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Morphotectonic Evolution of the Siwalik Hills between the Yamuna and the Markanda River Exits, NW Himalaya

Mahak Sharma[1,2], Ananya Divyadarshini[1], and Vimal Singh[1*]
[1]Department of Geology, Chhatra Marg, University of Delhi, Delhi - 110 007, India
[2]Department of Geology, Kurukshetra University, Kurukshetra - 136 119, India
E-mail: *vimalgeo@gmail.com*

ABSTRACT

The Main Frontal Thrust (MFT) marks the present day active deformation front of the Himalaya and separates it from the Indo-Gangetic plains. The dynamic growth of the outermost Siwalik hills due to thrusting along the MFT has a direct influence on the drainages which collectively control the landform evolution of the region. In this study, the Siwalik hills (called as the Dhanaura range in the study area) between the Markanda and the Yamuna river exits in the NW Himalaya is investigated for its morphotectonic evolution using geomorphic indices, longitudinal river profiles, and topographic profiles.

The results suggest presence of at least four structures that have merged to form the Dhanaura range. The first expression of the Siwalik hills was marked by the uplift of the surface due to a blind thrust in the northwestern part of the study area, followed by the growth of the Pataliyon anticline along a northeastern segment. The growth of the Dhanaura anticline occurred later by the merging of three MFT segments in the southern part of the study area. The Dhanaura anticline formed a barrier to the drainages arising from the initial northern topography, forcing them to get deflected. There also exists an unidentified structure to the north of the Dhanaura anticline as evident from the longitudinal river profiles, structural data, and drainage network of the area. Low mountain front sinuosity ratio, moderate hypsometric integral (HI) values and tilting of drainage basins in the study area suggest the structures are active.

INTRODUCTION

The Himalaya is one of the most extensively studied orogenic belts to understand the relationship between landscape morphology and active tectonics at the mountain front (Thakur, 1992; Rao, 1993; Malik and Nakata, 2003, Thakur and Pandey, 2004; Delcaillau et al., 2006, Malik and Mohanty, 2007; Singh and Tandon, 2008, 2010; Barnes et al., 2011; Singh and Jain, 2009; Kaushal et al., 2017; Divyadarshini and Singh, 2017, 2019). Continuous southward migration of the mountain front since the beginning of the Himalayan orogeny (Gansser, 1964; Yin, 2006), led to development of new landforms at the active Himalayan front that is marked by the Main Frontal Thrust (MFT). In this study, landforms associated with one such segment of the Himalayan front is investigated for its morphotectonic evolution.

The MFT separates the Himalaya from the Indo-Gangetic plains (Fig. 1a) (Nakata, 1989; Schelling and Arita, 1991; Yeats et al., 1992) and accommodates nearly 50% of the total convergence (i.e., ~10-20 mm/yr) between the Indo-Eurasian plates (Wesnousky et al., 1999; Lave and Avouac, 2000; Kumar et al., 2001, 2006, 2010; Mugnier et al., 2004). A series of NW-SE trending Siwalik hills at the frontal part of the Himalaya are evidences of this convergence. These hills are composed of middle Miocene-early Pleistocene Siwalik rocks and thrust over the recent Indo-Gangetic alluvium along the MFT (these are also known as the outermost Siwalik hills). They mostly represent fault-bend or fault-propagated folds developed over a blind or emergent MFT (e.g. Karunakaran and Rao, 1979; Raiverman et al., 1983; Nakata, 1989; Powers et al., 1998; Mishra and Mukhopadhyay, 2002; Srivastava et al., 2016, 2018; Divyadarshini and Singh, 2019). Upliftment of the Siwalik hills result in the reorganization of the antecedent drainages, which further impacts the landform evolution of the adjoining areas. Thus, morphotectonic investigation of the frontal ranges is important to understand the geomorphic development and also the fault growth pattern of the MFT.

Several studies have explored the relationship between landscape development and structures along the frontal Himalayan Siwalik hills (e.g., Janauri, Chandigarh and Mohand ranges in northwest, and the Frontal Churia ranges in the central part) (e.g., Nakata, 1972; Mukerji, 1976, 1990; Gupta, 1997; Friend et al., 1999; Mishra and Mukhopadhyay, 2002; Mukhopadhyay and Mishra, 2004, 2005; Thakur and Pandey, 2004; Malik and Nakata, 2003; Delcaillau et al., 2006; Singh and Tandon, 2008, 2010; Singh and Jain, 2009; Barnes et al., 2011; Srivastava et al., 2016, 2018; Divyadarshini and Singh, 2019); however, there lies some gaps where morphotectonic studies are yet to be carried out. One such area is the Dhanaura range present at the transition zone of the Nahan salient and Dehradun recess. This study investigates the Dhanaura range for its morphotectonic evolution using geomorphological techniques.

GEOLOGICAL SETTING

The Dhanaura Range is located to the southwest of the Dehradun (Fig. 1). It lies between the Nahan and the Mohand ranges in the NW Himalaya (Fig. 1a). To its north, it is bounded by the Kiarda Dun that represents a small intermontane valley at the western end of the Dehradun recess (Fig. 1b) (Virdi et al., 2006). To its south, the Dhanaura range is separated from the Indo-Gangetic plains by the MFT (Fig. 1b). The eastern and the western boundaries of the study area are marked by the Yamuna and the Markanda river exits (Fig. 1b).

The study area comprises of the Siwalik Group of rocks that are uplifted along the MFT. They are middle Miocene to Pleistocene in age (Pilgrim, 1910, 1913; Kumar 1999). The middle and upper Siwaliks are exposed in the Dhanaura range (Fig. 2). Here, the middle Siwalik Sub-group comprises of thick multistoried gray sandstones of the Dhok Pathan Formation exposed at the base of the sequence (Kumar et al., 1999). The upper Siwaliks are marked by the Tatrot and Pinjaur formations consisting of overbank mudstones, sandstones and conglomerates (Kumar et al., 1999). The biostratigraphy and magneto-stratigraphy suggests the rocks in the area range in age between ~ 6 Ma to 0.5 Ma (Nanda et al., 1991; Kumar et al., 1999).

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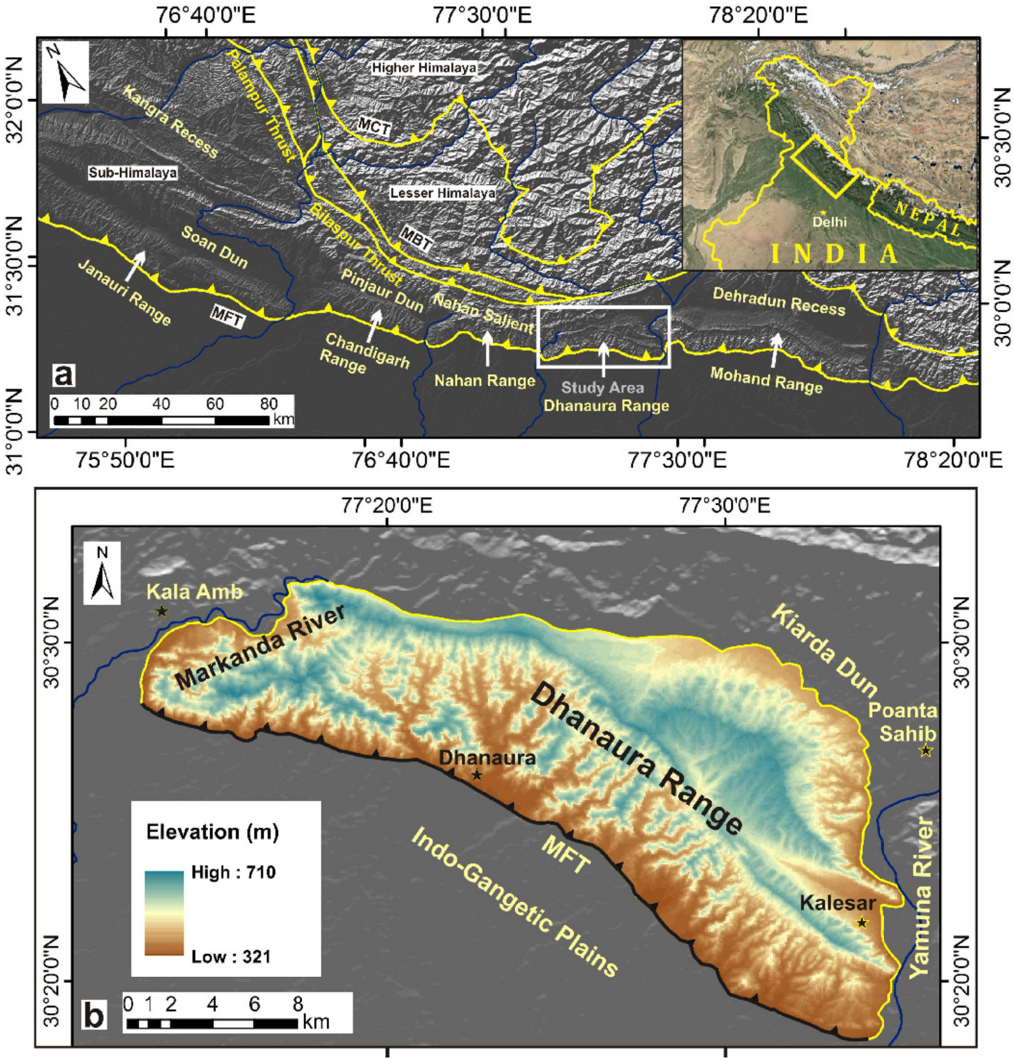

Fig. 1(a) Physiographic and tectonic map of the NW Himalaya. The outermost Siwalik hills developed along the Main Frontal Thrust (MFT) are also shown. The study area (marked by the rectangle) lies in between the Nahan and the Mohand ranges. **(b)** SRTM image showing the extent of the Dhanaura range (study area) and its elevation distribution.

The Dhanaura range shows a curvi-linear pattern and it is oriented NW-SE (Fig. 2). It is structurally controlled and marked by several faults, anticlines, and syncline. Primarily, there are four major structures identified in the area by previous workers - the MFT, the Dhanaura Anticline, the Kalesar Syncline, and the Pataliyon anticline (Fig. 2) (Mukhopadhyay and Mishra, 2004; Jayangondaperumal et al., 2009). The MFT has been displaced and offset by numerous transverse faults and lineaments (Shanker et al., 2011). The most significant transverse faults that have displaced and separated the study area from the adjoining physiographical continuities are (i) the Kala Amb fault (western end of the Dhanaura range) (Kumar et al., 2001) and (ii) the Yamuna tear fault (eastern end of the Dhanaura range) (Valdiya, 1976), that are also the mountain exit of the Markanda and the Yamuna rivers respectively (Fig. 2).

Structural studies reveal that the MFT is emergent in the present study area and the slip accommodated along it is ~ 4.1 km (Mukhopadhyay and Mishra, 2004; Kumar et al., 2006). A balanced cross-section from the study area suggests presence of a sharp crested NW-SE trending Dhanaura anticline near the mountain front (Mukhopadhyay and Mishra, 2004). The Dhanaura anticline is interpreted as a fault propagation fold along the MFT by Mukhopadhyay and Mishra, (2004), whereas, Srivastava (1981) and Raiverman (1983) described it as a cylindrical open fold with limbs dipping 20°-25° (Srivastava, 1981; Raiverman, 1983). Both the Dhanaura anticline and the MFT are curved (Fig. 2). The area to the north of the Dhanaura anticline is marked by the Kalesar syncline which is a NW-SE trending synclinal trough (Fig. 2). Further north, the Dhanaura range comprises of another anticline, marked as the Pataliyon anticline (Fig. 2). The Kalesar syncline lies in the eastern part of the study area between the Dhanaura and the Pataliyon anticlines (Srivastava, 2013). It is an important structural feature in this region; the synclinal valley is drained by the Sukh Rao stream, which joins the Yamuna river (Fig. 3).

METHODOLOGY

Reconstructing the evolutionary history of a region is challenging as it involves a complex response system to the combined effect of climate, base level, and tectonics. Study of landforms along active orogenic belts reveal a wealth of information about the growth of faults and folds, variation of structural styles, and relationship between surface processes and tectonics in driving the evolution of the landforms (Bull and McFadden, 1977; Seeber and Gornitz, 1983; Gregory and Schumm, 1987; Wells, 1988; Demoulin, 1998; Schumm et al., 2002; Keller and Pinter, 2002; Gupta, 1997; Delcaillau et al., 1998; Friend et al., 1999; Burbank and Anderson, 2012, Champel et al., 2002).

In the present study, geomorphic mapping and topographic analysis of the Dhanaura range is carried out using 90 m resolution Shuttle

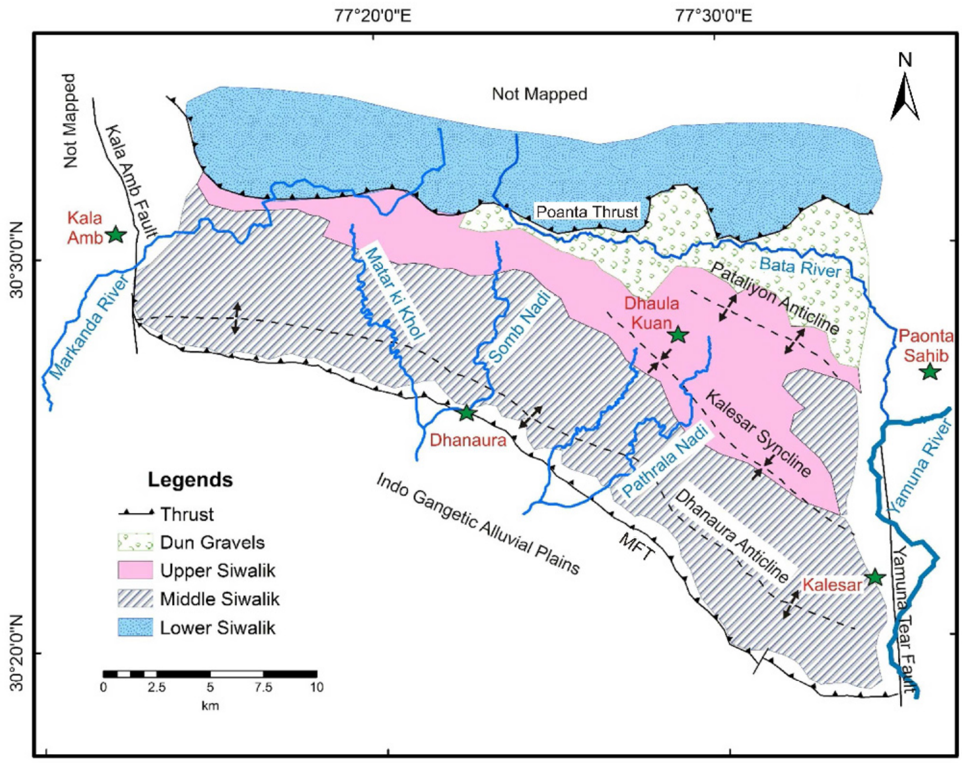

Fig. 2. Map showing geology and major structures present in the study area (modified after Philip et al., 2012).

Radar Topographic Mission (SRTM) digital elevation model (DEM), Google Earth image, and topographic maps. The SRTM data is processed in Arc GIS (9.3) software in order to (i) map the basins in the study area and demarcate the major drainage divides separating these basins, (ii) generate the profiles - both the longitudinal profiles of the rivers and the drainage divide profiles based on the contour data derived from the DEM, and (iii) calculate the geomorphic indices viz., mountain front sinuosity ratio, hypsometric integral, basin asymmetry factor and stream-length index, as per the conventional formulas given by the previous workers (e.g., Hack, 1973; Bull and McFadden, 1977; Keller and Pinter, 2002).

Surface topographic profiles and geomorphic indices are widely used techniques in tectono-geomorphic studies (Delcaillau et al., 2006; Singh and Tandon, 2008; Divyadarshini and Singh, 2019; Dey et al., 2018). A fault propagates laterally and lengthens by accumulating displacement (Cowie and Scholz, 1992a). The displacement-length profile of a fault (where propagation is unrestricted on both ends) displays a typical bow or bell-shaped curve in general, where the displacement is maximum at the center (point of initiation) and zero at the margins (Elliott, 1976; Cowie and Scholz, 1992b; Burbank et al., 1999). A fault can develop as an isolated structure that grows laterally and joins with the adjoining faults. Drainage divide profiles have been successfully used by previous workers to decipher the fault segmentation and growth pattern (Delcaillau et al., 2006; Singh and Tandon, 2008; Divyadarshini and Singh, 2019).

The mountain front sinuosity ratio (S_{mf}) is calculated as the ratio of length of the mountain front/junction between the mountain and the piedmont (L_{mf}), to the straight length of the associated range (L_s) (Bull and McFadden (1977).

$$S_{mf} = L_{mf} / L_s$$

The mountain front exhibits low S_{mf} values (varying between 1 and 1.2) in tectonically active region, whereas, mountain front with low tectonic activity show high S_{mf} values (>2) (Burbank and Anderson, 2012).

The hypsometric integral (HI) of a drainage basin is calculated by the equation

$$HI = (Z_{mean} - Z_{min}) / Z_{max} - Z_{min})$$

Here, Z_{mean} represents the mean elevation, Z_{max} is the maximum elevation and Z_{min} is the minimum elevation along the basin. H.I. values > 0.5 indicate that a larger proportion of the basin area lie at higher elevation, which in turn suggests tectonic uplift under conditions of uniform lithology and rainfall.

The asymmetry factor (AF) is used to detect the tilting direction of drainage basins in tectonically active areas (Hare and Gardner, 1985). It is calculated as:

$$AF = (Ar / At) 100$$

where, Ar - area of the basin to the right (in the downstream direction) of the main stream and At - total area of the basin. When AF is 50, it indicates symmetrical basins where drainage areas are similar on both sides of the trunk stream. AF values greater or less than 50 suggest tectonic tilt (Keller and Pinter, 2002).

The stream-length (SL) index is given by:

$$SL = (\Delta H / \Delta L)L$$

where, ΔH = change in elevation, ΔL = length of channel segment. L is the total length of the channel from its source to the midpoint of the particular segment. In general, the segments with high SL index indicate a change in lithology or the presence of an active fault (Hack, 1973; Keller and Pinter, 2002).

RESULTS

Geomorphic Mapping

The Dhanaura range covers an area of around 365 km^2 with a maximum elevation reaching up to 683 m. The major geomorphic units of the study area are the outermost hills, and related drainages, terraces and drainage divides (Fig. 3). The hills show a curvature, with its concave side towards the plains. They are highly dissected

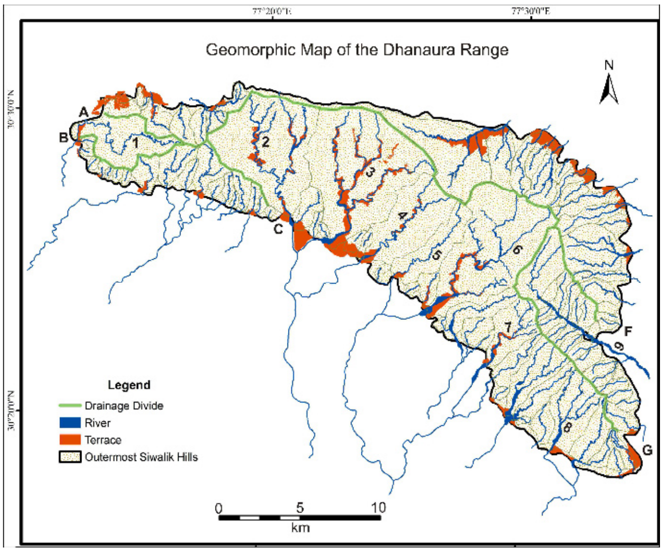

Fig. 3. Geomorphic map of the study area showing major rivers and distribution of various landforms. 1 - Stream 1, 2 - Matar ki Khol, 3 - Somb Nadi, 4 - Logarh ki Khol, 5 - Stream 5, 6 - Pathrala Nadi, 7 - Chikan Khol, 8 - Ambavali Khol, 9 - Sukh Rao. AF, AG, BF, BG, AC and BC are drainage divides of the Dhanaura range.

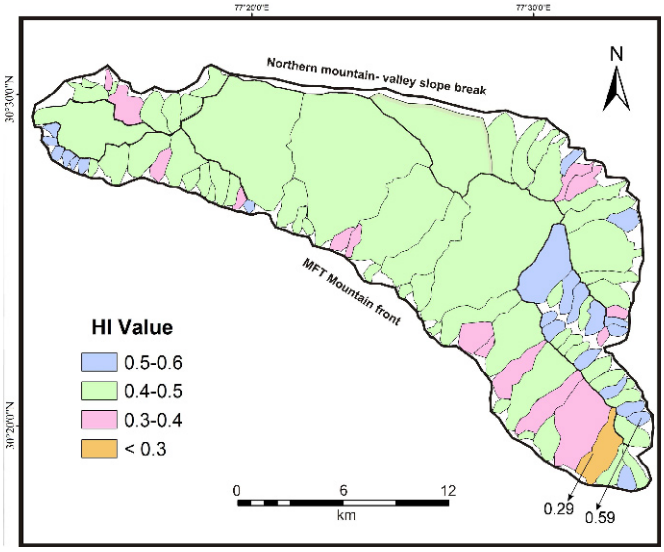

Fig.4. Map showing basins analyzed for hypsometric analysis and their classification on the basis of hypsometric integral values.

with a very sharp crest. These hills interestingly exhibit a bi-forked ridge pattern i.e., they bifurcate into two almost parallel ridges at the western and eastern ends (Fig. 3). In the west, the major drainage divides are E-W trending; they eventually change their trend to NW-SE in the east.

There are numerous streams arising from the Dhanaura range that are broadly classified as the north-flowing and south-flowing streams. The major streams in the study area are - Matar ki Khol, Somb Nadi, Lohgarh ki Khol, Pathrala Nadi, Chikan Khol, and Ambavali Khol (Fig. 3). Of all the streams, Somb Nadi is the longest. At least in three cases (Matar ki Khol, Somb Nadi and Pathrala Nadi), streams converge and show sudden change in flow direction. The streams draining the northern flank of the Siwalik hills are relatively smaller in size; they join the Bata river, which flows through the Kiarda Dun. Several stream terraces are identified associated with the major drainages of the study area (Fig. 3). Unpaired terraces are common but several paired terraces are also identified.

Hypsometric Integral Analysis

A total of 95 basins are identified on the Dhanaura range for hypsometric analysis (Fig. 4). The mouth of the basins is selected at the MFT for the south flank and at the mountain-valley slope break for the north flank. Based on the major flow directions, the basins are divided into two categories - north flowing (N or NE) and south flowing (S or SW). In general, the north flowing streams have much smaller catchment than the south flowing streams. Majority of the basins (approx. 60%) yield HI values between 0.4 and 0.5 (Figs. 4). Around 23% of the basins have HI value between 0.5 and 0.6, while 15% of them are between 0.3 and 0.4 (Figs. 4). Interestingly, in spite of variation in catchment area, most basins in the central part of the range show similar H.I. value i.e., ~0.45. Drainage basins on the northern flank show high HI values at the margins as well as in the middle part of the range (Fig. 4); whereas, drainage basins on the southern flank show high HI values only at the margins of the range (Fig. 4).

Longitudinal Profile and SL Index Values

The longitudinal river profile and SL index values are shown as useful tools to identify anomalies along the river course (e.g., Hack, 1973). Though, there are several streams originating on the Dhanaura range, longitudinal profile, and SL index analysis is carried out for eight major streams present on the southern flank of the range (Fig. 5). Results for individual rivers are discussed below:

a. *Stream 1:* It is a tributary of the Markanda river; several knick points are observed along its longitudinal profile (Fig. 5a). Out of these knick points, one is related to the Kala Amb fault, whereas, rest of the knick points does not correspond to any of the known structures or lithological breaks.

b. *Matar ki Khol:* It is a tributary of the Yamuna river. The profile of the river shows presence of around eight knick points and the major knick point corresponds to the axis of the Dhanaura anticline (Fig. 5b). High SL index value at the mouth of the river could be related to the MFT. Interestingly, there is not much variation across the lithological boundary between the Upper and the Middle Siwaliks (Fig. 5b).

c. *Somb Nadi:* It is one of the largest rivers originating on the Dhanaura range with a length of ~ 11 km along the southern flank of the range. Around eight high SL index peaks are identified on the longitudinal profile of the Somb Nadi (Fig. 5c). Some of these correspond to the axis of the Dhanaura anticline and the MFT (Fig. 5c). The lithological contact between the Middle and the Upper Siwaliks does not show any significant variation in the SL index value. There are several other segments with high values of SL index upstream of the Dhanaura anticline that does not correspond with any of the previously identified structures (Fig.5c).

d. *Lohgarh ki Khol:* Lohgarh ki Khol is a tributary of Somb Nadi joining it in the alluvial plains. In total, around seven SL index peaks are identified along the profile of the Lohgarh ki Khol. Similar to the previous streams, this stream also shows prominent knick points associated with the axis of the Dhanaura anticline and the MFT. Several other knick points are present at the upstream of the Dhanaura anticline (Fig. 5d). Knick point at the lithological contact between the upper and the middle Siwalik rocks is not observed(Fig. 5d).

e. *Stream 5:* It joins the Pathrala Nadi down in the plains. Around nine zones of high SL index values are observed along this stream. Two distinct knick points correspond to the Dhanaura anticline and the MFT (Fig. 5e). There are several knick points between the Dhanaura anticline and the lithological contact of the Upper and Middle Siwaliks.

f. *Pathrala Nadi:* It is the longest river (~ 14 km) in the study area

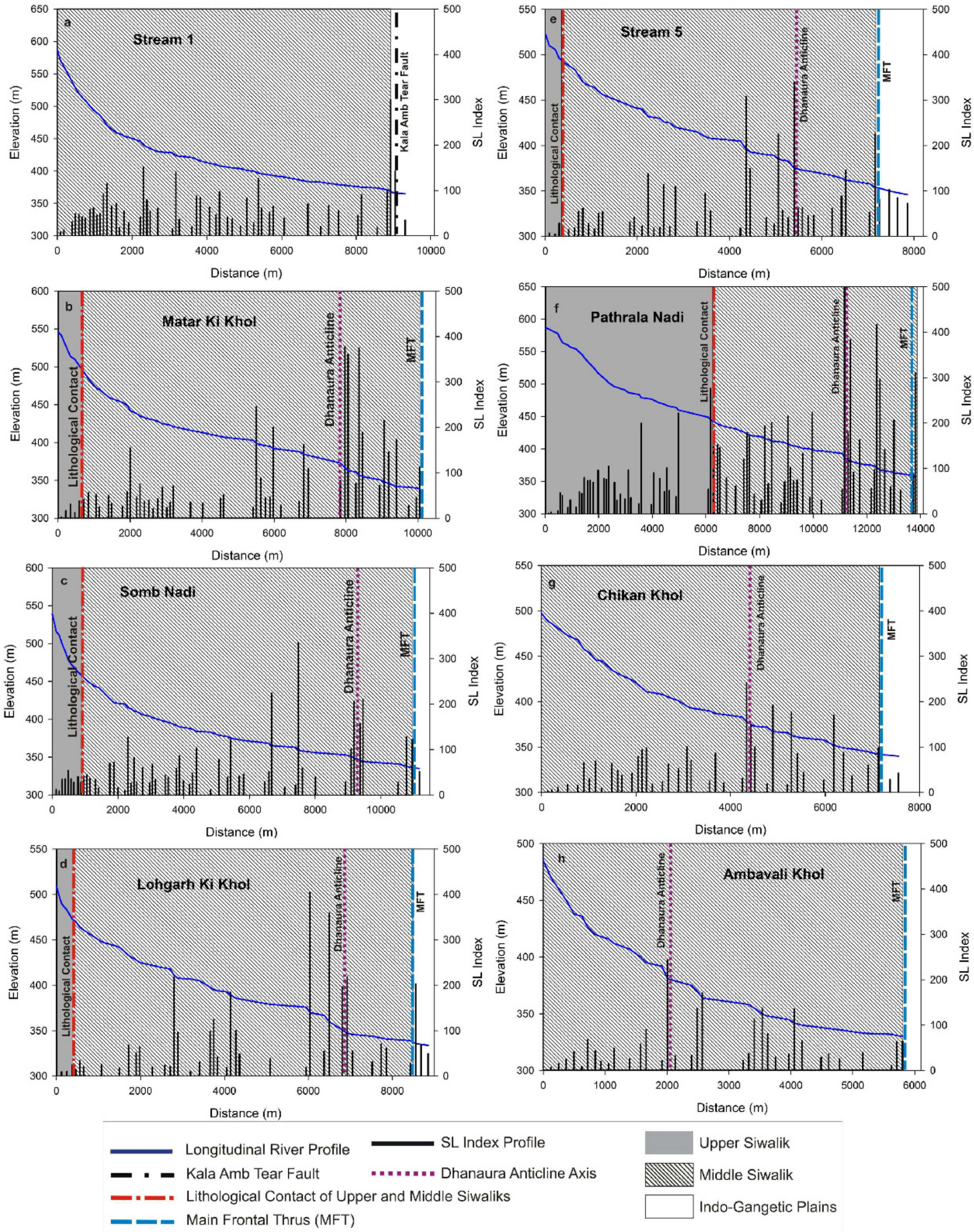

Fig. 5. (a-h) Graphs showing the longitudinal river profile and SL index values of major streams in the study area.

(Fig. 5f). Its longitudinal profile shows a sharp knick point and high SL index value at the lithological contact between the Middle and the Upper Siwalik rocks (Fig. 5f). Here also peak SL index is observed close to the axis of the Dhanaura anticline and the MFT. Several high SL index values are observed between the Dhanaura anticline and the lithological contact (Fig. 5f).

g. *Chikan Khol:* Chikan Khol is another stream which later joins the Yamuna River system. The SL index value for this stream ranges between 9 and 250. A variation in SL index values across Dhanaura anticline is observed (Fig. 5g). Prominent knick points and SL index peaks are present both upstream and downstream of the anticlinal axis. High SL index value at the mouth of the river could be related to the MFT (Fig. 5g).

h. *Ambavali Khol:* Ambavali Khol is also a tributary of the Yamuna river. Like Chikan Khol, it also shows high values of SL index and a sharp knick point near the axis of the Dhanaura anticline. Interestingly, there are several knick points between the Dhanaura anticline and the MFT (Fig. 5h).

Nearly all the streams in the study area (Somb Nadi, Lohgarh ki Khol, Pathrala Nadi, Chikan Khol and Ambavali Khol) show variation in SL index values across the axis of the Dhanaura anticline suggesting it to be a well-developed regional structure. Interestingly, only the Pathrala Nadi shows a distinct SL index peaks across the lithological contact of Middle and Upper Siwalik rocks. Occurrence of several steeper stream segments (marked by high SL index values) to the north of the Dhanaura anticline that do not correspond to any known structures or lithological contacts suggests that the presence of several unidentified structures in the study area.

Mountain Front Sinuosity Ratio

Mountain front sinuosity (S_{mf}) ratios for different segments of the study area are calculated to identify tectonically active segments. Depending upon the orientation of the mountain front, these have been divided it into three segments (Fig. 6). All the segments yield very low values of Smf, ranging between 1.2 - 1.4 (Table 1) suggesting that the mountain front is active.

Table 1. Mountain Front Sinuosity values of various segments

	L_{mf} (in km)	L_s (in km)	$S_{mf} = L_{mf}/L_s$	Inference
Segment I	0.7514	0.8972	1.2	Tectonically Active
Segment II	1.0953	1.4940	1.4	Tectonically Active
Segment III	0.5797	0.8241	1.4	Tectonically Active

Basin Asymmetry Factor

The asymmetry factor is an indicator of the tilting of the basins. It is calculated for the drainage basins in the study area based on which they are classified into three categories - right tilting (<0.5), left tilting (>0.5) and symmetric (0.5) (Fig. 6).

The results suggest that nearly all the basins on the Dhanaura range show tilting either towards left or towards right; there are very few basins that are symmetric. Most basins on the northern flank are tilted to the left (i.e. towards northwest). The basins on the southern flank show varying tilt (both towards southwest and south east). The larger south flank basins are generally tilted towards right.

Drainage Divide Profile Analysis

The drainage divide profiles of the Dhanaura range are analyzed to study the growth of the structures, and the interaction between the growing folds. The Dhanaura range is marked by the development of two major drainage divides (marked as AF, and AG) due to its bi-forked morphology (Fig. 7a). The results of drainage divide profile analysis indicate presence of at least four topographic segments that have interacted to form the Dhanaura range. The bell-shaped curve observed along the profiles AC and BC (Figs. 7b and 7c) represent the complete topography in the westernmost part of the Dhanaura range. At least three segments are identified on the profile along AF (Fig. 7d). The half-bell shaped curve at the western end of the profile (AF) is related to the same topography seen in the profiles AC and BC. The other two topographic segments are marked by two perfectly bell-shaped curves that merge with each other. The profile along AG is marked by four topographic segments (Fig. 7e). The half-bell shaped curve at the western end of the profile AG and the two bell shaped curves in its central part are related to the same segments identified on the profile along AF. The half-bell shaped curve at the eastern end of the profile is related to another topographic segment in the eastern part of the range. A sharp gradient is observed at the eastern tip of the profile along AG.

The bifurcation of the drainage divide at the eastern tip is probably due to erosion by the Markanda river that forms the base-level for streams arising from the Dhanuara range in this region. A big gap is observed in the middle part of the profile along BC, which is a wind gap (Fig. 7c); apart from that two more wind gaps are observed. The wind gaps suggest that once the Markanda or some other antecedent river flowed through this area.

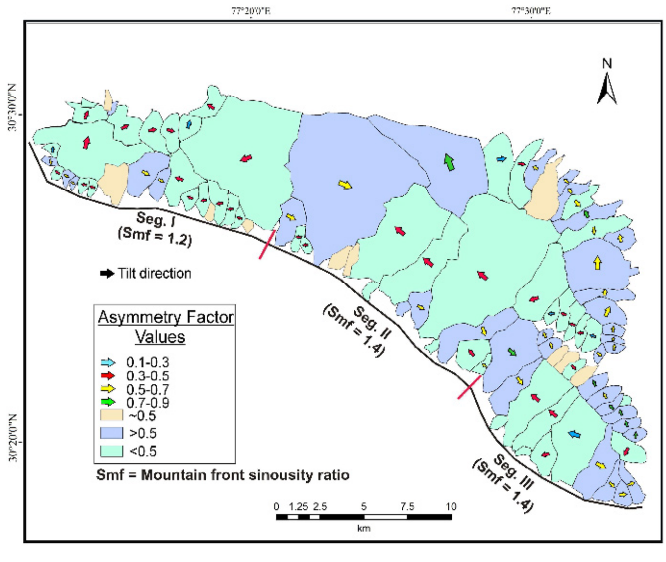

Fig. 6. Map showing the sinuosity ratio of the mountain front and asymmetry factor of the drainage basins along the Dhanaura range. The mountain front is classified into three divisions based upon the changing orientation of the Dhanaura range.

DISCUSSION

Structural Model of the Dhanaura Range

The Dhanaura range is structurally complex as it comprises of several structural segments i.e., the MFT, the Dhanaura anticline, the Pataliyon anticline, and the Kalesar syncline. The MFT in the study area - that forms the Dhanaura anticline - can be divided into three segments (marked as MFT 1, 2, and 3 on Fig. 7a) on the basis of change in the orientation of the anticline along strike. In the drainage divide profile along AC and BC (Fig. 7b), the bow shaped curve corresponds to MFT 1 at the western end of the Dhanaura anticline. The half bow shaped curve and abrupt gradient at the eastern end of the profile along AG can be related partly to erosion by the Yamuna River, and partly to the impact of the Yamuna tear fault which restricts the eastward propagation of the MFT; it corresponds to MFT 3 at the eastern end of the Dhanaura anticline (Fig. 7a). The MFT 2 in the central part of the Dhanuara anticline is not seen on the drainage divide profiles mainly due to the erosion by the Somb Nadi, Matar ki Khol and Pathrala Nadi; as a result, the main drainage divide in the central part follows the axis of the structures to the north of the Dhanaura anticline (Fig. 7a).

A balanced cross-section of the area by Mukhopadhyay and Mishra (2004) suggest the presence of a blind thrust to the north of the MFT, towards Dhaula Kaun; this blind thrust has resulted in the growth of an uplifted surface in the northwestern part of the Dhanaura range (Fig. 7a). The results of SL index analysis of streams arising on the Dhanaura range support the presence of an unidentified structure (Figs. 5c, 5d, 5e, 5g and 5h) to the north of the Dhanaura anticline as prominent knick points and high SL index value zones are observed corresponding to it. Also, field investigation shows presence of deformed and highly fractured Siwalik rocks in this zone (Fig. 8). The Pataliyon anticline is probably related to another eastward segment of this blind structure. Distinct bow shaped curves (corresponding to the northwestern surface uplift and the Pataliyon anticline) along profiles AF and AG support the existence of the blind thrusts in the Dhanaura range (Figs. 7d and 7e).

Topographic growth by merging of separate fault segments is

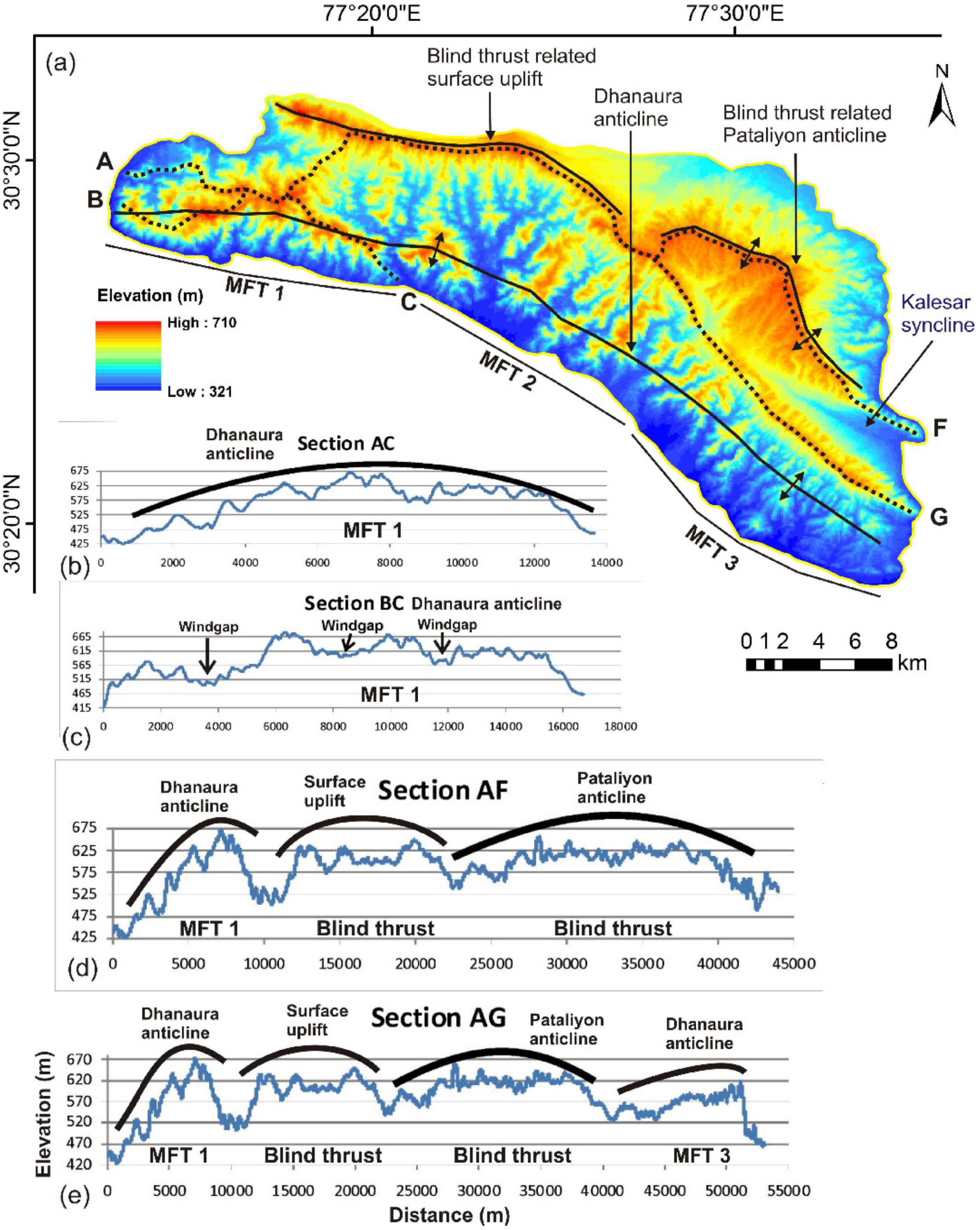

Fig. 7. Map showing the results of drainage divides profile analysis of the Dhanaura range. Segments of the MFT and the surface expression of the blind faults as inferred from the results are also shown.

Fig.8. Outcrop showing deformed and highly fractured rocks to the north of the Dhanaura anticline.

supported by the change in the orientation of the range from E-W to NW-SE. Low values of mountain front sinuosity ratio and the tilting of the drainage basins on the Dhanaura range indicate that the MFT is active in the study area. The HI values, varying mostly between 0.4 and 0.5 suggest that the basins on the Dhanaura range are in a steady state i.e., the streams are able to remove the mass added due to tectonic uplift along the MFT. Despite the weaker lithology of the hills, the moderate HI values suggest that the basins are continuously uplifting. The reason for the occurrence of some low values (around 0.3) is not clear; but we surmise that it could be related to the presence of some local structure due to which erosion in the basin is enhanced. Higher HI values (>0.5) are observed along the margins of the range implying the presence of a younger structure at the margins, so that the drainages are still not well developed, as a result low erosion. As already mentioned, there are two transverse structures present at the western and eastern ends of the Dhanaura range i.e., the Kala Amb fault and the Yamuna tear fault respectively. The tilting of the drainage

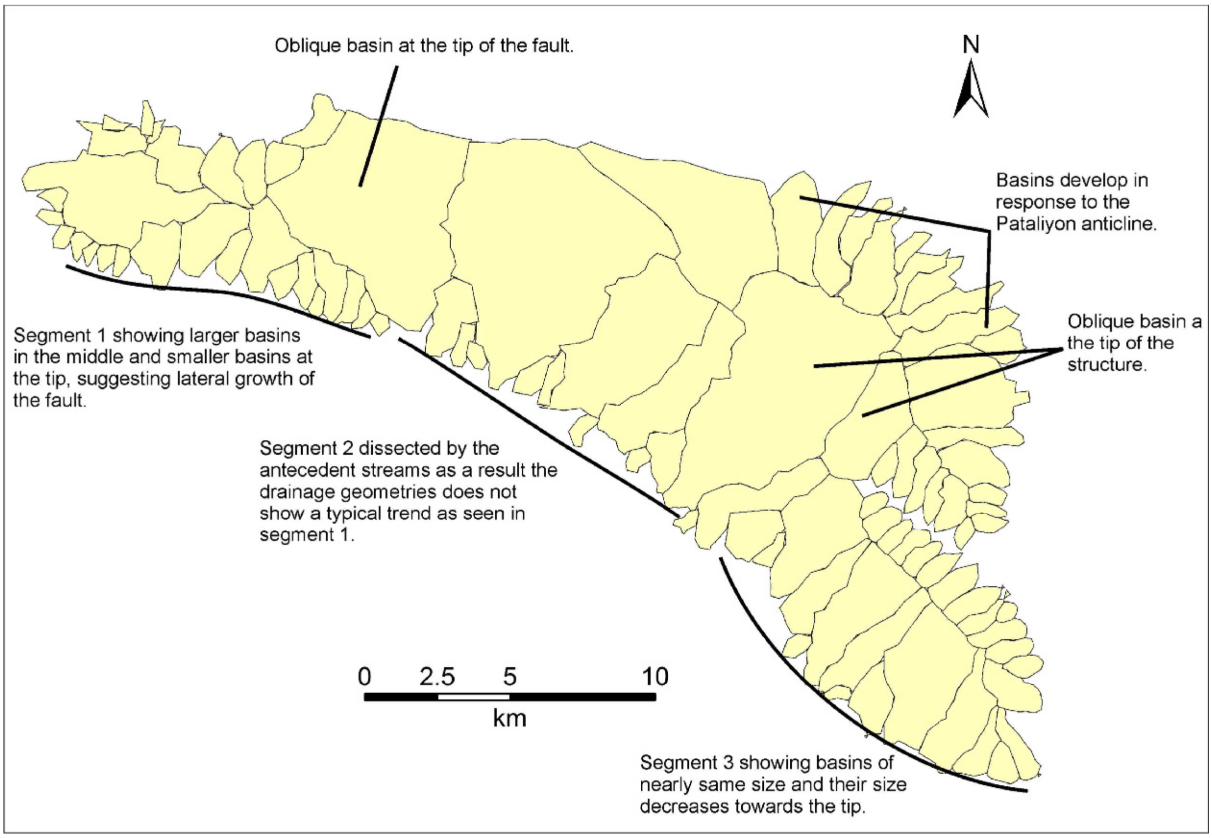

Fig.9. Map showing basin geometry variation and its linkage with the structural growth in the area.

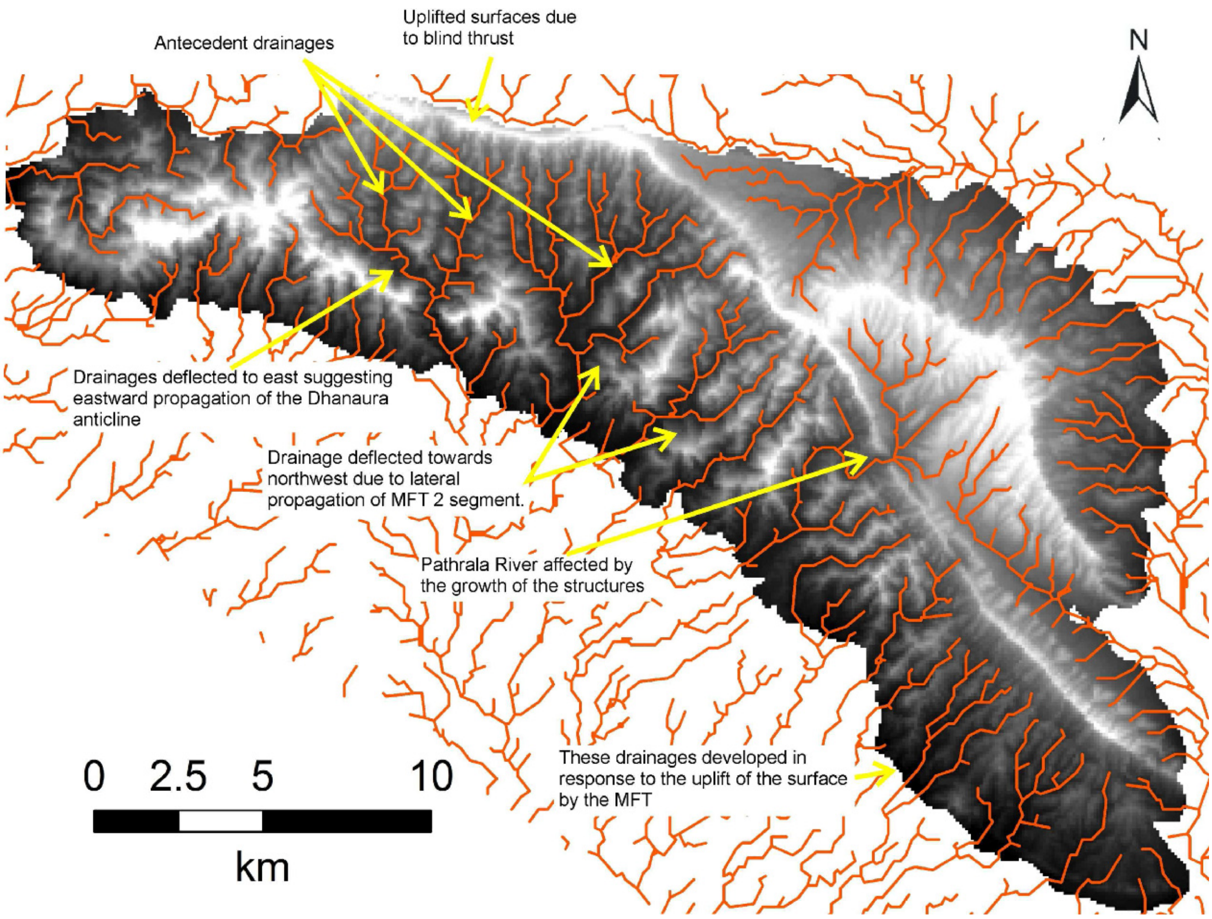

Fig.10. Map showing interaction between structure and drainages in the Dhanaura range.

basins at the tips of the Dhanaura range can be attributed to these tear faults.

Drainage development, reorganization and growth of structures

Leeder and Jackson (1993) demonstrated that small basins form where faults are active; and oblique basins form where the fault terminates or two faults merge. We use similar approach to study the drainage basins of the Dhanaura range. Several large basins are marked in the central part of the Dhanaura range, whereas, the tips of the MFT 1 and 3, and the Pataliyon anticline are marked by smaller basins. This indicates that the larger basins have formed in response to the topographic growth along the individual fault segments that merge in the central part of the range (Fig. 9). The size of the basins also point towards the age of the structures. The development of larger basins suggests that they are generated along older structures and more mature topography, whereas smaller basins have developed on the topography related to relatively younger structures. Larger drainage basins developed on the surface generated by the blind thrust to the north of the study area suggests that the blind thrust was initiated first in the central part of the Dhanaura range.

As the fault-related folds grow, they rise and widen, forcing the antecedent rivers to deflect around them (Divyadarshini and Singh, 2019). Generally, when the folds propagate towards each other, it is expected that the antecedent rivers will focus where the two structures join. Finally, as displacement increases at the interacting tips, the antecedent rivers are forced to deflect around the growing topography, leading to the development of wind gaps (they represent the former course of the antecedent rivers) along the fold crest (Jackson et al. 1996; Burbank et al., 1996). Investigation of the drainages along the Dhanaura range show that the larger south flowing streams such as Matar ki Khol, Somb Nadi, and Pathrala Nadi arise from the blind thrust related surface uplift, and the Pataliyon anticline in the northern part of the range (Fig. 10). These rivers cross the Dhanaura anticline in south and are marked by prominent knick points and high SL index zones along the anticlinal axis (Fig. 5). Drainage map of the area shows distinct deflection of these streams around the Dhanuara anticline (Fig.10). This suggests that these streams are antecedent to the Dhanaura anticline; thus, the northern surface and the Pataliyon anticline were uplifted prior to the Dhanaura anticline. It was followed by the initiation of the MFT in southern part of the range which led to the development of the Dhanaura anticline. Lateral propagation of the MFT forced the antecedent drainages and its tributaries to deflect around the Dhanaura anticline; this is further supported by the presence of several wind gaps on the drainage divide profiles of the range (Fig. 7). However, due to lack of structural data from the southern limb of the Kalesar syncline it is difficult to model its growth. Presence of synclinal depressions, valleys, and anticlines has resulted in more than one type of drainage pattern (sub-dendritic to trellis pattern). The Pathrala Nadi and other drainages show an eastward growth of the southern limb of the Kalesar syncline, as suggested by the drainage pattern (Fig. 10).

Based on the above discussion, an evolution model for the growth of the structures in the area is proposed (Fig. 11). Our study reveals that the initial surface uplift along the Dhanaura range occurred along a blind thrust in the northwestern part of the study area. Development of the Pataliyon anticline then took place to the east of the blind thrust related surface uplift. It was followed by the initiation of the MFT in the eastern part (i.e., segment 3) of the range, south of the Pataliyon anticline. Topographic growth along the MFT resulted in the formation of the Dhanaura anticline. The Kalesar syncline was developed in between the Dhanaura and the Pataliyon anticlines resulting in the generation of several small catchments draining into the syncline. This was followed by the development of the MFT (segment 1) in the western part of the Dhanaura range. Lateral propagation of the

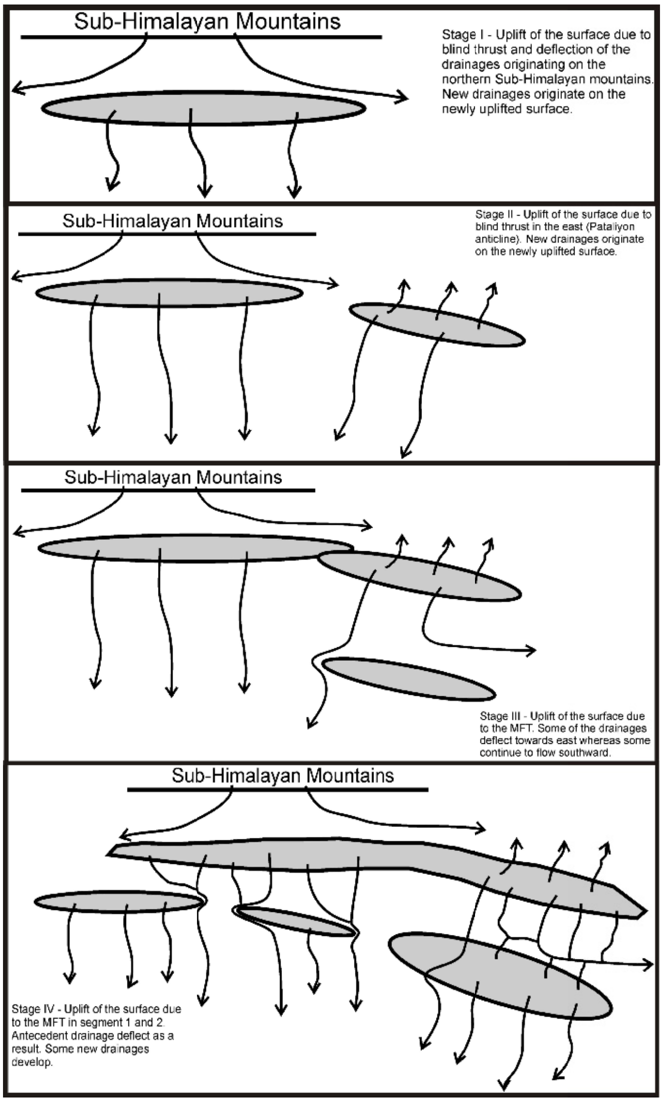

Fig.11. Model showing the evolution of structures and drainages along the Dhanaura range.

Dhanaura anticline led to the deflection of the antecedent drainages arising from the northern structures. It seems that the MFT in segment 2 also started developing simultaneously but due to erosion by the antecedent drainages its growth history is difficult to model. The structures finally merge to give rise to the present day morphology of the Dhanaura range.

CONCLUSIONS

Following are the important conclusions of this study:

1. A blind thrust resulted in the initial uplift of the surface in the northern part of the study area from which antecedent drainages such as Matar ki Khol, Somb Nadi, Pathrala Nadi etc. originate. These were the first expression of the Siwalik hills in the area.
2. The Pataliyon anticline in the north was the next to develop (east of the initially uplifted surface) and it also led to the generation of some new south flowing drainages.
3. This was followed by the initiation of the MFT. The MFT in the area comprises of three segments that merge together to form the Dhanaura anticline. The eastern most segment (i.e., MFT 3) developed first; development of this segment led to the formation of the Kalesar syncline between the Dhanaura and Pataliyon anticlines.
4. Segments 1 and 2 of the MFT are probably contemporaneous.

These segments uplifted the frontal area that acted as a barrier to the antecedent drainages.

5. Apart from the Dhanaura anticline, there exists an unidentified structure along which change in the magnitude of dip in the bedrock is observed. These have resulted in some local structures to which the drainages have responded.

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