Front. Earth Sci. 2012, 6(1): 29–38
DOI 10.1007/s11707-012-0297-z

RESEARCH ARTICLE

Tectonic control on the drainage system in a piedmont region in tectonically active eastern Himalayas

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Abstract The impact of neotectonic activity on drainage system has been studied in a large alluvial fan in the eastern Himalayan piedmont area between the Mal River and the Murti River. Two distinct E–W lineaments passing through this area had been identified by Nakata (1972, 1989) as active faults. The northern lineament manifested as Matiali scarp and the southern one manifested as Chalsa scarp represent the ramp anticlines over two blind faults, probably the Main Boundary Thrust (MBT) and the Himalayan Frontal Thrust (HFT), respectively. The fan surface is folded into two antiforms with a synform in between. These folds are interpreted as fault propagation folds over the two north dipping blind thrusts. Two lineaments trending NNE–SSW and nearly N–S, respectively, are identified, and parts of present day courses of the Murti and Neora Rivers follow them. These lineaments are named as Murti and Neora lineaments and are interpreted to represent a conjugate set of normal faults. The rivers have changed their courses by the influence of these normal faults along the Murti and Neora lineaments and their profiles show knick points where they cross E–W thrusts. The overall drainage pattern is changed from radial pattern in north of the Matiali scarp to a subparallel one in south due to these conjugate normal faults. The interfluve area between these two rivers is uplifted as a result of vertical movements on the above mentioned faults. Four major terraces and some minor terraces are present along the major river valleys and these are formed due to episodic upliftment of the ground and subsequent down-cutting of the rivers. The uppermost terrace shows a northerly slope north of the Chalsa scarp as a result of folding mentioned above. But rivers on this terrace form incised channels keeping their flow southerly suggesting that they are antecedent to the folding and their downcutting kept pace with the tectonism.

Keywords alluvial fan, drainage pattern, thrust, normal fault, active tectonic

Received June 28, 2011; accepted November 23, 2011

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1 Introduction

The foothills region of an active orogenic belt like the Himalayas is often characterized by active faults and complex alluvial terrace morphology. The eastern Himalayan foothills, east of the Tista River in Darjeeling-Jalpaiguri District in West Bengal show a large piedmont area (Fig. 1), which is drained by numerous major and minor rivers. The region between the Chel River and the Jaldhaka River (Fig. 1) represents an alluvial fan dissected by some major and many minor rivers. The major rivers such as the Chel, Neora, Murti and Jaldhaka originate in the zone of crystallines of the Higher Himalayas, and the minor rivers such as the Mal, Juranti, Kurti, Jiti, etc. originate in the northern part of the piedmont region. The rivers flow from north to south are braided in the study stretch. The rivers are mainly rain fed, and during monsoon and heavy rains in the Bhutan Himalayas the rivers carry large pebble and boulders compared to the sand-sized particles in the dry seasons. The rivers have formed large channel bars. In the northern part, the channel bars are mainly made up of pebbles and boulders whereas in the south they are of sand and pebbles. There are well developed terraces in the river valleys (Sinha Roy, 1981; Starkel et al., 2008).

An area of about 80 km^2 between the Mal River and the Murti River has been studied in details to understand the impact of neotectonic activity on river morphology. The courses of the major and minor rivers are influenced by both E–W thrusts and the nearly N–S transverse faults.

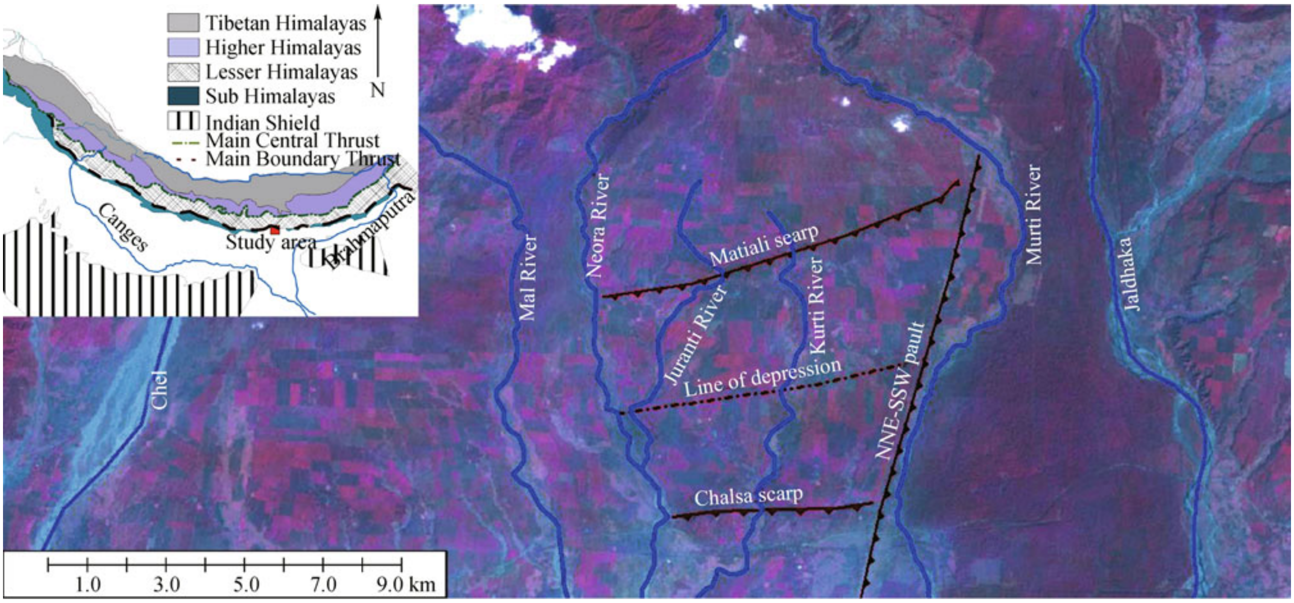


Fig. 1 Piedmont area in Darjeeling-Jalpaiguri District from Chel River to Jaldhaka River showing major rivers and lineaments on merged data of PAN and LISS image of IRS P6 of December 2002. Map showing the major tectonic divisions of Himalayas after Gansser (1964)

2 Regional geology and tectonic setting

Tectonically, the Himalayas are subdivided into five longitudinal belts, which are, from north to south, (i) Tibetan Himalayas, (ii) Higher Himalayas, (iii) Lesser Himalayas, (iv) Sub-Himalayas or Siwaliks, and (v) the piedmont zone of Quaternary sediments (Fig. 1). Major faults which separate one belt from the other are, from north to south, the South Tibetan Detachment separating the Tibetan and the Higher Himalayas, the Main Central Thrust (MCT) between the Higher and the Lesser Himalayas, the Main Boundary Thrust (MBT) between the Lesser Himalayas and the Siwaliks, and the Himalayan Frontal Thrust (HFT) separating the Quaternaries from the Siwaliks (Gansser, 1964; Hodges, 2000). In addition, there are transverse faults that cut across the orographic trend. The structural architecture of the Himalayas is defined by the thrusts mentioned above which branch upward from a basal detachment, and become progressively younger to the south (Auden, 1934; Gansser, 1964; Valdiya, 1986). England and Molnar (1997) concluded from a review of published studies that convergence rates between Indian plate and Euresian plate increase from (10±2) mm/a across the Pakisthan Himalayas west of 74°, to (17±8) mm/a in Northwest India between 74°–78° and to as much as (25±10) mm/a east of 88°. However, it is generally agreed that only as much as 50% of the total convergence occurs within the Himalayan are itself (England and Molnar, 1997; Holt et al., 2000; Wang et al., 2001). Crustal shortening across the Himalayas occurs within a zone centered about 100 km north of Siwalik foothills and the Main Frontal Thrust (MFT) or HFT (Banerjee and Burgman, 2002).

Piedmont areas in western Himalayas have been studied by many workers who have documented Late Quaternary tectonic movements in frontal part of the Himalayas (Lavé and Avouac 2000; Kumar et al. 2001; Malik et al. 2003; Lavé et al. 2005). It has been suggested that Late Quaternary piggyback movement on HFT and imbrication from MBT have resulted the formation of the typical geomorphology in the piedmont region with longitudinal valleys (or “Duns”) and ridges (Nakata, 1972; Malik and Nakata, 2003; Malik and Mathew, 2005; Philip and Virdi, 2007). Recently, Goswami and Pant (2007, 2008) have suggested from GIS–remote sensing based studies that the Kota-Pawalgarh Dun has also formed due to piggyback movement on HFT. However, such type of detailed information on different geological aspects is not available for the piedmont area of eastern Himalayas. In the present study therefore we have made an attempt to understand the tectonic control on the drainage pattern from detailed study of the imageries as well as extensive field study.

A number of distinct E–W lineaments in our study area had been identified by Nakata (1972, 1989) as active faults. One of these in the northern part (at Lat. 26°56′) is named here as Matiali scarp and another southern one (at Lat. 26°53′) as Chalsa scarp. According to Nakata, the Matiali scarp represents the trace of MBT and the Chalsa scarp represents the HFT. Two lineaments trending 13°–193° (NNE–SSW) and nearly N–S are also present, and parts of present day courses of the Murti River and the Neora River follow them, respectively. We interpret these lineaments to represent a conjugate set of normal faults, possibly having oblique slip nature.

3 Methodology

Major geomorphic surfaces, rivers and lineaments were first identified on the IRS P6 LISS III and PAN imageries of December, 2002 and on the Digital Elevation Model (DEM) with a spatial resolution of 90 m of SRTM data of NASA and NGA. Subsequently, an accurate drainage map (scale 1 : 10000) has been prepared from the Cartosat I PAN geocorrected data of December 2009 (Fig. 2). The spatial resolution of the Cartosat I is 2.5 m. A new DEM of the area with 10 m resolution has been prepared from Cartosat I stereodata using ERDAS 9 software (Fig. 3 (a)). In preparing this DEM the height-data at a number of ground control points determined by using hand-held GPS were utilized. River profiles and topographic profiles along different lines have been prepared from both the SRTM and Cartosat DEMs using Global Mapper 10 software. While the SRTM DEM covers a larger area, the Cartosat DEM has better resolution but covers a smaller region. In addition, Total Station Survey has been undertaken to prepare accurate profiles along the Mal River and the Neora River. The geographic coordinates of the primary station (88°45′11″E, 26°52′52″N) used for the Total Station Survey were obtained from Geodetic GPS measurements kindly made available by Mullick et al. (2009) from her own study. The profiles are drawn using Terramodel 10.41 software.

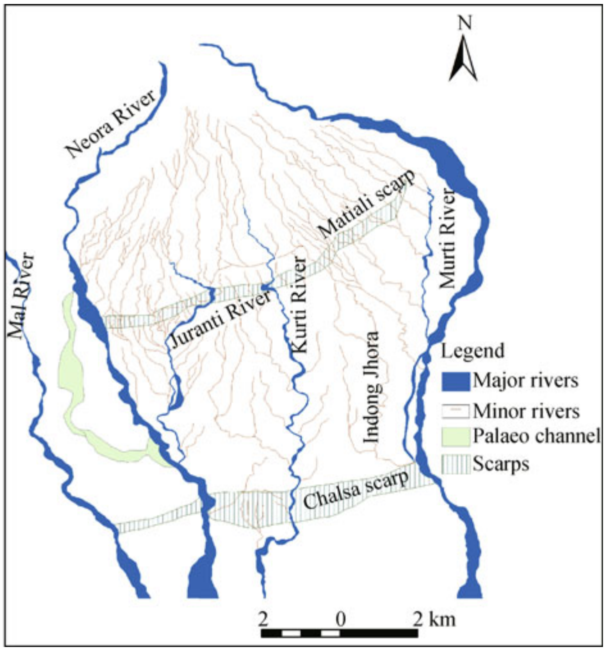


Fig. 2 Drainage map of the study area prepared from the Cartosat I data of December 2009

3.1 Geomorphology and tectonics

The area between the Chel River and the Jaldhaka River (Fig. 1) is an alluvial fan dissected by some major and many minor rivers. A part of this area between the Neora River and the Murti River is studied in detail whereas the other part of the fan is covered by reconnaissance study. The E–W transverse profile between the Neora River and the Murti River drawn from the DEM along a line north of the Matiali scarp shows a convex upward pattern typical of a fan (Fig. 3(b)); a longer profile along a line extending from the Chel River to the Jaldhaka River, south of the Matiali scarp (Fig. 3(c)) shows a similar upward convex form incised by a number of rivers.

The overall southerly sloping fan surface is cut across by two E–W scarps, the Matiali scarp in the north and the Chalsa scarp in the south (Figs. 4(a) and (b)). These scarps extend across the major river channels. The height of the Matiali scarp is highest (60 m) on the eastern bank of Neora. The height reduces eastward and the scarp dies out on the western bank of Murti after taking a north-eastern bend (Fig. 3(b)). It is present only as a faint lineament in Mal-Neora interfluve area and as a scarp with reduced height in the Mal-Chel area (Figs. 3(a)). The height of the Chalsa scarp is 90 m in the Neora-Murti interfluve area. It is also traceable from the Chel River to the Mal River and in the Murti-Jaldhaka interfluves area but with much lower height. A N–S profile on the fan shows that the fan surface is folded into two antiforms, whose crests are located on the two scarps, with a synform in between (Fig. 5). The northern limbs of these antiforms are distinguished by anomalous northerly slope of fan surface which is spectacular in the area north of the Chalsa scarp (Fig. 6(a)) and also north of the Matiali scarp (Fig. 6(b)). Similar pattern of folding can also be seen in the scarp section on eastern bank of the Mal River within clay beds (Fig. 6(c)). These folds are interpreted as fault propagation folds over two north dipping blind thrusts and the humps on scarps represent ramp anticlines (Suppe, 1985; Suppe and Medwedeff, 1990). These blind thrusts, which are branching up from basal detachment, represent the splay of MBT at Matiali and the splay of HFT at Chalsa. The two anticlines are separated by a synform. Axis of this synform is identified as a lineament in the imageries (Fig. 1) and as a line of depression in the DEMs (Fig. 3(a)).

Apart from the E–W lineaments, there are two other lineaments named as Neora and Murti lineaments along which the two rivers flow. A distinct NNE–SSW scarp defines the Murti lineament. It is present along the western bank of the Murti River and has dissected the surfaces and the river takes a sharp bend westward and flows along this line (Fig. 1). Similar prominent scarps are also present on east bank of the Neora River, and the river course is straight from north of the Matiali scarp. These two lineaments represent two conjugate faults. The interfluve area between the Neora River and the Murti River is at higher elevation than the interfluve areas to the west and

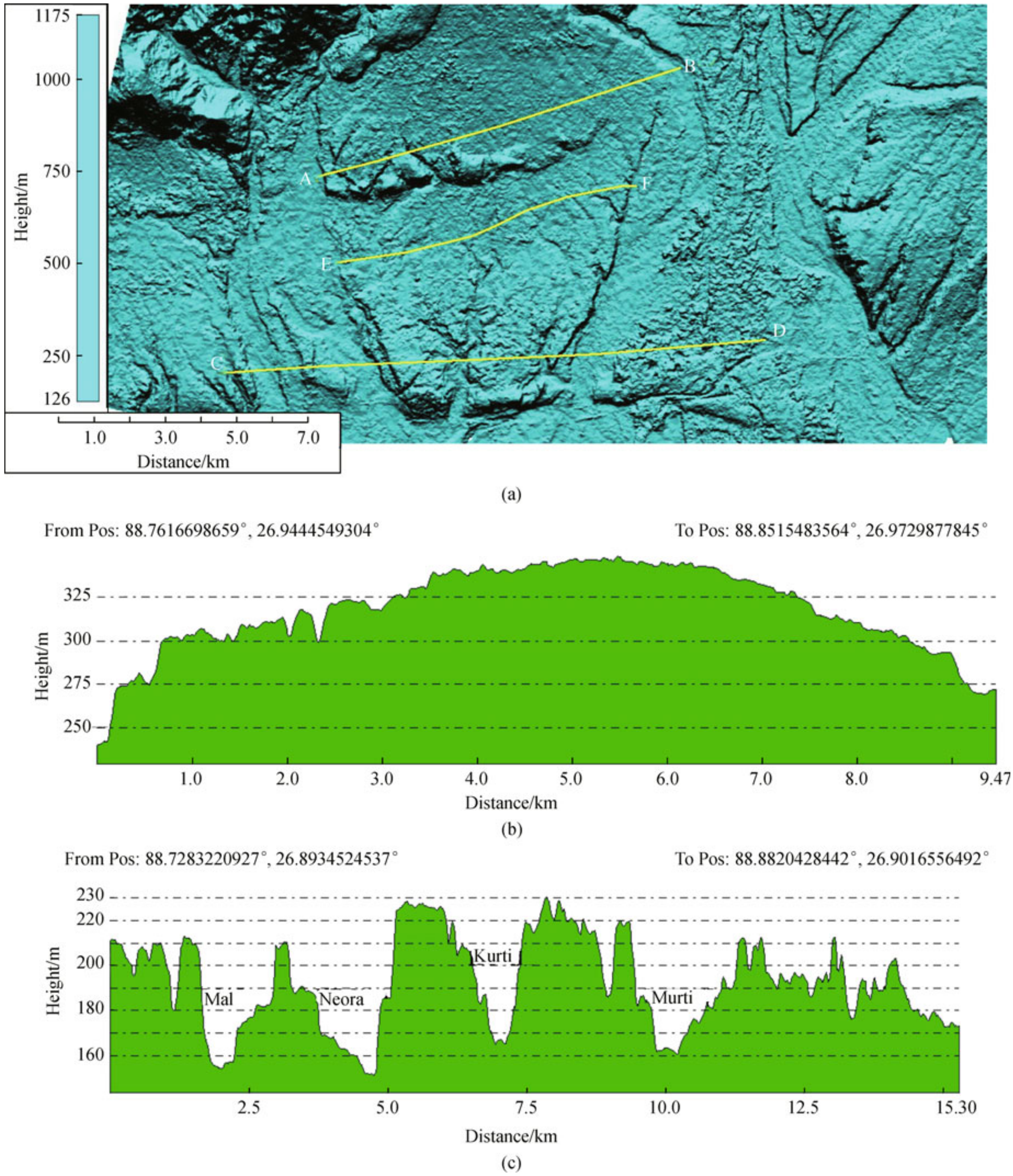
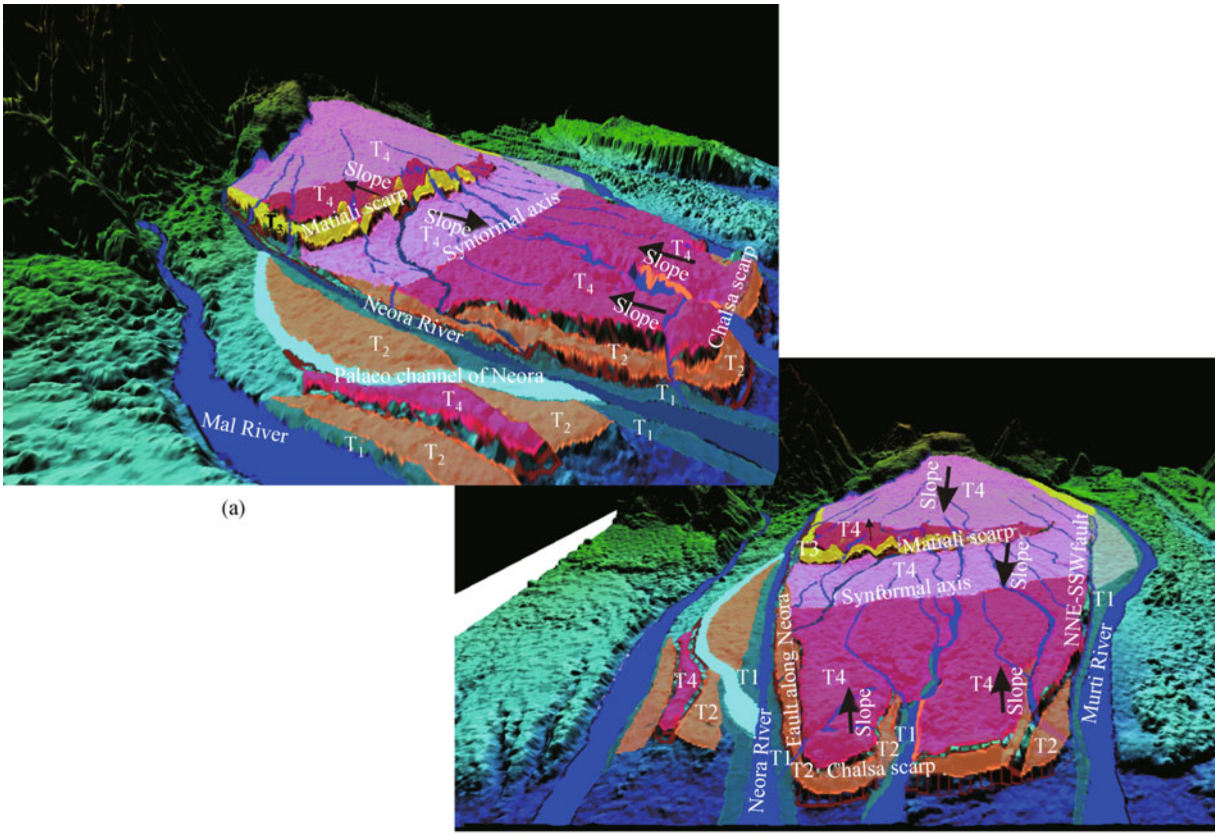


Fig. 3 (a) DEM prepared from the Cartosat I data of December, 2009 with 10 m spatial resolution showing two E–W profile lines AB and CD and the synformal axis as line EF; E–W profile on the DEM from (b) Neora to Murti north of Matiali scarp along line AB and (c) Mal to Jaldhaka south of Matiali scarp along CD also showing convex upward pattern showing convex upward pattern

east between the rivers of Mal and Neora and between the rivers of Murti and Jaldhaka, respectively (Fig. 3(c)). This raised block is interpreted to be due to vertical movements on the above mentioned two faults and the interfluve area between Neora and Murti is upthrown.

The area shows well developed terraces along the major river valleys. These terraces are formed due to episodic upliftment of the alluvial fan and subsequent downcutting of the rivers. There are four major terraces, named as T_1, T_2, T_3 and T_4, and some minor terraces in the study area (Fig. 7). T_4 is the major fan surface extending from north of the Matiali scarp to the Chalsa scarp. T_1 and T_2 are present along the river valleys in the block between the Matiali scarp and the Chalsa scarp whereas T_3 is present along the



(a)

(b)

Fig. 4 Three dimensional view of the area showing major geomorphic features and drainage looking from (a) west and (b) south

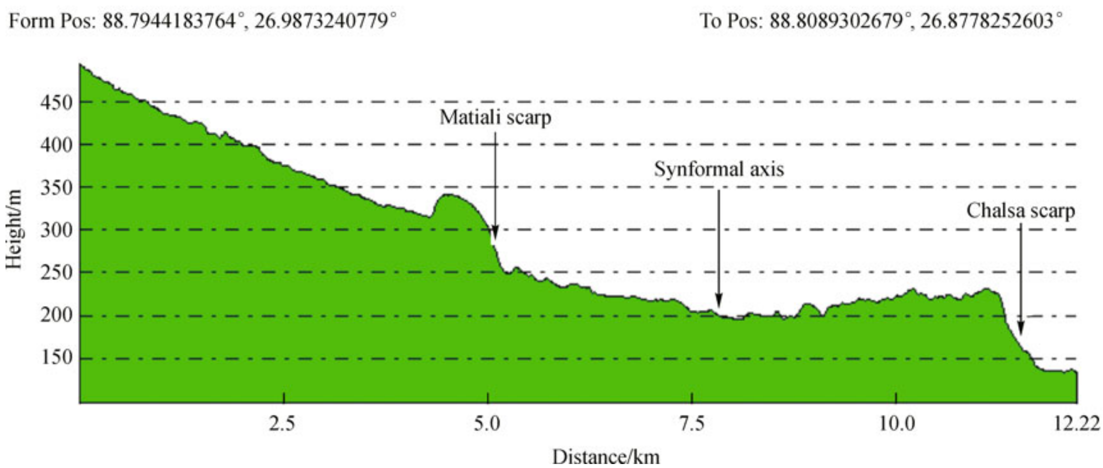


Fig. 5 T N–S profile of the alluvial fan which clearly shows that the T_4 fan surface is folded

river valleys north of the Matiali scarp. T_1, T_2 and T_4 terraces on either side of the Neora River are unpaired. They show much lower height in the western bank of the Neora River near the Chalsa scarp (Fig. 8). T_1 is absent in the eastern bank of the Neora River, and T_2 has created a high scarp whereas a wide T_1 is present along the western bank.

3.2 Drainage pattern

The area is drained by numerous streams (Fig. 2). Two distinct types of rivers can be identified in the studied area: 1) the rivers which originate from the Lesser and Higher Himalayas, and 2) the minor rivers which originate in the piedmont zone, on the fan. These streams cut across the

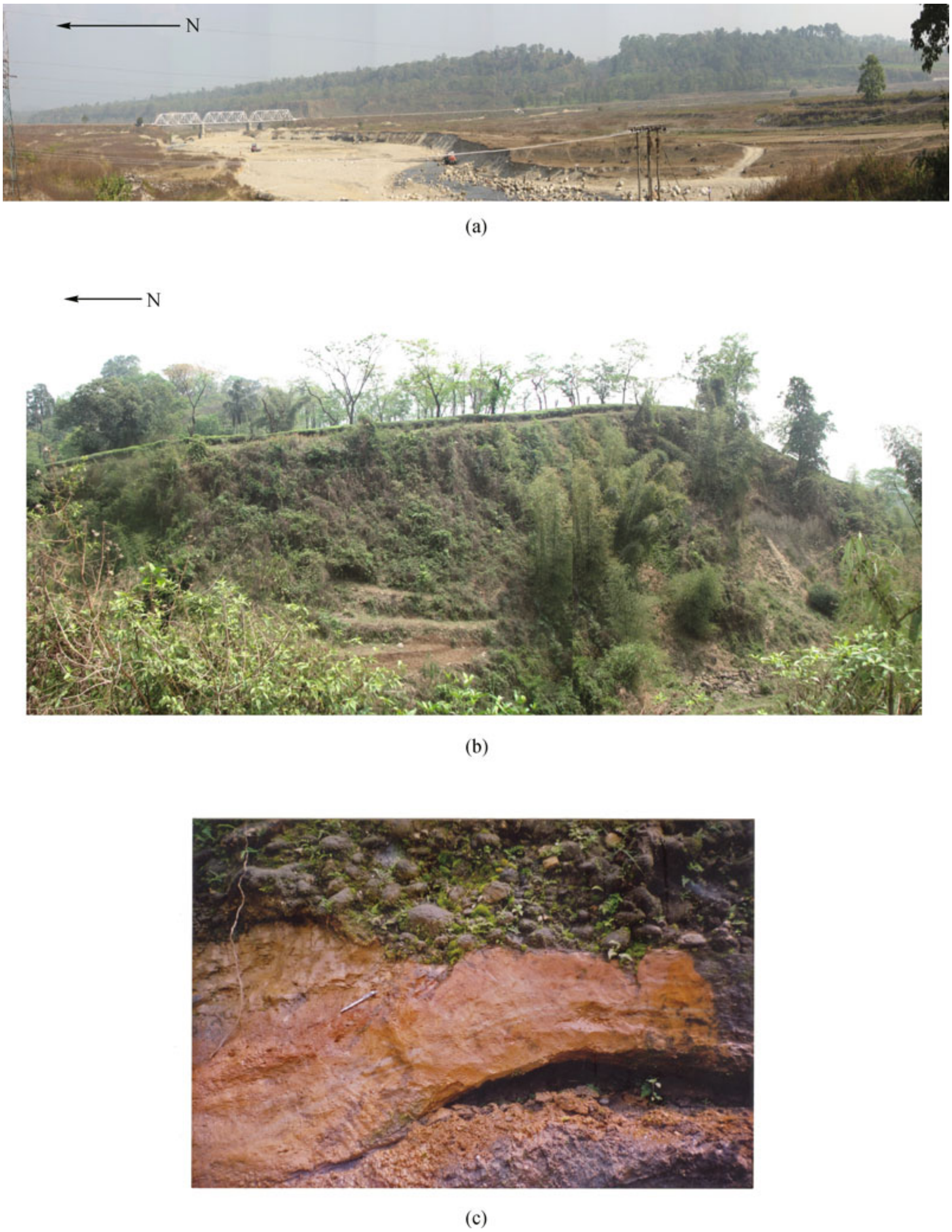


Fig. 6 Profile showing northern slope of the T4 surface just north of (a) Chalsa scarp and (b) Matiali scarp; (c) Folding of the clay beds in a scarp section on eastern bank of Mal River

Matiali scarp and Chalsa scarp and are therefore antecedent with respect to the thrusting. Streams flowing over the fan surface like the Juranti River and the Kurti River form incised channels, suggesting that erosion kept pace with the tectonic uplift resulting from thrusting. It is interesting to note that though the T_4 surface shows a northerly slope north of the Chalsa scarp, there are no northerly flowing rivers; all the rivers flow southerly, but their channels are incised. This is because the rivers are antecedent to the northerly tilting and their downcutting kept pace with the tectonism. There are some E–W streams at the back of the Matiali scarp at the foot of the northerly slope. They meet the bigger streams after crossing the scarp. These are consequent to the formation of the scarps. A few southerly flowing streams originate on the Matiali scarp and are also consequent to thrusting. Only a few streams originate from the Chalsa scarp. The portion of the Chalsa scarp from the Kurti River to the Murti River is highly modified by human activity. So the actual scenario of drainage in this portion could not be identified.

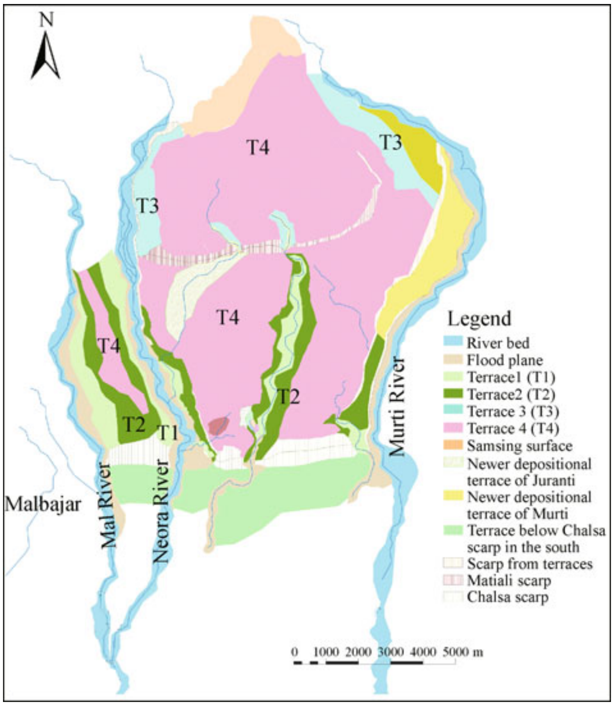


Fig. 7 Geomorphological map of the study area showing different terraces

The drainage pattern north of the Matiali scarp is radiating or divergent, as is typical of a fan. 1st order streams originate in the higher piedmont area and show a radial pattern forming 2nd and higher order streams to reach the major rivers of the Neora in the west and of the Murti in the east. The courses of the Neora and Murti in their upper reaches, north of the Matiali scarp appear to form parts of the radial drainage (Fig. 2). But their courses sharply change south of the Matiali scarp, and in this part the two rivers follow the two lineaments trending NNE–SSW and N–S, respectively. An abandoned paleochannel of the Neora appears to be a part of the radial pattern. Radial pattern of 1st and 2nd order streams appear to be truncated by the changed courses of Neora and Murti (Fig. 2). The Mal River also has the same trend as the Neora lineament. 2nd order stream courses also change direction close to Neora and Murti and follow the direction of the above lineaments. It can be logically concluded that the original radial drainage is modified by tectonism related to transverse faulting along the Neora and Muti lineaments.

The southeastern flowing the Juranti River originates north of the Matiali scarp and while crossing the scarp it shows a sharp bend (Fig. 2), toward southwest. It then follows a trend parallel to the Neora lineament. It shows another westerly bend and flows along the line of depression (synformal axis) and then again takes a course parallel to Neora lineament and ultimately flows almost westerly to meet Neora. The confluence is about 2 km north of the Chalsa scarp (Fig. 2) and here the Juranti River bed is about 1.5 m higher than the bed of the Neora. This difference in height is due to the frequent change in braided river course of the Neora.

The Kurti River also cuts the Chalsa scarp and the Matiali scarp. It shows a hair-pin bend with westerly closure along the Matiali scarp. At the Chalsa scarp, it shows a broad westerly bend. After crossing the Chalsa scarp it flows southerly and ultimately meets Neora at a distance of 9 km south of the Chalsa scarp.

A small river, Indong Jhora, originates in the piedmont zone north of the Matiali and forms a deeply incised channel on the main fan surface south of the Matiali scarp. Just north of the Chalsa scarp it takes a sharp easterly bend to meet the Murti River. Another unnamed tributary of the Murti is parallel to the Murti lineament (Fig. 2).

Drainage pattern with respect to major geomorphic features are shown in Fig. 4. The river profiles along the Neora and Juranti prepared from the DEM show knick points (Figs. 9(a) and (b)). The Neora profile shows a change in slope north and south of the synformal axis, the northern part being steeper. The Juranti profile shows three successive changes in slope. The slope of the Juranti River bed from north of the Matiali scarp to the toe of that scarp is highest, then it becomes almost flat on the major T_4 terrace surface up to the synformal axis and again it attains a higher slope to reach the main channel of the Neora. As the slope of the fan surface abruptly changes from southerly to northerly at the synformal axis, rivers like the Neora and the Juranti which are antecedent to this folding show changes in their slope as they cross the synformal axis. Profiles along the Mal River and the Neora River prepared from the Total Station Survey also show changes in slope in both the rivers on either side of the synformal axis (Figs. 10(a) and (b). The northern segment of the river profile shows steeper slope. In addition, the two rivers show knick points where they cross the Matiali scarp and Chalsa scarp. Such changes in channel slope reflect adjustment of the river courses due to structural development caused by tectonism.

The rivers of Neora, Kurti and Murti become meandering rivers after crossing the Chalsa scarp. They show very wide flood plains in this part.

The flood plains of these rivers have restricted areal extents in the upper reaches north of the Chalsa scarp and these widen out further south decimating the remnants of earlier fans and terraces. Thus, the present day alluvial fan surface is growing at the toe of the earlier fans.

4 Conclusions

The area under study is an alluvial fan which is deformed by thrusting along E–W direction as well as by N–S trending conjugate set of faulting. The drainage in this area is controlled by tectonism that gave rise to thrusting and normal faulting. The rivers change their slopes to adjust to

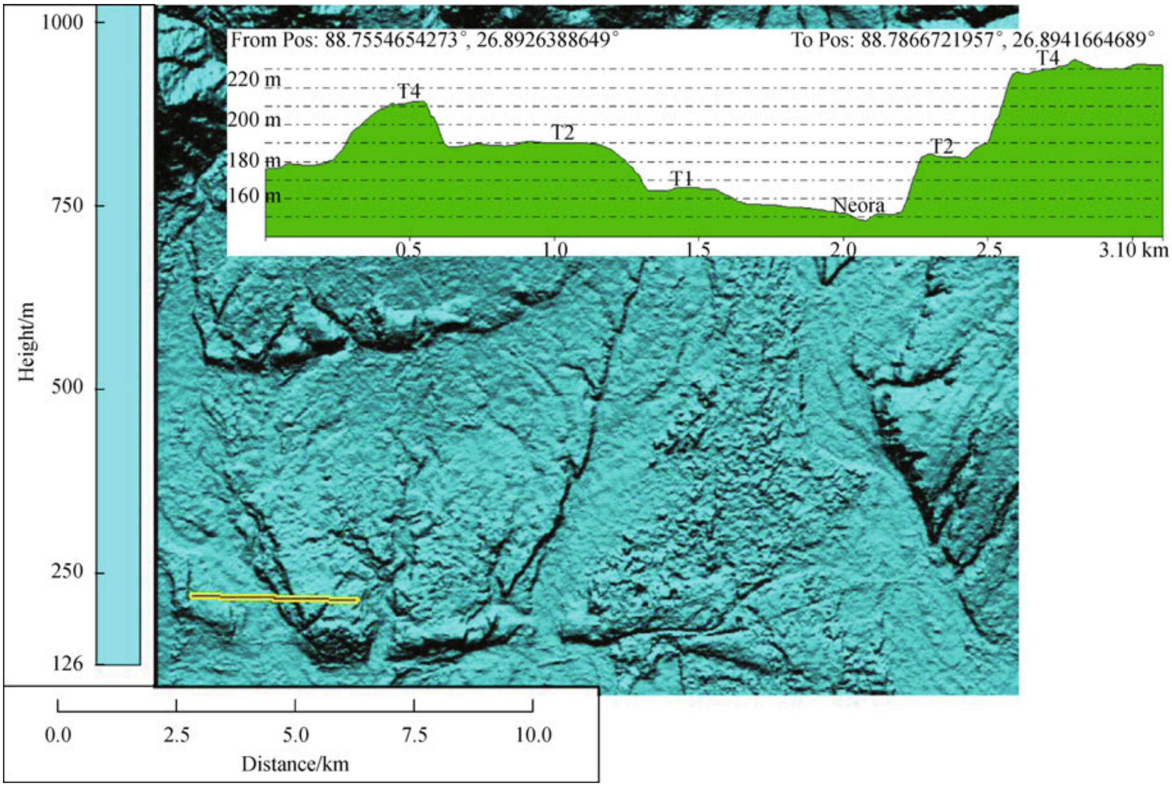


Fig. 8 Transverse E-W profile shows unpaired terraces on either side of Neora near the Chalsa scarp

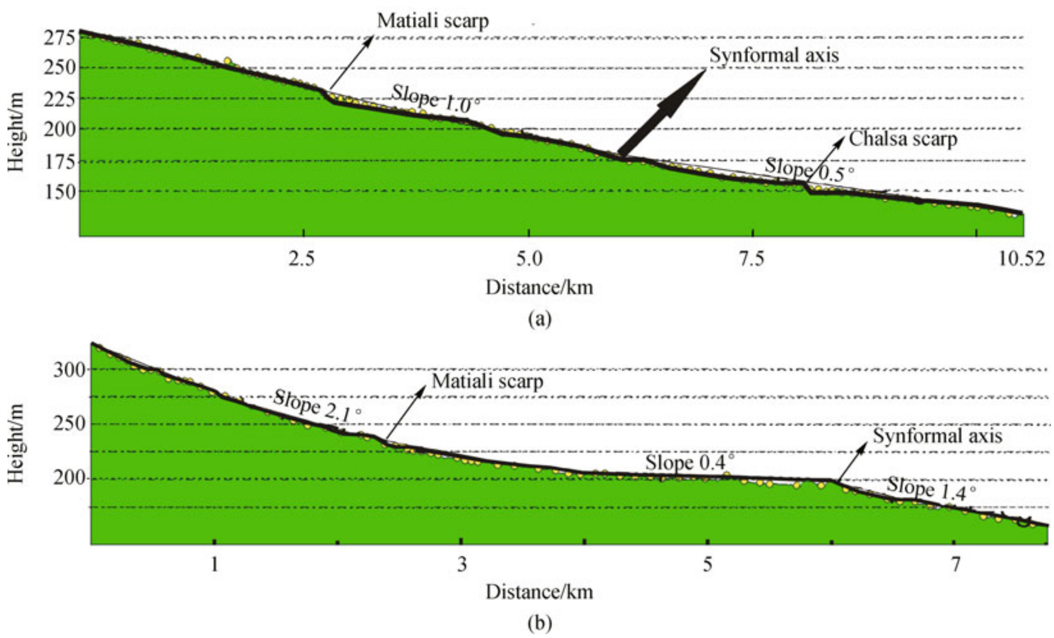


Fig. 9 Profile along the river bed of (a) Neora and (b) Juranti showing knick points near Matiali and Chalsa scarp and change in slope from synformal axis

geomorphic changes caused by the thrusts. The major drainage pattern has changed from radial to subparallel pattern due to two NNE–SSW and N–S trending faults along the Murti River and the Neora River, respectively.

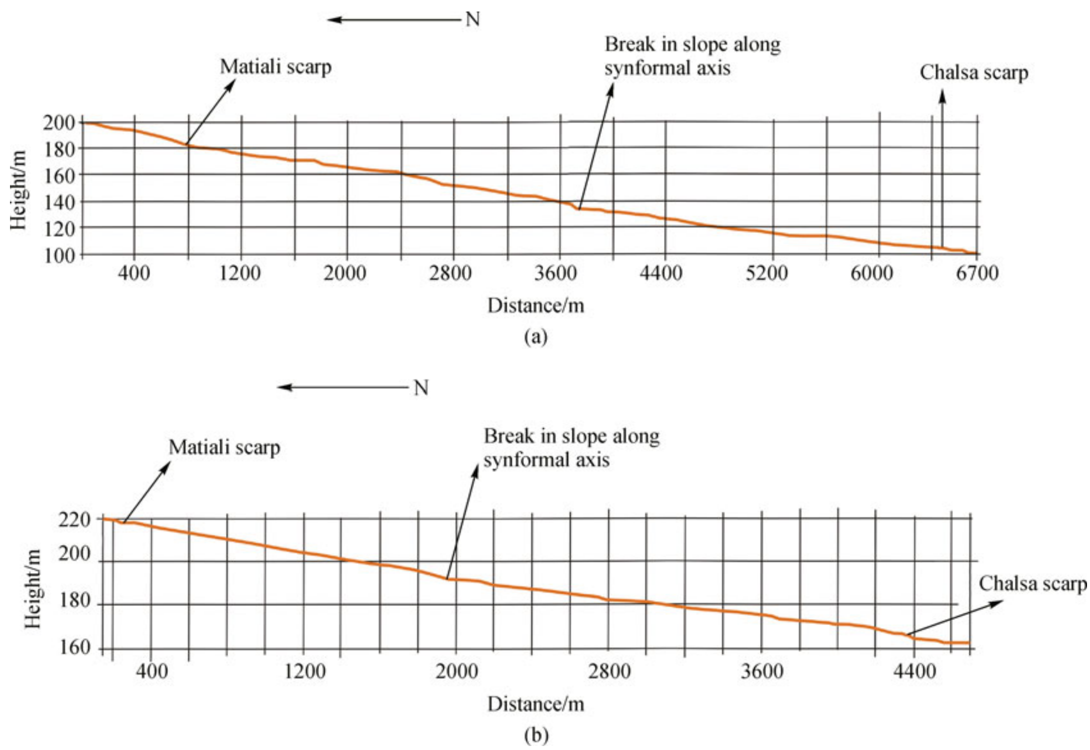


Fig. 10 Profiles of (a) Neora River bed and (b) Mal River bed, obtained from total station survey data showing the knick points and the major change in slope at the synformal axis

Acknowledgements We thank Dr. Mallika Mallick, Woman Scientist, Raman Center for Applied and Interdisciplinary Sciences, for providing the geographic location obtained from Geodetic survey of a point used as primary coordinate in Total Station Survey. A part of the present study was carried out in a project funded by Department of Science and Technology, Govt. of India and executed in Centre for studies on Man and Environment, Kolkata. C G. thanks UGC for funding a minor research project, Principal, Asutosh College for necessary permissions and help, and Head of the Department of Geology, University of Calcutta for infrastructural facilities for research. C G. also thanks Mr. A Ball and Mrs. B Ball for their hospitality during field work, Dr. P Jana, Dr. B Purkait, Dr. T Chakraborty and Dr. B Goswami for discussions and constant encouragement. Cooperation of colleagues in Asutosh College is also acknowledged. The manuscript is considerably improved by the constructive comments of the two anonymous reviewers and the pain staking corrections by the managing editor.

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