

# Assessment of Neotectonic Effect on Quaternary Deposits in Darjeeling Himalayas



Sunipa Mandal and Pinaki Roy

**Abstract** A quantitative assessment of landform and sediment in Quaternary deposits, focusing upon the Mountain Front Thrust (MFT) manifests neotectonics in the aftermath of the orogeny, is intended in the Darjeeling Sub-Himalayas, to feel the ever-fecund pulses of ground tremors. The Sub-Himalayan hilly terrain, generally without sediment cover, has a distinctive character on two sides of the Mountain Front Thrust in terms of drainage pattern and density, stream order, 1st order stream gradient, and shape and size of watershed basins. The sinuosity of MFT  $<1.4$  elicits tectonic deformation. Comparatively smaller and more elongated watershed basins residing at the southern flank of MFT suggest steepness along with tectonic imprints. Significantly more frequent occurrence of parallel drainage patterns, comparatively lower stream orders, and consequent reduction in drainage density on this thrust front are well anticipated. The River Tista in the area achieves minimum gradient on the crest of the MFT eliciting uplift. Frequent changes in river gradient around MFT without any correlation with lithologic changes testify tectonic effect. The valley floor-width/height ratios ( $<0.5$ ) derived from this river bear clear attestation to the tectonic youthfulness of the studied terrain. This uplift of the MFT recorded the basin subsidence in fluvial sequence building with thinning of valley cycles through vertical stacking of warped and tilted multi-generated terraces along River Tista in the Sub-Himalayan region. A concomitantly progressive increment of clast sizes and distal crystalline rocks in a vertical succession of sediment piles with southward migration on thrust shoulder along with enhancement of sedimentation rate upstream and channel incision suggests the directive measurements of tectonism, not climatic effect. The common presence of penecontemporaneous deformational structures in the pile is also suggestive of intermittent tectonic disturbances.

**Keywords** Neotectonism · Mountain Front Thrust · Landform · Sediment · Fluvial sequence building · Basin subsidence · Upliftment · Sedimentation rate · Darjeeling Sub-Himalayas

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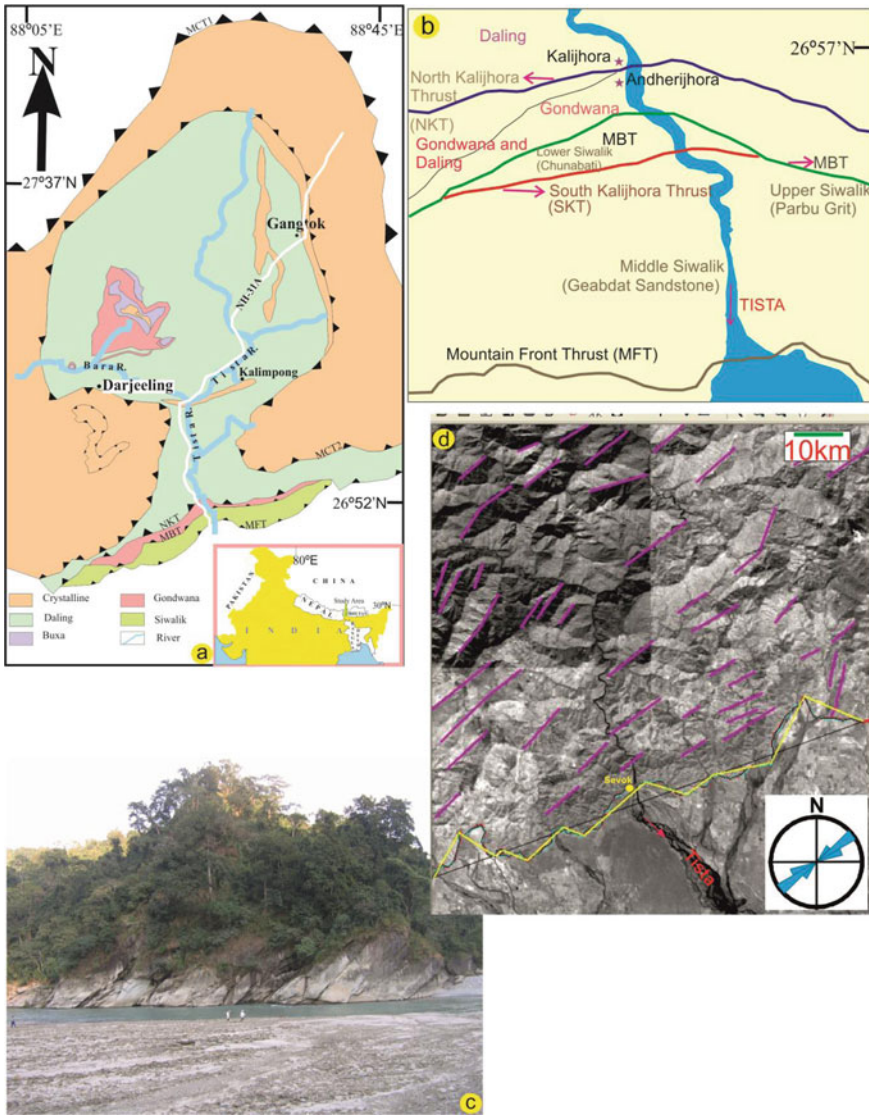
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## 1 Introduction

Tectonism creates and surficial processes that modify the earth's surface relief. The vertical component of plate-related movement is antecedent to topography, while erosion–deposition remoulds it. Exogenous sedimentary processes thus tend to obliterate the topographic signature of tectonism. The extent of obliteration depends on the climate-related rate of erosion and how frequently tectonism interrupts the drift. The compression has engendered successive thrusts, all dipping northward (Gansser 1964; Valdiya 1993), and has the potential to be reactivated. The latest among them, the Main Frontal Thrust (MFT; Gansser 1964, 1981; Nakata 1989) or the Himalayan Frontal Fault (HFF; Nakata 1972, 1989) still rises. A study across the precipice raised by the Himalayan Main Frontal Thrust or Himalayan Frontal Fault separating the rugged mountain range and the piedmont on its south is most apt for testing this percept. MFT being the youngest among all the major thrusts in the Himalayan region, any transect across it is likely to highlight the changing balance between tectonism and exogenous processes most explicitly (Fig. 1a). So, this paper focuses upon the hilly terrain mostly encompassing MFT both in the northern and southern part in the Sub-Himalayan zone having a little cover of Quaternary and Recent sediments and concentrates to work out the quantitative or semi-quantitative assessment of the geomorphic characteristics by using various indices derived from landforms and drainages along the course of the River Tista across the Sevok-Rangpo transect in the Darjeeling-Jalpaiguri districts, West Bengal (Fig. 1a). Notwithstanding, drainage and sedimentation are cogently affected. The signature of neotectonism is, however, expected to be more readily obliterated in the chosen area because of the wet climate. The River Tista encompassed in slices within the hilly region between the tectonically active MBT and MFT which had not yet been attested; except the documentation of genetic classification of finer sediments of the same river in the piedmont by Chakraborty and Ghosh (2010). A long-awaited demand for a specialist sedimentological analysis of Quaternary fluvial deposits in the context of neotectonism and climate change has largely been meted out through the present study. The present study also aims to address the reconstruction of the sequence building by a high-resolution process–product relationship with river base profile i.e., the profile of the imaginary slope on which the equilibrium between erosion and deposition is achieved, fluctuations by rapid subsidence, and consecutive basin upliftment. Vertical stacking of valley cycles records the subsidence. At least five terraces measuring around 15 m on average in height on these sediment piles have been recorded. The imperative is thinning of valley cycles with coarsening up the succession of sediment piles and the presence of maximum clast size along with the percentage of granite boulders in valley floor conglomerates increases up the succession. Besides, supportive documentation has been taken recourse by the presence of a conspicuous concentration of soft sedimentary deformational structures along some deformed and tilted beds.



**Fig. 1** Geological map of the north–south elongated eastern section of the Himalayan belt that includes the studied segment. The map highlights the major thrust sheets, four regional and one local, and the formations exposed between them. Location of the study area at the north-eastern fringe of India is indicated within the inset (modified after Ray et al. 2011) (a). Enlarge view of the area showing broad lithologies and their respective ages, indicated along with major tectonic elements within the studied part of the hilly terrain (modified after Ray et al. 2011) (b). Lower Siwalik Formation with northward dipping slivers along the River Tista in between SKT and MFT across Sevok-Rangpo transect (c). Lineament map generated through the combination of LISS-III and PAN images; rose diagram in inset depicts NNE-SSW trend (d)

## 2 Geological Background

Successive east–west elongated and southward verging thrusts dissect the ~2000 km-long Himalayan belt lengthwise in consequence to the plunge of the Indian plate under the Asian plate and resultant shortening of the low-density sediment cover on it (Fig. 1a). The Main Central Thrust (MCT 1) is the oldest among them and it extends from Nepal on the west up to the eastern end of the Himalayan belt. The Main Central Thrust (MCT 2), North Kalijhora Thrust (NKT), Main Boundary Thrust (MBT), South Kalijhora Thrust (SKT), and Mountain Front Thrust (MFT) have occurred progressively southward in succession (Fig. 1b and c). But the NKT and SKT (Matin and Mukul 2010 and references therein) among them are localized and confined almost entirely to the present study area, while the remaining three extend all over the Himalayan belt (Gansser 1964; Valdiya 1993; Decelles et al. 2001). North of the MCT2 high-grade crystalline massifs are exposed, they are mostly of Palaeoproterozoic age (Fig. 1a; Acharyya 1971; Ray and Neogi 2011; Long et al. 2011 and references therein). The area between the MCT2 and NKT exposes the Proterozoic metasediments, viz., the Daling and Buxa Groups of rocks. The NKT and MBT confine the Daling and Permo-Carboniferous Gondwanas, while the Lower Siwalik Formation (Chunabati) is confined between the MBT and SKT and the Upper and Middle Siwalik Formation are confined between SKT and MFT (Matin and Mukul 2010) of Mio-Pliocene Siwalik Group. The youngest of these thrusts at the south creates the high-relief mountain-front (MFT) bordering the Indo-Gangetic plain (Horton and DeCelles 2001 and references therein) (Fig. 1b). In the chosen area of study, a significant strike-slip displacement has made the tectonic history of the MFT complex (Gansser 1981; Nakata 1989). The major lineaments in the area align NNE-SSW, NW-SE, and E-W (Roy 1976; Acharyya 1976) (Fig. 1d). The River Tista negotiates this steep mountain front, emanating sudden enhancement in sedimentation rate that underscores significant hydraulic jump across the MFT. It is noteworthy that the river course of Tista on the mountainous region of the Himalayas was not demarcated in pre-1787 maps (Miall 1978; Islam and Higano 1999). The pre-1787 Tista could have been fed by rainwater only and emerge out from the mountain front, later on, it joined with the glacier-fed mountain-interior drainage system (Rennel 1794; Arrowsmith 1804; Carry 1811; Bahuguna et al. 2001; Chakraborty and Ghosh 2010) and thereby the discharge amount has been raised immensely followed by the devastating flood in the river in the year 1787 (Chakraborty and Ghosh 2010) and it has been directly linked with a major seismic event (Islam and Higano 1999).

Several related studies have been carried out in the foothills of the NE Himalayas, for example: geological (Medlicott 1864; Pilgrim 1913), geomorphological (Nakata 1972), neotectonic/active tectonic/morphotectonic (Delcaillau et al. 2006 and references therein; Mukul et al. 2007), seismic (Malik et al. 2003), and structural (Acharyya 1982; Basu and Sarkar 1990; DeCelles and Cavazza 1999; Mukhopadhyay and Mishra 2004, 2005; Ghosh et al. 2005; Meetei et al. 2007; Guha et al. 2007). However, only a few studies have focused on landscape development, conjunctively with the underlying relationship between landscape and structures (e.g. Nakata 1972).

The upliftment rate of the MFT was measured (Lavé and Avouac 2001) by using river incision on the piedmont at the immediate west of the present study area. The highest rate of uplift in the Himalayan belt along the MFT was recorded by Merritts and Hesterberg (1994). The drainage systems also characterize the early works on eastern Himalaya (Nakata 1989 and references therein), although no quantitative assessment has been invoked.

### 3 Methodology

For remote sensing studies LISS-III with a spatial resolution of 23.5 m and PAN images of National Remote Sensing Agency of India, while toposheets of Survey of India, digitized, served as the basic tools. Satellite imageries were further enhanced by standard image processing techniques such as contrast stretching, filtering, band rationing, colour composite, etc. The remotely sensed images were georeferenced with the help of Survey of India toposheets no. 78 A/8, A/12, B/5, B/9 (surveyed in 1932, 1962–63) on 1: 50,000 scales. Watersheds on two sides of the MFT ridge were outlined and GIS platforms were deployed to estimate areas covered by each of the watershed basins and to quantify the geomorphic attributes. Classical Sedimentology was the mainstay for the study of the Quaternary deposits.

Maximum clast size is determined in valley floor conglomerates following the usual practice of taking averages from the 10 largest clasts in every valley cycle of river terraces considered (Pettijohn et al. 1972).

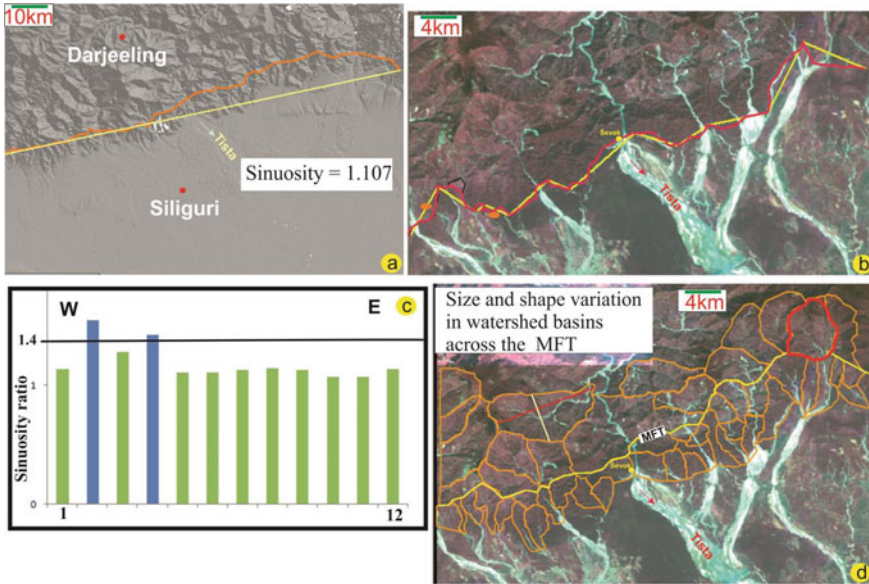
## 4 Results

### 4.1 Geomorphic Neotectonic Elements

The study area is delimited by NKT, MBT, SKT, and MFT, which are tectonically active major thrust planes (Fig. 1b). As a result, the landslide debris caused by the rejuvenation of these older lineaments during the Quaternary has been observed in many places. Seismically induced deformational structures are present in Quaternary sediments. The Quaternary sediments affected by the splay-faults related to NKT, MBT, SKT, and MFT indicate that the area is tectonically active (Fig. 1c).

#### 4.1.1 Sinuosity of MFT

Many workers have used the qualitative aspect of MFT to make general assessments of the degree of tectonic activity present (Burbank and Anderson 2001 and references therein). All geomorphic indices apart, the sinuosity index of MFT has been preferred



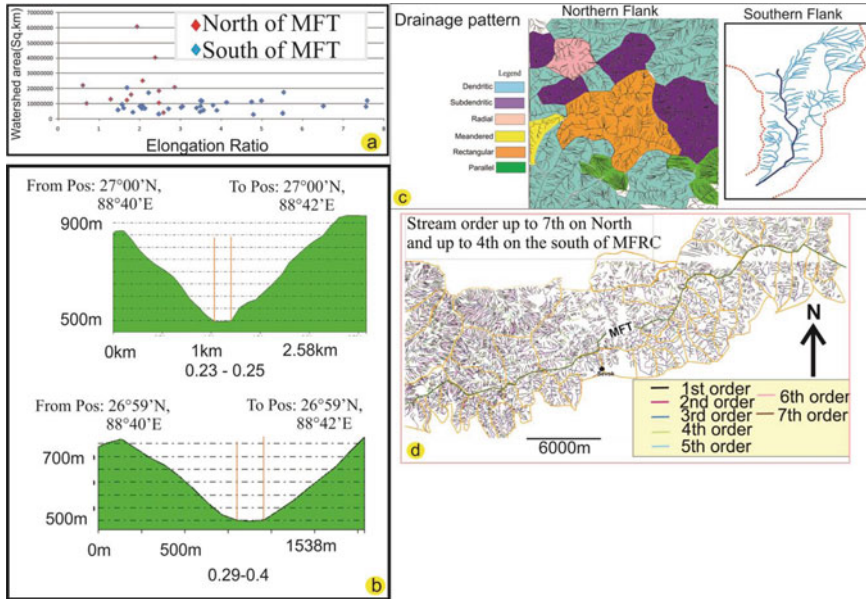
**Fig. 2** Contrasting topographic relief in the Sub-Himalayan hilly-terrain and the piedmont on the foothills of the entire Eastern Himalayan belt well documented on the SRTM DEM. Note that the mountain front sinuosity separates the rugged hilly-terrain from the smoothed piedmont. MFT/MFRC (Mountain Front Ridge Crest) is marked by solid orange line on SRTM DEM in the present study area and showing overall sinuosity of the region (a). The segment wise sinuosity (marked by red line) for successive directional segments from west to east along MFRC (b). Segment wise sinuosity ratios of the MFT in study area from west to east. Note the ratio is slightly higher than 1.4 in only two segments which are pointed as orange circle in Fig. 2b (c). The size and shape variation in watershed basins across the MFT (d)

because of its prominent revealing of tectonic activity. The sinuosity of the ridge crest ( $S_{mf}$ ) is measured as the ratio of the actual length of the chosen ridge ( $L_{mf}$ ) to the length of a straight line joining its two ends ( $L_s$ ) utilizing satellite imageries (Bull 1977, Bull and Mc Fadden 1977, Keller and Pinter 1996) (Fig. 2a, b). The sinuosity of the entire ridge crest in the study area is  $\sim 1.4$  in all but two of its unidirectional near-straight constituent segments it is  $>1.4$  (Fig. 2c).

#### 4.1.2 Watershed Area, Size and Shape

Morphometric analysis of a watershed provides a quantitative description of the drainage system, which is an important aspect for the characterization of watersheds (Strahler 1964). The Watershed system-related attributes were erected through the combination of GIS software namely TNT mips and Global mapper 10 and analysed a digital elevation model (DEM). According to Schumm (1956) elongation ratio of the watershed basin is defined as the ratio of the diameter of a circle of the same





**Fig. 3** Variation in elongation ratio of successive watershed from west to east along the studied stretch of the MFT on two sides of the thrust (north in Red and south in Blue) (a).  $V_f$  values along the River Tista on both sides of the MFT (b). Drainage pattern on both sides of MFT/MFRC (c). Stream orders within confinement of individual watershed basins on two sides of the MFT/MFRC. Note that higher stream orders are present on the northern flank of the MFT (d)

area as the basin to the maximum basin length. The elongation ratio of the watershed in the northern flank of the MFT and southern flank of the MFT are 2.85 and 7.59 respectively (Figs. 2d and 3a). Besides, the elongation ratio  $B_s$  (Ramírez-Herrera 1998), which is also used to describe the basin shape in horizontal projection and may be expressed by equation  $B_s = B_l/B_w$ , where  $B_l$  is the length of the basin, measured from its outlet to the most distal point in the drainage divide and  $B_w$  is the width of the basin measured across the short axis (Fig. 2d). The width vs. length ratio of the basins ranges from 0.59 to 0.86 on the northern flank, but never exceeds 0.43 on the southern scarp. The basins on the southern flank of the ridge are distinctly smaller and more elongated than those on its northern flank (Fig. 2d).

**4.1.3 Valley Floor Width to Height Ratio ( $V_f$ )**

The  $V_f$  (Bull 1977; Bull and McFadden 1977) of the River Tista have been quantified from the SRTM DEM (Fig. 3b). The location of the cross-valley transect within a drainage basin affects the values of  $V_f$ . Valley floors tend to become progressively narrower upstream from the mountain front and for a given stream system the values of  $V_f$  tend to become progressively larger downstream from the headwaters. The river

valley floor width to height ratio  $V_f$  in the River Tista on the north of the Mountain Front Ridge Crest (MFRC) 0.24 and 0.31 on the southern scarp face (Fig. 3b).

#### 4.1.4 Drainage Pattern

Under confinement of individual watershed sub-basins within the River Tista system, the drainage pattern is predominantly dendritic, but may also be trellis, semi-parallel, parallel, rectangular, and rarely radial on the northern flank of the Mountain Front Ridge Crest (c.f. Howard 1967). In contrast, there is a clear dominance of parallel, semi-parallel and rectangular patterns on the southern flank of the same ridge (Fig. 3c).

#### 4.1.5 Stream Order

Stream order is a measure of the position of a stream in the hierarchy of tributaries. Stream order that sorts out successive downstream convergence of streams, irrespective of the methodology adopted (Gravelius 1914; Horton 1945; Strahler 1952; Scheidegger 1965; Shreve 1967), shows higher orders on the northern flank than on the southern scarp of the MFT ridge (Fig. 3d).

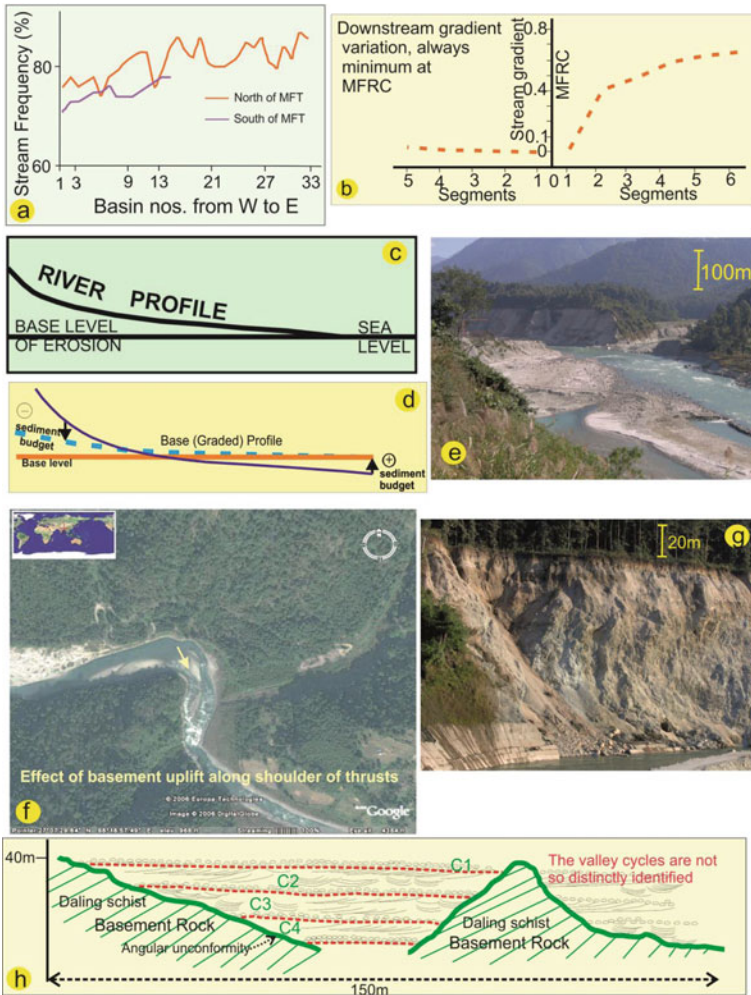
#### 4.1.6 Stream Frequency or Drainage Density

The cumulative length of all streams shown in the drainage basin of the River Tista has been measured on a mosaic of georeferenced toposheets simply by tracing the stream lengths by using GIS Platforms (Fig. 4a). The density of the drainage is given by the quotient of the cumulative length of the stream and the total drainage area. So the stream frequency or drainage density (Horton 1932, 1945; Faniran 1969) calculated based on the ratio between the total length of the streams versus the total area of the watershed basins is distinctly higher on immediate north than on the south of the MFT ridge crest (Fig. 4a).

#### 4.1.7 Longitudinal Gradient of Major Stream

The gradient in degrees ( $\theta$ ) is derived from Atan of elevation difference/horizontal distance between the two ends of a studied stretch. Derivation of gradient of the River Tista in the study area run across the MFT was conducted in successive straight channel segments from those adjacent to MFT, upstream and downstream in this way. The gradient turns out to be the minimum at the MFT ridge crest (Fig. 4b).





**Fig. 4** The curves document frequency in occurrence of first order streams in successive watershed basins adjacent to the MFT/MFRC. Note that the frequency increases from west to east on both sides of the MFT/MFRC (a). Stream gradient variation in successive straight segments (numbered 1–5 or 6), on two sides of the MFT with reference to the River Tista in the hilly-terrain. Note that minimum gradient attains at the MFT/MFRC (b). Schematic diagram showing riverine erosion–deposition equilibrium is determined by the position of base profile (c); deeper channel incision (degradation) denotes basin uplift (sediment budget positive) whereas sediment layer stack up (aggradation) delineates basin subsidence (sediment budget negative) and sediment accumulation related with base profile (d). A substantially thick aggradational succession between two thrusts, basin subsided at a greater rate and created accommodation space (e). Effect of basement uplift along shoulder of thrust: opposite stratigraphic trends would arise—river base profile drops at incision point, but rises where ponding takes place (f). Sediment filled the valley, even spilled over—erched terrace (g). Sketch derived out of field data showing fluvial sequence building pattern and flood-plain amalgamation during aggradation due to basin subsidence; Note individual channel succession marked by C-horizon and channel floor (thalweg) covered with conglomerate (h)

### 4.1.8 River Terraces

Two terraces among the multilevel terraces have been observed in the Kalijhora and Rambhi sections representing the older alluvium, which are nearly 100 and 80 m high respectively. The valley cycles (for definition see Sect. 4.2) in the terrace marked as G1–G11, are overall coarsening upward, though individual valley cycles are showing fining upward trend, which is quite unusual in the fluvial regime. The clast size is gradually increasing in younger valley cycles.

### 4.1.9 Tilted Bed

The beds within quaternary succession are tilted in two opposite directions.

### 4.1.10 Interpretation

The ruggedness of topography itself is a measure of tectonic activity in the studied hilly terrain. Less than 1.4 sinuosities in all but two of its directional segments manifest the neotectonic imprint (Bull and McFadden 1977; Keller and Pinter 1996) (Fig. 2b and c). Strahler (1952) states that the elongation ratio runs between 0.6 and 1.0 over a wide variety of climatic and geologic types. The regional slope can be derived from the size along with the elongation ratio of the watershed basins; the higher the tectonic effect greater would be the slope, in general (Figs. 2d and 3a). With continued evolution or less active tectonic processes, the elongated shape tends to evolve into a more circular shape (Bull and McFadden 1977). Relatively young drainage basins in active tectonic areas tend to be elongated in shape normal to the topographic slope of the mountain. The considerably higher ratios on the MFT scarp are the direct consequences of ground steepness. The primarily tectonically induced watershed basins, at the northern flank of the MFT, have become larger due to the integration of watersheds through progressive denudation. The distinctly more elongated and smaller watershed basins derived from the southern flank of the MFT indicate that the southern flank is steeper than the northern one and the tendency of shortening of the watershed basins adjacent to the MFT denote the neotectonic rejuvenation of the MFT ridge crest.

The tectonic imprint has been testified through the quantitative measurements of  $V_f$  on both sides of MFT speaks eloquently about the neotectonism from the threshold value of  $V_f$  (Fig. 3b) with allowing little net sedimentation and deep incision of river valley resulting due to either basement uplift or climatic shift to aridity (Blum and Tornqvist 2000). The valley incision develops successive multilevel terraces bearing oppositely directed tilted beds which can again delineate gradual upliftment of the MFT ridge crest. The loss of channel gradient must have caused widening of valley floor widths and that, in turn, explains the somewhat higher values of  $V_f$  immediate downstream of the MFT ridge crest or the southern flank of the MFT. The tectonic effect is likely to be obliterated at a faster rate in the case of a larger river like

the River Tista for its greater erosive power. Tectonic induced activity generates relief and thereby imparts an order in drainage distribution; slope determines river flow direction. Hence dendritic, trellis, parallel, semi-parallel, rectangular, and radial drainage patterns bespeak tectonic effect on the hilly terrain (Fig. 3c).

More pronounced lower ordering of stream and dominance of parallel and semi-parallel drainage pattern in the southern flank of the MFT and in consequence, drainage density is comparatively higher, 1st order streams have considerably lower gradients on the northern flank of the MFT ridge further corroborates steeper slope on its southern flank (Figs. 3d and 4a). So, the tectonic overprint is apparent. From the successive measurement of the overall stream gradient, it has been noticed that the gradient is found to attain the minimum value around the MFT (Fig. 4b). So, it denotes the upliftment of MFT and it negates the erosional activity of the river.

## 4.2 Sediments

### 4.2.1 Facies Analysis and Sequence Building

A multipronged approach with special emphasis on detailed high-resolution facies analysis, recognition of fluvial architectural elements with the temporal and spatial variability of deposits along the River Tista across a series of thrust planes merging southward have been synthesized. All together 16 facies have been identified and presented in Table 1. The proper analysis of facies of fluvial deposit also helps to understand the sequence building pattern through base-level fluctuations.

The Tista river course at the north of the MFT is quite a meandering type, controlled and restricted by canyons whereas the River Tista has become braided at the south of the MFT (Figs. 1b, 4c, d). In between the thrusts i.e. MBT and MFT, the valley was filled up with the sediment that even spilled over the valley shoulder (Fig. 4e–g). A 100 m thick pile of Tista sediment has accumulated between thrust sheets (NKT and MBT) encompassing the Dalings and the Gondwanas (Fig. 4h). Terraces, at least four in number coexist amongst which three are most spectacularly exposed through the present river channel flowing below the youngest terrace (Figs. 5a–d and 6a–c). The terraces are very large in dimension and the oldest terrace or T4 of the total vertical height of nearly 110 m, containing 11 valley cycles and nearly 75 channel cycles (Figs. 6c, d and 7a–c). Here the fluvial succession shows mainly three types of facies architectural elements (Fig. 8a–l). They are mainly of (1) Channel fills, (2) Bank attached bars, (3) Ripple flood plains. Several large-sized boulders (more than 3–4 m in dimension) of irregular shape are seen scattered in the vicinity of the River Tista valley in different terraces.

The channel fills facies exhibit lenticular bedforms, with cross-sets of pebble to sand-sized grains with fining upward sequence (Fig. 8c). Trough cross-stratification is very common (Fig. 8c). The bank attached bar facies is identified by epsilon cross-stratification (Fig. 8b and d). Sand silt alternation is common. Here sandstone unit

**Table 1** Quaternary fluvial sedimentary facies motif along the River Tista across Sevok-Rangpo transect

Facies designation	Facies name	Facies description	Facies interpretation
Gcm	Clast-supported massive gravel	The facies is characterized by haphazardly oriented clast-supported fabric. Body geometry is typical wedge-like and often the wedges pass laterally into cross-stratified sediment (Fig. 8a)	The down wedge fining and cross-stratification are attributable to reworking of scree deposits
Gcm	Clast-supported imbricated stratified gravel	Poorly sorted, clast-supported gravel having the tabular clasts imbricated though profoundly of clast imbrication may decrease laterally, in the direction of clast imbrications (Fig. 8b)	The facies represents gravel bars, possibly bank-attached. The majority of clasts constituted sliding bed load driven by flow of high velocity
Gsmx	Matrix-supported crudely cross-stratified gravel grading upward into sand	The facies bodies have flat bases, but slightly convex upward tops. Its texture is generally matrix-supported, but concentration of pebbles greater at the bottom of the beds effecting a coarse-tail frequency grading. The top part of the beds is almost entirely sandy within which faint cross-strata are often discernible. (Fig. 8c)	Upward decrease in frequency of occurrence of pebbles or in other words, upward increase in sand content may be attributed to increasing settling and infiltration of sand on waning of the flow. Such sand infiltration caused formation of sieve deposits as the water percolates rapidly downward through the under-saturated sediment (Todd 1989). They are coupled together spatially, might have been deposited within channels, the relatively coarser sediments on the bars and the finer ones within the interbar small channels. Repeated upward transitions from trough cross-strata to planar laminae within individual channel-fills suggest ephemeral nature of the river (Olsen 1989)

(continued)

Table 1 (continued)

Facies designation	Facies name	Facies description	Facies interpretation
Gmg	Normally graded poorly sorted gravel	This facies is dominated by matrix content but the base of the bed defined as clast-supported and clast-size decreases gradually towards up of the section (Fig. 8c)	The fluidal flow created from debris flow
Gmx	Cross-stratified clast to matrix-supported gravel	The facies is characterized by clast to matrix-supported gravel with steeply imbricated pebbles, manifested by cross-strata (Fig. 8d)	This facies may be depicted as the bar within channel thalweg
Gmm	Matrix-supported massive gravel	Its body geometry is lenticular, generally having flat base and convex top, but some having concave-up channel-form too. In this matrix-supported conglomerate the grain-size distribution is broadly bimodal, but both the pebble and sand fractions are poorly sorted. The clasts are randomly distributed and oriented, some standing almost vertical (Fig. 8e)	The matrix-supported fabric with chaotically arranged clasts, locally subvertical, points to high matrix strength of the parent flow that froze instantaneously as its shear strength exceeded shear stress applied on it (Blair and McPherson 1994). It is safe to assume that the flow had been a debris flow, at least, immediately prior to deposition

(continued)

Table 1 (continued)

Facies designation	Facies name	Facies description	Facies interpretation
Sm	Massive pebbly sand	This sand dominantly massive or faintly cross-stratified and have sparsely distributed floating over-sized pebbles (Fig. 8e-g)	The facies is a likely product of flash flood
SGt	Trough x-stratified pebbly sand	It is a poorly sorted coarse to medium grained sandstone. Individual facies units are internally characterized by a single co-set of trough cross-strata. They are broadly lenticular in shape having sharp bases with pebble tending to be concave-up. (Fig. 8c)	Relatively thinner isolated channel-fills, therefore, indicate shallowing of the channels as the distance from the main channels increased
Sr	Compound x-stratified sand	Pebble-free sandstone, coarse-grained and poorly sorted. The large but low angle cross-strata enclosed small scale steeper cross-strata; both have roughly the same direction of inclination. The facies bodies generally have flat bases, but discernibly convex upward tops (Fig. 8h)	The facies apparently represents longitudinal bars
Sh	Planar laminated sand	Planar laminated sand with sheet-like or tabular geometry generally overlying cross-stratified sandy gravel and gray mud interbedded silt with sand and the sandy beds have sharp lower contact with gutters (Fig. 8i)	Sheet flow product, possibly generated by reworking of bar-top sediment during falling water stage

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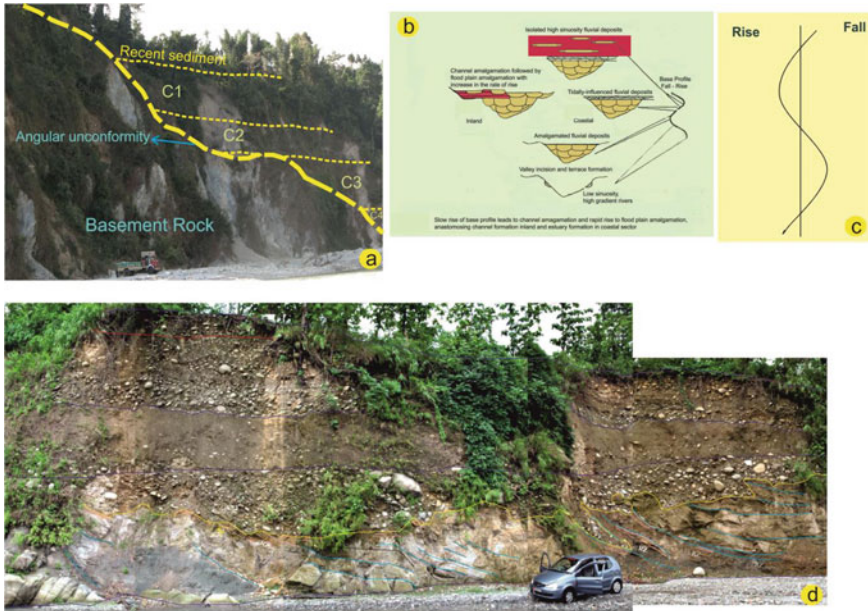
Table 1 (continued)

Facies designation	Facies name	Facies description	Facies interpretation
Shg	Planar laminated graded sand	This facies is characterized by sets of planar/low angle laminae, locally topped by small scale ripple laminae. Each couplet are encased below and above by reddish silt/mud laminae. The bed geometry is laterally wedging with flat base (Fig. 8j)	This facies is obviously a product of a high flow shear. Coarse grain-size suggests it can be of channel-base origin, either a linguoid bar or a cross-channel bar. However, atop a bar it suggests reworking of already settled sediment, winnowing out the fines, during low water stage
Sl	Planar laminated fine-grained sand periodically interrupted by silt stringers	This facies, very coarse grained within the sand grade, is characterized by sheet-like geometry, and laterally discontinuous, crude planar laminae inside. This facies in majority of cases overlies a major erosion surface. Locally, however, a relatively finer grained counterpart has been seen on top of bars (Fig. 8i)	This facies possibly formed close to the channel bank as the fine grain size of the sediment suggests. The body geometry, internal structure and intermittent inclined mud laminae cumulatively identifies the facies as of levee
St	Trough cross-stratified sand	This facies characterized by trough co-sets in a poorly sorted sandstone whose average grain size is smaller than that of longitudinal bar facies with which they are closely associated. The bed geometry is lenticular with bases commonly distinctively concave upward and top flat. (Fig. 8d)	The facies presumably represents channel fill sediments, between bars or between banks. The facies geometry corroborates its contention. The upward concomitant reduction in grain size with co-set thickness is possibly due to gradual reduction in depositional slope with channel filling

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Table 1 (continued)

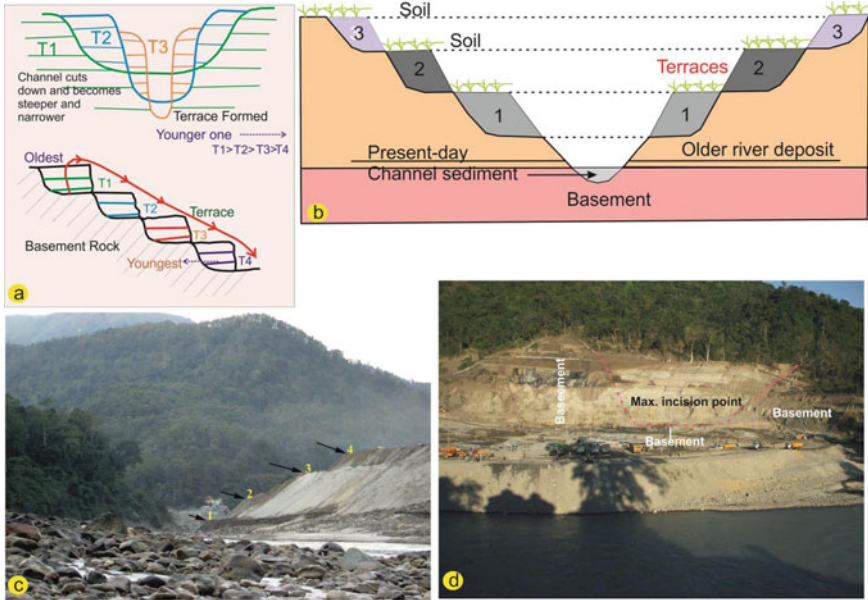
Facies designation	Facies name	Facies description	Facies interpretation
Sp	Tabular cross-stratified sand	This facies is internally characterized by normally graded tabular cross-strata. Cross-strata azimuths are at high angle between the sand and the encasing gravel deposits (Fig. 8d, k, l)	The geometry of the beds reveals identity of the facies as bars. Because of the tabular nature of the cross-strata, the bars are likely to be bank-attached in braided river
Fcl	Climbing Ripple laminated silt	This facies is characterized by a set of climbing ripples in sand. The small scale cross strata migrate in direction opposite to the inclination of the set boundaries enclosing them. The bed geometry is indeterminable (lenticular?). (Fig. 8k)	Since the ripple migrates opposite to the direction of the set boundaries cross-strata, the ripples can be interpreted to have back-flow origin. However, laterally uniform thickness of the sets of small scale cross-strata defies this contention. The more likely interpretation is that ripples climbed along upstream face of a bar, possibly longitudinal ones. The accretion on the upstream face of a longitudinal bar indicates relatively high rate of sedimentation
Frl	Ripple laminated silt and mud	This facies is defined by mud bodies having tabular geometry and also characterized by fine planar laminae. Rootlets often concentrate along the top surfaces of the beds. Multiple units of this facies may stack up vertically (Fig. 8f, k)	The facies elements along with the presence of root-casts; presumably denote it as the low energetic product of overbank deposit. Preferred concentration of iron encrustation suggests existence of omission surfaces which points to intervals between successive floods. Consequently, the vertical stacking of beds denotes basin subsidence



**Fig. 5** Field photograph showing aggradational record points to basin subsidence that followed, sediment filled the valley as well as negative sedimentation budget and the angular unconformity (yellow dotted line) placed between basement rock (Daling Schist) and channel sediments (a). Slow rise of base profile leads to channel amalgamation and rapid rise to flood plain (high accommodation space) amalgamation. Schematic diagram showing fluvial sequence building pattern changes with base profile fluctuations (b). A sinuous curve representing the record of base profile fluctuations (c). The Quaternary aggradational fluvial sediments overlies on the Siwalik sandstone, the contact (yellow) being very sharp but highly irregular. The Siwaliks is constituted by imbricated thrust slivers (blue bordered) at variable angles with the contact. The thrust slivers, at places, are topped by fragments of oxidized bands encrusted by iron (pink bordered) immediately overlying rootlet zones (RZ), together probably representing an unconformity (d)

trapped along parallel-sided coarse sand to finer material. The bank attached bars are usually made up of planar laminated beds (Fig. 8i, j and l). But other bar deposits occur as patches and are characterized by rippled flats (Fig. 8f and k).

Thick sand bodies of lenticular geometry juxtaposed one upon another laterally and vertically. Lenticular channel bodies floored by small pebbles are stacked up one over another and laterally variable thickness is defined as channel cycle and their succession is intermittently intercepted by large pebble conglomerates of comparatively greater lateral persistence defining the valley cycles which consist of various types of crystalline rocks (Figs. 7a–c, 9a–c). Mainly they comprise the clasts of (a) White crystalline granitic gneiss and Para gneisses of Paro/Kanchanjhanga/Darjeeling gneisses, (b) Daling schist, (c) Arkosic Gondwana Sandstone, (d) Quartzite of Gondwana, (e) Coarse and fine-grained Siwalik Sandstone. Each of the valley cycles is an individually fining upward sequence (Fig. 7c). But a thick unit of overall coarsening upward with individual fining upward valley

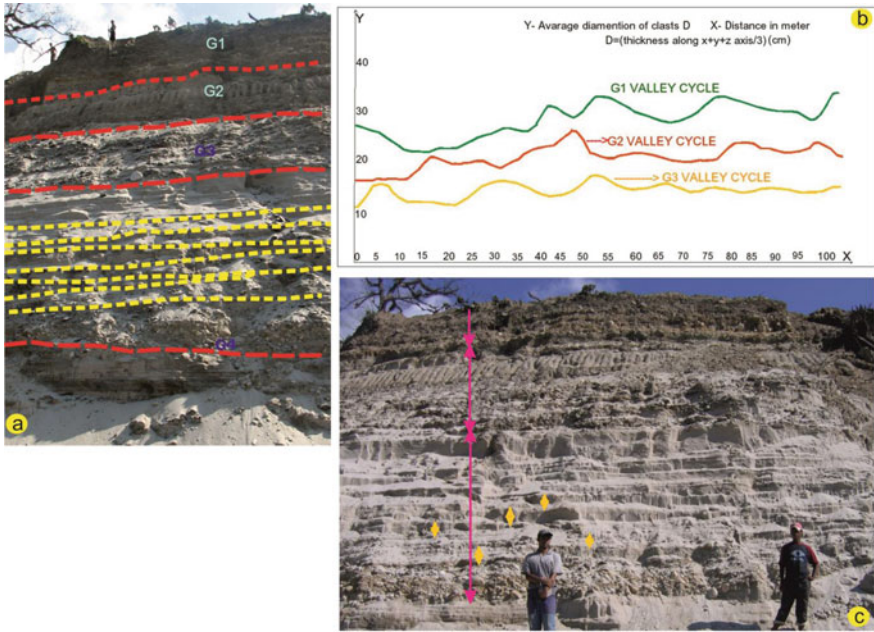


**Fig. 6** Drop in base profile tends to remove the previous record of fluvial deposition, if there is any. Residues may, however, be retained at the channel margin because the channel becomes increasingly narrower as it turns deeper, step by step. Terraces are formed, successive younger ones at lower levels (a). The schematic diagram showing the river cannibalizes its own sediments, digs and may penetrate the basement as well (b). Field photograph showing discrete terraces of several generations record the course of basin uplift (c). Valley (red dotted line) incised to the level of maximum incision point during previous basement uplift phase. The present river channel is incised all through the sediment pile and into the Gondwana-Siwalik basement (d)

cycle is very well exposed along the course of River Tista (Fig. 7a). In all the places alternate appearance of clast supported gravel-boulder beds are identified as similar to the first-order cycle while gravel-pebble-coarse to moderate sand fill cycles are 2nd order cycle, though they are genetically unrelated. But overall thinning of valley cycles up the succession has been distinctly recognized (Figs. 7a and 9a). Maximum clast size in valley floor conglomerates increases up the succession and the hallmark of sediment source is most apparent in clast composition. A progressive increment in contribution from crystalline rocks reflects a temporal increase (Fig. 9b). The laterally extensive conspicuous concentration of soft deformation structures like fluid-escape, single-lobated, multi-lobated, and imbricated convolutes, contorted laminae, and load structures are found within the sediment piles.

#### 4.2.2 Interpretation

The fluvial sediment cannot be part of the geological record unless going beneath the base level of erosion; thereby removing the previous record of fluvial deposition, if

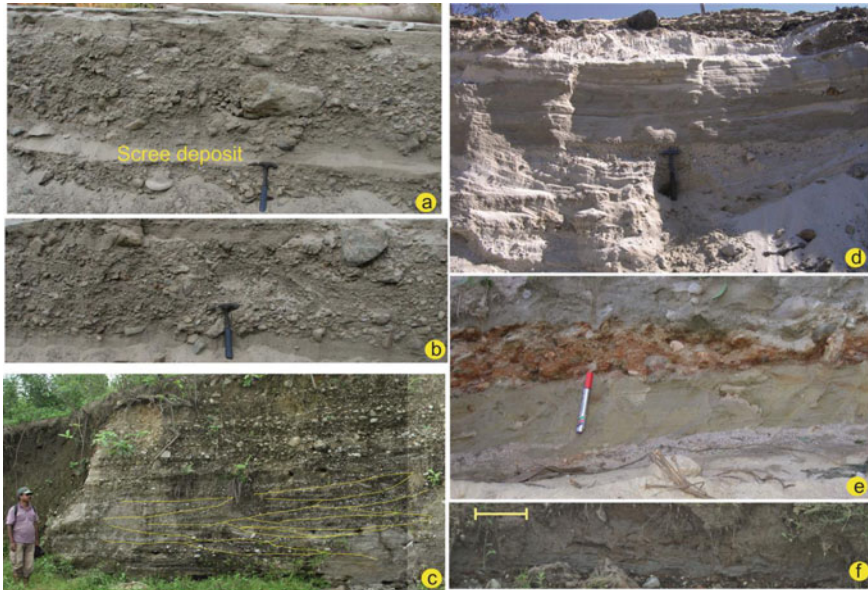


**Fig. 7** Valley cycle overall coarsening upward and individual cycles showing fining upward trend; individual valley cycle (red dotted line) and channel cycle (yellow dotted line) (a). Graphical representation of upward gradual increase in maximum clast size across successive valley cycles (G1–G3) also showing laterally persisting uniform clast size (b). Valley cycle (marked with magenta colour), Channel cycle (marked with yellow colour) in Quaternary Succession at Kalijhora and upward thinning of the valley cycles defined by these large pebble gravel beds, however, indicates progressive decrease in the rate of accommodation space creation (c)

there is any. Records of drop, in base profile, are generally very cryptic and difficult to recognize, as terraces are obliterated during aggradation with the rise of the base profile. The fluvial stratigraphic architecture is thus biased aggradational sequence or rise in base profile. Channel sands accumulated within depression have a greater chance of preservation (Fig. 5b and c).

On the other hand, the riverine erosional-depositional sequence in regional scale is solely determined by the position of a river profile and base profile, (Fig. 4c and d). The rate of deposition mainly depends on the gradient or slope characteristics. But the erosion is sometimes controlled by climatic conditions; as the slope is also controlled by tectonic activities or movements. The Tista river course at the north of the MFT is quite a meandering type, resulting in a negative sediment budget (Figs. 1b, 4c and d). In the following phase of basin subsidence between the thrusts i.e. MBT and MFT, the valley was filled up even with the spilled over sediment (Fig. 4e and f). However, on the upstream of thrust planes basin subsidence creates accommodation space at an enhanced rate in the pocket within hilly terrain where river base profile sufficiently rose to create accommodation space (cf. Blum and





**Fig. 8** Clast-supported massive gravel; scree deposits (a). Clast supported imbricated stratified gravel and upper part of the succession showing protrusion of vertically large sized gravel (b). Matrix-supported crudely cross-stratified gravel grading upward into sand and lower part of the deposits showing trough cross-stratified pebbly sand (c). Cross-stratified clast to matrix-supported gravel and also showing tabular cross-stratified sand (d). Matrix-supported massive gravel (e). Ripple laminated silt and mud (f). Massive pebbly sand (g). Compound cross-stratified sand (h). Planar laminated sand; Gray mud interbedded silt with sand and the sandy beds have sharp lower contact with gutters (i). Planar laminated graded sand (j). Climbing Ripple laminated silt (k). Planar laminated fine-grained sand periodically interrupted by silt stringers (l). Bar = 30 cm

Tornqvist 2000), cause ponding and sediment trapping. A thick pile of accumulation of sediment (100 m) in between thrust sheets (NKT and MBT) indicates the tectonic movement or upliftment is denoted by such a huge pile of sediment that could not accumulate over the base profile. But, here the sediment has accommodated such a huge height (100 m), which is now above the base level of erosion but once in the recent past, it was below the base unit of erosion (Fig. 6b–d). So, this can be sought again the source was uplifted or the accumulation site was subsided (Fig. 5a and d). Actually, it is more appropriate to assure that the accumulation site once gets subsided, forming an aggradational fluvial sequence of substantial thickness which has been grown up (Fig. 4e–h) due to the gradual increment in valley width with the progressive rise of base profile and depositing huge sediment pile in isolated pockets bounded between the thrusts namely MBT and MFT which is subjected to form the piggyback basins with rapid basin subsidence (Figs. 1b and 4f).

At a point in time, the trend was reversed and the basement of the depositional site started to rise (Fig. 4e–g). So, the sediment budget is positive and the pattern of the



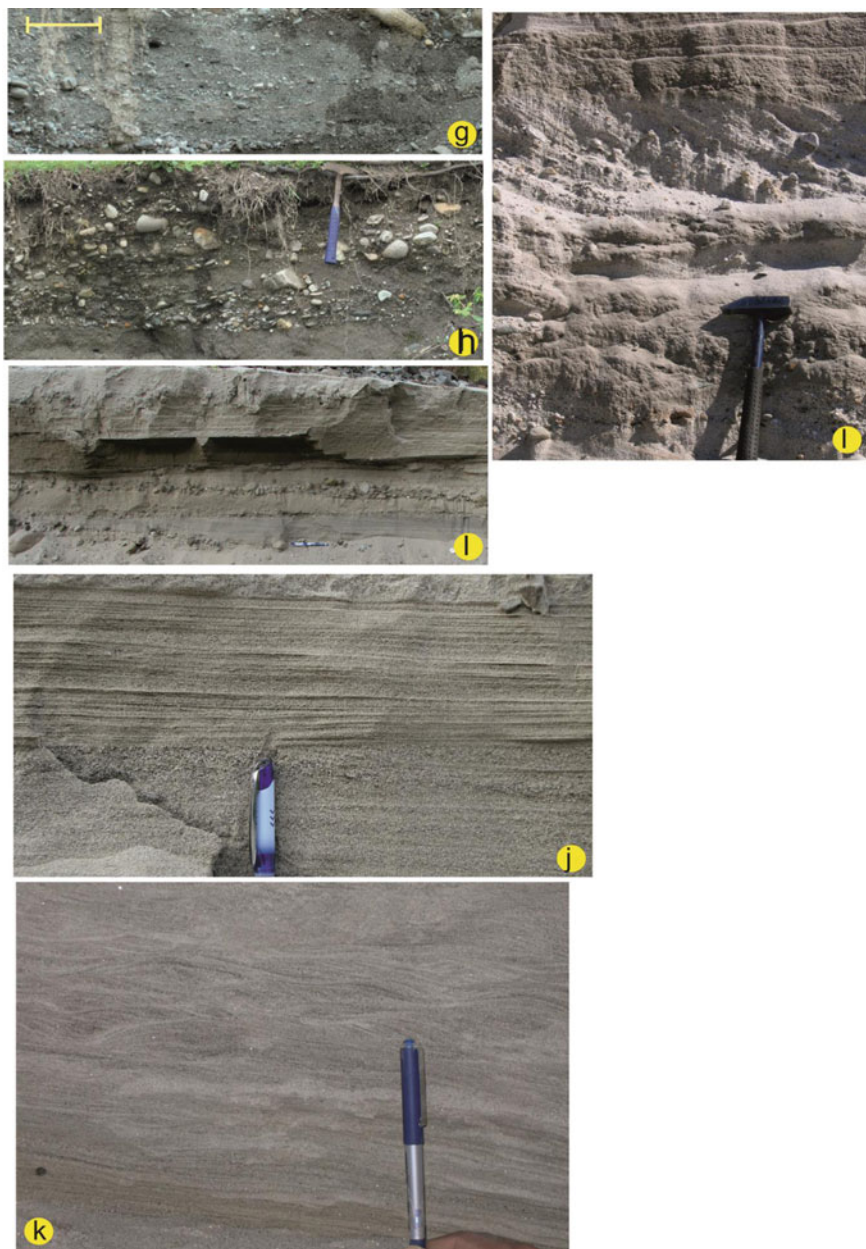
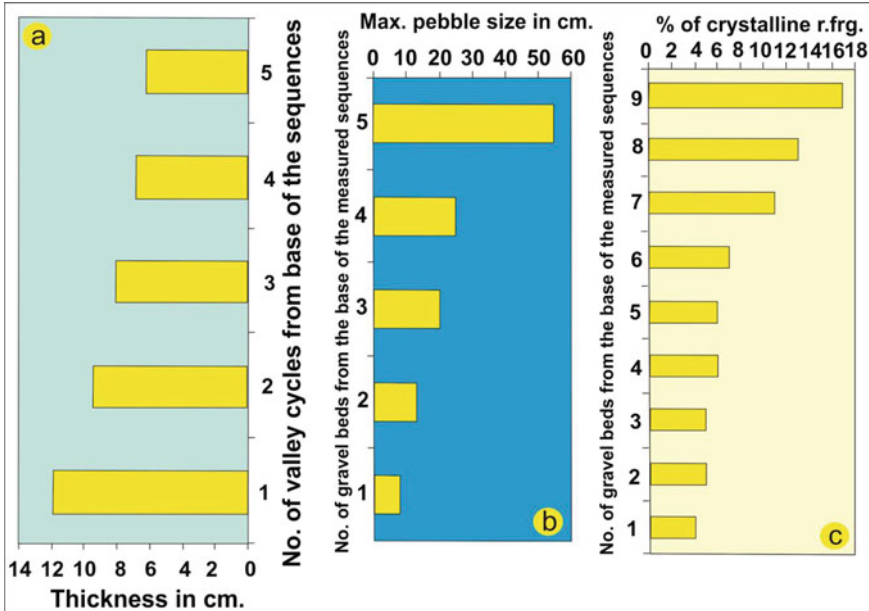


Fig. 8 (continued)



**Fig. 9** Up section decrease in valley cycle thickness indicate progressive decrease in the rate of subsidence of the small basin reducing the accommodation space (a). Up section increase in maximum clast size in successive coarser gravel beds implying upliftment (b). Up section increase in percentage of crystalline rock fragments in successive coarser gravel beds indicate progressive uplift of crystalline basement far north (c)

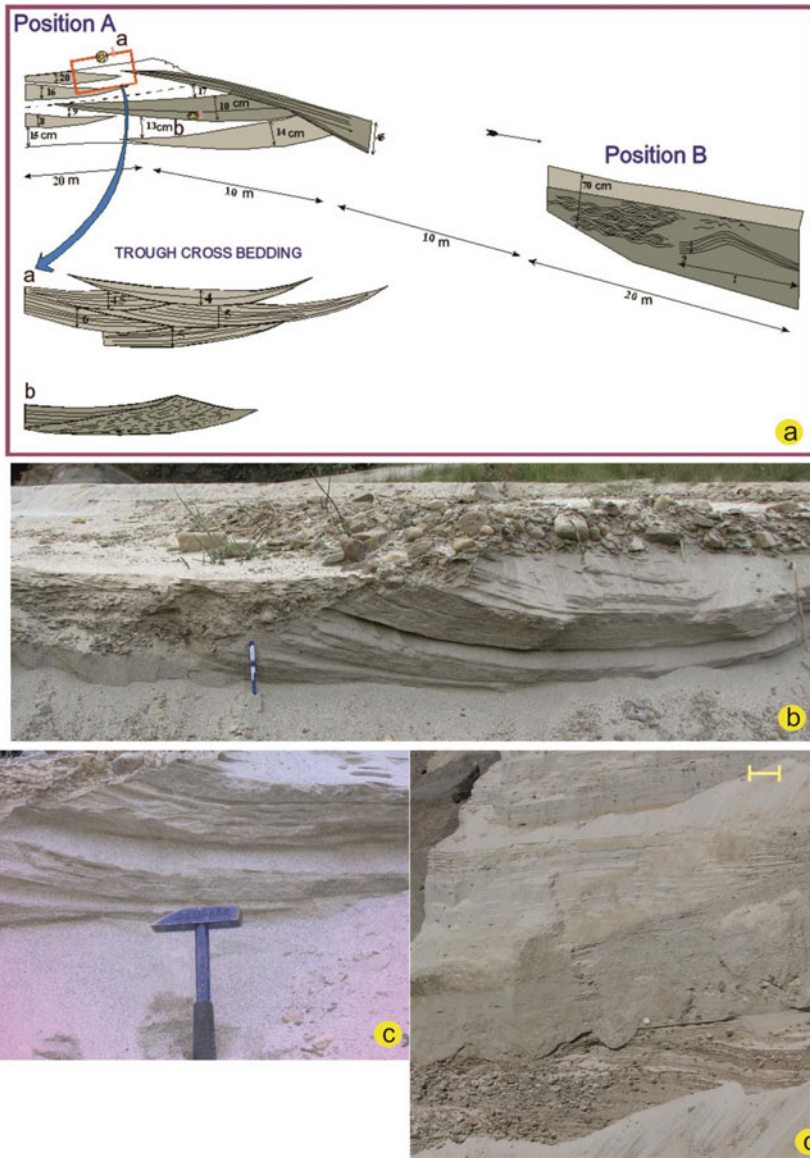
River Tista has become braided at the south of the MFT (Figs. 1b and 4f). Again, it has got uplifted forming degradation with fall in base profile so, the river cannibalized its own accumulated sediment, digs and may penetrate the basement as well (Figs. 5a and d, 6b–d); however, may be retained at the channel margins, and on the other hand, valley walls get eroded and terraces formed due to degradation at the southern flank of the MFT. More so over, it happened in more than one generating several terraces in Sevok-Rangpo transect along the River Tista onto the Gondwana basement rock (Fig. 6c and d). The absence of in-situ exposures of these rocks in the nearby vicinity, which are exposed beyond Boundary Thrust delineates upliftment. The deep concave-up geometry of the basement sediment contact indicates channel incision in a previous phase of basement uplift (Fig. 6d). Thinning of valley cycles up the succession indicates a gradual drop in the rate of base profile rise creating a progressively lesser and lesser amount of accommodation space (Figs. 7a and 9a). Consequently, an increase in maximum clast size in valley floor conglomerates renders the succession coarsening upward and this unusual trend of fluvial aggradations further support the gradual uplift of the source area (Figs. 7a and 9a). But the overall coarsening up successions indicates a faster effect of basement uplift along the shoulder of thrusts (Fig. 9b). In consonance with this, more distant sources contributed to a greater frequency in occurrence of plutonic rock clasts in this large pebble population records

progressive uplift of the granitic terrain far upstream (Fig. 9c), besides the rate of erosion enhanced at source through time.

The deformed beds oppositely directed and laterally persistent have been found in Quaternary sediments that may be formed due to tectonic jerking (Fig. 10a–d). The same manifestation has been further corroborated by soft deformational structures like contorted laminae, single and multi-lobated convolute structure, pseudonodule, load-structures/sagging, and fluid-escape structures, within the same sediment contents (Fig. 11a–e).

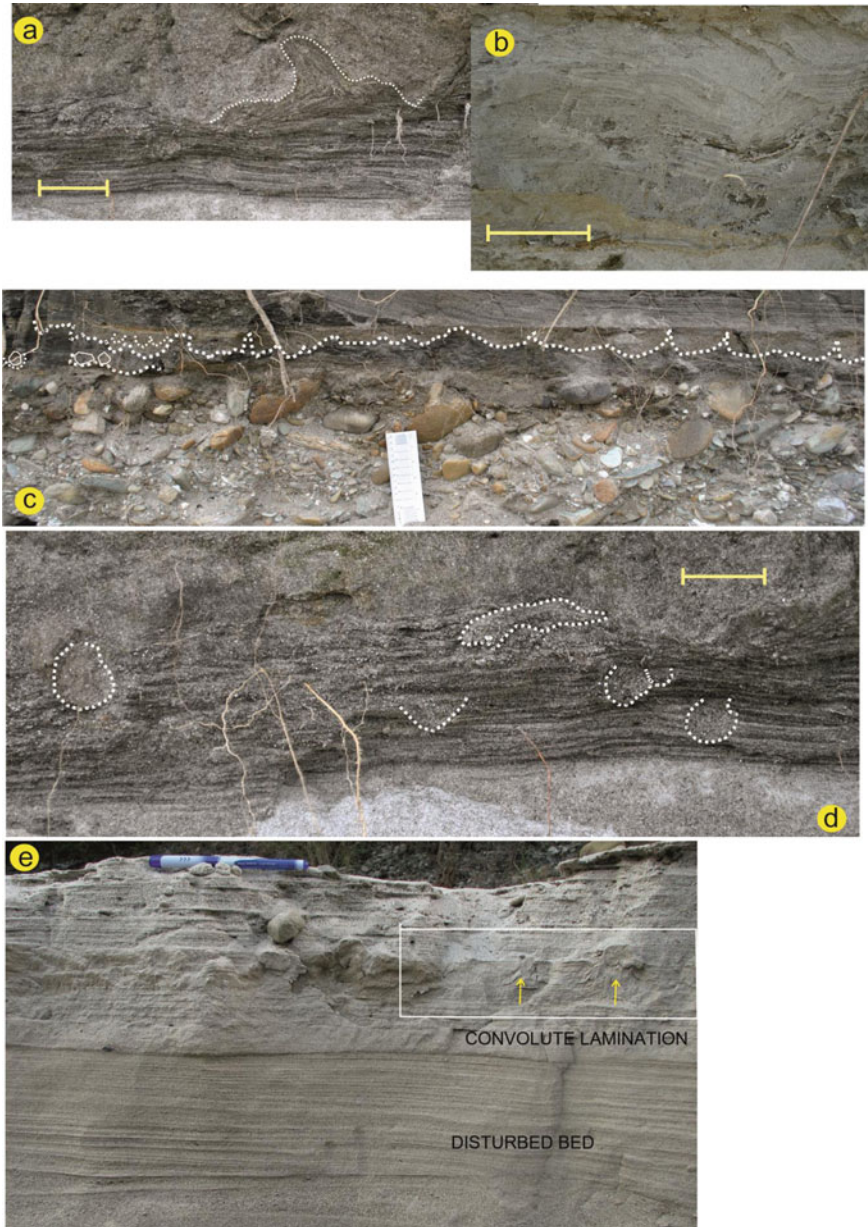
## 5 Conclusion

The documentations attest to the imprints of neotectonism along the River Tista along the Sevoke-Rangpo transect. In the topography, river valley configurations, watershed basin characters, lateral variations in drainage patterns in general, sediment characters, and records of repeated subsidence at places testimony to neotectonics continue in the Quaternary period. The entire study area achieves a minimum channel gradient on top of the ridge of MFT documenting its uplift. Basement uplift causing migration of base profile below the depositional surface compels the river to incise deeper. In consequence, the river valley becomes progressively narrower leaving out successive residual terraces at its margins, till the stratigraphic trend reverses with subsidence of the basin. The migration of the base profile above the depositional surface in consequence of the subsidence of the basin induces aggradation of river sediment and obliteration of the previously formed terraces during its course. Aggradational fluvial succession is fining upward even when the rate of rising of the base profile is steady; nonetheless, increasing rate leads to a transition from low to high accommodation stage, channel amalgamation rapidly giving way to flood plain amalgamation. Large pebble gravel beds intercepting the pile with increasing frequency and maximum clast size with the occurrence of plutonic rock clasts point to source uplift. Upward thinning of the valley cycles defined by these large pebble gravel beds, however, indicates a progressive decrease in the rate of accommodation space creation in the small basin and incising through a number of terraces of successive generations implies that eventual switching over of aggradation to degradation in consequence to neotectonic basin-floor uplift.



**Fig. 10** Diagram traced from field exposure showing tilted and deformed beds, oppositely directed within terraces; a panel of tilted beds in the two given positions shown in the diagram: **Position A** (orientation of bed— $342^{\circ}/15^{\circ}$  W orientation of cross-lamination— $15^{\circ}/10^{\circ}$   $285^{\circ}$ ) and **Position B** (orientation of bed— $20^{\circ}/10^{\circ}$   $110^{\circ}$  orientation of cross-lamination— $30^{\circ}/17^{\circ}$   $120^{\circ}$ ) (a). Warped and tilted beds in fluvial terrace along the River Tista in Sevok-Rangpo transect near Andherijhora (b). Field photograph showing ripple laminae with mud drape followed by massive and deformed beds (c). As the top most part of the deformed layer is completely homogenous in nature, it is unlikely that the downward bending of the laminae below is the result of loading and cross stratified nature of the sandy unit over major erosional surface (d)





**Fig. 11** Various types of Soft-deformational structures along the River Tista within Quaternary sediments as imprint of tectonic jerking: Fluid escape (a). Contorted laminae (b). Single-lobated and multi-lobated convolute (c). Pseudonodule and sagging (d). Deformed laminae and convolute laminanae with fluid-escape structure (marked by yellow arrow) (e). Yellow bar in the diagram depicts 30 cm

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