Geomorphic Development of the Deukhuri Dun , Nepal Sub-Himalaya

著者	KIMURA Kazuo
雑誌名	The science reports of the Tohoku University. 7th series, Geography
巻	48
号	1/2
ページ	65-83
発行年	1998-12
URL	http://hdl.handle.net/10097/45228

Geomorphic Development of the Deukhuri Dun, Nepal Sub-Himalaya

Kazuo KIMURA*

Abstract To approach the active tectonics of the Himalayan Front, fluvial terraces and their related deposits have been surveyed in an intermontane basin in the Sub-Himalaya (the Siwalik Hills). The Deukhuri Dun is a typical sub-Himalayan intermontane basin located in a historical seismic gap of the great Himalayan earthquakes. Therefore, this morphotectonic study provides a most basic and important information to the discussion of the seismicity in the Himalayan Foreland. The following five allostratigraphic groups, the Lamahi Terrace of the Middle Pleistocene, the Nimbugaon Terrace developed in late Pleistocene time, the Garhwa 1- and the Garhwa 2 terraces of Holocene units, and the present flood plain and alluvial cones are recognized in the Deukhuri Dun. The terraced deposits are unconformably underlain by the Himalayan molasses termed the Siwalik Group. The Siwaliks were derived from the Lesser- and the Higher Himalayas by south-flown foreland streams. By contrast, clast fabric of the terraced deposits shows north-current along the southern margin of the dun. This current reversal is commonly observed on the hanging wall of the Frontal Churia Thrust (FCT that is equivalent to the Himalaya Frontal Fault). The morphostructure indicates that the Deukhuri Dun was formed as a piggyback basin in the stage between the Upper Siwaliks and the Lamahi Terrace. The Nimbugaon Terrace was also developed under the crustal deformation maintaining the piggyback sequence. In this stage, the Deukhuri Dun was in a climax of an intermontane basin sequence. Profiles of the terraces suggest that morphogenic movement was going to change from the local subsidence of the dun to the broad upheaval of the Sub-Himalaya after the Nimbugaon Terrace stage. The Garhwa 1 and 2 terraces emerged under the uplifting trend in the Holocene. The morphostructure and morphogenesis of the Deukhuri Dun are similar to those of the other dun valleys such as the Dehra Dun in the Garhwal Front, the Hetauda Dun in the central Nepal Front and so on. In a sense of comparative seismo- and morphotectonics, these Sub-Himalayan piggyback basins on the FCT sheet can be chiefly developed by aseismic slip. Thus, the Deukhuri Dun was primarily formed without great earthquakes. On the other hand, the recent broad upheaval across the Sub-Himalaya in Midwestern Nepal implies that the great earthquakes occurred in the hinterland and contribute to the crustal shortening of the Himalayan Front.

* Graduate Student, Institute of Geography, Tohoku University, Sendai 980-8578, Japan
THE SCIENCE REPORTS OF THE TOHOKU UNIVERSITY, 7TH SERIES (GEOGRAPHY)
Vol. 48, Nos. 1/2, December, 1998, 65-83

Nonetheless, morphotectonic features suggesting the great earthquakes must be recorded on the Main Boundary Thrust sheet rather than on the FCT sheet.

Key words: Himalayan Front, active tectonics, upper Quaternary geology, fluvial terrace, piggyback-basin, morphogenesis, aseismic slip

1 Introduction

The Sub-Himalayan longitudinal intermontane basins, which are called "duns" in local languages, are commonly distributed in the stretching from the Garhwal- to the Nepal Front. They are developed on intensively deformed molasses, which are termed as the Siwalik Group, and are collecting younger valley fills called as the Dun Gravels. This geological setting implies that the Siwaliks and the Dun Gravels must record the morphogenesis of the Himalayan foreland, which is believed to have been developed by Quaternary tectonics. Therefore, dun valleys have been remarked as landform which provides a clue to elucidate active tectonics of the Himalayan Front (Nakata, 1972; Yamanaka and Yagi, 1984; Delcaillau *et al.*, 1987; Kimura, 1994, etc.). Geomorphic researches in the Sub-Himalaya, however, have been achieved in limited areas because of difficulty of field research. Moreover, the results of the previous studies are not well connected each other.

This paper discusses the geomorphic development of the Deukhuri (Rapti) Dun in order to fill the lack of information in Sub-Himalayan morphotectonics. In addition, it is expected to contribute to seismotectonics because the Deukhuri Dun is located in a historical seismic gap along the Himalayan Front. Bilham *et al.* (1995, 1997) pointed out that the area sandwiched by rapture zones of the 1905 Kangra earthquake and the 1934 Nepal-Bihar earthquake will be the main rapture zone of the next Himalayan great earthquake. Furthermore, Yeats and Lillie (1991) assumed that the Himalayan Front has the greatest potential for ground rapture at the Kangra-type earthquakes. Therefore, the morphostructure of the Deukhuri Dun provides a basic, necessary and the most important information to discuss a relation between morphogenesis and seismotectonics of the Himalayan foreland.

First of all, regional geology is summarised by the review of previous researches and additional field works. Morphostratigraphic discussion, which is completed by aerialphoto-interpretation and field observation, follows the summary geological background. Morphostructural relationship between the Siwaliks and the Dun Gravels (terraced valley fills) are examined through sedimentology, profile morphometry and analysis of surrounding geostructures. Finally geomorphic development of the Deukhuri Dun, which is supported by comparative morpho- and seismotectonics of dun valleys, is synthesized on the basis of those evidence.

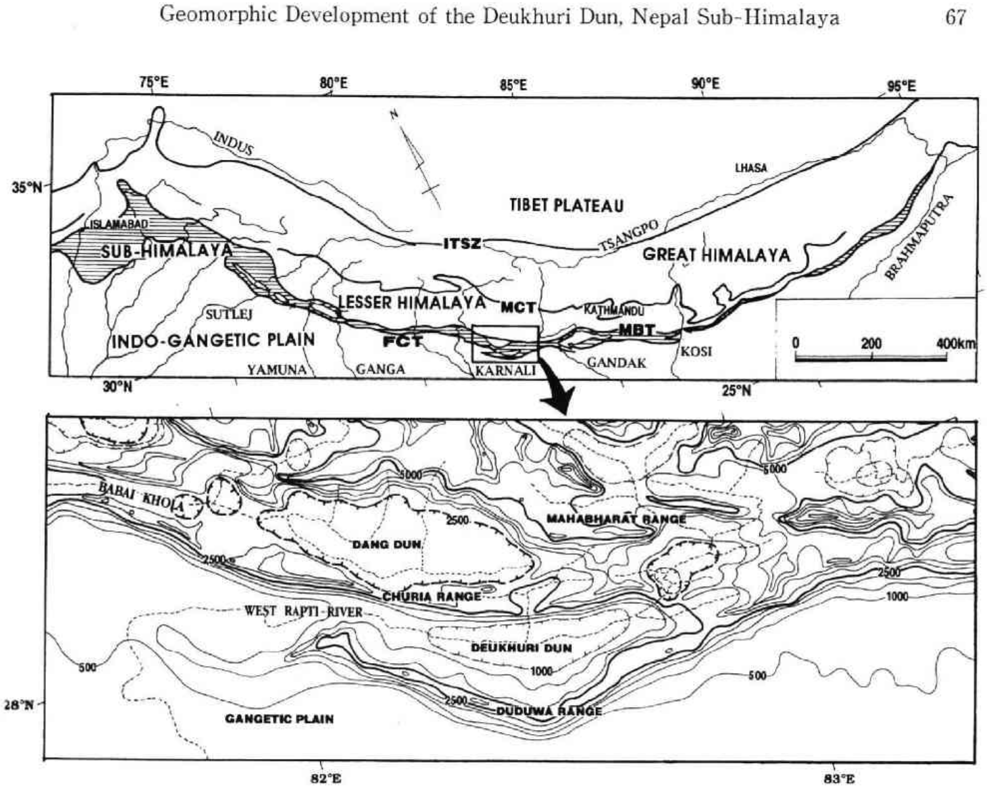


Fig. 1 : Physiographic outline of the area around the Deukhuri Dun
a) Simplified active tectonic map of the Himalayas (above)
b) Summit level map of the Sub-Himalaya in the Midwestern Nepal (below)

The study area is located in the Sub-Himalaya in the Midwestern Nepal (Fig. 1-a). The valley is often called the "Rapti Dun" (*e. g.*, Nakata *et al.*, 1990) after the Rapti River (so called the "West" Rapti River) which flows through the dun. However, the other major Rapti River (so called the "East" Rapti River) exists in the Central Nepal. This paper calls this basin as the "Deukhuri Dun" after the district name "Dang Deukhuri" in order to address the dun valley in the Midwestern Nepal.

The Deukhuri Dun extends about 60 km long in WNW-ESE direction with maximum width of 20 km. Its basin floor, consisting of terraced and unconsolidated deposits called "the Dun Gravel" (Sharma, 1990), ranges from 220 to 350 m. a. s. l. To the north of the dun, the Churia Range (Inner Churia Range) stands to separate the basin from the Dang Dun. The Duduwa Range (Outer Churia Range), which divides the Ganges Plain and the Deukhuri Dun, limits the south fringe of the valley. Westward extension of the two hilly mountain ranges is well-known as the Siwalik Hills. They generally form north-dipping hogbacks, which consist of the Miocene-Early Pleistocene molasses called the Siwalik Group, and their elevation is 600-860 m.

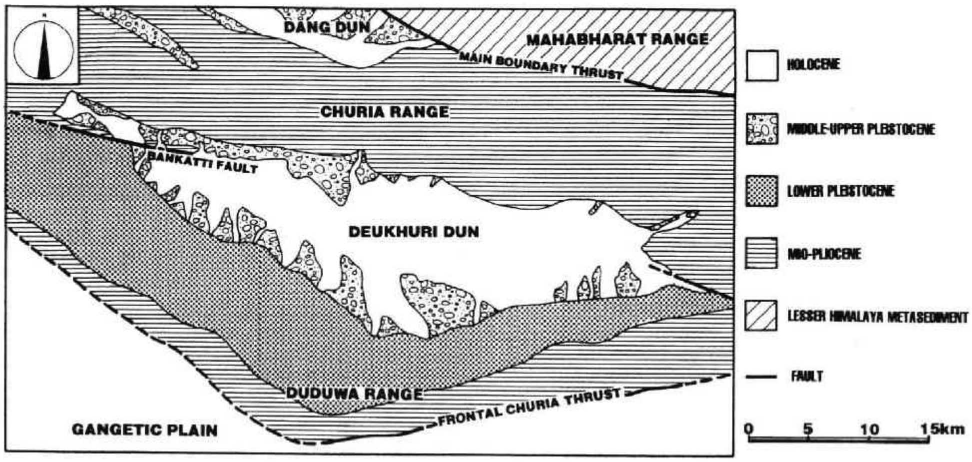


Fig. 2 : Geologic map of the Deukhuri Dun

a. s. l. (Fig. 1-b).

2 Regional geostructure

The Himalayas are composed of some NNW-SSE striking mountain ranges ; the Trans-Himalaya, the Great Himalaya, the Lesser Himalaya and the Sub-Himalaya (Siwalik Hills) from north to south. These sequential relief is believed to be the products of imbricated thrusts (*e. g.*, Seeber *et al.* 1981 ; Schelling and Arita, 1991 ; Kizaki, 1995). Dun valleys are intermontane basins in the Sub-Himalaya (Fig. 2), which is a foreland fold-and-thrust zone lying between the Main Boundary Thrust (MBT) and the Frontal Churia Thrust (FCT).

2.1. The Siwalik Group

The Siwaliks, which predominate in the Sub-Himalaya, are generally classified into three litho-stratigraphic units ; the Lower Siwaliks consisting of siltstone, the Middle Siwaliks dominated by sandstone and the Upper Siwaliks of conglomerate layers, in ascending order (Hagen, 1969 ; Itihara *et al.*, 1972). The ages of the Siwaliks are given through palaeomagnetic analysis (*e. g.*, Tokuoka *et al.*, 1986 ; Appel and Rosler, 1994). Just east of the Deukhuri Dun, the Siwaliks are dated as 12.5 Ma to *ca* 1 Ma (Appel and Rosler, 1994). The uppermost part of the Dhan Khola Formation (the Upper Siwaliks) could not be measured its age, because they consist of boulder beds. Thickness of the unmeasured layers is almost 500 metres. Judging from the facies and the thickness of the Upper Siwaliks, the foreland basin of the Siwaliks continued to Early to Middle Pleistocene age. Then, the ancient foreland basin was severely deformed by thrusting. As a result, the Siwaliks distributed around the Deukhuri Dun is separated to the following two geostructural belts.

2.2. The Central Churia Thrust (CCT) and its thrust sheet

As mapped by the Department of Mines and Geology, Nepal (1982), a fault line of E-W striking is drawn in the eastern part of the Deukhuri Dun along the Ransing Khola. In field observation, a reverse fault (100°/75°N) can be recognised in the western margin of the dun (the area around Bankatti village). Though these two fault lines are not traceable on the valley floor, they seem to form a series of fault system because of the following reasons. The two faults have common characters such as high-angled and north-dipping reverse faults, along which the Middle Siwaliks are in fault contact with the Upper Siwaliks or the Dun Gravels and so on. The litho-structural relationship shows that the reverse faults in the Deukhuri Dun are correlated to the Central Churia Thrust (CCT) in the Chitwan Dun (Tokuoka *et al.*, 1986). On the hanging wall of the fault, the Middle- and the Lower Siwaliks are generally observed as sequential foldings (Fig. 3). They are temporally named the Bhalbang Anticlinorium in this paper. The basin fills of the Deukhuri Dun bury or cut the fold-thrust complex. This morphostructural feature suggests that the CCT is not a main morphogenic agent in the post-Siwalikan stages.

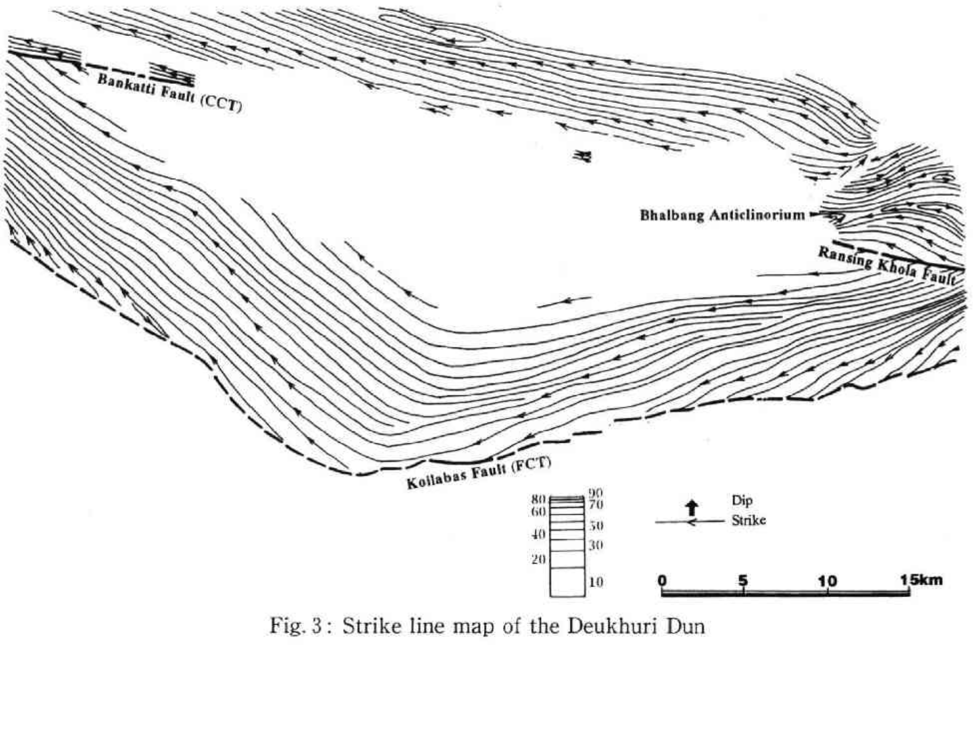


Fig. 3: Strike line map of the Deukhuri Dun

2.3. The Frontal Churia Thrust (FCT) and its thrust sheet

The southern foot of the Siwalik Hills is generally regarded as the Himalaya Frontal Fault (HFF ; Nakata, 1975) or Frontal Churia Thrust (FCT ; Tokuoka *et al.*, 1986), which is the southernmost active front of the Himalayan orogenic belt. A reverse fault (90°/20°N), along which consolidated sandstone beds (the Middle Siwaliks) have been thrusted over the red-weathered gravel, is observed near Koilabas village, the southern foot of the Duduwa Range. The fault must be a part of the FCT. The fault system draws an arch, which strikes NNW-SSE in the western part of study area and NNE-SSW in the eastern part. The Middle Siwaliks form homoclinally north-dipping (40-70°) hogbacks or a range front antiform on the hanging wall of the FCT. The Upper Siwaliks, which are dipping 25-70° northwards and also forming hogbacks, are conformably off-lapping the Middle Siwaliks and they fringe the south edge of the dun (Figs. 2, 3).

3 Terraces in the deukhuri dun

3.1. Description

The distribution of the fluvial terraces in the study area is delineated in Fig. 4. Each deposit is unconformably underlain by the Siwaliks. The following four levels of fluvial terraces, the Lamahi Terrace, the Nimbugaon Terrace, the Garhwa 1 Terrace and the Garhwa 2 Terrace, are classified by the continuity, facies of terrace deposits and soil development on their surfaces.

1) The Lamahi Terrace

The Lamahi Terrace is remained around the outlet of the Arjun Khola, which flows from the Inner Churia Range to the Rapti River, and scattering along the

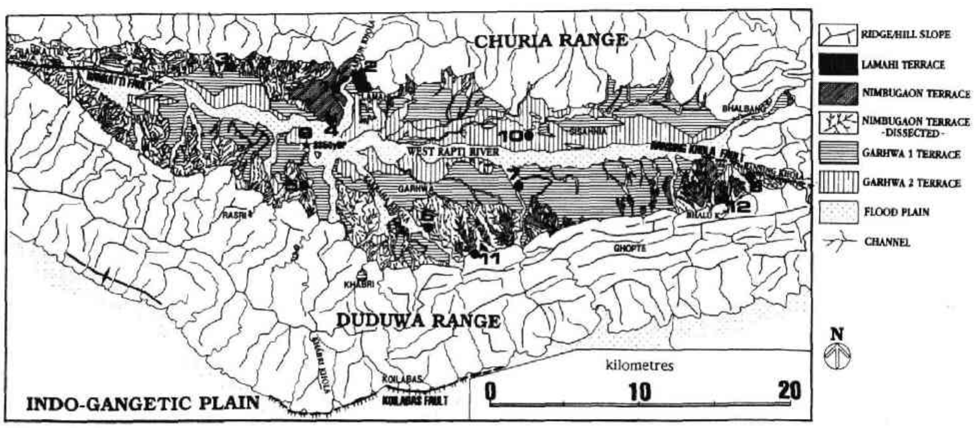


Fig. 4 : Geomorphic map of the Deukhuri Dun

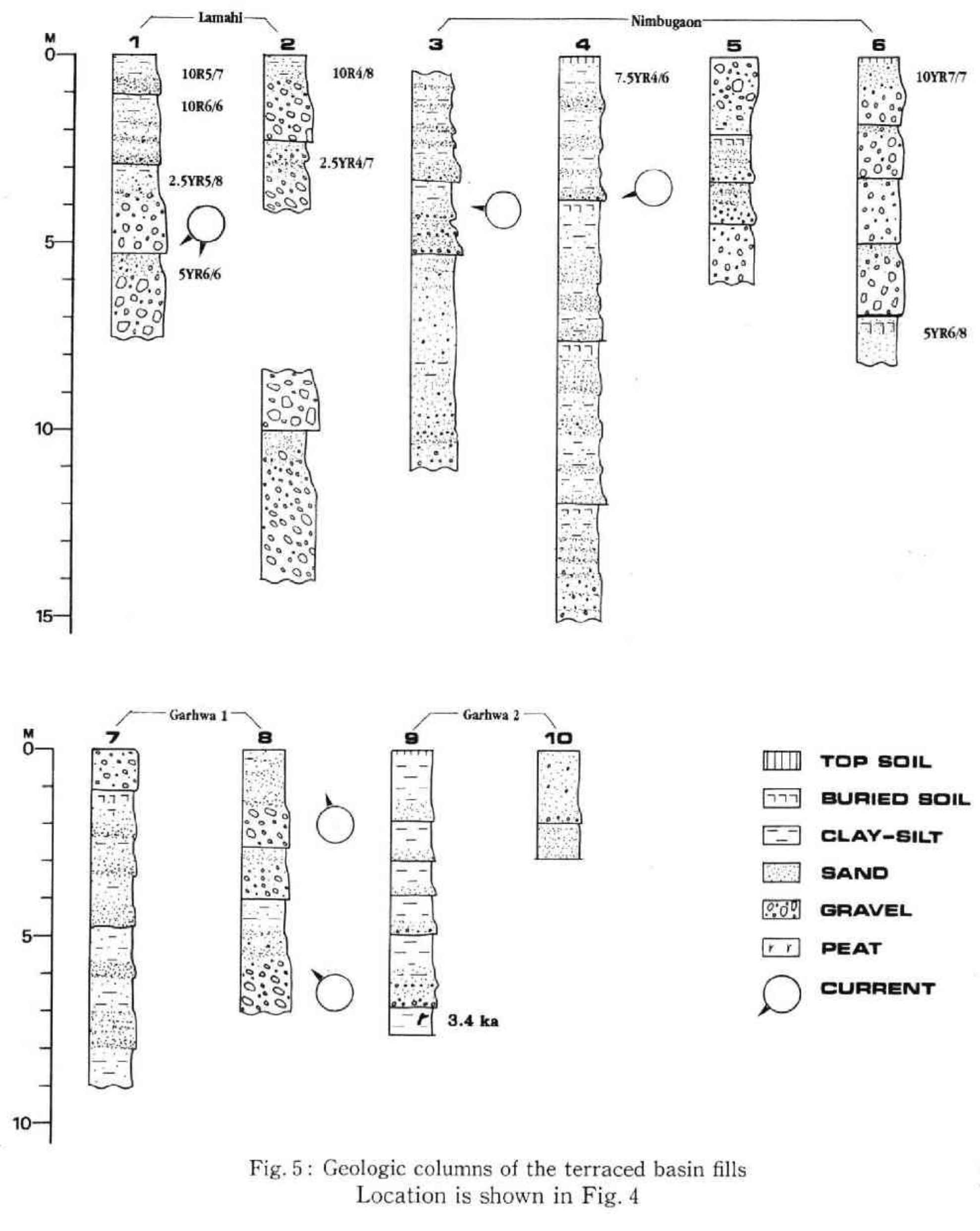


Fig. 5 : Geologic columns of the terraced basin fills
Location is shown in Fig. 4

southern fringe of the dun. The top of the geomorphic surface reaches about 50 m above the actual talweg, and it slants steeper than the river bed to the valley centre. Its depositional surface has been mostly lost, and changes to the round-topped hills. The red-weathering crusts, which ranges from 5YR 6/8 to 10R 5/7 in Munsell colour system, are observed on the terrace. The weathered zone is several to 10 metres in thickness.

The terrace deposits, more than 46 metres thick, unconformably off-lap the Upper Siwalik Formation at the southern margin of the valley. By contrast, the deposits are buried by younger morphostratigraphic units in the central part of the valley. They are composed of cobble-rich gravel with sandy matrix including pebble and boulder of 1 metre in diameter. The deposits are poorly-sorted and ill-stratified (Fig. 5). Lithologic composition shows that the gravels were derived from both the Lesser Himalayan Metasediments and the Siwaliks.

2) The Nimbugaon Terrace

The Nimbugaon Terrace is well developed along the south foot of the Duduwa Range, and is narrowly distributed along the northern fringe of the dun. It stands about 20-40 metres above the river bed. Its surface is dissected in dendritic pattern, and has changed to flat-topped ridges. Yellowish brown soils, ranging from 10YR 6/6 to 7.5YR 4/4 in Munsell colour system, cover the terrace surface. The thickness of the weathering crust is less than 2 metres.

The terrace deposits are more than 24 metres in thickness, and their base is commonly below the present stream level. Along the fringe of the dun, the Nimbugaon Terrace Deposits are in abutting with the Siwaliks. In the central part of the basin, the deposits are unconformably underlain by the red-weathered Lamahi Terrace Deposits. They consist of well-stratified sand layers including thin gravelly beds and organic silt bands. They can be subdivided into, at least, four sequential units. Each unit is a few metres in thickness and normal grading (Fig. 5). The lithologic composition of the gravels is varied in places. In the central part of the valley, metasedimentary rocks of the Lesser Himalayan origin accounts for 50-70% of pebble. By contrast, the soft silt- sandstone from the Siwaliks take the first place in the gravels along the margin of the dun.

3) The Garhwa Terraces

The Garhwa 1 Terrace is fringing the Nimbugaon Terrace, especially on the left bank of the West Rapti River. It attains 5-10 metres above the river bed. Unlike older terraces, the Garhwa 1 Terrace keeps its smooth original surface. Weathering crust has not yet matured and only yellowish gray soils, which ranges from 2.5Y to 10YR in Munsell colour system, is developed on the surface.

The deposits of the Garhwa 1 Terrace are more than 8 metres in thickness, and their base is situated below the present flood plain. They are in abutting with the Nimbugaon Terrace Deposits in places. Normal grading silty sand, some of which include organic matter, is dominant in the sediments (Fig. 5). Thin gravel beds, consisting chiefly of sub-rounded cobble, are observed at the middle course of the tributaries of the Rapti River. The lithologic composition of the Garhwa 1 Terrace

Deposits is similar to that of the Nimbugaon Terrace Deposits.

The Garhwa 2 Terrace, which is fringing the Garhwa 1 Terrace, is developed along the Rapti River. It dominates the east half (upper course) of the valley. The relative height of the terrace surface ranges from 2 to 5 metres above the river bed. Red weathering crust has not been developed on the terrace surface.

The deposits of the Garhwa 2 Terrace are composed of fresh yellowish gray to yellowish brown sand of several metres thick (Fig. 5). The deposits include some fragments of woods, which are measured as $3{,}350 \pm 90$ y B. P. in radiocarbon dating (NU-760). The sand layers are well stratified and planner bedding is common. They fill up the valley of the Rapti River to form its floor and small gullies by which older terraces are dissected.

3.2. Interpretation

1) Ages of the terraces

The sole absolute age of terraces in the study area was obtained from the Garhwa 2 Terrace Deposits (3.4 ka). Physical ages of the other terraces are unknown. In order to establish morphostratigraphy, dissection and weathering of terrace surfaces are applied in the Sub-Himalaya, which is the area of few datable materials (Yamanaka and Yagi, 1984 ; Iwata and Nakata, 1985 ; Kimura 1994 etc.).

The C-14 ages obtained from the Dang Dun (Yamanaka and Yagi, 1984) and the Hetauda Dun (Kimura, 1997) are good references to estimate the ages of the other Dun Gravels. According to them, the valley fills formed during the Last Glacial Climax (33,000-13,000 yrs B. P.) have been slightly weathered with thin yellowish soils, and keep their original sedimentary surfaces. These features are in common with those of the Nimbugaon Terrace in the study area. Therefore, the Nimbugaon Terrace corresponds to the geomorphic surfaces formed in the Last Glacial Stage. The Garhwa 1 Terrace, which was formed in between the Nimbugaon Terrace and the Garhwa 2 Terrace, was developed in the early Holocene.

The Lamahi Terrace has been intensively weathered and dissected. The red weathering crust of the Lamahi Terrace develops almost equivalent to that of the Higher Terrace in other dun valleys (Yamanaka and Yagi, 1984 ; Iwata and Nakata, 1985 ; Kimura, 1994). These deep red-weathered terraces are generally considered to have been exposed for longer time than 10^5 years in humid subtropic-temperate environment (Billard, 1985 ; Araki, 1988). Therefore, the Lamahi Terrace is considered to have emerged in Middle Pleistocene age.

2) Formation of the terrace deposits

The Lamahi Terrace Deposits are characterised by poorly-sorted boulders and they are distributed at the outlets of the large tributaries of the West Rapti River such as the Arjun Khola, the Kakraha Khola and so on. The terrace surfaces slant to the valley centre. These sedimentary feature are in accord with the present drainage system. The evidence displays that the Lamahi Terrace was formed as alluvial fans or cones, which were fringing the dun, in Middle Pleistocene age.

The Nimbugaon Terrace Deposits are dominated by well-stratified normal-grading beds, which are composed of pebble through flood loam . This sedimentary character demonstrates that the Nimbugaon Terrace was chiefly developed as a flood plain along a trunk stream. Broad distribution of the terrace deposits and their monotonous facies indicate that the West Rapti River formed a basin-wide flood plain in late Pleistocene time.

The Garhwa terraces are side-by-side to the present West Rapti River and its tributaries. The facies of the terrace deposits is in common with that of the Nimbugaon Terrace Deposits. However, thickness and depositional area of the Garhwa Terrace Deposits are far smaller than those of the Nimbugaon Terrace Deposits. These features mean that Garhwa Terraces were evolved as flood plain, which were curved on the Nimbugaon Terrace Deposits, in the Holocene.

4 Evolution of duns and crustal movement

4.1. Palaeocurrent-reversal showing the origin of the Deukhuri Dun

The origin of the Sub-Himalayan intermontane basins can be discussed by palaeocurrent analysis. Along the frontal margin of the Hetauda Dun, which is located in central Nepal, clast fabric of upper Quaternary sediments changed from southing to northing. The author formerly revealed that the current reversal was a resulted from growth of a frontal thrust ramp (Kimura, 1994). In other words, the geomorphic expression of the thrust ramp separated the Hetauda Dun (piggyback basin) from the Ganges Plain (foreland basin). Pivnic and Khan (1996) also clarified the transition from a foreland-basin to a piggyback basin, which occurred in the Panjab Sub-Himalaya, using the technique of palaeocurrent analysis. Similarly, the palaeocurrent analysis based on imbrication of conglomerate-gravel is applied to the areas in and around the Deukhuri Dun. As a result, palaeocurrent reversal is recognised in the stage between the Upper Siwaliks and the Lamahi Terrace Deposits (Fig. 6). The Upper Siwaliks in the study area, which is dominated by well-stratified cobble layers (the Dhan Khola Formation : Corvinus, 1991), shows that the cobbles supplied by northward current. The Lamahi Terrace Deposits also demonstrate north-current along the foot of the Inner Churia Range. The gravels distributed along the foot of the Duduwa Range (the Outer Churia Range), however, have been clearly formed by southward current. This means that the Duduwa Range was not a barrier between the dun and a foreland basin (the Ganges Plain) by the Upper Siwalik Stage. Then, the environment of the intermontane basin was established by the Lamahi

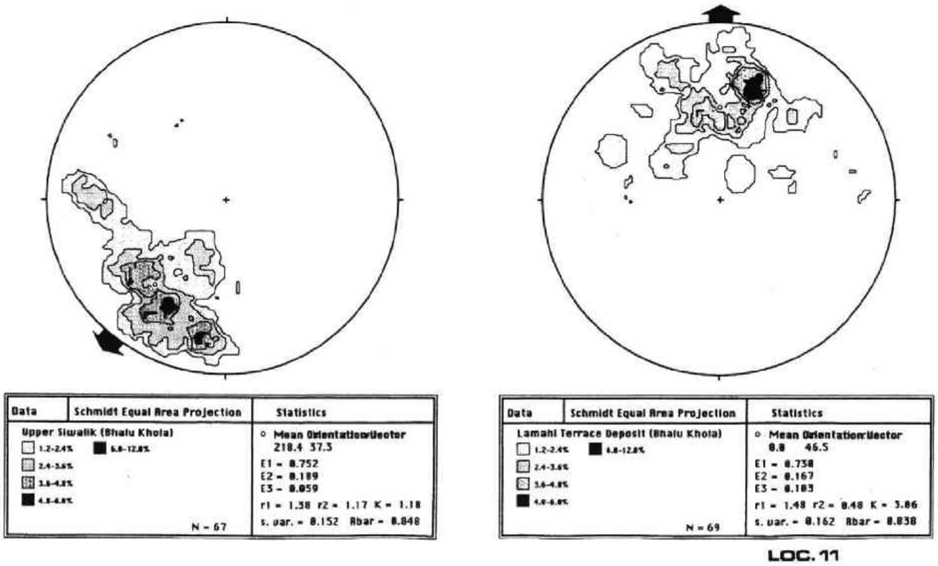


Fig. 6a

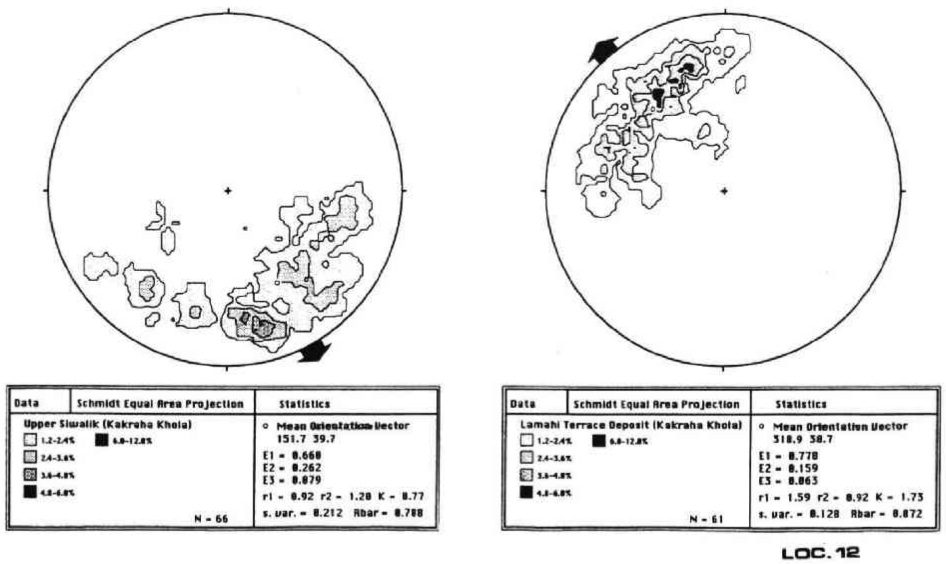
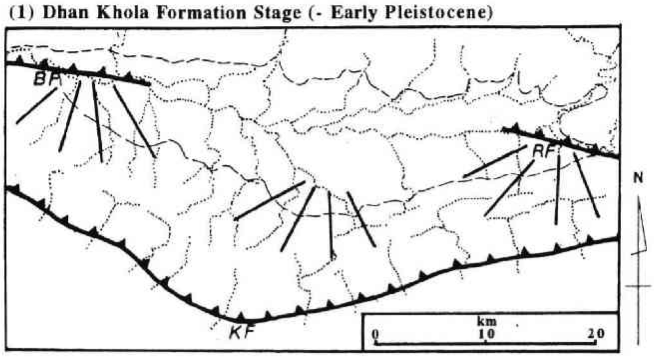


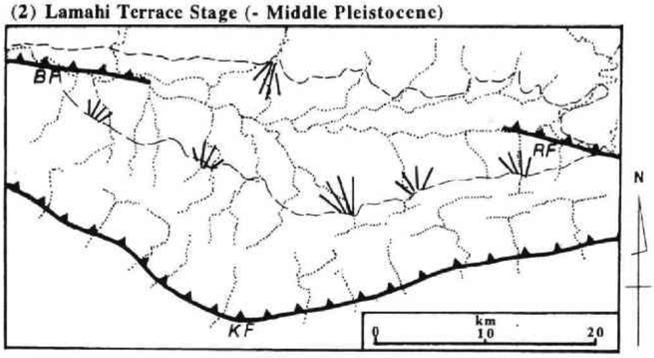
Fig. 6b

Fig. 6: Clast fabric of the Upper Siwaliks and the Basin Fills (plotting a-b plane of cobbles to lower hemisphere of Schmidt net)

(1) Dhan Khola Formation Stage (- Early Pleistocene)



(2) Lamahi Terrace Stage (- Middle Pleistocene)



(3) Nimbugaon Terrace Stage - (Late Pleistonece -)

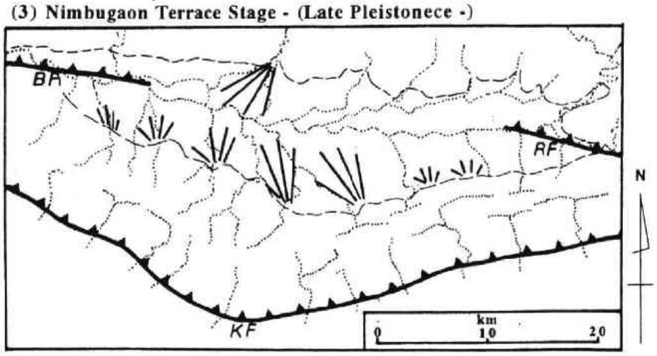


Fig. 7 : Palaeogeographic change in the area around the Deukhuri Dun (radial lines : outlets of foothill fans, broken line : outline of the sedimentary area of the dun fills, dot line : present drainage system)

Terrace Stage. Therefore, the Deukhuri Dun was formed in the age between the Upper Siwalik Stage and the Lamahi Terrace Stage. In other words, the growth of the Duduwa Range separated the dun from the foreland-basin of the Himalayas. The uplift of the Himalayan foothills is generally explained by vertical displacement of the HFF/FCT (Nakata, 1972 ; Tokuoka *et al*., 1986). The Duduwa Range, one of the southernmost foothills of the Himalayas, also developed on the hanging wall of the FCT and the palaeocurrent is changed on its thrust sheet. These facts suggest that the activities of the FCT form the Duduwa Range (thrust ramp) and dam-up the valley fills. Thus the Deukhuri Dun was formed as a piggyback (thrust-sheet-top) basin in Middle Pleistocene time (Fig. 7).

4.2. Cross-sections suggesting the deformation of the valley floor

The four terraces show changes in sedimentary environment in the dun. Causes of breaks in sedimentation are regarded as a result of tectonic base-level alternation, eustatic sea-level oscillation, changes of sedimentary conditions effected by climatic change and so on. The study area is located at more than 1,000 km far from the mouth of the Ganga, thus, sea-level oscillation caused by climatic change scarcely effected to the terrace formation. Climatic change may have effected to slope conditions surrounding the dun. However, the facies of the Nimbugaon Deposit of the Last Glacial Stage and the Garhwa Terrace Deposits of the Holocene, for example, are similar to each other. The fact displays that the effect of climatic change is not reflected in the terrace formation. Therefore alternations of depositional environment are chiefly resulting from crustal movement rather than other reasons.

The four levels of fluvial terraces are well developed along the Gurung Khola and the Arjun Khola. These tributaries of the West Rapti River show the N-S section of the Dun. Therefore, the longitudinal profiles of those tributaries and terraces are expected to illustrate the changes of valley floor deformation. Profile morphometry of fluvial surfaces is a trustworthy method of estimating crustal movement (Sugimura, 1967 ; Schumm, 1986). The N-S profile of the Deukhuri Dun (Fig. 8) displays that the Lamahi Terrace merges into the Nimbugaon Terrace. Even in stratigraphic relationship, the Nimbugaon Terrace Deposits are underlain by the Lamahi Terrace. In contrast, the Nimbugaon Terrace, the Garhwa terraces and the present flood plain are virtually parallel to each other. Younger surfaces are developed in the minor valleys carved on older surfaces. This morphostructural relationship suggests that the sense of the deformation changed in the stage between the Lamahi Terrace and the Nimbugaon Terrace.

The deformation trend of the Lamahi Terrace, which is remarkably slanted towards valley centre, is in accord with subsiding motion that formed the piggyback-basin. This crustal movement was apparent by the stage between the Lamahi

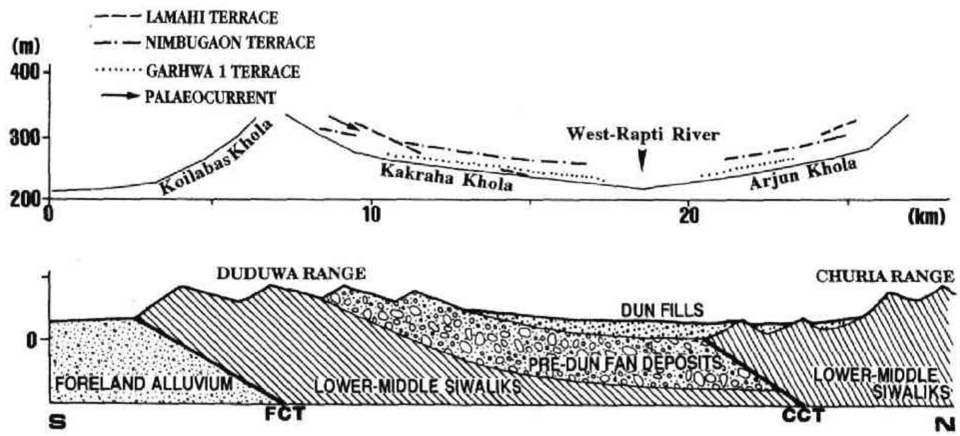


Fig. 8 : Cross section of the Deukhuri Dun

Terrace and the Nimbugaon Terrace. The morphostructural discontinuity between the Lamahi Terrace and the younger surfaces means that the development of piggy-back-basin, which is the subsiding motion on the hanging wall of the FCT, has been weaken since the formation of the Nimbugaon Terrace. The geomorphic surfaces and valley fills have not recorded tectonic deformation such as fault outcrops, tectonic bulges, active folds and so on. The Nimbugaon Terrace, which was the widest flood plain in the history of the dun, has been risen about 40 m from the floodplain, indicating the upheaval of the basin floor. This may imply that broad uplift over 30 km in wave length is going to disturb the crustal deformation, which has maintained the piggyback sequence, since Late Pleistocene age.

4.3. Morphogenesis and active tectonics

As mentioned above, the morphostructure of the area around the Deukhuri Dun is characterised by a piggyback sequence dominated by the FCT. The FCT or its equivalent are generally regarded as range-front thrust ramps branched off from a decollment beneath the Sub-Himalaya (*e. g.*, Seeber *et al.*, 1981 ; Schelling and Arita, 1991). This kind of sequential morphostructure is in common with other dun valleys such as the Dehra Dun in the Garhwal Front, the Hetauda Dun in the Central Nepal Front and so on. Though there is few geodetic and seismic data suggesting the active tectonics in the area around the Deukhuri Dun, the comparative seismo- and morphotectonics with other dun valleys can help to understand the relation between morphogenesis and earthquakes in the Western Nepal Front. On north-south sections, morphostructural profiles and growing rate of the Dehra Dun and the Hetauda Dun are in accord with the trend of crustal movement surveyed in interseismic periods

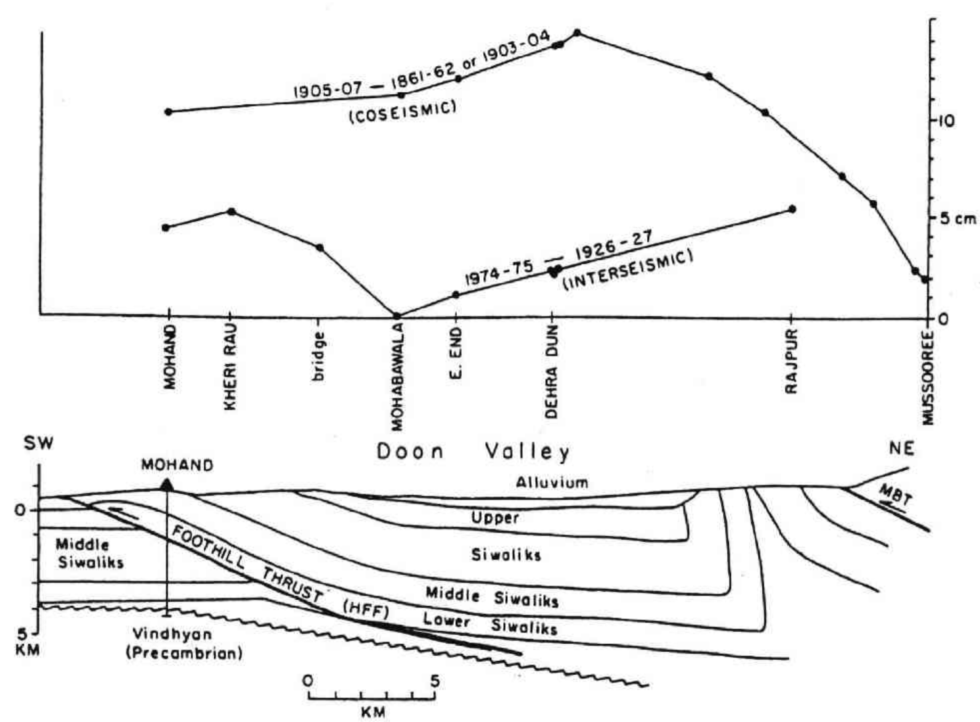


Fig. 9 : Coseismic and interseismic deformation of the Garhwal Sub-Himalaya (from Yeats and Lillie 1991)

(Rajal *et al.*, 1986 ; Jackson and Bilham, 1994). However, the crustal deformation caused by the 1905 Kangra earthquake (M8), which gave a catastrophic damage to the area around the Dehra Dun, is in conflict with the morphostructure. According to Middlemiss (1910), the Kangra earthquake gave broad upheaval to the Sub-Himalaya (Fig. 9). These facts suggest that the FCT (or HFF) is not the source fault of the Kangra-type great earthquakes. In other words, the Sub-Himalayan piggybacks can be grown by aseismic slip. The coseismic broad upwarping across the dun valley suggests that the Sub-Himalaya is partly shorten and thicken by great earthquakes due to the rapture of its hinterland (Fig. 10). Recent geodetic and seismic observation in the Himalayas indicate that the hanging wall of the MCT is slipped by creep, and the foot wall of the MCT is locked as an asperity (Bilham *et al.*, 1997 ; Nakata, 1997). The Himalayan great earthquakes are considered to occur on a shallow decollment, because they gave huge damages to the Himalayan foreland without surface rapture (Seeber *et al.*, 1981). Therefore, the main rapture zone of the next Kangra-type earthquake, which is estimated to occur in the western part of Nepal (Bilham *et al.*, 1995 ; 1997 ; Pandey *et al.*, 1997), will be located beneath the Lesser Himalaya rather

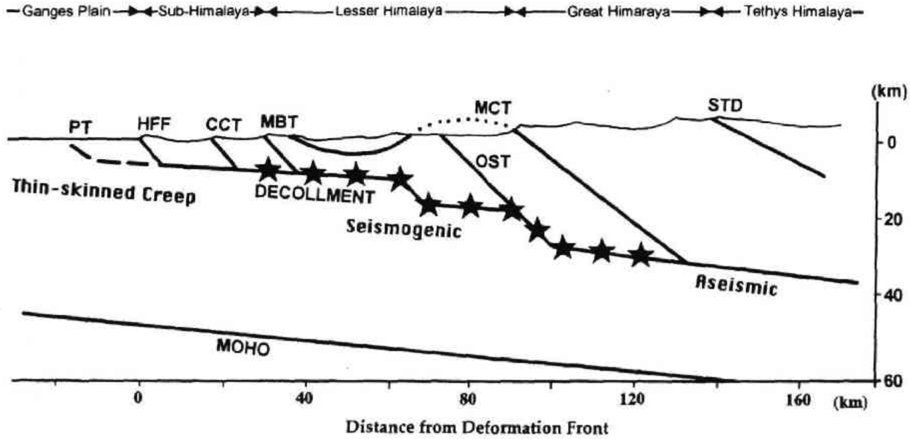


Fig. 10 : A cross-section illustrating the active tectonic setting of the Himalayas (PT : Protothrust, FCT : Frontal Churia Thrust, CCT : Central Churia Thrust, MBT : Main Boundary Thrust, MCT : Main Central Thrust, OST : Out-of-sequence Thrust, STD : South Tibetan Detachment, MDF : Main Detachment Fault). The Himalayan great earthquakes are considered to occur on a shallow decollment beneath the Himalayan Front (Seeber *et al.*, 1981). Recent geodetic research suggests that the foot wall of the MCT is locked as an asperity (Nakata, 1997). As mentioned in the dialogue, the Sub-Himalayan morphostructure have been chiefly developed by aseismic slip. Therefore, the source fault of the Himalayan great earthquakes is assumed to exist beneath the Lesser Himalaya.

than the Sub-Himalaya. Therefore, we must pay special attention to a strain that will be observed on the Main Boundary Thrust Sheet in order to predict the next great earthquake.

5 Conclusion

The geomorphic development of the Deukhuri Dun, resulted from the analysis of the terraces, the basin fills and the Siwaliks, is synthesized as follows.

1) In the stage between the Upper Siwaliks and the Lamahi Terrace (Early to Middle Pleistocene Age), the thrust ramp of the FCT uplifted as the dividing ridge between the Ganges Plain (foreland basin) and the Deukhuri Dun (piggyback basin).

2) The Lamahi Terrace Deposits, the first basin fills of the Deukhuri Dun, were deposited in Middle Pleistocene age. The growth of the piggyback basin continued by the Nimbugaon Terrace stage. Comparative seismo- and morphotectonics suggests that the morphogenesis is chiefly achieved by aseismic slip on the decollment beneath the Sub-Himalaya.

3) The Nimbugaon Terrace Deposits were accumulated to cover the Lamahi

Terrace Deposits in Late Pleistocene age. Since the emergence of the Nimbugaon Terrace, the growth of the piggyback-basin deposition has been weaken. This may imply that the crustal deformation of the Midwestern Nepal Front has been changing from the local subsiding of the dun to the broad upheaval of the Sub-Himalaya.

4) Under the uplifting trend, the Garhwa 1 and 2 terraces were formed in the Holocene. This broad upheaval of the Sub-Himalaya is affected by great earthquakes which occurred beneath the Lesser Himalaya.

Acknowledgment

This research was mostly carried out when I was dispatched from the Japan Overseas Cooperation Volunteers (JOCV) to the Department of Geology, Trichandra Campus, Tribhuvan University, Nepal (1992-1994). I express my heartfelt thanks to the concerned stuff members of the two organizations.

Emeritus Prof. K. Kizaki of the University of Ryukyus and Dr. K. Saijo at Miyagi University of Education gave me advice, assistance, and encouragement during this work. I have had useful discussions on this topic with Dr. T. Komatsubara, the Geological Survey of Japan, and Dr. Y. Otsuki at Tohoku University. The author is much indebted to Prof. T. Tamura of Tohoku University for critical reading of the manuscript.

References (* in Japanese)

Araki, S. (1988): Genesis and dating of red soils.* *Pedologist,* **32**, 203-210.

Appel, E. and Rosler, W. (1994): Magnetic polarity stratigraphy of the Neogene Surai Khola Section (Siwalik, SW Nepal). *Himalayan Geology,* **15**, 63-68.

Bilham, R., Bodin, P., and Jackson, M. (1995): Entering a great earthquake in Western Nepal: Historic inactivity and geodetic test for the development of strain. *Jour. Nepal Geol. Soc.,* **11**, 73-88.

Bilham, R., Larson, K., Freymueller, J., and Project Idyhim Members. (1997): GPS measurements of present day convergence across the Nepal Himalaya. *Nature,* **386**, 61-64.

Billard, A. (1985): Quaternary palaeosoils as indicators of the changing landscape on the northern and southern piedmonts of the Alps. In: Boardman, J. (ed), *Soils and Quaternary Landscape Evolution,* 373-388. John Wiley & Sons Ltd., New York, 391 p.

Chander, R. (1988): Interpretation of observed ground level changes due to the 1905 Kangra earthquake, NW Himalaya. *Tectonophysics,* **149**, 289-298.

Chander, R. (1992): Contemporary tectonics of the Himalayan frontal fault system-folds, blind thrust and the 1905 Kangra earthquake: Discussion. *Jour. Structural Geol.,* **14**, 621-623.

Corvinus, G. (1991): Litho- and biostratigraphy of the Siwalik succession in Surai Khola area, Nepal. *Palaeobotanist,* **38**, 293-297.

Delcaillau, B., Herail, G. and Mascle, H. (1987): Évolution ĝeomorphostructurale de front de chevauchement actifs; les des chevauchement intrasiwalik du Nêpal central. *Zeitchr. Geomorph. N. F.,* **31**: 339-360.

Department of Mines and Geology, Nepal. (1982): *1 : 125.000 Geological map of Far Western Development Region* (Sheet No. 63I-A & B)

Hagen, T. (1969): Reports on the Geological Survey of Nepal preliminary reconnaissance. *Denkshr. Naruf. Ges.*, **1** (86), 186 p.

Itihara, M., Shibasaki, T. and Miyamoto, N. (1972): Photogeological survey of the Siwalik ranges and the Terai plain, south eastern Nepal. *Jour. Geosci. Osaka City Univ.*, **75** (4), 77-99.

Iwata, S. and Nakata, T. (1985): River terraces and crustal movement in the area around Narayanghat, Central Nepal. *Jour. Nepal Geol. Soc.*, **5**, 33-42.

Jackson, M., and Bilham, R. (1994): Constraints on Himalayan deformation inferred from vertical velocity fields in Nepal and Tibet. *Jour. Geophys. Res.*, **99**, 13897-13891.

Kimura, K. (1994): Formation and deformation of river terraces in the Hetauda Dun, central Nepal —A contribution to the study of post Siwalikan tectonics—. *Sci. Repts. Tohoku Univ. Ser. 7 (Geography)*, **44**, 151-181.

Kimura, K. (1997): Thrust tectonics during the last 30,000 years in the Nepal Sub-Himalaya, inferred from radio carbon ages of the Dun Gravels. *Program and Abstracts : Japan Association for Quaternary Research*, **27**, 214-215.

Kizaki, K. (1995): Recent tectonics in the Nepal Himalayas: A synthesis. *Jour. Nepal Geol. Soc.*, **11**, 131-140.

Middlemiss, C.S. (1910): The Kangra earthquake of 4th April 1905. *Mem. Geol. Survey of India*, **38**.

Mugnier, J.L., Mascle, G., and Faucher, T., (1994) The structures of the frontal thrust of Himalaya (Siwaliks of western Nepal). *Himalayan Geology*, **15** (Siwalik Foreland Basin of Himalaya), 245-261.

Nakata, T. (1972): Geomorphic history and crustal movements of the foot-hills of the Himalayas. *Sci. Repts. Tohoku Univ., Ser. 7 (Geography)*, **22**, 39-177.

Nakata, T. (1975): On the Quaternary tectonics around the Himalayas. *Sci. Repts. Tohoku Univ., Ser. 7 (Geography)*, **25**, 111-118.

Nakata, T, Otsuki, K and Khan S. H. (1990): Active faults, stress field, and plate motion along the Indo-Eurasian plate boundary. *Tectonophysics*, **181**, 83-95.

Nakata, T. (1997) Uplift of the Himalayas and active faults. In : S. Kaizuka (ed), *Landforms of the World*, University of Tokyo Press*, 29-38.

Pandey, M.R., Tandukar, R.P., Avouac, J.P., Lave, J., and Massot, J.P. (1995): Interseismic strain accumulation on the Himalayan crustal ramp (Nepal). *Geophys. Res. Lett.*, **22**, 751-754.

Pandey, M.R., Tandukar, R.P., Chitrakar, G.R., Sapkota, S.N. and Kafle, B. (1997): Constraining a great earthquakes in Western Nepal in space and time. *News Bull. Nepal Geol. Soc.*, **14**, 48-49.

Pivnic, D.A. and Khan, J. (1996): Transition from foreland-to piggyback-basin deposition, Plio-Pleistocene Upper Siwalik Group, Shinghar Range, NW Pakistan. *Sedimentology*, **43**, 631-646.

Rajal, B.S., Virdi, N.S., and Hasija, N.L. (1986): Recent crustal uplift in the Doon Valley. *Proc. Int. Symp. Neotectonics in South Asia*, 146-159.

Schelling, D. and Arita, K. (1991): Thrust tectonics, crustal shortening, and structure of the far-eastern Nepal Himalaya. *Tectonics*, **10**, 851-62.

Schumm, S.A. (1986): Alluvial-river responses to active tectonics, In *Active Tectonics, Geophysical Research Forum*, 84-94, National Academy Press, Washington D.C., 266 p.

Seeber, L., Armbruster, J.G., and Quttmeyer, R.C. (1981): Seismicity and continental subduction in the Himalayan arc. In: Gupta, H.K. and Delany, F.M. (eds), *Zagros-Hindu Kush-Himalaya Geodynamic Evolution*, American Geophysical Union, 215-242.

Sharma, C.K. (1990): *Geology of Nepal Himalaya and Adjacent Countries*. Sangeeta Sharma, Kathmandu, Nepal, 499 p.

Sugimura, A., (1967): Uniform rates and duration period of Quaternary earth movements in Japan. *Osaka City Univ. Jour. Geosci.,* **10**, 25-35.

Tokuoka, T., Takayasu, K., Yoshida, M. and Hisatomi, K. (1986): The Churia (Siwalik) Group of the Arung Khola, West Central Nepal. *Mem. Fac. Sci., Shimane Univ.,* **20**, 135-210.

Yamanaka, H. and Yagi, H. (1984): Geomorphological Development of the Dang Dun, sub-Himalayan zone, southeastern Nepal. *Jour. Nepal Geol. Soc.,* **4**, 151-159.

Yeats, R.S., and Lillie, R.J. (1991): Contemporary tectonics of the Himalayan Frontal Fault System: Folds, blind thrusts, and the 1905 Kangra earthquake. *Jour. Structural Geology,* **13**, 215-225.

Yeats, R.S., Sieh, K., and Allen, C.R. (1997): *Geology of Earthquake.* Oxford University Press, 568 p.