ORIGINAL PAPER

Geomorphic analysis reveals active tectonic deformation on the eastern flank of the Pir Panjal Range, Kashmir Valley, India

Shabir Ahmad · M. I. Bhat · Christopher Madden · B. S. Bali

Abstract There are plenty of faults that show evidence that they are active. Most of the valley's floor is occupied by unconsolidated Karewa deposits, in particular on the south–southwest of the Kashmir Valley. In such situations, geomorphic data can reveal the location of active faults. Accordingly, we tried to identify geomorphic indices in SW of the Kashmir Valley (Veshav, Rambiara, and Romushi drainage basins), which revealed the area to be potentially tectonically active. This active faulting was further substantiated by drainage anomalies and field investigations, which provides evidence for an emergent out-of-sequence NE-dipping active reverse fault (identified first time on ground) named the Balapur Fault (BF). The BF can be traced over at least 40 km along the southwest side of the Kashmir Valley. The existence of the active Balapur Fault and of two other inferred faults north of the Panjal Thrust or Murree Thrust presents a picture of a more complex strain-partitioning regime in the Kashmir Himalayas than is usually visualized.

Keywords Geomorphic indices · Drainage anomalies · Balapur Fault · Field findings · SW Kashmir

Introduction

Drainage patterns are a powerful tool to trace the morphological character of an area. The gross character of drainage patterns is evident on topographic maps and aerial photographs;

S. Ahmad (✉) · M. I. Bhat · B. S. Bali
Department of Earth Sciences, University of Kashmir,
Srinagar 190006, India
e-mail: shabirgeo79@gmail.com

C. Madden
Department of Geosciences, Oregon State University,
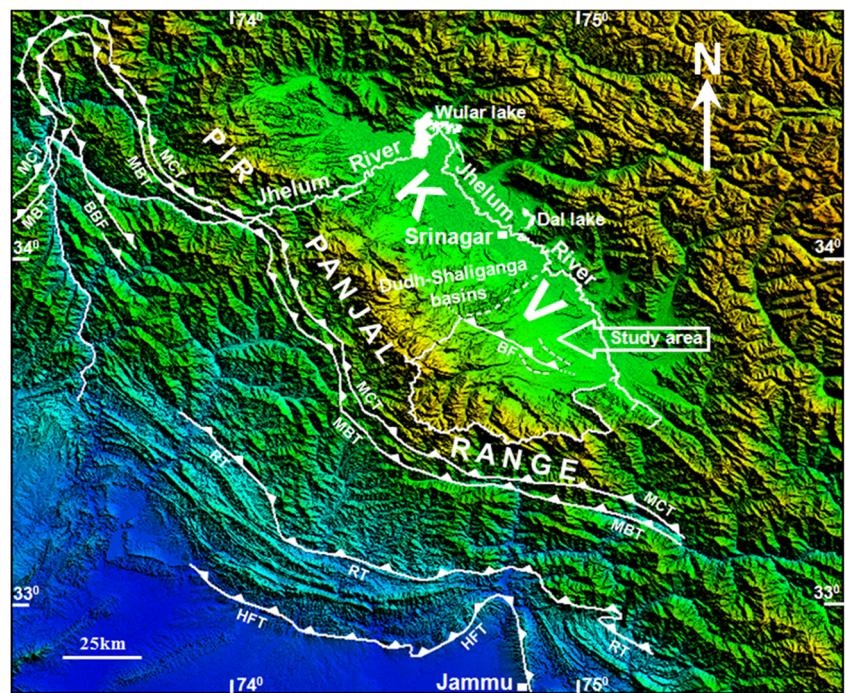Corvallis, OR 97331, USA

the patterns are useful for structural interpretation (Howard 1967; Kurz et al. 2007; Gloaguen et al. 2007, 2008). The nature of drainage pattern can vary greatly from one type of terrain to another. Its distribution depends on complex variables such as relief, slope, structure, climate, and vegetation characteristics. Furthermore, drainage pattern can provide important clues toward understanding the Quaternary tectonic activity of a region at both regional and local scales (Goldsworthy and Jackson 2000). At a regional scale, geomorphic indices provide basic reconnaissance tools to identify tectonically active regions (Keller 1986), their vulnerability to tectonic deformation, and level of tectonic activity (Keller 1986; Keller and Pinter 1996; Demoulin 1998).

Located in the zone of collision between the Indian and Eurasian plates, and having emerged out of mainly fluvio-glacial environment during Quaternary period, the Kashmir Valley is indeed an excellent case study for neotectonic activity. Besides, being a part of one of the most seismically active belts in the Himalayas, the presence of tilted fluvio-lacustrine deposits and clear fault scarps cutting Quaternary deposits, particularly along eastern flank of the Pir Panjal Range, are some of the key features suggesting recent tectonic activity in the region. However, little attention has been paid to the region, despite a few studies are available in literature such as lineament analysis (Gaju and Khar 1984), observations of southward-facing fault scarp segments (Yeats et al. 1992), and severe northward trajectory deflections in the tributaries of Jhelum (Bhat et al. 2008). However, all the above studies are devoid of any detailed analysis or field data. Therefore, the present study deals with the regional signatures of active tectonics using characteristics of drainage and geomorphic indices together with field observations of localized faulting in SW of the Kashmir Valley (Fig. 1). The study area is bounded on the west and southeast by the crest of the Pir Panjal Range. The eastern side is demarcated by the

river Jhelum, the trunk river of the Kashmir Valley. Its northwestern boundary is differentiated by Dudhganga–Shaliganga catchments, respectively.

Geotectonic setting

The reconnaissance geological mapping was carried out with the aid of published data (Wadia 1975; Bhatt 1976, 1989; Raza et al. 1978). The exposed bedrock and surficial units in and around the study area are shown in Fig. 2 and the stratigraphic succession is given in Table 1.

The Panjal Volcanic Series (Middlemiss 1910) (Upper Carboniferous-Permian) are the oldest rocks exposed in the upper reaches of the study area and, together with Triassic limestone, constitutes the bedrock of the headwaters. Most of the area is covered by fluvio-glacial sediments, collectively known as the Karewas or *wudr* in Kashmiri dialect (Plio-Pleistocene), which has been assigned Group status (Farooqi and Desai 1974; Bhatt 1989); these consist of a 1,300-m thick sequence of unconsolidated clays, sands, and conglomerates with lignite beds unconformably lying on the bedrock and are overlain by the recent river alluvium (Bhatt 1975, 1976; Wadia 1975; Burbank and Johnson 1982; Singh 1982). The Karewa Group has been subdivided into the progressively younger Hirpur, Nagum, and Dilpur Formations, respectively (Bhatt 1989). The Hirpur Formation broadly consists of gray to bluish–gray clays, light-gray sandy clays, fine to coarse-grained green to purple sands, conglomerates, lignite, and lignitic clays. The Nagum Formation is made up of fine to coarse-grained

greenish to purplish sands, gray and ochre sandy clays, ochre and cream-colored marls and gravels. The upper Dilpur Formation mostly consists of brown silts. The cross-sectional exposures of these stratigraphic units are currently observed along river sections and plateau margins of the Kashmir Valley. The Karewa Group have been studied in sections located along the Rambiara and Romushi rivers, which constitute two of the main tributaries of the northwesterly flowing Jhelum River that forms the main drainage system of the Kashmir Valley.

The Kashmir Valley is an intermontane basin in NW Himalaya. Kashmir basin lies to the northeast of the Pir Panjal Range, an elevated range which constitutes the frontal Himalaya in the area. Southwest of the Pir Panjal Range is a complex pattern of faulting with the superposition of several thrusts including from northeast to southwest, the MCT/Panjal, MBT/Murree, Riasi, and Kotli thrusts (Thakur et al. 2010). These faults are considered to be imbrications of the northward rooted basal décollement known as Main Himalayan Thrust (Schelling and Arita 1991; Brown et al. 1996; DeCelles et al. 2001). The southern-most deformation front of Kashmir Himalaya is defined by an active fold belt known as Suring-Mustgarh anticline that extends from river Beas in southeast to Jhelum in the northwest rather than by an emergent thrust. Several out-of-sequence faults (Fig. 1) have been mapped between Himalayan Frontal Thrust (HFT) and Main Boundary Thrust (MBT). These include the Riasi Thrust (RT), the Kotli Thrust (KT), and the Bagh–Balakot Fault (BBF). The latter was the source fault of Oct 2005

Fig. 2 Geological map of the Kashmir Valley (modified after Raza et al. 1978). *MCT* Main Central Thrust; *MBT*, Main Boundary Thrust; *BF*, Balapur Fault. Kashmir Valley has been devastated by earthquakes in the past as shown by place names: *1*, Khadanyar; *2*, Dobgam; *3*, Sopor; *4*, Larodora; *5*, Pattan; *6*, Bijbihara; *7*, Hassanpur; *8*, Hussainpur
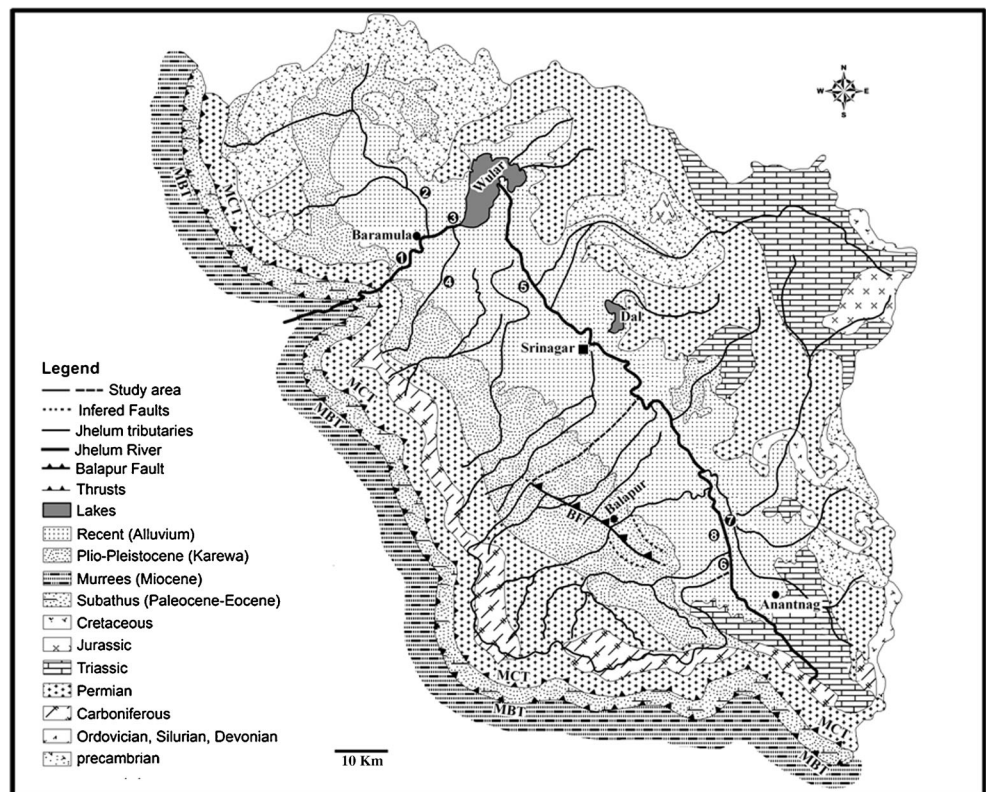

Mw 7.6 Muzzafarabad earthquake (Kaneda et al. 2008; Hussain et al. 2009; Thakur et al. 2010) which claimed more than 80,000 lives (Hough et al. 2009). No out-of-sequence faulting is known north of the MCT/Panjal Thrust or MBT/Murree Thrust except the structure observed by Yeats et al. (1992), a southwest-facing scarp in Kashmir Valley which is considered as a possible active fault. Burbank and Johnson (1982) revealed that

Kashmir Valley is experiencing uplift along its southwestern margin. Besides, Ahmad et al. (2009) suggested that the present landform structure and trunk channel of the Jhelum River in Kashmir Valley are indicative of the presence of three faults which follow the river Jhelum (Figs. 2 and 3). However, all the three studies lacks of relevant field data with respect to the fault existence on the surface.

Table 1 Geological succession of southwest Kashmir Valley (compiled after Wadia 1975; Bhatt 1976, 1989)

Formation/group			Lithology	Age
Alluvial deposits			Clay, sandy clay, silt with occasional gravel	Recent to subrecent
Loess–Paleosol succession of Dilpur Formation	Dilpur Formation	Karewa Group	Layers of brown silt vary from calcareous to non-calcareous types	Upper Pleistocene
Krungus Member	Nagum Formation		Gravels, sand, sandy clay, marl and silt	Middle Pleistocene
Pampur Member				
Shupiyan Member				
Angular unconformity			Angular unconformity	
Methawoin Member	Hirpur Formation			
Rambiara Member			Clay, sandy clay, conglomerate, varve sediment, liginite, and sand	Pliocene to Pleistocene
Er. Unconformity				
Dubjan Member				
Unconformity				
Triassic Formation			Limestones, shales, etc.	Triassic
Panjal Trap	Panjal volcanic series		Andesite, basalts, etc.	Permian
Agglomeratic slate			Slates	Carboniferous

Fig. 3 Study area with location features marked on the 90 m resolution DEM produced by SRTM. *Blue lines* are rivers over which *white arrows* are showing river flow, *white solid and dotted lines* marking the outer boundary of the drainage basin refer to hard rock (where basin demarcation is clear) and soft sediment terrain (where basin demarcation is problematic due to inter-basin crossover of streams, see Fig. 4 for more detail), the rest of the *dashed lines* are marked as inferred faults (*F–F*), respectively. For cross sections of A–A′, B–B′, C–C′, and D–D′ refer to Fig. 8. *White star* near Yusmarg shows cross section of a monoclinal fold, refer to Fig. 5
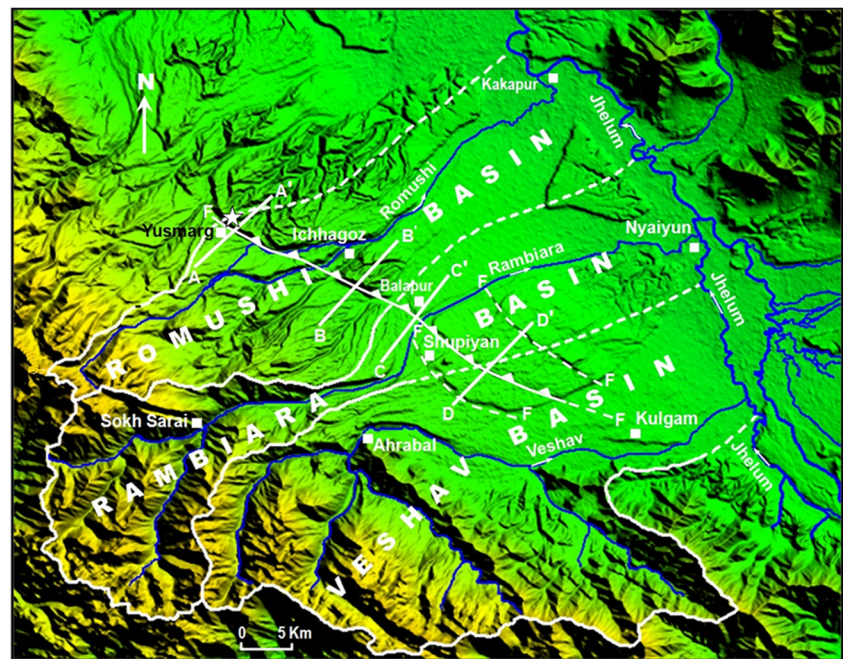
Drainage characteristics of the southwestern Kashmir Valley

The drainage characteristics of the southwestern Kashmir Valley are shown in Fig. 4. The solid and dotted lines marking the outer boundary between drainage basins refer to headwaters region where basin demarcation is clear and downstream fan areas, respectively. All the three tributaries of Jhelum (Veshav, Rambiara, and Romushi) rise from the high-altitude lakes and snow-covered mountains of the Pir Panjal Range in the SW.

The Veshav River drains the major segment of northern face of the Pir Panjal between the Sundartop (3,879 m) and Budil Pir pass (4,264 m) and therefore has a larger catchment area than either Rambiara and Romushi catchments. It generally flows NE however, from source up to Ahrabal where it forms a famous waterfall of 10 m within hard rock terrain flows NNE direction. From Ahrabal to Kulgam, it flows almost eastward and finally NE direction before its confluence with the Jhelum between the Palapur and Napur villages. It attains 67.4 km length and merges with the Jhelum about 12 km downstream of Kulgam Town.

The Rambiara River drains from Rupri pass of the Pir Panjal (4,085 m) and Naba Pir pass (4,253 m). The confluence of two streams, Rupri Nar and Yanga Nar at Sokh Saria, forms the Rambiara River. The Rambiara River maintains a general NE direction from its source (high-altitude lakes) to its mouth at Nyaiyun; however, at Tsogom, it turns NNE until the Balapur Village where it regains its NE flow. Downstream of Shupiyan Town, the tributaries on both side of the Rambiara River get divided into a large number of rivulets which spread over wide area on the Karewa floor.

However, most of these rivulets join the main channel before its confluence with the Jhelum. The total length of Rambiara River is 72.25 km.

The Romushi River drains between Katsgalu pass (4,234 m) and Sunset peak (4,745 m). The upper torrents unite near Pakharpur to give rise to a sizable stream which becomes a wide sandy plain in the Karewa slopes. It also maintains an average transverse (NE) flow until its confluence with the Jhelum near Kakapor and has a total length of 53.4 km.

All the drainage basins (Veshav, Rambiara, and Romushi) show trellis pattern with high incision over hard rocks, like agglomeratic slate, Panjal Traps, and limestone, and flow with more irregular, broad, and braided approach and the tributaries depict an (uncommon) irregular, crossover drainage pattern over the Karewa sediments. It must be mentioned that one of the tributary of Veshav channel named Kandai Kol depicts a barbed drainage pattern, which flow in opposite direction and merges with the master stream (Veshav) in a hook-shaped bend.

Material and methods

We characterize late Quaternary deformation in the southwest of Kashmir Valley in two ways. To quantify the relative activity of regional tilting identified by Burbank and Johnson (1982), we analyze geomorphic indices of drainages within the study area. To characterize the continuity, style, and relative activity of faults identified by Yeats et al. (1992) and Bhat et al. (2008), we conducted Digital Elevation Model (DEM) and field mapping. Geomorphic

Fig. 4 Drainage characteristics of SW Kashmir Valley, drainage lines have been drawn from the 1:50,000 topographic maps
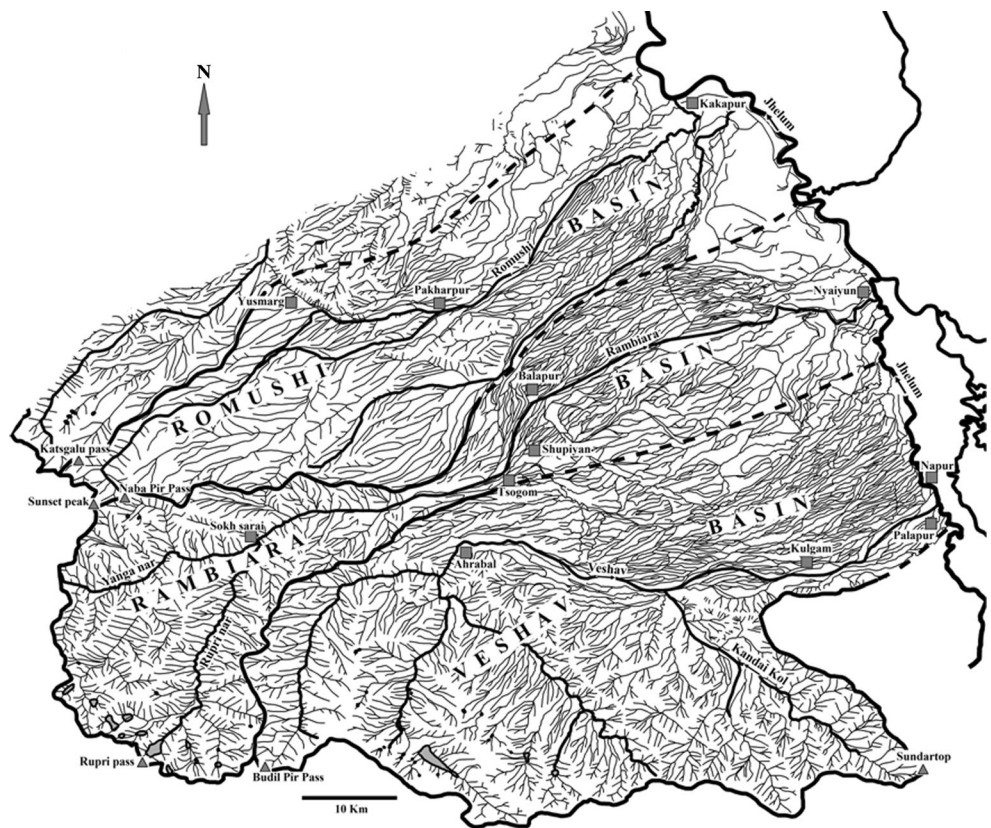
indices may indicate active tectonics in a region (Keller 1986; Goldsworthy and Jackson 2000). Furthermore, while a single any geomorphic index can produce its impact on drainage basin, a group of geomorphic indices along with their mutual correlations allows addressing the issue successfully and identifying a particular characteristic of a drainage basin, its vulnerability to tectonic deformation, and the level of tectonic activity (Keller 1986; Keller and Pinter 1996; Demoulin 1998). We analyzed the drainage system using a combination of two data sources. The primary data source is 1:50,000 topographic maps produced by the Geological Survey of India and 90 m resolution DEM derived from Shuttle Radar Topography Mission (SRTM). Several geomorphic indices for Veshav, Rambiara, and Romushi drainage basins have been computed (Table 2), and drainage features have been digitized from topographic maps which have been overlapped on SRTM 90 m DEM by using "software" Global Mapper.

For the second type of analysis in our study, we identify geomorphic features on aerial photographs and DEMs and confirm this mapping in the field to identify recently active fault traces (Wallace 1990).

Geomorphic indices: definition and results

Hypsometric integral (H_i)

The hypsometric integral (H_i), or area elevation analysis (Strahler 1952), is a quantitative measure of the degree of dissection of a drainage basin and is calculated by using the equation (Pike and Wilson 1971),

$$H_i = (h_{mean} - h_{min})/(h_{max} - h_{min})$$

Where H_i is the hypsometric integral, and h_{max}, h_{min}, and h_{mean} are the maximum, the minimum, and the mean

Table 2 Calculated geomorphic indices of Veshav, Rambiara, and Romushi drainage basins, southwest Kashmir Valley

Name of river	Basin area (km², A	Basin length (km), L	Hypsometric integral, H_i	Basin elongation ratio, E_b	Drainage basin asymmetry, AF
Veshav	616.88	43.16	0.49	0.65	70.20
Rambiara	641.06	59.62	0.51	0.48	61.52
Romushi	413.21	47.16	0.38	0.49	63.33

elevation, respectively. The maximum and the minimum heights are read directly from topographic maps or DEMs, and the mean elevation is obtained by randomly sampling a minimum of 50 points on the map and then calculating the mean value (Pike and Wilson 1971). Hypsometric integral reflects a competition between erosion and tectonics with respect to base level erosion. According to Keller and Pinter (1996), high hypsometric integral value reflects a dominant role of tectonic activity on drainage basins characterized by smooth upland landform surfaces with deeply incised streams. Conversely, intermediate to low values reveal erosional impact over tectonics and produce dissected drainage basins. Therefore, hypsometric integral would be expected to have a higher value for younger or youthful stage of landscapes and lower value for older ones as the landscape is denuded towards a stage of maturity and old stages (Strahler 1952; Keller and Pinter 2002). Hypsometric integral is a powerful tool for differentiating tectonically active regions from inactive ones.

The H_i sampling values were obtained from topographic maps, which were overlain on 90 m SRTM of the study area. The calculated H_i values, given in Table 2, vary from 0.38 (Romushi) to 0.49 (Veshav) and to 0.51 (Rambiara). They indicate youthful to mature landscape for the three Veshav, Rambiara, and Romushi basins, suggesting that the study area above and below the mean elevation is in equilibrium condition.

Basin elongation ratio (E_b)

The elongation ratio is a representation of the shape of a river basin. According to Schumm (1956), elongation ratio is defined as the ratio of the diameter of a circle having the same area as the basin and the maximum basin length. The parameter is calculated by using the following equation (Schumm 1956)

$$E_b = \frac{2\sqrt{A_b/\pi}}{l_b}$$

Where A_b is the diameter of a circle of the same area as the drainage basin and l_b is basin length measured from its mouth to the most distant point on the watershed limit. Basin elongation ratio also reflects competing roles of tectonics versus erosion. Whereas tectonics creates elongated basins, erosion over time tends to shape it into an oval/circular. According to Strahler (1964), E_b, over a wide variety of climatic and geologic types, usually ranges from 0.6 for an elongate, tectonically active/new basin to 1.0 for tectonically quiescent, oval to circular basin. Based on these general criteria, he classified drainage basins as: circular (>0.9), oval (0.8–0.9), less elongated (0.7–0.8), and elongated (<0.7). Bull and McFadden (1977) consider low value

for basin elongation ratio as a proxy indicator of recent tectonic activity.

The computed E_b values of all the basins of the study area are given in Table 2. They vary from 0.48 (Rambiara) to 0.49 (Romushi) and 0.65 (Veshav) pointing to the tectonically active setting in Rambiara and Romushi basins and slightly active tectonic inference to Veshav basin. Although the study area is being influenced by stream capture and lateral shifting of main rivers thereby, tends to initiate a process from oval to circular basin boundaries. However, the overall nature of all the three basins (Romushi, Rambiara, and Veshav) lies in elongated pattern, suggesting tectonically active setting of all the three basins.

Drainage basin asymmetry (AF)

This parameter allows determination of the general tilt of the basin landscape, irrelative of whether the tilt is due to local or regional tectonic deformation (Hare and Gardner 1985). The parameter is calculated by using the equation (Gardner et al. 1987)

$$AF = (A_r/A_t)100$$

Where AF is the asymmetry factor, A_r is the drainage area on the downstream right of the main drainage line and A_t is the total drainage area. When AF is greater than 50, the channel has shifted towards the downstream left side of the drainage basin. On the other hand, when AF value is less than 50, it indicates that the channel has shifted towards the downstream right side of the drainage basin.

Following Strahler's (1957) stream ordering scheme, the AF for Veshav and Rambiara rivers were extracted from the fifth order and for Romushi River from the fourth order Table 2. The values respectively of 70.20, 61.52, and 63.33 indicate that all channels (Veshav, Rambiara, and Romushi) have shifted downstream to the northwest of their basins. This downstream shifting of all rivers (Veshav, Rambiara, and Romushi) is possibly due to the obstruction by faulting (discussed below).

Tectonic geomorphology

An integration of topography and landforms together with the characteristics of the drainage features of Veshav, Rambiara, and Romushi, and the behavior of their tributaries reveals a series of fault scarps cutting Karawa deposits in the south–west Kashmir Valley (Fig. 5). An anticlinal fold-related reverse fault is exposed on a scarp face on the left bank of Rambiara River in Balapur Village at about 3 km north of Shupiyan Town (Fig. 6). The fault is named as Balapur Fault (BF) after its location in Balapur Village (N
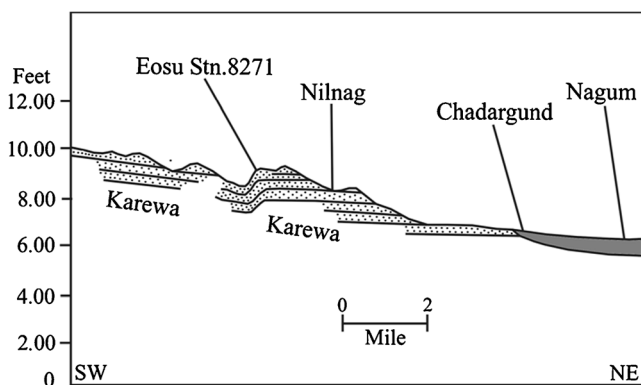
Fig. 5 Cross section of a monoclinal fold extracted from Middlemiss (1911) cross section of Nilnag-Tatakuti across Pir Panjal Range

33°75′, E 74°83′). Stratigraphic relations clearly reflect that clasts of the Shupiyan gravels (lower member of the Upper Karewa) rotated along the fault contact and were juxtaposed against sands, silts, and clay silts of the Methowoin member (upper member of the Lower Karewa) (Fig. 7a, b).

Using geomorphic manifestations such as stream capture and beheaded streams, features widely recognized as typical geomorphic expression of a tectonic structure (fault or fold) (Schumm 1977; Bloom 1979), we tried to characterize the extension of the Balapur Fault northwest and southeast from Balapur Village. Therefore, series of the (Fig. 3) topographic profiles were constructed (Fig. 8). We also observed some indications of stream capture (Fig. 9a). Another anticline has been observed by Bhatt (1989) on the left bank of Romushi River about 4 km upstream of Ichhagoz Village which recall the Balapur Fault-related anticlinal fold. Further northwest, Middlemiss (1911) described a monoclinal structure near Yusmarg (Fig. 5). Therefore, compiling all the other evidences in favor of a structure at Ichhagoz and Yusmarg, and also some anomalous south-facing escarpments on the topographic profiles expressed as and stream captures, strongly suggest an extension of the Balapur Fault northwestward.

A southeastward trace of the fault, from Balapur Village across the Shupiyan Karewa, is characterized by some stream captures (Fig. 9b). The fault trace is also highlighted by a feeble, south-facing topographic scarp as D–D′ in Fig. 8. Based on the geomorphic observations, we can infer that the BF is a quite significant structural feature, traceable over at least 40 km. Two other small feeble south-facing scarps (Figs. 8 and 9) are also characterized by such drainage features as stream capture and deflections (Fig. 9b) and upward steps in topographic profiles (Fig. 8, D–D). Finally, a tributary of the Veshav River named Kandai Kol joins the master channel (Veshav) in a hook-shaped bend, a drainage pattern generally developed due to stream capture (Singh 1998). It cannot be said with any confidence that this feature is either prolonged with Balapur Fault or any other secondary structure because field work was not carried out in that area, thereby remaining for future strategy. However, drainage characteristics most likely reflect structural control underneath. Therefore, it is evident that southwest Kashmir Valley is dissected by at least three NW-SE trending emergent faults in its middle part.

Discussion

Our analyses of geomorphic indices of drainage basins (Veshav, Rambiara, and Romushi) and tectonic geomorphology indicate that the region is tectonically active. The geomorphic indices (hypsometric integral, basin elongation ratio, and basin asymmetry factor) not only provide evidence about regional tectonic deformation of the area (Keller 1986) but also its level of tectonic

Fig. 6 Photograph of a scarp (approx. 37 m high from river bed) on the left bank of the Rambiara River showing the Balapur Fault contact between Methawoin Member (Lower Karewas) and Shupiyan Member (Upper Karewas) at Balapur Village
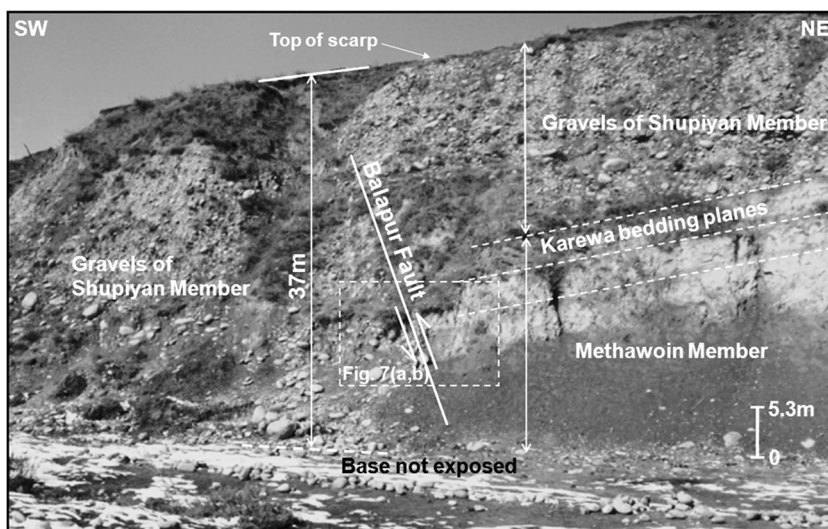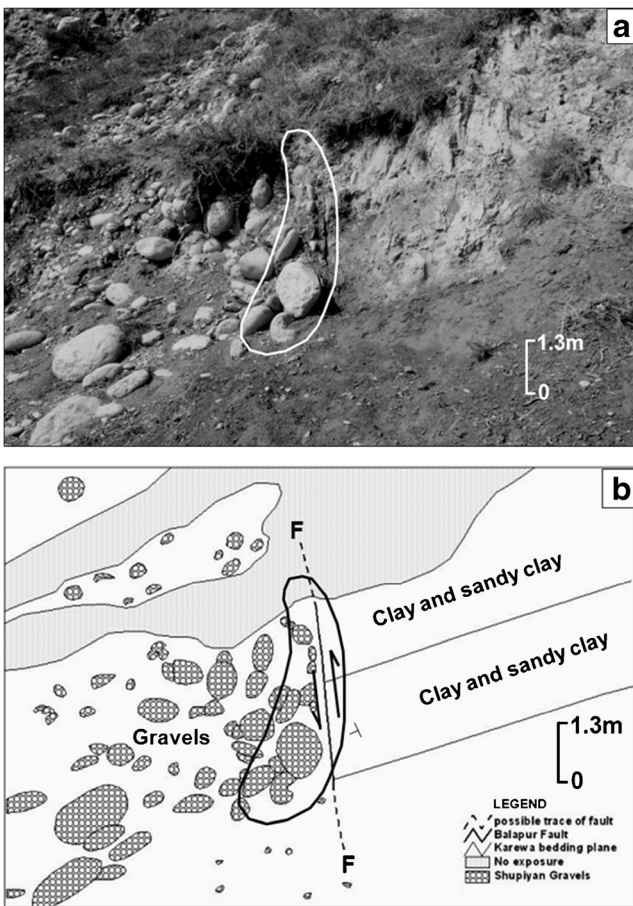
Fig. 7 **a** Photograph shows close contact of gravels (Shupiyan Member) with sandy clay and clay (Methawoin Member) along with rotated gravels due to movement of Balapur Fault encircled with *black polygon*. **b** Sketch of field relationships shown in **a**

activity (Keller 1986; Keller and Pinter 1996; Demoulin 1998). Deformation of Quaternary deposits by a 40-km-long fault system on the southwest side of the Kashmir Valley on digital elevation models and in the field supports the results of our geomorphic analysis.

Hypsometric integral values varying from 0 to 1 (e.g., values close to 0 in highly eroded regions and values close to 1 in slightly eroded regions) (Pedrera et al. 2009). Therefore, landscapes characterized by low relief contrasts (mature landscapes) have low hypsometric integrals (e.g., towards 0), whereas landscapes with high relief contrasts (youthful landscapes) display high hypsometric integrals (e.g., towards 1) (Strahler 1952). Moderate to relatively high hypsometric integral values ranging from 0.38 (Romushi) to 0.49 (Veshav) and to 0.51 (Rambiara) indicate that all the drainage basins have relatively high relief contrasts and qualify as youthful landscapes. Because high hypsometric values can reflect either tectonic deformation or erosion related to climatic processes, such as glaciation, the values obtained for the Romushi, Veshav, and Rambiara rivers must be evaluated in the context of local climatic and tectonic influences. The upper flanks of the Pir Panjal Range were glaciated into the late Pleistocene (De Terra and Paterson 1939; Bhatt and Chatterji 1976), so high hypsometric intervals could be driven by relief contrasts caused by glacial erosion in the upper part of the basins. However, the presence of faults cutting late Quaternary deposits within the drainage basins that were evaluated, and tilted Quaternary strata on either side of these faults (Bhatt 1976), suggests that in addition to glaciation, late Quaternary deformation also contributes to high hypsometric integrals on the southwest side of the Kashmir Valley.

Montgomery et al. (2001) suggests that for mountain belts which have similar climatic settings, hypsometric
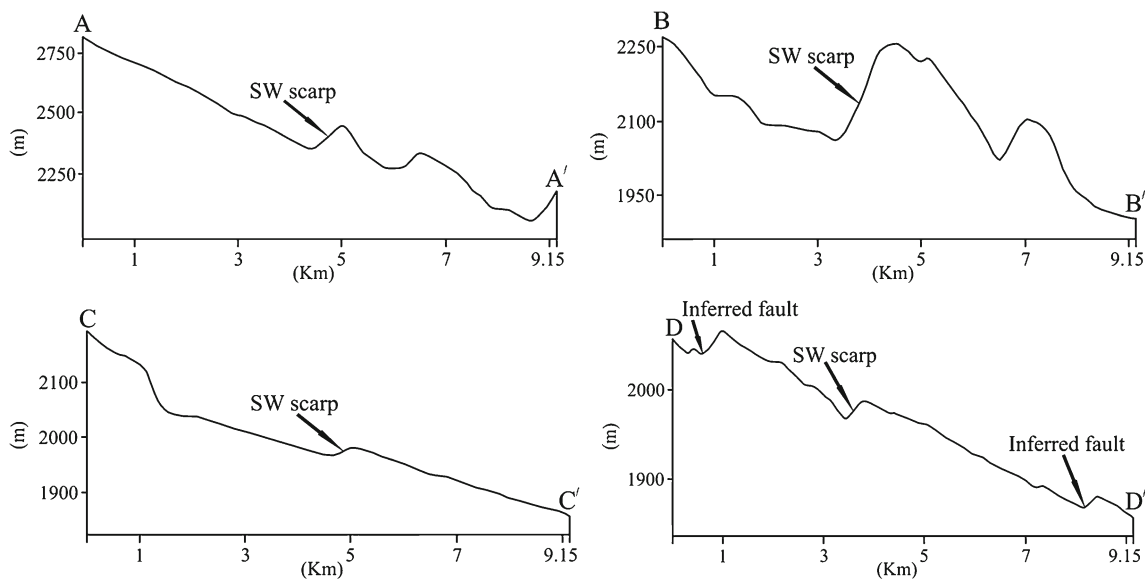

Fig. 8 Topographic profiles across Balapur Fault; for location of cross sections, refer to Fig. 3 (A–A′, B–B′, C–C′, D–D′)

Fig. 9 **a** Part of the drainage map of the study area, *white polygons* marking the northwestward expression of the Balapur Fault based on stream capture in Romushi and part of Rambiara basins from Balapur Village up to Yusmarg. *White thick solid and dashed lines* are drainage divide between the sub-basins in the area. **b** *Solid and dashed polygons* marking the southeast extension of Balapur Fault from Balapur Village along with two inferred faults through the stream captures
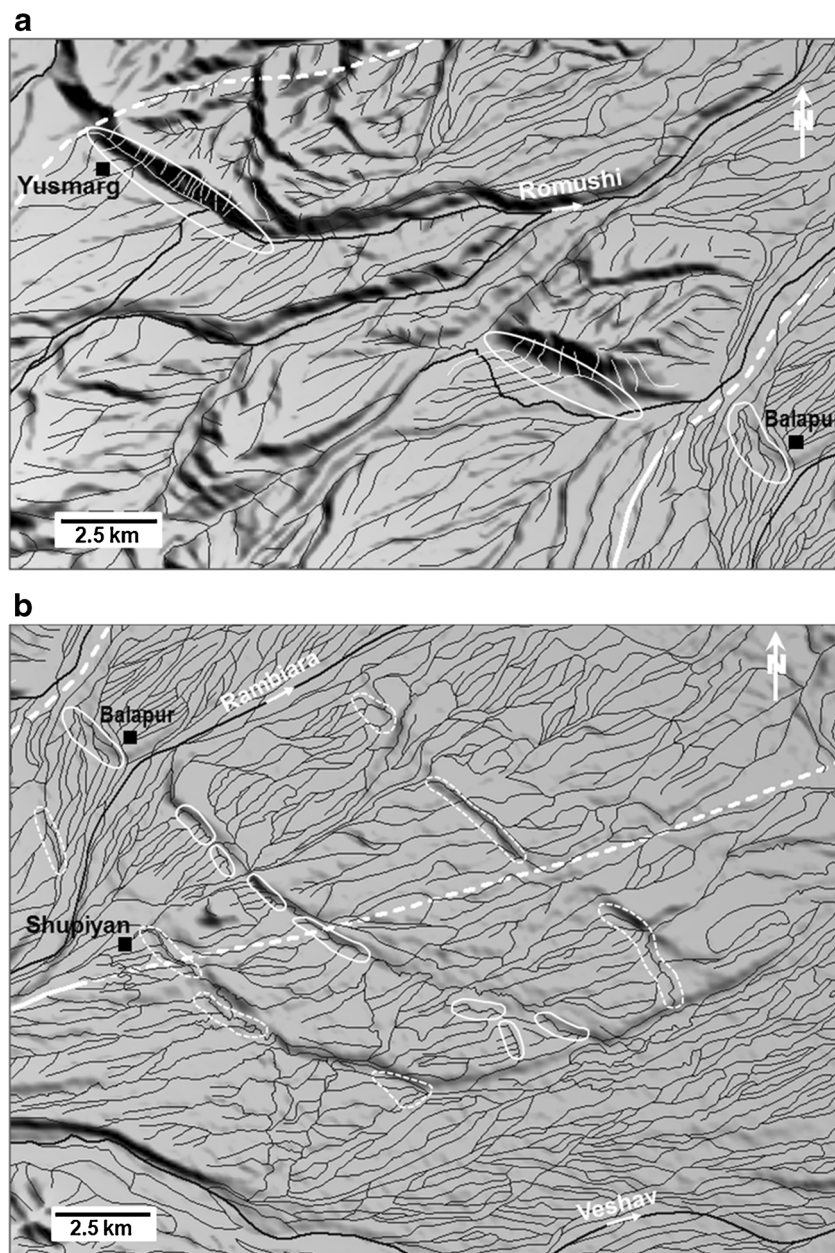
values can be used to compare as proxies for tectonic activity. Because the drainages evaluated in this study have similar climate and bedrock, we argue that tectonic activity is greatest to the southeast, in the vicinity of the Rambiara River basin, and lower in the vicinity of the Romushi and Veshav basins. The area with the highest activity is also coincident with the location of the most well-pronounced fault scarps on the southwest side of the valley.

Basin elongation ratio is considered a proxy for recent tectonic activity (Bull and McFadden 1977). Elongated basins on the topographic slope of a mountain front reflect relatively tectonically active areas (Bull and McFadden 1977; Ramírez-Herrera 1998). For tectonically active, slightly active, and inactive basins, the values are <0.50,

0.50–0.75, and >0.75, respectively (Cuong and Zuchiewick 2001). Thus, circular basins have values closer to 1 and elongate basins have lower values closer to 0. The lowest values (<0.50) reflect narrow, elongate basin shape, commonly accompanied by high local relief and steep valley slopes indicative of tectonic deformation. In our case, the study area is gentle and mostly covered by similar lithology, consisting of fluvio-lacustrine deposits. The basin elongation ratio values vary from 0.48 (Rambiara) to 0.49 (Romushi) and 0.65 (Veshav) suggesting medium to strong influence of active tectonics on the Veshav and Rambiara-Romushi drainage basins.

Drainage basin asymmetry is used to quantify tectonic tilting at small drainage basins or larger areas (Hare and

Gardner 1985). This is a strong indicator of tectonic activity because this index is minimally influenced by lithology (e.g., dipping strata) nor localized climate (e.g., vegetation difference between north and south-facing slopes) (Gardner et al. 1987). In general, drainage basin tilt can be inferred where truck channel receive long adjacent tributaries on the downstream right as compared to short adjacent tributaries on the downstream left of the trunk channel (Keller and Pinter 1996). This is the case for the Veshav and Romushi basins, where large tributary streams are joined from the right of their main drainage line, suggesting northwest tilting. Supporting evidence of northwest titling of the Rambiara basin is the development of higher number of unpaired terraces on the right bank of the Rambiara River as compared to the single terrace on the left bank (Farooqi and Desai 1974; Bhatt 1989). Conversely, the trunk channels (Veshav, Rambiara, and Romushi) together with their adjacent streams are shifted or migrated either northwest or southeast (Fig. 9), probably as a consequence of relatively recent activity of Balapur and associated faults.

The orientation of headwater streams (Veshav, Rambiara, and Romushi) perpendicular to the observed BF and associated structures (Fig. 3) is likely the consequence of regional tilting that parallels the axis of the Pir Panjal Range due to slip on the underlying MHT. This inference is supported by the observations of northeast tilting of fluvio-lacustrine deposits and V-shaped canyons upstream of the BF. Downstream deflection of these drainages to the northwest and southeast likely reflects the influence of more local fault activity (e.g., BF). These observations are offer an insight into the Late Quaternary tectonic processes that have contributed to the present-day topography of the Pir Panjal Range: the geomorphic indices described above reflect regional deformation related to the MHT at depth, and localized faulting on the southwest side of the valley reflects minor imbricate, out-of-sequence splays of the MHT.

Conclusion

Until now, the Himalayan intermontane basin known as Kashmir Valley was not characterized by the outcropping of active faults. Using geomorphic data (geomorphic indices), in the southwest of the Kashmir Valley (Veshav, Rambiara, and Romushi drainage basins), we are able to show the area is tectonically active and being subjected to regional tilting along the northeast flank of the Pir Panjal Range. Field investigations confirm the presence of emergent out-of-sequence, NE-dipping active reverse fault, named BF, which can be traced over at least 40 km along the southwest side of the Kashmir Valley. Deformation in the footwall of the BF suggests that regional tilting on the northeast flank of the Pir Panjal Range is likely due to slip on the MHT at depth or another unrecognized fault southwest of the BF. The interplay of these faults paints a picture of more complex strain-partitioning regime in the Kashmir Himalayas than is usually visualized.

References

Ahmad B, Bhat MI, Bali BS (2009) Historical record of earthquakes in the Kashmir Valley. Him Geol 30(1):75–84

Bhat MI, Malik MA, Bali BS (2008) Tectonic geomorphology of the Pir Panjal Range. Workshop on October 8, 2005 Kashmir Earthquake and after. Jam Univ. pp. 39–42

Bhatt DK (1975) On the Quaternary geology of the Kashmir Valley with special reference to stratigraphy and sedimentation. Geol Surv Ind Misc Pub 24(1):188–203

Bhatt DK (1976) Stratigraphical status of Karewa Group of Kashmir, India. Him Geol 6:197–208

Bhatt DK (1989) Lithostratigraphy of the Karewa Group, Kashmir Valley, India and a critical review of its fossil record. Mem Geol Surv Ind 122:1–85

Bhatt DK, Chatterji AK (1976) An appraisal of field observations on the geology of the Plio-Pleistocene Karewa Group and more recent Quaternary deposits of Kashmir Valley. Proc. VI Indian Colloq Micropaleontol Stratigr pp. 11–21

Bloom AL (1979) Geomorphology. Prentice-Hall, New Delhi

Brown LD, Zhao W, Nelson KD, Hauck M, Alsdorf D, Ross A, Cogan M, Clark M, Liu X, Che J (1996) INDEPTH deep seismic reflection of a regionally extensive high-amplitude basement reflector, and associated "bright spots" beneath the Yadong-Gulu Rift, Tibet. Science 274:1688–1690

Bull WB, McFadden LD (1977) Tectonic geomorphology north and south of the Garlock Fault, California. In: Doehring, DO (eds) Geomorphology in arid regions. Proceeding of the 8th Annual Geomorphology Symposium. State University of New York at Binghamton, Binghamton. pp. 115–138

Burbank DW, Johnson GD (1982) Intermontane-basin development in the past 4 Myr in the north-west Himalaya. Nature 298:432–436

Cuong NQ, Zuchiewick WA (2001) Morphotectonic properties of the Lo River Fault near Tam Dao in North Vietnam. Natural Hazards and Earth System Sciences 1:15–22

De Terra H, Paterson TT (1939) Studies on the Ice Age in India and associated human cultures. Carnegie Inst. Pub. No. 493, Washington, p 354

DeCelles PG, Robinson DM, Quade J, Copland P, Upreti BN, Ojha TP, Garzione CN (2001) Regional structure and the stratigraphy of the Himalayan fold-thrust belt, far western Nepal. Tectonics 20:487–509

Demoulin A (1998) Testing the tectonic significance of some parameters of longitudinal profiles: the case of the Ardenne (Belgium, NW Europe). Geomorphology 24:189–208

Farooqi IA, Desai RN (1974) Stratigraphy of Karewas, India. J Geol Surv India 15(3):299–305

Ganju JL, Khar BB (1984) Tectonics and hydrocarbon prospects of Kashmir Valley—possible exploratory targets. Petroleum Asia Journal 207–216

Gardner TW, Back W, Bullard TF, Hare PW, Kesel RH, Lowe DR, Menges CM, Mora SC, Pazzaglia FJ, Sasowsky ID, Troester JW, Wells SG (1987) Central America and the Caribbean. In: Graf WL (ed) Geomorphic systems of North America. Geol Soc Am, Boulder. Centennial Special vol. 2, pp. 343–401

Gloaguen R, Marpu PR, Niemeyer I (2007) Automatic extraction of faults and fractal analysis from remote sensing data. Nonlinear Process Geophys 14(2):131–138

Gloaguen R, Kaessner A, Wobbe F, Shahzad F, Mahmood SA (2008) Remote sensing analysis of crustal deformation using river networks. In: IEEE International Geosciences and Remote Sensing Symposium, Boston. pp. IV-1–IV-4

Goldsworthy M, Jackson J (2000) Active normal fault evolution in Greece revealed by geomorphology and drainage pattern. J Geol Soc Lon 157:967–981

Hare PW, Gardner TW (1985) Geomorphic indicators of vertical neotectonism along converging plate margins, Nicoya Peninsula, Costa Rica. In: Morisawa M, Hack JT (eds) Tectonic geomorphology. Proceedings of the 15th Annual Binghamton Geomorphology Symposium. Allen Unwin, Boston (Sept 1984)

Hough SE, Bilham R, Bhat MI (2009) Kashmir Valley mega earthquakes. American Scientist 97(1):42–49. doi:10.1511/2009.76.1

Howard AD (1967) Drainage analysis in geologic interpretation, a summation. Am Assoc Petrol Geol 51:2246–2259

Hussain A, Yeats RS, MonaLisa (2009) Geological setting of the 8th October, 2005 Kashmir 518 earthquake. J Seismol 13:315–325

Kaneda H, Nakata T, Tsutsumi H, Kondo H, Sugito N, Awata Y, Akhtar SS, Majid A, Khattak W, Awan AA, Yeats RS, Hussain A, Kausar AB (2008) Surface rupture of the 2005 Kashmir, Pakistan, earthquake, and its active tectonic implications. Seism Soc Am Bull 98:521–557

Keller EA (1986) Investigation of active tectonics: use of surficial earth processes. In: Panel on active tectonics. National Academy, Washington, DC. pp. 138—147

Keller EA, Pinter N (1996) Active tectonics: earthquakes, uplift and landscapes. Prentice Hall, Upper Saddle River, p 338

Keller EA, Pinter N (2002) Active tectonics: earthquakes, uplift, and landscape, 2nd edn. Prentice Hall, Englewood Cliffs, p 362

Kurz T, Gloaguen R, Ebinger C, Casey M, Abebe B (2007) Deformation distribution and type in the Main Ethiopian Rift (MER): a remote sensing study. Jour Afr E Sc 48(2–3):100–114

Middlemiss CS (1910) A revise of the Silurian-Trias sequence in Kashmir. Geol Surv India Records 40:206–260

Middlemiss CS (1911) Sections in Pir Panjal and Sindh Valley, Kashmir. Geol Surv India Records 41(2):115–144

Montgomery DR, Balco G, Willett SD (2001) Climate, tectonics, and the morphology of the Andes. Geology 29(7):579–582

Pedrera A, Perez-Peña JV, Galindo-Zaldivar J, Azañon JM, Azor A (2009) Testing the sensitivity of geomorphic indices in areas of low-rate active folding (eastern Betic Cordillera, Spain). Geomorphology 105:218–231

Pike RJ, Wilson SE (1971) Elevation relief ratio, hypsometric integral and geomorphic area–altitude analysis. Geol Soc Amer Bull 62:1079–1084

Ramírez-Herrera MT (1998) Geomorphic assessment of active tectonics in the Acambay Graben, Mexican volcanic belt. Earth Surf Proc Land 23:317–332

Raza M, Ahmad A, Mohammad A (1978) The valley of Kashmir: a geographical interpretation, Vol. 1: the land. Vikas, New Delhi, p 59

Schelling D, Arita K (1991) Thrust tectonics, crustal shortening, and the structure of the far-eastern Nepal Himalaya. Tectonics 10:851–862

Schumm SA (1956) Evolution of drainage systems and slopes badlands at Perth Amboy, NJ. Geol Soc Amer Bull 67:597–646

Schumm SA (1977) The fluvial system. Wiley, New York, p 338

Singh IB (1982) Sedimentation pattern in the Karewa basin, Kashmir Valley, India and its geological significance. J Palaeon Soc India 27:71–110

Singh D (1998) Geomorphology. Prayag Pustak Bhawan 20-A, University road Allahabad, p. 612

Strahler AN (1952) Hypsometric (area–altitude) analysis of erosional topography. Geol Soc Amer Bull 63:1117–1142

Strahler AN (1957) Quantitative analysis of watershed geomorphology. Am Geophys Union Transactions 38:913–920

Strahler AN (1964) Quantitative geomorphology of drainage basins and channel networks. In: Chow VT (ed) Handbook of applied hydrology. McGraw-Hill, New York, pp 439–476

Thakur VC, Jayangondaperumal R, Malik MA (2010) Redefining Medlicott–Wadia's main boundary fault from Jhelum to Yamuna: an active fault strand of the main boundary thrust in northwest Himalaya. Tectonophysics. doi:10.1016/j.tecto. Cited 14 Mar 2010

Wadia DN (1975) Geology of India, 4th edn. Tata McGraw-Hill, New Delhi, p 344, Tenth reprint (1989)

Wallace RE (1990) Geomorphic expression. In: Wallace RE (ed), The San Andreas Fault System, California. USGS Prof Paper 1515: 14–58

Yeats RS, Nakata T, Farah A, Fort M, Mizra MA, Pandey MR, Stein RS (1992) The Himalayan frontal fault system. Annales Tectonicae 6:85–98