Geomorphic Indicators of Balapur Fault in Kashmir Basin and Kinematic Analysis with Respect to NW Himalaya

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ABSTRACT

Geomorphic features can be used to retrieve and evaluate active tectonic features in tectonic orogens and data can be easily generated from coarse resolution DEMs (SRTM, ASTER), Google maps, topographic maps, aerial photographs and Landsat-ETM. Several geomorphic features have suggested that the SW Kashmir is tectonically active. We investigate geomorphic features, especially fluvial terraces and made an attempt to identify terrace deformations and escarpments specifically along the Balapur fault (BF) to assess the recent tectonic activity along the structure. The present study revealed two extensive terraces on right bank and a single terrace on the left bank of Rambiara River have been deformed and developed prominent SW-facing fault scarps. Field data indicated that the Balapur fault is connected with an anticlinal fold of asymmetric type with average 14° NE dip (forelimb) and average 25° SW dip (backlimb); except at Sukhnag, where forelimb and backlimb have average dip of 48° NE and 17° SW, respectively. Based on kinematic analysis, the average orientation of fold axis is found to be NW-SE, coinciding with the general trend of the Himalayan structures in northwest segment and particularly with the strike of the Balapur fault. Therefore, kinematic analysis suggest that the structure (BF) is pushed across its NW-SE strike from NE and SW sides, respectively, to produce fault associated anticlinal fold of asymmetrical type.

Keywords: *Fault-bend fold, Geomorphic features, Kashmir basin, Kinematic analysis, Terrace mapping.*

INTRODUCTION

Geomorphic signatures can be used as pivotal tools to confirm recent tectonic activity in active orogens (Keller and Pinter, 2002). These are also useful indicators to assist in differentiating tectonically active segments of geologic structures and establishing the structural evolution of a region (Ul-Hadi *et al.*, 2012). These features can be easily obtained and highlighted using freely available high resolution satellite data, such as Digital Elevation Model (DEM), Shuttle Radar Topographic Mission (SRTM), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Google maps and topographic maps, and therefore are of great use to understand the tectonically emerged geomorphic anomalies (Jordan, 2003; Arrowsmith and Zielke, 2009; Wechsler *et al.*, 2009; Yang *et al.*, 2011). These datasets provide new opportunities for better understanding of earth surface processes (Tarolli, 2014). The widespread availability of high quality and high-resolution topographic data encourage the development of simple morphological tools, which can be used to deduce recent tectonic activity (Brocklehurst, 2010).

Fluvial terraces are widely used landforms to identify and evaluate tectonic activity from the late Pleistocene to present (Keller and Pinter, 1996). These features (terraces) are particularly useful to provide information on rates of rock uplift and significant climatic events (Rockwell *et al.,* 1984; Molnar, 1987; Bishop and Bousquent, 1989; Bullard and Lettis, 1993; Molnar *et al.,* 1994; Lave´ and Avouac, 2000; Singh *et al.,* 2008; Ray and Srivastava, 2010; Sinha *et al.,* 2010; Jayangondaperumal *et al.,* 2013; Vassalo *et al*., 2015). Moreover, tectonic uplift is retrieved from river incision and account for initial terrace geometry (Lave´ and Avouac, 2000). The slip rate of the fault system can also be calculated by using known ages of different terraces and their surface displacements (Rockwell *et al.,* 1984; Jayangondaperumal *et al.,* 2013).

Kinematic analysis is used to analyze the potential for the various modes of rock slope failures (plane, wedge, and toppling), that occur due to the presence of unfavorably oriented discontinuities. The discontinuities are geologic breaks such as joints, faults, bedding planes, foliation, and shear zones that can potentially serve as failure planes. In addition, kinematic analysis of structural elements is useful to analyze regional stress mechanism, which can be compared with local stress conditions (Ramsay, 1967). The stereonets are circular graphs, which can be used for plotting planes on the basis of dip direction and dip amount. The orientations of discontinuities can be represented on a stereonet in the form of great circles and poles or dip vectors (Billings, 1987). Cluster of poles of discontinuity orientations on stereonets are identified by visual investigation and using density contours on stereonets (Hoek and Bray, 1981).

The Kashmir basin is surrounded by two linear mountain ranges such as Pir Panjal and great Himalaya, with development of excellent drainage system running by Jhelum River (Fig. 1). It is occupied by range of structures and lithologies from northeast and southwest; however, most dominant Formation is the Plio-Pleistocene unconsolidated Karewa deposits, where outcrops are rarely exposed except along road cuts and streams. Since left bank tributaries (Pir Panjal range) have preserved outstanding fluvial terraces (Jaiswal *et al.,* 2009), which have not been mapped so far, and therefore in the present study, we made an attempt to map these terraces and tried to find out their relation with Balapur fault. In addition, we used published optically stimulated luminescence (OSL) ages from the uplifted terraces to find the fault uplift rates. Since the Balapur fault is running in weakly consolidated Karewa deposits and associated with an anticlinal fold (Ahmad and Bhat, 2012; Ahmad *et al.,* 2014 a,b,c, 2015 a,b, Ahmad 2014). Therefore, we collected field data of bedding planes to analyze the fault scarp geometry, kinematics and stress directions, because it was impossible to obtain structural data like joints, foliation and/or lineation in such type of lithology.

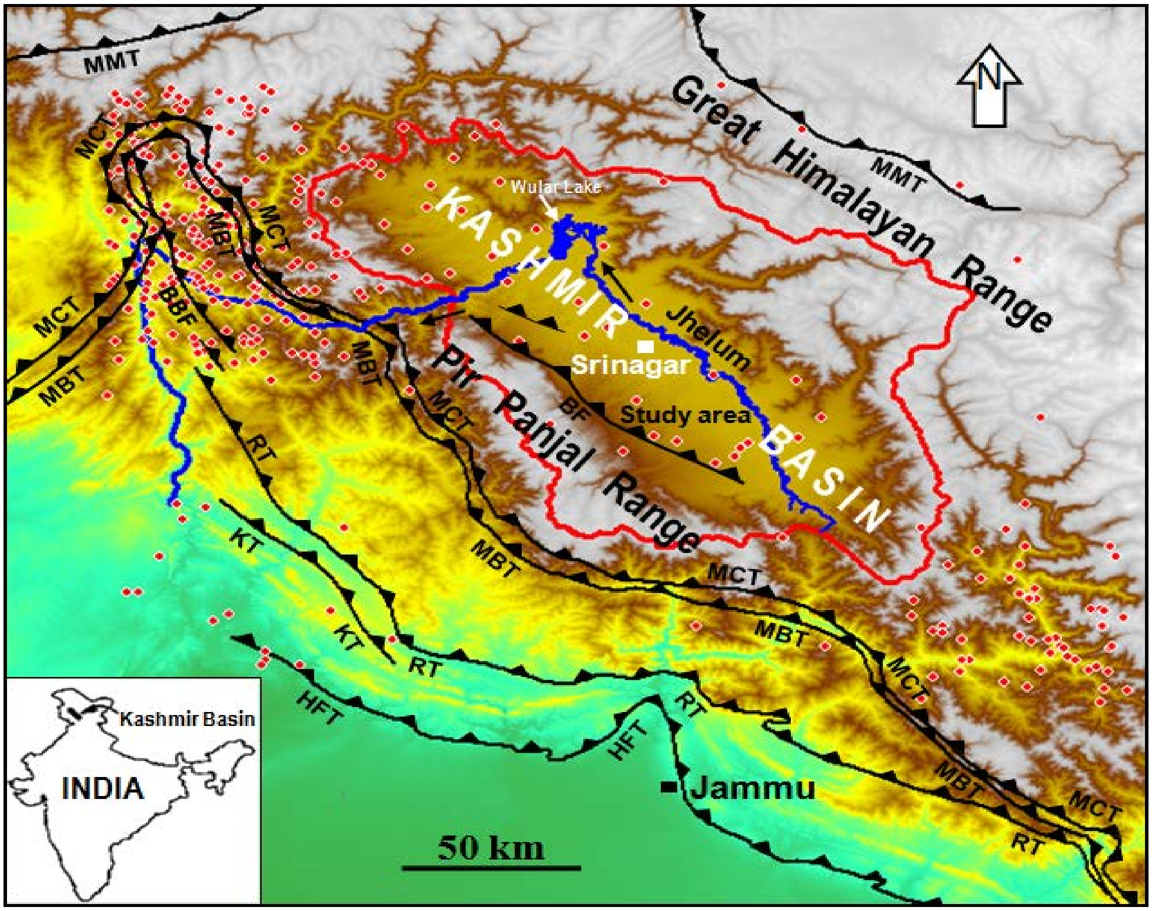

Fig. 1. Major Himalayan structures in and around Kashmir basin (after Ahmad *et al.,* 2017).

Regional geology and tectonic setting

The Kashmir basin possesses almost complete stratigraphic record, ranging from Precambrian to Holocene (Fig. 2). It has Salkhala Series (Precambrian) and Dogra Slates (lower Cambrian) as basement floor (Wadia, 1975; Krishnan, 1982). These Formations are considered as the oldest stratigraphic basement rocks succeeded by a more or less full sequence of fossiliferous Paleozoic, such as Panjal Volcanic Series (Panjal Trap and Agglomeratic Slate), Gneissose granite, Gondwana Shale, Fenestella Shale, Syringothyris Limestone, Permo - Triassic rocks, Conglomerate Beds, and Varved Clays in various parts of Kashmir (Lydekker, 1876; Middlemiss, 1910; Wadia, 1975; Krishnan, 1982). However, significant part of the Kashmir basin (Pir Panjal range) is covered by fluvio-glacial sediments, which are collectively known as Karewa (Plio-Pleistocene), and has assigned a Group status (Farooqi and Desai, 1974; Bhatt, 1989). These consist of a 1300 m thick sequence of unconsolidated clays, sands, and conglomerates with lignite beds unconformably lying on the bedrock and 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 consists of brown silts known as loess, which has aeolian origin (Bronger *et al.*, 1987). The loess is a cap unit for underlying Hirpur and Nagum Formations and characterized by the presence of interbedded profiles of paleosols. The cross sectional exposures of these unconsolidated Karewa units are observed along river sections, road cuts and plateau margins.

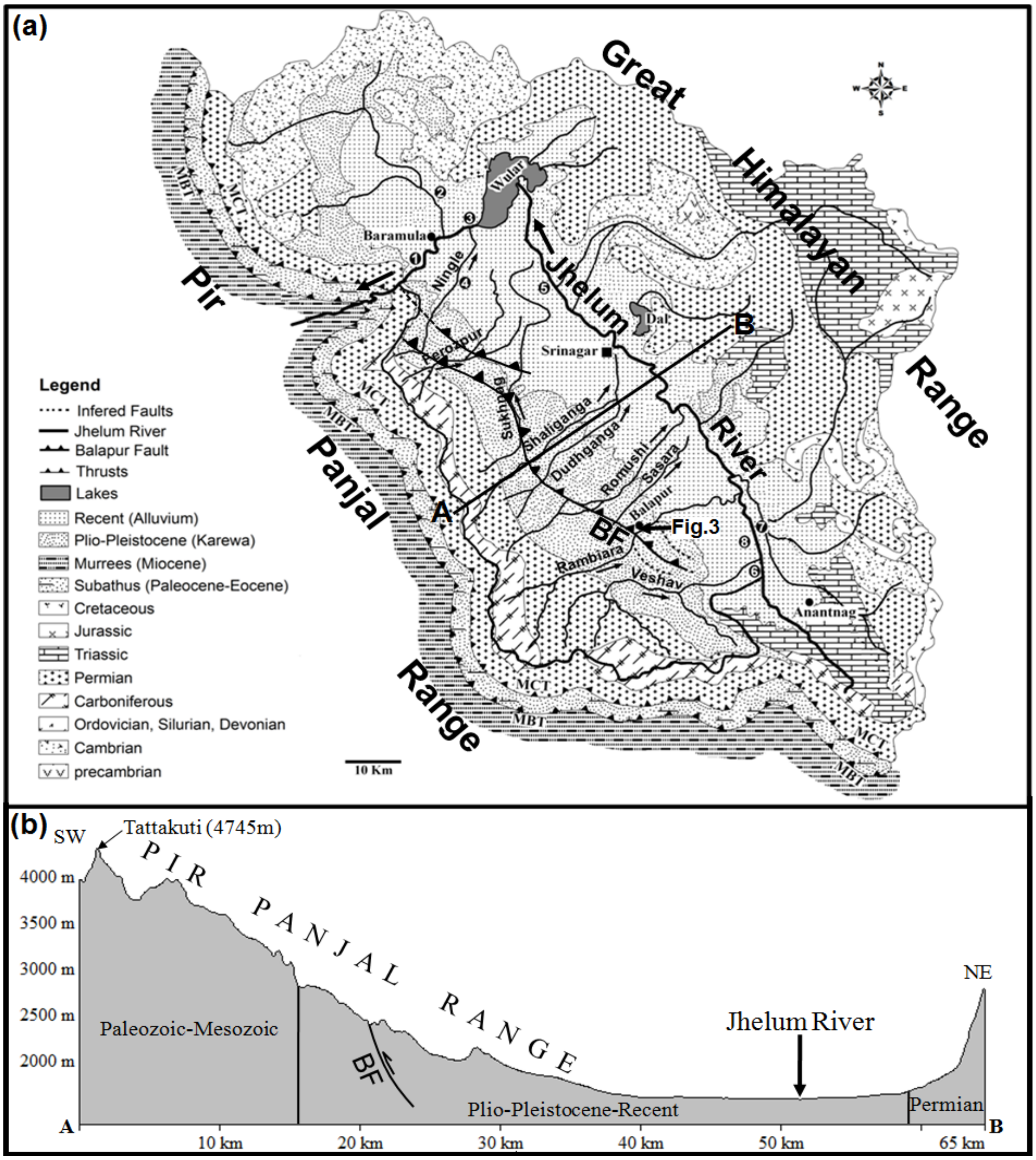

Fig. 2(a). Geological Formations and structures of the Kashmir Himalaya (adapted from Ahmad *et al.*, 2015a). MCT: Main Central Thrust; MBT: Main Boundary Thrust; BF: Balapur fault. The numbers are for the names of locations of historical earthquake as: 1 Khadanyar, 2 Dobgam, 3 Sopor, 4 Larodora, 5 Pattan, 6 Bijbihara, 7 Hassanpur, 8 Hussainpur. (b) A–B schematic geological cross section and surface topography of the SW Kashmir basin.

The Kashmir basin is bounded by two prominent thrust faults, such as Zanskar Thrust on northeast and Panjal Thrust on southwest (Wadia, 1931; Agrawal and Agrawal, 2005) with NW-SE trends. According to Wadia (1931), the older basement rocks (Precambrian and Paleozoic-Mesozoic) have travelled along regional tectonic plane, known as the Panjal Thrust over the younger rocks of autochthonous belt. This results two major axes of orogenic upheaval along the Pir Panjal and the Great Himalayan ranges. This concept was further elucidated by Burbank (1983) and Burbank and Johnson (1983), who suggested that the Kashmir basin is evolved due to shifting of NE thrust complex from the base of the Great Himalayan side to the southwest forefront of the Pir Panjal range i.e. the NE thrust complex was replaced by the existing structural basement complex (MBT/MCT). Whereas, Bhat (1982) presented a rift-reactivation model to explain the formation of the Kashmir basin along two deep seated faults, i.e. the Panjal Thrust from the west and Zanskar Thrust from the east. However, recent geomorphic inferences have suggested that the Kashmir basin is evolved due to dextral strike-slip fault, accompanied with pull-apart character (Alam *et al.,* 2015a,b). In particular, Kashmir basin has complex pattern of faulting in the southwest of the Pir Panjal range with the superposition of several thrusts, such as MCT/Panjal Thrust (PT), MBT/Murree Thrust (MT), Riasi Thrust (RT), and Kotli thrust (KT) (Thakur *et al.,* 2010). These faults are considered to be imbrications of the northward rooted basal decollement, known as Main Himalayan Thrust (Schelling and Arita, 1991; Brown *et al.,* 1996; DeCelles *et al.,* 2001). In addition, several faults have also been inferred in the Kashmir basin (Ganju and Khar, 1984; Yeats *et al.,* 1992; Alam *et al.,* 2015a,b), which however lack relevant field data. Among all of the inferred faults in the basin, the Balapur fault (BF) is the only established structure with ~95 km length in NW-SE direction, which has been confirmed through field observations, paleoseismic analysis and different geomorphic methods (Ahmad, 2010, 2014; Madden *et al.,* 2010, 2011; Ahmad and Bhat, 2012; Ahmad *et al.,* 2014, 2015ab). It is a high angle thrust (reverse) fault, which cuts Plio-Pleistocene Karewa deposits and develops prominent southwest scarp. Paleoseismic investigations of the BF reveal a shortening rate of 0.3-1.5 mm/yr (Madden *et al.,* 2011). The date of most recent slip on BF is probably >1 ka (Meigs *et al.,* 2012).

METHODOLOGY

In the present study, we used published literature related to Balapur fault and noted that the fault is running in unconsolidated Karewa deposits in NW-SE direction. The traditional methods for obtaining structural data is not so useful to provide an indication pertinent to active deformation, because such type of lithology together with its uniform character is known not to retain surface evidence of faulting for any longer time due to fast erosion unless tectonic uplift greatly exceeds erosion. Moreover, southwest Kashmir (Pir Panjal range) is densely covered by natural and artificial vegetation, where outcrops are rarely exposed except along road cuts and streams. Hence, the best course is to rely on fluvial terraces to identify and map any type of tectonic deformation or scarp development (Rockwell *et al.,* 1984; Molnar, 1987; Bishop and Bousquent, 1989; Bullard and Lettis, 1993; Molnar *et al.,* 1994; Lave´ and Avouac, 2000; Singh *et al.,* 2008; Ray and Srivastava, 2010; Sinha *et al.,* 2010;

Jayangondaperumal *et al.*, 2013). Since Rambiara stream is one of the biggest tributary of the Jhelum river distinctly visible on any satellite imagery and has developed several unpaired terraces, and therefore we made an attempt to map the active deformation on river terraces along the Balapur fault. Terrace mapping can provide vital information about the precise deformation of Balapur fault. In order to map the terraces in the field, we initially interpreted high resolution Google earth images, SRTM, ASTER and topo-sheets (1:50,000); followed by detailed field observations and finally prepared the terrace map of the Balapur fault along the Rambiara river. In addition, we correlated earlier published radiocarbon/OSL/TL dates from the uplifted terraces.

Structural analysis is a useful exercise to provide regional stress mechanism when compared with local stress conditions (Ramsay, 1967). Applications of 3-dimensional orientation data of lines (e.g., foliation, cleavage) and planes (e.g., beds, faults) collected in the field in a 2-dimensional graphical form permits to determine the angular relationships between planar features in 3-dimensional space or establish the plunge and trend of large scale folds from orientation of data (Ramsay, 1967; Ragan, 1985; Billings, 1987; Hatcher, 1995; Davis and Reynolds, 1996). The field data can be plotted by using freely available Allmendinger's stereonet software program (2012) (http://www.geo.cornell.edu/geology/ faculty/ RWA/Old Programs.html). In the present study, we collected and plotted the field data (dip/strike) to understand the stress mechanism with local stress conditions, geometry and growth of the structure.

The Balapur fault system

The Balapur fault is a reverse fault, exposed on the left bank of Rambiara river near Balapur village (~3km north of Shopian) (Fig. 3). The fault has been assigned its name near Balapur village (N 33°75′, E 74°83′) (Ahmad, 2010) supplemented with paleoseismic and geomorphic data (Madden *et al.*, 2010, 2011; Ahmad and Bhat, 2012; Ahmad *et al.*, 2014 a,b,c, 2015 a,b; Ahmad 2014). The stratigraphic relations clearly reflect that the clasts of the Shopian gravels (lower Member of the upper Karewa) are rotated along the fault contact and juxtaposed against sandy clay, clay and clay silts of the Methowoin Member (upper member of the lower Karewa) (Fig. 3). The average dip and strike of the Balapur fault is ~60^{o} NE and 330, respectively. The vertical separation of litho-stratigraphic units across the fault is 13m, which suggested that the structure is hammered by several high magnitude earthquakes in historical time (Madden *et al.*, 2011; Ahmad b *et al.*, 2015). Since, surface rupture (faults) earthquakes are uncommon in the Himalaya (Bilham *et al.*, 2013); however, they are reported along the Balapur fault in late Quaternary sediments with significant deformation on the basis of paleoseismic investigation, geomorphic anomalies and development of prominent scarps on the surface (Madden *et al.*, 2010; Ahmad *et al.*, 2015a,b). Several geomorphic features have been documented along the Balapur fault in NW and SE of Balapur village and if structural data (e.g., dip/strike of bedding planes) could be obtained that may provide some inferences regarding stress directions of the segment vis-à-vis overall trend of the Himalaya in general and NW segment in particular.

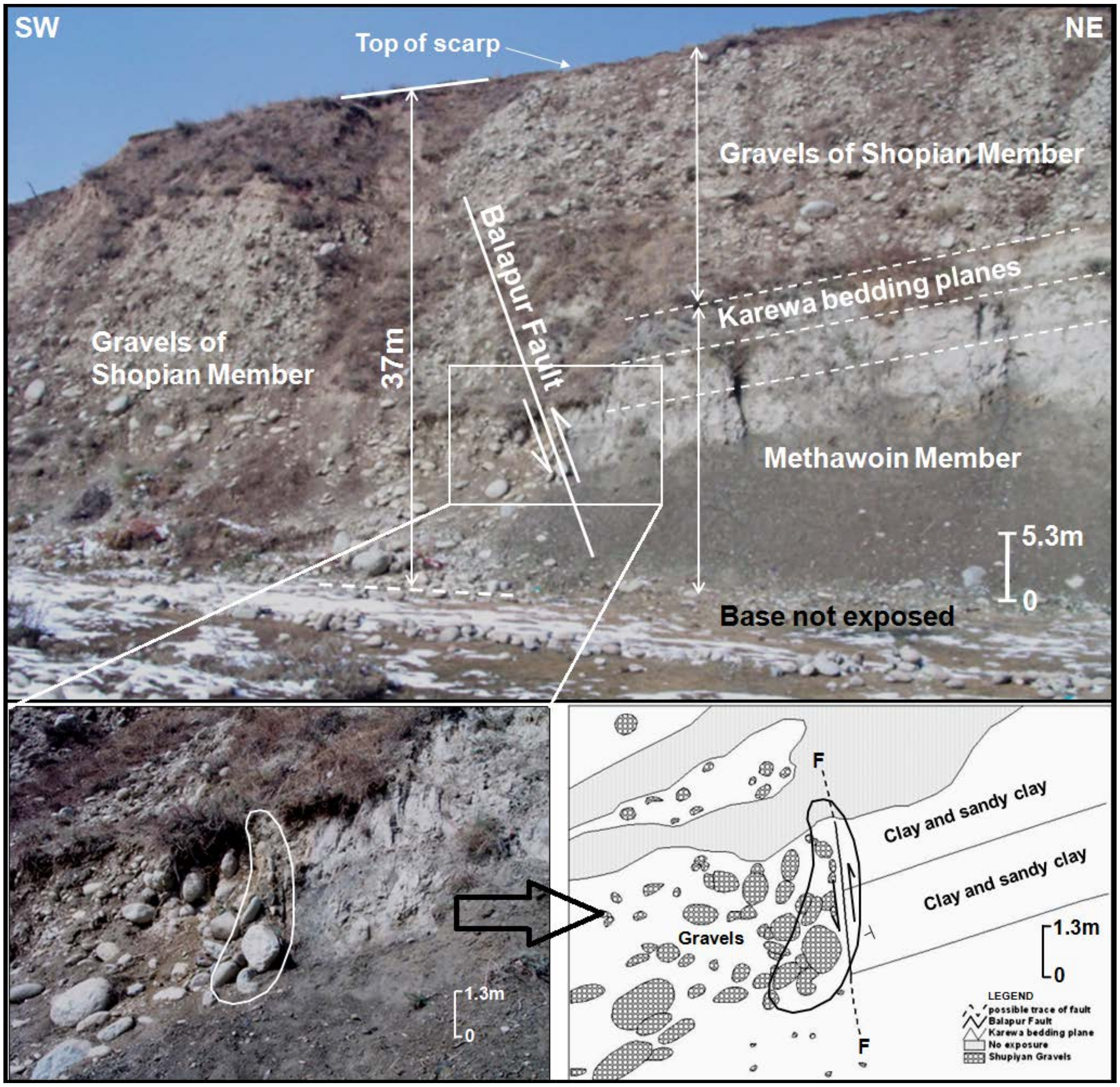

Fig. 3. Exposed Balapur fault scarp (~37 m high from river bed) on the left bank of the Rambiara river with lithological contact between upper Member of lower Karewa (Methawoin) and lower Member of upper Karewa (Shopian) near Balapur village (after Ahmad *et al.*, 2014a). Note the rotation of gravels due to movement of Balapur Fault encircled by polygons.

RERSULTS AND DISCUSSION

Earlier studies have reported that the Rambiara river valley has developed several unpaired fluvial terraces in the Quaternary period (Farooqi and Desai, 1974; Bhatt, 1989). But, these studies don't show terrace map and particularly lack terrace deformation in relation to tectonic activity. Therefore, we mapped these terraces in the Rambiara river valley particularly in and around Balapur fault and noted their association with tectonic activity (Fig. 4). There are two extensive terraces (T_1 and T_2) on the right bank and two comparatively small terraces (T_1 and T_2) on the left bank. A third narrow terrace (T_3) does not proceed to any significant distance. T_1 along the left bank depicts wide appearance and deviates significantly from the channel course. These terraces are Pleistocene to

Holocene age. The older terraces are usually thick, consisting of unconsolidated gravels and boulders, embedded with silty sand, clay, clayey silt matrix and capped by loess, whereas the younger terraces and active flood plain deposits are thin and devoid of any loess deposits. A topographic profile drawn across Rambiara river (section line A-B in Fig. 5) on the hanging wall block of the Balapur fault shows relatively higher elevation of the right bank terraces. Any deformation caused by the Balapur fault is expected to be reflected in the topographic profiles across the fault. Profiles drawn across the fault shows that the fault has indeed deformed the terraces and created SW-facing fault scarps; such as two on the right bank (T_1 and T_2) and one on the left bank (T_2) of the Rambiara river (Fig. 5b-d). T_1 and T_2 on the right bank show 18.5 m and 18 m southwest facing scarps, whereas T_2 on the left bank show ~11.5 m similar scarp. Furthermore, topographic profiles of inferred faults on the northeast and southwest of the Balapur fault (section lines d-d'and e-e') again showed fault induced deformation of the T_1 and creation of 14.8 m and 14.1 m SW-facing scarps on the right bank (Fig. 5e, f). However, poor exposures and private horticultural activity in the area did not permit exploration of stratigraphic relationships across these fault scarps. The optically stimulated luminescence (OSL) dating of a sample collected from the lower strath terrace (hanging wall block) on the left bank of Rambiara river near the Balapur fault (Fig. 4) reflects 0.3-0.5 mm/yr slip rate (Madden *et al.*, 2011). The low slip rate and high angle dip of the fault suggest that the fault has absorbed least stress in relation to the overall Indian-Eurasian collision at present. However, earthquake clusters in and around Balapur fault and prominent southwest facing scarp in weakly consolidated lithology with minute loess thickness suggests that the fault is currently active (Ahmad, 2014; Ahmad B *et al.*, 2015), and may reactivate in future as the seismic gap is completely vacant for more than a century (e.g., Avouac *et al.*, 2006; Gahalaut, 2006; Parsons *et al.*, 2006).

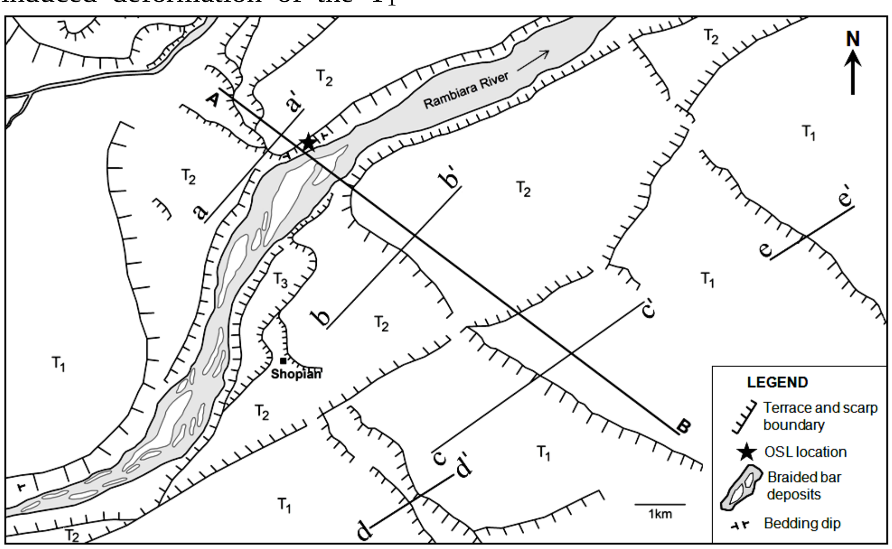

Fig. 4. Schematic of unpaired terraces and scarps along the Balapur fault in Rambiara river valley. Topographic profiles of all section lines (A-B, a-a’, b-b’, c-c’, d-d’ and e-e’) are shown in figure 5.

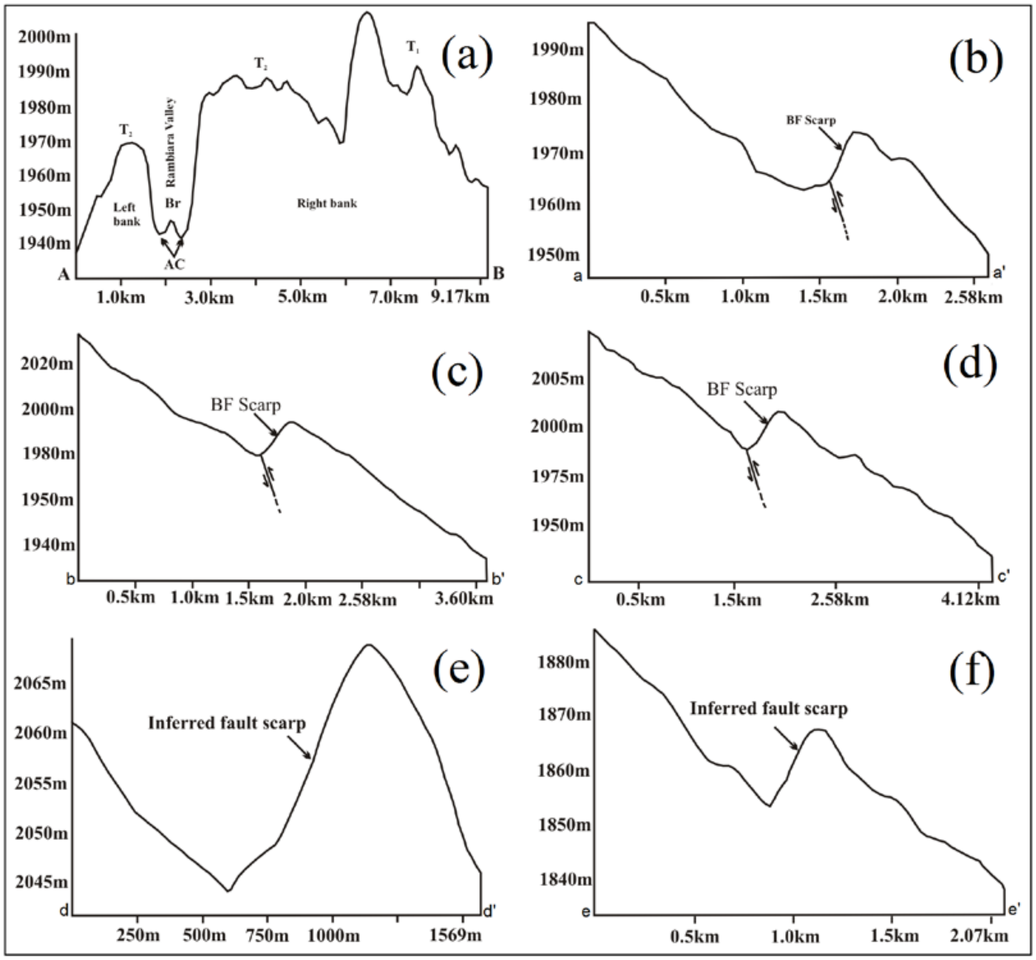

Fig. 5. (a) Topographic profile of Rambiara terraces. Br: braided bar deposit, Ac: active channel. Other profiles (b to f) depict terrace surfaces deformed by the Balapur fault and its splays as inferred faults in northeast and southwest respectively.

Kinematic analysis

We have undertaken traverses across and along the strike of Balapur fault to collect the structural data (dip/strike of beds/fault/fold) in order to understand the geometry and growth of the structure (Balapur fault). The upper Member of lower Karewa (Methowoin) strata is uplifted and folded into an asymmetric anticline; forming SW-facing prominent scarp along the fault. The overall configuration of the scarp is an asymmetrical-type fold with fold axis plunging northwest at low angles. In general, the anticline does not show a single and linear axial trace instead it shows segmental growth of hinges and coalescing pattern suggesting progressive growth of the fold structure. The structural data (dip/strike) is collected from different locations as shown in figure 6. The entire database has been consolidated into four segments (Fig. 7) for geometric analysis of the fold structure. The segment (a) shows anticline with gentle dipping beds in northeast (~7^0) and steep dipping beds (~50^0) in southwest. Segment (b) shows anticlinal fold and a few secondary fold structures with the beds dipping northeast at low angles (~9^0) and southwest at high angles (~31^0). Segment (c) has an anticline with beds dipping gently 5^0-8^0 on the forelimb and > 43^0 in the backlimb. The beds in the central part are almost sub-horizontal. In segment (d), anticline has high angle dip in northeast and moderate dip in southwest. The plot of bedding measurements in all the segments ($\sigma1$ = Plunge 04.5 / trend 225; Fig. 7a), ($\sigma1$ = 03.9/218, $\sigma2$ = 01.4/308.5 and $\sigma3$ 85.59/58.5 directions: Fig. 7b), ($\sigma1$ = 24.3 /247.8, $\sigma2$ = 01.6/157.1 and $\sigma3$ = 65.6/63.5 directions; Fig. 7c) and ($\sigma1$ = 02.9 /231, $\sigma2$ = 02.9/141.6 and $\sigma3$ = 84.3/351.8 directions; Fig. 7d) reveal that the maximum compressive stress is mostly horizontal in SW-NE direction except oblique compression with WSW-ENE in Shaliganga river valley. Hence, it is inferred that the fault associated anticlinal fold type structure is developed in response to SW-NE horizontal to semi horizontal compression. The stereo plots in all the segments show general anticlinal fold type geometry with limbs dipping gently to northeast and steeply to southwest; except in Sukhnag segment, where limbs show opposite attitude of dip. The axial trace of all the segments shows a general NW-SE trend, which coincides with general strike of main Himalayan structures in NW segment. Furthermore, the attitude of bedding geometry indicates that the anticline is associated with Balapur fault indicating a growing fault-bend fold structure with prominent southwest facing scarp (Fig. 8) (e.g., Suppe, 1983).

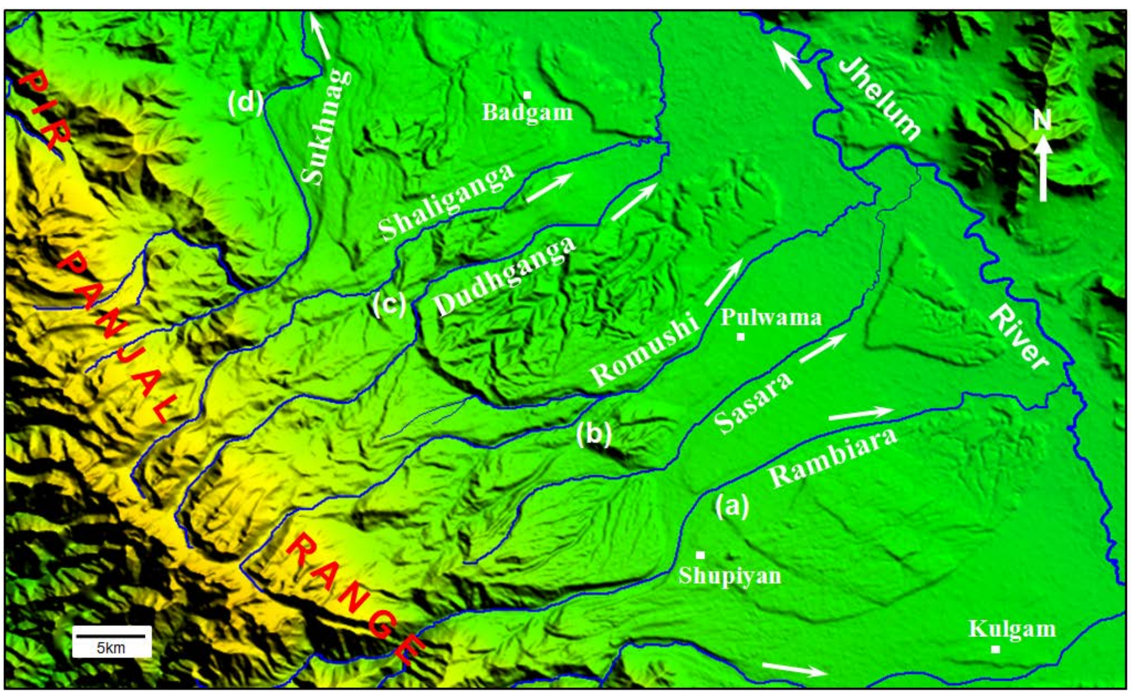

Fig. 6. DEM of part of study area showing structural data collection (dip/strike) spots of beds (a), (b), (c) and (d), refer stereo plots in figure 7.

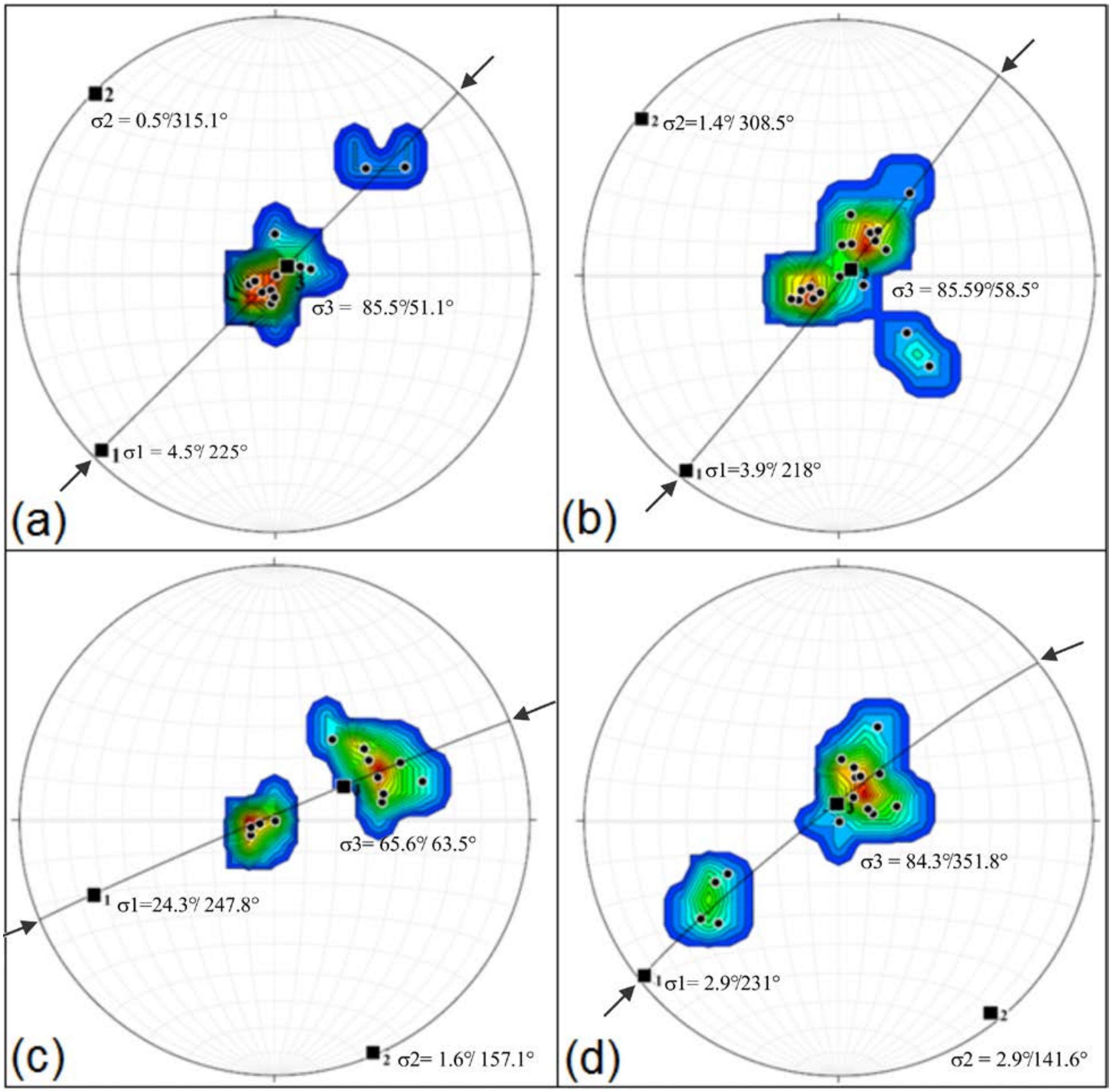

Fig. 7. Stereo plots of domain wise attitude of different beds along the northwest strike of Balapur fault (a) Rambiara, (b) Sasara-Romushi, (c) Shaliganga and (d) Sukhnag.

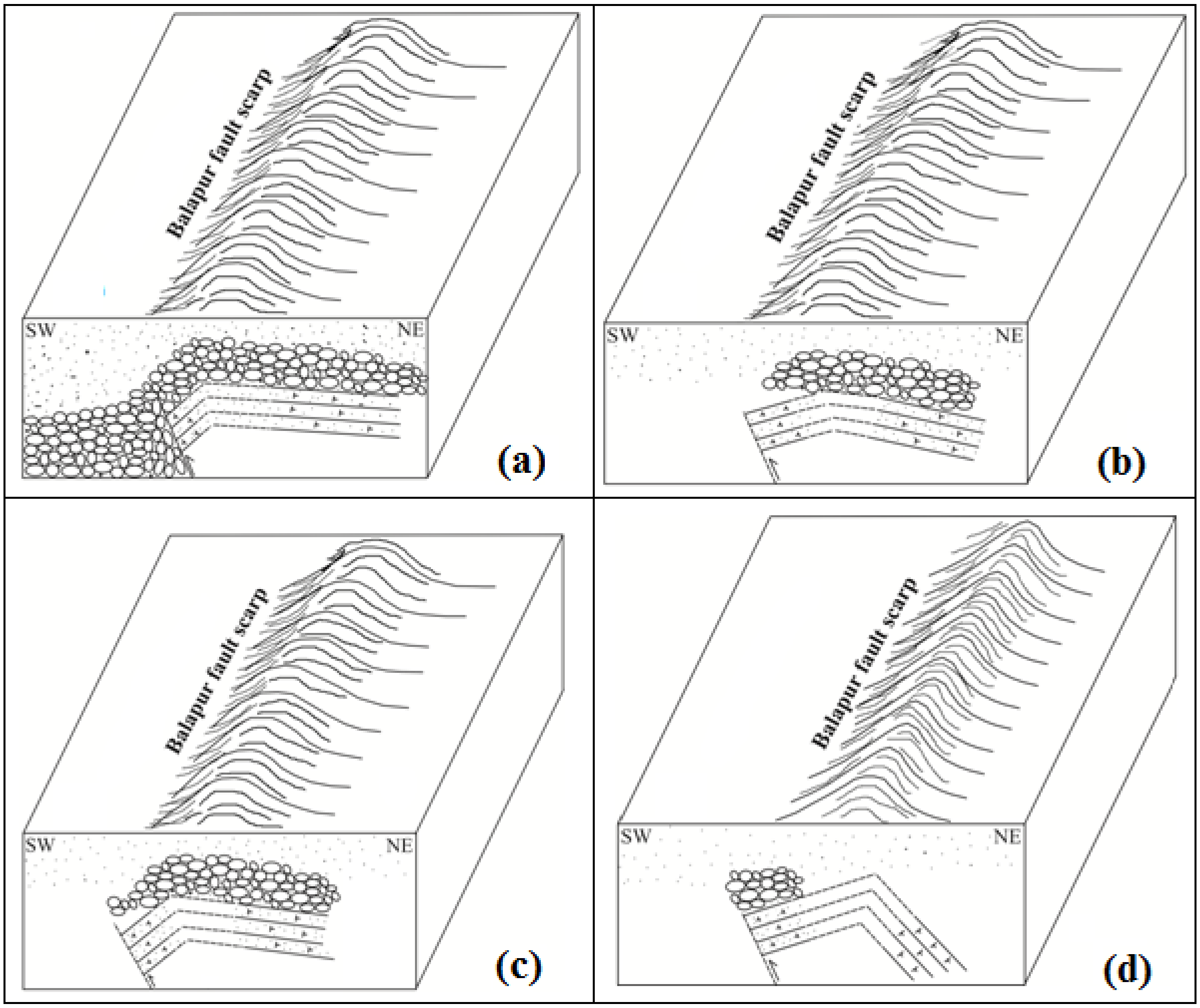

Fig. 8. Cross section of Balapur fault showing relationship of bedding planes with fault and overlying scarp development at different locations marked in figure 6 (a) Rambiara near Balapur village, (b) Sasara and Romushi between Manshiwor and Batmaran and between Chaki-badrinath and Kelar villages, (c) Shaliganga between Wusan Udar and Gurvet villages and (d) Sukhnag between Biru and Vedpura villages.

CONCLUSION

The Balapur fault within the Kashmir basin is mostly responsible for the change of landform configuration of SW Kashmir with development of prominent SW-facing fault scarps in weakly consolidated Karewa lithology. Since southwest Kashmir (Pir Panjal range) has excellent fluvial stream network and terraces, which we investigated for deformation or scarps development related to Balapur fault. Terrace mapping indeed reveals deformation of two extensive terraces on right bank with 18.5 m and 18 m SW-facing fault scarps and one on left bank with ~11.5 m SW-facing fault scarp in Rambiara river valley. In addition, terrace profiles also reveal deformation of splay faults in northeast (14.1 m scarp) and southwest (14.8 m scarp) of Balapur fault on the right bank of Rambiara river. Subsequently, stereo plots of structural elements (strike/dip) of bedding planes suggest linkage of an asymmetric anticlinal structure along the NW-SE strike of Balapur fault. The fold has an average forelimb dip of 14^0 northeast and backlimb dip of 25^0 southwest except in Sukhnag river valley, where forelimb has higher (48^0) northeast dip and backlimb has lower (17^0) southwest. Based on kinematic analysis of all the studied segments, the orientation of fold axes is in general NW-SE, coinciding with the general strike of the Himalaya in northwest segment. The kinematic analysis suggests that NW-SE trending Balapur fault is pushed across from NE and SW in horizontal to semi horizontal direction as a result creating a fault-bend fold of anticlinal-type in NW segments.

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