Evolution of landscape in a piedmont section of Eastern Himalayan foothills along India-Bhutan border: A tectono-geomorphic perspective

Chandreyee CHAKRABARTI GOSWAMI[1*] https://orcid.org/0000-0002-1059-7766;
e-mail: chandreyee.chakraborty@gmail.com

Prasun JANA[2] https://orcid.org/0000-0002-7813-2404; e-mail: prasun_456@rediffmail.com

John C WEBER[3] https://orcid.org/0000-0002-8555-3661; e-mail: weberj@gvsu.edu

** Corresponding author*

1 Department of Geology, University of Calcutta, 35, Ballygunge Circular Road, Kolkata 700019, India

2 Geological Survey of India, Northern Region, Sector E, Lucknow 226024, India

3 Department of Geology, Grand Valley State University, 1 Campus Drive, Allendale, MI 49401 USA

Citation: Chakrabarti Goswami C, Jana P, Weber JC (2019) Evolution of landscape in a piedmont section of Eastern Himalayan foothills along India-Bhutan border: A tectono-geomorphic perspective. Journal of Mountain Science 16(12). https://doi.org/10.1007/s11629-018-5208-7

Abstract: The present study area involves part of a deformed coalesced fan located along the Himalayan Frontal Thrust (HFT) on the east of river Tista near the India-Bhutan border. The area is marked by two spectacular E-W trending south-sloping scarps namely the Matiali (ca. 60 m) and Chalsa (ca. 90 m) Scarps and a north-sloping E-W trending Thaljhora (ca. 80 m) Scarp. Our work comprises of a comparative study of geomorphology and geologic history in the adjacent interfluves of Jaldhaka-Gathia and Neora-Murti rivers to understand the tectonic history of the area. We mapped the Jaldhaka-Gathia river interfluve at a 1:25,000 scale and report a hitherto unidentified northerly sloping small scarp of ca. 5m height named the Nagrakata Scarp. This scarp was identified using satellite images, DEMs, and total station survey. We interpret that the two north-sloping, E-W trending scarps (Thaljhora and Nagrakata Scarps) are manifestations of steep limbs of anticlines over blind south-dipping back thrusts. Together they form a wrinkle-ridge pair behind the north-dipping HFT, which is manifested by south-sloping Chalsa Scarp. We propose a plausible geomorphic model interpreting that deformation along the small fan in the Jaldhaka-Gathia interfluves is younger compared to fan deposition and deformation in the adjacent Mal-Murti interfluve. The most recent geomorphology of the Jaldhaka-Gathia interfluve is controlled by tectonism associated with the thrust below the Nagrakata Scarp where the youngest deformation episode is recorded to at around ~6 ka and is likely related to motion on a splay off of the thrust beneath the Thaljhora Scarp.

Keywords: Eastern Himalayas; Thaljhora Scarp; Nagrakata Scarp; Drainage; Back-thrust; Wrinkle-ridge

Received: 11-Sep-2018
1st Revision: 13-Mar-2019
2nd Revision: 09-Jun-2019
Accepted: 15-Aug-2019

Introduction

Detailed geological research in the eastern Himalaya lags behind that of the western Himalayas due to difficult logistics, heavy rainfall, and scanty exposures. Though systematic mapping of the Eastern Himalayas in India and Bhutan

(1:50,000 scale) has been done by the Geological Survey of India (GSI), this area still demands more critical and detailed scientific study. Most of the comprehensive geological studies in eastern Himalayas are restricted to the geology of the Higher and Lesser Himalaya, with only very limited work on the active geological structures in the foothills which record deformation of Quaternary deposits (Long et al. 2011; Saha 2013; Basu 2013). Deformation and uplift of the Himalayas has been active in the Quaternary. This deformation controls many present and characteristic geomorphic features, such as tectonic scarps formed by active thrust faulting on the major thrusts of the Himalayas, along with transverse scarps formed by active normal and strike slip faults at high angles to the active thrust faults.

The map traces of some of these faults make cuspate-lobate patterns suggesting the possibility of differential thrust fault growth or oroclinal bending (e.g., Ray 2006). The Himalayan front itself is also sinuous in both the western and eastern parts. Orogen-scale curvature at an intermediate scale is expressed as salients and recesses. The salient–re-entrant transitions are typically manifestations of lateral or oblique ramps, or tear faults (Mukul et al. 2014). Salients are normally associated with mountain fronts defined by frontal imbricate faults, whereas recesses are open to the foreland. The morphology of Himalayan salients, recesses, and associated cross-structures reflect variations in the deformation kinematics along the length of the Himalayan arc over space and time.

In the foothills of the frontal Himalaya, growing anticlines and the Himalayan Frontal Thrust (HFT) accommodate a significant part of the total plate convergence (Delcaillau 1992; Lave´ and Avouac 2000). For example, in the area east of Tista River, 11.1±1.5 mm/yr out of a total of ~40 mm/yr (https://www.unavco.org/software/geodetic-utilities/plate-motion-calculator) of shortening is taken up across a set of four E–W trending thrust faults: the Gorubathan, Matiali, Chalsa and Baradighi Faults (Mullick et al. 2009).

In addition to the northerly dipping Himalayan regional thrusts, there are also south-dipping back-thrusts in places, such as in the Sarpang re-entrant (Dasgupta et al. 2013; Dutta Gupta et al. 2017). When anticlines grow over a blind thrust fault as a result of both flexural slip folding of near-surface strata and the nucleation and growth of *en echelon* arrays of back-thrust faults, wrinkle ridge structures form as a geomorphic expression of that phenomena (Schultz 2000) Wrinkle ridges occur in two principal forms: 1) broad ridge, kilometers wide and meters high; and 2) sinuous, discontinuous, or echelon crenulations (“wrinkles”) located on or near the main wrinkle ridge (Schultz 2000).

One major recess in the Darjeeling-Sikkim Himalaya located in the east of Tista River from the Gish River to Diana River; this area is segmented by the Chel-Mal, Mal-Murti and Jaldhaka-Gathia interfluves. Since the pioneering work of Nakata (1972), the area between the Chel and Murti River has attracted the attention of many workers, and considerable work has also been done on the neotectonics of Chalsa Fault and the Gish transverse zone (Mukul et al 2005; Mullick et al. 2009; Kar et al. 2014; Goswami Chakrabarti et al. 2013, 2014; Kumar et al. 2011). But in the east of Jaldhaka River, within Jaldhaka-Gathia interfluve, where the Chalsa Fault scarp fades out, remains less thoroughly studied. Our study focuses on reconstructing the Quaternary tectonics in the Jaldhaka-Gathia and Mal-Murti interfluve regions from a careful study of the the geomorphology and geology. We present a comprehensive study of the Gorubathan/Jaldhaka recess from the Mal River to the Gathia River. The study area includes both the Mal-Murti interfluve and less studied Jaldhaka-Gathia interfluve.

1 Material and Methods

1.1 Geomorphology and active structures in Jaldhaka Recess

The 2400 km long arcuate Himalayan front is sinuous and is characterised by many salients and recesses in both the western and eastern Himalaya (Figure 1). The study area is located in a small recess in the Eastern Himalayan foothills named the Gorubathan (Mukul et al. 2014) or alternatively, the Jaldhaka recess (Dasgupta et al. 2013). The Jaldhaka recess occurs east of the Gish Transverse Zone (GTZ). This recess includes the development

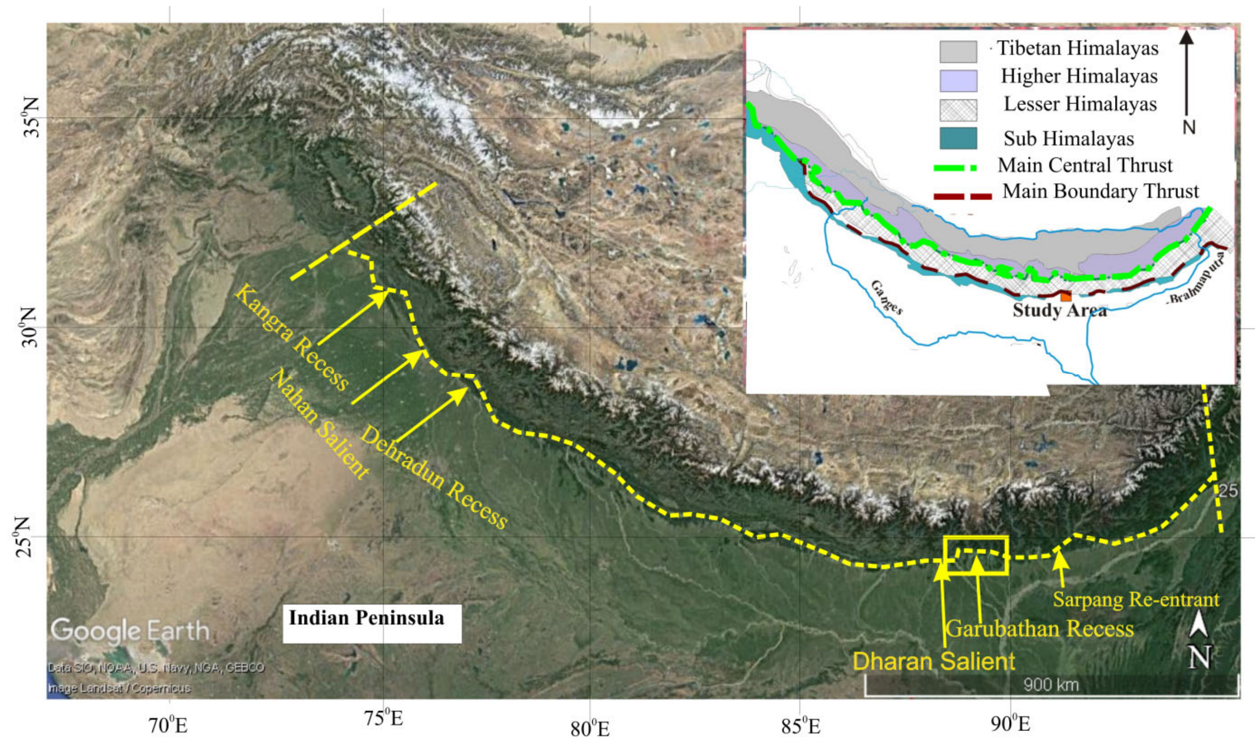

Figure 1 Map showing the sinuous front of the Himalayan arc and salients and recesses separated by transition zones (yellow dashed line and labels) on a Google Earth image. The yellow rectangle denotes the Gorubathan/Jaldhaka recess, in which the study area is located. Inset: Major tectonic subdivisions of the Himalayas (after Gansser 1964).

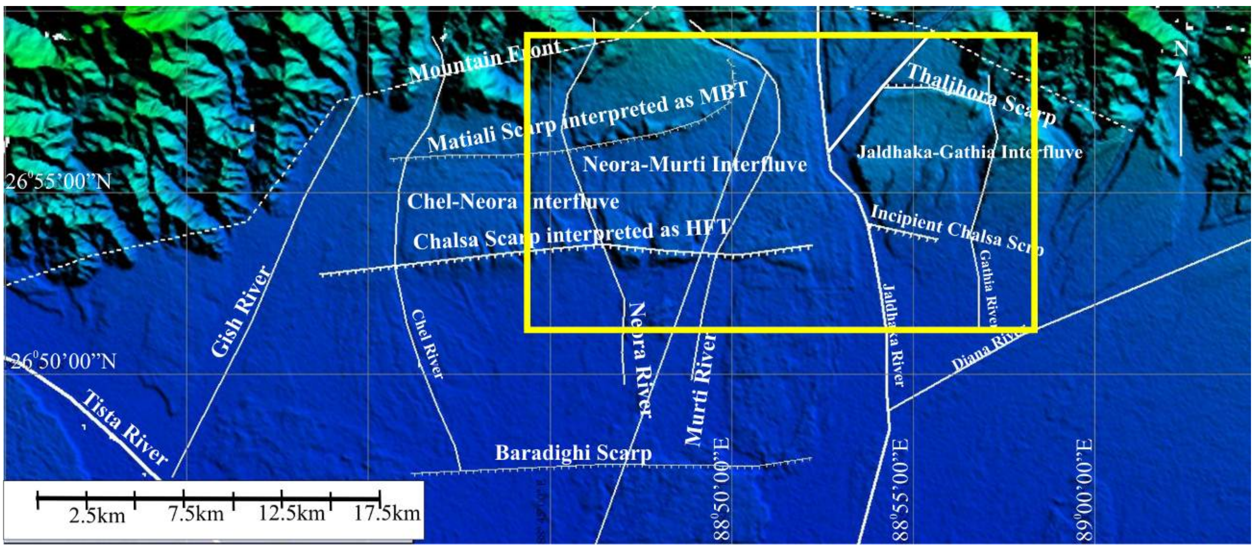

Figure 2 Positions of major rivers and structural lineaments in the Himalayan front piedmont zone between the Tista and Diana Rivers shown on a Cartosat 1 DEM base map. The yellow rectangle represents the present study area as well as that of Nakata (1972).

of a wide piedmont with deformed alluvial fans and river terraces. From the Chel River to the Diana River, sharp, south-facing and north-facing scarps trending E-W within the piedmont parallel the major Himalayan thrusts. One such prominent north-sloping scarp, east of Jaldhaka River was identified and named the Thaljhora Scarp by Nakata (1972). Orthogonally, transverse lineaments are developed, and through which antecedent major drainages flow (Figure 2). One such prominent north-sloping scarp, east of the Jaldhaka River was identified and named as the

Thaljhora Scarp by Nakata (1972).

The surface geology east of GTZ, which is marked at surface by the Gish River, is made up of Quaternary sediments forming part of a large, coalesced alluvial fan that extends from the Chel to Daina Rivers (Figure 2). This coalesced fan can be divided into three sub-areas: the Chel-Neora interfluve, Neora-Murti interfluve, and the Jaldhaka-Diana interfluve. The Jaldhaka-Diana interfluve is much less studied than the adjoining Neora-Murti interfluve. The major fan surfaces of this Jaldhaka recess were identified and mapped as Baikunthapur, Rangamati, Matiali, and Samsing surfaces, from south to north, and the river terraces as the higher, middle and lower terraces (Nakata 1989; Das and Chattopadhyay 1993a, b; Guha et al. 2007). Earlier workers did not differentiate fan surfaces in the Jaldhaka-Diana interfluve area from those of the Mal-Murti interfluve. In recent studies, the fan surfaces in the Chel-Jaldhaka interfluve have been mapped and interpreted as depositional fan surfaces and river terraces (Goswami Chakraborty et al. 2013; Kar et al. 2014; Ghosh et al. 2015). The south-sloping alluvial fans are interrupted by three E-W trending scarps. Among these, in the Chel-Murti interfluve, two are south-sloping and are named as Matiali (northern) and Chalsa (southern) scarps. The third scarp is north-sloping, is named as Thaljhora Scarp, and lies in the Jaldhaka-Gathia River interfluve (Figures 2, 3).

The geology of the Jaldhaka recess is dominated by post-Siwalik fluvial and fan deposits characterised by coarsening-upward sediments that form a number of small, adjacent fans which coexist with large Tista mega-fan (Kar et al. 2014). Many previous workers have suggested that Himalayan tectonics controls the geological and geomorphological evolution of this area (Nakata 1972, 1989; Guha et al. 2007; Goswami Chakrabarti et al. 2012, 2013). These fan surfaces are dissected by E-W trending tectonic scarps with ages between 33 ka and 22 ka (Guha et al. 2007). Recent studies have shown that the host fans started growing prior to ~171 ka and up to 72ka. Fan deposition was followed by degradation and deformation (Singh et al. 2016). The aggradational alluvial fans formed primarily due to climatic controls and were subsequently tectonically deformed to form the present day geomorphology (Goswami Chakrabarti et al. 2014). However, a second opinion exists which suggests that this fan–terrace system was controlled primarily by the fluctuation of the Asian summer monsoon rather than by a significant influence of Himalayan tectonics (Kar et al. 2014). A recent palynological study, possibly supporting this second opinion, shows cyclic weakening and strengthening of monsoon in last ~50 ka in this region (Ghosh et al. 2015). The south-sloping alluvial fans are interrupted by three E-W trending scarps. These include the Matiali (northernmost and south-sloping) and Chalsa (southernmost and south-sloping) scarps in the Chel-Murti interfluve. The third scarp is the north-sloping Thaljhora Scarp in the Jaldhaka-Gathia interfluve (Figure 3). The E-W trending, south-sloping scarps, *viz* the Matiali and Chalsa Scarps, have however been interpreted as having formed by deformation over the blind Main Boundary Thrust (MBT) and Himalayan Frontal Thrust (HFT) (Nakata 1972, 1989; Goswami Chakrabarti et al. 2013 and references therein). In

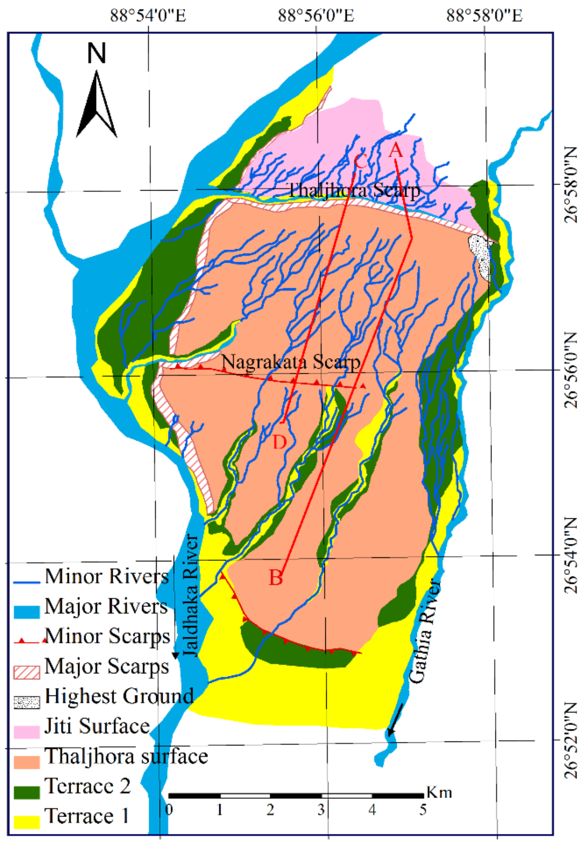

Figure 3 Geologic-geomorphic map of the present eastern Himalayan front, Jaldhaka-Gathia interfluve study area. Line C-D denotes the line of the total station survey shown in Figure 4.

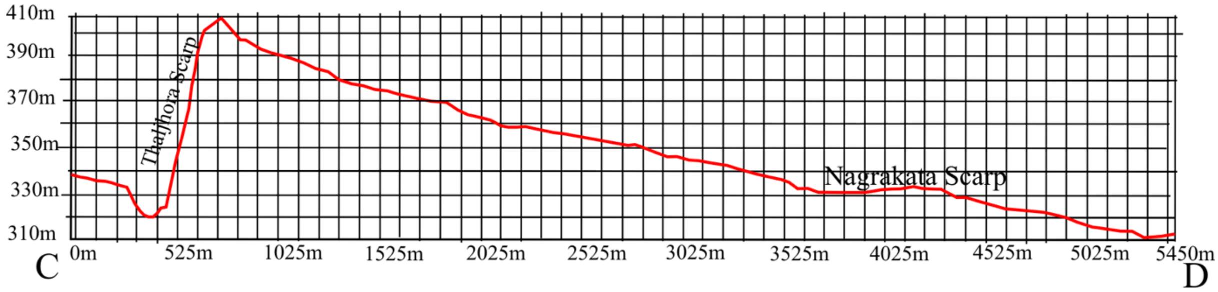

Figure 4 Total station survey profile C-D on the Thaljhora and Jiti surfaces across the Thaljhora and Nagrakata Scarps. See Figure 3 for the line of survey for the profile section.

a recent study, Srivastava et al. (2017) proposed to locally name the MBT and HFT the Ramgarh Thrust. The origin of the Thaljhora Scarp remains to be explained.

1.2 Methods

We prepared a 1:25,000 scale geological-geomorphological map by analysing the Survey of India Toposheet 73B/13, using Cartosat I DEM, and studying IRS P6 LISS IV MSS images using ERDAS Imagine Professional and ArcGIS 9.1 software. In addition, we did an extensive field study and focused total station surveys (Figure 3). We studied sediment from natural sections to understand both the sedimentation and timing of the important deformed geomorphic surfaces. The materials of different surfaces we were dated using the OSL method (Appendix 1) to constrain the timing of the depositional and deformation events. We constructed longitudinal and transverse profiles along depositional surfaces and river profiles using Global Mapper 15 software. Longitudinal profiles along key depositional surfaces were also constructed via our total station surveys (Figure 4).

Finally, on the basis of our results, we attempt to construct a plausible model for the development of the landscape and drainages in the study area *vis-a-vis* the Quaternary tectonics. We use a schematic cartoon to summarize our interpretation of the landscape evolution, present-day geomorphology, and Quaternary tectonics of the study area (Figure 5).

1.3 Materials

The major geomorphic features and units that we mapped in the Jaldhaka-Gathia River interfluve are an alluvial fan surface, river terraces, and the fault scarps mentioned above. We have identified two depositional surfaces and two major river terraces in the Jaldhaka-Gathia River interfluve, which are different from the depositional surfaces of Mal-Murti interfluve area both in terms of the sediment character and antiquity. The latter is interpreted from the soil character, grain size, geomorphic forms, and OSL ages. In the following sections, we describe the character of these depositional surfaces, the nature of the river

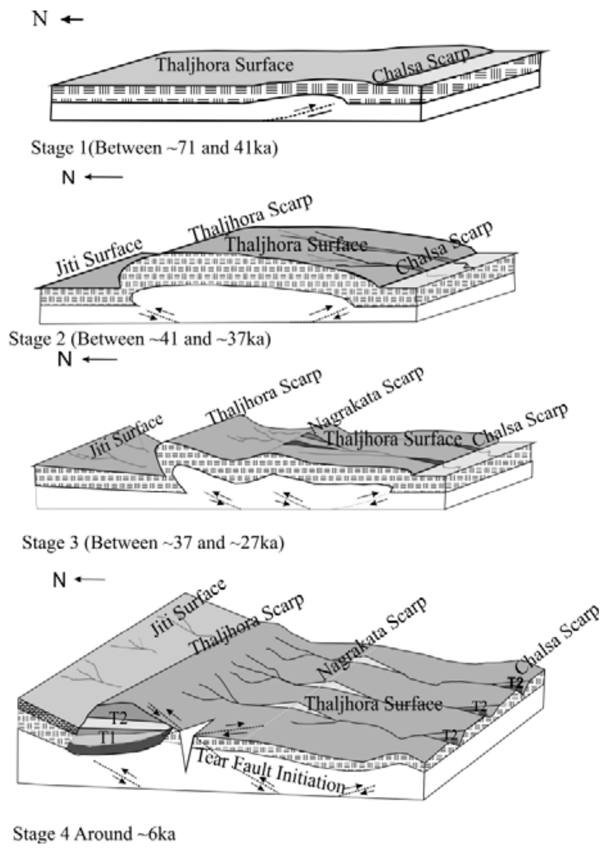

Figure 5 Interpretative and diagrammatic (not to scale) time-series cartoon showing the tectonic and geomorphic evolution of the landscape and the present day geomorphology of the Jaldhaka-Gathia interfluve study area. T1 and T2 mean Terrace 1 and Terrace 2 shown in Figure 3.

terraces and scarps, and then compare them with similar landforms from the Mal-Murti interfluve. The upper-reach interfluve between the Gathia and Diana Rivers lies in neighbouring state of Bhutan or is heavily forested, so we concentrated our study within just the Jaldhaka-Gathia interfluve.

There are two distinctly different depositional surfaces north and south of the Thaljhora Scarp (Figures 3, 5): the Jiti Surface and the Thaljhora Surface. The triangular surface north of the Thaljhora Scarp is bounded by the Jiti River to the north, the Thaljhora River to the south, and the Gathia River to the east. We named this surface the Jiti surface (Stage 2, Figure 5). The general slope of the surface is towards south. The Jiti surface has an average height of 325 m. This surface does not show a convex upward profile like fan surfaces do. The soil covering it is silvery grey. The material making up this surface is mainly boulders and pebbles with very thin sand beds. The pebble beds are dipping easterly and unconformably overly lower reddish-yellow cross-bedded sands (Figure 6). The lower yellow cross-bedded sands correlate with material of the Thaljhora Surface and continue below the surface material covering the Jiti surface (Figure 6a, 6b). The silvery-grey Jiti surface is relatively young, considering its very low oxidation compared with any of the depositional surfaces in the Mal-Neora interfluve, as well as the depositional surface south of Thaljhora Scarp. This Jiti surface was earlier mapped as a high river terrace (HRT) by Nakata (1989), but it cannot be correlated with any of the high river terraces in the Mal-Murti interfluve area in terms of height, sediment character, or the oxidation of overlying soil. In the Mal-Murti interfluve area, the HRT is composed mainly of thick sand beds alternating with pebble beds.

The Thaljhora Surface is characterised by a highly oxidised red soil in the northern part and a brown soil in the southern part. Though this surface was mapped as the Rangamati surface by earlier workers, we re-interpret this as a much younger surface than Rangamati surface and named it the Thaljhora Surface (Figure 3). The Thaljhora Surface is made up of highly rounded boulders in beds along with thick sand beds. The general slope of this surface is towards south. (Stage 1, Figure 5). It is highly dissected by rivers and gullies, some with anomalous slopes other

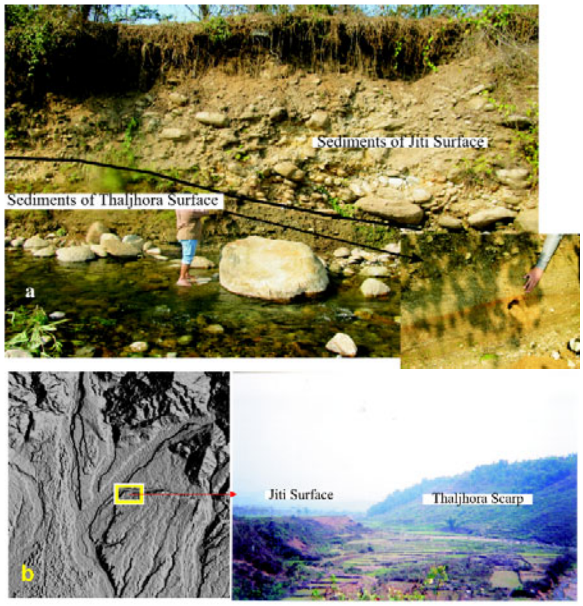

Figure 6 Photographs showing sediment comprising the Jiti and Thaljhora Surfaces: a) Coarse-grained boulder beds of Jiti surface overlying the pebble and sand beds of Thaljhora Surface. Inset: Sand beds with cross-bedding of the Thaljhora Surface below the sediment of Jiti surface. b) The Thaljhora and Jiti surfaces on the two sides of Thaljhora River.

than the regional southerly slope of the surface. The N-S profile along this surface shows warping. The surface is deformed to form two, almost parallel, E-W trending ridges and valleys. The northern faces of the ridges are steeper than the southern faces and appear as scarps. The northernmost scarp is higher and is named the Thaljhora Scarp. The southern, lower scarp is named the Nagrakata Scarp (Figure 7). The average height of the Thaljhora Surface is 335-340 m. The western boundary of this surface is marked by a lineament characterised by a very high (~50 m) N-S scarp with triangular facets (Figure 8a, 8b) along the eastern bank of the Jaldhaka River. The Jaldhaka River flows along this lineament along a sharp easterly bend. The eastern boundary of this surface is marked by another N-S lineament with a faceted scarp face which guides the course of the Gathia River (Figure 8c). The “block” between the Jaldhaka and Gathia River is uplifted compared to those along the Murti-Jaldhaka and Gathia-Diana interfluves. The northern part of this surface slopes towards southwest, while the southern portion slopes southeast (Figure 9). This surface includes a hump-like structure just south of the Thaljhora Scarp with maximum height of 375m. The soil and

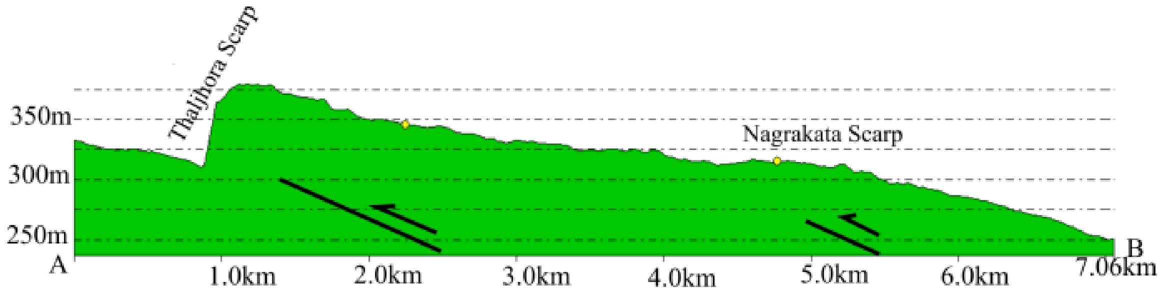

Figure 7 N-S profiles across the Thaljhora Scarp from Cartosat 1 DEM (A-B), and our total station survey in Figure 4 show warping of the Thaljhora Surface due to deformation by anticlinal folding. The subsurface structural geology is interpreted in profile A-B. The location of profile A-B is shown in Figure 3.

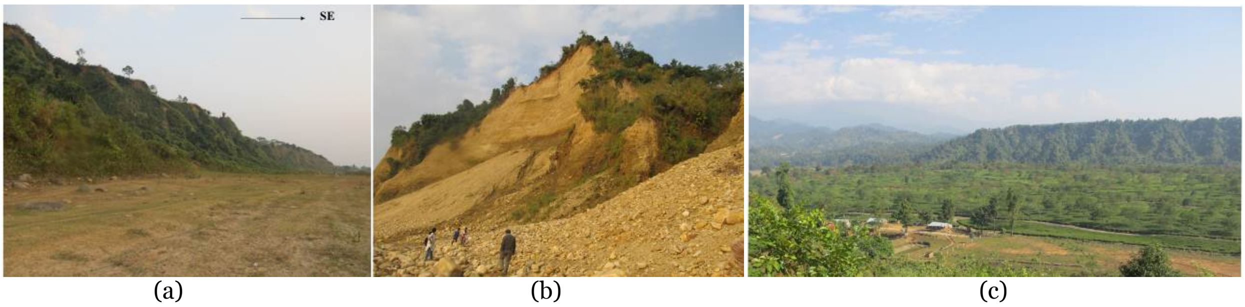

Figure 8 Geomorphic evidence for transverse (cross) faults along the Jaldhaka and Gathia Rivers: Triangular facets on the scarp along the eastern bank of Jaldhaka River as viewed from the south a) and the northeast b). c) Triangular facets on the scarp along the eastern bank of Gathia River as viewed from the east.

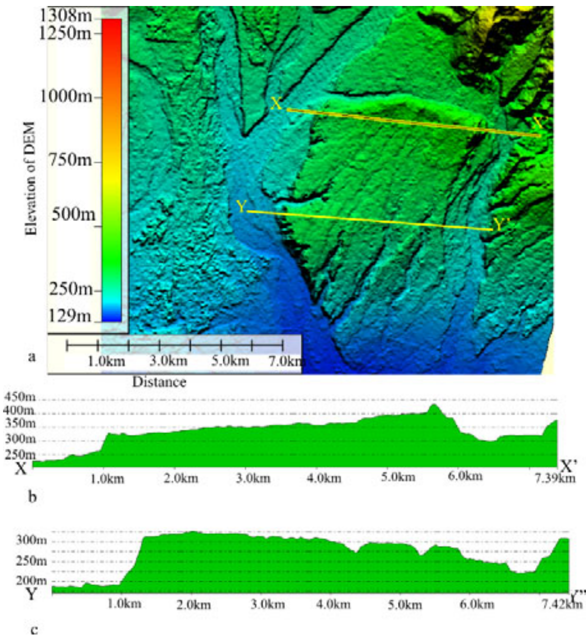

Figure 9 a) Locations of the E-W profiles along X-X' and Y-Y' on the Cartosat 1 DEM. The profiles along the X-X' line north of the Nagrakata Scarp shows the b) westerly slope and along Y-Y' line south of that scarp shows c) easterly surface slope.

sediment character are the same for both the hump and the Thaljhora Surface. There is no sharp vertical scarp between the Thaljhora Surface and this hump (Figure 10).

In addition to mapping and studying the Thaljhora and Jiti surfaces, we also mapped and studied terraces along the major rivers. The T2 terrace surfaces are high terraces present along the major rivers. They have been down-cut by the rivers. The elevation of the T2 terraces varies from 260 m in north to 225 m in south and they are thus almost horizontal. These surfaces are characterised by a light yellow to yellowish-grey soil cover. The T1 surfaces are just above the modern flood plains present along all rivers in the study area. T1 surfaces are characterised by grey soil, horizontal attitudes, and average heights of 180m.

1.4 Drainages

The Jaldhaka River is the major river in the study area. Its tributaries are named the Jiti, Gathia, Diana and Khuji Rivers. Apart from the Jaldhaka River and its main tributaries, numerous additional small streams drain this area (Figure 11). There are two distinct drainage divides in this basin; these are marked by the Thaljhora and Nagrakata Scarps described above.

Streams in the area may be classified as: (i)

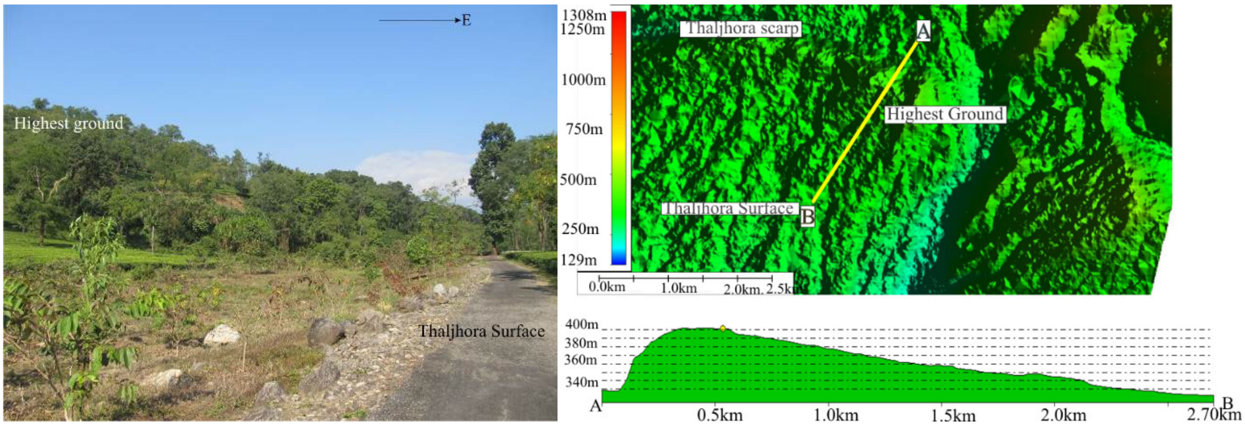

Figure 10 The highest area on the Thaljhora Surface represents a dome shaped hillock with no vertical scarp that is present along the western bank of Gathia River. Profile A-B was constructed is shown on accompanying index map and was constructed from Cartosat 1 DEM.

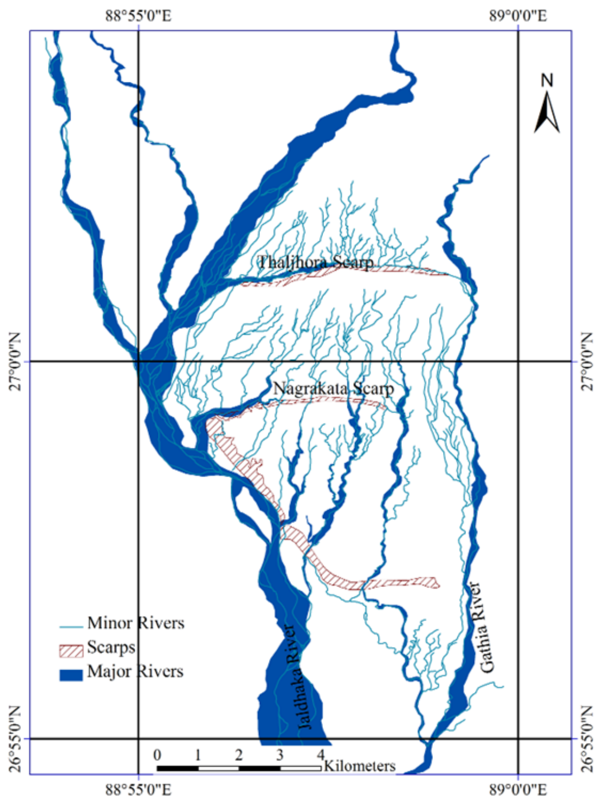

Figure 11 Drainage map of our Jaldhaka-Gathia interfluve study area showing the relationship between the major and minor rivers and fault scarps. For comparison of drainage pattern and the relationship of drainage with the fault scarps, see the similar map for the adjacent Mal-Murti interfluve which was previously published by Goswami Chakrabarti et al. (2012).

the streams flowing on the Jiti surface and (ii) those flowing on the Thaljhora Surface. Streams north of Thaljhora Scarp are totally confined to flowing on the Jiti surface. Streams originating from the Thaljhora Scarp flow southerly and, after crossing the Nagrakata Scarp, these small streams form deep gorges. All of the streams with deep gorges follow NNE-SSW lineament/faults parallel to the Gathia River and then join the Jaldhaka River in the southwest.

The study area shows a parallel drainage pattern in general. All of the major rivers like the Jaldhaka, Gathia and Jiti Rivers follow abnormally straight courses The Jaldhaka River follows a straight course for a considerable distance, about 8km, with only one significant sharp easterly bend. After that bend, it forms a broadly rectangular drainage pattern as it shifts distinctly towards east following E-W lineaments. The Jiti River also shows an abnormally straight, NE-SW trending course before meeting the river Jaldhaka (Figure 11).

River profiles along the Jaldhaka and Gathia Rivers show significant knickpoints where they cross the Thaljhora and the Nagrakata Scarps. The Jiti River also shows a major knickpoint where it crosses the Thaljhora Scarp. Even minor rivers, e.g. those originating from the Thaljhora hill, also show knickpoints where they cross the small Nagrakata Scarp (Figure 12).

The Thaljhora River course is partially defined by a linear marshy patch of land just below the Thaljhora Scarp. This marshy patch shows a gentle slope towards west in western part and the relatively steeper slope towards east in eastern part. The profile of this part of Thaljhora River also shows an anomalous convex pattern (Figure13).

There is another linear N-S trending marshy land marked by the Kurti River and present within the Thaljhora Surface south of Nagrakata Scarp

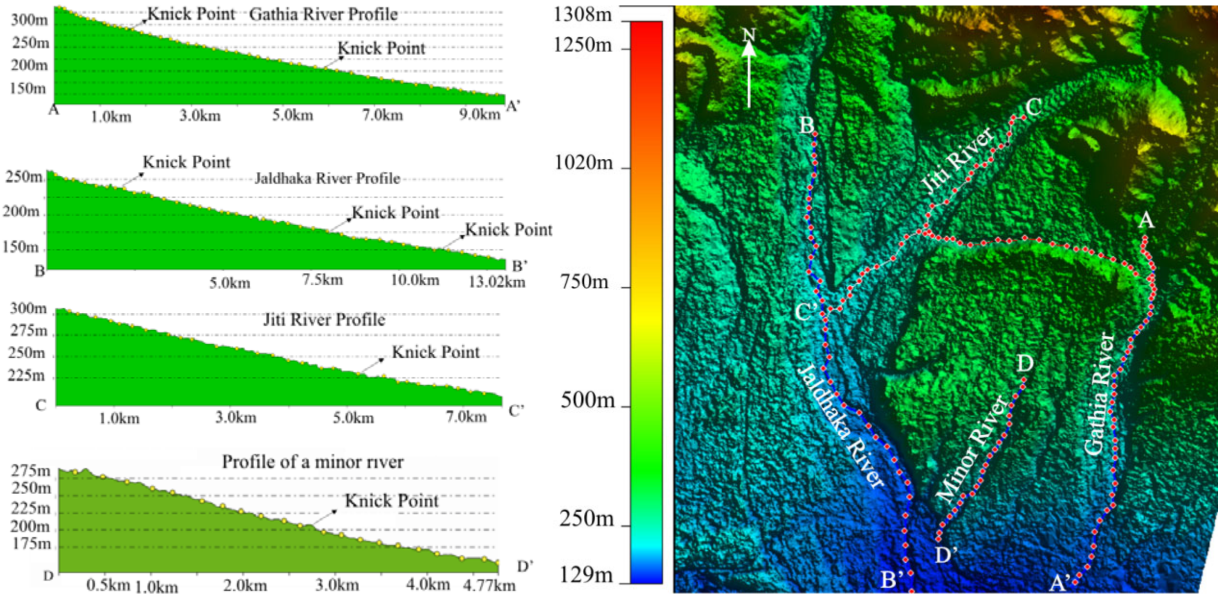

Figure 12 Longitudinal profiles of the rivers in the Jaldhaka-Gathia interfluve: A-A': Gathia River, B-B': Jaldhaka River, C-C': Jiti River, and D-D': a minor River. These profiles consistently show major knickpoints where these rivers cross the Thaljhora and Nagrakata Scarps. The index map and profiles were constructed from the Cartosat 1 DEM.

(Figure 11).

2 Results

2.1 Materials, surfaces, scarps, and active structures

The river terrace and the fan surface sediment is essentially fluvial with coarsening upward sequences, but can be differentiated in terms of antiquity using colour, grain size variation, OSL ages, and deformation structures.

The terraces formed along the eastern bank of Jiti River north of the Thaljhora Scarp formed by the fresh supply of young alluvial sediments and are characterised by loose grey coloured, pebble and boulder beds (Figure 6)

The material below the Jiti surface is grey in colour with angular and subrounded boulders in beds resting over older fan material. These older materials are similar to those below the Thaljhora Surface, and are comprised of cross-bedded sand and

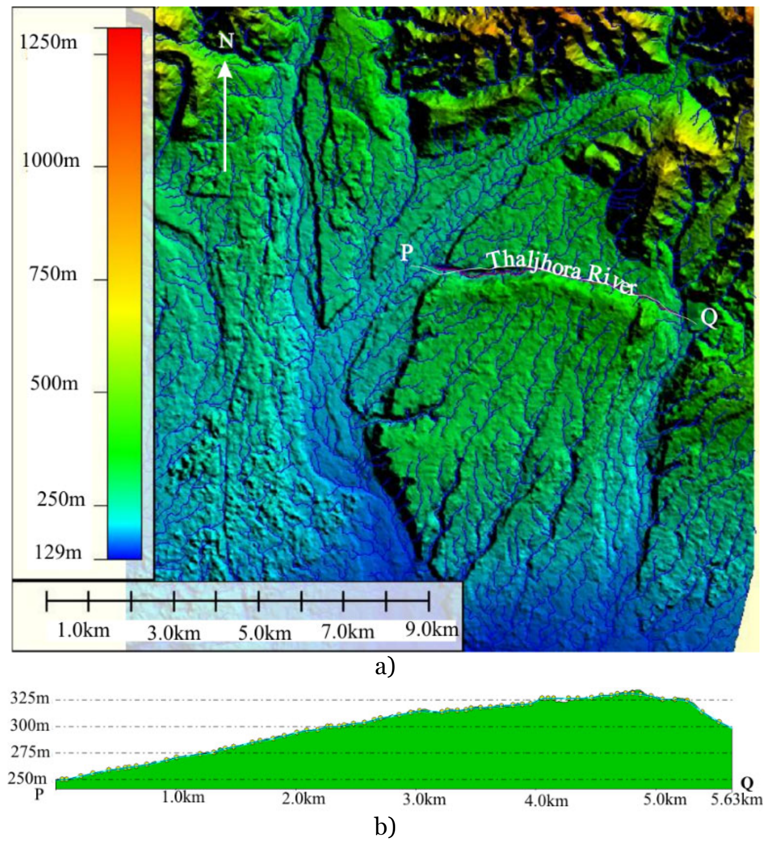

Figure 13 Longitudinal profile along the Thaljhora River showing an anomalous convex pattern. a) The Cartosat 1 DEM showing the Thaljhora River; b) The profile along the line P-Q shows the slope towards the west is gentle and some portions, almost horizontal.

pebble beds. The older fan material is yellowish grey to reddish yellow in colour, indicating moderate oxidation. This contrasts with the low oxidation of the material below the Jiti surface which is manifested by its thin soil cover and grey colour. The older fan material resembles the material below the Thaljhora Surface just south of Thaljhora Scarp. The material of Jiti surface is thus resting over the older fan deposit that forms the Thaljhora Surface (Figure 6a).

South of the Thaljhora Scarp, the situation is quite different. Here the depositional surface is characterised by a thick red soil cover and with thick sand and clay beds (Figure 14). The sediments beneath the Thaljhora Surface are coarsening upward and contain rounded pebbles and boulders in beds. The sediments lying to the south of the Nagrakata Scarp on the same surface are more oxidised with sand, clay and boulder beds containing very large granitic boulders (> 3m in diameter). Oxidation thus increases from Jiti surface to Thaljhora Surface and further south to the Nagrakata Scarp (Figure 14).

We interpret this phenomenon of consecutive older materials towards south below the same depositional surface as due to the existence of a southerly dipping blind thrust underlying the Nagrakata Scarp, with the finer and older sand beds having been thrust over the boulder beds. The rivers that form deep gorges south of the Nagrakata Scarp have eroded the upper sand and clay beds and relict granitic boulders are scattered on the Thaljhora Surface as erosional remnants.

Although the material below the Thaljhora Surface is characterised by coarsening upward sand and pebble beds, we also found distinct black and yellow clay beds as broad lenses below the Thaljhora and the Nagrakata Scarps within the fan material. These clay beds are indicators of deposition in low energy settings that likely resulted on the down-thrown sides of the blind thrust faults. Relative subsidence below the scarps is resulted in the bogging of river flow in those areas.

Apart from the E-W trending faults manifested by E-W trending scarps, there are two cross-faults, along the Jaldhaka River in west, and the Gathia River in the east. They are evident by high vertical scarps with no river terrace risers and well-developed triangular facets along the eastern banks of both rivers. Our total station survey (from the north of the Thaljhora Scarp to the south of the Nagrakata Scarp) shows deformation of the Thaljhora depositional surface to the exact height and slope of the Thaljhora and Nagrakata Scarps (Figure 4).

The Jaldhaka-Gathia and Mal-Murti interfluves are cut by both E-W (parallel to the trend of the Himalayan thrusts) and N-S (transverse to the trend of the Himalayan thrusts) scarps. The Thaljhora Scarp is the most important and most spectacular E-W trending scarp. It is a north-sloping, ca. 80m high, scarp, interpreted as having formed along the Main Boundary Thrust

North of Nagrakata Scarp looking towards north.
(a)

South of Nagrakata Scarp looking towards north
(b)

Figure 14 Sediments below the Thaljhora Surface north (a) and south (b) of the Nagrakata Scarp. Materials south of the scarp are more oxidised and contain thicker sand beds than those north of the scarp. In addition, sand appears only as lenses, not in thick beds within pebble beds, north of the scarp.

(MBT), and found at a similar latitude to that of the adjacent, south-sloping Matiali scarp mapped by Nakata (1989). Radiocarbon dating on sediments from the Thaljhora Scarp showed that the scarp deformed the alluvial cover after 27210±240 BP (Guha et al. 2007). Unlike the Chalsa and Matiali scarps, the Thaljhora Scarp is north-sloping. In addition, its slope is much higher than those of the Matiali and Chalsa Scarps. Moreover, it has no breaks in slope as do the Chalsa and Matiali scarps (Goswami Chakrabarti et al. 2013). Finally, the north face of this scarp is steeper than its southern face (Figure 4). We found that the sediment of the Thaljhora Surface just north of this scarp dips northward at about ~20° (Figure 15). Our new OSL date for the grey sandy clay at the base of the northern face of the scarp is 37 ± 7 ka. Another clay bed from at ~10m high from the base of the scarp dates to 27ka (Singh et al. 2016). Both of these units are cut by the scarp (Figure 16).

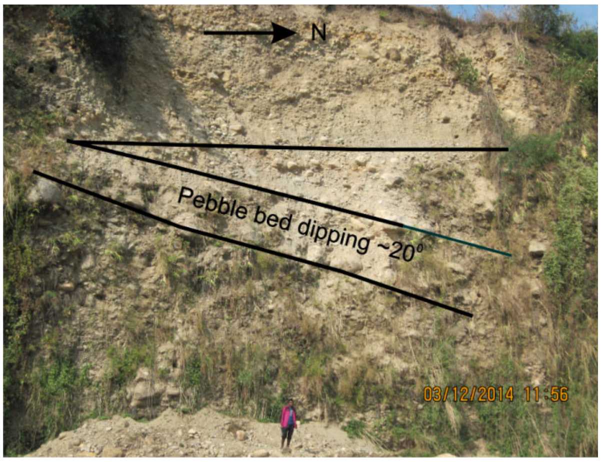

Figure 15 Pebble beds of the Thaljhora Surface, 10m north of Thaljora Scarp, which dip north at ~20°. This represents the steep limb of the anticline developed over the south-dipping blind thrust below the Thaljhora Scarp.

The southern limit of the study area is marked by the more diffuse, south-sloping Chalsa Scarp, which eventually dies out. The Chalsa Scarp is prominent up to the Murti-Jaldhaka interfluve. Then it bends towards south and, east of Jaldhaka, it becomes quite diffuse where it bends again toward the south and then dies out in the Jaldhaka-Gathia interfluve.

Apart from the two scarps describe above, we also report for the first time the presence of an additional, small, ca. 5m tall, north-sloping scarp, which we call the Nagrakata Scarp, which is found between the Thaljhora and Chalsa Scarps cutting the Thaljhora Surface. The Nagrakata Scarp can be identified as a clear lineament on satellite images, toposheets, and DEMs. Moreover, it is quite easily discernible on our total station survey profile (Figure 4). This E-W lineament is also marked by

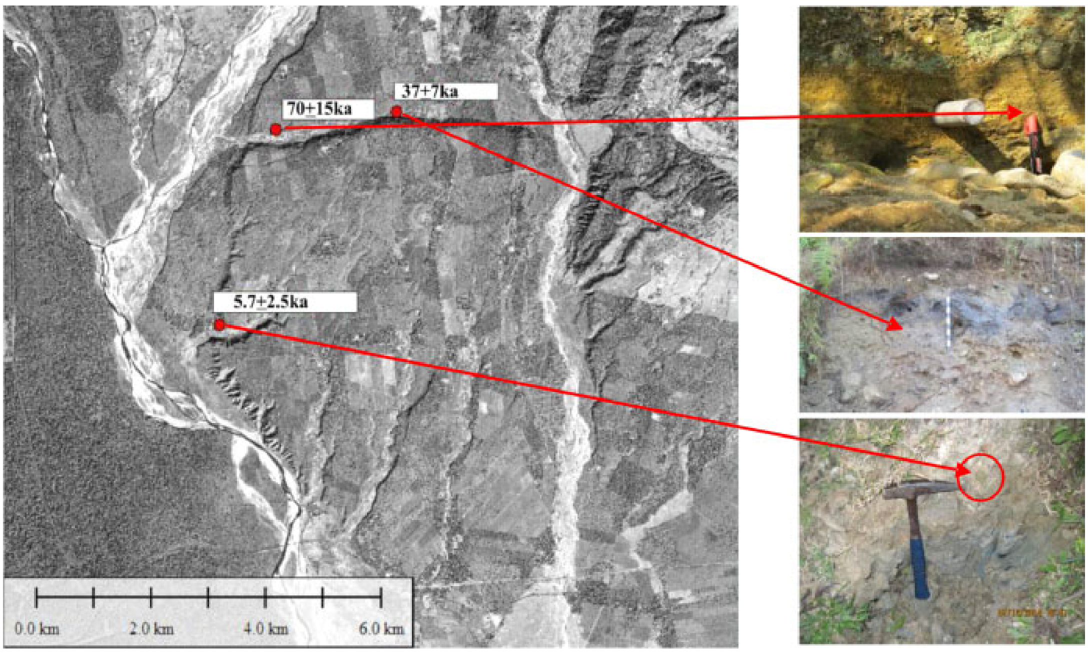

Figure 16 Sediments from material of Thaljhora Surface in the north and south banks of the Thaljhora River and in the south bank of the gully along the base of the Nagrakata Scarp. These samples were dated via the OSL method. The OSL results are given in Table 1.

the presence of an E-W gully. There are distinct unpaired terraces in the two sides of this gully (Figure 17). This scarp curves towards the northeast and dies out near the Kurti River.

Two types of transverse scarps are observed in the study area: a) river terrace boundaries that are marked by the vertical risers or 'scarps', and b) NNE-SSW and NNW-SSE lineaments along the eastern bank of Jaldhaka and Gathia River which are marked by very high vertical scarps with triangular facets. These scarps are not associated with river terraces (Figure 8). In the northern portion of study area, the southeasterly flowing Jiti River meets the Jaldhaka River. Here the course of the Jaldhaka River is along an N-S lineament and that of Jiti River is along a NW-SE trending lineament. The NW-SE profile crossing the Jaldhaka and Jiti River shows two deep river valleys separated by high-ground which indicates subsidence or incision of the fan surface along the two river valleys that follow two cross-fault traces (Figure 18).

2.2 OSL ages

The cross-bedded, sandy clay of the Thaljhora Surface lies beneath an unconformity overlain by sediment of the Jiti surface, which at the northern bank of Thaljhora River, dates to 70 ± 15 ka by the OSL method. This is the oldest dated material in the interfluve area that we studied (Figure 16). The grey sandy clay at the base of the northern face of the Thaljhora Scarp dates to 37 ± 7 ka and is at a higher elevation than the 70 ± 15 ka sandy clay described above. Another clay bed at ~10m high from the base of the scarp dates ~ 27ka (reported in Singh et al. 2016) (Figure 16).The yellow clay below the Nagrakata Scarp is exposed within an E-W gully and was dated for the first time in our study at 5.7 ± 2.5 ka (Figure16). The OSL methods that we used to determine these ages are described fully in Appendix 1.

2.3 Drainage patterns

From the drainage map (Figure 11), we interpret that the drainage network in our study area is much younger than that in the Neora-Murti interfluve. 1st and 2nd order streams are common in the Jaldhaka-Gathia interfluve, whereas 3rd and higher order streams are abundant in Neora-Murti basin. In addition, in the Jaldhaka-Gathia interfluve, the drainage pattern is controlled by the N-S faults, for example, along the Jaldhaka and Gathia Rivers. Not a single river from north of the

Figure 17 The western boundary of the lineament along the Nagrakata Scarp is marked by a prominent E-W gully. **Note:** the unpaired terraces on the two sides of the gully. T2 (Terrace 2 shown in Figure 3) is the second highest river terrace from the river bed.

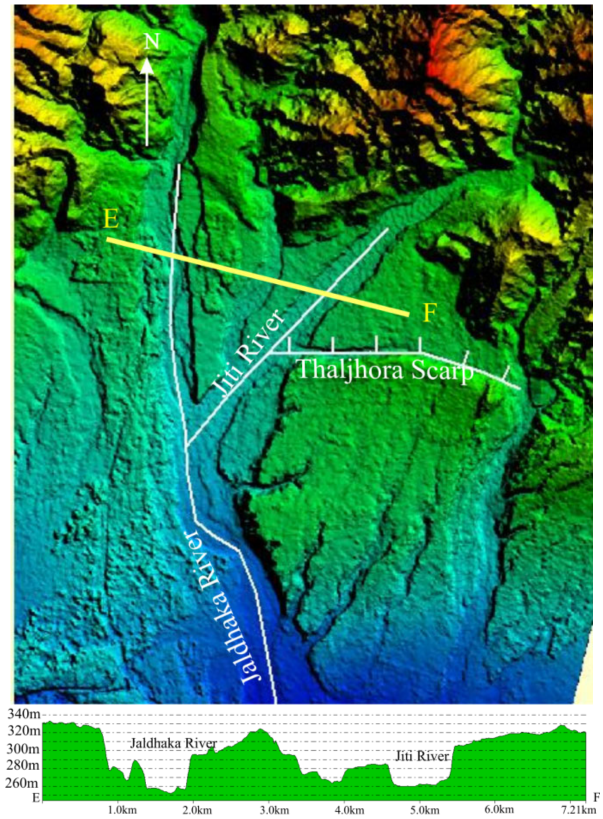

Figure 18 Map showing NW-SE profile E-F crossing the Jaldhaka and Jiti River showing two deep river valleys separated by high-ground. The map and profile were constructed using the Cartosat 1 DEM.

Thaljhora Scarp crosses that scarp, whereas both the Juranti and Kurti rivers in the Neora-Murti interfluve both cross the Matiali and the Chalsa Scarps. This indicates a relatively younger age for the Thaljhora Scarp. The Thaljhora River also forms a linear lake with a gentle slope toward the west and a steep slope towards east at the base of the Thaljhora Scarp (Figure 13). The drainage over the Jiti surface shows neither the characteristic radial pattern of an alluvial fan nor does it show a convex upward surface profile similar to that of the Neora-Murti interfluve area that lies north of Matiali scarp. Thus the Jiti surface does not represent an alluvial fan, but is rather a conical surface that likely formed by debris flow over the remnant of the Thaljhora Surface. The formation of Jiti surface is thus similar to that of Samsing surface which is interpreted as a debris flow over the T_4 surface in the Neora-Murti interfluve (Nakata 1989; Goswami Chakrabarti 2013).

The Jaldhaka River shows a sharp easterly bend parallel to the trend of the fault underlying the newly identified Nagrakata Scarp. The Jiti River in the NW corner of the study area flows along a NE-SW trending fault and meets the Jaldhaka River after crossing the Thaljhora Scarp.

The interfluve between the Jaldhaka River and the Gathia River is elevated and has been uplifted relative to the adjacent Murti-Jaldhaka and Gathia-Diana interfluve by two faults along these two rivers *viz*. the Jaldhaka and Gathia Faults (Figure 9), but the amount of uplift is not same along the two faults. In northern portion of the fan surface, the surface is sloping towards WSW, whereas south of the Nagrakata Scarp, the surface slopes ESE; the fan sediments also dip ESE (Figure 19). We interpret this pattern as due to differential uplift along the Jaldhaka and Gathia faults which controls the movement along the cross-fault below the Nagrakata Scarp and causes rotation.

3 Discussion

We interpret that the dome shaped high-ground along the western bank of Gathia River on the southern flank of Thaljhora Scarp is a part of the Thaljhora fan surface. There is no sharp break between the Thaljhora Surface and this high-ground and the soil and sediment characteristics are also same for the two. Due to the differential as well as rotational deformation of the Thaljhora Surface, the NE part has experienced maximum uplift and thus high-ground formed there.

The geomorphology of the area fits that of a wrinkle-ridge system (Schultz 2000), where the Thaljhora Scarp represents the ridge and the Nagrakata Scarp is the wrinkle (Figure 20). This wrinkle-ridge system formed over two south-dipping thrusts, which are back-thrusts of the Himalayan regional thrusts *viz.* the MCT, MBT and HFT, which are north-dipping thrusts. The development of the topography in the area can further be explained by the formation of an active fold over a blind thrust that causes displacement of the ground surface as a function of geometry of the buried thrust fault, which is likely dipping at ~15° towards south and is linked to an even more gently dipping décollement associated with the major Himalayan thrusts (e.g., Ellis and Densemore 2006).

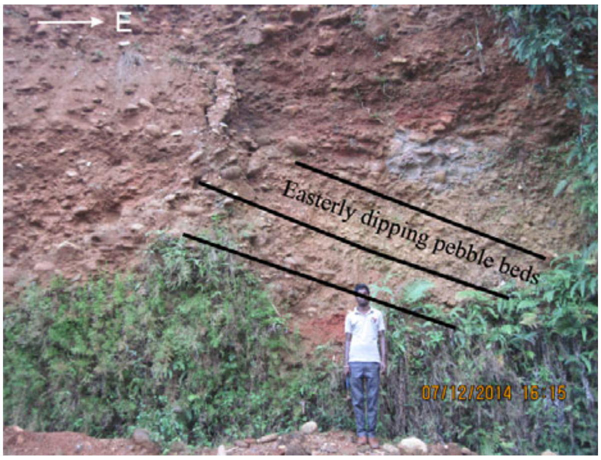

Figure 19 Sediments of Thaljhora Surface dipping toward the ESE south of Nagrakata Scarp.

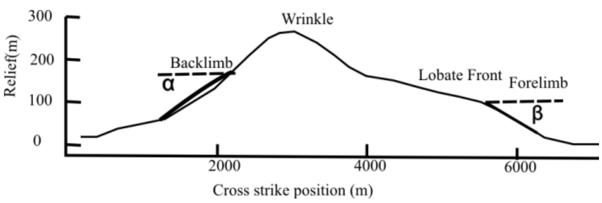

Figure 20 Characteristic of a wrinkle-ridge system as originally diagrammed by Schultz (2000). Compare this diagram to the observed profile shown in Figure 7. The comparison shows that a pattern very similar to the idealized one is observed in our study area. The angle α denotes the angle between the slope of backlimb with the horizontal and β is the angle between the slopes of the forelimb with the horizontal.

Compared with that in the adjacent Neora-Murti interfluve, deformation in our Jaldhaka-Gathia interfluve study area is younger. OSL dates from the Neora-Murti interfluve indicate formation of the fan surface from about 171 ka to 72 ka; then deformation of the fan began with the fault activation and development of the Chalsa Scarp at about 41 ka. In contrast, the oldest material on Thaljhora Surface north of Thaljhora Scarp dates back to ~70 ka and the sandy clay bed from the base of Thaljhora Scarp is around 37 ka, and another clay bed from a slightly higher horizon formed at 27 ka.This indicates that this fan between the Jaldhaka and Gathia Rivers started forming at about 70 ka and at least two phases of activation of the blind thrust below the Thaljhora Scarp took place at approximately 37 ka and 27 ka. The Chalsa Scarp in the Neora-Murti interfluve represents a thrusting event that began at about ~41 ka, but backthrusting that resulting the Thaljhora Scarp is younger and began at approximately ~37 ka (Guha et al. 2007; Singh et al. 2016). The yellow, sandy-clay bed from the base of the Nagrakata Scarp exposed in an E-W gully gives an OSL age of ~6ka indicating that the thrusting that formed the Nagrakata Scarp is younger than ~6ka. This provides evidence for the youngest thrusting event in this area, which is again much younger that the ~41ka thrusting that formed the Chalsa Scarp in the adjacent Neora-Murti interfluve (Singh et al. 2016).

The present day geomorphology of our Jaldhaka-Gathia interfluve study area is dominantly controlled by back-thrusting which is manifested by the Thaljhora and Nagrakata Scarps. This back-thrusting system, specifically the splay on which the Nagrakata Scarp is formed, is active and developing. The geomorphology and drainage systems are to a lesser extent also controlled by N-S trending cross faults along which the major rivers like Jaldhaka and Gathia flow.

The sequence of the events forming the present-day geomorphology in the Jaldhaka-Gathia interfluve is as follows and is presented in Figure 5. An alluvial fan formed at the mountain front during late Pleistocene time before ~71 ka with the Thaljhora Surface as its top surface. This surface was then deformed via the formation of an anticlinal over the north-dipping Himalayan Frontal Thrust (HFT) whose expression in the landscape is manifested by the Chalsa Scarp (Stage 1).

A south-dipping back-thrust next formed north of the HFT surface trace (i.e., the Chalsa Scarp) at approximately 37 ka. Thrusting along this south-dipping back-thrust resulted in the formation of the north-sloping Thaljhora Scarp as a second anticline with a steep northern limb and created a pop-up structure (Stage 2). From the newly formed Thaljhora anticlinal hill and Thaljhora Scarp, minor south-flowing rivers were generated and began forming a dendritic pattern. A second phase of movement on the Thaljhora fault took place at about ~27 ka and caused uplift and incision and the higher terraces (T_2) to be abandoned along the rivers. Initiation of Nagrakata Scarp as a result of a splay faulting of the Thaljhora fault south of the Thaljhora Scarp also took place around this time (Stage 3).

Simultaneous thrusting on the HFT and back-thrusting on the splay south of the Thaljhora Scarp at approximately 6 ka caused tear (cross) faulting with a rotational component. This movement resulted firstly the uplift of the newly formed Nagrakata Scarp to ca. 5 m and secondly the formation of different slopes north and south of the connecting cross-fault (Figure 10) (Figure 5, Stage 3 and Stage 4). Due to its new anomalous anticlinal surface slope, minor rivers initiated south of the Nagrakata Scarp, started downcutting, and began forming deep gorges enhancing the parallel drainage pattern parallel to the major rivers like Jaldhaka and Gathia (Stage 4). Due to the anticlinal surface uplift, high-ground formed in the northeastern part of the Thaljhora Surface. Similarly, the southwestern part of the surface was also uplifted and a ca. 130 m scarp formed along the Jaldhaka River (Stage 4).

Uplifted old and new depositional terraces formed along the rivers and record deposition between thrusting and back-thrusting pulses. Splay back-thrusting formed the Nagrakata Scarp and thrust older sediment of the Thaljhora Surface over younger sediment. This was followed by the erosion of the older sediment north of the Nagrakata Scarp resulting in a difference in the soil character on the two sides of that scarp. Material on the southern side is more oxidised due to its greater antiquity (Figure 14).

4 Conclusions

The formation of alluvial fans has been ascribed to two extrinsic factors: climate and tectonism. We concur that the Neora-Murti interfluve fan formed initially by a heavy sediment influx in the late Pleistocene due to climatic change and was then later deformed by thrusting and folding. From our study of the Jaldhaka-Gathia interfluve, we conclude that thrusting, back-thrusting, and folding were the dominant causative factors in shaping this deformed fan segment. The geomorphological imprints of deformation that we interpret correlate well with known thrusts and cross (transverse) faults and were used to identify new back-thrusts and anticlines. The formation and deformation of the fan segment in the Jaldhaka-Gathia interfluve are both younger than the age of the fans and deformation in the adjacent Neora-Murti interfluve. The geomorphology of the Jaldhaka-Gathia interfluve is dominated by the results of back-thrusting, unlike the Neora-Murti interfluve where it is governed by the movement on the thrust splays off of the regional MBT and HFT. In the Jaldhaka-Gathia interfluve, present-day geomorphologic development can be attributed to splay back-thrusting beneath the Nagrakata Scarp – this is the youngest faulting in this area. More detail sedimentological, paleoseismic, and geodetic studies would give an even better understanding of the relative importance of tectonics and climate in shaping the geomorphology of and of the seismic hazard posed to the Jaldhaka-Gathia interfluve region.

Acknowledgement

We heartily thank Dr. Manoj K Jaiswal IISER Kolkata for providing three new geochronological ages of sediment via the OSL method. The present study is part of the Fast Track Project for Young scientists granted to Chandreyee Chakraborty Goswami by the Department of Science and Technology, Government of India (Grant No. SR/FTP/ES-47/2013) and executed in the Department of Geology, University of Calcutta. Prasun Jana thanks Mr Soumitra Dasgupta for helping us to sketch the interpretative cartoon in Figure 5 in its initial stage. Chandreyee Chakraborty Goswami thanks her daughter Basudha for her constant support during field work and sacrificing her time and studies for our work during the manuscript preparation. We are grateful to Prof. D Mukhopadhyay and Sri Bikash Chandra Poddar for the discussion and support throughout this study.

Electronic supplementary material: Supplementary material (Appendix 1) is available in the online version of this article at https://doi.org/10.1007/s11629-018-5208-7

References

Basu S (2013) Geology of sikkim and darjeeling district of West Bengal. Geological Society of India. p 255.

Das A, Chattopadhyay GS (1993a) Use of soil in building up the quaternary stratigraphy of North Bengal. Records of the Geological Survey of India 121 (2–8): 87-91.

Das A, Chattopadhyay GS (1993b) Neotectonics in the Tista, Jaldhaka and Torsa Interfluve belt of North Bengal. Records of the Geological Survey of India 121 (2–8): 101-109Dasgupta S, Mazumdar K, Moirangcha LH, et al. (2013) Seismic landscape from Sarpang Re-entrant, Bhutan Himalaya foredeep, Assam, India: Constrains from geomorphology and geology. Tectonophysics 592 : 130-140. https://doi.org/10.1016/j.tecto.2013.02.021.

Delcaillau B (1992) The Himalayan Siwalik of Eastern Nepal. Functioning and evolution of a piedmont. Memoirs and Geography Documents, CNRS editions, France. p 205.

Durcan AJ, King GE, Duller GA (2015) DRAC: Dose Rate and Age Calculator for trapped charge dating. Quaternary Geochronology 2: 54-61. https://doi.org/10.1016/j.quageo.2015.03.012

Dutta Gupta T, Mukhopadhyay B, Dasgupta S, et al. (2017) Neo-tectonic activity in Sarpang Re-entrant, frontal Bhutan Himalaya, Kokrajhar District, Assam, India: Constrain from geological, geomorphological and GPS surveys. Indian Journal of Geosciences 71(1): 181-194. https://doi.org/10.1016/j.quaint.2012.12.020

Ellis MA, Densmore AL (2006) First-order topography over blind thrusts. Geological Society of America Special Paper 398: 251-266. https://doi.org/10.1130/2006. 2398(15)

Gansser A (1964) Geology of the Himalayas. Interscience. Wiley, New York. p 289.

Ghosh R, Bera S, Sarkar A, et al. (2015) A ~50 ka record of monsoonal variability in the Darjeeling foothill region, eastern Himalayas. Quaternary Science Reviews 114: 100-115. https://doi.org/10.1016/j.quascirev.2015.02.002

Goswami (Chakrabarti) C, Mukhopadhyay D, Poddar BC (2013) Geomorphology in relation to tectonics: A case study from the eastern Himalayan foothills of West Bengal, India. Quaternary International 298: 80-92. https://doi.org/10.1016/j.quaint.2012.12.020

Goswami (Chakrabarti) C, Mukhopadhyay D, Poddar BC (2014) Reply to Comments from R. Kar and T. Chakraborty on "Geomorphology in relation to tectonics: A case study from the eastern Himalayan foothill of West Bengal, India". Quaternary International 338: 119-124. https://doi.org/10.1016/j.quaint.2014.01.042

Goswami C, Mukhopadhyay D, Poddar BC (2012) Tectonic control on the drainage system in a piedmont region in tectonically active eastern Himalayas, Frontier of Earth Science 6(1): 29-38. https://doi.org/10.1007/s11707-012-0297

Guha D, Bardhan S, Basir SR, et al. (2007) Imprints of Himalayan thrust tectonics on the Quaternary piedmont sediments of the Neora–Jaldhaka Valley, Darjeeling–Sikkim Sub-Himalayas, India. Journal of Asian Earth Sciences 30: 464-473. https://doi.org/10.1016/j.jseaes.2006.11.010

Kar R, Ckaraborty T, Chakraborty C, et al. (2014) Morpho-sedimentary characteristics of the Quaternary Matiali fan and associated river terraces, Jalpaiguri, India: Implications for climatic controls. Geomorphology 227: 137-152. https://doi.org/10.1016/j.geomorph.2014.05.014

Kumar S, Wesnousky SG, Jayangondaperumal R, et al. (2011) Paleoseismological evidence of surface faulting along the northeastern Himalayan front, India: Timing, size, and spatial extent of great earthquakes. Journal of Geophysical Research 115: B12422. https://doi.org/10.1029/2009JB006789

Lave` J, Avouac JP (2000) Active folding of fluvial terraces across the Siwalik Hills, Himalaya of central Nepal. Journal of Geophysical Research 105: 5735-5770.

Long S, McQuarrie N, Tobgay T, et al. (2011) Tectonostratigraphy of the Lesser Himalaya of Bhutan: Implications for the alongstrike stratigraphic continuity of the northern Indian margin. Geological Society America Bulletin 123: 1406-1423. https://doi.org/10.1130/B30273.1

Mukul M, Jade S, Ansari K. et al. (2014) Seismotectonic Implications of strike-slip earthquakes in the Darjeeling-Sikkim Himalaya. Current Science 106(2): 198-210.

Mukul M, Matin A (2005) Tectonics of the Himalayan Mountain Front, Darjiling Himalayas, India. Annual Report of Centre of Mathematical Modeling and Computer Simulation, Bangalore. http://www.cmmacs.ernet.in/cmmacs/Publications/Annual_rep/2004-5/chapter2. Pdf

Mullick M, Riguzzi F, Mukhopadhyay D (2009) Estimates of motion and strain rates across active faults in the frontal part of eastern Himalayas in North Bengal from GPS measurements. Terra Nova 21: 410-415.

Murray AS, Wintle AG (2000) Luminescence dating of quartz using an improved single aliquot regenerative-dose protocol. Radiation Measurement 32: 57-73.

Nakata T (1972) Geomorphic history and crustal movements of the foothills of the Himalayas. Tohoku University Science Reports: 7th Series (Geography) 22: 39-177.

Nakata T (1989) Active faults of the Himalaya of India and Nepal. GSA Special Paper 232: 243-264.

Ray SK (2006) Scaling properties of thrust fault traces in the Himalayas and inferences on thrust fault growth. Journal of Structural Geology 28: 1307-1315. https://doi.org/10.1016/j.jsg.2006.02.010

Saha D (2013) Lesser Himalayan sequences in Eastern Himalaya and their deformation: Implications for Paleoproterozoic tectonic activity along the northern margin of India. Geoscience Frontiers 4(3):289-304. https://doi.org/10.1016/j.gsf.2013.01.004

Scultz AR (2000) Localization of bedding plane slip and backthrust faults above blind thrust faults: Keys to wrinkle ridge structure. Joirnal of Geophysical Research 105(5): 12035-12052. https://doi.org/10.1029/1999JE001212

Singh A, Jaiswal MK, Pattanayak JK, et al. (2016) Luminescence Chronology of Alluvial fan in North Bengal, India: Implications to Tectonics and Climate. Geochronometria 43: 102-112. https://doi.org/10.1515/geochr-2015-0037

Srivastava V, Mukul M, Mukul M (2017) Quaternary deformation in the Gorubathan recess: Insights on the structural and landscape evolution in the frontal Darjiling Himalaya. Quate