# Active fault study along foothill zone of Kumaun Sub-Himalaya: influence on landscape shaping and drainage evolution

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**The Kumaun Sub-Himalaya region is one of the most active regions falling into Seismic Zone V along the Himalaya. The geomorphology and drainage patterns in the area of active faulting and related growing fold provide significant information on the ongoing tectonic activity. The Kaladungi Fault (KF), an imbricated thrust fault of the Himalayan Frontal Thrust system provides an excellent example of forward and lateral propagation of fault and related folding in both directions along the strike of the fault. The KF has displaced the distal part of the Kaladungi fan surface resulting into formation of south-facing active fault scarp with variable heights along the front. In the east, the uplifted fan surface is ~60 m, is comparatively higher in the central part with height of ~200 m and ~80 m high in the west. The variation in heights along the fault is attributed to lateral propagation of fault and associated fold in both directions (i.e. east and west) from the centre. These clearly testify displacement starting at nucleation in the centre and propagating laterally in an elliptical manner. The northwest and southeast propagation of KF has resulted into diversion of the Dabka and Baur rivers respectively. A marked diversion of the modern Dabka river along its present course from east to west can be traced between Shivlalpur and Karampur towns, covering a distance of about 10–12 km. Similarly, the Baur river is shifted from west to east by about 5–6 km between Kamola and Kaladungi towns. The diversion of Dabka and Baur rivers can well be justified by the existence of palaeo-wind-gaps through which these rivers flowed earlier during the recent past. The wind-gaps are characterized by about 0.5–1.0 km wide incised valley extending in NE–SW direction between Kaladungi and Karampur along the frontal zone.**

**Keywords:** Active fault, fold and thrust belt, lateral propagation, river diversion.

## Introduction

ONGOING tectonic activity in the Himalayan terrain is well revealed by the occurrence of moderate to large-magnitudes earthquakes as well as prominent tectonically controlled geomorphic indicators. The most prominent large-magnitude earthquakes which have occurred along the Himalayan arc in the last 100 years are: 1905 Kangra ($M_w$ 7.8), 1934 Bihar ($M_w$ 8.4), 1950 Upper Assam ($M_w$ 8.4) and 2005 Muzaffarabad ($M_w$ 7.6) earthquakes[1–6]. In the Himalayan region several studies have revealed that geomorphic expression like displaced and warped Late Pleistocene and Holocene surfaces along active faults in the frontal zone, the signatures of palaeo-lake formation due to movement along active faults, gullied surfaces marked by ravines and the development of canyons/deep narrow gorges, entrenched channels and waterfalls are indicative of active tectonic and fault displacement, and its influence over the evolution of the landscape[4,6–19]. It has been proved that careful evaluation of geomorphic features can help in understanding the influence of tectonics on landscape change and drainage evolution[6,8,18,20–28]. Understanding of past drainage evolution may be derived from present-day river patterns, which provide insights into past deformational events within active mountain belts[29]. Numerous conceptual models and field studies suggest that in tectonically active regions, the fault growth and associated deformation have direct control over shaping the landscape and drainage evolution[6,15,16,18,24,25,29–31]. Fault growth, related folding and propagation of fold in the frontal and lateral directions are usually observed in fold-and-thrust belts. The process of active faulting and associated fold growth, lateral propagation and fault segmentation as well as linkage in many tectonically active regions have influenced the shaping of the landscape[15,24,32,33]. Also, it has been suggested that displacement during each major earthquake along active faults most likely contributes towards the growth of the fault and fold[34]. These active faults could be considered as a source for future earthquakes[18,35]. Continuous deformation and related growth of the landform

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creates fluvial diversions; such geomorphic indicators can be used to reconstruct the fold history of the region[6,30,33]. Lateral propagation of fault and associated fold has usually caused diversion of river channels leaving behind the palaeo-water or palaeo-wind-gaps as observed along several areas; for example (a) Pakuashan anticline, foothills of Taiwan[15], (b) Wheller ridge, California[30,36], (c) Tien Shan, Kyrgyzstan[37], (d) eastern Ecuadorin Andes[33], (e) Kerman Province, SE Tehran[38], (f) Janauri anticline along the Himalayan Frontal Thrust (HFT), India[6,18] and (g) Zagros Simply folded belt, Iran[39]. In this article we present surface manifestation of lateral propagation of fault and related fold growth along HFT in the foothill zone of Kumaun Sub-Himalaya (Figure 1). The fault propagation and fold development have caused the Dabka and Baur rivers to divert from their earlier course to the present one in different stages (Figures 1–4).

## Geomorphology of the study area

In the present study along the Himalayan front, we used the Survey of India Toposheet (1 : 50,000 scale), the Shuttle Radar Topographic Mission (SRTM, 3 arc sec data with spatial resolution of about 90 m), IRS-1D LISS-III digital image of 29 September 1997 (with resolution of 23 m) and CARTOSAT-1 stereo-othrokit data of 11 November 2005 with resolution of 2.5 m for identification and mapping of tectono-geomorphic features (Figures 1–4). Using these data we generated shaded relief image and 3D perspective surface view of the terrain, which helped us in delineating prominent displaced and deformed young fluvial and alluvial fan surfaces revealed by active fault scarps, back-tilting of terraces, deflection of channels and palaeo-wind-gaps (Figures 2–4).

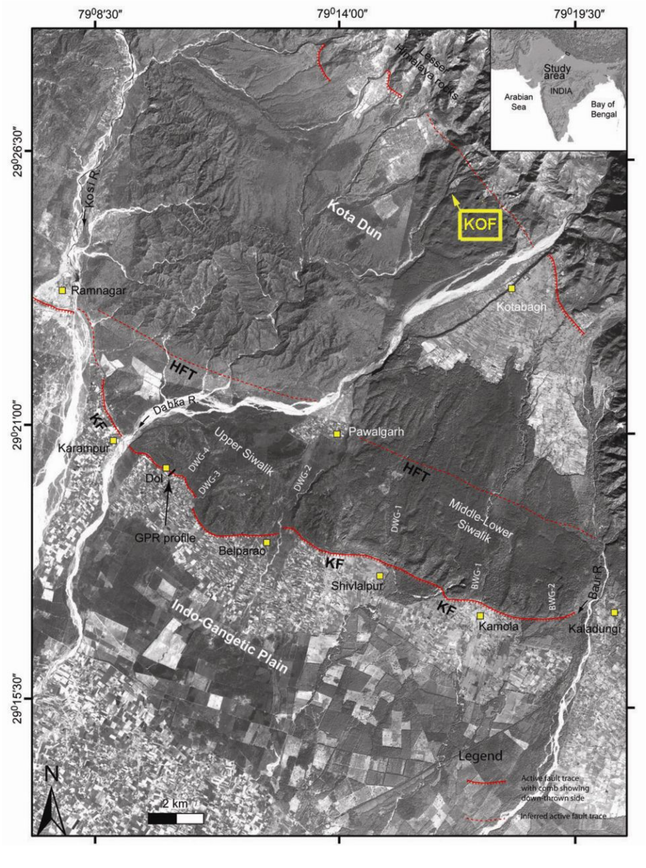

**Figure 1.** CARTOSAT-1 data showing the distribution of active fault traces around Kaladungi–Kotabagh area. The Kaladungi fan is flanked by Baur river to its east and Dabka river to its west. The fan is displaced by Kotabagh Fault (KOF) in its proximal end and by Kaladungi Fault (KF) in distal part. KF represents imbricated fault of Himalayan Frontal Thrust (HFT). DWG1–3, Wind-gaps of Dabka river; BWG1 and 2, Wind-gaps of Baur river.

Geomorphologically, the study area can be categorized in four broad zones from north to south[7,9,40,41]: (1) The folded Sub-Himalayan range comprises of Middle–Lower Siwalik succession in the eastern part and Upper Siwalik succession in the western part, bounded to the south by major Kotabagh Fault (KOF), (2) Kota Dun (Dun = valley) – marks the intermontane valley confined between Upper Siwaliks range and Lesser Himalayan rocks. (3) Sub-Himalaya – youngest detached range comprising of Upper–Middle Siwalik rocks demarcating the southernmost fringes of Himalaya. (4) The Indo-Gangetic Plains which represents the present foreland basin (Figures 1 and 2). The area comprises two major active faults – the Kotabagh Fault (KOF) which separates the Lower Siwalik Hill from Late Pleistocene to Early Holocene gravel fills of Kota Dun and the HFT separating the Quaternary alluvial deposits of the Indo-Gangetic Plains from detached Sub-Himalayan range[7] (Figures 1–3). These faults have displaced young surfaces resulting into development of prominent south-facing fault scarps ranging in height from about 30 to 90 m (refs 7, 42, 43). Younger fault scarps with lesser height of about 13 m were also reported[44], and also during the present study we came across fault scarps ranging in height from 9 to 12 m, which are formed due to uplift of river beds and deposits that belong to Dabka and Baur rivers (Figures 2).

The area is characterized by two major antecedent rivers, Dabka and Baur, having their catchment in the Lesser Himalaya (Figure 1). These rivers flow transverse to the growing anticline in the frontal part. The Kaladungi alluvial fan extending for about 14–16 km N–S and about 16–17 km E–W is the most conspicuous landform observed in the study area (Figures 1 and 3 *a*). Presently, the Kaladungi fan on its east is flanked by the Baur river and on west by the Dabka river (Figures 1 and 2). It represents a coaleased alluvial fan surface formed by sediments deposited by these two major rivers along with several southwest-flowing rivers emerging from the Lower Himalaya debouching into the alluvial plain (Figure 1). The Kaladungi fan surface has been displaced by KOF near its proximal part, and more prominently in the distal part by the Kaladungi Fault (KF) that lies along the front; this has resulted into formation of south-facing fault scarps (Figures 1–4). Topographic profiles drawn

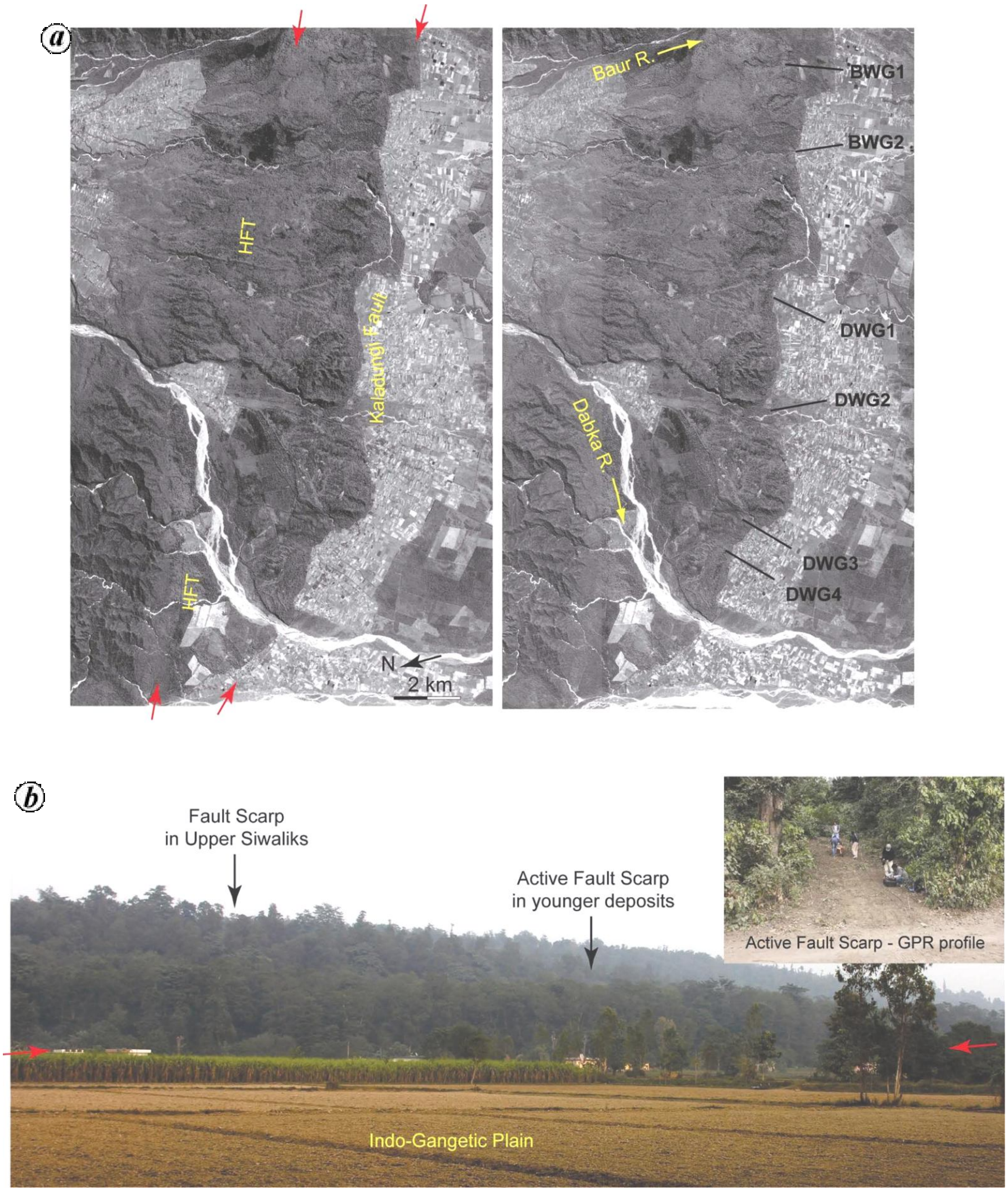

**Figure 2.** ***a***, Stereo-pair of CARTOSAT-1 data covering the area of Kaladungi fan from east to west along KF. ***b***, A view of south-facing active fault scarp east of Dol village. (Inset) Location of GPR profile collected at Dol.

(SW to NE) across KF and fan area clearly show warping and back-tilting of the fan surface towards northeast (Figure 4 *a–h*). This deformation is attributed to long-term displacement–deformation on KF (Figure 4 *a–h*). Also slight internal deformation marked by warping was noticed in the central portion of the fan surface; this is probably related to the movement taking place along HFT (Figures 2–4). This fault trace is marked as Himalayan Frontal Tectonic Line (HFTL)[7]. From the stereo-photo interpretation, 3D perspective view and topographic profiles, it has been noticed that the height of the uplifted fan comprising Upper Siwalik and Middle–Lower Siwalik surface is more (~ 200 m) in the central part and reduces towards east (~ 60 m) and west (~ 80 m) (Figure 4 *g*). The variation in fold height along the strike of the fault line can be attributed to lateral propagation of fault and related fold growth on either side (Figure 4 *a* and *g*). It has been suggested that in thrust-and-fold belts the displacement is initiated with a nucleation close to the centre of each fault and propagates laterally in an elliptical manner[6,25,32,34]. The lateral propagation of the fold along KF has resulted into diversion of the Dabka river to west and the Baur river to east (Figures 1–3 and 4 *a*, *g*). A prominent diversion of the modern Dabka river along its present course from east to west can be traced out well between Shivlalpur and Karampur towns (Figures 1–3).

This is justified by the existence of wind-gaps DW1, DW2, DW3 and DW4, through which it flowed earlier during Recent geologic past (Figures 1–4 and 5 *a*). The wind-gaps are characterized by about 0.5–1.0 km wide incised hanging valleys extending in NE–SW direction. A total distance of about 10–12 km can be accounted for the shift-diversion between DWG1 to DWG4 (Figures 1, 2 *a*, 3 and 4 *a*, *g*). Similarly, the Baur river is shifted from west to east marked by two palaeo-wind-gaps, BWG1 and BWG2, between Kamola and Kaladungi towns. The total shift from west to east is about 5–6 km for Baur river (Figures 1, 2, 4 *a*, *g*, *h* and 5 *b*, *c*). Presently, some of the wind-gaps either of Dabka river or Baur river on the alluvial fan surface as well as the palaeo-channels in the Indo-Gangetic Plain are drained by smaller streams emerging from the nearby area (Figures 1–3). Based on the above observations from satellite data interpretation and ground truthing, it is suggested that the fault and related fold growth was not instantaneous but the displacement during each major earthquake along the active fault contributes towards the evolution of this landscape.

Considering the phenomenon of lateral propagation of fault and related folding, topographic profile extracted across the uplifted Kaladungi fan and across the fold along the strike, an attempt has been made to reconstruct the evolution of the landscape vis-à-vis drainage in the region (Figures 2 *a*–*h*, 3 and 5).

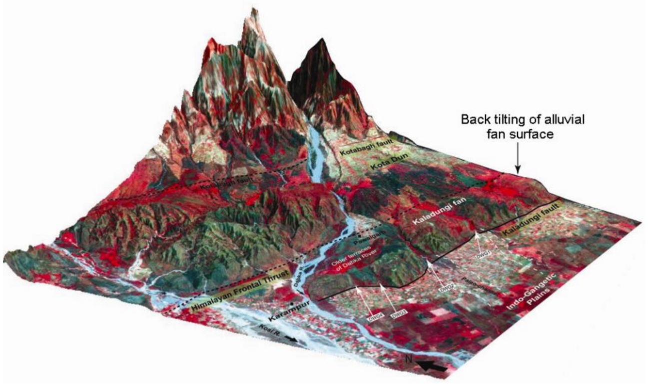

**Figure 3.** A 3D perspective view of the terrain of the study area, foothills of Kumaun Himalaya (USGS SRTM 3 arcsec data and IRS LISS III data). The Kaladungi fan has been displaced in its proximal part by Kotabagh Fault and in the middle part by HFT (?) and in the frontal most distal part by KF, an imbricated splay of HFT system. The KF has vertically displaced and back-tilted the fan surface which can be seen in the frontal part, resulting into south-facing fault scarp. Uplifted palaeo-valleys marked by wind-gaps of Dabka river are observed from the central part of the fold towards west (DWG1–4). Note that the height reduces towards west. The reduction of height of the fan surface towards NW is attributed to a phenomenon of lateral propagation of KF along strike. This has caused disruption and deflection of the Dabka river along its present course at the back of growing anticline, finally debauch in alluvial plain at Karampur. The palaeo-channel in the Indo-Gangetic Plain is drained by a smaller stream emerging from the nearby area of the distal part of alluvial fan.

## Ground Penetrating Radar survey

Active fault traces reported from this area[7,9,40] and also palaeoseismic studies carried out near Belparao have helped in understanding the ongoing deformation along active fault[44]. To confirm the active faulting, we conducted Ground Penetrating Radar (GPR) survey across a NW–SE facing active fault scarp near Dhol (Figures 1, 2 *a*, *b* and 6 *a*, *b*).

The GPR data were collected using SIR 3000 single-channel system with 200 MHz shielded antenna. A total profile of 20 m length was collected in common-offset continuous mode (Figures 1 and 6 *a*, *b*). We were able to achieve a depth of about 6 m from the surface. A prominent inclined reflection indicative of a low-angle fault strand dipping towards NE was identified between 0 and 13 m horizontal marker, and between 0 and 5 m vertical marker (Figure 6). The hanging wall in NW marked by distinct georadar reflections is suggestive of folding within the sediment succession. These warped reflections are truncated along the fault plane and do not extend on the SW side (Figure 6). The fault trace is almost horizontal, suggesting thrust movement from NE to SW.

## Discussion and conclusion

The forward and lateral propagation of fault and related folding is one of the most commonly observed phenomena in thrust-and-fold belt[15,16,37,45]. The geomorphology and drainage patterns in the area of active faulting and related growing fold provide information on the ongoing tectonic activity of the area[25,33]. Drainage diversions and the development of wind or water-gaps on the active growing structures are the usual manifestation of lateral propagation of fault and associated fold in the active regions. One of the best-studied evidences of lateral propagation of faulting and folding is that of Wheeler Ridge, USA, where presence of more than one wind or water-gap is suggestive of lateral movement of fault-and-fold[31]. In the present study the diversion of the Dabka and Baur rivers and existence of their wind-gaps, DWG1-4 and BWG1-2 respectively, in the uplifted distal part of the Kaladungi alluvial fan has been used to delineate the ongoing tectonic deformation pattern in the frontal part of the Himalaya along KF, an imbricated fault of HFT (Figures 1, 2 *a*, 3, 4 *a*, *g* and *h*; and 5 *a*–*c*). Field studies and GPR profile helped us to get information about the ongoing deformation along KF along a NE dipping thrust fault (Figures 2 *a*, *b* and 6 *a*, *b*). Similar deformation on a low angle fault is reported from palaeoseismic studies near Belparao village along the KF[44].

The deflections of the Dabka and Baur rivers are attributed to forward and lateral propagation of fault-and-fold in the frontal part of the Himalaya along the HFT system. From the overall deformation pattern of

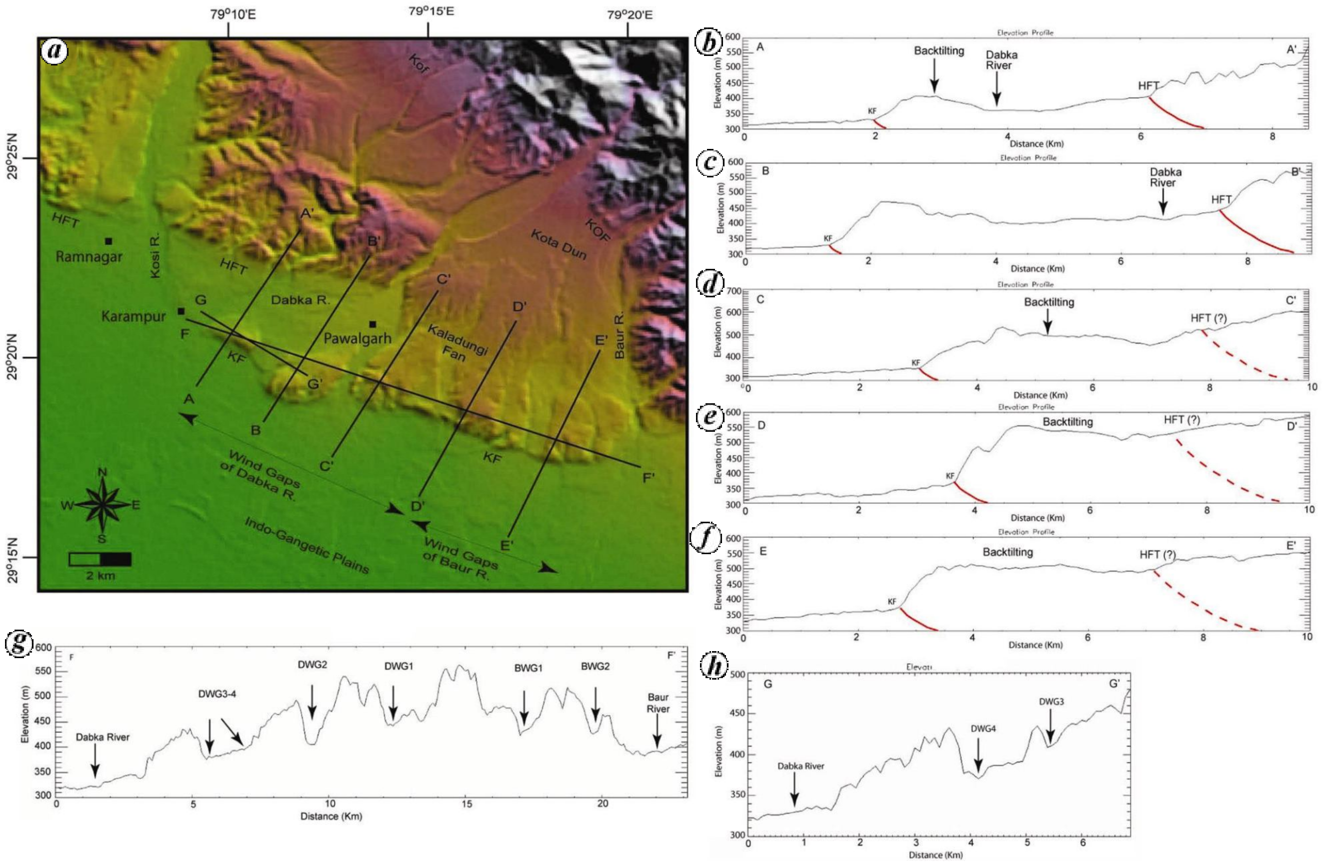

**Figure 4** ***a*–*h*.** DEM from SRTM data of the area around Kaladungi and Karampur in the foothills of Kumaun Himalaya. Black lines showing transects of topographic profiles across the Kaladungi alluvial fan. Where *AA*′, *BB*′, *CC*′, *DD*′ and *EE*′ are the profiles drawn across the distal and middle portion of the fan area from NNW to SSE and *FF*′ is the profile crossing the fan surface diagonally along the strike of the fault and fold to know the present channels and the wind-gaps of Dabka and Baur rivers. All profiles across the fan show prominent south-facing scarp (60–70 m) and back-tilting of fan surface towards NE in the frontal part caused by movement along KF. Topographic expression of KF dies out towards the east and west sides of the fan surface, which can be seen in profile FF′. The height of the uplifted surface reduces towards east (~ 60) and west (~ 80) with maximum in the centre (~ 200 m). At least four wind-gaps of Dabka river (DWG1–4) are identified starting from the centre towards west and two wind-gaps of Baur river (BWG-1 and 2) towards east. *GG*′ shows the profile taken across wind-gaps 3 and 4.

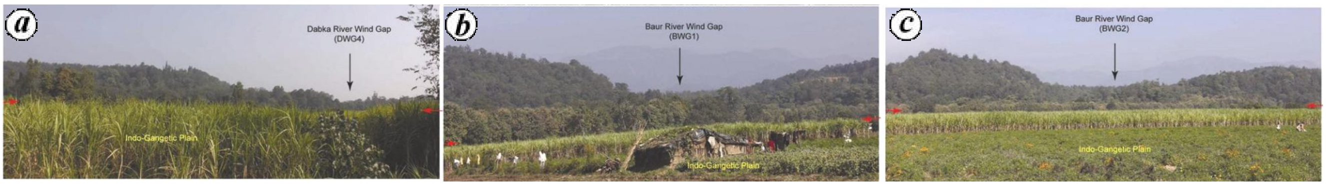

**Figure 5.** ***a***, Field photograph showing the western edge of wind-gap DWG-4 that belongs to Dabka river near Dhol (refer Figure 1 for location); ***b***, ***c***, Wind-gaps of Baur river (BWG1 and BWG2) along KF near Kamola village. Red arrows show the trace of active fault along KF.

the Kaladungi fan surface, it is suggested that initially (Stage I) the major (Dabka and Baur rivers) and minor streams were responsible for the deposition of alluvial fan in the foothill zone of Kumaun Himalaya (Figures 1, 3 and 7 *a*). During this period the HFT did not play a major role in this part of the region. All rivers flowed down directly on the Indo-Gangetic Plains. Later (Stage II) the tectonic activity propagated towards the foreland resulting in the development of a new fault line, the KF, which represents a young imbricated fault of HFT. Episodic movement along KF started displacing/uplifting the Kaladungi alluvial fan surface, resulting in the formation of south-facing fault scarps (Figures 1, 2 *a*, *b*, 3 and 7 *b*). During the process of fold growth by addition of displacement on fault due to major earthquakes, the rivers got channelized and started incising their own fan deposits. It is most likely that the Dabka and Baur rivers were capable to cope with the rate of uplift along KF until further propagation of fold in NW and SE directions. In Stage III, as the fault-and-fold propagated further, the erosive power in the channels of Dabka and Baur rivers was not enough to keep-up with the rate

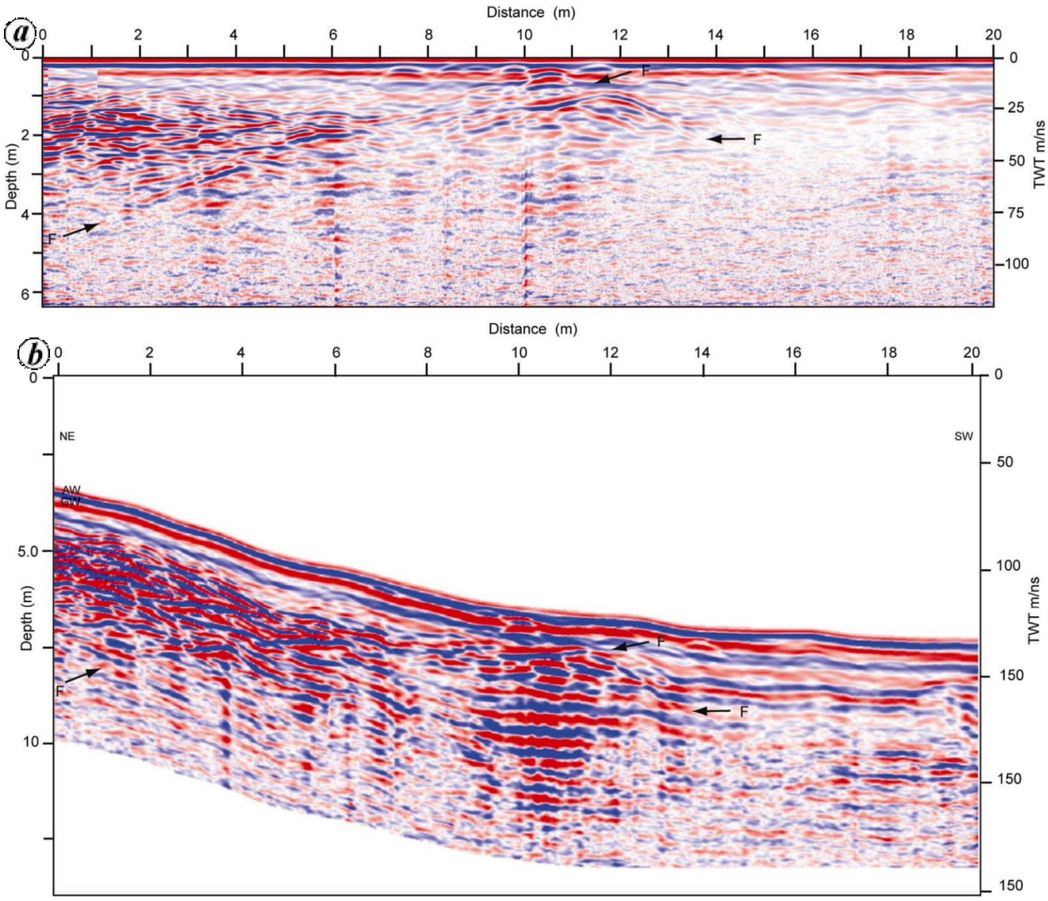

**Figure 6.** ***a***, Unprocessed Ground Penetrating Radar profile collected across active fault scarp at Dhol village (refer Figure 1 for location). The hanging wall in the northeastern portion of the profile shows prominent warping of georadar reflections. These reflections are truncated along a low angle, north-dipping fault strand. Fault strand is marked by black arrows extending between 0 and 13 m horizontal marker, and between 0 and 5 m vertical marker.

of uplift; the rivers thus were disrupted–deflected along their present courses in NW and SE directions (Figures 4*a*, *g* and 7*c*). It is suggested that the faulting in the frontal part initiated in the centre of KF and propagated laterally along the strike of the fold towards east and west directions; this can well be justified by the higher elevation of uplifted fan surface in the central portion (~ 200 m) and reduces towards east (~ 60 m) and west (~ 80 m; Figures 4*a* and *g*). Considering the wind-gaps of both the rivers, i.e. DWG 1–4 and BWG 1 and 2, it is suggested that Dabka river experienced more events of deflection compared to Baur river (Figure 4*a* and *g*).

Along the Himalayan arc similar evidences have been reported from the NW and NE parts[6,18,29,35] and from western Nepal[24]. And also from foothill zone of Taiwan[15,16] and eastern Ecuadorian[33], where the diversion of the rivers and formation of wind-gaps are the prominent indicators attributed to the phenomenon of forward and lateral fault-fold growth. It has been suggested that dip of the detachment (fault system) plays a significant role in drainage development and landscape evolution in the regions of active fold related folding[24]. When the detachment (fault-plane) is horizontal and lateral propagation rate is much higher than the convergence rate, drainage development is controlled by the relative rate of tectonic uplift and fluvial incision, but when the angle of the detachment is non-zero (fault plane), the lateral displacement gradient and associated fold propagation sets up an axial slope at the back of the growing structure causing diversion of all drainages[24]. However, they suggested that no wind or water-gap will form on the growing anticline. But several studies have indicated development of wind or water-gaps as the fault and associated fold propagates[15,16,30,33,36,37,45]. We suggest a similar mechanism to explain the diversion of the Dabka and Baur rivers along their present courses in the foothill zone of Kumaun Himalaya.

From our studies we conclude that initially the tectonic active fault propagated forward along KF, and then the fault propagated laterally on either sides, i.e. towards east and west along the strike causing diversion of both rivers. The existence of more than one wind-gap of the respective rivers is indicative of multiple shifting of the channels. Dabka river with four wind-gaps and Baur

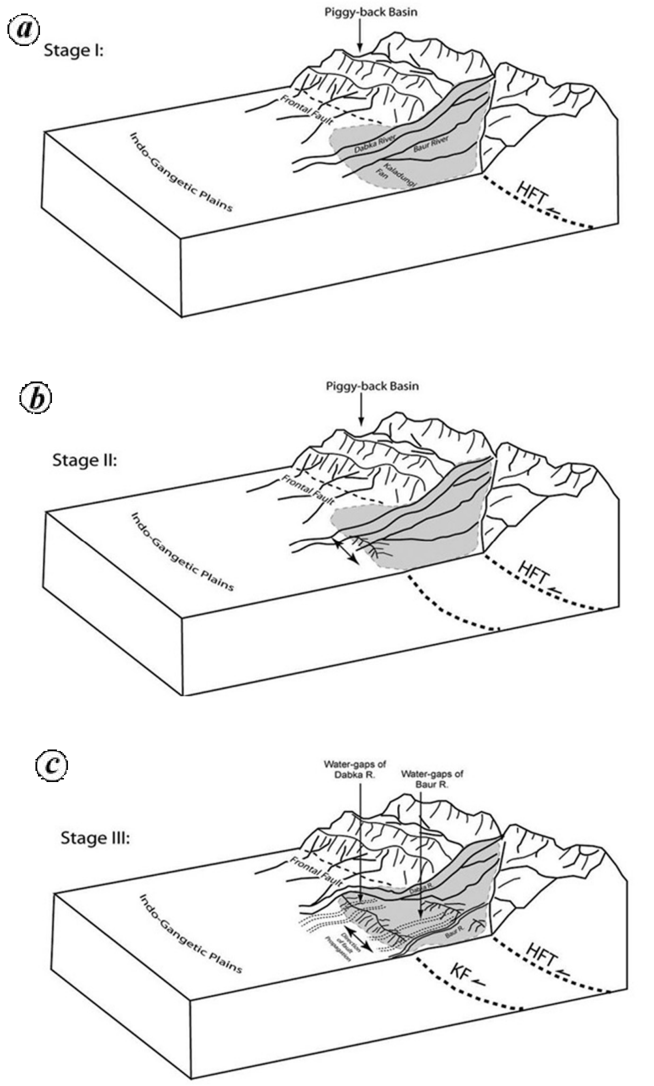

**Figure 7.** ***a***, Stage I: Prior to the foreland propagation of tectonic activity along KF, the HFT was the frontal most thrust. The Dabka and Baur rivers along with other minor streams were responsible for the deposition of the Kaladungi alluvial fan. ***b***, Stage II: Propagation of tectonic activity towards foreland along Kaladungi Fault forming new fault line. Uplift of the Kaladungi fan deposits. Uplift along this fault initiated from the centre of the fold and propagated laterally in an elliptical manner as commonly observed in thrust-and-fold belts. Major rivers (Dabka and Baur) got channelized and started incising their own fan surface. ***c***, Stage III: The faults started growing and propagating laterally along the strike in NW and SE directions. The lateral propagation of KF was responsible of the disruption and deflection of Dabka river towards NW and Baur River towards SE, leaving behind signatures in the form of wind-gaps. These wind-gaps represent the palaeovalleys of the major rivers.

river with two, suggest that KF moved laterally more towards NW compared to SE. The fault and associated fold growth was incremental and not instantaneous. This is justified from the occurrence of more than one wind-gap.

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1. Seeber, L., Armbruster, J. G. and Quittmeyer, R. C., *Seismicity and Continental Subduction in the Himalayan Arc*, AGU, Geodynamics Series 5, Washington, DC, 1982.
2. Ambraseys, N. and Bilham, R., A note on the Kangra $M_s = 7.8$ earthquake of 4 April 1905. *Curr. Sci.*, 2000, **79**(1), 45–50.
3. Bilham, R., Gaur, V. K. and Molnar, P., Himalayan seismic hazard. *Science*, 2001, **293**, 1442–1444.
4. Malik, J. N., Nakata, T., Philip, G., Suresh, N. and Virdi, N. S., Active fault and palaeoseismic investigation: evidence of historic earthquake along Chandigarh Fault in the frontal Himalayan zone, NW India. *J. Himalayan Geol.*, 2008, **29**(2), 109–117.
5. Kaneda, H. *et al.*, Surface rupture of the 2005 Kashmir, Pakistan, earthquake and its active tectonic implications. *Bull. Seismol. Soc. Am.*, 2008, **98**(2), 521–557; doi: 10.1785/0120070073.
6. Malik, J. N. *et al.*, Active fault, fault growth and segment linkage along the Janauri anticline (frontal foreland fold), NW Himalaya, India. *Tectonophysics*, 2010, 483, 327–343, doi: 10.1016/j.tecto.2009.10.028.
7. Nakata, T., Geomorphic history and crustal movements of foothills of the Himalaya. Sendai. Institute of Geographysics, Tohoku University, Japan, 1972, p. 77.
8. Seeber, L. and Gornitz, V., River profiles along the Himalayan arc as indicators of active tectonics. *Tectonophysics*, 1983, **92**, 335–367.
9. Nakata, T., Active faults of the Himalaya of India and Nepal. *Geol. Soc. Am., Spl. Pap.*, 1989, **232**, 243–264.
10. Yeats, R. S., Nakata, T., Farah, A., Fort, M., Mirza, M. A., Pandey, M. R. and Stein, R. S., The Himalayan frontal fault system. *Ann. Tecton.* (*Suppl.*), 1992, **6**, 85–98.
11. Valdiya, K. S., Rana, R. S., Sharma, P. K. and Dey, P., Active Himalayan Frontal Fault, Main Boundary Thrust and Ramgarh Thrust in southern Kumaun. *J. Geol Soc. India*, 1992, **40**, 509–529.
12. Valdiya, K. S., Reactivation of faults, active folds and geomorphic rejuvenation in Eastern Kumaun Himalaya: wider implications. *Indian J. Geol.*, 1999, **71**(1), 53–63.
13. Wesnousky, S. G., Kumar, S., Mohindra, R. and Thakur, V. C., Uplift and convergence along the Himalayan Frontal Thrust. *Tectonics*, 1999, **18**(6), 967–976.
14. Lavé, J. and Avouac, J. P., Active folding of fluvial terraces across the Siwalik Hills, Himalayas of central Nepal. *J. Geophys. Res. B*, 2000, **105**(B3), 5735–5770.
15. Delcaillau, B. *et al.*, Morphotectonic evidence from lateral propagation of active frontal fold; Pakuashan anticline, foothills of Taiwan. *Geomorphology*, 1998, **24**, 263–290.
16. Delcaillau, B., Geomorphic response to growing fault-related folds: example from the foothills of central Taiwan. *Geodin. Acta,* 2001, **14**, 265–287.
17. Malik, J. N. and Nakata, T., Active faults and related Late Quaternary deformation along the northwestern Himalayan Frontal Zone, India. *Ann. Geophs.,* 2003, **46**(5), 917–936.
18. Malik, J. N. and Mohanty, C., Active tectonic influence on the evolution of drainage and landscape: geomorphic signatures from frontal and hinterland areas along Northwestern Himalaya, India. *J. Asian Earth Sci.*, 2007, **29**(5–6), 604–618.
19. Jayangondaperumal, R., Wesnousky S. G. and Chaudhari, B. K., Note on early to late Holocene surface faulting along the northeastern Himalayan Frontal Thrust. *Bull. Seismol. Soc. Am.*, 2011, **101**(6), 3060–3064; doi: 10.1785/0120110051.
20. Gregory, D. I. and Schumm, S. A., The effect of active tectonics on alluvial river morphology. In *River – Environment and Processes* (ed. Richards, K.), Institute of British Geographers Special Publication, Blackwell, New York, 1987, vol. 18, pp. 41–68.
21. McCalpin, J. P., *Paleoseismology*, Academic Press, New York, 1996, p. 588.
22. Malik, J. N., Sohoni, P. S., Merh, S. S. and Karanth, R. V., Paleoseismology and neotectonism of Kachchh, Western India. In *Active Fault Research for the New Millennium*. Proceedings of the Hokudan, International Symposium and School on Active Faulting (eds Okumura, K., Takada, K. and Goto, H.), Japan, 2000, pp. 251–259.

23. Burbank, D.-W. and Anderson, R. S., *Tectonic Geomorphology*, Blackwell Science, 2001, p. 274.
24. Champel, B., Vander, B. P., Mugnier, J. L. and Leturmy, P., Growth and lateral propagation of fault-related folds in the Siwaliks of western Nepal: rates, mechanisms, and geomorphic signature. *J. Geophys. Res.*, 2002, **107**, 2-1–2-18.
25. Schumm, S. A., Dumont, J. F. and Holbrook, M. J., *Active Tectonics and Alluvial Rivers*, Cambridge University Press, Cambridge, 2002, p. 276.
26. Silva, P. G., Goy, J. L., Zazo, C. and Bardaji, T., Fault-generated mountain fronts in southeast Spain: geomorphologic assessment of tectonic and seismic activity. *Geomorphology*, 2003, **50**, 203–225.
27. Riquelmea, R., Martinod, J., Herail, G., Darrozesa, J. and Charrierb, R., A geomorphological approach to determining the Neogene to Recent tectonic deformation in the Coastal Cordillera of northern Chile (Atacama). *Tectonophysics*, 2003, **361**, 255–275.
28. Delcaillau, B., Carozza, J. M. and Laville, E., Recent fold growth and drainage development: the Janauri and Chandigarh anticlines in the Siwalik foothills, northwest India. *Geomorphology*, 2006, **76**, 241–256.
29. Friend, P. F., Jones, N.-E. and Vincent, S. J., Drainage evolution in active mountain belts: extrapolation backwards from present-day Himalayan river patterns. *Spec. Publ., Int. Assoc., Sediment*, 1999, **28**, 305–313.
30. Keller, E. A., Larry, G. and Tierney, T. E., Geomorphic criteria to determine direction of lateral propagation of reverse faulting and folding. *Geology*, 1999, **27**(6), 515–518.
31. Van der Woerd, J. *et al.*, Rapid active thrusting along the northwestern range front of the Tanghe Nan Shan (western Ganshu China). *J. Geophys. Res.*, 2001, **106**, 30475–30504.
32. Davis, K., Burbank, D. W., Fisher, D., Wallace, S. and Nobes, D., Thrust-fault growth and segment linkage in the active Ostler fault zone, New Zealand. *J. Struct. Geol.*, 2005, **27**, 1528–1546.
33. Bés de Berc, S., Soula, J. C., Baby, P., Souris, M., Christophoul, F. and Rosero, J., Geomorphic evidence of active deformation and uplift in a modern continental wedge-top-foredeep transition: example of the eastern Ecuadorian Andes. *Tectonophysics*, 2005, **399**, 315–350.
34. Walsh, J. J., Nicol, A. and Childs, C., An alternative model for the growth of faults. *J. Struct. Geol.*, 2002, **24**, 1669–1675.
35. Malik, J. N., Sahoo, A. K., Shah, A., Shinde, D. P., Juyal, N. and Singhvi, A. K., Paleoseismic evidence from trench investigation along Hajipur fault, Himalayan Frontal Thrust, NW Himalaya: implications of the faulting pattern on landscape evolution and seismic hazard. *J. Struct. Geol.*, 2010, **32**, 350–361, doi: 10.1016/j.jsg.2010.01.005.
36. Muller, K. and Talling, P., Geomorphic evidence for tear faults accommodating lateral propagation of an active fault-bend fold, Wheeler Ridge, California. *J. Struct. Geol.*, 1997, **19**(3–4), 391–411.
37. Burbank, D.-W., McLean, J.-K., Bullen, M., Abdrakhmatov, K.-Y. and Miller, M.-M., Partitioning of intermontane basins by thrust-related folding, Tien Shan, Kyrgyzstan, *Basin Res.*, 1999, **11**, 75–92.
38. Walker, T. R., A remote sensing study of active folding and faulting in southern Kerman province, S.E. Iran. *J. Struct. Geol.*, 2006, **28**, 654–668.
39. Burberry, C., Cosgrove, J. W. and Liu, G. J., Spatial arrangement of fold types in the Zagros Simply folded belt, Iran, indicative by landform morphology and drainage pattern characteristics in the Earth and Atmospheric Sciences. *J. Maps*, 2008, 417–430.
40. Shah, A. A., Identification of active tectonic features around Ramnagar and KotaBagh area of Nainital Foothills. M Tech Thesis, IIT Kanpur, 2005, p. 77.
41. Goswami, P. K. and Pant, C. C., Geomorphology and tectonics of Kota–Pawalgarh Duns, Central Kumaun Sub-Himalaya. *Curr. Sci.*, 2007, **92**(5), 685–690.
42. Valdiya, K. S., Joshi, D. D., Sanwal, R. and Tandon, S. K., Geomorphological development across the active Main Boundary Thrust: an example from Nainital Hills in Kumaun Himalaya. *J. Geol. Soc. India*, 1984, **25**, 761–774.
43. Valdiya, K. S., The Main Boundary Thrust zone of Himalaya, India. *Ann. Tecton.*, 1992, **6**, 54–84.
44. Kumar, S., Wesnousky, S. G., Rockwell, T. K., Briggs, R. W., Thakur, V. C. and Jayangondaperumal, R., Paleoseismic evidence of great surface rupture earthquakes along the Indian Himalaya. *J. Geophys. Res.*, 2006, **111**, B03304; doi: 10.1029/2004JB003309.
45. Jackson, J., Norris, R. and Youngson, J., The structural evolution of active fault and fold systems in central Otago, New Zealand: evidence revealed by drainage patterns. *J. Struct. Geol*., 1996, **18**, 217–234.

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