

Active tectonic influence on the evolution of drainage and landscape: Geomorphic signatures from frontal and hinterland areas along the Northwestern Himalaya, India

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Abstract

The Kangra Re-entrant in the NW Himalaya is one of the most seismically active regions, falling into Seismic Zone V along the Himalaya. In 1905 the area experienced one of the great Himalayan earthquakes with magnitude 7.8. The frontal fault system – the Himalayan Frontal Thrust (HFT) associated with the foreland fold – Janauri Anticline, along with other major as well as secondary hinterland thrust faults, provides an ideal site to study the ongoing tectonic activity which has influenced the evolution of drainage and landscape in the region. The present study suggests that the flat-uplifted surface in the central portion of the Janauri Anticline represents the paleo-exit of the Sutlej River. It is suggested that initially when the tectonic activity propagated southward along the HFT the Janauri Anticline grew along two separate fault segments (north and south faults), the gap between these two fault and the related folds allowed the Sutlej River to flow across this area. Later, the radial propagation of the faults towards each other resulted in an interaction of the fault tips, which caused the rapid uplift of the area. Rapid uplift resulted in the disruption and longitudinal deflection of the Sutlej river channel. Fluvial deposits on the flat surface suggest that an earlier fluvial system flowed across this area in the recent past. Geomorphic signatures, like the sharp mountain fronts along the HFT in some places, as well as along various hinterland subordinate faults like the Nalagarh Thrust (NaT), the Barsar Thrust (BaT) and the Jawalamukhi Thrust (JMT); the change in the channel pattern, marked by a tight incised meander of the Beas channel upstream of the JMT indicate active tectonic movements in the area. The prominent V-shaped valleys of the Beas and Sutlej rivers, flowing across the thrust fronts, with Vf values ranging from <1.0–1.5 are also suggestive of ongoing tectonic activity along major and hinterland faults. This suggests that not only is the HFT system active, but also the other major and secondary hinterland faults, viz. the MBT, MCT, SnT, NaT, BaT, and the JMT can be shown to have undergone recent tectonic displacement.

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1. Introduction

Due to the Indian–Eurasian collision the Himalaya is one of the most tectonically active regions of the world. For this reason it has attracted the attention of geomorphologists for several decades. Ongoing tectonic activity is well indicated by moderate to large magnitude earthquakes, as well as prominent tectonically controlled geo-

morphic indicators. The most prominent earthquakes with $M > 8$ which have occurred along the Himalayan arc in the last 100 years are: 1905 Kangra (M 7.8); 1934 Bihar (M 8.4); and the 1950 Upper Assam (M 8.5) earthquakes (Seeber and Armbruster, 1981; Ambraseys and Bilham, 2000; Bilham et al., 2001). Numerous studies in the Himalayan domain have recorded geomorphic expressions like displaced and warped late Pleistocene and Holocene surfaces along active faults in the frontal zone (Nakata, 1989; Valdiya et al., 1984; Valdiya, 1992; Yeats et al., 1992; Wesnousky et al., 1999; Lavé and Avouac, 2000;

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Kumar et al., 2001; Malik and Nakata, 2003; Malik et al., 2003), the evidence of paleo-lake formation due to movements along active faults, gullied surfaces marked by ravines and the development of canyons/deep narrow gorges, entrenched channels and waterfalls, all indicative of active tectonics and fault displacement and its influence over the evolution of the landscape (Seeber and Gornitz, 1983; Valdiya, 1996, 1999; Nakata, 1972; Malik and Nakata, 2003).

The evolution of a complex-rugged landscape is the result of highly scale-dependent interactions involving climatic, tectonic and surface processes, however, the geodynamics of mountain building and topographic evolution are not yet completely understood, although numerous conceptual and physical models indicate that surficial erosion plays a significant role (Riquelmea et al., 2003). Therefore, the investigation of geomorphic expression of the drainage pattern in any mountain building area can assist us to understand the overall evolution of the landscape and also in recognize ongoing active tectonic movement.

Several studies have proved that the careful evaluation of geomorphic features and geomorphic indexes such as the Valley width/height ratio (Vf), the Mountain-front sinuosity index (Smf), the River gradient index etc. provide a wealth of information which assists our understanding of the influence of tectonics on landscape change and drainage evolution (e.g. Bull and McFadden, 1977; Seeber and Gornitz, 1983; Gregory and Schumm, 1987; Wells et al., 1988; Rhea, 1993; Demoulin, 1998; McCalpin, 1996; Malik et al., 2001; Burbank and Anderson, 2001; Champel et al., 2002; Schumm et al., 2002; Silva et al., 2003; Riquelmea et al., 2003). It has also been suggested that an understanding of past drainage evolution may be derived from present-day river patterns, which provide an insight into past deformational events within active mountain belts (Friend et al., 1999). Numerous conceptual models and field investigations suggest that in tectonically active regions fault growth and associated deformation have a direct control in shaping the landscape and drainage evolution (Gupta, 1997; Delcaillau et al., 1998; Hitchcock and Kelson, 1999; Friend et al., 1999; Burbank and Anderson, 2001; Van der Woerd et al., 2001; Champel et al., 2002). Fault growth/propagation and related folding in active thrust-fold belt is generally attributed to the superimposition of slip during several major earthquakes on fault planes (Walsh et al., 2002), where deformation creates fluvial diversions, such geomorphic indicators can be used to reconstruct the fold history of the region (Bés de Berc et al., 2005).

Investigations in the Canyonlands Graben, Utah reveals that the fault growth process involves two broad categories (1) fault growth by radial propagation and (2) growth by segment linkage (Cartwright et al., 1995). This suggests that either a single fault kept growing by accumulating more displacement over time, developing an elongated fault, or two/more smaller fault segments grow over time, and link-up to form a single fault. This phenomenon has

been noticed commonly in the intracontinental mountain building process, where the tectonic activity is initiated by the nucleation, growth and the lateral propagation of thrust faults (Burbank et al., 1999; Champel et al., 2002). Active thrust-related fold growth includes the deflection of antecedent rivers from an axial course and the development of several wind gaps (Burbank et al., 1999; Champel et al., 2002; Bés de Berc et al., 2005). Several examples of the longitudinal deflection of river courses in response to fold growth have been reported from the NW and NE Himalayan arc (Friend et al., 1999) and western Nepal (Champel et al., 2002).

The present study of the NW Himalaya (lat N31–32 and long E75 30'–77) (Fig. 1) has been concentrated upon the delineation of tectonically controlled geomorphic expression, the present drainage network and related geomorphic indexes designed calculated to understand the ongoing pattern of deformation.

2. Tectonic and geological background

Since the initial collision along the Indus-Tsangpo Suture Zone (ISSZ) (Gansser, 1964) at ~50 Ma, the zone of deformation has successively shifted southward, resulting in faulting and folding along the Main Central Thrust (MCT); the Main Boundary Thrust (MBT) and the Himalayan Frontal Thrust (HFT) (Figs. 1 and 2) (Gansser, 1964; Seeber and Armbruster, 1981; Lyon-Caen and Molnar, 1983). The presently most active deformation zone lies along the HFT, which marks the boundary between the youngest Siwalik Hill range and the Indo-Gangetic Plain (Nakata, 1989).

The study area forms the part of Kangra Re-entrant, where the thrust faults and associated folded ranges are distributed in a ~100 km wide zone between the HFT and the MCT, comprising several splays of imbricated faults (Fig. 2). The MCT, MBT and secondary faults like PaT (Palampur Thrust) shows typical 'sinuous' patterns, striking N-S and WNW-ESE, whereas, other prominent tectonic features, like the HFT, and secondary faults: SnT (Soan Thrust), NaT (Nalagarh Thrust), BaT (Barsar Thrust) and the JMT (Jawalumukhi Thrust) show NNW-SSE trend, parallel to the arc.

Recent studies suggest that tectonic lineaments with sinuous patterns represent oblique ramps and those with trends parallel to the trend of orogenic belt represent frontal ramps (Dubey and Bhakuni, 2004). These tectonic features mark the major lithological as well as geomorphological boundaries in the area. The HFT, which is seen cutting the Siwaliks at the surface (Powers et al., 1998), is the southernmost frontal thrust which marks the boundary between the Janauri Anticline (frontal foreland fold) composed of late Tertiary to early Quaternary molassic sediments (Upper Siwalik), from Quaternary alluvial deposits of Indo-Gangetic Plain (Raiverman et al., 1994). The Janauri Anticline is the youngest and southernmost mountain chain of the Himalayan orogenic belt. To its

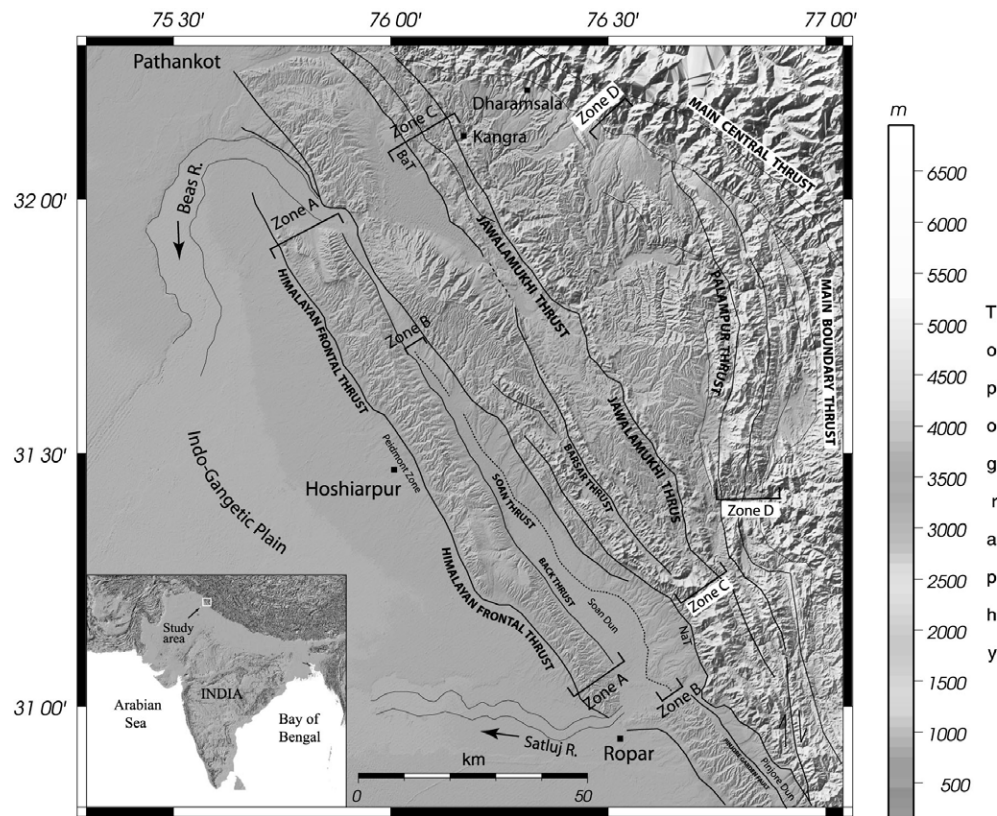


Fig. 1. DEM of the study area (USGS/SRTM data) illustrating major faults marked by continuous lines and major geomorphic divisions around NW Himalaya. Major faults are after Gansser (1964), Valdiya et al. (1984) and Powers et al. (1998). Note the brackets marked by zones A–D show the locations of the Zones categorized for Mountain front sinuosity (after Mohanty, 2004). Inset shows DEM of India with location of study area.

north it is bounded by a south-dipping back-thrust (Powers et al., 1998). The boundary between the Lower Tertiary hill range and the Soan Dun – a longitudinal intermontane valley is marked by the SnT. This valley is filled by thick alluvium of late Pleistocene to Holocene age, representing the debris deposited by coalesced alluvial-fan and finer fluvial deposits, overlying the Middle and Lower Siwalik succession. The SnT has brought Middle Siwaliks over Upper Siwalik and younger deposits (Powers et al., 1998). Other hill ranges between the SnT and MBT, consisting of an inter-layered succession of conglomerate, sandstone, claystone etc of Lower and Middle Tertiary sediments, are bounded to their south by the BaT, NaT, JMT, PaT, etc. To the north the boundary between the Lesser Himalayan sedimentary and metasedimentary rocks is marked by the MBT, and between Lesser Himalayan and the Higher Himalayan Crystallines, by the MCT (Fig. 2).

Several tectonic models have been proposed for the evolution of the Himalaya (e.g. Powell and Conaghan, 1973; LeFort, 1975; Stöcklin, 1980), which suggest that the zone of plate convergence progressively shifted towards the foreland. According to the most acceptable evolutionary model, the convergence initiated along the Indus-Sangpo Suture, later the intracontinental thrust-MCT was formed south of the suture zone, and then finally the MBT was developed (LeFort, 1975; Stöcklin, 1980). This evolutionary model also suggests that at each stage, the convergence

shifted to the newly formed younger tectonic structure and older fault systems became inactive. According to this model the MBT is now active and MCT is dormant. Finally the deformation shifted to the HFT which marks the southernmost limit of the Himalayan orogenic belt (Valdiya, 2003). Subsequently the steady-state model was proposed, also with a gradual shift of the deformational front towards the foreland, but in which the MBT and MCT are considered to be contemporaneous features and MCT is still active (Seeber et al., 1981; Seeber and Armbruster, 1981). This view is supported by knick points in river profiles which cross the MCT and from the evidence of uplifted terraces in the Higher Himalaya (Seeber and Gornitz, 1983). As mentioned earlier, according to the evolutionary model the older structural features are no longer active, but there are several geological and geomorphological evidences which indicate ongoing tectonic activity along the MCT (Valdiya, 1980; Seeber and Gornitz, 1983) as well as along the MBT (Valdiya, 1992; Nakata, 1989; Malik and Nakata, 2003).

3. Methodology

For several decades geomorphological indicators have been used as one of the most powerful tools to delineate tectonically influenced landscapes, and these features have been extremely helpful in deciphering the role of tectonics

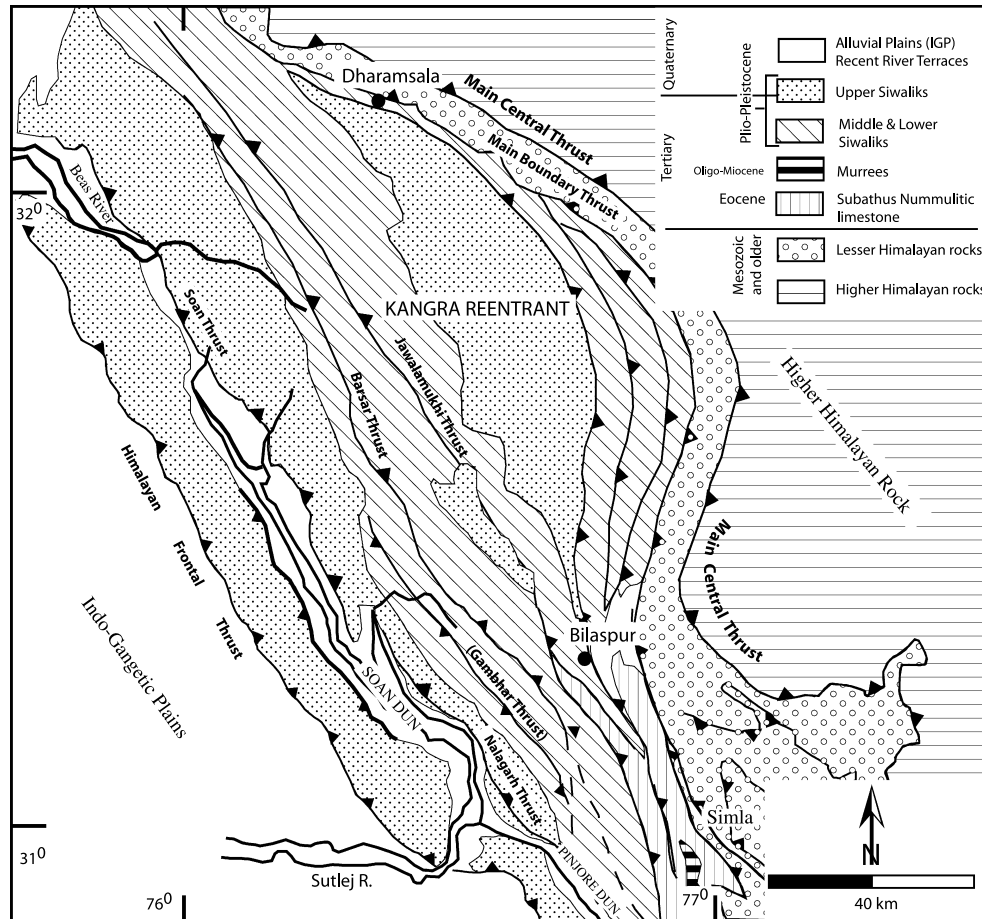


Fig. 2. Generalized geological map of northwestern Himalayan Front around the Kangra Re-entrant (after Gansser, 1964; Valdiya et al., 1984; Powers et al., 1998).

in the evolution of the landscape. Prominent indicators are the development of a sharp morphology along active fronts, mountain front sinuosity, entrenched channels, or a high degree of incision along the channels flowing across active faults, the formation of linear valleys along fault traces, a sudden change in channel morphology, a sudden change in the base level of the channel floor – marked by pronounced knick-points in the river profiles etc (e.g. Bull and McFadden, 1977; Bull, 1984; Seeber and Gornitz, 1983; Ouchi, 1985; Wells et al., 1988; Rhea, 1993; Schumm et al., 2002; Silva et al., 2003; Riquelmea et al., 2003; Bishop et al., 2003). For the identification of tectonically controlled geomorphological features, along with the Survey of India Toposheets (1:50,000 scale), high resolution CORONA declassified satellite photos with stereo-pair to view the terrain in 3-D were used. The Shuttle Radar Topographic Mission (SRTM) 3 arc second data with resolution of about 90 m and MrSid (Multi-resolution Seamless Image Database)-LANDSAT data with resolution of 28.5 m was also used for creating a shaded relief image and a 3-D surface perspective view of the terrain (Fig. 3), which assisted the delineation of prominent geomorphological features and allowed the terrain to be viewed in three dimensions. DEM (SRTM) data was also utilized to

extract the drainage of the area and to construct the terrain, as well as channel cross-profiles to understand the ongoing pattern of deformation (Figs. 4a, b).

3.1. Morphometric analysis

As mentioned earlier geomorphological indexes developed by Bull and McFadden (1977) have been used extensively and tested as a valuable tools in tectonically active areas, such as the SW USA (Bull and McFadden, 1977; Rockwell et al., 1984), Costa Rica (Wells et al., 1988), Oregon Coast Range, USA (Rhea, 1993), the Kachchh region, India (Sohoni et al., 1999), southeast Spain (Silva et al., 2003) and western Taiwan (Chen et al., 2003). For this study two indexes: Valley width/height ratio (Vf) and Mountain front sinuosity (Smf) studied by Mohanty (2004) were taken into consideration, since the combination of these two indexes allows the inference of tectonic activity along the faulted fronts (Silva et al., 2003). Transverse valley profiles were constructed using data for the drainage extracted from the DEM (Fig. 4a) for the major channels of Beas and Sulej rivers where they cross the major fault-bounded fronts viz. the MBT, PaT, JMT, BaT, NaT and the SnT (Figs. 5 and 6). A total of 10

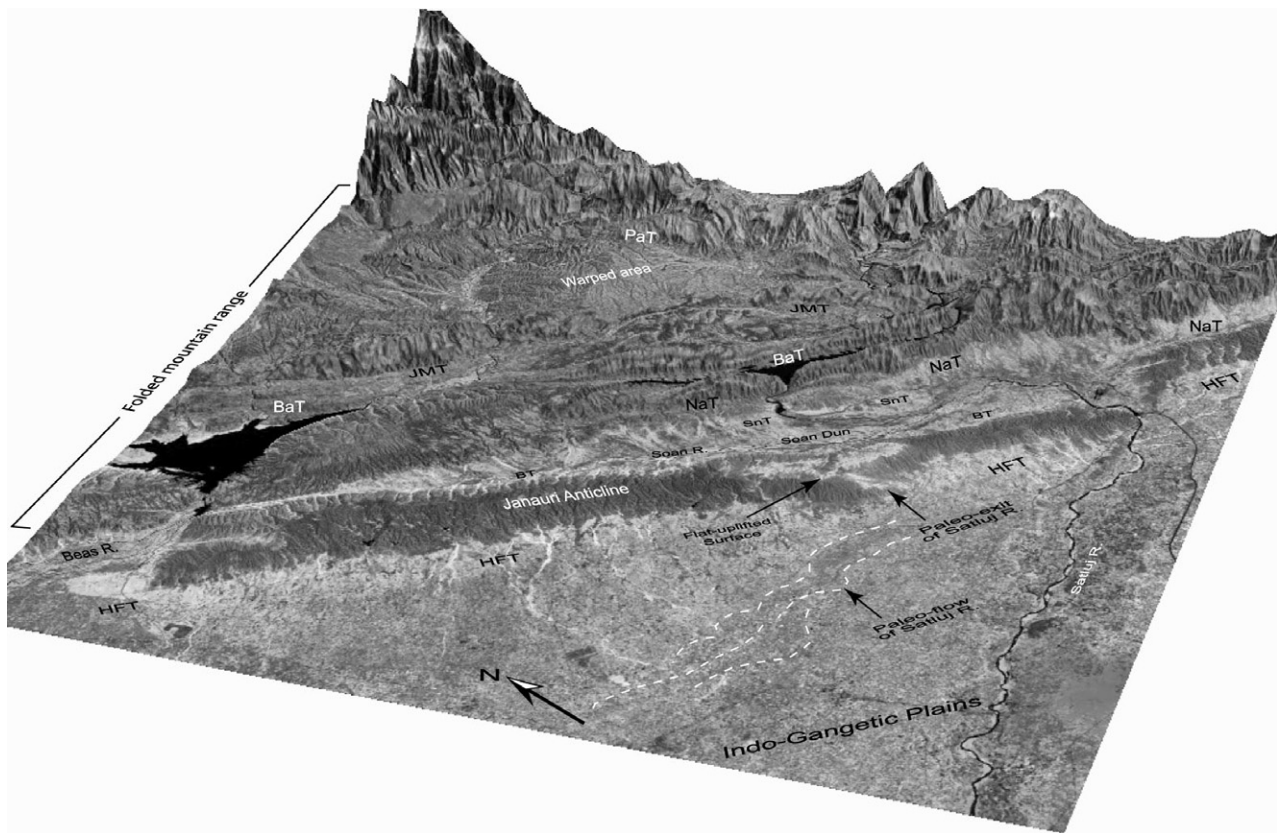


Fig. 3. 3-D perspective view of the terrain of the study area, NW Himalaya (USGS/SRTM 3 arc second data and MrSid LANDSAT data). The Sutlej River in the east and the Beas River in the west define the ends of the NNW-SSE striking Janauri Anticline. The Janauri Anticline is bounded to the south by the Himalayan Frontal Thrust (HFT). At most places along the HFT the piedmont zone has a diffuse boundary against the low-lying Indo-Gangetic Plain. The flat-uplifted surface in the central portion of the Janauri Anticline marks the paleo-water gap or paleo-exit of the Sutlej River. The rapid uplift of the flat-surface was due to lateral propagation of two fault segments towards each other and overlapping of the fault tips. The gap between these two faults allowed the Sutlej channel to flow across the growing ridge. Due to the rapid uplift the Sutlej River was not capable of cutting across the growing anticline, thus was disrupted and deflected along its present course. Paleo-flow of the channel of the Sutlej River across the Indo-Gangetic Plain is shown by white-discontinuous lines. To the north of the Janauri Anticline the hinterland faulted thrust fronts are marked by sharp boundaries. The up-warped area to the north of the Jawalamukhi Thrust (JMT) is indicative of active deformation in the region. BT – Back Thrust; SnT – Soan Thrust; NaT – Nalagarh Thrust; BaT – Barsar Thrust; PaT – Palampur Thrust.

channel cross-profiles were drawn (five each) for both the rivers to calculate Valley width/height ratios: $V_f = 2V_{fw} / (E_{ld} - E_{sc}) + (E_{rd} - E_{sc})$ developed by Bull and McFadden (1977). Where, V_{fw} represents valley width; E_{ld} – altitude of left bank; E_{rd} – altitude of right bank; E_{sc} – altitude of channel. The cross channel profiles of the Beas and Sutlej rivers, as well as the tributaries crossing the active fronts, are marked by deeply incised gorges showing ‘V-shaped’ narrow valleys (Figs. 5 and 6). The analysis reveals that the V_f values for the Beas River range from 0.32 to 11.5, and for Sutlej River from 0.4 to 20 (Table 1). Studies carried along Pacific coast of Costa Rica suggests that rivers marked by narrow-deep valleys crossing the mountain fronts show low V_f values <1.0 ; large V_f values >1.0 are associated with broader valleys (Wells et al., 1988). A similar analysis, carried out by Silva et al. (2003) in SE Spain, also suggests that V-shaped valleys with low V_f values <1.0 develop in response to active uplift, and that broad U-shaped valleys with high V_f values >1.0 indicate major lateral erosion, due to the stability of base-level or to tectonic quiescence. Looking at the shape of the

valley floors of the Beas and Sutlej Rivers and the values of V_f , it appears that values of the V_f index <1.0 (V-shaped) are observed along fronts which have experienced the most active tectonic uplift, whereas fronts with V_f indices of 1–1.5 are moderately active and those with >1.5 , marked by broad (U-shaped) valleys, were developed by the lateral migration of channels in response to a stable base-level, or to tectonic quiescence.

The Mountain Front Sinuosity Index ($Smf = Lmf/Ls$) is a measure of the degree of irregularity or sinuosity at the base of a topographic escarpment, where Lmf is the length along the topographic mountain front and piedmont, and Ls is the straight line length of the mountain front (Bull and McFadden, 1977). The morphology of a mountain front depends upon the degree of tectonic activity along the front. Active fronts will show straight profiles with lower values of Smf , and inactive or less active fronts are marked by irregular or more eroded profiles, with higher Smf values (Wells et al., 1988). A Smf analysis was carried out by Mohanty (2004) in the NW Himalaya along various fault systems and was reported in her unpublished Master’s

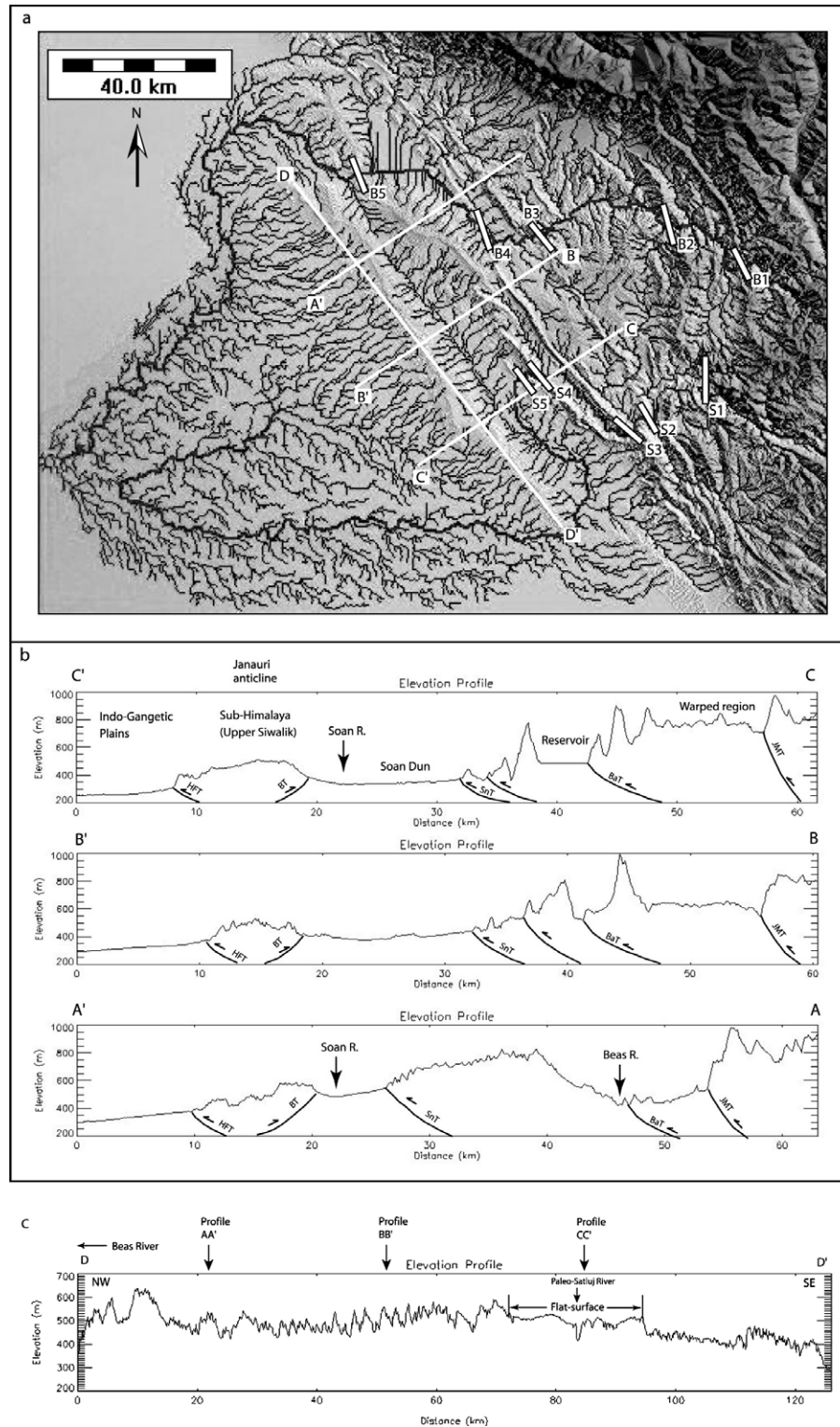


Fig. 4. (a) Drainage network of the study area (drainage extracted from DEM), streams with order higher than 3 are shown. White continuous lines indicate topographic profiles AA', BB', CC' and DD'. White-boxes show the location of transverse channel profiles of the Beas and Sutlej rivers. These profiles were drawn at places where the Beas and Sutlej Rivers cross faulted fronts; (b) topographic profiles: AA', BB' and CC' show sharp breaks indicative of north dipping thrust faults, except in the frontal portion with a south dipping back-thrust; (c) topographic profile: DD' along the Janauri Anticline shows intense dissection in the NW and SE portion compared with the central portion which has a flat surface.

Thesis. She divided the area between HFT and MBT into four major zones: (1) Zone A – along the HFT and Back Thrust, (2) Zone B – along the Soan Thrust, (3) Zone C

– along Barsar and Jawalamukhi thrusts and (4) Zone D – along the Palampur Thrust and MBT (Fig. 1). The Smf values calculated for various fronts range from 1.11 to

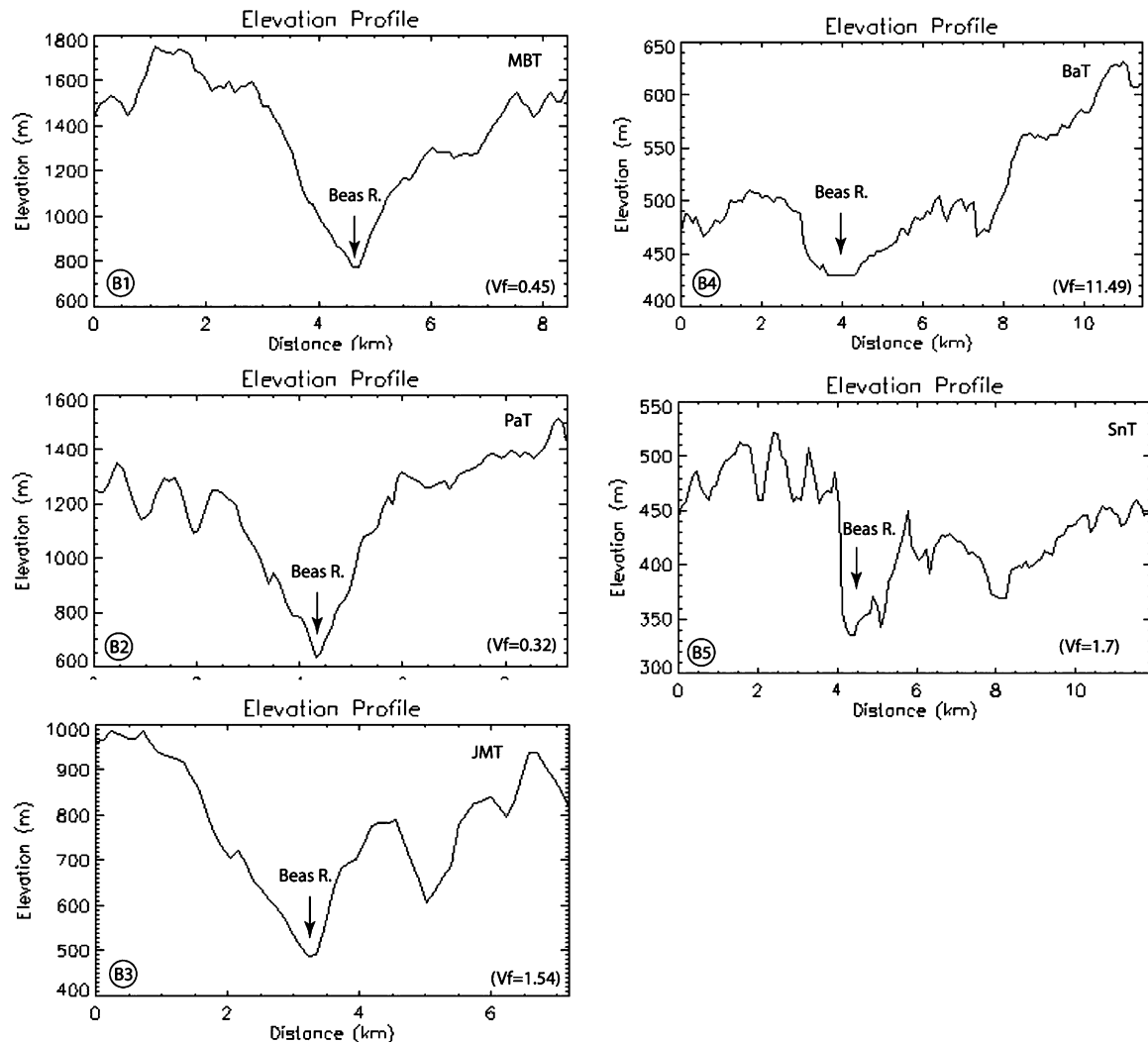


Fig. 5. Transverse channel profiles of Beas River crossing the folded-thrust fronts, viz. the MBT, PaT, JMT, BaT and SnT. All river profiles show well developed 'V-shaped' valleys, suggesting that ongoing tectonic movements along these faults are responsible for the formation of narrow deeply incised gorges near the faulted fronts. The profile along the front bounded by BaT shows a slightly wider channel, indicating that the front is experiencing intermediate tectonic activity. Calculated (V_f) values are given in brackets at the lower right in each profile (refer Fig. 4a for location).

1.38. Studies analyzing the Smf from other regions, such as the SW USA (Bull and McFadden, 1977; Rockwell et al., 1984), Costa Rica (Wells et al., 1988), Oregon Coast Range, USA (Rhea, 1993), the Kachchh region, India (Sohoni et al., 1999) and southeast Spain (Silva et al., 2003) suggest that mountain fronts with low values of Smf (<1.6) are categorized as active fronts. Comparing the results of these studies, the Smf values obtained by Mohanty (2004) indicate that all fronts fall in the 'active front' category, where Zone A shows a mean value of Smf = 1.28, Zone B Smf = 1.38, Zone C Smf = 1.22 and Zone D Smf = 1.11. The data also suggests that Zones C and D are the most active, compared with the other zones. This is complimented by the sharp and less dissected morphology of the fronts (Figs. 1 and 3). The lower values of Smf in Zone A could be due to the existence of the back-thrust, where the amount of slip transferred to the HFT system is partitioned between the HFT and its associated back-thrust (Fig. 1).

4. Geomorphology

Geomorphologically the area can be classified into four broad zones, from north to south (Nakata, 1972; Powers et al., 1998) (Figs. 2 and 3): (1) folded mountain ranges, bounded to their south by major thrust faults; (2) Soan Dun (Dun = valley) – marks an intermontane valley, or piggy-back basin confined between the Lower Siwalik and the Sub-Himalayan (Upper Siwaliks) ranges; (3) Sub-Himalaya (Janauri Anticline) – youngest detached range demarcating the southernmost fringes of Himalaya, and (4) The Indo-Gangetic Plain which represents the present foreland basin. The northern part of the area is marked by several intermontane basins confined between two thrust fronts.

The present drainage in the area is dominated by two major antecedent rivers, the Sutlej and the Beas, together with the Soan River (main tributary of the Sutlej) (Figs. 3 and 4a). The Sutlej and Beas Rivers emerge from the

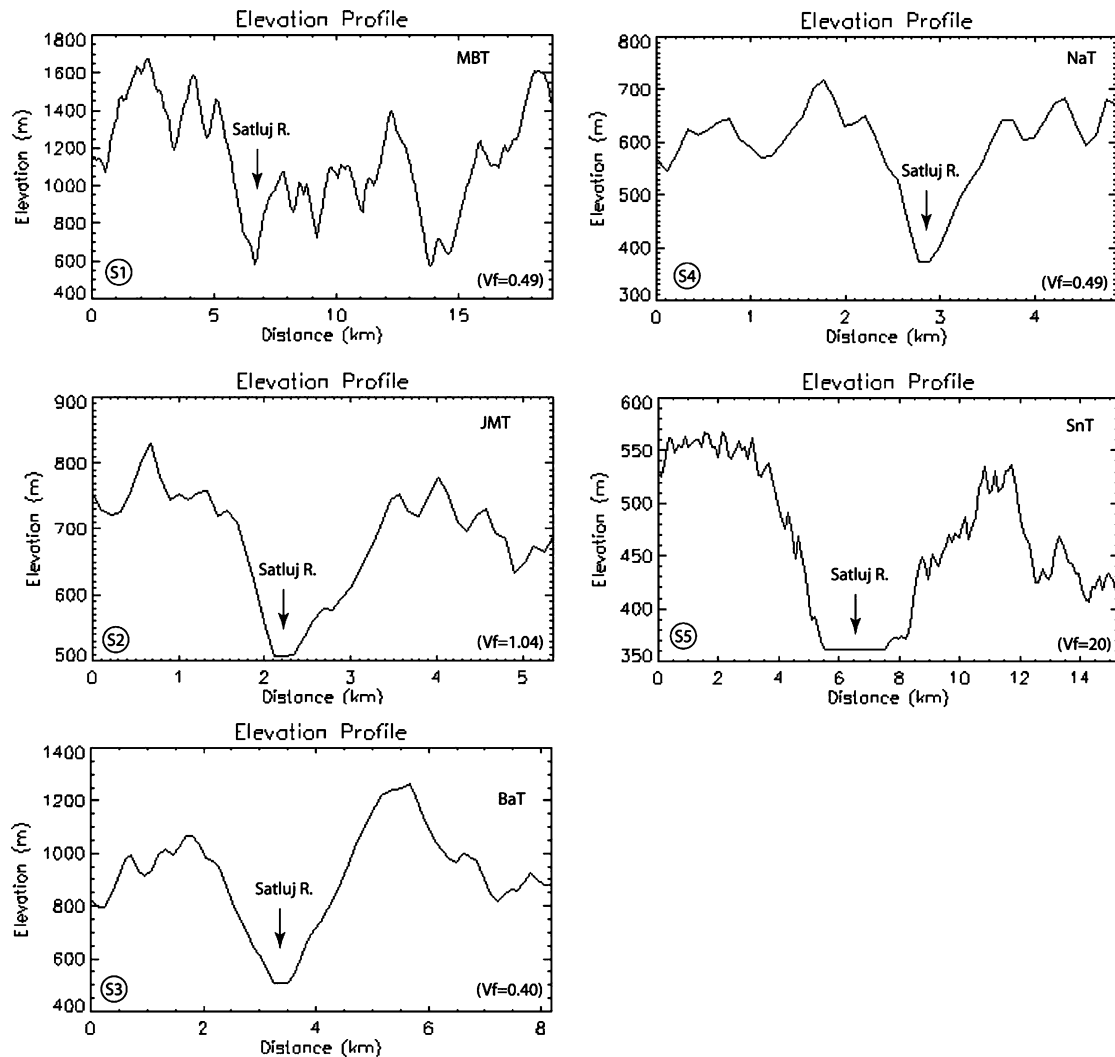


Fig. 6. Transverse channel profiles of Sutlej River crossing the folded ranges bounded to their south by MBT, JMT, BaT, NaT and SnT. River profiles show 'V-shaped' valleys indicative of active tectonic movements along these faults and the continued uplift was responsible of the formation of narrow deeply incised gorges. The cross-profile along the front bounded by SnT with broad valley is indicative of intermediate tectonic activity. Calculated (Vf) values are given in brackets at the lower right for each profile (refer Fig. 4a for locations profiles).

Table 1

Details of morphometric parameter used for calculating Valley width/height ratios (Vf)

Eld (m)	Erd (m)	Esc (m)	(Eld – Esc)	(Erd – Esc)	Vfw(m)	$Vf = \frac{2vfw}{(Eld-Esc)+(Erd-Esc)}$	Fault name (profile number)
<i>Beas R.</i>							
1600	1310	800	800	510	300	0.458	MBT (B1)
1260	1300	640	620	660	210.5	0.328	PaT (B2)
920	800	490	430	310	571.4	1.544	JMT (B3)
510	470	930	80	40	689.6	11.49	BaT (B4)
485	450	335	150	115	631.5	1.706	SnT (B5)
<i>Sutlej R.</i>							
1400	1200	600	800	600	344.8	0.492	MBT (S1)
730	770	510	220	260	250	1.041	JMT (S2)
1060	1250	520	540	730	259.2	0.408	BaT (S3)
670	640	380	290	260	136.3	0.495	NaT (S4)
470	450	360	110	90	2000	20	SnT (S5)

Refer Fig. 3 for fault nomenclature.

Higher Himalaya and flow across the Lesser Himalaya and Sub-Himalaya before debouching onto the Indo-Gangetic Plain. During their journey these two major rivers flows

transversely (antecedent), cutting through the folded-thrust fronts, and longitudinally around the growing ridges (anticlines). The Soan River sourced from the Lower Siwalik

Hills, flows longitudinally in SSW direction along the Soan Dun for a distance of about 40 km before joining the Sutlej River. Also the Sutlej and Beas Rivers flow longitudinally along the northern fringe of the Janauri Anticline, covering distances of about 45 and 25 km, respectively. Today these two major rivers diverge and flow on either side of the Janauri anticline, the Beas taking a direction NNW and the Sutlej SSW parallel to the range (Figs. 1, 3, and 4a).

Regionally the area is marked by several NNW-SSE trending fold ranges bounded to the south by major thrust faults, viz. SnT, BaT, JMT, PaT, etc. (Figs. 1–4). The ranges associated with these faults have an elevation ranging between 800 and 1000 m, and greater than 2000 m further north (Figs. 1 and 4b). Several longitudinal synclinal (intermontane) valleys are confined between these folded ranges. The Soan Dun, confined between the Lower Tertiary hill range to its north and the Janauri Anticline to its

south, is one of the most prominent intermontane valleys in the area. It is 15–20 km wide and extends laterally for about 100 km in NNW-SSE direction parallel to the front. The Janauri Anticline extending ~100 km NNW-SSE represents the youngest foreland folded front, flanked by the HFT to its south and associated back-thrust to the north as marked by Powers et al. (1998) in balanced cross-section (see Fig. 6a of Powers et al., 1998). This is well justified by the occurrence of active fault scarps on both flanks of the anticline in its central portion (Fig. 7). The Janauri Anticline shows very conspicuous topography, compared to the other foreland folds along the Himalayan arc (Figs. 1 and 3). The topographic elevation ranges from 650 m in the northwest to 430 m in the southeast. In the central portion, the anticline typically shows a flat top, with an elevation ranging from 510 to 530 m (Fig. 4c). This flat-topped area is less dissected, compared with the northwestern and southeastern portions, and also shows a low drainage density. It extends for about 20–22 km in length in NNW-SSE direction and is about 12–14 km wide from N to S. In the flat topped area a well-exposed late Quaternary (?) fluvial succession is seen at several locations viz. Jaijon, Haleran, Malhowal, Bathri, Harwan, Naniwan etc. (Fig. 8) (refer to Fig. 7 for locations). On the way from Jaijon to Santokhgarh near Haleran village the lithosection shows a planar to trough cross-stratified gravelly unit (2–3 m thick) overlying a finer Siwalik succession, dipping at about 10° due north (Fig. 8a). Crude imbricated elongated clasts showing an inclination due SW (with the long axis perpendicular to flow) were recorded. About 3 km from Bathri, near Pandori village, the exposed Quaternary fluvial succession shows a horizontal, to planar, cross-stratified, massive sandy lithounit about 6 m thick with the occasional occurrence of calcretized clay and gravelly troughs (Fig. 8b). This is overlain by a 3–4 m planar to trough cross-stratified gravel lithofacies along with a sandy facies, suggesting deposition in a shallow incised channel. The gravelly lithounit is matrix-supported, consisting of rounded to well-rounded, sandstone clasts ranging in size from 12 to 35 cm (Figs. 8b, d). Gravel spreads were noticed along the northern and southern boundary of the anticline (Fig. 8c). Fluvial deposits overlying the older Siwalik succession in the flat area were deposited by a major river which flowed across this region, until it was disrupted–deflected.

From the above observations it is suggested that the central portion marked by the flat top of the Janauri Anticline represents a paleo-wind gap of the Sutlej River, and the development and evolution of the Janauri anticline involved fault growth by segment linkage (Fig. 9). At the initial Stage I: prior to the commencement of activity along HFT, and prior to the formation of the Soan Dun, all the major rivers sourced from Higher Himalaya were debouching directly onto the plains (Fig. 9a). At this time NaT was the most frontal thrust. Later, at Stage II: tectonic activity propagated southward along HFT forming a new fault line. At this stage the thrust faults causing the formation of the Janauri Anticline were two separate fault seg-

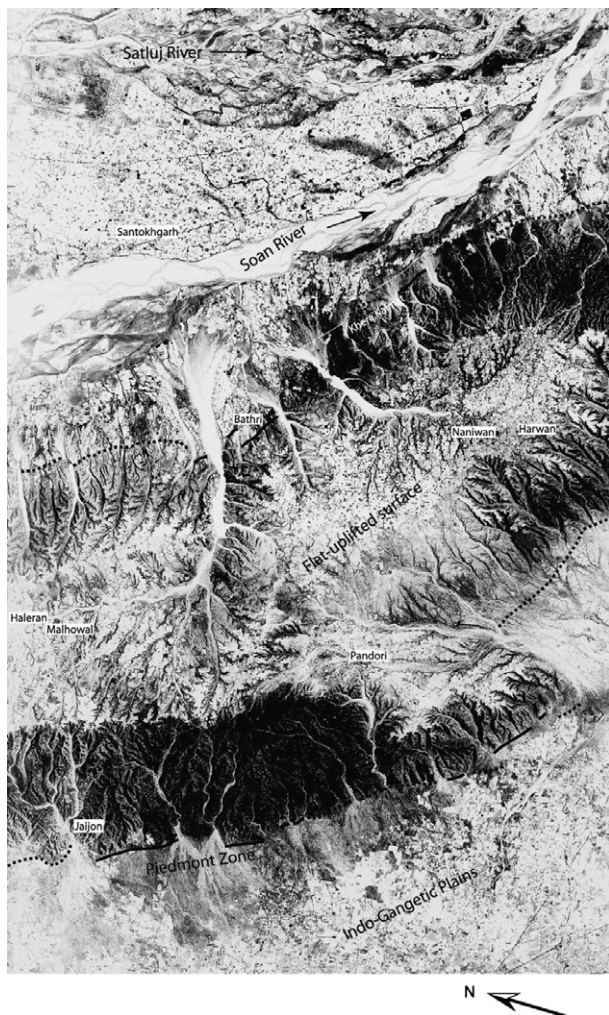


Fig. 7. CORONA photo showing the morphology of the landscape around the flat-surface on the Janauri Anticline and the distribution of active fault traces on the either side of the flat surface uplifted between the HFT and the back-thrust (BT). Continuous lines show the traces of active faults. Dashed lines are inferred faults, or where the expression of the fault scarps are concealed due to a high rate of deposition/erosion.

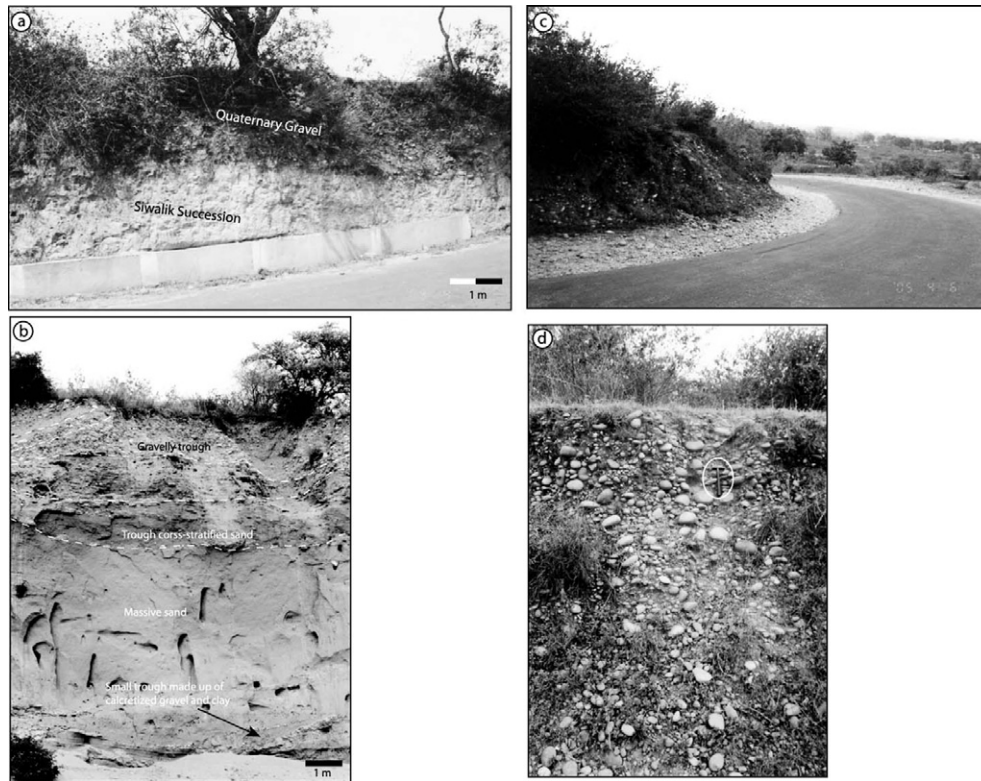


Fig. 8. (a) Planar to trough cross-stratified gravel facies overlying finer Siwalik succession on the way from Jaijon to Santokhgarh near Haleran village; (b) exposed fluvial succession about 3 km from Bathri near Pandori village showing horizontal to planar cross-stratified massive sandy lithounit, with the occasional occurrence of calcretized clay and gravelly troughs, overlain by planar to trough cross-stratified gravel lithofacies and sandy units; (c) view of gravel deposits south of Bathri village; (d) close-up view of gravel deposit south of Bathri village. Circle marks the hammer (14 cm in length) for scale.

ments (north and south faults), which allowed the Sutlej channel to flow across the area confined between these two faults (Fig. 9b). During Stage III: these faults started growing towards each other by lateral propagation, where the southern fault propagated northward and the northern fault propagated southward (Fig. 9c). It has been suggested by Dawers and Anders (1995) that generally the lateral propagation of faults results in a considerable increase in length, due to the increase in the amount of displacement on faults. Continued propagation (Stage IV) caused fault tip interaction of these two fault segments. The transition zone between the two overlapping fault segments was uplifted, due to rapid movement along the faults at the same time (Fig. 9d). As discussed earlier, partitioning of slip between the HFT and associated back-thrusts might also have contributed to the rapid uplift of the flat-surface. Until then, this area must have provided the way for the Sutlej River to flow across the uplift. It is most likely that erosion in the channel of Sutlej River was not powerful enough to keep-up with the rate of uplift, thus the river was disrupted–deflected to its present course in SSE direction, through the newly formed piggy-back Soan Dun (Fig. 9d). It is presumed that this uplift probably took place during the late Quaternary period. Keeping in mind the ‘steady state’ model, it is logical that before the frontal fault (HFT) came into existence, the Sutlej and the Beas rivers debouched directly onto the Indo-Gangetic Plain,

and at that particular time the NaT was the most frontal boundary thrust, with similar relationship as we see today between the HFT and the Indo-Gangetic Plain (Figs. 9a, b). But later, due to the rapid growth and propagation of the fault segments and the related growth of the fold, the major rivers, like Sutlej and Beas, were not powerful enough to keep-up with the rate of uplift and were deflected into their present courses.

Tracing paleo-course of the Sutlej River from CORONA satellite photo and LANDSAT MrSid data (Figs. 3, 10) suggests that, at present, this paleo-course is occupied by narrow channels emerging from the Indo-Gangetic Plain a few km down the piedmont zone. The paleo-channel can be well seen on LANDSAT imagery by its prominent reddish tone. Also in the lower reaches the trace is marked by a wide channel boundary and shows a higher stream order, the same as the other two major rivers, i.e. Sutlej and Beas (Fig. 4a). However, no remnant of such prominent channels is observed in the upper reaches in the piedmont zone. The possibility is, that due to the higher rate of erosion and deposition in the piedmont zone near the front, the channel trace seems to have been buried by thick alluvial fan sediments deposited by streams generated after uplift along the Janauri Anticline.

Apart from this evidence, other geomorphic signatures such as sharply marked mountain fronts along various subordinate faults, a change in channel pattern and a

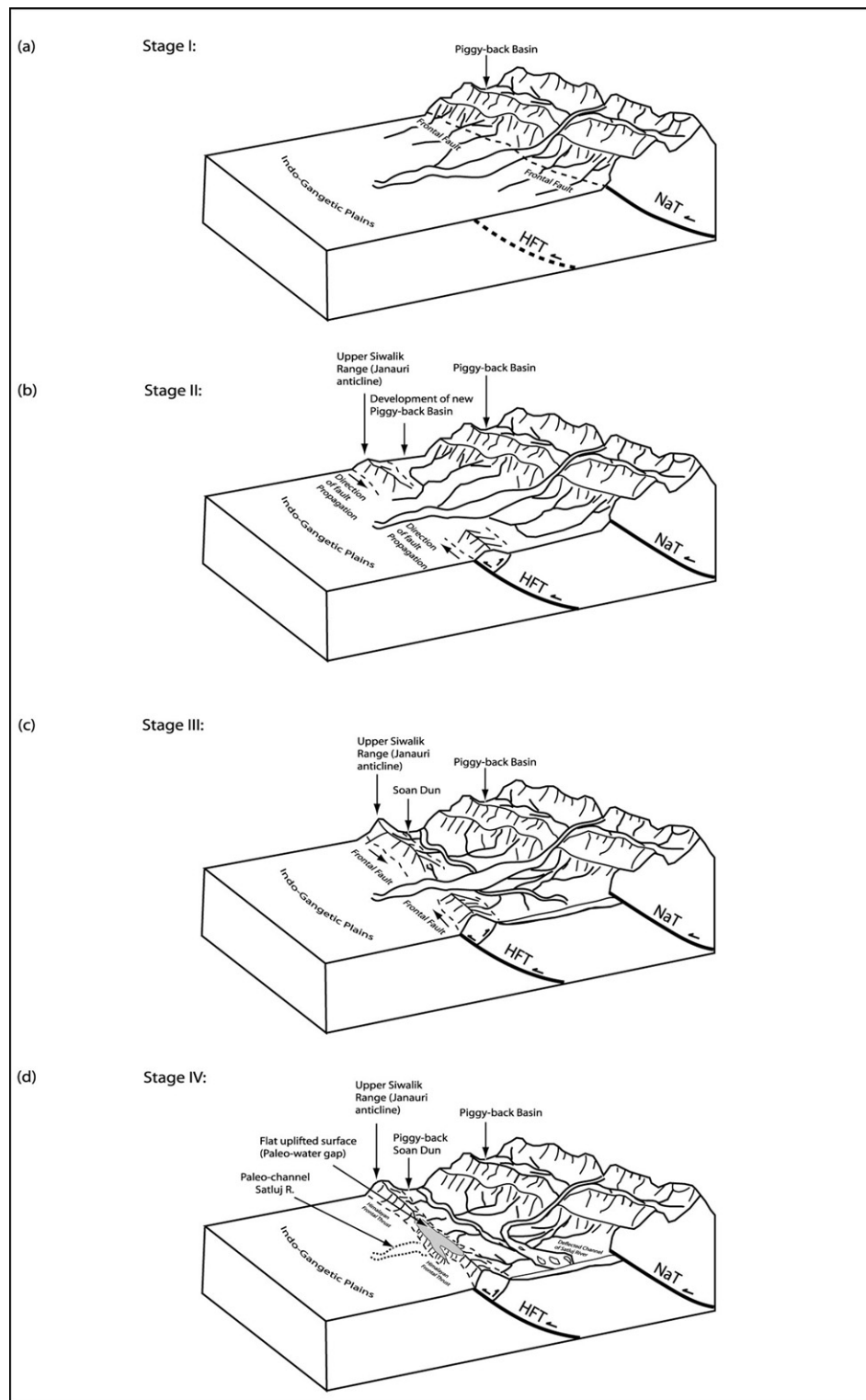


Fig. 9. Schematic diagram illustrating the geomorphic evolution of the terrain around NW Himalaya: (a) Stage I: prior to the commencement of activity along the HFT and prior to the formation of Soan Dun all the major rivers sourced from Higher Himalaya were debouching directly onto the plains. The NaT was the most frontal thrust; (b) Stage II: propagation of tectonic activity southward along HFT forming new fault line. The thrust faults causing the Janauri Anticline were two separate individual fault segments (north and south faults), which allowed the Sutlej channel to flow across the area confined between the two faults; (c) Stage III: the faults grew towards each other by lateral propagation, the southern fault propagated northward and the northern fault propagated southward; (d) Stage IV: continued propagation caused fault tip interaction of the two fault segments. The transition zone between the two overlapping fault segments was uplifted due to rapid movement along both faults. Due to rapid uplift the Sutlej River was not powerful enough to keep-up with the rate of uplift, thus was disrupted and deflected along its present course.

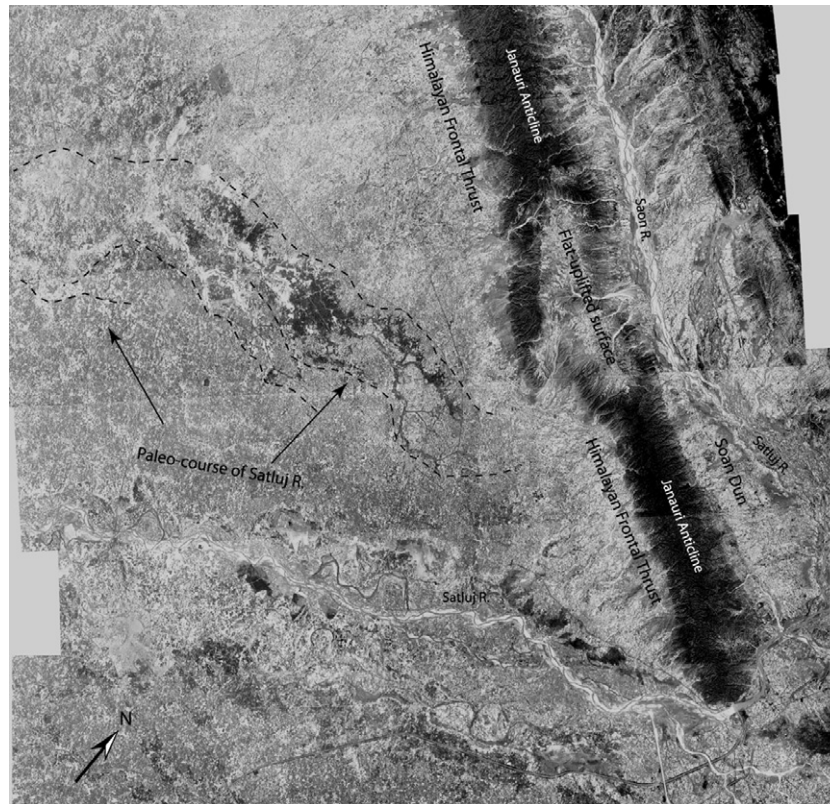


Fig. 10. CORONA satellite photo showing well defined paleo-course of the Sutlej River, which in the past flowed across the flat-uplifted surface. The course is presently occupied by narrow channel-network and can be traced easily a few km away from the piedmont zone. (Dashed line marked the boundary of Paleo-Sutlej drainage in alluvial plain area.)

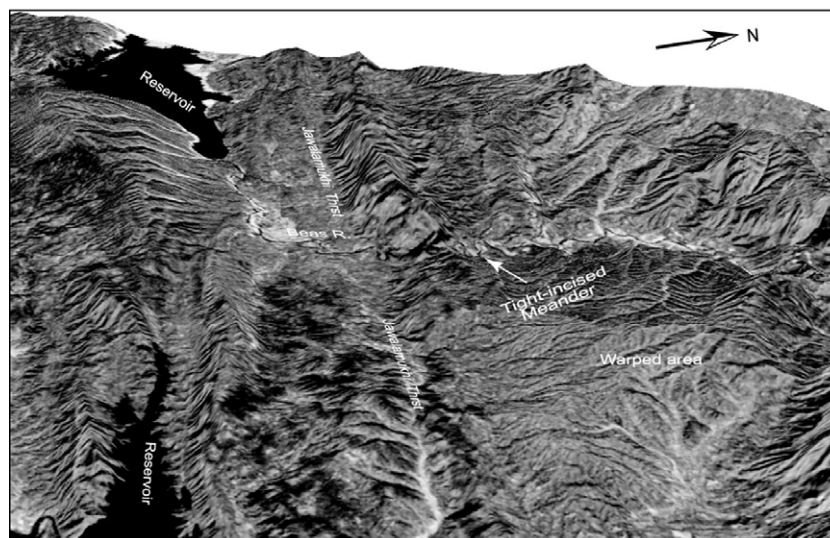


Fig. 11. 3-D perspective view of the terrain in the upstream region of the Beas River showing change in channel pattern due to ongoing tectonic uplift along the JMT. Upstream the channel before it crosses the uplift is marked by a tight or compressed meander channel, with a higher degree of incision near the uplift axis. In the lower reaches, after flowing through the folded range the channel is marked by a straight-braided channel network.

change in channel floor near active faults were observed along the hinterland faults north of the HFT domain. Prominent mountain fronts are observed along the NaT, BaT and JMT. However, apart from some places, the mountain fronts along the HFT and SnT are diffuse. This is well justified by the higher values of Mountain Front Sinuosity in Zones A ($S_{mf} = 1.28$) and B ($S_{mf} = 1.38$)

than Zones C ($S_{mf} = 1.22$) and D ($S_{mf} = 1.11$). Also, the most prominent evidence of the influence of active tectonic movement on the channel pattern is observed at the local scale, where the SW flowing Beas River crosses the JMT (NNW-SSE) (Fig. 11). The channel upstream of the uplifted area is marked by a tight or compressed meander, whereas, when the channel crosses the thrust

front it has an almost straight course (Fig. 11). The sharp front along the JMT and up-warping of the area to the north, indicates the active nature of this fault (Figs. 3 and 11). From the above geomorphic indicators it can be inferred that the thrust faults from HFT to MBT are all active, although the HFT system is less active than NaT, BaT, JMT and MBT.

5. Discussion

5.1. Tectonic influence on evolution of landscape and drainage

Evidence of the deflection of the course of the Sutlej and Beas Rivers observed in the NW Himalaya can be used to define the fold history of Janauri Anticline. The present study has shown that the disruption and deflection of the course of the Sutlej River was probably caused by the combination of fault growth and segment overlap/linkage of two fault segments that propagated towards each other, resulting in the uplift of the river bed. Fluvial deposits preserved on the flat-uplifted surface of Janauri Anticline indicate that this uplifted surface probably marks the paleo-water gap or paleo-exit of the Sutlej River. Investigations of large-scale drainage patterns from the Nepal Himalaya suggest that influence of the growth of an active fold on the course of a river may be variable, whereas some rivers maintain their initial course by cutting across the growing relief, others may be deflected for several kilometers (Gupta, 1997). The present study suggests that the uplift of the flat-surface is most likely related to the lateral propagation of fault segments and overlapping of fault tips (Figs. 9a–d). Initially the fault (HFT) bounding the Janauri Anticline to the south was two separate segments. The gap between these two faults allowed the Sutlej River to flow across the growing ridge (Figs. 9b, c). Later continued propagation of these faults towards each other resulted in fault tip interaction, causing rapid uplift of the transition zone between them. Due to rapid uplift the Sutlej River, even though it is a major river, was not capable of cutting across the growing anticline, and was disrupted and deflected along its present course (Figs. 9d). It has been suggested that tectonic movements along HFT were initiated at around 1.5–1.7 Ma, during the late Pleistocene (Validya, 2003). Also the biostratigraphic and megnetostratigraphic data from the western Nepal Himalaya suggests that, since more than 1.8 Ma, the frontal part of Himalaya has been affected by tectonic activity (Mugnier et al., 1999). Therefore, it is logical to suggest that the Janauri Anticline started to grow during the late-Middle Pleistocene. The less dissected morphology of the uplifted flat-surface, compared to the rest of the Janauri Anticline ridge suggests that this uplift was much younger.

Along with the above observations calculation of geomorphic indices like Valley width/height ratio (Vf) and Mountain front sinuosity (Smf) provided a quantitative approach for characterizing the influence of tectonics on

landscape morphology and drainage evolution. Vf indexes of cross-channel profiles along the Beas and its tributaries show the value of Vf ranges between 0.32 and 11.49. Vf values where the Beas River crosses the MBT = 0.45; PaT = 0.32; JMT = 1.54; SnT = 1.74 and shows a higher value of 11.49 at the BaT (Table 1; Fig. 5). All the profiles with lower Vf values are marked by V-shaped valley floors, indicative of river incision due to active tectonic uplift along these faults. Whereas, the higher values of Vf along the BaT, with broad U-shaped valley profiles, suggest a moderately active or inactive front. Profiles studied along the Sutlej River show Vf values ranging from 0.40 to 20, with the Vf values along MBT = 0.49; JMT = 1.04; BaT = 0.40; NaT = 0.49 and SnT = 20. Values ranging from 0.40 to 0.49 are associated with V-shaped to slightly broad shaped valleys, indicating moderate to active tectonic activity along the faults. The higher values of Vf along the SnT are associated with a broad U-shaped valley suggestive of an inactive front. From this analysis it can be inferred that the river channels crossing the thrust fronts with Vf indices <1.0 are the most tectonically active fronts, whereas fronts with Vf indices of 1–1.5 are moderately active, and in those with Vf >1.5 are marked by broad (U-shaped) valleys suggesting lateral migration of the channels in response to a stable base-level or tectonic quiescence.

Mountain front sinuosity (Smf) along the various fronts, categorized as zones A–D (Fig. 1), gave mean values of Smf ranging from 1.11 to 1.38 (Mohanty, 2004). Where zones D-along the MBT (Smf = 1.11) and C along JMT–BaT (Smf = 1.22) show lower values compared with zone A (Smf = 1.28) along the HFT – backthrust, and B (Smf = 1.38) along SnT. Values of Smf for all zones suggest that these fault systems fall under the category of active Class-I faults as suggested by Bull and McFadden (1977). From the Smf values it is suggested that the fault systems in zones C and D are more active than in zones A and B. According to several workers the most active front in the Himalayan domain is the frontal fault zone, i.e. along the HFT (e.g. Nakata, 1972, 1989; Validya, 2003; Thakur, 2004) and since the collision the tectonic activity has progressively shifted southwards towards the foreland (e.g. Powell and Conaghan, 1973; LeFort, 1975; Stöcklin, 1980). However, several lines of evidence, like sharp fronts with lower values of mountain front sinuosity (Smf), deeply incised channels crossing the thrust fronts with lower Vf values, changes in channel pattern, etc. observed during the present study demonstrate that it is not only the fault system along the HFT which is active, with the front fault accommodating or consuming the overall slip, but that part of the slip is accommodated by the hinterland fault systems in zones C and D.

This interpretation can be confirmed by measurements of the present rate of convergence in the Himalayan region. GPS studies between the sub-Himalaya and the Higher Himalaya across the Kangra reentrant during the period from 1995 to 2000 by Banerjee and Bürgmann (2002) showed that in a zone between the HFT and 100 km north of the

Siwalik Foothills the rate of shortening was 14 ± 1 mm/yr. A similar rate of 14 ± 2 mm/yr was deduced from the restoration of balanced geological cross-sections over a distance of 140 km across the Kangra reentrant (Powers et al., 1998). Inversion of the GPS data indicates that although the HFT would have accommodated most of the shortening across the Himalaya during the Quaternary, at present the HFT is locked over a width of 100 km and showed no movement during the period of observation; slip must be taken up by faults to the north of this zone.

6. Conclusions

From the present study it has been inferred that major tectonic features – HFT, MBT and MCT as well as the secondary thrusts – SnT, NaT, BaT, JMT and PaT have played an important role in shaping the present complex landscape of the NW Himalaya. Fluvial deposits preserved on the flat-uplifted surface of the Janauri Anticline indicate that this uplifted surface marks the paleo-water gap or paleo-exit of the Sutlej River. The uplift of the flat-surface was probably related to the lateral propagation of fault segments and overlapping of fault tips, where initially the fault consisted of two separate fault segments in the geological past. The gap between these two faults allowed the Sutlej channel to flow across the growing ridge. Continued propagation of these faults towards each other resulted in fault tip interaction causing rapid uplift of the transition zone between them. Due to rapid uplift, the Sutlej River, even though it is a major river, was not capable of cutting across the growing anticline, thus was disrupted–deflected into its present course. It is suggested that the Janauri Anticline started growing during late-Middle Pleistocene and the less dissected morphology of the uplifted flat-surface, as compared to the rest of the Janauri Anticline ridge suggests that the uplift must have been much younger. The prominent V-shaped valleys of the Beas and Sutlej rivers flowing across the thrust fronts with Vf values ranging from <1.0 to 1.5 also suggest active tectonic activity along the major as well as the hinterland faults. The Mountain front sinuosity Smf values ranging from 1.11 to 1.38 from all the zones (zone A–D) suggests that all the fault systems are active. However, slightly higher values of Smf along the HFT and also the diffuse front suggest that the HFT is less active than the hinterland faults. Not only is the HFT system active but also all the other major and secondary hinterland faults, viz. the MBT, MCT, SnT, NaT, BaT, and JMT are also active, and have taken part in recent tectonic movements.

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