwegs to the surface is about 110 m. Terrace deposits are represented by medium sorted gravel (max. 70 cm) over 100 m thick, which has sub-round to round shape (Fig. 11-a). Most of the gravel was supplied from the Lesser Himalayan Metasediments (Fig. 12). The terrace surface is extensively underlain by red weathered silt that is 4 to 10 m thick. Rubification of the weathering crust ranges from 10R 5/8 to 5YR 5/8.

The U2 Terrace develops well on the left bank of the Rapti River. It stands about 100 m high from the flood plain. Litho-facies and characters of the terrace deposit are almost similar to those of the U1 Terrace. A difference between the U1 and U2 Terraces is surface level, which is several meter lower on the U2 surface than on the U1 Terrace. Red weathering crust, which ranges from 10R 5/8 to 5YR 6/8 in colour, develops 2 to 10 m depth.

4.2.3. The Middle Terrace group

The M1 Terraces are distributed on both sides of the Rapti River. They are fill-top terraces developed 20 to 60 m high above the river bed. Transverse sections of the terrace are asymmetrical; cliff facing southwest, and their surfaces are dipping northeastwards. Terrace deposits are alternating beds of medium sorted gravel and silty sand, and their lithologic composition is almost similar to that of older gravel (Fig. 11-b). Gravelly beds include large boulders, which are 70 to 120 cm in diameter. Total thickness of the accumulation is 7 to 20 m or more. The M1 Terrace also has reddish brown soils on its surface. Soil colour ranges from 5YR 6/6 to 7.5YR 6/8, and rubified horizon reaches 1 to 4 m deep from the surfaces.

The M2 Terrace is developing on the left bank of the Rapti River. Its relative height from the present river bed is about 30 m. Terrace-composing sediments are less than 17 m thick. They consist of sub-round to sub-angular boulders and cobbles of the Lesser Himalayan Metasediments or the Lower Siwaliks origin (Fig. 12). They are covered with orange soils of a few meter thick that are 5YR 5/8 to 7.5YR 6/8 in the Munsell colour system.

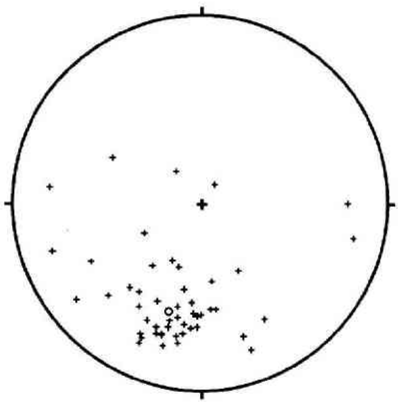
4.2.4. The Lower Terrace group

The lower surface is divided into four levels of fluvial terraces. They scatter on both sides of the Rapti River narrowly. Relative height from the river bed to the surface ranges 5 to 30 m. The terrace deposits comprise poorly sorted boulders with 3 to 26 m thick (Fig. 11-c). Boulders, distributed at the foot of the Mahabharat Range, are interfingered or covered with colluvium. Lithologic characters of the sediment are in common with those of the M2 Terrace deposit. Red weathering crust hat not yet developed on the surface, whose soil colour ranges from 7.5YR 6/6 to 2.5Y 7/4, from 0.4 to 2 m in depth.

4.3. Northern slope of the Churia Range

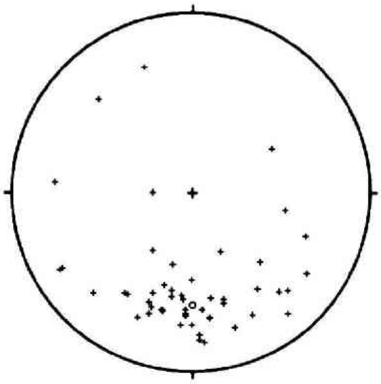
4.3.1. The Upper Terrace

The Upper Terrace develops well in eastern part of the study area, and reduces its distribution to the upstream of Karra Khola. In the area to the east of Makri Khola, these surfaces are dissected to the ridges, which have accordance of summit level.



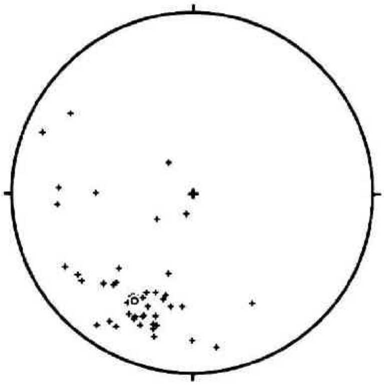
Data	Schmidt Equal Area Projection	Statistics
+ Hetauda Loc.17(US)		o Mean Lineation Vector 196.3 39.0
		E1 = 0.798 E2 = 0.127 E3 = 0.075
		r1 = 1.84 r2 = 0.52 K = 3.54
	N = 53	s. var. = 0.134 Rbar = 0.866

Fig. 13-a Upper Siwalik (Loc. 17 in Fig. 6).



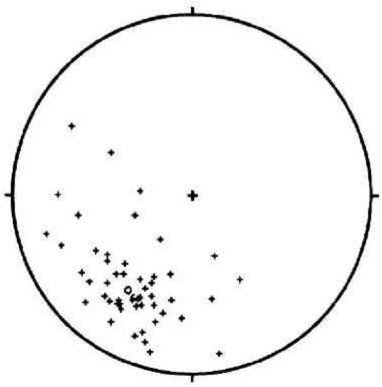
Data	Schmidt Equal Area Projection	Statistics
+ Hetauda Loc.17(DG)		o Mean Lineation Vector 179.5 36.9
		E1 = 0.751 E2 = 0.169 E3 = 0.080
		r1 = 1.49 r2 = 0.75 K = 1.98
	N = 51	s. var. = 0.184 Rbar = 0.816

Fig. 13-b Base of the Upper Terrace deposit (Loc. 17 in Fig. 6).



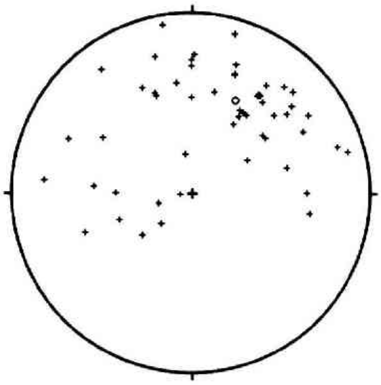
Data	Schmidt Equal Area Projection	Statistics
+ Hetauda Loc.04(U2)	N = 50	o Mean Lineation Vector 207.9 32.5 E1 = 0.821 E2 = 0.126 E3 = 0.053 r1 = 1.88 r2 = 0.87 K = 2.16 s. var. = 0.114 Rbar = 0.886

Fig. 13-c Upper Terrace deposit (Loc. 4 in Fig. 6).



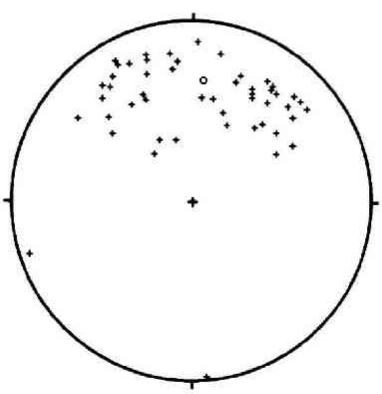
Data	Schmidt Equal Area Projection	Statistics
+ Hetauda Loc.13(U2)	N = 52	o Mean Lineation Vector 214.0 35.9 E1 = 0.828 E2 = 0.115 E3 = 0.057 r1 = 1.97 r2 = 0.70 K = 2.82 s. var. = 0.101 Rbar = 0.899

Fig. 13-d Upper Terrace deposit (Loc. 13 in Fig. 6).



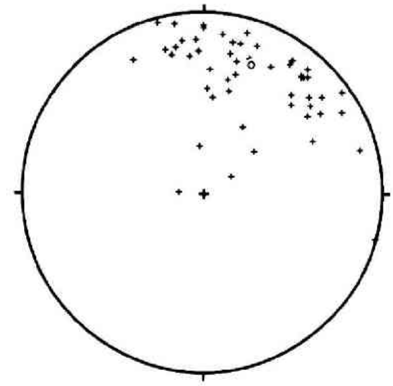
Data	Schmidt Equal Area Projection	Statistics
+ Hetauda Loc.20(M1)		○ Mean Lineation Vector 25.7 42.0 E1 = 0.648 E2 = 0.235 E3 = 0.116 r1 = 1.01 r2 = 0.71 K = 1.43 s. var. = 0.234 Rbar = 0.766
	N = 54	

Fig. 13-e M1 Terrace deposit (Loc. 20 in Fig. 6).



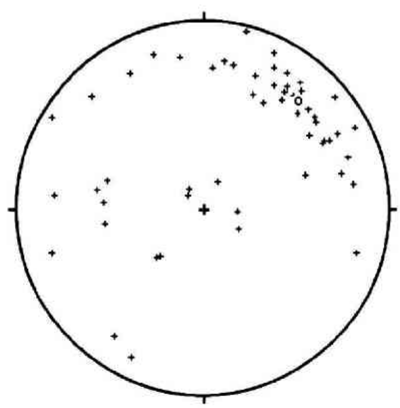
Data	Schmidt Equal Area Projection	Statistics
+ Hetauda Loc.24(M1)		○ Mean Lineation Vector 5.5 32.6 E1 = 0.725 E2 = 0.220 E3 = 0.054 r1 = 1.19 r2 = 1.40 K = 0.85 s. var. = 0.198 Rbar = 0.802
	N = 51	

Fig. 13-f M1 Terrace deposit (Loc. 24 in Fig. 6).



Data	Schmidt Equal Area Projection	Statistics
+ Hetauda Loc.14(M2)	N = 54	o Mean Lineation Vector 20.6 24.5 E1 = 0.774 E2 = 0.152 E3 = 0.074 r1 = 1.63 r2 = 0.72 K = 2.26 s. var. = 0.134 Rbar = 0.866

Fig. 13-g M2 Terrace deposit (Loc. 14 in Fig. 6).



Data	Schmidt Equal Area Projection	Statistics
+ Hetauda Loc.27(M2)	N = 53	o Mean Lineation Vector 41.7 23.1 E1 = 0.613 E2 = 0.242 E3 = 0.145 r1 = 0.93 r2 = 0.52 K = 1.80 s. var. = 0.353 Rbar = 0.647

Fig. 13-h M2 Terrace deposit (Loc. 27 in Fig. 6).

Fig. 13 Clast fabric of the Upper Siwalik and the Dun Gravel (plotting poles of a-b plane of gravel to the lower hemisphere).

The Upper Terraces are well distributed along Makri Khola, Churia Khola and near the dividing ridge of the Churia Range. The relative height of terrace scarps reaches 130 m at the western part of the study area. It decreases eastwards and the surface are buried by younger deposits in the centre of the valley. The surfaces are underlain by alternating beds of thick medium-sorted gravel and thin silty sand (Fig. 11-a). Gravels sometimes have imbricated structure, which shows north-south current (Fig. 13). The lithologic composition, consisting of the Lesser Himalaya Metasediments, follows that fact (Fig. 12). Terrace surfaces often truncate these deposits. The top of the deposit is severely weathered and changes to red clay. This character demonstrates that the Upper surface had been formed as alluvial fans, and modified to an erosion surface. The weathering crust of the Upper Terrace surface develops 3 to 10 m thick, and its rubification is ranging from 10R 6/8 to 5YR 6/8.

4.3.2. The Middle Terrace group

The area between the Makri Khola and Churia Khola provides the M1 Terrace. It stands about 60 m high above the river level near the divides. In the centre of valley floor, however, the surface is close to the river bed. At Gauritar, the east-central part of the valley, the M1 Terrace surfaces are mostly covered with younger deposits. Around Gothdanda, southeastern margin on the dun, the terrace comprises the dividing ridge of the Churia Range with the flat topped surface. Terrace deposits are characterized by interfingered beds of gravel and silty sand (Fig. 11-b). Their gravelly beds consist of metamorphic and carbonates rocks derived from theLesser Himalaya, and sandstone and siltstone from the Lower Siwaliks (Fig. 12). Fabric of gravel has a multimodal feature, which illustrates palaeocurrent changed frequently during the M1 Terrace formation (Fig. 13). Total thickness of the deposits increases from north (less than 10 m) to south (over 50 m). It has 2.5YR 5/8-5YR 6/8 coloured weathering crust of 2 to 7 m thick.

The M2 Terrace develops in front of the upper surfaces as fans with thin deposit. Relative height of the surface is about 40 m above the river bed, the highest in the western part of the study area, and decreases towards east. Some M2 Terrace surfaces are situated in the valley between older surfaces, and their deposits overlap the red weathered sediments. Nevertheless, the thickness of the terrace deposits is generally less than 20 m. They consist of the alternating beds of well-rounded gravel and silty sand, and rarely include thin organic silt (Fig. 11-b). Lithologic composition of the gravel resembles to that of the M1 Terrace deposits. The lower part of the gravel has a feature of poorly stratified fan deposits. On the other hand, the upper part is well-beded gravel with imbricated structure which indicates palaeocurrent direction from SSW to NNE (Fig. 13). The rubified soil, which ranges from 2.5YR 6/8 to 7.5YR 6/8 in colour, develops 1-4 m deep from the terrace surface.

4.3.3. The Lower Terrace group

The upper course of Karra Khola is dominated by the Lower Terrace group. They are slightly dissected fans formed by the tributaries of Karra Khola. The surfaces generally develop in front of the Middle Terraces. Based on stratigraphy of alluvial-fan deposits, these fans are divided into three morphogenetic sequences. Their surface level, however, is interesecting each other. They stand less than 20 m above the alluvial plain. Terrace deposits of silty sand layers, which are more than 10 m thick, show lacustrine or swamp deposit nature (Fig. 11-d). Upper gravel, conformably underlain by the lacustrine, is around 10 m in thickness and it is similar to older deposits in lithologic character. Grain sizes of the particles, however, are finer than those of older sediments. The base level of the deposits is commonly below the river beds. Weathering crust is immature on the surface, and its top soil colour ranges from 7.5YR 5/7 to 2.5Y 5/5.

5 Discussion

5.1. Chronology of geomorphological surfaces

The absolute ages of the geomorphological surfaces are unknown in the study area. Soil colour is a considerable marker to correlate the terraces, which have few datable material. Harden (1982) examines the relationship between the soil development of geomorphic surfaces and their ages, and devises weathering index for the relative dating. She points out soil colour index is one of the best for time marker. Soil colour, however, depends on various conditions such as climate, parent material, soil hydrology and so on (Birkeland 1984 ; Araki 1986 ; Kato 1988 *etc.*). In spite of the problems in accuracy, local morphochronological studies have been completed by the technique of soil analysis (Birkeland 1985 ; Billard 1985 *etc.*). This paper presents the local-limited correlation using the field data of the soil colours accompanied with continuity and dissection of terrace surfaces (Table 2).

Table 2 Correlation of Sub-Himalayan Geomorphological Surfaces in Nepal (surface rubification)

study area	Dang Dun	Northcentral Chitwan Dun	Hetauda Dun
source / estimated age	Yamanaka & Yagi, 1984	Iwata & Nakata, 1985	this paper
400-500 ka	Highest Terrace (reddish brown)		Highest Surface (10R-2.5YR)
	Higher Terrace (reddish brown)	Highest Terrace (10R-5YR)	
120-200 ka		Higher Terrace (2.5-5YR)	Upper Terrace (10R-5YR)
	Middle Terrace (red ?)	Middle Terrace (5-10YR)	Middle Terrace (2.5-7.5YR)
16-26 ka (C-14)	Lower Terrace (pale brown)	Lower Terrace (10YR)	Lower Terrace (7.5YR-2.5Y)
Holocene		River bed (2.5Y)	Flood plain (10YR-2.5Y)

The sole absolute age given in the Nepal Sub-Himalaya is of the L1 Terrace in the Dang Dun (Yamanaka and Yagi 1984), which had been formed since the age between 16,000 and 26,000 yrs BP. Red weathering crust has not yet matured on the terrace surface, and their rubification shows less than 7.5YR. Therefore, terraces without red soils are considered to have developed after the Last Glacial Climax Stage. In the Hetauda Dun, the Lower surface group corresponds to this stage.

The Middle surface group in the study area has thin, less than 5 m thick, and reddish brown soils (2.5YR-7.5YR hues). Though these red coloured soils are known to be distributed in humid tropical, subtropical and warm temperate zones (Kato 1986), the red weathered soils are not observed on younger geomorphic units (the Lower Terraces and the flood plains). This means that it takes 10^4-10^5 years order to develop red soils in the Sub-Himalaya, and rubified weathering crust indicates the past warm and humid environment. The Middle Terraces have experienced, at least, once

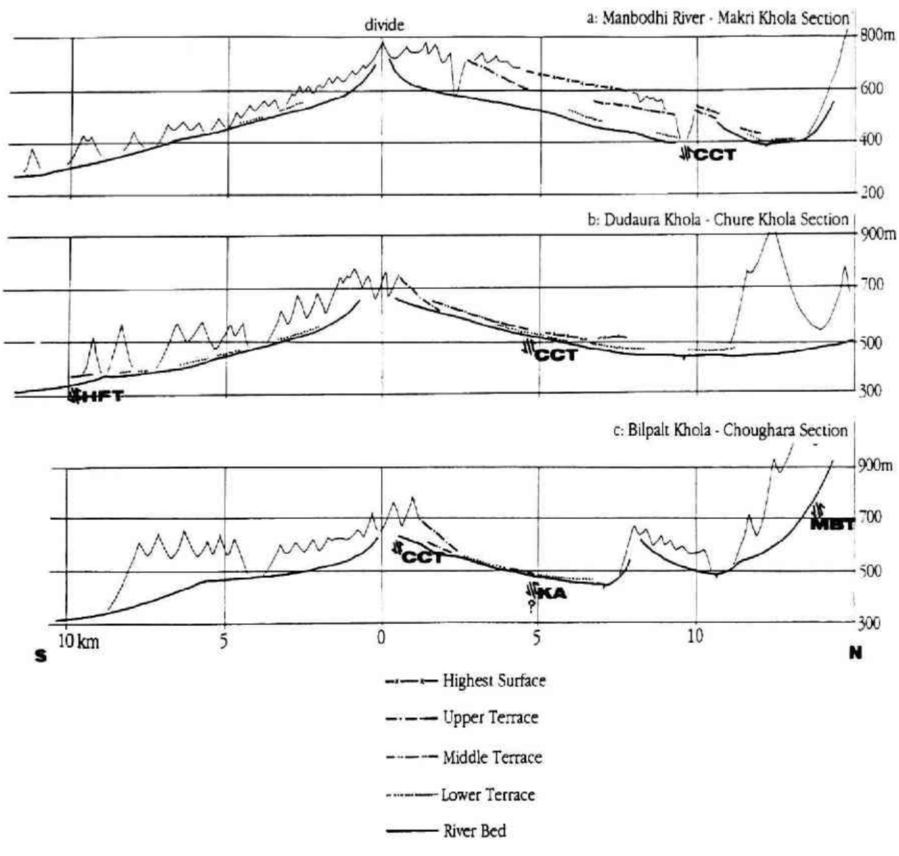


Fig. 14 Profiles of crests, terraces and river beds in the study area.

ancient subtropical climatic stage. On the other hand, the surface keeps flat and is slightly dissected. Accordingly, the chronology of the Middle Terrace is presumed the interstadial in the Last Glacial or the Last Interglacial Stage.

The Upper Terrace surface is intensively red-weathered. It must have experienced multicyclic climatic changes. Depositional surfaces, however, remain on the top of Upper Terraces. Therefore, it is sure that the origin of the Upper surfaces goes back to the late Middle Pleistocene. Detailed estimation of the age of the Upper surface is a problem to be solved in future.

The Highest erosion surface is excessively weathered and dissected. On the basis of stratigraphy, the surface developed after deposition of the Upper Siwaliks. The occurrence of the Highest surface corresponds to the early Middle Pleistocene.

5.2. Transverse profiles

The most of tributaries of the Rapti River and Karra Khola flow across the dun floor. Therefore longitudinal profiles of terraces and tributaries evince the history of base level changes of the Hetauda Dun (Fig. 14).

The U1 Terrace's profile is deformed on the points across the CCT. The U2 Terrace is steeply inclined towards dun centre near the divide of the Churia Range. Southwards extension of the terrace would be higher than the summit of the divide. In the eastern part of the study area, the U2 Terrace is also tilted towards northeast just behind the CCT. It clearly implies that the crustal movement, after the development of the Upper Terraces, has generated the Churia Range. Even in the western part, which is far from the CCT, the terrace has behaved as same as in the eastern part. It suggests that the Trisuli Fault has deformed the Upper Terraces.

Younger geomorphic units, the Middle and Lower Terraces, are generally parallel to the present river bed, and intersect the U2 Terrace in the central part of the valley. On the Karra Khola Anticline, the Lower Terraces are bent convex. Especially, the L1 Terrace deposit is folded along the Karra Khola Anticline. The dip amount of the sedimentary beds decreases in ascending order (Fig. 8). It means that younger sediments offlap older beds as growing of the anticline.

5.3. Evolution of the Hetauda Dun

The above mentioned characteristics of the terrace deposits and the surfaces indicate the three phases of the dun evolution (Fig. 15).

The Hetauda Dun stretches out about 1,000 km upstream from the Mouth of the Ganga, and separated from the Bengal Bay by the Churia Range and the vast Gangetic Plain. In the dun, thus, it is difficult to presume the base level change caused by the eustatic sea-level oscillation in 10^4-10^5 years order. Drainage systems, passing through the study area, originate from the Lesser Himalaya or the Churia Range, both

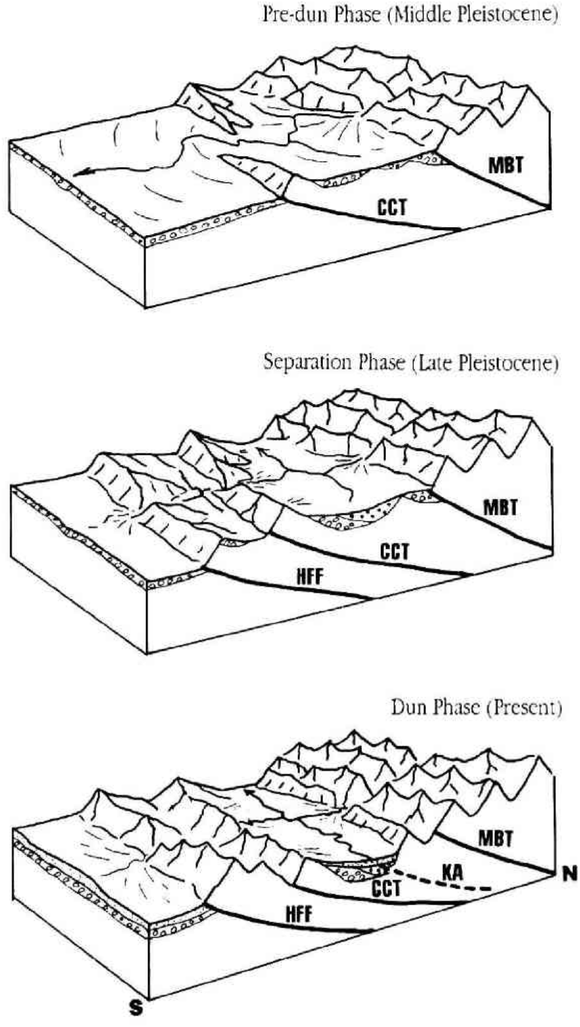


Fig. 15 Geomorphological development of the area around Hetauda Dun.

of which are subtropical hilly mountains. Climatic change is estimated to have trivially affected to sedimentary processes in the area. Therefore, the three phases of the dun evolution are chiefly lead to endogenetic processes such as faulting.

5.3.1. Pre-Dun Phase

Each deposits of the Highest and the Upper surfaces have alluvial-fan nature. The fill-top surface of the Upper Terrace reaches the divides of the Churia Range. Their deposits consist of quartzite, limestone and schist of the Lesser Himalaya origin. Cobble fabric clearly indicates that the sediment was derived from north. These features display that the Highest and Upper surfaces had been developed as multicyclic piedmont alluvial plains at the foot of the Lesser Himalaya.

Pre-Dun fans, consisting of the top of foreland basin, had developed until the Middle Pleistocene. Sedimentological settings and lithologic facies of the Pre-Dun deposits are similar to those of the Churiamai Formation, accumulated in the latest Siwalik Stage. Unlike in the Chitwan Dun, the boundary between the terrace deposits and the Upper Siwalik is transitional or diastem. These features show the piedmont alluvial plain had intermittently developed since the late Pliocene.

The Kiseri Khola Fault (MBT) still played a role of the boundary thrust in the latest Siwalik Stage (Sah *et al.*, 1994). Though there is no evidence that the fault displaces Quaternary units, the continuous development of the piedmont alluvial plains indicates that the MBT had bounded between the Himalayas and the foreland basins until the Middle Pleistocene.

5.3.2. Separation Phase

The Middle Terraces and their deposits imply changes of sedimentary environment. The deposits have similar characteristics of those of older sediments in both lithologic composition and litho-facies. Unlike the Pre-Dun sediments, the depocentre of the Middle Terrace deposits are in accord with the valley line of the dun. Palaeocurrent analysis shows that the most of the Middle Terraces are formed by channels flown from south to north. There is no terrace on the south slope of the Churia Range except the Lower terraces. These characteristics show that the generation of the Churia Range truncated palaeochannels flown from the Mahabharat Range to the Gangetic Plain, and the study area was closed as an intermontane basin in this phase.

The inversion of the regional drainage system occurred while the M1 Terrace was forming, which corresponds to the Last Interglacial Stage or the interstadial in the Last Glacial Stage. This palaeogeographic change could be explained by a local crustal movement. In the beginning of the Separation Phase, the CCT was active because the Middle Terraces are partly deformed by the thrust. Though the origin of the HFF is unknown, the frontal thrust with anticlinal range had not been a topographic barrier between the dun and the Gangetic Plain in the prior stages. The Trisuli Fault has partly cooperated to bend up the Upper Terrace on the northern slope of the Churia Range. These data mean that the Churia Range has been generated by the rapid deformation of the hanging wall of the HFF, the south belt of the Siwaliks, accompanied with the CCT and their subordinate structures. The neotectonics of the Himalayan Front is characterized by the shift of active front from the MBT toward south under the NNE-SSW shortening (*e.g.* Kizaki 1988). The local crustal movement, which made the anticlinal fold and the frontal thrust, is in accord with the shortening of the Siwalik belt reflecting the stress field of the Himalayas.

5.3.3. Dun Phase

The Lower Terrace deposits, which have accumulated in the Last Glacial Stage (30-10 ka), include lacustrine or swamp sediments more than 10 m thick. Occurrence of lacustrine suggests the temporal intersect of drainage system lead by endogenic agency. The L1 Terrace deposits, the lowest member of the post separation sediments, are folded in the centre of the valley. These deformations are observed along the Karra Khola Anticline and the Trisuli Fault. Judging from their distribution, the two active structures would be composed of a tectonic system. Its winding hinge line suggests that the structures are the express of a semi-blind thrust. Dip amount of the beds consisting the L1 Terrace decreases in ascending order. Younger sediments off lap older beds as growing of the anticline. Those features indicate that the sedimentary environment of the valley has still been modified by tectonic shortening.

6 Concluding remarks

Geomorphologically the Hetauda Dun is divided into the following five groups and twelve surfaces ; H1 and H2 erosion surfaces, U1 and U2 Terraces, M1 and M2 Terraces, L1, L2, L3 and L4 Terraces and flood plains. Three sedimentary phases are recognized, and they are affected by activities of imbricated thrusts in the Sub-Himalaya ; MBT, CCT, HFF and their associated structures.

The Higher and Upper surfaces, piedmont alluvial fans at the foot of the Lesser Himalaya, had been formed during the Pre-Dun Phase, which corresponds to the Middle Pleistocene. The vertical displacement of the MBT caused to keep the sedimentary environment.

Dun separation, the upheaval of the hanging walls of the HFF and the CCT, occurred in the age of the Middle Terrace formation. The terrace deposits are thin fan sediment accumulated towards the centre of the valley. The separation phase goes back to the Last Interglacial Stage and/ or the interstadial in the Last Glacial.

Since the outlining of the basin, a typical sedimentary environment of dun, wet lowland, has arisen. The youngest geomorphological units, which show swamp or lake nature, are controlled by crustal deformation. An active fold, related with blind thrusts, has grown on the Lower Terrace of the valley, and it modified the sedimentary condition of the dun.

More detailed chronology and quantitative discussions of crustal movement, however, will remain to be solved in future.

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