AUSTRIAN JOURNAL OF EARTH SCIENCES
[MITTEILUNGEN DER ÖSTERREICHISCHEN GEOLOGISCHEN GESELLSCHAFT]

AN INTERNATIONAL JOURNAL OF THE AUSTRIAN GEOLOGICAL SOCIETY
VOLUME 97 2004 2005

EDITING: Grasemann Bernhard, Wagreich Michael
PUBLISCHER: Österreichische Geologische Gesellschaft
Neulinggasse 38, A-1031 Wien
TYPESETTER: Irnberger Norbert, www.irnberger.net
Copy-Shop Urban, Bahnstraße 26a, 2130 Mistelbach
PRINTER: Holzhausen Druck & Medien GmbH
Holzhausenplatz 1, 1140 Wien
ISSN 0251-7493

Austrian Journal of Earth Sciences | Volume 97 | 82 - 93 | Vienna | 2005

Quantitative morphotectonics of the southern Shillong Plateau (Bangladesh/India).

S. BISWAS[1)*)] & B. GRASEMANN[2)]

[1)] Department of Geological Sciences, Jahangirnagar University, Dhaka, Bangladesh
[2)] Department of Geological Sciences, Structural Processes Group, University of Vienna, Austria
[*)] Coresponding author

KEYWORDS

tectonic geomporphology
Shillong Plateau
fluvial erosion
exhumation
uplift

Abstract

Digital Elevation data (SRTM) and high-resolution satellite images have been used to identify lineaments, faults, geomorphic indices and fluvial responses in order to better understand of young uplift, exhumution, and erosion of the seismically active Shillong Plateau in E India. Lineament patterns along the Dauki Fault of southern margin of the Shillong Plateau are influenced by fault strike and indicate that the effect of tectonic activity decreases to both the western and eastern termination of the fault from a central active fault part. The active regions are characterized by low values of mountain front sinuosity and valley floor width to height ratios, and high values of stream gradient index and drainage density. The calculated geomorphic indices and other fluvial responses support the idea that the rugged topography and v-shaped valleys are not only a product of monsoon climate-driven erosion but also strongly influenced by active tectonics along the fault zone. The drainage basin (catchment area) asymmetry, 3D stream network, and transverse topographic symmetry factor suggest a differential uplift in different zones have been effective to build the present landscape. Lateral strike slip movements have been identified along the fault zone, allowed the tectonic blocks spaced re-orderly with in a N-S shortening setting. Successive faulting parallel to the main Dauki Fault facilitated greater uplift in the northern parts where basement rocks were uplifted at about 2 km from sea level. The Dauki Fault segmented into five distinct parts at its eastern termination displaying a horse-tail structure geometry. One part of Dauki Fault, which is located below alluvium cover south of the Shillong Plateau in Bangladesh, is mechanically responsible for Tertiary sediments deformed into a monocline. The Dauki Fault has a complex evolution in space and time, and is closely associated with the growth and exhumation of the Shillong Plateau.

Das Shillong Plateau in Ostindien ist eine spektakuläre topographische Struktur südlich der Front des Himalaya Gebirges. Das Shillong Plateau hat auf einer Höhe von 2 km archäische Gesteine exhumiert, welche im Brahmaputra Becken in einer Tiefe von mehreren Kilometern liegen. Die Heraushebung entlang der Dauki Fault am Südrand des Plateaus begann im Pliozän. Diese Arbeit verwendet digitale Höhenmodelle (SRTM-Daten) und hochauflösende Sattelitenbilder um die Raumorientierung von Störungen zu kartieren. Die Quantifizierung geomorphologischer Indizes hilft die Interaktion von Erosion und aktiver Tektonik von einer Region besser zu verstehen, in welcher es in historischer Zeit mehrere große Erdbeben gegeben hat. Das Lineamentmuster entlang der Dauki Fault ist im Wesentlichen vom Streichen der Störung bestimmt, wobei die Dichte von Westen nach Osten zunimmt. Tektonisch aktive Regionen zeigen einen niedrigen Grad an Sinuosität der Gebirgsfront und ein niedriges Verhältnis der Breite der Täler zu ihrer Höhe. Der Gradient sowie die Dichte der Flüsse sind in aktiven Regionen hoch. Die Summe der berechneten geomorphologischen Indizes unterstützt die Idee, dass die Formung der Topographie nicht nur ein Resultat der vom Monsunklima bestimmten Erosionstätigkeit ist, sonder dass die Morphologie Ausdruck der aktiven Tektonik entlang der Dauki Fault ist. Die Asymmetrie des Entwässerungssystems und die 3D Geometrie des Flussnetzwerkes zeigt eine differentielle Heraushebung, welche mit unterschiedlichen Raten zur Formung der heutigen Topographie geführt hat. Zusätzlich konnte entlang von Störungen eine Seitenverschiebungskomponente festgestellt werden, welche als Ausgleichsbewegungen in einem verkürzenden Deformationsfeld interpretiert werden. Differentielle Bewegung an Scherzonen parallel zur Dauki Fault ermöglichten eine größere Heraushebung in den nördlichen Teilen bis zu etwa 2 km Seehöhe. An ihrem östlichen Ende ist die Dauki Fault in 5 Äste segmentiert (*horse-tail*). Ein weiterer Ast der Störung zieht südlich vom Shillong Plateau nach Bangladesh, wo tertiäre Sedimente über der blinden Überschiebung eine monokline Falte bilden. Als wichtigstes Ergebnis fassen wir zusammen, dass die Entwicklung der Dauki Fault am Südrand des Shillong Plateaus eine komplexe räumliche und zeitliche Entwicklung hat, welche eng mit der Heraushebung des Shillong Plateaus im Zusammenhang steht.

1. Introduction

The north-eastern flank of peninsular India is one of the most tectonically active regions in the world where Late Cretaceous Tertiary sediments together with underlying Jurassic rocks and Precambrian granites/gneiss are exposed along the fringes of the Shillong Plateau (Dasgupta and Biswas, 2000). Bilham and England (2001) suggested that the uplift of the Shillong Plateau is accommodated by the S dipping Oldham fault in the north of the Plateau, co-seismic displacement upon which was responsible for the devastating M_w 8.1 Assam earthquake in 1897. These authors further speculated that the Oldham Fault together with the Dauki Fault to the south of the plateau (Fig.1) forms a high-angle conjugate part crustal scale shear zone, allowing uplift of the plateau of tens of km-scale pop-up structure. Alternative investigations speculate that the Dauki Fault is rather a north dipping low-angle thrust, responsible for a southwards transport of the Shillong Plateau (Molnar, 1987; Johnson and Alam, 1991).

The W-E striking Dauki Fault (Fig.1) separates the plateau from the tens of kilometres succession of sediments of the Sylhet Trough (Evans, 1964). This fault has a major influence on the evolution of the landscape and sedimentation style of the area. Surprisingly, the fault has not been studied in detail, probably because of administrational access issues due to its location along the border between India and Bangladesh, as well as poor outcrop exposures, dense vegetation and other logistic problems. The southern part of Shillong Plateau receives 5,000-10,000 mm of rainfall per year (e.g. parts of southern Meghalaya state of India receives more than 10,000 mm rainfall per year) associated with high erosion rates, which severely modify or erase morphotectonic signals. Therefore, this tectonic surface processes studies use data, derived from remote sensing techniques (e.g., satellite images, digital elevation models – DEM, shuttle radar topography mission – SRTM) and geological maps integrated using geographical information systems. The presented work demonstrates a variable and complex interplay between progressive tectonic evolution and erosion along the southern part of the Shillong Plateau as well as parts of it support the interpretation of the Dauki Fault as a high-angle crustal scale shear zone, that facilitated uplift of the

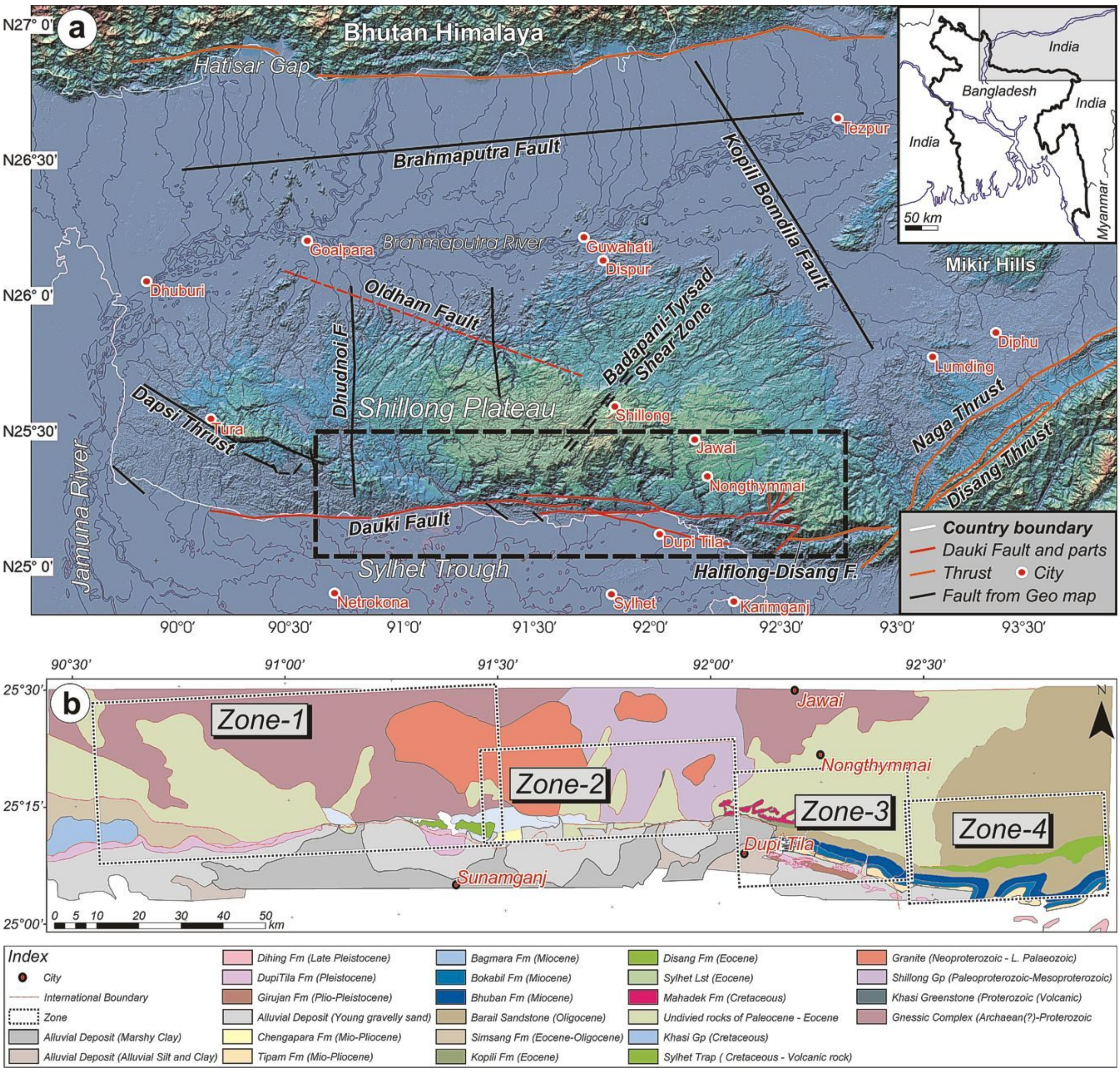

Figure 1: Topographic and Geologic maps of the study area. a) Topographic map of Eastern Himalayan foothills, Brahmaputra basin, Shillong Plateau, Mikir Hills, Northern part of Sylhet Trough and part of Naga Hills. Digital elevation data uses reflectance map of 90 m resolution with vertical exaggeration of 3X (sun azimuth 335°, sun elevation 45°, colours HIS elevation). b) Generalized geological map of southern fringe of Shillong Plateau (compiled after Sengupta et. al., 1998; Alam et. al., 1990; Nag et al., 2001; and Biswas, 1996). Zone-1 – 4 indicate tectonomorphic sub-areas investigated quantitatively in Figures 2 – 5.

plateau. We show that the fault is a multi-phase complex fault zone, which has a major S directed thrusting component with local elements of sinistral and dextral wrench.

2. Geologic Setting

Shillong Plateau, roughly rectangular in shape, covering an area of about 4x10^4 km^2, is considered to be an uplifted horst-like feature, bounded by the E–W trending high angle reverse Dauki and Brahmaputra faults (Rajendran et al., 2004) in the south and the north, respectively (Fig.1). The north and south bounded faults allowed the Plateau to rise up as a 'pop-up' structure (Bilham and England, 2001). In the west, the Shillong Plateau is marked by Brahmaputra River, termed the Jamuna River in Bangladesh part and in the east by Kopili-Bomdial Fault zone (Evans, 1964; Desikachar, 1974; Acharyya, 1980; Nandy, 1986; Dasgupta and Biswas, 2000). Others N–S trending structures that also traverse the plateau are the Nongchram fault (Golani, 1991), Um Ngot lineaments, and Dudhnoi Fault (Kayal, 1987). Another important structure observed on the Shillong Plateau is the NE–SW trending Badapani-Tyrsad shear zone (Kumar et al., 1996). Beside this, a number of N-S, E-W and NW-SE lineaments cross the Plateau.

The Plateau consists of an Archean gneissic complex, meta-sedimentary Shillong Group rocks, mafic igneous rocks, porphyritic granites, Sylhet trough flood basalts, ultramafic-alkaline-carbonatite complexes and in the southern flank Cretaceous-Tertiary sediments (Fig.1). The Sylhet Trough contains succession of Tertiary-Quaternary sediments ranging in thickness from 13 to 17 km (Evans, 1964; Hiller and Elahi, 1984). The Sylhet Trough and adjoining areas evolved from a passive continental margin (pre-Oligocene) to a foreland basin that was linked to the Indo-Burman ranges (Oligocene to Miocene), and subsequently to a foreland basin linked to south-directed over thrusting of the Shillong Plateau (Pliocene to Holocene) (Johnson and Alam, 1991). The geological history of the area started when India rifted from combined Gondwanaland (Alam, 1989; Acharayya, 1980). In Late Triassic/Early Jurassic, the southern fringe of the Plateau, including Sylhet Trough, became open to marine sedimentation. This period included igneous activity and the formation of basaltic rocks, which are now cropping out at Garo Hills, north of Sylhet Trough and at Mikir Hills (Rao and Kumar, 1997). This period also includes the formation of number of basic and ultrabasic intrusive (Dasgupta and Biswas, 2000; Harijan et al., 2003). During the Eocene limestones were deposited in stable shallow marine environment at the southern part of present day Shillong Plateau region (Jauhiri and Agarwal, 2001). At the end of Eocene, the whole area exposed a major regressive phase (Banerji, 1984). In the Oligocene, large-scale uplift and erosion resulted in the marine retreat and progressive development of prograding deltaic conditions in E India (Alam, 1989). In Miocene, collision of Indian Plate with the Tibetan and Burmese Plates, resulted large influx of clastic sediment in to the basin south of now exposed Shillong Plateau. During the Late Tertiary, the area experienced further tectonic 'upheavals', while co-existed fluvial delta complex in the lower plains suffered from subsidence. As the Shillong Plateau is draped by Mesozoic to Miocene rocks, and Pliocene and younger strata are absent, it has been suggested that the massif has emerged rapidly since Plio-Pliocene time (Johnson and Alam, 1991).

3. The Data Used

1. Satellite Images: Georeferred Landsat TM and ETM+ images of path/row 136-138/42-43 of WRS-2 grid layer (data courtesy: Global Land cover facility, Earth Science Data Interface of Maryland University)
2. Digital Elevation Model (DEM): The Shuttle Radar Topography Mission (SRTM) data of 90 m resolution from http://edc.usgs.gov/
3. Geologic data: shape files were generated from Geological Survey of India map (Sengupta et al., 1998), Geological Survey of Bangladesh map (Alam et al., 1990), number of published articles (Nag et al., 2001) and from field work.
4. Topographic maps: Topographic map of scale 1:50000 (Survey of Bangladesh) and topographic map of US Army of scale 1:250,000 (courtesy: University of Berkeley Library).

4. Lineament Fabrics

Tectonically active regions show higher intensities of lineaments than tectonically quiet zones. Analyses of lineaments in an area where exposures are poor and covered by thick vegetation typically can provide indications of tectonic activities. In an area of very dense vegetation, identification of lineaments via image interpretation may be ambiguous or even impossible. However, draping of satellite images on digital elevation models (DEM) significantly enhances the detection of lineaments and faults, or more specifically, minimizes the problem of lack of variation in tone texture and/or pattern on the surface. In this work, satellite image with DEM integration technique spectacularly reveals scarps and other linear features related to the Dauki Fault. Only those lineaments were considered that either (i) define a clear topographic expression or (ii) where mapped or otherwise known faults could be located in images.

The study area comprises more than 10,000 km^2, therefore this work is separated into four sub-zones, termed Zone-1, Zone-2, Zone-3 and Zone-4 (Fig.1b) based upon geomorphological variations. The Sylhet Trough exhibits flat topography and most of the area is covered by alluvium. Lineaments were only identified by river patterns (Surma, Kushiyara, Luba, Hari river etc). Zone-1 (area of N25°7'47''–25°27'40'' and E90°33'32''–91°29'29'') extends from the Sommessari River in the west to Jadukata River in the east and shows lineament azimuth concentration direction of E-W, NW-SE, and SE-NW. The dominant quadrant follows the trend of Dauki Fault and associated faults and some other follow the trend of Dapsi Thrust which is marked at the south of Tura. Zone-2 extends west of Khasimara River to the Dauki River (N25°8'50''–25°20'30'' and E91°27'28''–92°3') and displays the most active and complex portion of the Dauki Fault. Here, several segments of the fault shortly cross-cut by deeply incised rivers can be identified (Fig. 1). This zone exhibits an E-W dominant linea-

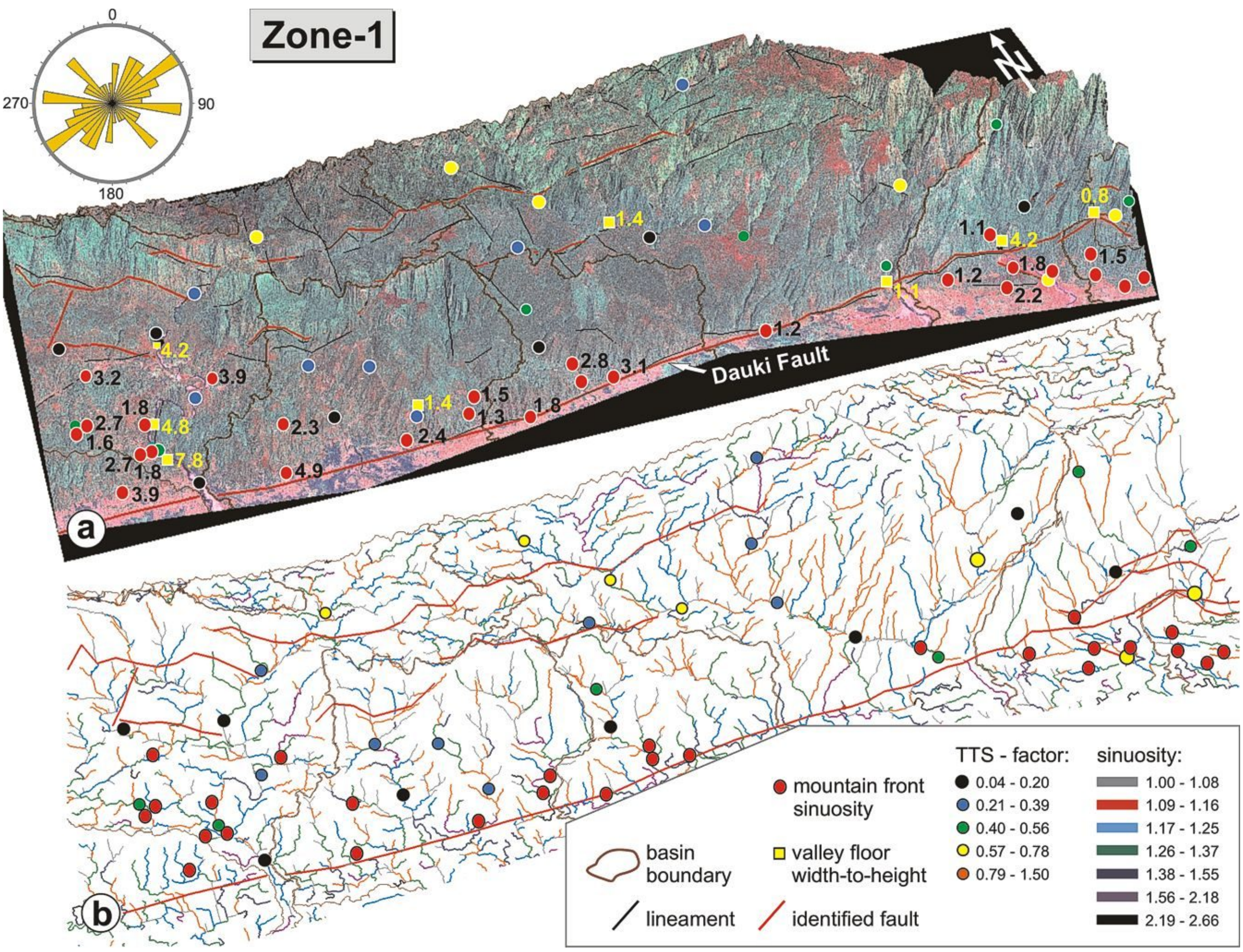

Figure 2: Geomorphic indices and structural features of Zone-1. a) Landsat ETM+ (band 7,4,2 - panchromatic band was used to increase resolution of all bands to 14.5 m) draped on SRTM elevation data (90 m resolutions) with a vertical exaggeration of 3X. Image extent is N25°7'33'' to 25°28'52'' and E90°32'49'' to 91°30'36' b) 3D river network (termed 3D stream profile in text) of Zone-1 displaying the sinuosity of Strahler Stream Order 4 in its colour code with other geomorphic and structural features. TTS – Transverse Topographic Symmetry.

ment assemblage. Zone-3 and Zone-4 are the eastern part of the study area extending from Dauki Bazar to Halflong (area between N25°2'6''-25°26'57'' and E92°3'9'' – 92° 54'). Zone 3 incorporates a complex part of the fault system with E-W and NE-SW striking lineament sets. Further east, in Zone-4, lineaments follow the general trend of Dauki Fault and Daisang-Halflong Thrust. Rose diagrams displaying lineaments analysed in the different zones are shown in Figures 2-5. As shown below, the lineament pattern and the geomorphological indices suggest an increasing tectonic activity along the Dauki Fault at the central part (around Dauki Bazar area) both from the west and the east.

5. Tectonic geomorphology of the southern margin of Shillong Plateau

5.1. Geomorphic Setting

Topography of the southern part of Shillong Plateau is an expression of differential uplift (Srinivasan et al., 2003) associated with basement controlled block faulting (Murthy et al. 1969). The monsoon-dominated erosion can account for the rugged landscape along the southern margin of the plateau. The plateau is extended in EW direction with an average elevation of 1600 m (Rao and Kumar, 1997) while topography is asymmetric along north south profile: the southern margin of the plateau is characterized by deep gorges, incised river valleys, waterfalls, and straight topographic features, the northern boundary shows a relatively smoother, staircase-type topography. The eastern boundary is limited by Kopili-Bomdila Fault, which dissects the Mikir Hills. The Shillong Plateau stopped its westward propagation by the Brahmaputra River where the river bends near about 90°, to change course from westwards to southwards. The panorama view of the whole plateau (Fig. 1) shows a significant number of N-S, NE-SW, NW-SE striking lineaments, most of which can be combined with joints and faults in the basement rock. However, one of the main tectonic elements of the Bengal Basin is the Dauki Fault, which separates the Shillong Plateau from the Sylhet Trough. Episodic uplift accompanied by prolonged weathering and erosion likely resulted in exhumation and exposure of basement rocks along some parts of the fault. Intense erosion probably has enhanced widening of existing fractures and formation of rounded hills. The linear V-shape deep valley in Zone-3 supports the possibility of widening of existing NE-SW trending fractures. The rounded Tertiary hills in south of Dauki Fault near Jaintiapur provide the example of intense erosion, which differs from the hills formed north of the fault trace. The traces of the Dauki Fault along the southern margin of Shillong Plateau transect in Cretaceous, Eocene, Oligocene, and in Miocene rocks.

5.2. Geomorphic Indices

The rugged topography and V-shaped valleys suggest a rapid and tectonically induced incision at the southern part of the Shillong Plateau. For this area, we use several geomorphic indices, which are based on the topographic data, in order to evaluate the relative rate at which constructive and destructive processes are operating in the landscape. A comprehensive introduction to these techniques is given in Keller and Pinter (2002).

5.2.1. Mountain Front Sinuosity

Tectonically active mountain fronts are straighter than mountain fronts in regions where erosion dominates over tectonics (Keller and Pinter, 2002). This reflects the balance between erosional forces that tend to cut embayment into a mountain front and tectonic forces that tend to produce a straight mountain front coincident with an active range-bounding fault. An index for this balance is simply defined as (Bull and McFadden, 1977):

$$S_{mf} = \frac{L_{mf}}{L_s} \qquad \text{(Equ. 1)}$$

Where S_{mf} is mountain front sinuosity index, L_{mf} is the straight-line distance along contour line, and L_s is the true distance along the same contour line. In this study, S_{mf} was calculated from the SRTM data generated contours. Contours were derived with help of ArcScene Software (ESRI) and were calculated in the GIS environment after careful comparison with the topographic map. These data reveal that S_{mf} records low values (1.067 to 1.6, see Fig. 2, 3) in those areas (i.e. Zone-2 and Zone-3) where the Dauki Fault has most horizontal and/or vertical displacement. The values increases towards west in Zone-2 as well as in the eastern parts of the study area where high values (S_{mf} >2) are associated with erosion-dominated areas and only minor tectonics signals.

5.2.2. Valley Floor width-to-height ratios

The ratio of valley floor width to height is an index based on the observation that incised streams with narrow valley floors and V-shaped valley profiles mark areas undergoing rapid uplift. It is defined by Bull (1977) as:

$$V_f = \frac{2V_{wf}}{(E_{ld} - E_{sc}) + (E_{rd} - E_{sc})} \qquad \text{(Equ. 2)}$$

Where, V_f is the valley floor width-to-height ratios, V_{wf} is the width of valley floor, E_{ld} and E_{rd} are elevations of the left and right valley divides (looking downstream), and Esc is the elevation of the valley floor. High values of V_f are usually related to low tectonic activities whereas low values are associated with active areas of undergoing relatively rapid uplift and valley incision (Azor et al., 2002). The values for the input parameters into equ. 2 were measured along the different valley profile from Nitai River (Zone-1) to Dibang River (east of Zone-3). The parameters were calculated from the SRTM data using Microdem 8.0 software (BLM). We selected valley profiles (in most cases) at a distance of 200 m – 5 km northward from active mountain front. In Zone-1, the Nitai river shows very high values (>15) whereas the Jadukata river records values from 1-5. Zone-2 and Zone-3 show very low values, indicating the dominance of tectonics over erosion (Fig. 3, 4). Clearly, the high values are typical for the western side of the fault zone where erosion dominates over tectonics but the values are low where the fault trace is straight. These results suggest again that the eastern part of the study area is tectonically more active and uplifted than the western part.

5.2.3. Stream - Gradient Index

Stream-gradient index may be used to evaluate possible relationships between tectonic activity, rock resistance and topography (Hack, 1973). The stream-gradient index or stream length-gradient index is defined by

$$I_{sg} = \frac{\Delta H}{L_r} L_{tc} \qquad \text{(Equ. 3)}$$

Where $\Delta H/L_r$ is the channel slope (average slope for every small stream) and L_{tc} is the total channel length from the site upstream to the highest point on the channel. This index is sensitive to the channel slope and correlates with the stream power, which is related to the ability of a stream to erode its bed and transport sediments. The I_{sg} for the Strahler Stream Order for a polyline river network of order 3 were calculated and plotted spatially (Fig. 6). The parameters of streams were calculated using RiverTools software (Rivix, LLC) and comparing with the topographic map. The indices are anomalously high in Zone-2 and for some rivers in Zone-3. Generally all rivers west of Jadukata show low I_{sg} which is consistent with V_f. The tributaries of Jadukata that are flowing west, Um Parsamat, Um Pymagithuli, Um Sohryngkew, Dauki, and Hari correspond to deep incision, showing high values of I_{sg} (Fig. 2, 3).

5.2.4. Transverse Topographic Symmetry Factor and Drainage Basin Asymmetry

Transverse Topographic symmetry is a quantitative index to evaluate drainage basin (i.e. the catchment area) asymmetry and is defined as (Cox, 1994):

$$T = \frac{D_a}{D_d} \qquad \text{(Equ. 4)}$$

Where D_a is the distance from the midline of the drainage basin to the midline of the active meander belt, and D_d is the distance from the basin midline to the basin divide. This index does not provide direct evidence of ground tilting but is useful as a reconnaissance method for rapidly identifying possible tilt. For a perfectly symmetric basin, T = 0. As the asymmetry increases, T increases towards 1, assuming that the migration of stream channels is an indication of possible ground tilting where the bedrock has negligible influence on stream migration. This index was calculated and plotted from the Dauki Fault trace northward for strahler stream order 5 rivers in order to have a rough estimate of a possible basin tilt. Different T values are plotted in Figures 2-5.

The drainage basin asymmetry can easily be visualized and interpreted using a 3D skeleton of river networks (Fig. 2-5). Tributaries to streams that flow down steep regional slopes may be asymmetrical with active tilting, with longer distances between the channel and the drainage divide on the high side of the basin. Zone-1 incorporates the drainage basins-11, 13, 14, 15 and 16 (numbers are given in the Figure 6) where the Sommessari, and Jadukata are the main rivers. Basin-13 provides an interesting view of the active tectonics where the basin has been incised deeply despite the fact that half of the area contains weathering resistant gneissic complexes and granites. The asymmetry indicates that this basin is elevated in its northeastern part. The Jadukata river flows along the western side of the basin (looking northward), and tributaries of the Jadukata are longer for the eastern than the western side (Fig.2). Basin-11 is nearly symmetrical, and the main river runs along at the center of the basin. Zone-2 contains Basin-9, and parts of 8 and 10 where the Dauki, Um krem, Um Sohryngkew, Um Pymagithuli, Umlong are the main rivers. The Um Sohryngkew and Um Pymagithuli rivers deeply incise Basin-9 to the same level, exposing basement rocks (Fig. 3). The tributaries in this basin have symmetrical length to the main channel. Basin-8, in Dauki river also deeply incised the bedrock. The south of this zone is adjacent to the straight segment of the Dauki Fault. This deep incision suggests additional vertical block movement, which has focused more activity in this zone. Zone-3 contains

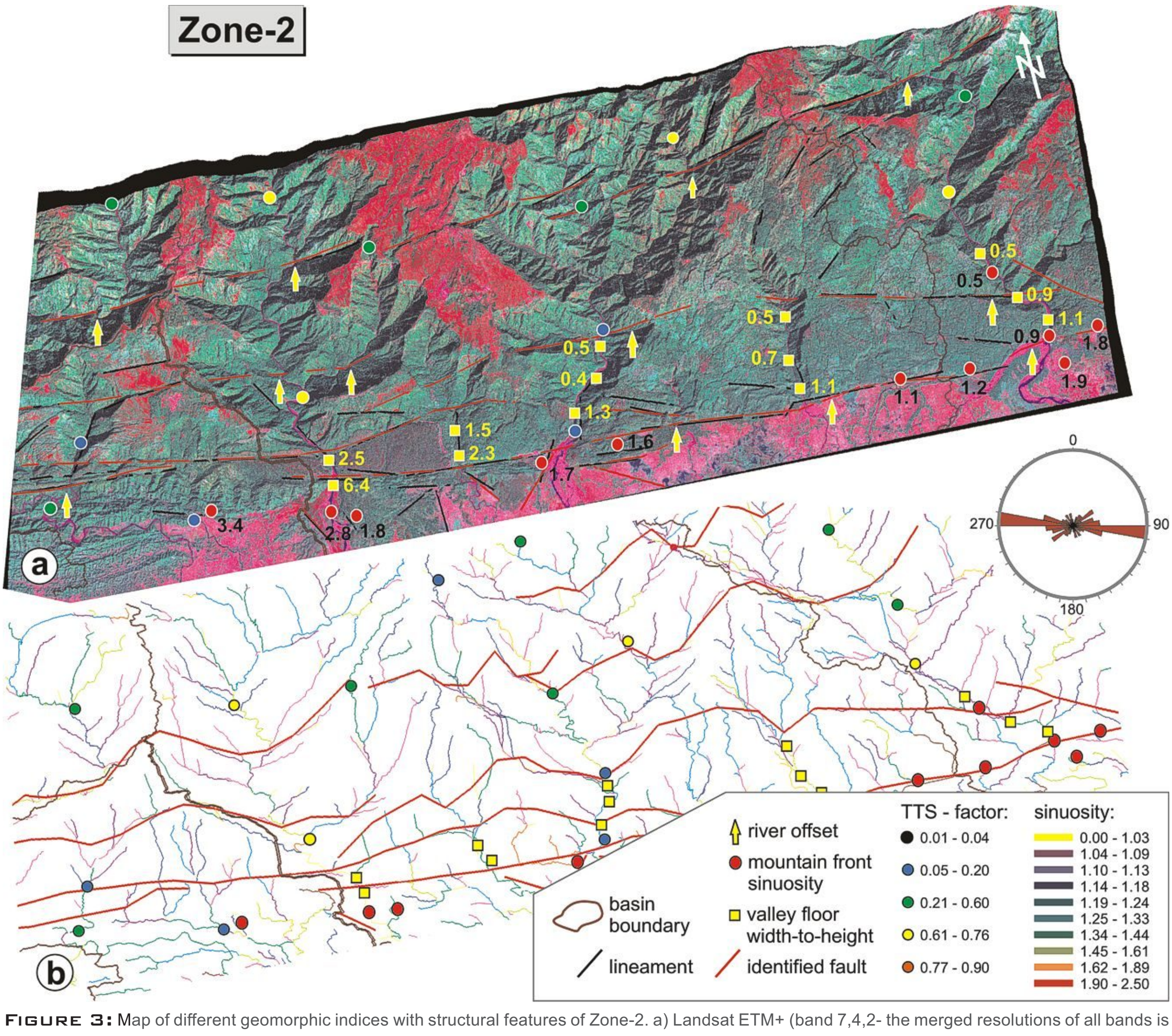

Figure 3: Map of different geomorphic indices with structural features of Zone-2. a) Landsat ETM+ (band 7,4,2- the merged resolutions of all bands is 14.5 m) over SRTM elevation data (90 m resolutions) with a vertical exaggeration of 3X. The image extent is N25°8'38'' to 25°22'38'' and E91°27'18'' to 92°3'18''. Stream offsets are marked by yellow arrows on river near by Mailang, Um Pymagithuli, Um Sohryngkew, Um Krem, and on Dauki river respectively from west to east. b) 3D river network (termed 3D stream profile in text) of Zone-2 displaying the sinuosity in its colour code with other geomorphic and structural features. TTS – Transverse Topographic Symmetry.

Basin-8 where the Dauki, Hari and Luba are the main rivers flowing from north to south. These rivers also significantly incised the southern margin of the plateau where mainly Tertiary rocks are exposed. Main rivers clearly maintain incision through the interior of the zones and local asymmetry along some river suggests some westward tilting of the block. In Zone-4, the Luba, Gumra, Simleng, Jatinga are the main rivers. They flow from east to west following trends of major faults. Asymmetry of the basin is observed where the Dauki Fault is segmented.

5.3 Fluvial response:

Twenty drainage basins were investigated along the southern front of the Shillong Plateau, among which Basins 5 to 17 (from the Jatinga river in the east to the Somessari river in the west) are used in this study. Dendritic drainage patterns are generally observed in all basins. However, tributaries of the Jadukata River (Basin-13, see Fig. 2) and the river pattern in Basin-8, southeast of the area of investigation, show trellis patterns, which suggest that the drainages are also controlled by some linear structures. Additionally, the following parameters were used in order to evaluate the tectonic activity:

5.3.1. Drainage density

Drainage density (i.e. the number and length of channels per unit area) along the Dauki Fault zone generally varies from ~1 to 5 km^{-1}, where 1.5 to 2 km^{-1} is the dominant density. The numbers increase in Basin-8, 9, and 13 where incision is clearly visible

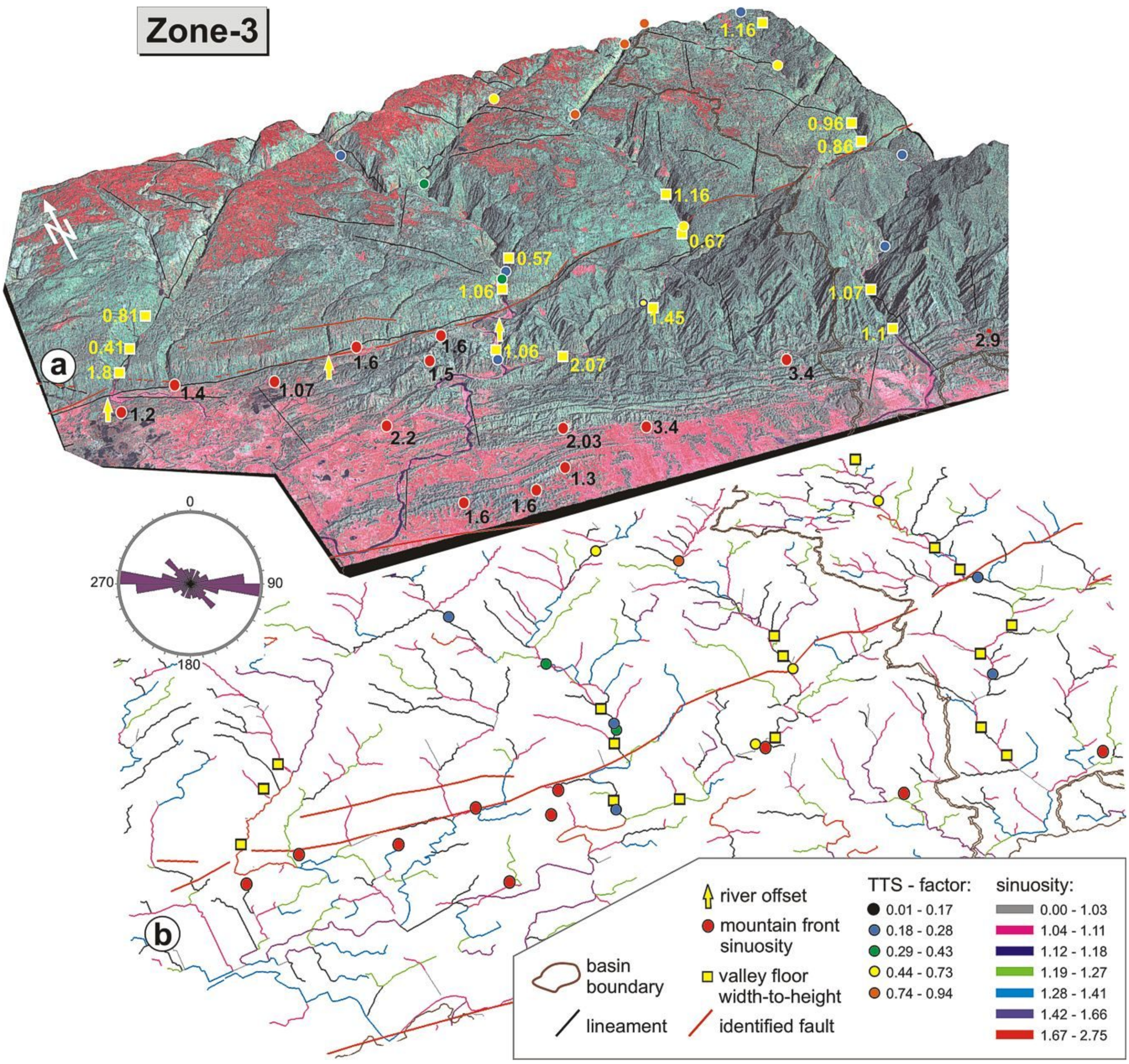

Figure 4: Geomorphic indices and structural features of Zone-4. a) Landsat ETM+ (band 7,4,2 - the merged resolution of all bands is 14.5 m) draped on SRTM elevation data (90 m resolution) with a vertical exaggeration of 3X. The image is bounded by N25°1'56'' to 25°16'44'' and E92°3'3'' to 92°27'10''. Stream offsets are marked by yellow arrows on river Rangpani, Nayagang and on river Hari from west to east. b) 3D river network (termed 3D stream profile in text) of Zone-4. TTS – Transverse Topographic Symmetry.

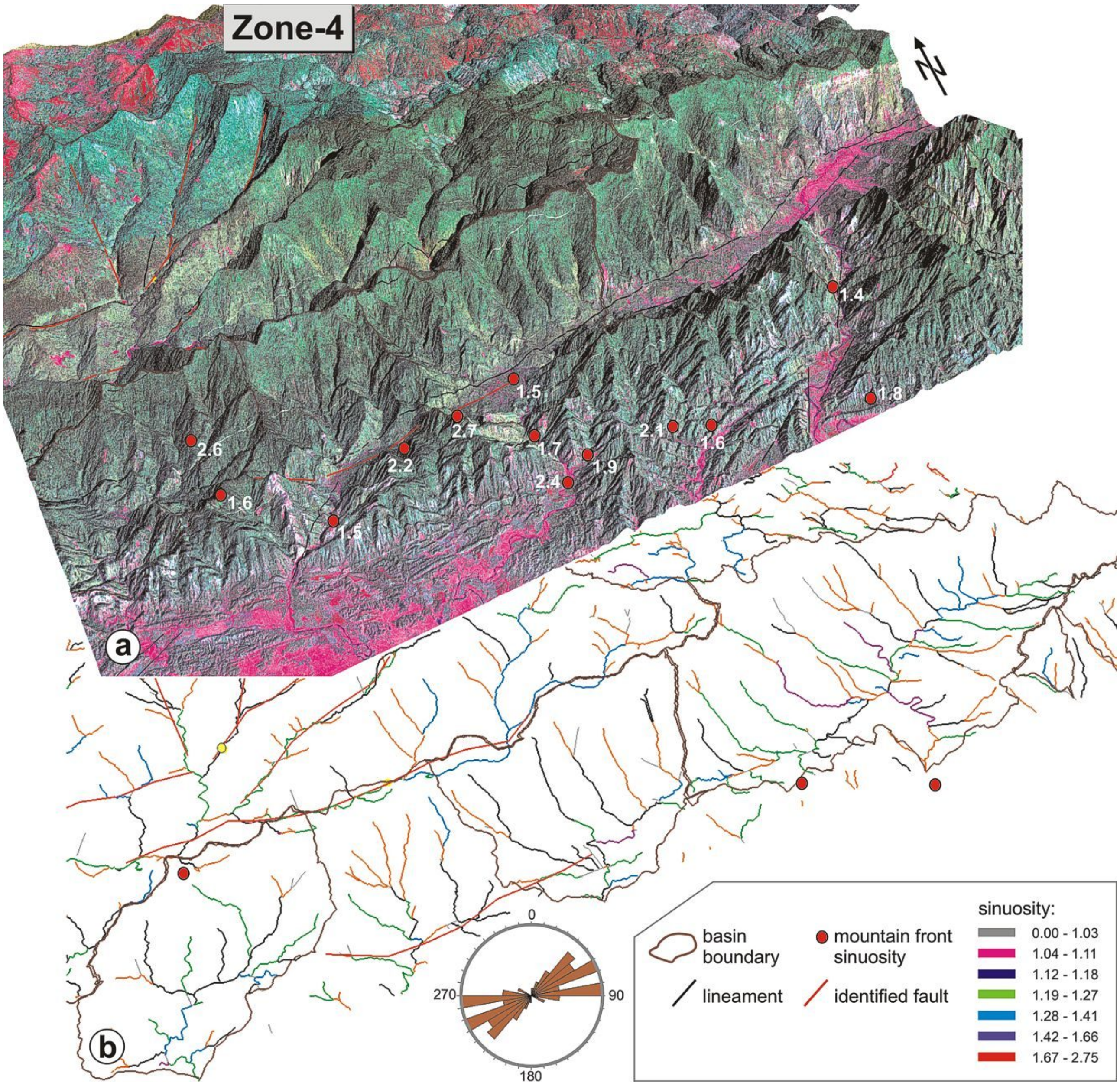

Figure 5: Map showing different geomorphic indices with structural features of Zone-4. a) Landsat ETM+ (band 7,4,2 - panchromatic band was used to increase resolution of all bands to 14.5 m) draped on SRTM elevation data (90 m resolutions) with a vertical exaggeration of 3X. The image is bounded by N24°58'55'' to 25°15'7'' and E92°26'42'' to 92°54'46''. b) 3D river network (termed 3D stream profile in text) of Zone-4.

in the DEM., the overall development of drainage pattern along the fault zone is roughly uniform however.

5.3.2. Sinuosity

The sinuosity is defined as the channel length divided by valley length. Rivers meander in order to maintain a channel slope in equilibrium. Any tectonic deformation that changes the slope of the river valley may result in a corresponding change in sinuosity. Where meandering rivers cross tectonic up-warps, they tend to be less sinuous on the upstream flank and more sinuous on the downstream flank. The sinuosity for Strahler Stream Order 3 was used to check this criterion, especially where new faults have been identified. Sinuosity variation for the area is 1 to 3.5 and a change in this magnitude is associated with locations, where rivers cross E-W striking faults (Fig. 2, 4) mapped from the satellite image and the DEM.

5.3.3. Offset streams

Offset streams reflect movements on strike-slip faults (Keller and Pinter, 2002). Systematic offset of stream reaches below the fault relative to the reaches upstream can provide essential characteristics for determining sense of movement of active strike-slip fault. Estimation of the magnitude of the offset may be hindered by continuing fluvial activities including re-distribution of fluvial sediments. Therefore, in this work we focus solely on the sense of movement of the mapped faults. Examples of offset streams are shown as arrow marker in Figures 3 and 4.

5.3.4. Stream longitudinal profile and 3D stream profile

A stream longitudinal profile is a plot of channel or valley length with respect to channel or valley elevation above sea level. The longitudinal profiles for most streams form a relatively smooth curve, with low gradients in downstream reaches that gradually increase upstream. Perturbations in a stream's longitudinal profile can be caused by changes in geologic substrate, and variations in water or sediment input from tributaries. If such anomalies are traced across several streams, however perturbations may be due to tectonic activity. Convex segments or knickpoints can be masked with other tectonic indices to support the isolated signal from tectonic activity. We present 6 longitudinal stream profiles along the rivers Jadukata, Shella, Um Sohryngkew, Dauki, Hari, and Luba (Fig. 6). Additionally, a 3D skeleton for each river network has been constructed (i.e. 3D stream profile) in order to visualize the spatial distribution of perturbations (Fig. 2, 4).

5.4. Structural features

The Dauki Fault is the main structural feature in the study area, forming a zone of distributed deformation rather than a single fault. At Dauki Bazar (N25°11'19'', E92°1.5'), the type locality of the fault, the fault has maximum displacement (exposing biggest fault scarp), which progressively drops to zero in both east and west directions. In the eastern strand, the Dauki Fault bifurcates east of 92°20' (Dasgupta and Biswas, 2000) reducing the displacements on individual fault block throws. This gives the fault zone a step like character. At 92°30', the Dauki Fault is segmented into at least in five parts (Fig. 1 and Fig. 6) displays a horse-tail structure geometry. The southern branch eventually forms a part of the Plateau but disappears at E 92°43'. The other E-W striking fault, the Halflong-Disang Fault, is firstly identifiable at 92°27', a few km south of the Dauki Fault from where its displacement increases towards E. And in this area, the Halflong-Disang Fault marks the edge of Shillong Plateau before it links up with the Halflong Thrust/Disang Thrust near Halflong. A blind fault passes under the alluvium at south of Atgram known from seismic sections (Hiller and Elahi, 1984) of Sylhet Trough. Above this fault tip, the Tertiary sediments south of the Dauki Fault pile up, forming hills up to almost 700m. From Dauki Bazar, the westward propagation of Dauki Fault is nearly straight and the trace is sharp up to Theriaghat where Murthy et al. (1969) mapped three step-like segments of Dauki Fault. The present studies also identified few other faults parallel to the Dauki Fault in the same area (Fig. 3). West of the Jadukata River, the fault again changes strike towards SW.

A closer inspection of the trace of the Dauki Fault reveals a complex zone of deformation: In Zone-1, some other faults are present parallel to the Dauki Fault (Fig. 2). In Zone-2, other secondary faults record right- and left-lateral displacement senses (Fig. 2, 3). In the river Um Pymagithuli, four faults traces can be identified from south to north based upon the evidence of sharp topographic changes, distinct linear features, tonal difference on the satellite image and from other geomorphic indices such as river sinuosity, longitudinal stream profile, and stream offset. At least five faults traces can be easily recognized into river Sohryngkew. The blind fault, which passes under the alluvium, south of Atgram and Dupi Tila hill range is probably mainly responsible for the local surface uplift causing a sharp change in erosional patterns (south of Dauki Fault in Zone-3). Linear ridge-like features in Zone-3 (Fig. 4) show conspicuous 'kink' type geometry in the DEM. Because in this area, the rocks are of uniform composition and uniformly dip south (Chowdhury et al., 1996), we speculate that the observed geometrical effect is the result of erosion along bedding parallel fractures.

6. Discussion

High-resolution DEM data and Satellite images are a useful tool for quantitatively investigating lineaments and faults, geomorphic indices and other fluvial responses in order to get a better understanding of active tectonics in an area like the southern margin of the Shillong Plateau, where dense vegetation and poor outcrop quality is an issue. Lineament patterns reveal that the expression of tectonic activity is strongest in Zone-2 (Fig. 3). All the geomorphic indices further support the idea that Zone-2 experienced more recent deformation than the other zones in the study area. Low values of mountain front sinuosity and valley floor width to height, and high values of stream gradient index in Zone-2 are in accord with high tectonic activity compared to the power of fluviatile erosion. Therefore, the suggestion that the topography of Zone-2 is mainly controlled by erosion (annual precipitation > 10,000 mm/year) is absolutely not supported by the geomorphologic parameters determined in this study. Furthermore, exposed rocks in Zone-2 are basement complex, granite intrusions, Paleozoic rocks, Jurassic and Cretaceous volcanic and thick successions of Tertiary sedimentary rocks, are the result of a few deeply incised rivers (Fig. 3). We therefore suggest that the appearance of rugged topography and v-shaped valleys is not only a product of climate-driven erosion but also reflects an active tectonic signal. Transverse topographic symmetry factors and drainage basin asymmetry analyses reveal that the southern part of the Shillong Plateau is not tilted as one entire block in one direction. Some of the drainage basins support this tilting while others record symmetry of the drainage basin. For example, the drainage basin containing the Jadukata River (Basin-13) has been tilted towards the west whereas the adjacent eastern drainage (Basin-11) shows no evidence for tilting (Fig. 2). Differences of incision levels of different rivers also support a model of differential uplift among different blocks. This is consistent with the block-faulting model (Murthy et al., 1969), which creates vertical uplift with magnitudes increasing from south to north. The drainage density along the Dauki Fault varies from ~1 to 5 km^{-1}. Higher densities are also consistent with higher tectonic activity in Zone-2. Newly calculated 3D stream profile visualizations further support differential uplift along the southern part of Shillong Plateau. The faults that are parallel to the Dauki Fault in Zone-2 and 3 indicate that the Dauki Fault represents a complex fault zone that facilitated basement rock uplift at higher altitudes in the north. The Dauki Fault has been considered as thrust fault. However, newly traced faults in Zone-1 and 2 constrain additional dextral and sinistral displacement components. In Zone-1, alongside the Dapsi Thrust (Kayal,

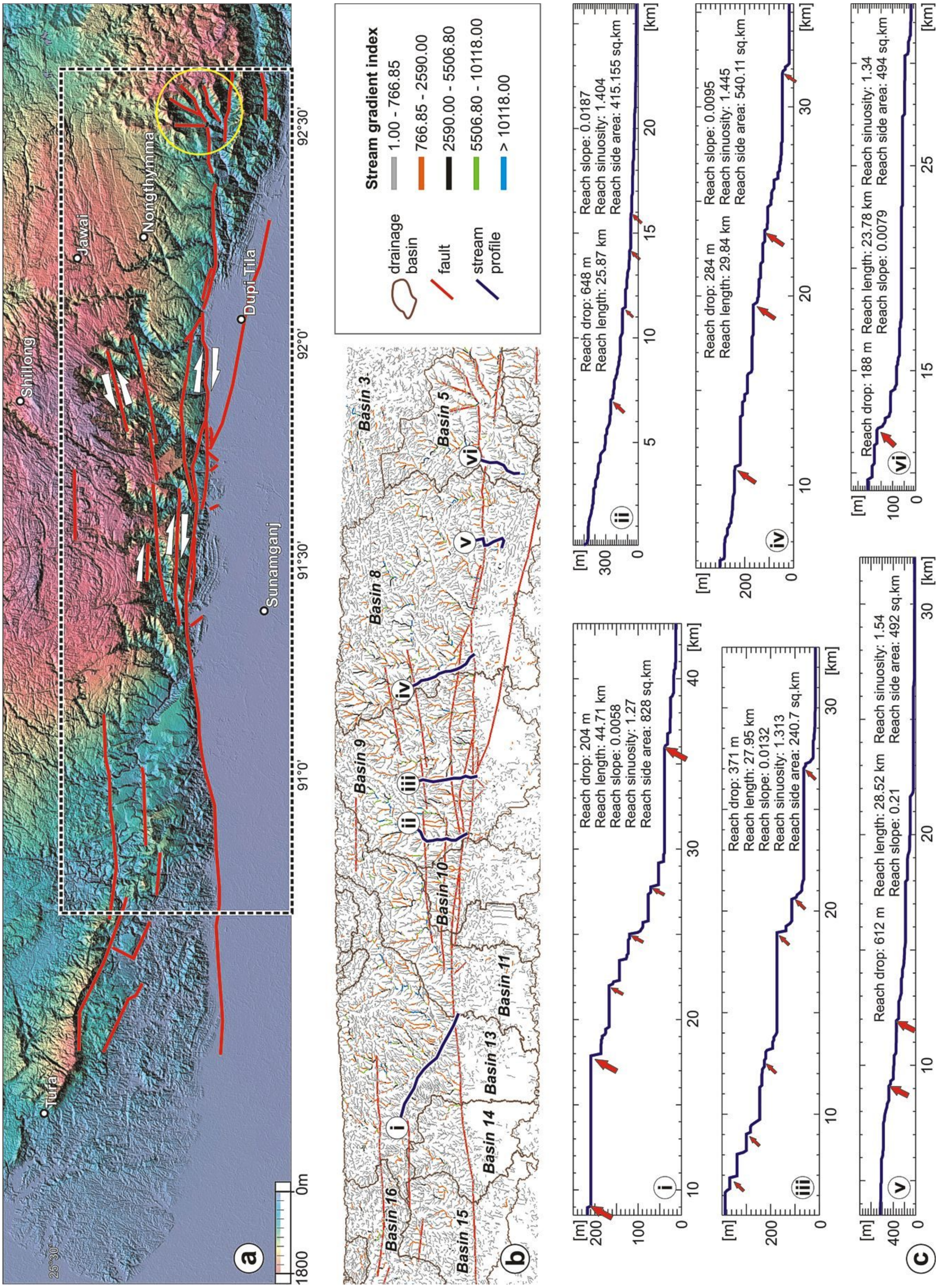

Figure 6: Map showing structural features, stream gradient index, drainage basin divide and longitudinal stream profile for few selective rivers. a) Interpreted faults in Digital Elevation Model (vertical exaggeration 3X). b) Stream gradient index (I_{sg}) with drainage basin boundary of the studied area. c) Longitudinal stream profile (positions are marked on b) along (i) Jadukata river, (ii) Shella river, (iii) Um Sohryngkew, (iv) Dauki river, (v) Hari river, and (vi) Luba river. Knickpoints of corresponding faults are marked by arrows.

1998) south of Tura (see Fig. 1 for the location), two other faults can be identified from distinct topographic river patterns and scarps (Fig. 2), all of which are parallel to the strike of the Dauki Fault. The main trace of the Dauki Fault, which is remarkably straight at Zone-2 shows an additional right-lateral displacement component along the mountain front evidenced by offset rivers (Rangpani, Dauki, Um Krem and Sohryngkew, see Fig. 6). There is discussion about the eastward propagation of the Dauki Fault (Murthy et al., 1969; Dasgupta and Biwas, 2000). And the questions remains how the Dauki Fault links with the Naga-Diasang thrust. We propose that the Dauki Fault termination by splaying into sub-faults (horse-tail structure, Fig. 6). Whole conspicuous geometry is may not the product of heterogeneous rock erosion because the entire horse-tail structure is located in Oligocene rocks (Barail Formation).

Another important tectonomorphological observation south of the Dauki Fault in Zone-3 and 4 is that the geomorphic indices record a higher tectonic signal south of the fault. This observation is explained by a blind fault that is located under the alluvium south of Dupi Tila and Atgram. We speculate that perturbation strain (Exner et al, 2005), caused by slip on the Dauki Fault and this blind fault, uplifted a large scale monoclinal structure in the area between the two parts of the fault (Murthy, 1969, Dasgupta and Biswas, 2000). Further investigations will reveal whether the blind fault represents an individual fault ellipse, part of Dauki Fault zone or an extension of Daisang – Halflong Fault. The lineaments following the Luba, Hari and Naya Gang rivers show similar strike directions of two set faults that have been observed in the exposure of Jaintiapur and adjacent areas (Biswas, 1995) and which are probably related to the formation of the monocline.

7. Conclusions

1) Geomorphological investigations, based on remote sensing techniques and 3D visualizations support a general interpretation of the Dauki Fault as a north dipping, high angle reverse fault that facilitated the exhumation of the Shillong Plateau.
2) The Dauki Fault is not a single crustal planar feature but a multi-component, mature fault zone with complex development in space and time. Geomorphic indices suggest a highly active middle fault section where the topography is built up faster than its destruction by fluviatile erosion controlled by the Monsoonal climate. In contrast towards the western and eastern terminations of the fault, the tectonic activity decreases and erosion controls the shape of the topography.
3) Sub-parallel faults of the Dauki Fault zone bound large block areas, which record different senses of tilting. As a result, sinistral and dextral wrenching is locally observed by offset rivers.
4) The Dauki Fault together with an at least kinematically related blind thrust to the south are responsible for the deformation of the Tertiary sediments in large-scale monoclinal structures. Perturbation strain caused by these two faults uplifted the deformed sediments south of the Dauki Fault up to nearly 700 m.
5) Although devastating historical earthquakes occurred at the northern margin of the Shillong Plateau, the geomorphic signals of the uplift of the plateau with respect to the surrounding sediments of the Brahmaputra Basin are significantly larger along the southern margin. This observation suggests that the Dauki Fault is the major structure controlling the uplift of the plateau.

Acknowledgements

We thank Gerhard Wiesmayr for his invaluable assistance in the field and Christoph Janda for help with processing digital data sets. Djordje Grujic is acknowledged for his valuable comments. We thank Mike Edwards for helpful comments and linguistic corrections. Erich Draganits and Michael Meyer are thanked for critical and constructive reviews. The research was supported by the Austrian Academic Exchange Service (Project-1734-4/EZA/2000) and FWF project 15668. Nokia Mobile Software Integration Eisenstadt (Austria) are thanked for their support with Nokia high resolution CRTs.

References

Acharyya, S.K., 1980. Structural framework and tectonic evolution of the eastern Himalaya. Himalayan Geology, 11,412-439.

Alam, M., 1989. Geology and depositional history of Cenozoic sediments of the Bengal Basin of Bangladesh. Palaeogeography, Palaeoclimatology, Palaeoecology, 69, 125-139.

Alam, M.K., Hasan, A.K.M.S., Khan, M.R. and Whitney, J.W., 1990. Geological Map of Bangladesh. Geological Survey of Bangladesh, Dhaka.

Azor, A., Keller, E.A. and Yeats, R.S., 2002. Geomorphic indicators of active fold growth: south mountain - Oak ridge anticline, Ventura Basin, Southern California. GSA Bulletin, 114(6), 745-753.

Banerji, R.K., 1984. Post-Eocene biofacies, paleoenvironments, and paleogeography of the Bengal Basin, India. Palaeogeography, Palaeoclimatology, Palaeoecology, 45, 49-73.

Bilham, R. and England, P., 2001. Plateau 'pop-up' in the great 1897 Assam earthquake. Nature, 410(6830), 806-809.

Biswas, S., 1996. Structural and tectonic set-up of Jaintiapur and adjacent areas, Sylhet district, along with a contribution to the petrography of the exposed Cenozoic deposits. M.Sc Thesis, Janahgirnagar University, Savar, Dhaka, 127 pp.

Bull, W.B., 1977. Tectonic Geomorphology of the Mojave Desert. U.S. Geological Survey Contract Report 14-08-001-G-394, Office of Earthquakes, Volcanoes, and Engineering, Melano Park, CA, 188pp.

Bull, W.B. and McFadden, L.D., 1977. Tectonic geomorphology north and south of the Garlock fault, California. In: D.O. Doehring (Editor), eigth Annual Geomorphology Symposium. Geomorphology in Arid Regions. State University of New York at Binghamton, Bringhamton, NY, pp. 115-138.

Chowdhury, K.R., Biswas, S. and Ahmed, A.M.M., 1996. The structural and tectonic set-up of Jaintiapur and adjacent areas, Sylhet District, Bangladesh. Bangladesh Geoscience Journal, 2, 1-14.

Cox, R.T., 1994. Analysis of drainage basin symmetry as a rapid technique to identify areas of possible Quaternary tilt-block tectonics: an example from the Mississippi Embayment. Geological Society of America Bulletin, 106, 571-581.

Das, J.D., 2004. Active tectonics of the Eastern Himalyan foothills region and adjoining Brahmaputra Basin based on satellite images. International Journal of Remote Sensing, 25(3), 549-557.

Dasupta, A.B. and Biswas, A.K., 2000. Geology of Assam. Geological Society of India, Bangalore, 170 pp.

Desikachar, S.V., 1974. A review of the tectonic and geological history of eastern India in terms of 'plate-tectonics' theory. Journal of Geological Society of India, 15, 137-149.

Evans, P., 1964. The tectonic framework of Assam. Journal of Geological Society of India, 5, 80-96.

Exner, U., Mancktelow, N.S. and Grasemann, B., 2004. Progressive development of s-type flanking folds in simple shear. Journal of Structural Geology 26(12), 2191-2201.

Golani, P.R., 1991. Nangcharam fault: a major dislocation zone from western Meghalaya. Journal of Geological Society of India, 37, 31-38.

Hack, J.T., 1973. Stream-Profile analysis and stream-gradient index. U.S. Geological Survey Journal of Research, 1, 421-429.

Harijan, N., Sen, A.K., Sarkar, S., Das, J.D. and Kanungo, D.P., 2003. Geomorphotectonics around the Sung Valley carbonatite complex, Shillong Plateau, Northeastern Inida: a remote sensing and GIS approach. Journal of Geological Society of India, 62, 103-109.

Hiller, K. and Elahi, M., 1984. Structural development and hydrocarbon entrapment in the Surma Basin, Bangladesh (NW Indo-Burman fold belt), 5th offshore SE Asia conference, Singapore, pp. 56-63.

Jauhri, A.K. and Agarwal, K.K., 2001. Early Palaeogene in the south Shillong Plateau, NE India: local biostratigraphic signals of global tectonic and oceanic changes. Palaeogeography, Palaeoclimatology, Palaeoecology, 168(1-2), 187-203.

Johnson, S.Y. and Alam, A.M. N, 1991. Sedimentation and tectonics of the Sylhet trough, Bangladesh. Geological Society of America Bulletin, 103(11), 1513-1527.

Kayal, J.R., 1987. Microseismicity and source mechanism study: Shillong Plateau, Northeast India. Bulletin of Seismological Society of America, 77(1), 184-194.

Kayal, J.R., 1998. Seismicity of northeast India and surroundings - development over the past 100 years. Journal of Geophysics, 19, 9-34.

Keller, E.A. and Pinter, N., 2002. Active Tectonics-Earthquake, Uplift, and landscape. 2nd ed. Prentice Hall, New Jersy, 362 pp.

Kumar, D., Mamallan, R. and Dwivedy, K.K., 1996. Carbonatite magmatism in northeast India. Journal of Southeast Asian Earth Sciences, 13(2), 145-158.

Molnar, P., 1987. The distribution of intensity associated with the great 1897 Assam Earthquake and bounds on the extent of the rupture zone. Journal of Geological Society of India, 30, 13-27.

Murthy, M.V., Talukdar, S.C., Bhattacharya, A.C. and Chakrabarti, C., 1969. The Dauki Fault of Assam. Bulletin of ONGC, 6(2), 57-64.

Nag, S., Gaur, R.K. and Paul, T., 2001. Late Cretaceous-Tertiary sediments and associated faults in southern Meghalaya Plateau of India vis-a-vis South Tibet: their interrelationships and regional implications. Journal of Geological Society of India, 57, 327-338.

Nandy, D.R., 1986. Tectonics, Seismicity and gravity of Northeastern India and Adjoining region. Memoirs Geological Society of India, 119, 13-16.

Rajendran, C.P.K., Rajendran, Duarah B. P., Baruah S., and Earnest A., 2004. Interpreting the style of faulting and paleoseismicity associated with the 1897 Shillong, northeast India, earthquake: Implications for regional tectonism. Tectonics, 23(4), TC4009.

Rao, N.P. and Kumar, M.R., 1997. Uplift and tectonics of the Shillong Plateau, northeast India. Journal of Physics of the Earth, 45(3), 167-176.

Sengupta, S., Sangma, L. and Srivastava, S.S., 1998. Geological and mineralogical Map of Northeastern India. Geological Survery of India, Hyderabad.

Srinivasan, V., 2003. Deciphering differential uplift in Shillong plateau using remote sensing. Journal of the Geological Society of India, 62(6), 773-778..

Received: 10. January 2005
Accepted: 14. February 2005

Subrata BISWAS[1)*)] & Bernhard GRASEMANN[2)]

[1)] Department of Geological Sciences, Jahangirnagar University, Dhaka, Bangladesh

[2)] Department of Geological Sciences, Structural Processes Group, University of Vienna, Austria

[*)] Coresponding author