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ORIGINAL PAPER

Four major unknown active faults identified, using satellite data, in India and Pakistan portions of NW Himalaya

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Abstract New mapping through geomorphic analysis of tectonic landforms using a variety of freely available satellite data, including shuttle radar topography and Google Maps, has revealed four major curvilinear ~NW–SE trending faults in NW Himalaya regions of India and Pakistan. From north-west to south-east, these are named as Mawer, Tunda, Gulmarg, and Mughal Road fault zones. Some of these faults show evidence of oblique faulting where thrusting is accompanied by a small component of sinistral strike–slip faulting, and this possibly increases towards south-east. The active nature of deformation on these faults is demonstrated by occurrence of triangular facets, fault rupture scarps, topographic breaks, displaced ridges, shutter ridges, deflected drainages, plus uplift and back tilting of Holocene sedimentary deposits. This is further supported by the fact that these fault traces truncate the previously mapped active structures such as Kashmir basin/ Balapore fault and main boundary thrust. The abrupt termination of most of these faults in north-west indicates a strong structural control. These faults are active, and their dimensions and geometrical configurations indicate their potential to host major earthquakes that could be similar or greater than what we witnessed during Kashmir earthquake of 2005. Further, active deformation is also mapped within Udhampur Piggyback basin, which lies within the Riasi fault system in Jammu and Kashmir, NW Himalaya. The emergent thrusting further suggests splay faulting from one of the branches of the Riasi fault system (Mandili-Kishanpur thrust). The structural configuration of the basin indicates a possible structural control on the formation and deformation of the basin. The geomorphic expression of active faulting is manifested in the overall morphology of the oval-shaped basin (similar to Kashmir basin in NW Himalaya). The shape is structurally controlled by faults as the whole of the basin is riding on Riasi fault system. Within the valley, the active

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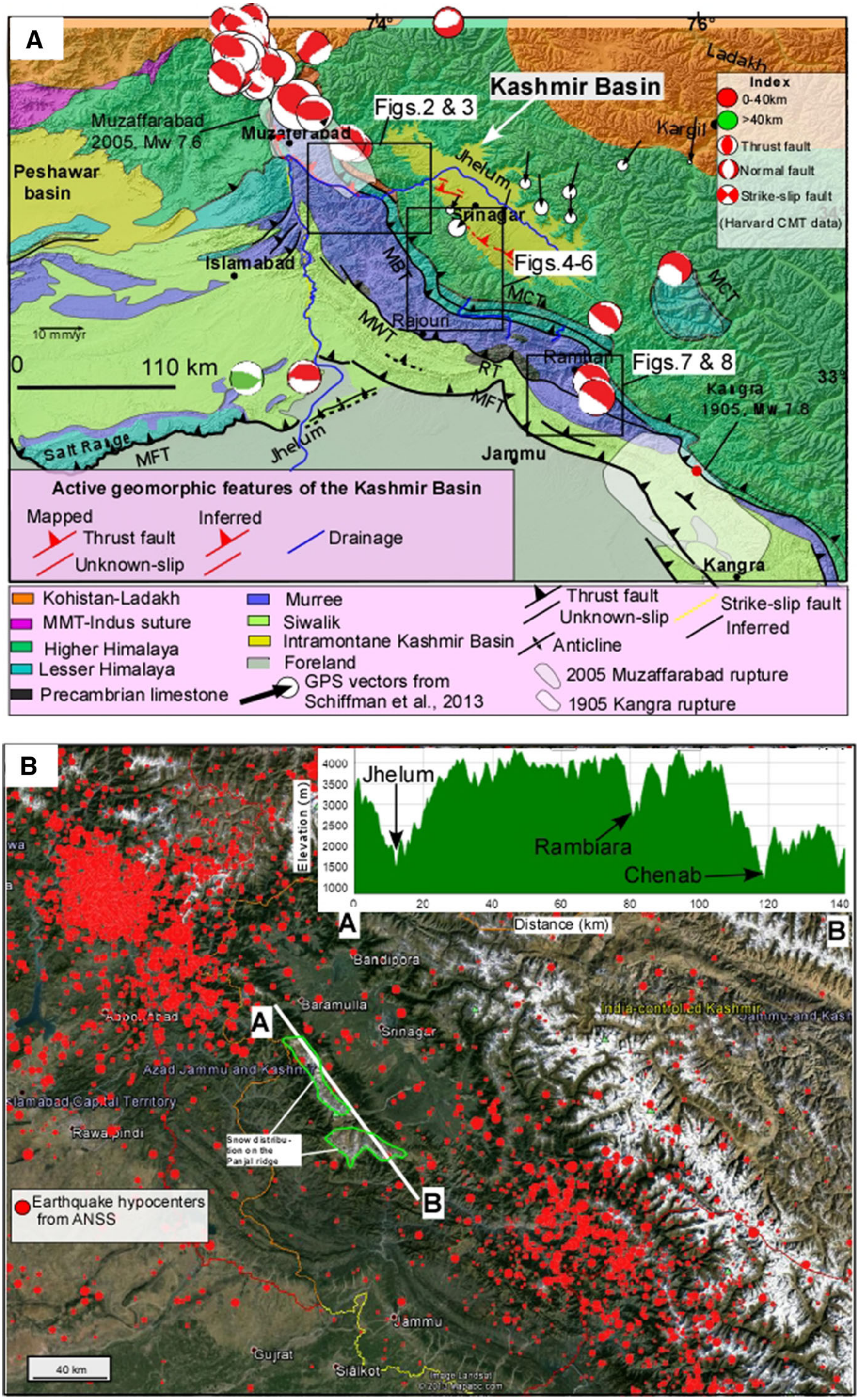
faults are only visible on the ~SE portion. This has divided the basin into two distinctive geomorphic divisions: SE and NW domains. These domains are delineated by a structural break that could be ~NE–SW trending fault zone because the mapped faults do not continue beyond this topographic break in the basin. And since the SE tectonic domain is faulted, the streams are deeply incising into the bedrock forming deep canyons. The tributaries are short because their lengths are trimmed by the faults. Thus, the tributaries on the hanging wall have permanently lost their headwater source and are orphaned. Such geomorphic features are not visible in the NW domains, which have not been faulted, and thus, the streams are following the natural slope. All the streams feed the basin merge into a major stream (Tawi River) that cuts through the anticlinal ridge of Suruin–Mastgarh anticline. This river roughly follows the interpreted ~NE–SW trending topographic break, which could mean that it follows a fault. Such an interpretation is backed by the evidence that the anticlinal ridge is only broken at this portion of the ridge.

Keywords Tunda fault · Udhampur basin · Mawer fault · Riasi fault · Holocene · Jammu and Kashmir

1 Introduction

After the Kashmir 2005 earthquake (Fig. 1), which was the first recent earthquake to have ruptured the surface in Himalaya, and an out-of-sequence thrusting event (Avouac et al. 2006), the need to map and understand the earthquake potential along out-of-sequence thrusting has multiplied, particularly in NW Himalayan portions of India and Pakistan. Although recently some progress has been made in mapping of the active geological landforms in the region (e.g. Pathier et al. 2006; Avouac et al. 2006; Kaneda et al. 2008; Hussain and Yeats 2009; Shabir and Bhat 2012; Shah 2013, 2016; Gavillot 2014; Vassallo et al. 2015; Gavillot et al. 2016), bulk of geomorphic mapping of active tectonic structures in the region (Fig. 1) remains to be achieved. This is primarily because of decades of political instability that has largely hampered geological investigation(s) in the region (Shah 2016). Therefore, this work attempts to map large-scale unknown active tectonic landforms in the region (Fig. 1). These landforms are a product of progressive deformation because of the underthrusting of the Indian lithosphere along the active Main Himalayan Thrust (MHT) below the Tibetan Plateau (Yeats et al. 1992). The fact that the regional convergence of India and Tibet is distributed differently along the entire length (~2000 km) of the Himalayan orogen (Yin 2006) bears considerable importance in NW Himalaya. This is mainly because of the scale of tectonic complexity, particularly at Hazara syntaxis. Although the Himalayan Frontal Thrust (HFT) is the major structure that absorbs a significant amount of convergence in the region with the overall distribution partitioned on frontal and interior structures (Shah 2013, 2015a; Gavillot 2014; Vassallo et al. 2015; Gavillot et al. 2016), such a convergence distribution on mapped structures will change if new active structures are added to the existing tectonic map of the region. This will have a significant role in seismic hazard mapping of the region and the understanding of the regional tectonics. The work presented herein therefore shows new mapping of a number of potentially active faults that should be incorporated into any seismic hazard mapping and deformation budget allocation scheme of NW Himalaya.


A
74°
76°
Ladakh
Kashmir Basin
Index
0-40km
>40km
Thrust fault
Normal fault
Strike-slip fault
(Harvard CMT data)
Muzaffarabad 2005, Mw 7.6
Muzaffarabad
Figs.2 & 3
Kargil
Peshawar basin
Jhelum
Srinagar
Figs.4-6
Islamabad
MBT
MCT
MWT
Rajouri
10 mm/yr
0 110 km
Ramban
Figs.7 & 8
RT
MFT
33°
34°
Kangra 1905, Mw 7.8
Salt Range
MFT
Jhelum
Jammu
Kangra
Active geomorphic features of the Kashmir Basin
Mapped
Inferred
Thrust fault
Unknown-slip
Drainage
Kohistan-Ladakh
MMT-Indus suture
Higher Himalaya
Lesser Himalaya
Precambrian limestone
Murree
Siwalik
Intramontane Kashmir Basin
Foreland
GPS vectors from Schiffman et al., 2013
Thrust fault
Unknown-slip
Strike-slip fault
Inferred
Anticline
2005 Muzaffarabad rupture
1905 Kangra rupture
B
Elevation (m)
4000
3500
3000
2500
2000
1500
1000
Jhelum
Rambiara
Chenab
0
20
40
60
80
100
120
140
Distance (km)
A
B
Bandipora
Baramulla
Srinagar
India-controlled Kashmir
Jammu and Kashmir
Abbottabad
Azad Jammu and Kashmir
Islamabad Capital Territory
Rawalpindi
Snow distribution on the Panjal ridge
Earthquake hypocenters from ANSS
Jammu
Gujrat
Sialkot
40 km
Image Landsat
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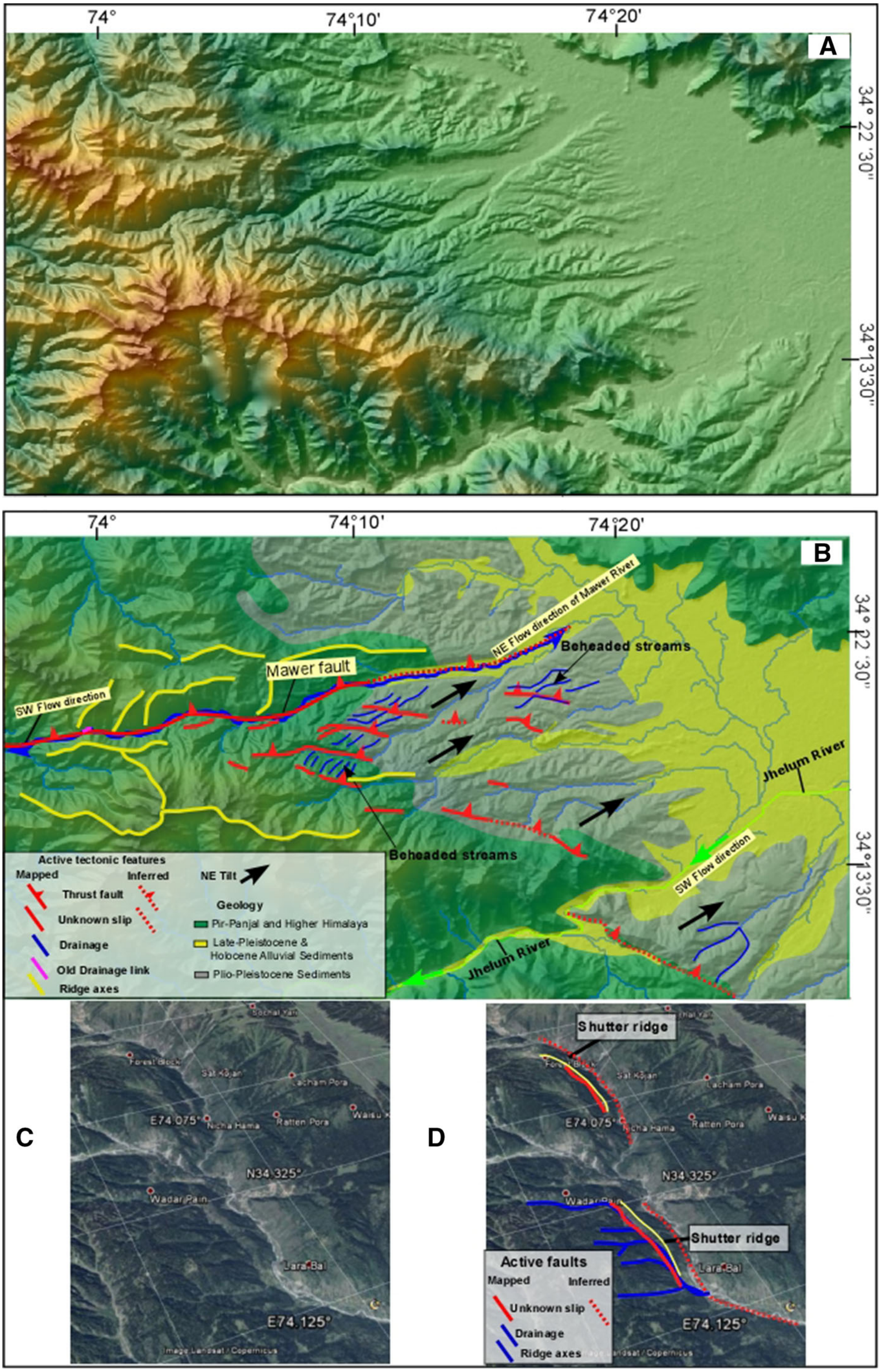
◀**Fig. 1** Regional geological and simplified structural map of a portion of the NW Himalaya (after Shah 2016). The study area locations are shown in *rectangular boxes*. **a** Earthquake hypocenters obtained from USGS Advanced National Seismic System are plotted on the Google satellite images. The distribution of snow on the Panjal ridge suggests a possibly fault control as variations are along the fault traces. **b** The topographic profile shows three major rivers in the region that have carved prominent V-shaped valleys, and these rivers cut through stratigraphy. The riding of Jhelum River across the structural grain of the region indicates a strong structural control. *MCT* main central thrust, *MBT* main boundary thrust, *MWT* Medlicott–Wadia thrust (MWT), Riasi fault (RF), and *MFT* main frontal thrust

2 Tectonic framework

The regional geological and structural map (Fig. 1) of Jammu and Kashmir region shows a serious of ~south-west verging faults that are younger towards the deformation front. These were formed as a result of the collision between Indian and the Eurasia plates since Eocene (Le Fort 1975; Tapponnier and Molnar 1977), and some of these faults are still actively growing (Pathier et al. 2006; Avouac et al. 2006; Thakur et al. 2010; Malik et al. 2010; Schiffman et al. 2013; Shah 2013, 2016, 2017; Malik et al. 2014; Gavillot 2014; Vassallo et al. 2015; Gavillot et al. 2016). Similarly regional folds were also initiated during the collision, and their orientation is ~orthogonal to the regional stress vector akin to faults. The Himalayan thrust-and-fold belt forms dominant deformation domain south of the India–Eurasia collision suture zone, while as escape tectonics, via strike–slip faulting, is the primarily deformation style to the north of the suture zone (Tapponnier and Molnar 1977).

The geological map of the study areas shows that bulk of the rock sequences is dipping ~NE, which indicates younger rocks should ideally outcrop towards the ~NE portions. The reverse is true (Fig. 2), which suggests a very strong structural control on the geology of the region where older rocks are exposed towards the NE through a series of major ~NE dipping thrust faults, which are usually younger towards the deformation front; these are main central thrust (MCT), main boundary thrust (MBT), Riasi fault (RF), and Himalayan Frontal Thrust (HFT). These major Himalayan thrust faults merge at depth with the Main Himalayan Thrust, which is the plate-boundary décollement between Indian and Eurasian tectonic plates (Le Fort 1975; Tapponnier and Molnar 1977; Hodges 2000; Valdiya 2003; Gavillot 2014; Vassallo et al. 2015; Gavillot et al. 2016). Two major exposures of Sirban Limestone, Precambrian in age, have been mapped to the south of MBT and these are surrounded by younger rocks (Fig. 2). At one exposure, the Riasi fault juxtaposes Sirban Limestone onto the younger units; however, no fault has been associated with the second exposure (Fig. 1).

The western extend of our study areas is delineated by the moment magnitude 7.6 Muzaffarabad earthquake region that occurred on 8 October 2005 in northern Pakistan and Kashmir region (Fig. 1), and caused more than 80,000 deaths (Pathier et al. 2006). The fault rupture extends for ~80 km where it cuts through the Hazara syntaxis and has reactivated the Tanda and the Muzaffarabad faults (Fig. 1). The strong structural control on the propagation of rupture is suggested by its abrupt termination at the hairpin turn of the MBT (Avouac et al. 2006). The fault has placed Precambrian limestone and shales onto tertiary molasse of the Murree Formation or/above Proterozoic schists (Searle et al. 1996).


A
74°
74°10'
74°20'
34° 22 '30"
34°13'30"
B
Mawer fault
SW Flow direction
NE Flow direction of Mawer River
Beheaded streams
Beheaded streams
Jhelum River
SW Flow direction
Jhelum River
Active tectonic features
Mapped
Inferred
NE Tilt
Thrust fault
Unknown slip
Drainage
Old Drainage link
Ridge axes
Geology
Pir-Panjal and Higher Himalaya
Late-Pleistocene & Holocene Alluvial Sediments
Plio-Pleistocene Sediments
C
Forest Block
Sat Kojan
Lacham Pora
E74.075°
Nicha Hama
Ratten Pora
N34.325°
Wadar Pain
Lara Bal
E74.125°
D
Shutter ridge
Shutter ridge
Active faults
Mapped
Inferred
Unknown slip
Drainage
Ridge axes

◀**Fig. 2** Evidence for active thrust faulting in support of newly identified Mawer fault. Uninterpreted topography is on the *top* (**a**), and the mapped active faults and bedrock geology are on the bottom (**b**; location in Fig. 1). High-resolution Google images (**c**, d) show a small portion of the active fault trace where shutter ridges and fault scarps are visible. Image was created by using the freely available 90-m-resolution SRTM data

3 Methodology

The classical work of Tapponnier and Molnar (1977), which was done using the Landsat imagery and fault plane solutions of 14 earthquakes, principally laid the foundation of active tectonics of Tibet. Such methods have subsequently been adapted by a vast number of studies throughout the world (e.g. Jackson and McKenzie 1984; Nakata 1989; Sieh and Natawidjaja 2000; Malik and Nakata 2003; Shyu et al. 2005; Taylor and Yin 2009; Shah 2013, 2016; Malik et al. 2014; Wang et al. 2014). These works have demonstrated the significance of using satellite data, digital elevation models, and high-quality imagery to map active geomorphic features. Such geomorphic analysis in combination with geological, seismological, and geodetic data sets forms a robust methodology for mapping of active landforms. The present work adapts such a methodology to map active landforms in previously unexplored portions of NW Himalaya (Fig. 1) in Jammu and Kashmir (Pakistan and India) where such preliminary work has not been done previously. The motivation is to map large-scale unknown active structures that could be understood, and interpreted in the regional context. The mapping was achieved by using freely available satellite data that include shuttle radar topography and Google Maps. The geomorphic analysis was done by probing changes (modifications) in river channels, incision and erosion pattern, topographic breaks, fault scarps, uplifted/tilted Holocene landforms. The geomorphological mapping was augmented with seismological, geological, and geodetic data to support the geomorphic observations.

4 Results and interpretations

4.1 Tectonic topography and geomorphology

4.1.1 Mawer fault zone

A major curvilinear ~NW-facing fault trace is mapped (Fig. 2) for ~35 km. It continues to the west and possibly connects with Muzaffarabad fault (Avouac et al. 2006) in Pakistan-administered Kashmir. The fault cuts through the Kashmir basin where it has displaced Holocene sediments (Burbank and Johnson 1983). Possibly the recently mapped active fault traces in Kashmir basin (Shah 2016) do not continue further west as such evidence is lacking, and it could be because of this discontinuity. A prominent tributary of Jhelum River flows along the fault trace and it continues to the west; however, the small drainage divide (Fig. 2) has bifurcated the major river, which was possibly flowing along the fault. The striking feature of the fault zone is the presence of a series of prominent topographic breaks where ridge crests are discontinued along the strike of the fault zone (Fig. 2). Shutter rides and fault scarps are clearly visible on the high-resolution Google images (Fig. 2d). V-shaped gorges are >500 metres deep and are carved by the tributaries (Fig. 1c), suggesting active movements along the fault. This fault is named as Mawer fault, and it is based on the river that ~follows the fault trace in Kashmir basin (Fig. 2). At

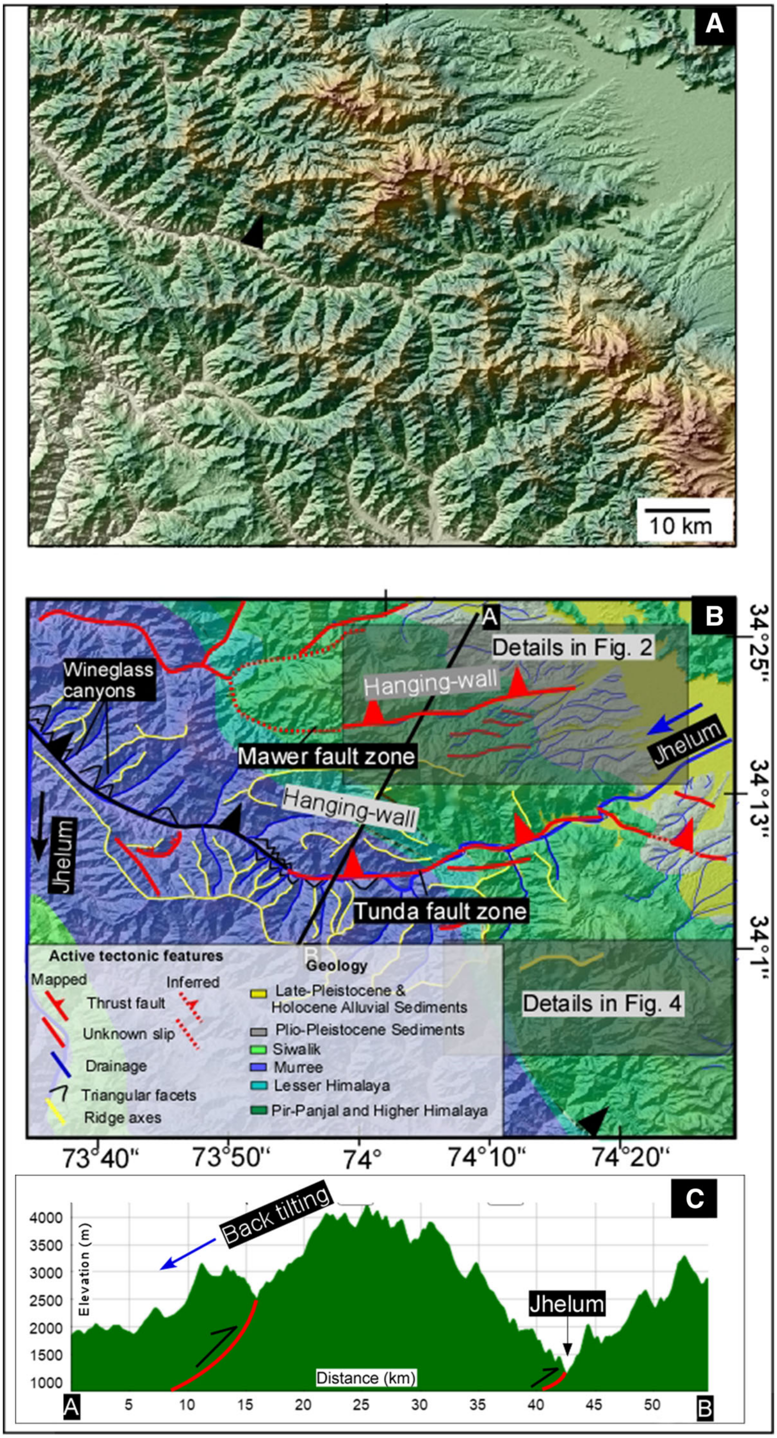
~16 km NW of this fault zone, there is another fault that runs for ~27 km from the Kashmir basin, and continues to the west and merges with the Mawer fault, forming a triangular structure in map and cross-sectional views. The trace of this fault is not very clear; however, the topographic discontinuity is very distinct (Fig. 1). This is interpreted as a splay fault of Mawer fault zone. It seems that the two faults merge at depth and continue as a single structure. The actual distance at which they merge can be estimated once the dip amount of the faults is known, which may be done in the future; however, the possibility of conducting a detailed fieldwork along the entire stretch of the fault zone is easy because of the decades-old political problem between India and Pakistan (Shah 2016).

4.1.2 Tunda fault zone west of Kashmir basin

About 20 km south of the Mawer fault zone, another major fault is mapped for a length of ~45 km that breaks through a portion of the Kashmir basin and it continues to the west, and connects with the Tunda fault on which moment magnitude 7.6 Muzaffarabad earthquake occurred in 2005 in northern Pakistan and Kashmir region (Fig. 1). The remarkable structural discontinuity all along the fault zone is shown by a number of topographic breaks via ridge crests and triangular facets (Fig. 3). The triangular facets are very distinct on the western portions of the fault zone with well-developed wineglass canyons on the hanging-wall block. There are some triangular facets on the footwall side as well, which may indicate relative motion or these could just be bedding planes. The streams on the hanging-wall block show subtle indication of left-lateral motion, particularly on the western portion of the fault zone. This could mean oblique faulting, which is quite prevalent in south (see below). This fault is named as Tunda fault because it is the eastern extension of the previously mapped Tunda fault (e.g. Avouac et al. 2006). Jhelum River follows the trace of the fault when it abruptly turns west in Kashmir basin and flows NNW through Baramulla to Muzaffarabad (Pakistan) along the fault trace (Fig. 3). The previously mapped active Kashmir basin fault (Shah 2013, 2016) is cut by the Tunda fault, and this suggests that the fault is younger than the KBF. The trace of the fault is curvilinear, and the strike changes from being ~E–W on the eastern portion to ~NW–SE on the western portion of the major fault zone (Fig. 3). The course of the Jhelum River is possibly directly controlled by this fault zone because it rides on the fault zone, and flows across the structural grain of the region (Fig. 1); thus, it is not an antecedent stream, and its course is strongly controlled by underlying structures.

4.1.3 Gulmarg fault zone

Further south of the Tunda fault zone, another thrust fault is mapped that has strike length of ~40 km (Fig. 4). Right in the Kashmir basin where the famous tourist destination Gulmarg is located, the fault shows signatures of left-lateral motion for ~4.5 km. This is shown by displacement of ridge crest on either sides of the fault. A number of small ~SE dipping normal faults possibly suggest sinistral motion along with thrusting (Fig. 5). Prominent left-lateral drag on ridges along the entire fault zone further indicates oblique nature of faulting. The geomorphic expression of ridges preserves evidence of deformed, dragged, distorted, and broken crests, which confirms the fault zone. This is also suggested by a number of small ~SE dipping normal faults that are mapped along the strike of the fault zone, and these cut through the Holocene glacial landforms. The deep incision and a series of un-paired terrace formation by the river mainly obvious in Kashmir basin along the hanging-wall block of the fault zone (Fig. 4) further indicate active uplift. Since this


A
10 km
B
Details in Fig. 2
Wineglass canyons
Hanging-wall
Mawer fault zone
Jhelum
Hanging-wall
Jhelum
Tunda fault zone
Details in Fig. 4
34°25''
34°13''
34°1''
73°40''
73°50''
74°
74°10''
74°20''
Active tectonic features
Mapped
Inferred
Thrust fault
Unknown slip
Drainage
Triangular facets
Ridge axes
Geology
Late-Pleistocene & Holocene Alluvial Sediments
Plio-Pleistocene Sediments
Siwalik
Murree
Lesser Himalaya
Pir-Panjal and Higher Himalaya
C
Back tilting
Jhelum
Elevation (m)
Distance (km)
A
B

◀ **Fig. 3** Evidence for active thrust faulting in support of newly identified eastern extension of the previously mapped Tunda fault. Uninterpreted topography is on the *top*, and the mapped active faults and bedrock geology are on the *bottom* (location in Fig. 1). Topographic profile shows deep valleys *carved* by rivers through the Mawer and Tunda fault zones. Image was created by using the freely available 90-m-resolution SRTM data

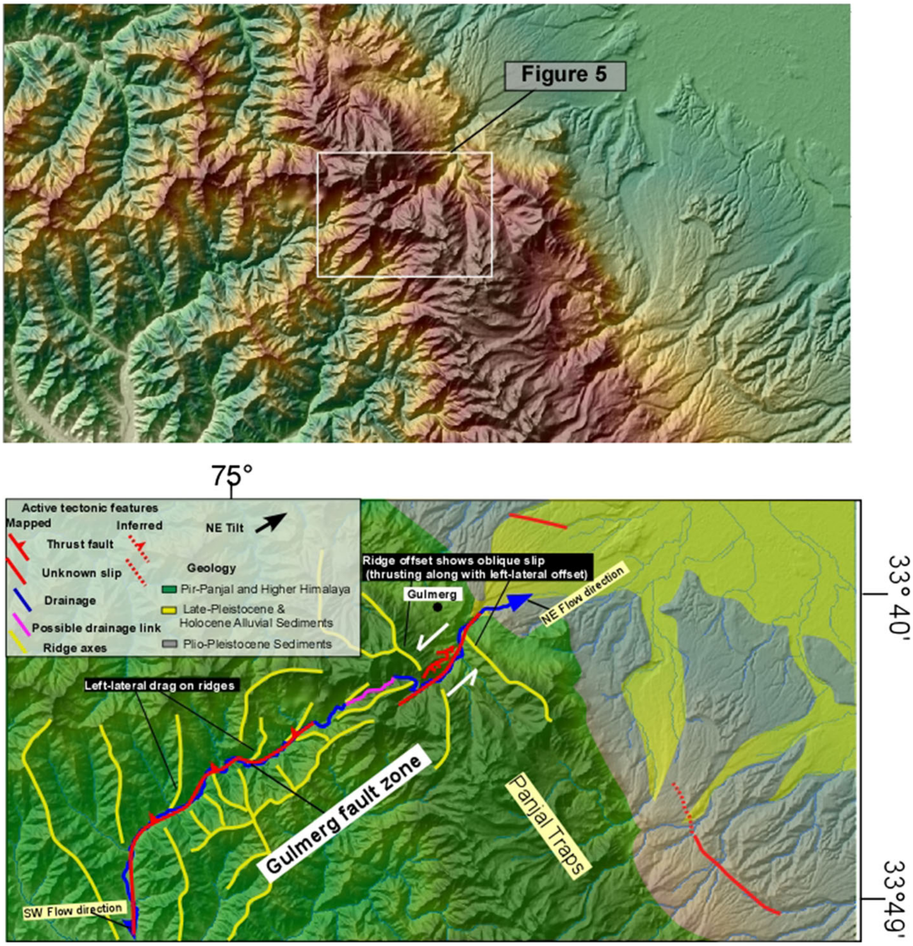


Fig. 4 Evidence for active oblique thrust faulting in support of newly identified Gulmarg fault. Uninterpreted topography is on the *top*, and the mapped active faults and bedrock geology are on the *bottom* (location in Fig. 1). ~SE dipping normal faults support the sinistral component of thrusting along the fault. Image was created by using the freely available 90-m-resolution SRTM data

fault has displaced Holocene deposits of Kashmir basin, the fault zone is active, and we have named it as Gulmarg fault zone because it is located close to the famous location "Gulmarg" in Kashmir (Fig. 4).

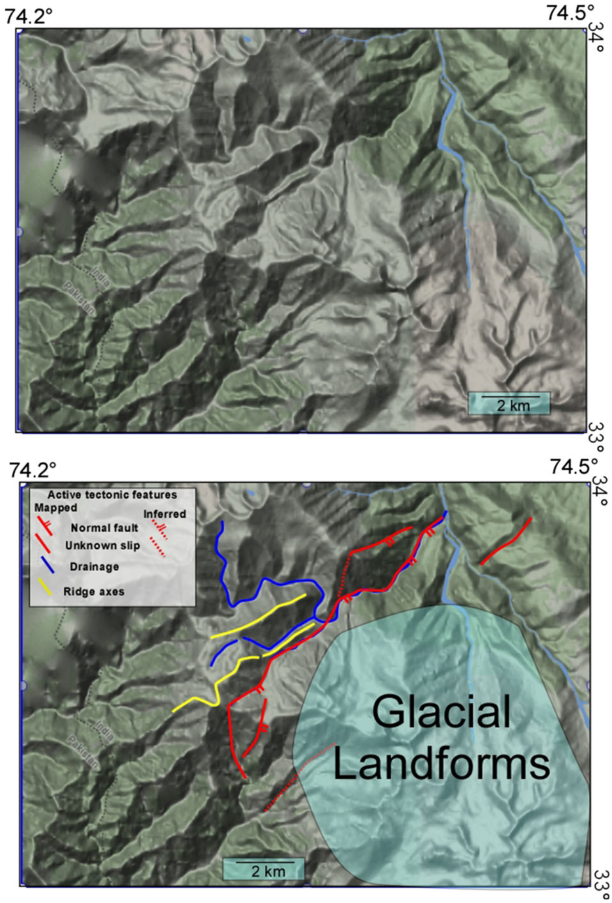
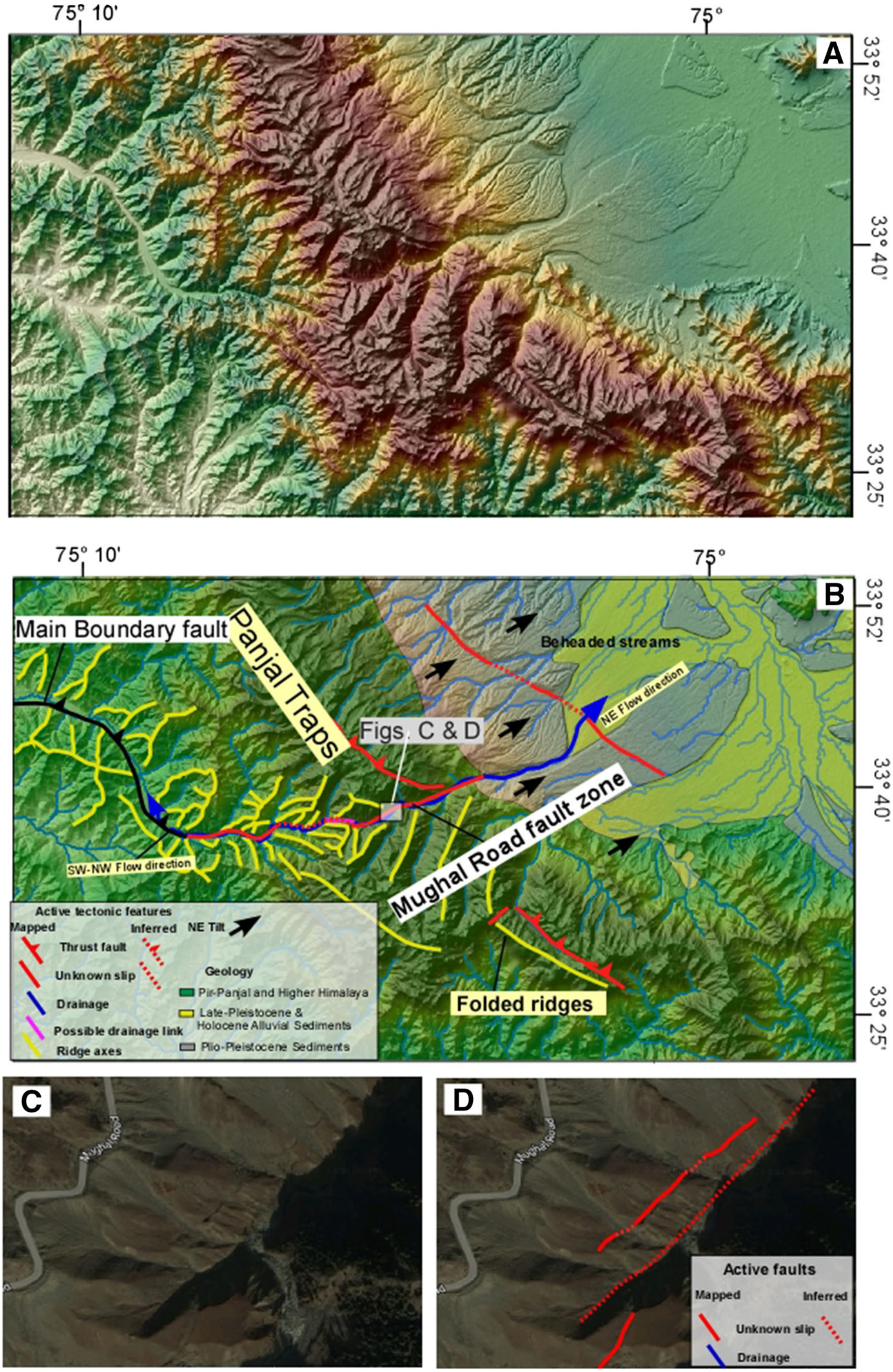


Fig. 5 Evidence for active oblique faulting in support of newly identified Gulmarg fault. Uninterpreted topography is on the *top*, and the mapped active faults are on the *bottom* (location in Fig. 1). ~SE dipping normal faults support the sinistral component of thrusting along the fault. Image was created by using the freely available Google terrain images

4.1.4 Mughal Road fault zone

Further south of Gulmarg fault at ~45 km, another major fault zone is mapped that runs ~E–W for ~40 km. The fault zone is beautifully preserved via geomorphic expression of ridges, which preserve evidence of recent faulting and active left-lateral drag (Fig. 6). A number of ridge crests are broken, and the evidence of left-lateral drag is visible on the hanging-wall block. The footwall block shows folded ridges, which further suggest left-lateral movement along with thirsting. This fault has displaced and uplifted the Holocene deposits of Kashmir basin (Fig. 6d); therefore, this fault zone is active. It is herein named as Mughal Road fault because the famous road in Jammu and Kashmir region roughly follows the trace of the fault. A prominent tributary of Jhelum River flows along the fault trace, and it continues to the west; however, the small drainage divide (Fig. 6) has bifurcated the major river, which was possibly flowing along the fault into two large tributaries that flow into India and Pakistan portions of disputed Kashmir.


75° 10'
75°
A
33° 52'
33° 40'
33° 25'
B
Main Boundary fault
Panjal Traps
Beheaded streams
NE Flow direction
Figs. C & D
Mughal Road fault zone
SW-NW Flow direction
Folded ridges
Active tectonic features
Mapped
Inferred
NE Tilt
Thrust fault
Unknown slip
Drainage
Possible drainage link
Ridge axes
Geology
Pir-Panjal and Higher Himalaya
Late-Pleistocene & Holocene Alluvial Sediments
Plio-Pleistocene Sediments
C
Mughal Road
D
Mughal Road
Active faults
Mapped
Inferred
Unknown slip
Drainage

◀**Fig. 6** Evidence for active oblique thrust faulting in support of newly identified Mughal Road fault. Uninterpreted topography is on the *top*, and the mapped active faults and bedrock geology are on the *bottom* (location in Fig. 1). The drag on the ridges of hanging-wall block supports the sinistral component along with thrusting, this is further supplemented by the folding of Panjal ridge. Note that the *western portion* of the fault continues with main boundary fault; however, the previously mapped trend of MBT truncates the fault (Figs. 1, and 9). This implies that either the mapped trace of MBT is discontinued and terminated in Kashmir basin, or Mughal Road fault (and other three fault maps herein) truncates the MBT fault system. Image was created by using the freely available 90-m-resolution SRTM data. High-resolution Google satellite images show (**c**, **d**) a portion of the fault system where faults are visible on surface as a mule track

4.1.5 Snow distribution on Panjal ridge

The snow distribution on the Panjal ridge (Fig. 1b) shows a pattern that indicates that it is largely controlled by the movement on the fault. This is prominently evident at Gulmarg fault where its distribution is mostly asymmetrical compared to the distribution on the entire ridge, and at Mawer, Tunda, and Gulmarg fault zones (Fig. 1b). The distribution is probably related to the movement on faults where elevations associated with thrusting and left-lateral strike–slip motion might have caused the patterns.

4.1.6 Active faults in Udhampur piggyback basin

Three ~NW-facing fault scarps are mapped in the south-eastern portion of Udhampur synclinal valley (Figs. 7, 8), which is ~47 km long and ~13 km wide, filled with Quaternary to Recent fluvial sediments (Gavillot 2014; Vassallo et al. 2015; Gavillot et al. 2016). The south-easternmost fault scarp is ~12 km long, curvilinear, and fluvial terraces are displaced ~140 m up dip (scarp 1 in Fig. 8). The major stream that follows the fault has deeply incised into the fluvial terraces, as well as bedrock formations, forming deep gorges, and characteristic V-shaped valleys (Fig. 8b). The stream beheading is very prominent at the fault scarp where a network of small tributaries drains into the major stream that follows the fault trace. The scarp is very sharp and clearly visible on the satellite data (Fig. 8a). The bed rock geology shows the beds are dipping ~NE, and are cut through by the fault, which has back-tilted the entire sequence, and exposed the bedding surfaces of underlying layers, which are clearly visible on Google satellite images.

Similar geomorphic characteristics are observed along the two other scarps (scarp 2, and 3 in Fig. 8), which are located to the NW of the first fault scarp. The strike length of second fault scarp is ~18 with an average vertical displacement of ~112 m (Fig. 8b). The third fault scarp is a complex fault scarp zone, ~5 km wide, and consists of a total of 1 large and 4 smaller scarplets. The larger scarp is ~14 km long and shows vertical displacement of >200 m (Fig. 8b).

The overall topography subsides north-westward along the strike of the valley, and two distinct tectono-geomorphic zones are mapped. These have roughly divided the entire valley into two distinctive geomorphic divisions, SE and NW domains, which are delineated by a structural break that could be ~NE–SW trending fault zone. Since all the mapped faults do not continue beyond this topographic break in the basin, it is likely a fault (mapped as inferred in Fig. 4).

SE domain is faulted, and streams are deeply incising into the bedrock forming deep canyons, and supplying a variety of sediments to downstream regions by greatly eroding through a succession of rocks. The tributaries are short because their lengths are trimmed by the faults. Thus, the tributaries on the hanging wall have permanently lost their

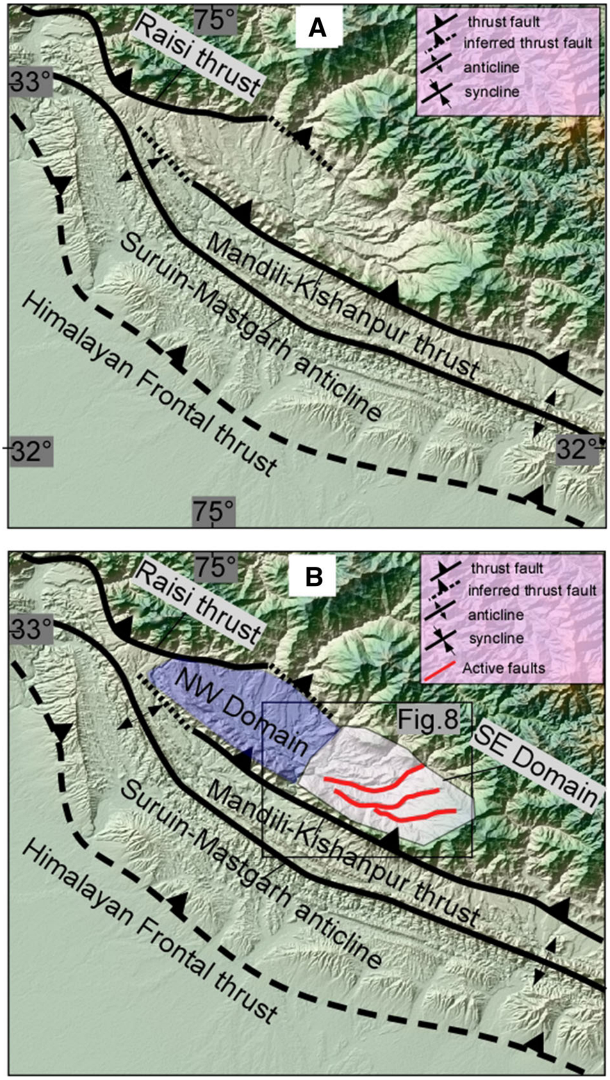


Fig. 7 Evidence for active thrust faults in the Udhampur piggyback basin, NW Himalaya. Uninterpreted topography is on the top with previously mapped faults. Mapped active faults (this study) and bedrock are on the bottom (details in Fig. 4); location is shown in Fig. 1 (freely available 90-m-resolution SRTM data used)

headwater source and are orphaned (Fig. 8). This is in contrast to the NW domains which have not been faulted, and thus, the streams are following the natural slope, and the tributaries are connected with their headwaters. The streams do not cut deeper through the bedrock, are unable to form deep canyons, and could not supply a variety of sediments to downstream regions. Thus, the current sediments derived from the valley are partly fault controlled, and thus, studying these should provide signatures of the deformation history of the region, which needs to be analysed in greater detail. All the streams merge into a major stream that cuts through the anticlinal ridge of Suruin–Mastgarh anticline (Figs. 7, 8). This has resulted in characteristic drainage pattern within the valley where all the streams merge

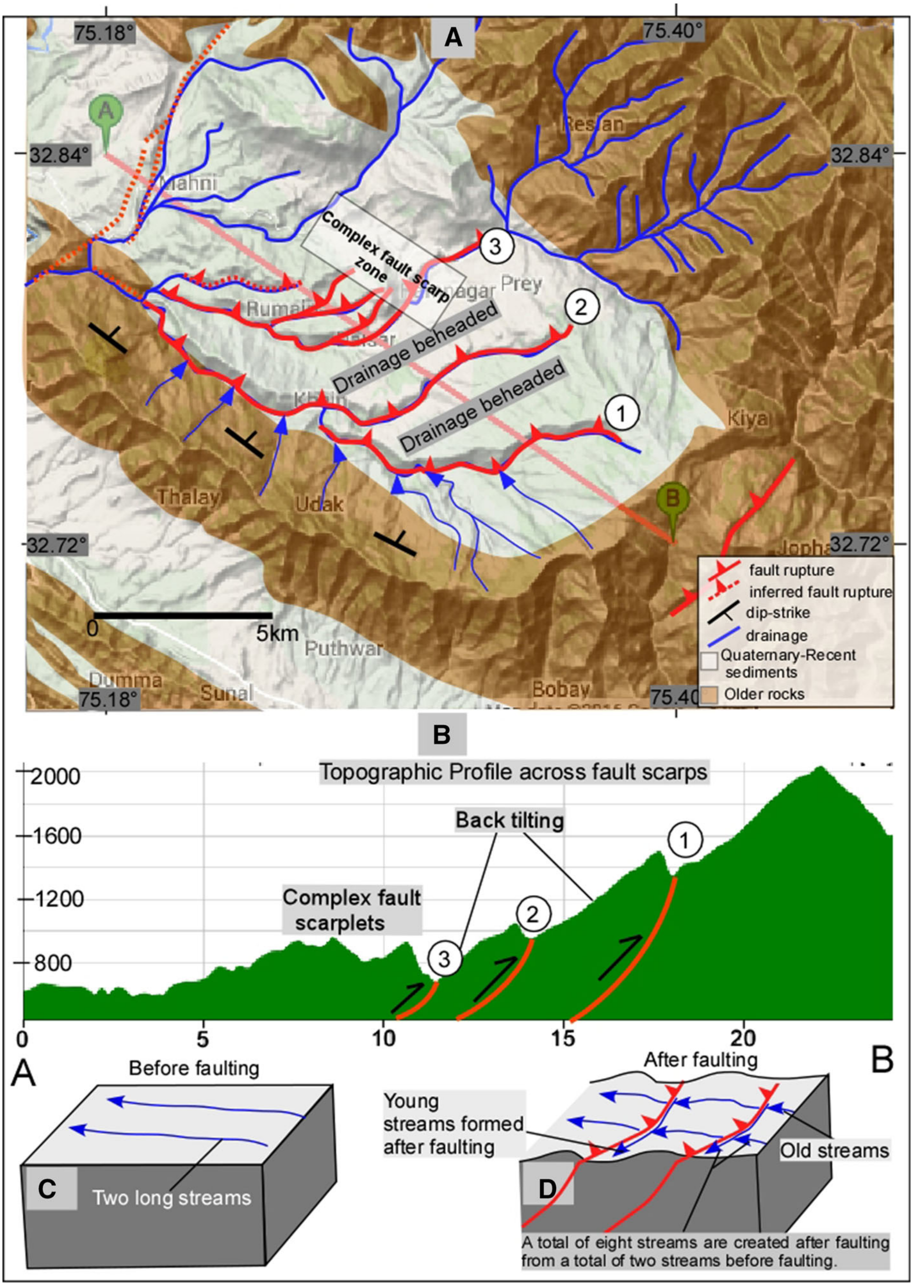


Fig. 8 Evidence of active tectonic landforms (location in Figs. 1 and 6). **a** Three main faults cutting through Holocene fluvial sediments and beheading a number of streams. **b** Topographic profiles across the fault scarps highlight the vertical uplift and back tilting at the faults. Diagrams (**c** and **d**) show how these small faults show modified the drainage in the area

into the major stream which is locally named as Tawi River. This river roughly follows the interpreted ~NE–SW trending topographic break, which could mean that it follows a fault. Such an interpretation is strongly backed by the evidence that the anticlinal ridge is only broken at this region. How could such a break occur without faulting? The fact that the topographic break cuts through the bedding planes clearly suggests a structural discontinuity.

4.1.7 Active faults and their influence on fluvial flooding in Udhampur piggyback basin

Previous studies have shown the Udhampur valley (Figs. 1 and 7), which is located ~25 km from Jammu, NW Himalaya, as a synclinal valley (Gavillot 2014; Vassallo et al. 2015). However, since it is sandwiched between two actively growing major fault traces of the Riasi fault system (Gavillot et al. 2016), it is hereby interpreted as a piggyback basin and named as Udhampur piggyback basin. The SE domain of the basin will be relatively least affected by fluvial floods as deep and wider gorges, which are carved by active faults have more capacity to carry water. In contrast, the NW domain cannot carry more waters as depth of the stream valley is shallow, and deep carving and wider canyons are absent. Therefore, areas on the hanging-wall blocks of the SE domain (e.g. Martha and Ramnagar) will be relatively safer during fluvial flooding than areas on the NW domain (e.g. Udhampur and Kiramchi). It appears that if Riasi fault moves, the entire basin could be dragged downwards, creating further subsidence and more rejuvenated river degradation on SE than on NW (e.g. Shah 2015b, 2016, Simpson 2014). Since Sirban Limestone (Fig. 1) lies underneath the valley, there are more chances of its chemical weathering and subsequent erosion, which could be directly facilitated by faulting through which water can easily percolate and could result in caving in of the valley. This is important information for any construction works in the area.

4.1.8 Seismological data

Instrumental earthquake data were obtained from the freely available Web portal of USGS Advanced National Seismic System. The data are plotted on the Google satellite image, and it shows the distribution of earthquake hypocenters throughout the region with concentrated clusters to the north-west region, where the 2005 Muzaffarabad earthquake occurred, and to the south-east (Fig. 1b; Shah 2013, 2016). The available centroid–moment tensor solutions of earthquakes from the study region show dominantly thrust mechanisms (Fig. 1b), which indicate a ~NW–SE striking fault with either a NE or a SW dipping fault plane. The structural grain of the region is consistent with the regional ~NE dipping gentle fault plane and inconsistent with the ~SW steeply dipping fault plane. The data are not relocated, so the possible errors associated with their vertical and horizontal locations (Shah 2016) have not been rectified. Further the available data are insufficient and could not be related to all the structures that are mapped above. For example, the oblique pattern is not shown by these mechanisms. Thus, there is a need to develop a technique to use small-magnitude earthquakes to extract the fault plane solutions.

5 Discussion

5.1 Active oblique thrusting in NW Himalaya

Little is known about the active tectonic structures in Jammu and Kashmir (both Pakistan- and Indian-administered) region of NW Himalaya, although recently some progress has been made in mapping of active geological landforms (e.g. Pathier et al. 2006; Kaneda et al. 2008; Hussain and Yeats 2009; Shabir and Bhat 2012; Shah 2013, 2016; Gavillot 2014; Vassallo et al. 2015; Gavillot et al. 2016), but still much of detailed work remains to be done. The research herein reports mapping of four new major ~NW–SE trending faults (Mawer, Tunda, Gulmarg, and Mughal Road) in NW Himalaya (Figs. 2–9), and these terminate in north-west. Importantly, all these faults truncate the previously mapped traces of MBT, and MCT (e.g. compare the latest maps in Gavillot 2014; Vassallo et al. 2015 with our map in Figs. 2–9). This is significant because previous studies have established that fault traces of MBT and MCT are not truncated by any structure in the region (Fig. 1). If the newly mapped faults indeed truncate them, it could mean that the faults are tectonically active and potentially dangerous. This is supported by our geomorphic analysis where Holocene deposits are uplifted and displaced (Figs. 2–8). This will have huge regional and tectonic implications because the mapped structures are located north of MFT, the major thrust that accommodates roughly half of the regional India–Eurasia plate convergence. The active nature of faulting could mean that these faults are capable of repeating a similar or bigger earthquake than the one witnessed in Muzaffarabad in 2005 (Avouac et al. 2006; Pathier et al. 2006).

Further, our mapping demonstrates that the orientation of all the four major faults possibly resembles an en echelon or stepping pattern (e.g. Thakur et al. 2010). The relative age relationships of these faults can be visualized by their association with rocks and structures. These faults cut through the ~290-Ma-old Panjal Traps (Shellnutt and Jahn 2011; Shellnutt et al. 2014), and some (e.g. Mawer, and Tunda fault systems) also pierce through a portion of Kashmir basin (Fig. 2, 3) where it cuts through young Kashmir basin fault/Balapore fault (Shabir and Bhat 2012; Shah 2013, 2016). Theses age relationships indicate that these faults are active. This interpretation is further supported by the fact that Mawer fault continues to north-west, and possibly merges with the MCT in the Pakistan side of Himalayan range (Figs. 2–5 and 8). Similarly the two other major faults south of Mawer fault (Figs. 2–5, and 8) cut through fault traces of MCT, and MBT, which also indicates their active nature because some portions of the MBT are active (e.g. Vassallo et al. 2015; Gavillot et al. 2016). Herein it is interpreted that the Tunda fault system, on which the moment magnitude 7.6 Muzaffarabad earthquake occurred on 8 October 2005 in northern Pakistan and Kashmir region (Fig. 1) and caused more than 80,000 deaths (Avouac et al. 2006; Pathier et al. 2006), continues further east until the Kashmir basin (Fig. 2, 3, 9). This fault has placed Precambrian limestone and shales onto tertiary molasse of the Murree Formation (Searle et al. 1996) in Pakistan side, while as the Indian side remains to be explored. This means that the Tunda fault system mapped herein could possibly have accumulated strain to slip in the near future, and it could be true to most of the faults that are mapped herein. This demands more work on ground.

The obliquity of India–Asia convergence increases towards western syntaxes (Zhao et al. 1993; Bettinelli et al. 2006; Molnar and Stock 2009), and this is manifested on regional structures with prominent thrusts along with strike–slip faults on which the deformation partitions (Kundu et al. 2014; Murphy et al. 2014). In NW Himalaya, the

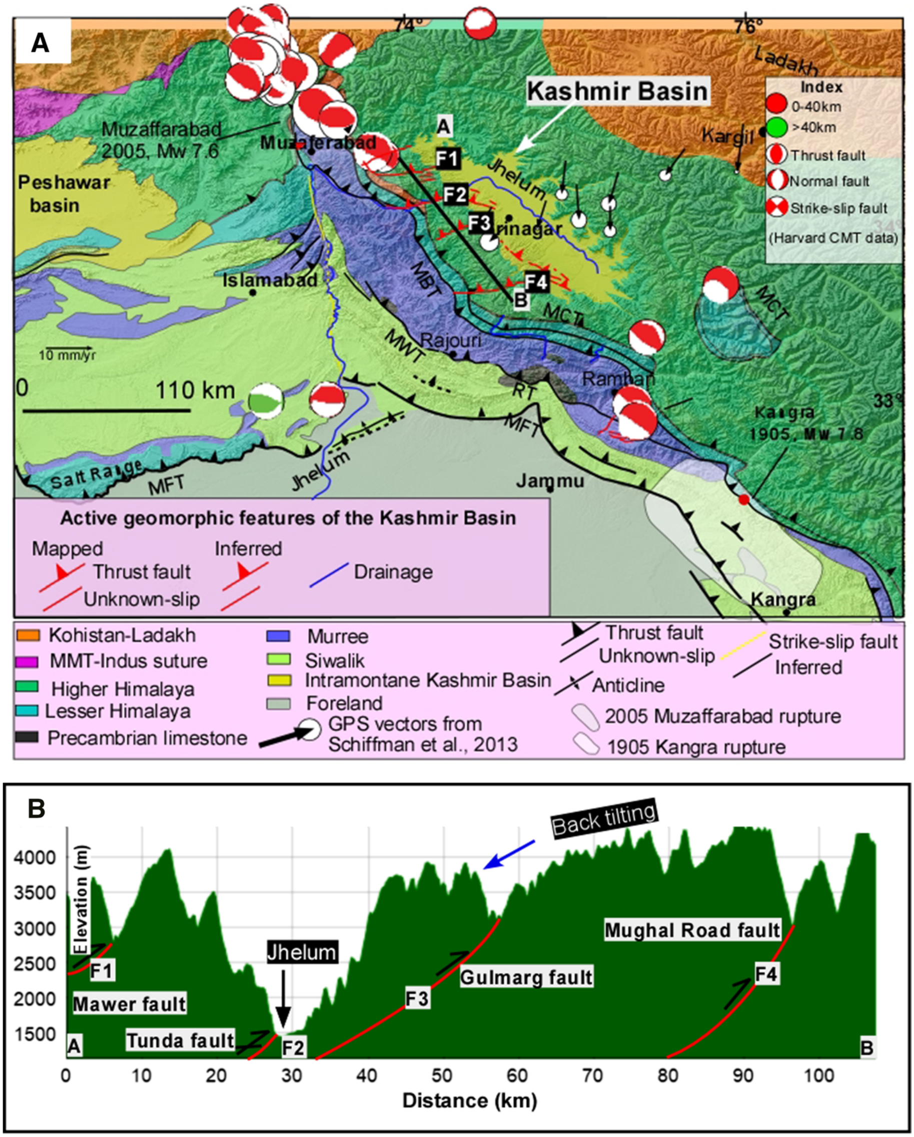


Fig. 9 Regional geological and simplified structural map of a portion of the NW Himalaya (after Shah 2016). The study area locations are shown in *rectangular boxes*. **a** Earthquake hypocenters obtained from USGS Advanced National Seismic System are plotted on the Google satellite images. The distribution of snow on the Panjal ridge suggests a possibly fault control as variations are along the fault traces. **b** The topographic profile shows three major rivers in the region that have carved prominent V-shaped valleys, and these rivers cut through stratigraphy. The riding of Jhelum River across the structural grain of the region indicates a strong structural control. *MCT* main central thrust, *MBT* main boundary thrust, *MWT* Medlicott–Wadia thrust , *RF* Riasi fault and *MFT* main frontal thrust

oblique plate convergence is accommodated on regional thrust faults (MCT, MBT, and HFT), which primarily accommodate arc-normal convergence, and on the Karakoram fault system that accommodates the arc-parallel component (Kundu et al. 2014; Murphy et al.

2014). Our geomorphic analysis of tectonic landforms demonstrates a new series of tectonically active faults and some with a small component of sinistral motion along with thrusting, and these are located south of the Tunda fault (Figs. 2–9). This could suggest that the obliquity increases southwards. These faults terminate in Kashmir basin on east, and their ~NE–SW strike is oblique to the ~NW–SE strike of the regional structures, MCT, MBT, and MFT. Further west, these structures terminate at the junctions of the MBT or MCT fault systems. This indicates a strong structural control on their growth and perhaps propagation.

Further, an interesting relationship between snow distribution pattern and faulting of the Panjal ridge is visible (Fig. 1b). This may indicate the distribution is largely controlled by the movement on faults, particularly at Mughal Road fault where the snow distribution is largely asymmetrical. The distribution varies at Mawer, Tunda, and Gulmarg fault zones (Fig. 1b. It seems that the overall snow distribution is probably related to the movement on faults where elevations change because the thrusting and left-lateral strike–slip motion might have contributed to the temperature variations, and hence the snow distribution.

5.2 Active deformation in Udhampur piggyback basin

A number of new active faults are also mapped in Udhampur piggyback basin (Figs. 7, 8) where faults have cut through Holocene fluvial sediments (Gavillot 2014; Vassallo et al. 2015; Gavillot et al. 2016), and exposed older formations. The basin is located within the actively growing Riasi fault system, thereby suggesting splay faulting from the Mandili-Kishanpur thrust (MKT), a local name for the Riasi fault system, which is an actively growing (~200-km-long) segment of a regional fault system that extends and connects on west to Balakot–Bagh fault, on which deadly Mw 7.6 Muzaffarabad earthquake occurred in 2005 (Lavé and Avouac 2000). The strike of the mapped faults is curved, ~NE to ~NW, with potential fault plane dip direction also changing from ~NW to ~NE, and these faults are delineated on north-east by Tanhal thrust (TT), and to south-west by MKT (Figs. 7, 8). The beheading of streams is clearly visible where the length of the streams has been trimmed by faulting (Fig. 8d). The whole basin narrows down to north-west, and north-east, which coincides with the branching of the two major fault traces of the RF (Fig. 1). Importantly, the basin has a synclinal ridge (Gavillot et al. 2016) to the north-east where the two fault branches come closer forming an oval-shaped basin on map view (Figs. 7, 8). Together these interpretations suggest a strong structural control on the formation and deformation of the basin. The lack of such a basin to the immediate north-west and south-east of RF further reinforces this interpretation. Such basins do occur further south-east, the geometry, and morphology of those are also, possibly, controlled by faults at depth.

It is important to note that at first glance the mapped fault scarps look morphologically very similar to normal faults, and it seems the basin is collapsing along ~NW dipping fault planes. However, the geomorphology and topographic profile of the basin shows a series of prominent scarps that have vertically uplifted river terraces with obvious back tilting to ~NW. This suggest ~NW dipping fault plane, which can be only be explained by a thrust geometry, because normal faults with such a geometry cannot possibly form the observed geomorphology and fault scarp morphology of the basin (Fig. 8). The faults do run parallel to the bedding planes for a short distance (Figs. 7, 8), which may complicate their association with thrusting. However, the thrust geometry is more appropriate and explains the observed geomorphology and topography.

6 Conclusions

The active tectonic geomorphic landforms mapped during this study suggest distributed deformation pattern within NW Himalaya. The mapping of an array of four major ~NW–SE trending faults (Mawer, Tunda, Gulmarg, and Mughal Road) in the western portion of the Himalayan orogenic belt (Fig. 9) further suggests that the deformation is largely taken up by oblique thrusting. The abrupt termination of most of these faults in north-west perhaps indicates a strong structural control on their growth and possibly development. The faults are active and shall possibly pose series of seismic hazards similar or greater than what was witnessed during Kashmir earthquake of 2005.

Further, active deformation is reported within Udhampur Piggyback basin, which lies within the Riasi fault system in Jammu and Kashmir, NW Himalaya. The emergent thrusting further suggests splay faulting from one of the branches of the RF system (Mandili-Kishanpur thrust (MKT)). The structural configuration of the basin indicates a possible structural control on the formation and deformation of the basin. Since the bulk of the geomorphic features in Jammu and Kashmir region remains to be mapped, it is likely that new active faults might be discovered in future. The presence of new active faults pose potential problems to the regional deformation budget allocation along known structures in NW Himalaya (Shah 2016), which directly impacts the seismic hazards of the region.

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