

Earthquake geology of Kashmir Basin and its implications for future large earthquakes

A. A. Shah

Received: 14 September 2012 / Accepted: 9 February 2013 / Published online: 28 February 2013
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Abstract Two major traces of active thrust faults were identified in the Kashmir Basin (KB) using satellite images and by mapping active geomorphic features. The \sim N130°E strike of the mapped thrust faults is consistent with the regional \sim NE–SW convergence along the Indian–Eurasian collision zone. The \sim NE dipping thrust faults have uplifted the young alluvial fan surfaces at the SW side of the KB. This created a major tectono-geomorphic boundary along the entire strike length of the KB that is characterised by (1) a low relief with sediment-filled sluggish streams to the SE and (2) an uplifted region, with actively flowing streams to the SW. The overall tectono-geomorphic expression suggests that recent activity along these faults has tilted the entire Kashmir valley towards NE. Further, the Mw 7.6 earthquake, which struck Northern Pakistan and Kashmir on 8 October 2005, also suggests a similar strike and NE dipping fault plane, which could indicate that the KB fault is continuous over a distance of \sim 210 km and connects on the west with the Balakot Bagh fault. However, the geomorphic and the structural evidences of such a structure are not very apparent on the north-west, which thus suggest that it is not a contiguous structure with the Balakot Bagh fault. Therefore, it is more likely that the KB fault is an independent thrust, a possible ramp on the Main Himalayan Thrust, which has uplifting the SW portion of the KB and drowning everything to the NE (e.g. Madden et al. 2011). Furthermore, it seems very likely that the KB fault could be a right stepping segment of the Balakot Bagh fault, similar to Riasi Thrust, as proposed by Thakur et al. (2010). The earthquake magnitude is measured by estimating the fault rupture

parameters (e.g. Wells and Coppersmith in Bull Seismol Soc Am 84:974–1002, 1994). Therefore, the total strike length of the mapped KB fault is \sim 120 km and by assuming a dip of 29° (Avouac et al. in Earth Planet Sci Lett 249:514–528, 2006) and a down-dip limit of 20 km, a Mw of 7.6 is possible on this fault.

Keywords Kashmir Basin · Thrust fault · Geomorphic features · Active tectonics · Himalaya

Introduction

The Kashmir Basin (KB), \sim 790 km N of Delhi (India), is classified as one of the Neogene–Quaternary intermontane basins (Burbank and Johnson 1983) of the Himalayas. These basins occur at many places in the Himalaya and southern Tibet (Hodges 2000) and are divided into three major types. (1) The extensional basins, which are located just north of the Himalayan crest and are associated with \sim E striking South Tibetan fault system (Burchfiel et al. 1992). (2) These are related to the kinematically linked displacement on NW and NE-striking strike-slip faults and north-trending rift systems in southern Tibet (Molnar and Tapponnier 1978). (3) The ‘thrust top’ or ‘piggy-back’ basins, for example, the Kashmir Basin (Fig. 1). Such basins are located to the north of the Himalayan thrust front and south of the range crest (Burbank and Johnson 1982). The KB contains strata, which are equivalent in age and similar in lithology to the Upper Siwalik Group (Burbank and Johnson 1982). The basal part of the sequence is slightly older, perhaps 5 Ma, but much of that succession is of late Pliocene–Pleistocene age, with deposition continuing locally into the Holocene age (Burbank and Johnson 1983).

A. A. Shah (✉)
Earth Observatory of Singapore, Nanyang Technological
University, Singapore 639798, Singapore
e-mail: afroz.shah@gmail.com; afroz@ntu.edu.sg

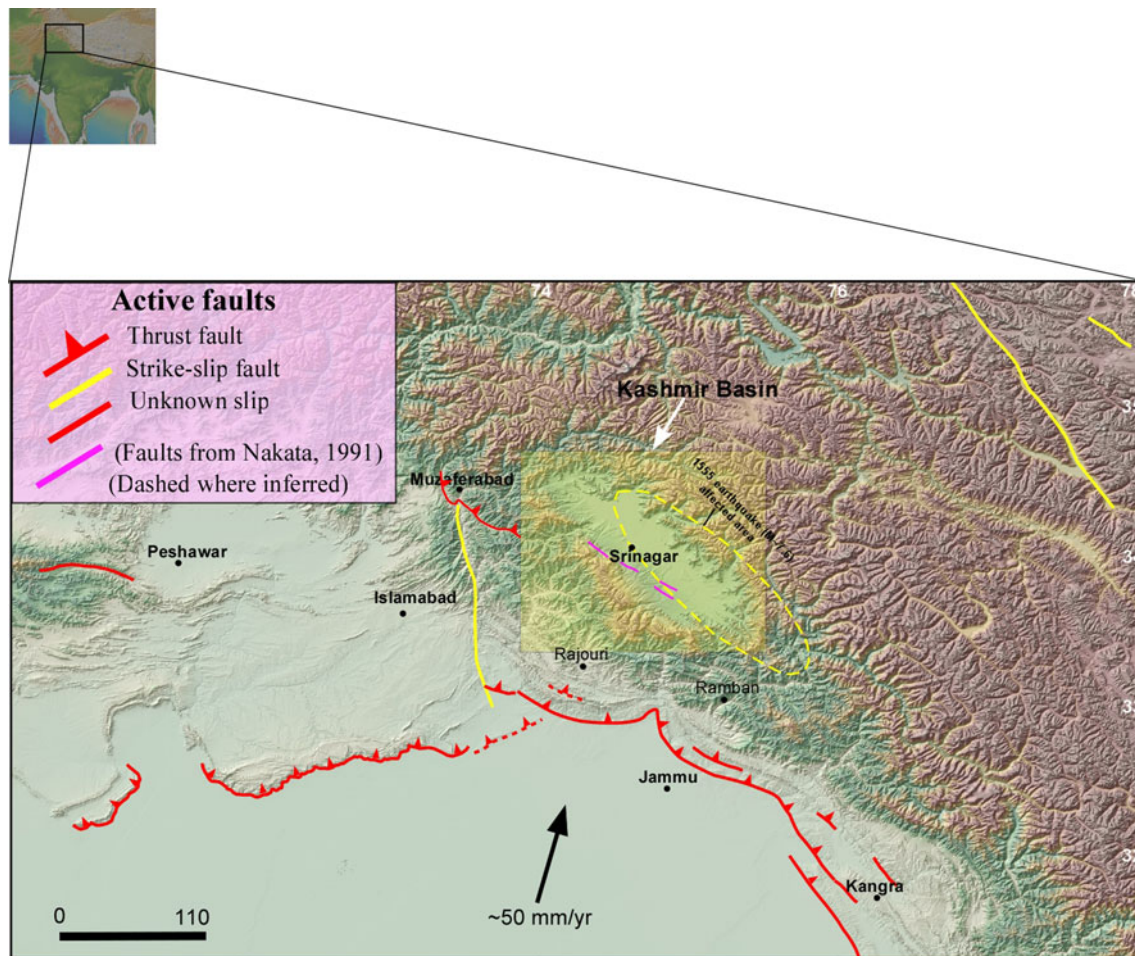


Fig. 1 Topographic map shows some of the major active faults around the Kashmir Basin, a few of these faults are mapped in detail (e.g. Nakata et al. 1991; Malik and Nakata 2003; Avouac et al. 2006;

Kumar et al. 2010; Valli et al. 2007, 2008; Malik et al. 2010a, b; Rajendran 2004 and references herein). The *arrow* shows the average motion of Indian plate relative to Eurasia (Bettinelli et al. 2006)

The strike length of the Kashmir Basin is ~ 150 km and is ~ 50 km across (Figs. 1 and 2). It is located on the western portion of the Himalayan orogenic system and is ~ 100 km away from the actively growing frontal part of the Himalaya. The bulk shortening along the central part of the orogenic system is mainly accommodated along the Himalayan Frontal Thrust (HFT) (e.g. Ader et al. 2012 as a latest reference). However, as revealed from satellite images, the convergent deformation along the NW Himalayas is not concentrated on the front and is distributed across the width (e.g. Nakata 1989, 1991; Kaneda et al. 2008; Madden et al. 2010, 2011).

Since the KB is one such regions in the NW Himalayas where deformation is distributed away from the front (e.g. Nakata 1989, 1991; Kaneda et al. 2008; Madden et al. 2010, 2011), therefore, in this work, the active geomorphic elements of such distributed deformation are mapped. This is achieved by using a variety of freely available satellite

data, which include Shuttle Radar Topography Mission (SRTM), Google maps and Global Multi-Resolution Topography (GMRT).

Regional tectonics

The $\sim 2,000$ -km-long Himalayan orogenic system was formed due to continent–continent collision between the Indian and Eurasian plates, which started in the Eocene (Yin and Harrison 2000; Leech et al. 2005; Guillot et al. 2008) and continues till today. The Kashmir Valley is included on the western side of this long orogenic belt (Figs. 1 and 2). The regional geological and tectonic setting of the Himalaya has been discussed in a number of previous works (e.g. Yin 2006 as one of the best reviews).

The present-day deformation of the Himalayan orogenic system is measured by a system of dense global positioning

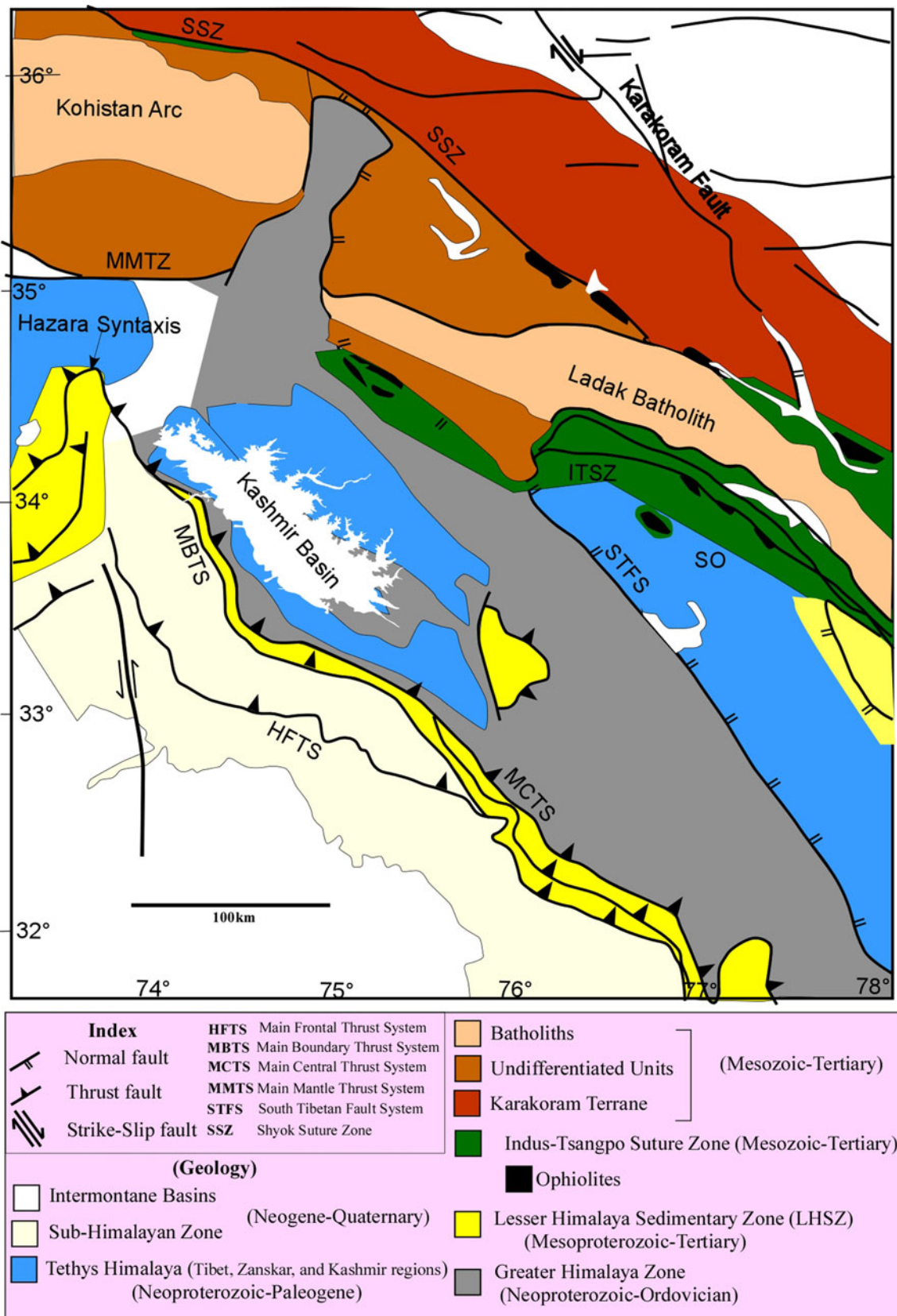


Fig. 2 Tectonic map of a portion of NW Himalayas (modified after Hodges 2000)

system (GPS) networks, which suggest that approximately one-half (~ 20 mm/year) of the convergence between the Indian and Eurasian plates may be accommodated through crustal shortening in the Himalayan fold thrust belt (e.g. DeMets et al. 1994; Bilham et al. 1997; Larson et al. 1999; Lave and Avouac 2000; Malaimani et al. 2000; Mugnier et al. 2003; Sridevi Jade et al. 2011). This developed a series of S-vergent thrusts and the deformation has progressively shifted towards S (Powell and Conaghan 1973; LeFort 1975; Mattauer 1986; Hauck et al. 1998; Hodges 2000; DeCelles et al. 2002; Murphy and Yin 2003; Yin 2006).

Active deformation of the Kashmir Basin

The ongoing deformation in the KB is reflected in its seismicity, geology, topography and geomorphology (Figs. 1, 2, 3, 4, 5). The earthquake data reflect the diffuse nature of seismicity within the KB (see below) when compared with regions at its E and W (Fig. 3). The bedrock is of Neogene-Quaternary deposits and is surrounded by the Neoproterozoic-Paleogene rocks of the Tethyan Himalayas (e.g. Hodges 2000; Fig. 2).

Seismicity

The seismicity data from the National Earthquake Information Centre (NEIC) suggest that most of the earthquakes are shallow (0–40 km) within and around the KB (Fig. 3) and the overall distribution is uneven, with more concentrated patches along the Hazara Syntaxis and on the eastern side of the KB.

The earthquakes within the KB are very diffuse and are potentially limited to a depth of ~ 40 km (Fig. 3b). Thus, by using the Centroid Moment Tensor (CMT) solutions, the principles of which are presented in Ekström et al. (2005), earthquakes can be assigned to a particular fault system. However, the CMT solutions of the earthquakes in KB are not possible, because these are with $M_b < 5$. Nevertheless, the available regional CMT solutions in and around the KB show predominantly thrust mechanisms (Fig. 3a). These suggest a \sim NW–SE striking fault that can have either a NE or a SW dip (Fig. 3a). However, the locations and depths of these earthquakes could be mislocated by tens of kilometres. Thus, a dense local seismic network will be required to more accurately determine the locations of such small earthquakes and to determine whether they can be attributed to local faults. Further, the seismicity related to the 2005 earthquake appears to stop abruptly at the Kashmir Basin, suggesting a segment boundary.

Tectonic geomorphology

Fold and thrust mountains surround the oval-shaped KB, which stretches \sim NW–SE (Fig. 1). A quick look at the regional topography suggests that the regions on the NE of the valley are drowned, while those on the SW are uplifted (Fig. 4). A detailed geomorphic investigation during this study revealed some compelling evidences, which demonstrate that there are broadly three main traces of active faults within the valley (Fig. 4). The geomorphic expression of these faults vary along the strike, where it mostly crops out as discontinuous traces and pierces through some of the young deposits, which are ~ 50 – 100 ka old (e.g. Jaiswal et al. 2009; Meigs et al. 2010; Madden et al. 2011); for example, Fig. 5a, b shows a \sim NW–SE trending thrust fault on the western portion of the thrust system, which cuts alluvial fan surfaces and forms active SW facing scarps, some of which are >100 m high and also show back tilting (Fig. 5b).

The regional topography also suggests a greater uplift and tilt of the footwall of the south-western fault than that of fans in the centre of the KB that are on the hanging wall of the faults, which indicates there must be deformation occurring SW of the fault system too; however, this is beyond the scope of the present work and thus it will be investigated in the future.

Results and interpretations

Two major traces of active thrust faults are mapped in the south-west KB using the classical active fault mapping techniques (e.g. mapping of active geomorphic features or indicators, which includes mapping of the young river terraces, alluvial fan surfaces and topographic breaks). All of the faults trend \sim NW–SE and preserve geomorphic evidences of recent activity, wherein they cut across the ~ 50 – 100 ka old deposits (e.g. Jaiswal et al. 2009; Meigs et al. 2010; Madden et al. 2011). For example, a young fan surface has an apparent uplift of ~ 100 m along one of the traces and also shows back tilting (Figs. 5a, b). There is a slight indication of an oblique motion along some of these traces. However, with the present resolution of the imagery, it is hard to estimate the slip. These faults dip towards NE and uplift the young deposits on the SW of the basin thereby drowning everything to the NE portion of the basin (Figs. 4 and 5).

The geomorphic expression of the Kashmir Valley is modified due to these faults and has therefore roughly divide the valley into two major tectono-geomorphic terranes. These are: (1) north-eastern terrane (NET) and (2) south-western terrane (SWT) (Fig. 4b). The former is a low-relief area, with sediment-filled sluggish streams.

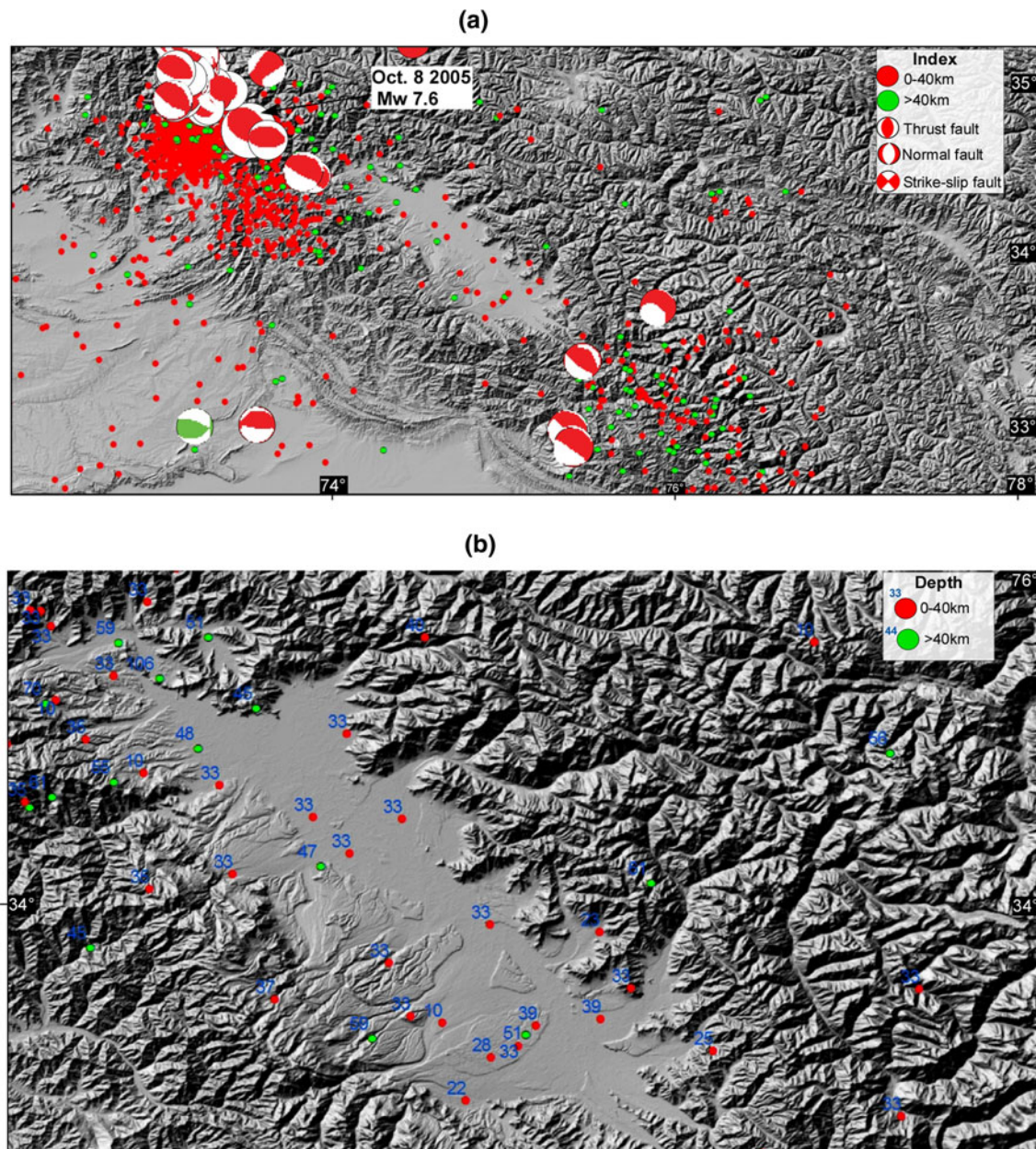


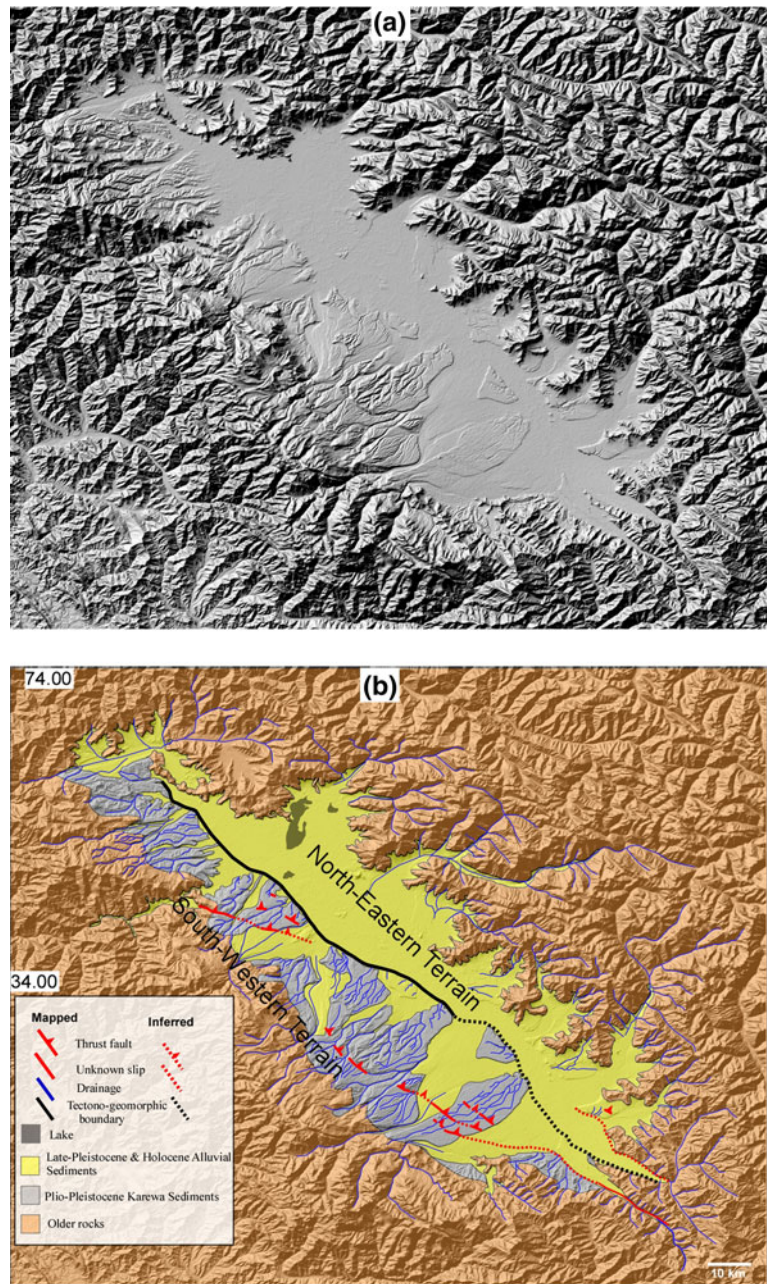
Fig. 3 **a** The seismicity data (NEIC, 1973–2012 and CMT catalogue, 1976–2012) plotted on the SRTM topographic image of the Kashmir Basin (KB) and its adjacent regions. **b** Shows the enlarged view of the KB and the NEIC earthquakes with annotated depth in blue

The latter is an uplifted region, with actively flowing streams (Figs. 3 and 4b). This suggests that the south-west side of the valley is climbing a ramp on the Main Himalayan Thrust (MHT), uplifting the SW side and drowning everything to the NE (e.g. Madden et al. 2011). Further, the fault scarps are prominent on the eastern half of the SWT and die-out towards the western half, which suggests that the convergence rates measured by the GPS networks in this area should be higher on the SE.

Discussion and conclusion

The ongoing collision deformation along the ~2,000-km-long Himalayan orogenic belt is distributed differently along the central and western portions of the belt. For example, the bulk shortening along the central part is mainly accommodated along the Himalayan Frontal Thrust (HFT) system (e.g. Nakata 1989; Wesnousky et al. 1999; Lave and Avouac 2000; Malik and Nakata 2003; Ader et al. 2012). In contrast, along the NW Himalayas, the

Fig. 4 Evidence for active thrust faults in the Kashmir Basin. Uninterpreted topography is on the *top*. Mapped active faults and bedrock are on the *bottom* (freely available 90-m-resolution SRTM data used)

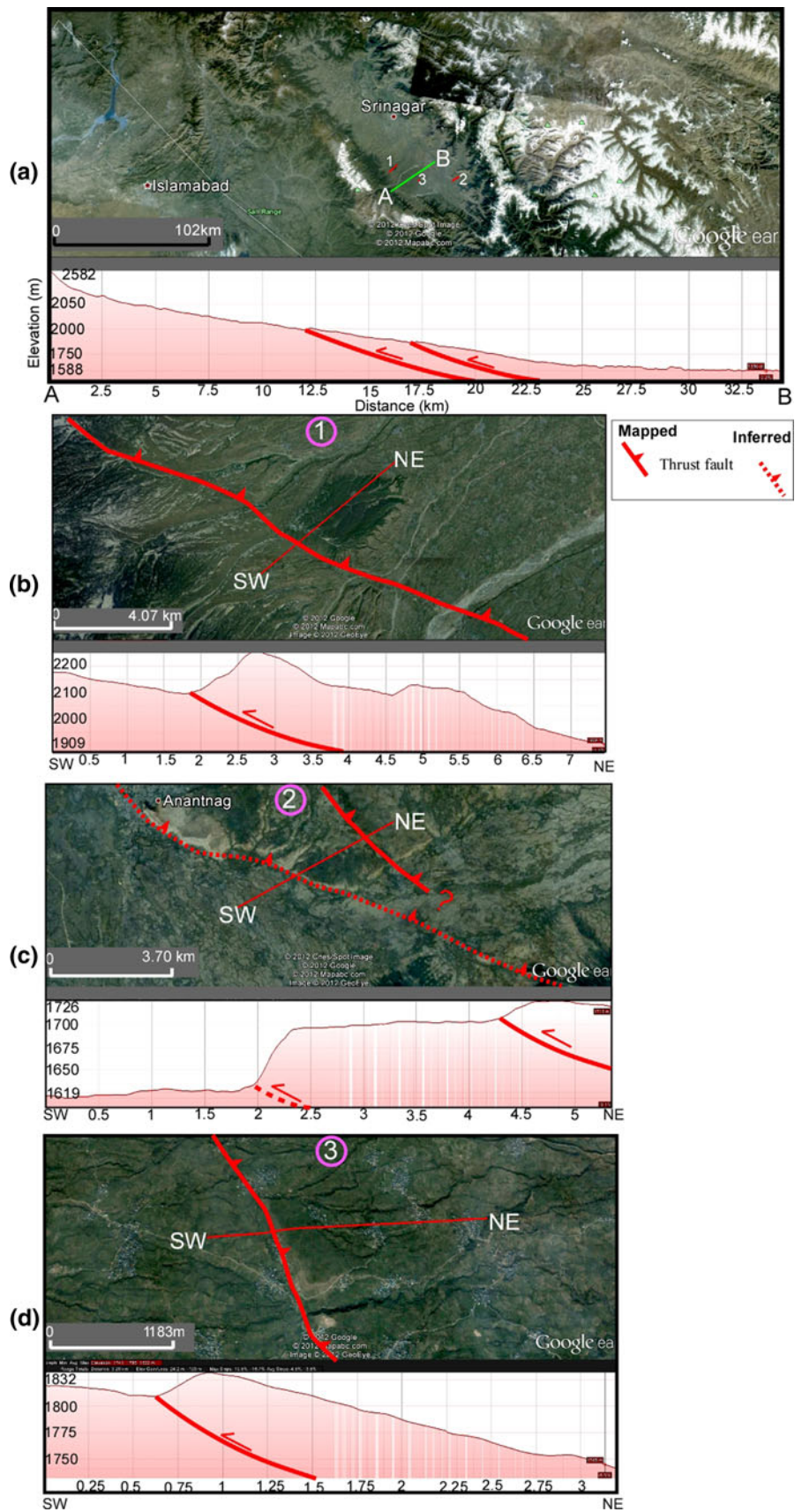


convergent deformation is not concentrated on the front and is distributed across the width of the belt (e.g. Meigs et al. 2010, Kaneda et al. 2008). Distributed deformation is also supported by the active geomorphic observations within the Kashmir Basin (e.g. Nakata et al. 1991; Madden et al. 2010, 2011 and this study).

The $\sim N130^{\circ}E$ strike of the mapped thrust faults is consistent with the regional $\sim NE-SW$ convergence along the collision zone (Figs. 1 and 6). This is also backed by the regional CMT solutions around the KB, which suggest recent activity on similar faults (Fig. 3). The Mw 7.6 earthquake,

which struck Northern Pakistan and Kashmir on 8 October 2005, also suggests a similar north-east-dipping fault plane striking $N133^{\circ}E$ with a rake of 123° and a dip angle of 40° (<http://www.seismology.hawaii.edu/CMTsearch>). These similarities could suggest that the fault trace is continuous over a distance of ~ 210 km and connects on the west with the Balakot Bagh fault. However, the geomorphic expression of such a fault is not clear on the north-west, neither are there any evidence(s) of structural or topographic breaks, which could suggest that it is a contiguous structure. Therefore, it is more likely that the Kashmir Basin

Fig. 5 3D Google images show the location of topographic profiles and associated profiles on some of the mapped fault scarps shows on Fig. 3 above. **a** A topographic profile on the fault scarps along the eastern side of the Kashmir Basin **b** A fault *vertically* displaces a fluvial surface up to ~100 m and is tilted to NE. **c** shows two young fault scarps, one of which is not well preserved and is displaced ~100 m and the other one is ~26 m high. **d** The fault displaces a young fluvial surface up to ~30 m creating a scarp, which is tilted to NE



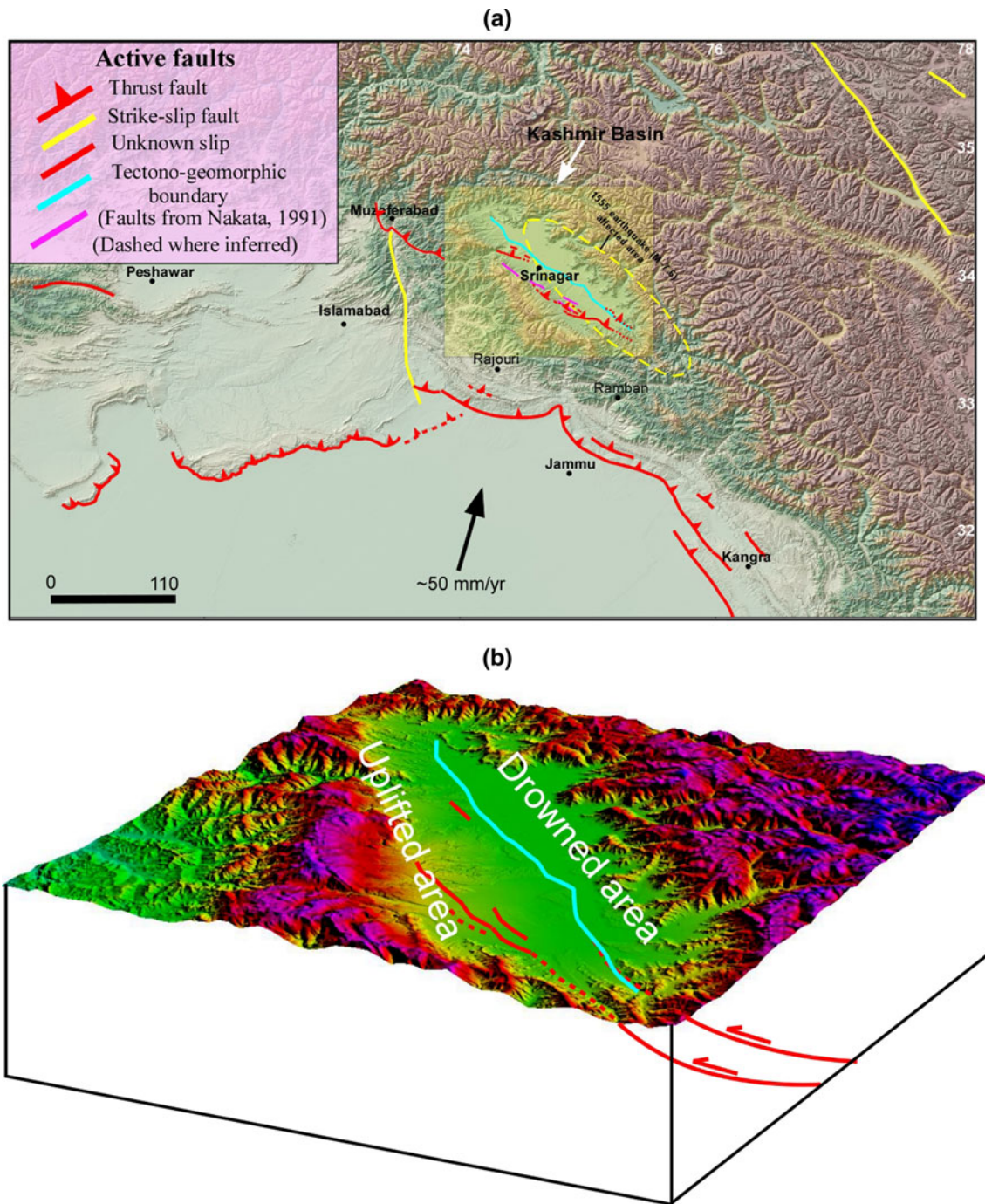


Fig. 6 **a** STRM image shows the Kashmir Basin and its tectonic geomorphology. **b** The active thrust faults have uplifted \sim half of the valley and drowned the other half

fault is an independent thrust, a possible ramp on the MHT, which has uplifting the SW portion of the KB and drowning everything to the NE (e.g. Madden et al. 2011).

Furthermore, Thakur et al. (2010) have argued that rather than extending into the Kashmir Basin, the Balakot Bagh fault steps right and continues as the active Riasi

Thrust based on the juxtaposition of similar bedrock along both faults. As discussed above, there is a clear geomorphic evidence of active thrusting in the Kashmir basin and fault stepping is also a possibility. In this scenario, the Balakot Bagh fault steps right and continues as KB fault (some portion of which is named as Balapur fault, e.g., Madden

et al. 2011 and Shabir and Bhat (2012)). Therefore, it suggests the Balakot Bagh could continue on the east as the Riasi Thrust and the Kashmi Basin fault.

How big an earthquake could hit the Kashmir Basin

The future earthquake potential of a fault is commonly evaluated from the estimates of fault rupture parameters that are in turn related to earthquake magnitude (e.g. Wells and Coppersmith 1994). Therefore, using the strike length of the mapped fault, which is ~ 80 km, plus the length from the inferred portion, which is ~ 40 km, the total strike length of the fault would be ~ 120 km. Further, by assuming a dip of 29° (Avouac et al. 2006) and a down-dip limit of 20 km, a M_w of 7.6 is possible on this fault.

Further, a historical record of 13 earthquakes in the valley over the last millennium, which includes the damaging earthquakes of 1555 and 1885, indicates that the Kashmir Valley is a locus of active deformation (e.g. Madden et al. 2011). Therefore, the active geomorphic evidences presented here suggest that these historical events must have ruptured the surface, which are now preserved as active fault scarps (Fig. 4). Therefore, the ongoing paleoseismic work (e.g. Madden et al. 2011) and the proposed investigations will further unravel the earthquake chronology of the KB. This will be an extremely useful step towards the hazard mitigation of the region.

Acknowledgments This study has benefited from discussions with Prof. K. Sieh and P. Tapponnier (Earth Observatory of Singapore). I am thankful to Prof. J. N. Malik (IIT Kanpur) and B.A. Shah (IIT Kharagpur) for insightful inputs. I am very thankful to Chris Maden and two anonymous reviewers for helpful suggestions, which greatly improved the contents of this contribution. I am also thankful to Dr. Soumyajit Mukherjee (IIT Bombay), who did the topic editorial handling and his comments and suggestions greatly improved the contents of the manuscript. Chief Editorial handling: Christian Dullo (IFM GeoMar), managing editorial handling: Monika Dullo.

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