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ORIGINAL ARTICLE

Geological setting of the 8 October 2005 Kashmir earthquake

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Abstract The source of the 8 October 2005 earthquake of *M* 7.6 was the northwest-striking Balakot–Bagh (B–B) fault, which had been mapped by the Geological Survey of Pakistan prior to the earthquake but had not been recognized as active except for a 16-km section near Muzaffarabad. The fault follows the Indus–Kohistan Seismic Zone (IKSZ); both cut across and locally offset the Hazara–Kashmir Syntaxis defined by the Main Boundary and Panjal thrusts. The fault has no expression in facies of the Miocene–Pleistocene Siwalik Group but does offset late Pleistocene terrace surfaces in Pakistan-administered Jammu-Kashmir. Two en-échelon anticlines near Muzaffarabad and Balakot expose Precambrian Muzaffarabad Limestone and are cut by the B–B fault on their southwest sides, suggesting that folding and exposure of Precambrian rocks by erosion accompanied Quaternary displacement along the fault. The B–B fault has reverse separation, northeast side up; uplift of the northeast side accompanied displacement, producing higher topography and steeper stream gradients northeast of the fault. No surface expression of the B–B fault has been found northwest of the syntaxis, although the IKSZ and steeper stream gradients continue at least as far as the Indus River, the site of the Pattan earthquake of *M* 6.2 in 1974. To the southeast, northwest-striking faults were mapped by the Geological Survey of Pakistan. One of these faults, the Riasi thrust, cuts across the southwest flank of an anticline exposing Precambrian limestone. Farther southeast, in Indian-administered territory, Holocene activity on the Riasi thrust has been described. In the Kangra reentrant still farther southeast, active faulting may follow the Soan thrust, along which Holocene and Pleistocene offsets have been described. The Soan thrust, rather than the south flank of the Janauri anticline, may represent the surface projection of the 1905 Kangra earthquake of *M* 7.8.

Keywords 2005 Kashmir earthquake · Balakot-Bagh fault · Riasi thrust · Indus-Kohistan Seismic Zone · 1905 Kangra earthquake

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1 Introductory statement

A massive earthquake of M=7.6 (US Geological Survey) struck northern Pakistan and adjacent India on 8 October, 2005, with its epicenter at 34° 29' 35" N, 73° 37' 44" E. The epicenter was approximately 19 km northeast of Muzaffarabad and 95 km north–northeast of Islamabad, Pakistan. Heavy damage was sustained in Pakistani-administered Jammu-Kashmir and the North–West Frontier Province and in adjacent parts of Indian-administered Jammu-Kashmir. The official death toll was 86,000.

This was the largest historical earthquake on the Indus–Kohistan Seismic Zone (IKSZ) of Armbruster et al. (1978) and Seeber and Armbruster (1979). It was the first Himalayan earthquake to be accompanied by surface rupture, reactivating the Balakot–Bagh (B–B) reverse fault (Fig. 1) and, locally, offsetting the Main Boundary thrust (MBT). A field investigation by Yeats et al. (2006), Kumahara and Nakata (2006) and Kaneda et al. (2008) revealed a surface rupture 70 km long, with up to 7-m vertical separation, mostly along the preexisting B–B fault. The B–B fault dips northeast. Near Muzaffarabad, the fault separates Precambrian limestone and shale on the northeast from Miocene Murree Formation on the southwest; farther southeast, the fault is entirely within the Murree Formation or forms the contact between the Murree and Kamlial formations (Fig. 2). Large landslides and structural damage were concentrated close to the fault on its hanging-wall side. Northwest of the end of the surface rupture, heavy damage was sustained northwest to the Indus River, site of the 1974 Pattan earthquake of M 6.2 (Fig. 1).

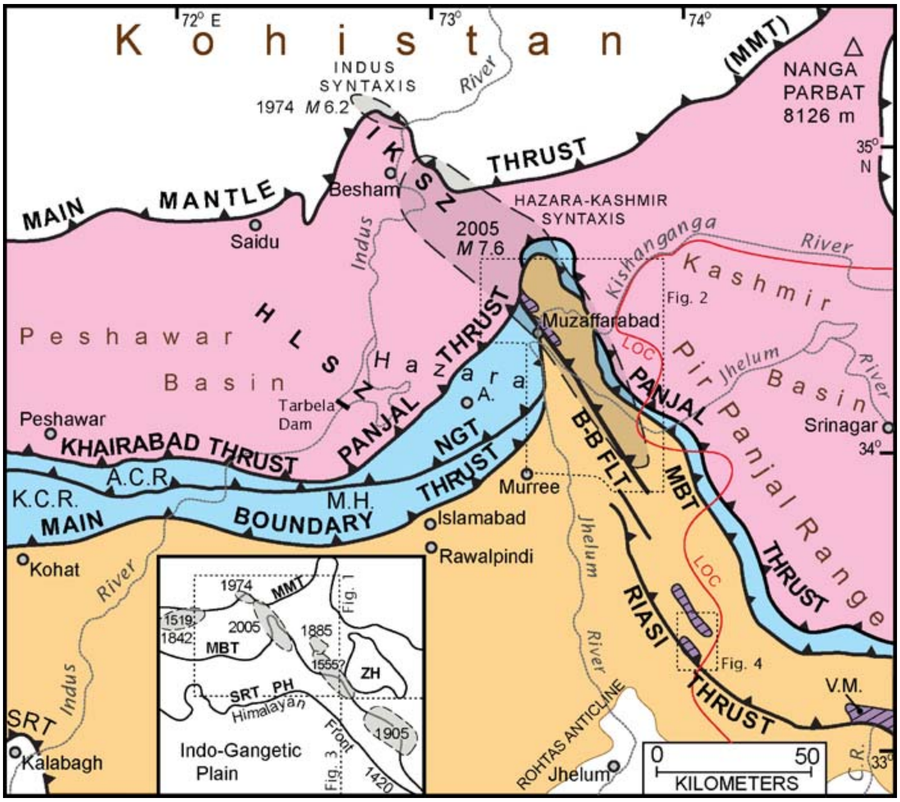

Fig. 1 Regional map of the northwest Himalaya showing major tectonic units, large historical earthquakes (*dashed*, *shaded ovals* with dates), the Indus–Kohistan Seismic Zone, Hazara Lower Seismic Zone, and possible active fault extensions of the Balakot–Bagh fault to the southeast, including the Riasi thrust. *Diagonal-lined pattern*: Paleocene and Precambrian limestone reentrants in the Sub-Himalaya. *A*, Abbottabad; *B–B FLT*, Balakot–Bagh fault; *ACR*, Attock–Cherat Range; *CR*, Chenab River; *HFT*, Himalayan Front thrust; *IKSZ*, Indus–Kohistan Seismic Zone; *HLSZ*, Hazara Lower Seismic Zone; *KCR*, Kala Chitta Range; *MBT*, Main Boundary thrust; *MH*, Margalla Hills; *MMT*, Main Mantle thrust; *NGT*, Nathia Gali thrust; *PH*, Pabbi Hills; *SRT*, Salt Range thrust; *VM*, Vaishnodevi Mountains; *ZH*, Zanskar Himalaya; 1420 locates possible earthquake on the HFT for which only paleoseismic evidence is known; *LOC*, Line of Control between India and Pakistan

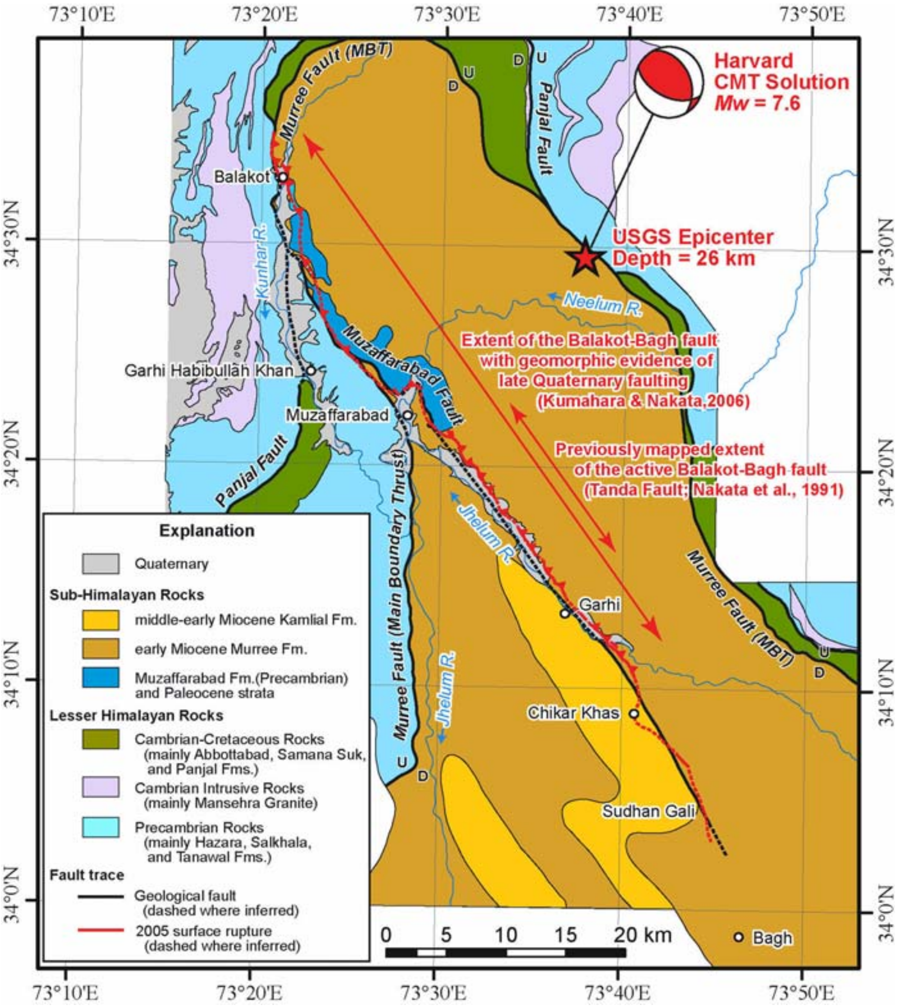

Fig. 2 The Balakot–Bagh fault in the Hazara–Kashmir Syntaxis, from Kaneda et al. (2008). The Main Boundary (Murree) and Panjal thrusts are deflected at the B–B fault due to uplift of the northeast, hanging-wall side, or, less likely, left slip on the B–B fault, or both. The Jhelum River follows the footwall of the B–B fault and turns abruptly south at the MBT. The Neelum River cuts across an anticline underlain by Precambrian and Paleocene strata and may be antecedent to anticlinal growth. Southeast of Muzaffarabad, the B–B fault juxtaposes Murree Formation on the northeast against Kamlial Formation on the southwest

Parsons et al. (2006) showed increased stresses in this region northwest of Balakot as well as to the southeast into Indian-administered Jammu-Kashmir, the location of a possible seismic gap between the 2005 earthquake and the Kangra earthquake of *M* 7.8 in 1905 (Wallace et al. 2005), a gap that might have been previously filled by an earthquake of *M* 7.6 in 1555 (Bendick et al. 2007).

Here, we show that the surface rupture struck an existing active fault that could have been characterized as active but, except for a 16-km section of the fault near Muzaffarabad (Tanda fault of Nakata et al. 1991), was not. The B–B fault offsets mapped geological formations and the MBT. In addition, it is expressed in tectonic geomorphology and as higher ground northeast of the fault. The presence of higher terrain northeast of a zone of active seismicity in India and Nepal indicates that an analogous continuation of the higher topography in India and Nepal is controlled by active faulting, north side up, and not by the Main Central thrust (MCT), which in India and Nepal is at the surface above the seismic zone. The active Indus Syntaxis occurs close to the Indus River, west of which the seismicity trend is more westerly, is more diffuse, and may include an earthquake of *M* 7.6 on 19 February 1842 in eastern Afghanistan (Ambraseys and Bilham 2003; Ambraseys and Douglas 2004; Fig. 1).

2 Tectonics of the Himalaya

The Himalaya of India and Nepal is subdivided into several large thrust plates (Fig. 3): the largely crystalline High Himalaya with the MCT at its base, the Lesser Himalaya, largely metasedimentary and

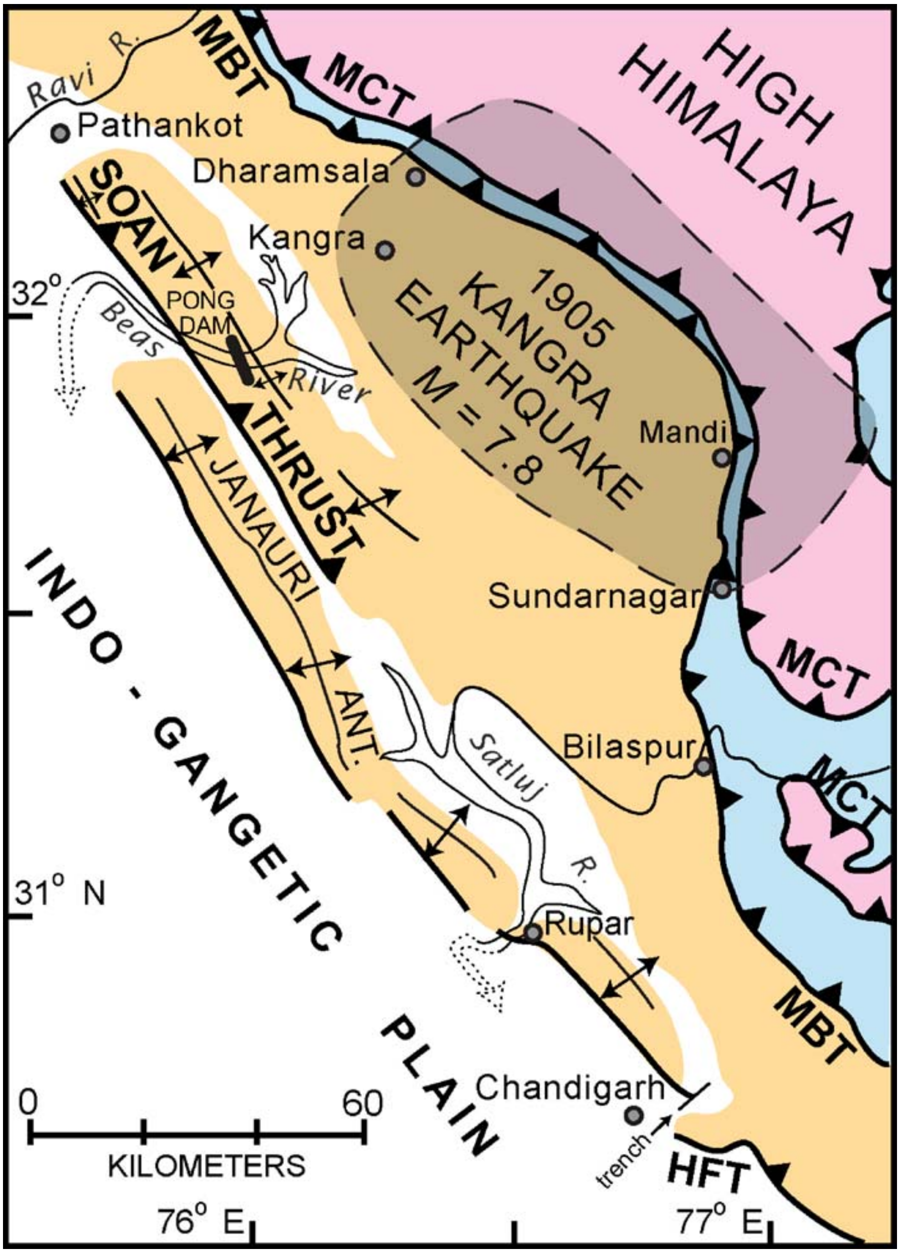

Fig. 3 Kangra reentrant in northwest India, showing the meizoseismal zone of the 1905 Kangra earthquake from Wallace et al. (2005) and a possible surface expression of the source fault at the Soan (Satlitta) thrust rather than the Himalayan Front thrust (*HFT*). *MBT*, Main Boundary thrust; *MCT*, Main Central thrust. Clear areas undelain by Quaternary alluvial deposits. Teeth toward hanging wall of thrusts; solid teeth mark potentially active faults. Paleoseismic excavation near Chandigarh with evidence for a surface rupture around AD 1420 (Kumar et al. 2006) Modified from Yeats et al. (1992)

sedimentary rocks of Precambrian to Tertiary age with the MBT at its base, the Sub-Himalaya, nonmarine clastic strata dominated by the Murree (Dharamsala) Formation and overlying Siwalik Group, with the active Himalayan Front thrust at the base, and a set of newly recognized active faults in the Indo-Gangetic Plain south of the Himalayan range front (Yeats and Thakur in press). The High Himalaya is overlain by and in fault contact with a Paleozoic sequence with Tethyan affinity; the bounding fault is called the South Tibetan detachment or the Trans-Himadri fault of Valdiya (1989). Both the Tethyan sequence and, locally, the High Himalayan sequence are truncated on the north by the Indus–Tsangpo suture zone containing ophiolite and ultramafic rocks, marking the original boundary of the India–Eurasia collision.

A zone of moderate seismicity about 50 km wide characterizes the Himalaya of Nepal and northwest India just south of the surface trace of the MCT (Ni and Barazangi 1984; Baranowski et al. 1984), with most fault plane solutions delineating a fault plane dipping moderately north. This zone includes two damaging, moderate-size earthquakes in northwest India: the 19 October 1991 M 7 Uttarkashi earthquake and 29 March 1999 M 6.8 Chamoli earthquake. Active faulting occurs locally along the traces of the MBT and MCT in Nepal (Nakata 1989) and in northwest India (Oatney et al. 2001; Thakur and Pandey 2004), although the sense of displacement differs from that of the original thrusts: either strike slip or north-side-down.

Around the Kangra reentrant in northwest India (Fig. 3), the MCT and MBT are within a few hundred meters of each other so that rocks of the Lesser Himalaya are nearly cut out. Here, the MCT is called the Panjal thrust. Except for a large tectonic window in the Zanskar Himalaya (inset to Fig. 1), the High Himalayan crystalline rocks are not exposed, and Tethyan metasediments and metavolcanics, including the Panjal Traps, extend to the Panjal thrust (Thakur 1992, 1998).

3 Tectonics of the Himalaya in Pakistan

The thin, locally discontinuous Lesser Himalayan sequence continues to Indian- and Pakistani-administered Jammu-Kashmir (DiPietro and Pogue 2004; Fig. 1), where the major thrusts bend sharply from northwest to south in the Hazara–Kashmir Syntaxis (HKS) of Wadia (1931). The MBT was mapped previously by Calkins et al. (1975) as the Murree thrust. West of Muzaffarabad, the two thrusts diverge such that a thicker Lesser Himalayan sequence is present across Hazara (Calkins et al. 1975) and in the Attock–Cherat Range south of Peshawar (Yeats and Hussain 1987; Fig. 1). North of the syntaxis, the western continuation of the Indus–Tsangpo suture zone marking the India–Eurasia boundary is called the Main Mantle thrust, or MMT, which extends westward across the projection of the HKS and is not folded. However, the MMT is bowed northward at the Indus River in the Indus Syntaxis (DiPietro et al. 1999; DiPietro and Pogue 2004), evidence that it might still be active there (Fig. 1).

North of the Panjal thrust (Khairabad thrust in the Attock–Cherat Range; MCT of the central Himalaya), Precambrian metasediments, including the Salkhala Formation, Gandaf Formation, Manki Slate, and Tanawal Quartzite, are overlain by a Tethyan Paleozoic and Mesozoic sequence (Pogue et al. 1992) that is metamorphosed north of the Peshawar Basin (DiPietro 1991; Hussain et al. 2004a). These rocks are intruded by plutons of several ages, including the Mansehra Granite and Swat Gneiss, largely of Cambrian age, and the late Paleozoic Ambela alkaline complex (DiPietro et al. 1999; Hussain et al. 2004a, b).

South of the Panjal thrust, the Lesser Himalaya comprises two thrust-bounded successions, juxtaposed across the Nathia Gali thrust (Fig. 1). The northern sequence is dominantly Hazara Slate, which is Precambrian based on the evidence of slate fragments in a boulder bed at the base of the overlying Abbottabad Group. The Abbottabad Group, including limestone and shale, is at least in part Cambrian based on fossils found in the Hazira Shale (Latif 1974). In the Attock–Cherat Range, a thrust-bounded sequence of limestone and quartzite south of the continuation of the Hazara Slate (Yeats and Hussain 1987) lacks fossils and is probably Precambrian. In Hazara, the Abbottabad Group is overlain by a Jurassic and Cretaceous sequence that is correlated to formations of that age south of the Nathia Gali thrust in the Margalla Hills (Fig. 1) and Kala Chitta Range (Fig. 1), where they comprise a fold-thrust belt of Mesozoic and early Tertiary strata that extends to the MBT. The similarity of the Paleocene successions in these thrust-bounded blocks in the Attock–Cherat Range indicates that they were juxtaposed in latest Cretaceous–earliest Tertiary time (Yeats and Hussain 1987).

South of the MBT in Pakistan, the Sub-Himalaya reaches its greatest breadth in the entire Himalaya. Clastic deposits of the Miocene Murree Formation and overlying Siwalik Group of Miocene–Pleistocene age (Burbank and Raynolds 1984) underlie the Potwar Plateau, an oil-producing region that has been described based on surface and subsurface data. At the southern edge rises the Salt Range, in which Eocambrian evaporites of the Salt Range Formation are overlain by Cambrian, Permian, and Mesozoic strata with affinities to Gondwanaland (Gee 1989). Similar strata are found to the south in the subsurface of the Indo-Gangetic Plains and to the north in the subsurface of the Potwar Plateau (Yeats and Lawrence 1984; Lillie et al. 1987; Pennock et al. 1989).

The MBT initiated about 2.1 Ma, based on relations within the Siwalik Group (Burbank and

Raynolds 1984). During the Pleistocene, the Salt Range was thrust southward over the floodplain of the Jhelum River along the Salt Range thrust (Fig. 1), the local name for the Himalayan Front thrust (Yeats et al. 1984). The subsurface relations suggest that this thrust is a décollement in which the Phanerozoic section overrides the basement on Eocambrian salt (Jaumé and Lillie 1988). In addition to translation, the Siwalik Group of the Salt Range was rotated counterclockwise (Opdyke et al. 1982).

Most of the strata within the HKS are Murree Formation, including redbeds north of Muzaffarabad that have developed slaty cleavage (Bossart et al. 1988), indicating deep burial. South of Muzaffarabad, the Murree is overlain by the Kamlial Formation (Fig. 2) and, farther south, by younger formations of the Siwalik Group. Near Muzaffarabad and extending north to Balakot and south to Kotli (Fig. 1), the Murree is underlain by marine Paleocene strata and by the Muzaffarabad Limestone of Precambrian age (Calkins et al. 2004; Iqbal et al. 2004). The Muzaffarabad Limestone does not correlate with the Abbottabad Group west of the MBT.

4 Balakot–Bagh fault and possible correlatives to the southeast

The presence of a northwest-trending tectonic feature cutting across the HKS was first documented by Armbruster et al. (1978) from a local seismic network centered on Tarbela Dam based on an alignment of epicenters in 1973–1974 extending from the Jhelum River within the HKS northwest to the Indus River, where the damaging Pattan earthquake (Pennington 1979) struck in 1974. This was named the IKSZ, which they considered to be a possible extension of the Riasi thrust to the southeast. The local network analysis was extended to 1977 by Seeber and Armbruster (1979), who identified a second, weaker seismic zone, the Hazara Lower Seismic Zone (HLSZ), parallel to the first zone and extending through Tarbela Dam. Active seismicity in both of these zones has continued to the present (MonaLisa et al. in press). Seeber and Gornitz (1983) connected the IKSZ with the band of moderate seismicity extending through the Himalaya farther east and observed a relation between the band of seismicity and relatively high gradients of longitudinal profiles of rivers crossing it. The HLSZ is also marked by a topographic gradient: the northeastern edge of the Peshawar Basin.

The first recognition of active faulting along the IKSZ was by Nakata et al. (1991), who found a vertical dislocation of Pleistocene fan surfaces at the foot of the Muzaffarabad anticlinal ridge. This fault was named the Tanda fault and mapped for a distance of about 16 km (Fig. 2). The Geological Survey of Pakistan (GSP) mapped a set of quadrangles that included northwest–southeast-striking faults close to the IKSZ (Akhtar et al. 2004; Anwar et al. 2004; Calkins et al. 2004; Hussain et al. 2004b; Iqbal et al. 2004; Mughal et al. 2004; Hussain and Yeats 2006) that were not at that time recognized as active but were later shown to be reactivated during the 2005 earthquake by Kumahara and Nakata (2006), Avouac et al. (2006), and Kaneda et al. (2008; Fig. 2). Evidence for faulting included juxtaposition in two en-échelon anticlines of the Precambrian Muzaffarabad Limestone against Murree Formation on the southwest and juxtaposition of Murree Formation against Kamlial Formation farther southeast (Fig. 2). Immediately after the earthquake, GSP field parties recognized the correspondence of massive damage and landsliding to these faults, and Hussain and Yeats (2006) named the fault the Balakot–Bagh fault based on the proximity of both heavily damaged towns to the fault trace and to the discovery shortly after the earthquake of surface rupture by Baig (2006). The 2005 surface rupture followed this mapped fault (Balakot–Garhi fault of Kumahara and Nakata 2006) south of the Jhelum River but not as far as the southeast end of the fault trace near Sudhan Gali (Fig. 2; Kaneda et al. 2008).

Farther southeast, additional faults were mapped by GSP as stepped to the right from the Balakot–Bagh fault based on similar criteria. East of Kotli, two anticlines of Muzaffarabad Limestone overlain by Paleocene marine strata have the same relations to faulting as those in the Muzaffarabad anticline at Muzaffarabad (Figs. 1, 4). The southwestern anticline is bounded by a reverse fault on its southwest side, southwest of which the Murree is juxtaposed against the Dhok Pathan Formation of the Siwalik Group on the Riasi thrust (Fig. 4; Hussain et al. 2004b). A narrow sliver of Precambrian Hazara Formation is found along this fault (Fig. 4; Hussain et al. 2004b). South of these anticlines (and south of Fig. 4), S.

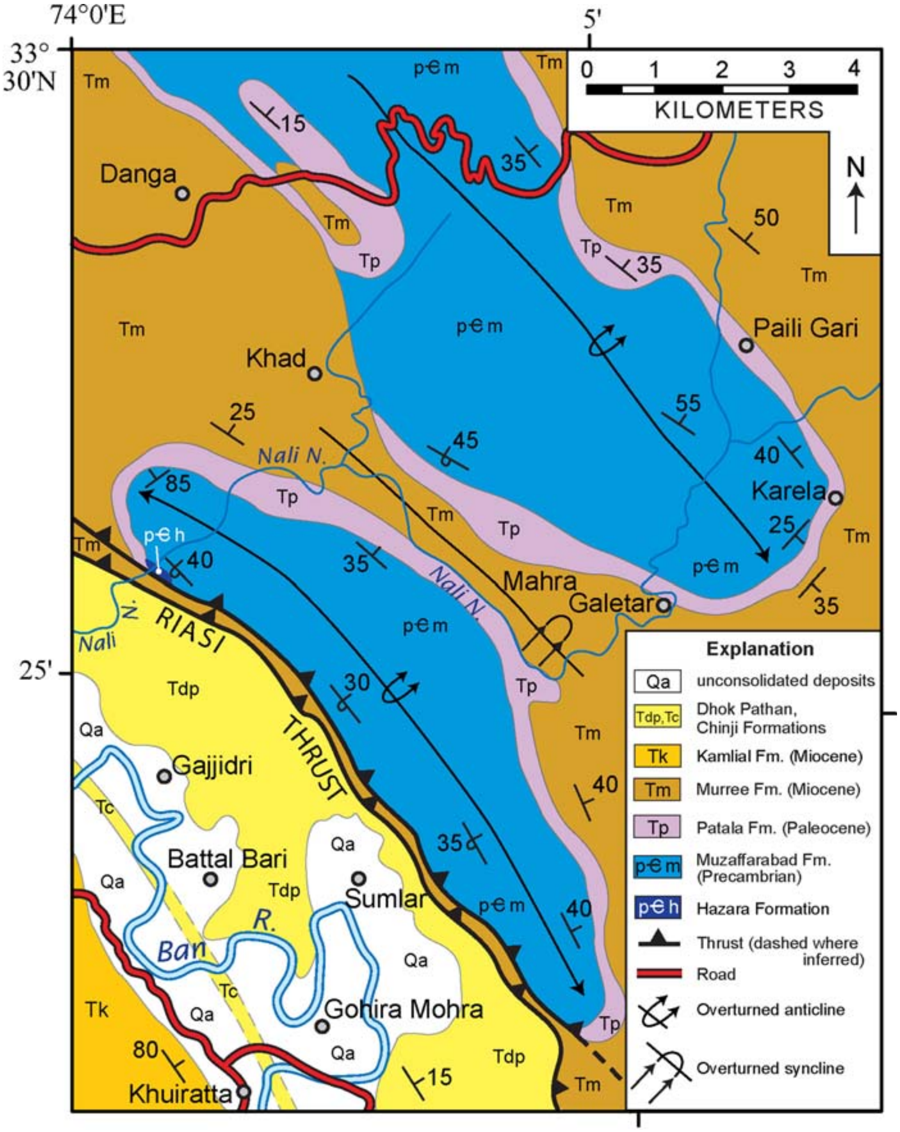

Fig. 4 Map of part of the Khuiratta 43 K/3 quadrangle near Kotli showing two overturned anticlines underlain by Precambrian Muzaffarabad Limestone, Paleocene limestone, and Murree Formation, which is in fault contact with Precambrian limestone on the southwest side of the southwestern anticline. Nearby on the southwest, the Riasi thrust juxtaposes Murree Formation against Dhok Pathan Formation, part of the Siwalik Group. The Nali River cuts across the southwestern anticline and may be antecedent to it. N. = nala, small stream. After S. Hussain et al. (2004b)

Hussain et al. 2004b) mapped the Riasi fault bringing Murree Formation against late Quaternary surficial deposits. The absence of Muzaffarabad Limestone detritus in the nearby Dhok Pathan Formation indicates that uplift and erosion of the anticline postdated Dhok Pathan deposition. The footwall of the Riasi thrust is in the broad Ban River alluvial plain that extends northwest–southeast, parallel to the thrust; in addition, a stream follows the Murree Formation in the syncline between the two anticlines. Other streams cut across the anticlines and may be antecedent to anticlinal growth (Fig. 4), similar to the crossing of the Muzaffarabad anticline by the Neelum River (Fig. 2).

In Indian-administered Jammu-Kashmir, the Riasi thrust forms a reentrant at the Chenab River (Valdiya 1992; Thakur 1992; Fig. 1) where folded Siwalik Group is overlain uncomfortably by upper Pleistocene gravel and Holocene scree, and both are overridden by the thrust (Krishnaswamy et al. 1970). The hanging wall contains the Precambrian Great Limestone of the Vaishnodevi Mountains (VM, Fig. 1), a formation similar to the Muzaffarabad Limestone; this is overlain by marine Eocene Subathu Formation and by Murree Formation (Valdiya 1992). Thakur's (1992) map continues this thrust northwest into Pakistani-administered Jammu-Kashmir where it connects with mapping by GSP (Figs. 1 and 4).

Thakur also continues the Riasi thrust southeast, bringing Murree (Dharamsala) against Siwalik southeast of the Chenab River, southeast of which is the Kangra reentrant. In the broad syntaxis between the east–northeast-trending Pabbi Hills east of the Salt Range (PH, Fig. 1 inset) and the northwest-trending Janauri anticline in the Kangra reentrant (Fig. 3), the Himalayan Front thrust is not well defined. The Siwaliks appear to dip into the Indo-Gangetic Plain without an active surface fault, although Powers et al. (1998), using subsurface well and seismic data, mapped a décollement between the deformed nonmarine strata and Precambrian basement. Well data show a fault in the frontal Janauri anticline, but Powers et al. (1998) did not find evidence that this fault is active. In contrast to Middlemiss (1910), Wallace et al. (2005) limited the meizoseismal zone of the 4 April 1905 *M* 7.8 earthquake to the northeastern part of the Kangra reentrant such that the upward projection of the rupture would be within the reentrant rather than at the Janauri anticline (Fig. 3). Valdiya (1992), following Talukdar and Sudhakar (1972), pointed out that the Soan (Satlitta) thrust, north of the Janauri anticline and the Soan River Dun, juxtaposed Siwalik against recent fluvial clay and displaced and uplifted older terraces west of Pong Dam by 60–140 m (Talukdar and Sudhakar 1972).

If so, the 1905 earthquake might have been a larger version of the 2005 Kashmir earthquake, with a gap between the 2005 and 1905 earthquakes previously filled by earthquakes of *M* 7.6 in September 1555 and *M* 6.3 on 29 May 1885 in Kashmir (Ambraseys and Douglas 2004; Bendick et al. 2007). Alternatively, the 1555 and 1885 earthquakes might have ruptured faults across strike to the northeast in the Kashmir Basin, such as those shown in Fig. 2 of Yeats et al. (1992), in which case the seismic gap would not have ruptured in modern times.

Northwest of Balakot, a zone of heavy damage and 2005 aftershocks (Parsons et al. 2006) extended northwest to the Indus River, following the IKSZ. However, despite an extensive search by GSP and Japanese collaborators, no surface rupture was found, even though there were more aftershocks in that region than in the area of surface rupture to the southeast (Bendick et al. 2007). An extension of the IKSZ west of the Indus River is not well defined by network data (Seeber and Armbruster 1979). Farther west, in the Kunar district of eastern Afghanistan, an earthquake of *M* 7.6 on 19 February 1842 and a large earthquake in the same region on 3 January 1519 might be related to the western extension of the IKSZ (Ambraseys and Douglas 2004; see description in electronic supplement to Ambraseys and Bilham 2003). However, as is the case farther east, the topography rises northward in Swat; Seeber and Gornitz (1983) described a steepening of the gradients of the Swat and Pinjkora rivers but did not describe a steepening of the Kunar River farther west.

5 Age of Balakot–Bagh fault

There is no stratigraphic evidence that the B–B fault was active during deposition of the Siwalik Group, which locally extended into the Brunhes Magnetic Chron, perhaps as young as 400 ka (Keller et al. 1977). In Pakistan, the fault mainly cuts older formations of the Siwalik Group, so that the age relations between the B–B fault and the Siwalik Group cannot be established in Pakistan except east of Kotli (Fig. 4), where the upper Siwalik Dhok Pathan Formation in the footwall of the Riasi thrust is close to exposed Muzaffarabad Formation in the hanging wall but contains no detritus from that formation. Near the Chenab River in Indian-administered Jammu-Kashmir, Ram (1984) and Valdiya (1992) observed that the Great Limestone, uplifted along the Riasi thrust, did not contribute detritus to upper Siwalik strata present close to the thrust, indicating that there, as well as the Kotli area, uplift of the hanging wall of the B–B fault began after the end of Siwalik deposition.

The discordance between the northwest strike of the B–B fault, the southwest-facing topographic slope

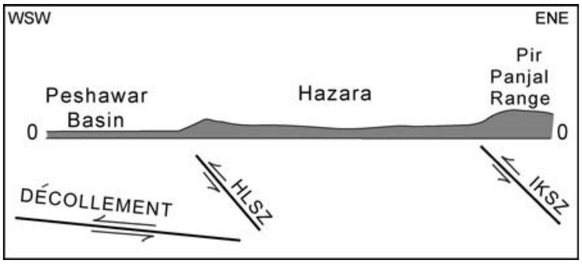

Fig. 5 Cartoon showing relation of the Indus–Kohistan seismic zone (*IKSZ*) and Balakot–Bagh fault to high topography to the northeast, and relation of the Hazara Lower Seismic Zone (*HLSZ*) to the northeast edge of the Peshawar Basin. Inspired by Seeber and Armbruster (1979)

above the IKSZ and the HLSZ, and the west to west–southwest strike of formations in Hazara and the deformed belt in the northern Potwar Plateau suggests that counterclockwise rotation of the Siwalik Group (Opdyke et al. 1982) predated the B–B fault, if rotation accompanied southward transport on a décollement in Eocambrian salt.

Nakata et al. (1991) showed that terrace surfaces were offset across the Tanda fault, part of the B–B fault. Kaneda et al. (2008) infer that fill terraces offset by the B–B fault are up to 30 ka in age based on climatic considerations (Kaneda et al. 2008). A separation of around 120 m in 30,000 years results in a rate of 4 mm/year; the exposure of Precambrian limestone in the cores of anticlines on the hanging wall of the B–B fault suggests much more displacement. Probably all displacement could have accumulated in the past 400,000–500,000 years, after the end of Siwalik deposition and during a period of uplift and incision of major rivers, some of which appear to be antecedent to anticlinal growth.

6 Conclusions

The 2005 earthquake within the HKS demonstrated that the MBT and Panjal thrust are not active as north-over-south thrusts, just as their counterparts are not active farther east in India and Nepal. The MBT has a left separation at the Balakot–Bagh fault (Fig. 2), which is probably due to relative uplift of the northeast side, exposing more Murree Formation, or, less likely, to left-lateral offset, or perhaps both. The hairpin bend of the MBT and Panjal thrust is not shared by the next major fault to the north, the MMT (Fig. 1), suggesting that latest motion on the MMT is younger.

The Balakot–Bagh fault and the IKSZ of which it is a part are best expressed at the surface as a topographic gradient to higher ground to the northeast. In this regard, the model in Fig. 5 of Seeber and Gornitz (1983) is instructive, except that we would not connect the active fault with the MCT, as they do. That model is clearly incorrect in Nepal based on the active-fault mapping of Nakata (1989). But we agree with their connecting the active thrust to the basement décollement, implying that some of the shortening across the Himalaya is taken up on this zone (Fig. 5).

Kaneda et al. (2008) showed that the 2005 ruptures took place on a fault that had ruptured previously and could have been mapped prior to the earthquake, as Nakata et al. (1991) did. Evidence for this longer-term displacement includes the presence of older deformed terraces, the deformation, uplift, and erosion of hanging-wall anticlines, and the offset of the MBT. Displacement of a widespread fill terrace redeformed during the earthquake, assumed to have an age of 10–30 ka, results in a shortening rate across the Balakot–Bagh fault of 1.4–4.1 mm/year, less than 10% of estimates of shortening between the Higher Himalaya and the Indian plate. This indicates that the 2005 Kashmir earthquake relieved only a small part of the accumulated strain between the Himalaya and the Indian plate.

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