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Cause of right-lateral strike-slip movement in recent seismic activity in the Hazara-Kashmir Syntaxis, NW Himalaya

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Abstract

This paper reinvestigates the causes of right-lateral strike-slip (RLSS) component in the Focal Mechanism Solutions (FMS) for 16 aftershocks of magnitude ≥ 4.0. The aftershocks lie in a NW-SE trending zone between the Indus Suture and the Hazara-Kashmir Syntaxis, mostly in the Hazara, Banna and Kaghan nappes. The FMS indicate thrusting/reverse faulting to be the dominant mechanism with prominent right-lateral strike-slip component. The rupture planes have NW-SE trend and NE dip.

Four types of FMS have been obtained: reverse/thrust with prominent RLSS component, reverse/thrust with minor RLSS component, pure RLSS and pure Normal. On the basis of the nature, strike, dip and depths of these FMS, two possibilities can be proposed. The NW striking, shallow dipping (<45^0NE) FMS (1, 13 and 16) having depths ≥ 10 km and reverse/thrust mechanism with minor RLSS component are due to the Indus Kohistan Seismic Zone (IKSZ). It is, therefore, proposed that instead of pure thrust/reverse blind zone as indicated by previous workers, the IKSZ comprises some RLSS faults as well. Alternatively, the NW striking, steeply dipping (> 45^0 NE) FMS having depth ≤ 10 km and reverse/thrust mechanism with prominent (2-6, 8-10, 12, 14, 15, 17) to pure RLSS component (FMS 7) are due to the Balakot-Bagh Fault (BBF), a surface trace of the IKSZ. Hence, either the BBF is not a pure reverse fault but has a prominent RLSS component, or it is RLSS fault. One normal FMS (11) is considered to be an anomaly in the data. The horizontal principal stress axis (P-axis) for all the FMS follows NNE-SSE direction except for FMS 6, and is similar to the observations made by the previous workers.

1. Introduction

The October 08, 2005 Muzaffarabad Earthquake occurred in the Hazara-Kashmir Syntaxis (HKS), which is a NW trending antiformal structure (Fig. 1) bounded by the Main Boundary Thrust (MBT). One of the most spectacular features of the Himalayan orogen, the HKS is flanked on its east by the Kashmir basin and on its west by the Peshawar basin. Northern Pakistan is characterized by a series of major thrusts. The Shyok Suture or Main Karakoram Thrust (MKT) demarcates the Hindukush-Karakoram belt in the north from the Kohistan island arc. Towards south, the Indus Suture or Main Mantle Thrust (MMT) sutures the Kohistan arc to the NW Himalayan Fold-and-Thrust belt. The southernmost is the MBT, which juxtaposes lesser Himalayan rocks over the sub-Himalayan Neogene molasse (Fig. 1). The recent seismicity of the NW Himalaya in Pakistan is associated largely with the HKS (Le Forte, 1975; Armbruster et al., 1978; Mattauer, 1986; Ni and Barazangai, 1984; MonaLisa, 2009).

The distribution of the epicenters of 423 selected aftershocks, from a total of 6,000 (Fig. 2), shows a prominent NW-SE pattern beyond the syntaxial bend of the HKS (MonaLisa, 2009). The analysis of the October 08 main shock and 16 aftershocks (MonaLisa et al., 2008) produce thrust/reverse Focal Mechanism Solutions (FMS). It was observed by these authors that a right-lateral strike-slip (RLSS) component existed in these solutions. In the present work, we have attempted to reinvestigate these FMS with the help of some more reliable seismological data from the local observatories as well as international seismological networks. We have found a dominant RLSS component in all the 17 FMS. This paper discusses the causes of this dominant RLSS component (Figs. 3 and 4).

1.1. *Seismotectonics and seismicity in the Pakistan Himalayas*

The ongoing northward subduction of the Indian plate beneath the Eurasian plate is the main cause of the high seismicity in the northwest Himalaya. The dominant compression features (MKT, MMT, MBT, Panjal Thrust and several others), along with the transpression features (Jhelum, Thakot, Puran and Raikot Faults), have been elucidated by a number of workers (Sercombe et al., 1998; MonaLisa et al., 2004, 2007) through geological, geophysical and seismological studies. Existence of shallow to deep crustal faults, such as the NW trending Indus Kohistan Seismic Zone (Armbruster et al., 1978) and Balakot-Bagh Fault (BBF) (Hussain et al., 2008), has also been proposed (MonaLisa et al., 2008). The HKS is a complex structure and an expression of the change in the direction of the Panjal Thrust and the MBT that are folded around its apex (Figs. 1 and 2). Along the western limb of the syntaxis these thrusts and the Balakot-Bagh Fault (also called as the Muzaffarabad Thrust) are truncated by the active strike-slip Jhelum Fault (Baig, 2006).

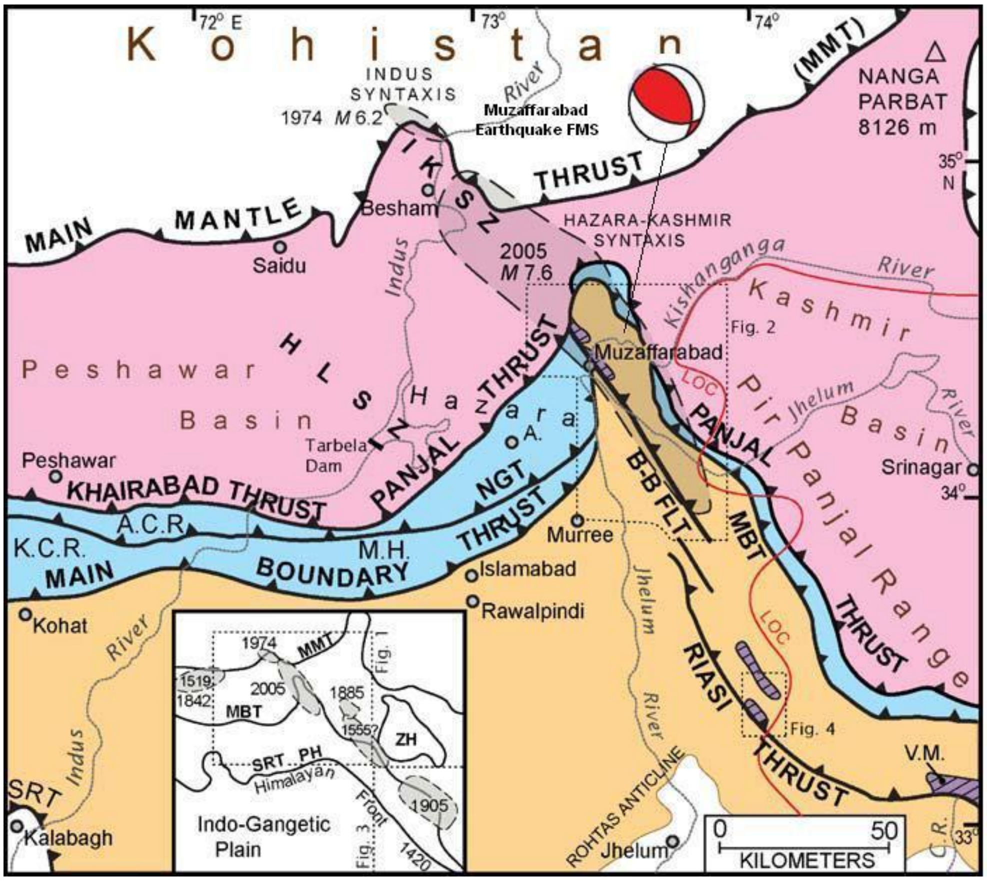


Fig. 1. Regional map of the northwest Himalaya showing major tectonic units, large historical earthquakes (dashed, shaded ovals with dates), the Indus–Kohistan Seismic Zone, Hazara Lower Seismic Zone, and possible active fault extensions of the Balakot–Bagh fault to the southeast, including the Riasi 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 (after Hussain et al. (2008). Figs. 1, 2, 3 and 4 on the map refer to those of Hussain et al. 2009 and are not shown here.

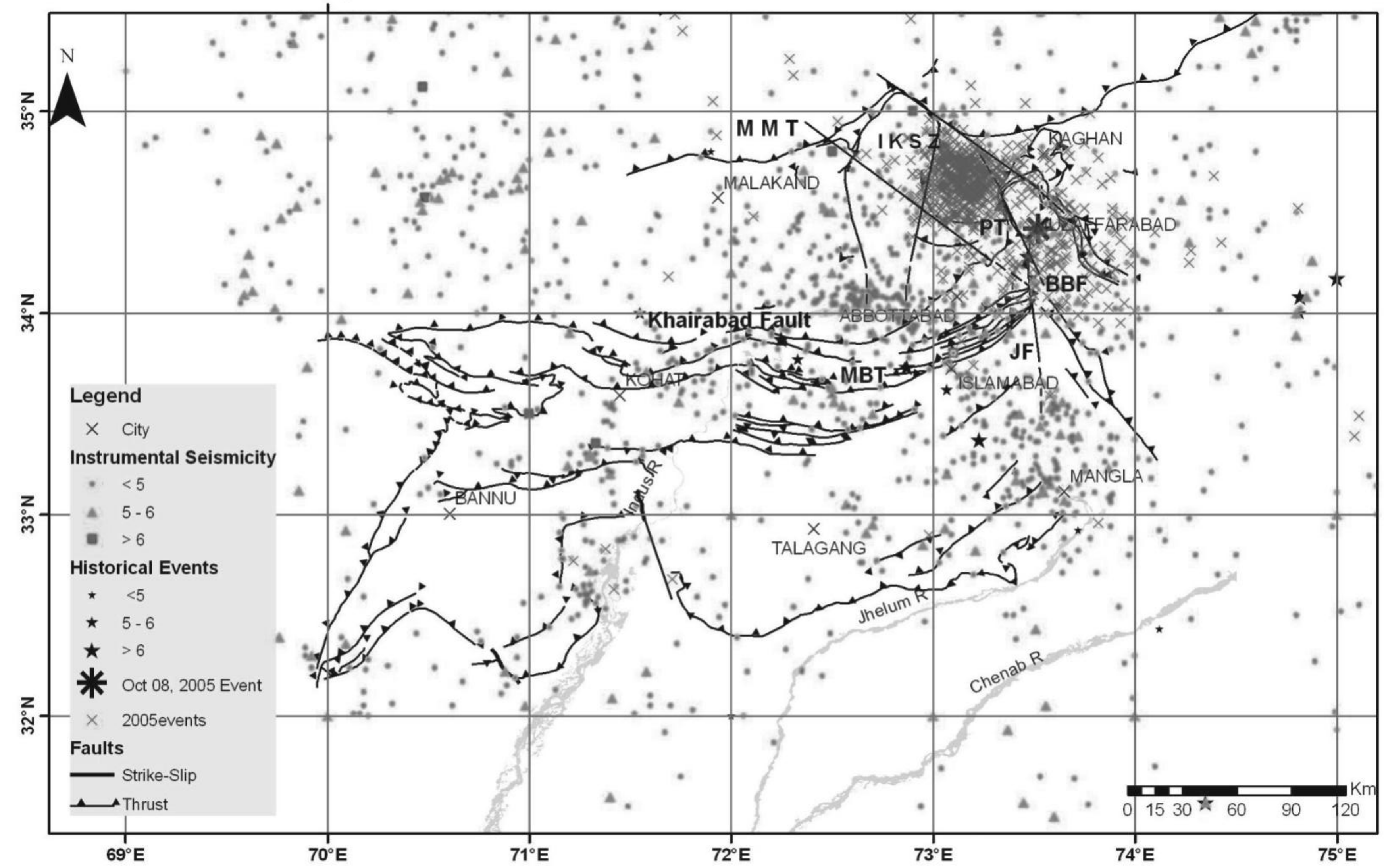


Fig. 2. Seismotectonic map of the area showing seismicity, structure and aftershock distribution of October 8, 2005 Muzaffarabad Earthquake. MMT: Main Mantle Thrust; MBT: Main Boundary Thrust; JF: Jhelum Fault; SRT: Salt Range Thrust; PT: Panjal Thrust; BBT: Balakot-Bagh Fault; IKSZ: Indus Kohistan Seismic Zone (after MonaLisa, 2009).

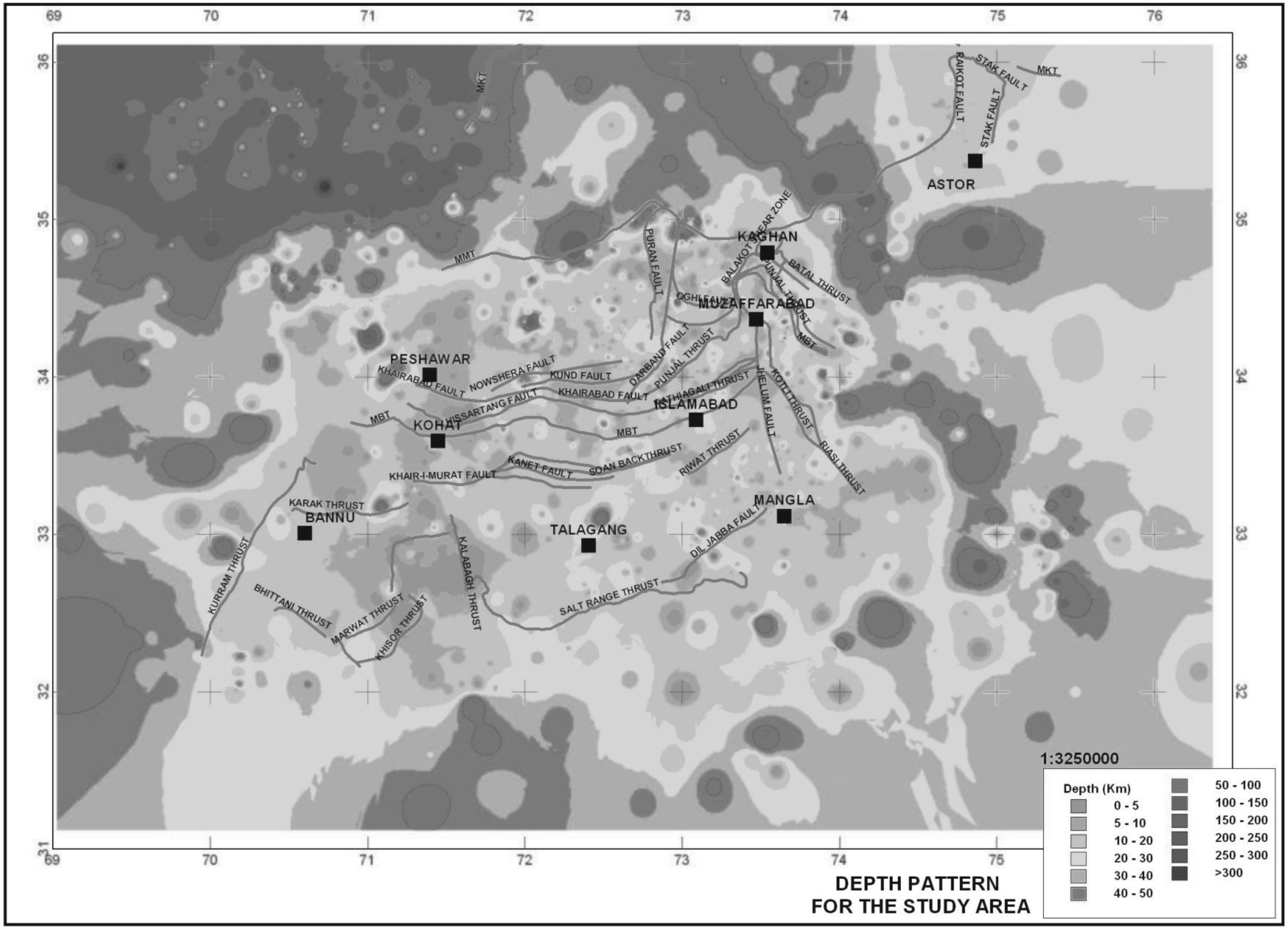


Fig. 3. Seismicity pattern in terms of depth for the NW Himalayan Fold-and-Thrust Belt and surrounding area.

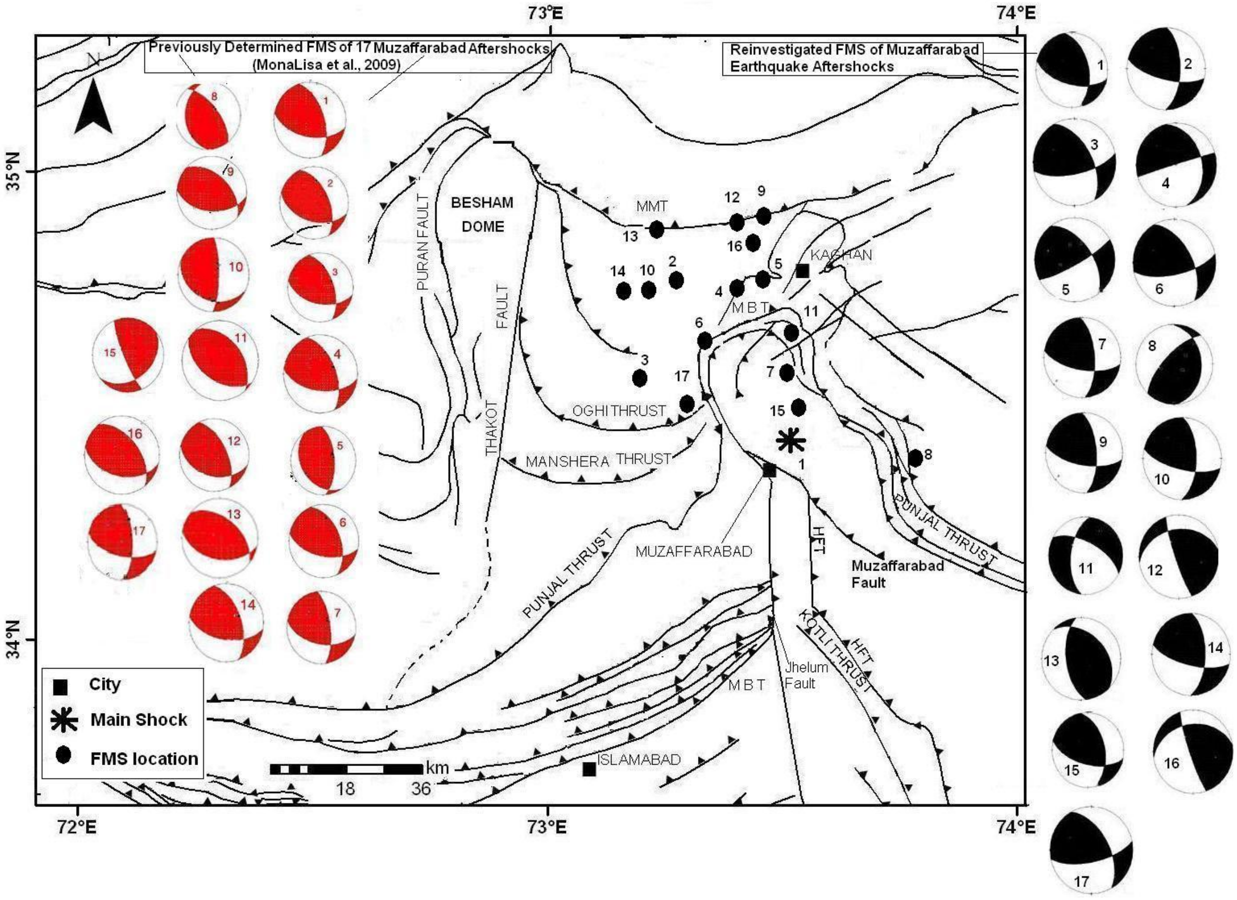


Fig. 4. Major structures and focal mechanism solutions of the main shock and 16 aftershocks, including the main event (1) of October 08, 2005 Muzaffarabad Earthquake. The reinvestigated FMS and the previously analysed FMS (MonaLisa et al., 2009) of the Muzaffarabad Earthquake are given on the right and left side of the HKS, respectively, for comparison.

The Himalayan region has been experiencing major earthquakes (some exceeding 8.0 M_w), like the 1905 Kangra Earthquake, 1934 Bihar-Nepal, and 1950 Assam Earthquake. The October 8, 2005 Muzaffarabad Earthquake of 7.6 M_w is the worst ever recorded earthquake not only in Pakistan, but in the entire Himalaya as far as loss of life is concerned. Recently, MonaLisa et al. (2008) and MonaLisa (2009) have declared the cause of this earthquake to be the IKSZ, which reactivated the BBF. Some other events that caused loss of life and destruction in northwestern Himalaya of Pakistan during the recent past are the 1974 Pattan Earthquake of m_b 6.0, Rawalpindi Earthquake of 1977 having m_b 5.2, two Bunji earthquakes of m_b 5.3 and 6.0 that occurred in 2002, and two Batagram earthquakes of m_b 5.3 and 5.5 that took place in 2004. It is worth noting that the NW Himalayan seismicity has been recorded at a shallow levels, i.e. < 70 km (Fig. 3).

2. Right-lateral strike-slip component in the FMS

2.1. Evidences from focal mechanism solutions

In this study an attempt is made to investigate the causes of a very prominent RLSS component found in the re-investigated FMS of the 16 aftershocks of the Muzaffarabad Earthquake. As mentioned earlier, MonaLisa et al. (2008) determined the FMS of the Muzaffarabad Earthquake and 16 of its aftershocks (≥ Mw 4.0) with thrust/reverse solutions. The revised parameters essential for FMS, i.e. the appropriate number of recording stations (in the present case all of the local stations: Water and Power Development Authority, Pakistan Atomic Energy Commission and Pakistan Meteorological Department, along with international observatories data such as the United States Geological Survey and International Seismological Centre), azimuthal angle, take-off angle and first motion polarities have been used to construct beach ball diagrams of FMS. The lower-hemisphere fault plane solutions have been determined using the software programs, namely AZMTAK and PMAN of Suetsugu (1997) in FORTRAN. All the 17 reinvestigated FMS are plotted on the available structural map (Fig. 4, Tables 1 and 2).

Table 1. Source parameters of the 17 earthquakes used in FMS determination (after MonaLisa et al., 2009).

FMS Nos.	**Date D/M/Y**	**Time H: M: S**	**Latitude (N)**	**Longitude (E)**	**Depth (km)**	**Magnitude (M_w)**
1	08/10/05	03:50	34.42	73.52	13	7.6
2	08/10/05	10:46	34.76	73.28	8	6.4
3	08/10/05	12:08	34.56	73.20	10	5.7
4	08:10:05	12:25	34.76	73.40	10	5.7
5	08:10:05	21:13	34.77	73.45	10	6.0
6	08/10/05	21:45	34.65	73.36	10	5.7
7	09/10/05	08:30	34.56	73.51	10	5.8
8	09/10/05	19:20	34.38	73.79	10	5.5
9	12/10/05	20:23	34.90	73.46	10	5.8
10	13/10/05	20:49	34.74	73.19	10	5.7
11	19/10/05	02:33	34.66	73.53	05	5.8
12	19/10/05	03:16	34.90	73.38	10	5.5
13	23/10/2005	15:04	34.88	73.19	10	5.9
14	28/10/05	21:34	34.74	73.13	10	5.5
15	06/11/05	02:11	34.47	73.54	10	5.7
16	21/11/05	08:26	34.84	73.40	10	5.5
17	25/12/05	08:02	34.50	73.30	10	5.7

Table 2. FMS parameters for the 17 events of the Muzaffarabad Earthquake (after MonaLisa et al., 2009).

FMS No.	**Nature of FMS**	**Fault Plane (FP)**		**Auxiliary Plane (AP)**		**P-Axis**		**T-Axis**	
		Strike	**Dip**	**Strike**	**Dip**	**Strike**	**Plunge**	**Strike**	**Plunge**
1	THRUST	342^0	57^0NE	101^0	53^0 NW	42^0	2^0	310^0	53^0
2	THRUST	335^0	54^0NE	107^0	48^0 NW	42^0	4^0	305^0	63^0
3	THRUST	340^0	57^0NE	102^0	51^0 NW	42^0	4^0	306^0	56^0
4	THRUST	339^0	56^0NE	97^0	54^0 NW	38^0	1^0	307^0	53^0
5	THRUST	357^0	62^0NE	145^0	32^0 NW	75^0	15^0	300^0	69^0
6	THRUST	339^0	51^0NE	102^0	56^0 NW	219^0	3^0	314^0	57^0
7	THRUST	353^0	69^0NE	101^0	52^0 NW	50^0	10^0	310^0	44^0
8	THRUST	321^0	64^0NE	179^0	31^0 NW	65^0	17^0	198^0	66^0
9	THRUST	313^0	49^0NE	95^0	48^0 NW	24^0	0^0	293^0	70^0
10	THRUST	1^0	77^0NE	113^0	31^0 NW	69^0	27^0	302^0	50^0
11	THRUST	320^0	43^0NE	124^0	48^0 NW	138^0	3^0	329^0	82^0
12	THRUST	334^0	60^0NE	105^0	41^0 NW	43^0	10^0	294^0	62^0
13	THRUST	309^0	48^0NE	101^0	46^0 NW	25^0	1^0	291^0	75^0
14	THRUST	341^0	57^0NE	99^0	54^0 NW	41^0	2^0	309^0	53^0
15	THRUST	157^0	81^0NE	52^0	33^0 NW	88^0	28^0	35^0	45^0
16	THRUST	322^0	52^0NE	103^0	45^0 NW	34^0	4^0	293^0	69^0
17	THRUST	358^0	66^0NE	104^0	59^0 NW	52^0	4^0	319^0	40^0

Table 3. Reinvestigated FMS parameters obtained for the 17 events of the Muzaffarabad Earthquake.

FMS No.	**Nature of FMS**	**Fault Plane (FP)**		**Auxiliary Plane (AP)**		**P-Axis**		**T-Axis**	
		Strike	**Dip**	**Strike**	**Dip**	**Strike**	**Plunge**	**Strike**	**Plunge**
1	Reverse with minor RLSSC	342^0	57^0NE	101^0	53^0 NW	42^0	2^0	310^0	53^0
2	Reverse with prominent RLSSC	355^0	61^0NE	107^0	48^0 NW	43^0	4^0	309^0	61^0
3	Reverse with prominent RLSSC	340^0	57^0NE	103^0	57^0 NW	42^0	4^0	306^0	56^0
4	Reverse with prominent RLSSC	339^0	56^0NE	97^0	78^0 NW	38^0	1^0	317^0	59^0
5	Reverse with prominent RLSSC	337^0	53^0NE	175^0	72^0 NW	75^0	15^0	312^0	57^0
6	Reverse with prominent RLSSC	339^0	51^0NE	102^0	56^0 NW	219^0	3^0	314^0	57^0
7	RLSSC	358^0	78^0NE	131^0	62^0 NW	50^0	10^0	310^0	44^0
8	Thrust with minor RLSSC	357^0	44^0NE	92^0	31^0 NW	65^0	17^0	198^0	66^0
9	Reverse with prominent RLSSC	355^0	74^0NE	95^0	67^0 NW	24^0	0^0	293^0	60^0
10	Reverse with prominent RLSSC	357^0	77^0NE	113^0	69^0 NW	69^0	27^0	302^0	50^0
11	NORMAL	320^0	33^0NE	134^0	38^0 NW	138^0	3^0	329^0	62^0
12	Reverse with prominent RLSSC	348^0	50^0NE	178^0	82^0 NW	43^0	10^0	294^0	72^0
13	Thrust with minor RLSSC	353^0	38^0NE	178^0	46^0 NW	25^0	1^0	291^0	75^0
14	Reverse with prominent RLSSC	357^0	77^0NE	132^0	65^0 NW	41^0	2^0	309^0	53^0
15	Reverse with prominent RLSSC	342^0	57^0NE	101^0	53^0 NW	42^0	2^0	310^0	53^0
16	Reverse with minor RLSSC	347^0	53^0NE	171^0	86^0 NW	43^0	10^0	294^0	72^0
17	Reverse with prominent RLSSC	336^0	54^0NE	177^0	70^0 NW	75^0	15^0	312^0	57^0

Except five (1, 7, 8, 11 and 15), all the FMS are located outside the HKS, in the Hazara, Banna and Kaghan nappe zones of Treloar (1989). Structurally, the area is very complex and all of these events are situated mid-way between the Indus Suture and the syntaxis region faults (Fig. 4). There also occurs the NS trending, steeply dipping, left-lateral strike-slip Jhelum Fault, along with the MBT and Punjal Thrust (Fig. 4). These structures are thin-skinned; no known deeper structure has so far been documented from or near the epicentral location. The only major subsurface structure occurring in the core of the syntaxis, at a few km distances, is the Bagh Basement Fault (BBF). The make up of the Indus Suture in northern Pakistan ranges from a sharp contact between the Kohistan magmatic arc and the Indian Plate to a melange showing substantial lithological variation from place to place (Jan and Rafiq, 2007). The IKSZ underlies this area (MonaLisa et al., 2008).

Four types of reinvestigated FMS have been obtained (Tables 1 and 3) during this study:

a) Reverse/thrust with prominent RLSS component
b) Reverse/thrust with minor RLSS component
c) pure RLSS
d) pure normal

a) Reverse/thrust with prominent RLSS component and pure RLSS

The reinvestigated FMS 2-6, 8-10, 12, 14, 15 and 17 are the reverse/thrust with prominent RLSS component, whereas FMS 7 is a pure RLSS solution (Fig. 5). Except the FMS 7, 8 and 15, all ten FMS (2-6, 9, 10, 12, 14, and 17) are located in the Hazara, Banna and Kaghan Nappe Zones (Fig. 4). The FMS 7, 8 and 15 are located in HKS (Fig. 4). All these FMS have the focal depths of 10 km, except FMS 2 (8 km), as reported by local observatory. These FMS are from an area located to the east of the Besham dome (Fig. 4). In this domal structure, basement uplift is an ongoing process (Baig and Lawrence, 1987; Treloar et al., 1989) and is the reason for generating the nearby right-lateral strike-slip faults. Hussain et al. (2008) reported the 60 km long, NW striking and steeply dipping Muzaffarabad Fault or Balakot-Bagh Fault (BBF), which stretches from Balakot to Muzaffarabad and further on to Uri in India. All the FMS (2-6, 8-10, 12, 14, 15, 17) indicate NW striking, steeply dipping (> 450 NE) reverse/thrust fault with prominent RLSS component except one (7) which is of pure RLSS nature (Fig. 5). We propose that this is due to the Balakot-Bagh Fault (BBF), which has been labeled as the surface trace of IKSZ by Hussain et al. (2008). We think that BBF is not a pure reverse fault, but has a prominent RLSS component; it may even be a pure RLSS fault (but more FMS data are needed to prove this). It is worth keeping in mind that downward extension of the BBF to this depth has not been reported earlier.

b and c) Reverse/thrust with minor RLSS component and pure RLSS

The FMS 1 (main shock, 13 km deep), 13 and 16 (both 10 km deep), as shown in Table 1, indicate a NW striking, shallow dipping (< 450 NE) thrust FMS with minor RLSS components (Table 2 and Fig. 5). FMS 1, the main shock, is located inside the HKS, whereas FMS 13 and 16 are located in the Banna nappe zone (Treloar et al., 1989), near the MMT. We relate these three FMS with IKSZ, not only on the basis of depth, but also to the shallow dipping nature of the fault planes, which is a characteristic feature of the IKSZ (Armbruster et al., 1978). It is, therefore, propose that IKSZ is not pure thrust/reverse blind zone as suggested by previous workers (Armbruster et al., 1978; Seeber and Armbruster, 1981), but it encompasses some right-lateral strike-slip faults as well.

It is worth noting that reverse faulting with strike-slip component FMS has also been determined by previous workers (Sercombe et al., 1998; MonaLisa et al., 2004, 2007) and is, therefore, not uncommon to the Himalayan earthquakes.

d) Pure normal

Only one aftershock, i.e. FMS (11), shows normal faulting (Table 2 and Fig. 5). The epicentral location of this event is in the northeastern limb of the HKS (Fig. 4). We consider this normal FMS as an anomaly in the data, possibly arising out of a small number of FMS parameters.

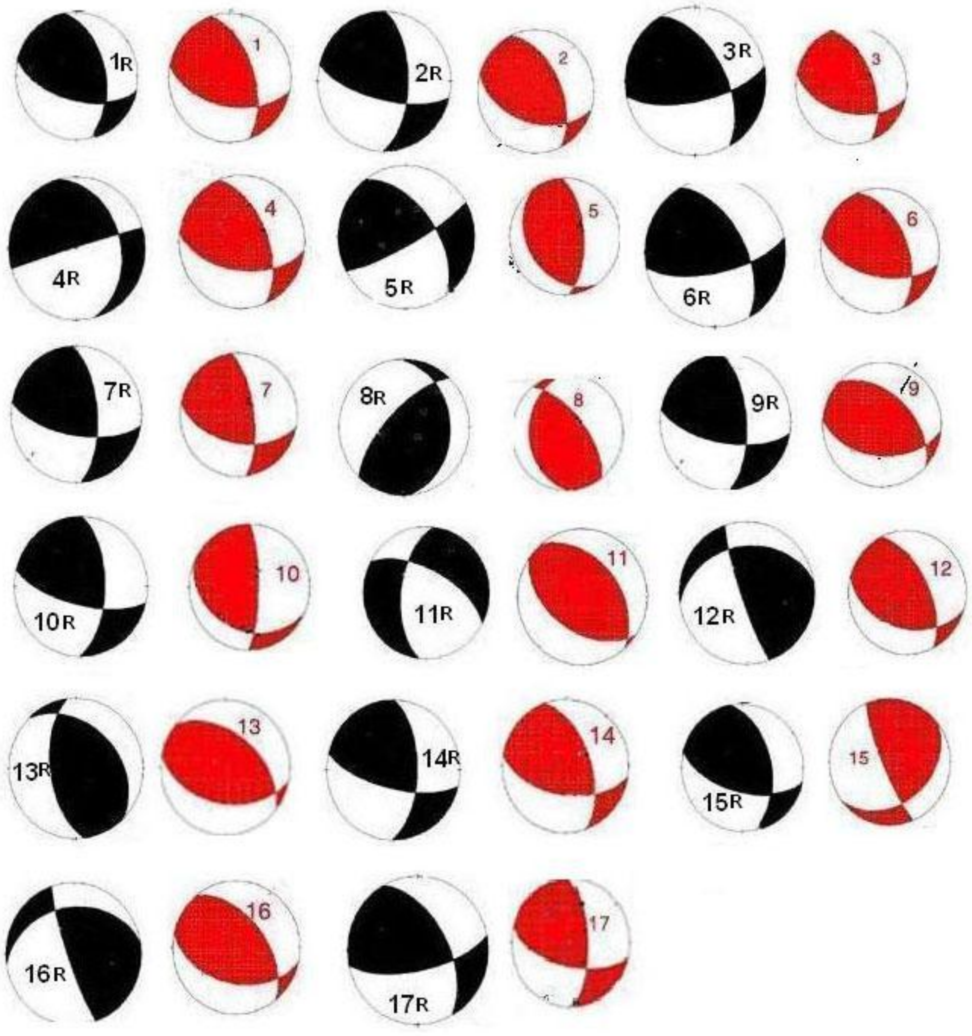


Fig. 5. The Focal Mechanism Solutions of previously analysed aftershocks (1, 2, 3, …) by MonaLisa et al., 2009, and reinvestigated aftershocks (1R, 2R, 3R,…) of the present work.

The horizontal principal stress axis (P-axis) for all the FMS follows NNE-SSE direction (Table 3) except for FMS 6, which is located on the northeastern tip of the HKS (Fig. 4). Burg et al. (2005) observed a similar direction of P-axis in this area.

2.2 Evidence from Man-made Structures

It has been observed that about 70% of the fatalities from the earthquakes were caused by the collapse of buildings, especially the collapse of weak masonry buildings (adobe, rubble stone, etc.). These building types are very common in northern Pakistan, where most of the buildings are of stone, soil and timber; and single storey. The buildings have a heavy mud roof supported on unshaped timber with a smoke hole. Modern houses, close to the major roads, on the other hand, are of concrete blocks, but poorly designed and constructed.

There is a strong evidence of right-lateral motion observed in the deformed concrete houses (Fig. 6a), from west to east, as indicated by displacement on the left margins of the walls and deformed window frames. The Balakot Bridge, immediately after the earthquake showed a very clear displacement to the South and East. The movement measured about one meter. The movement in the left pier (amount about one meter) and over right pier/wall is evident in Fig. 6b.

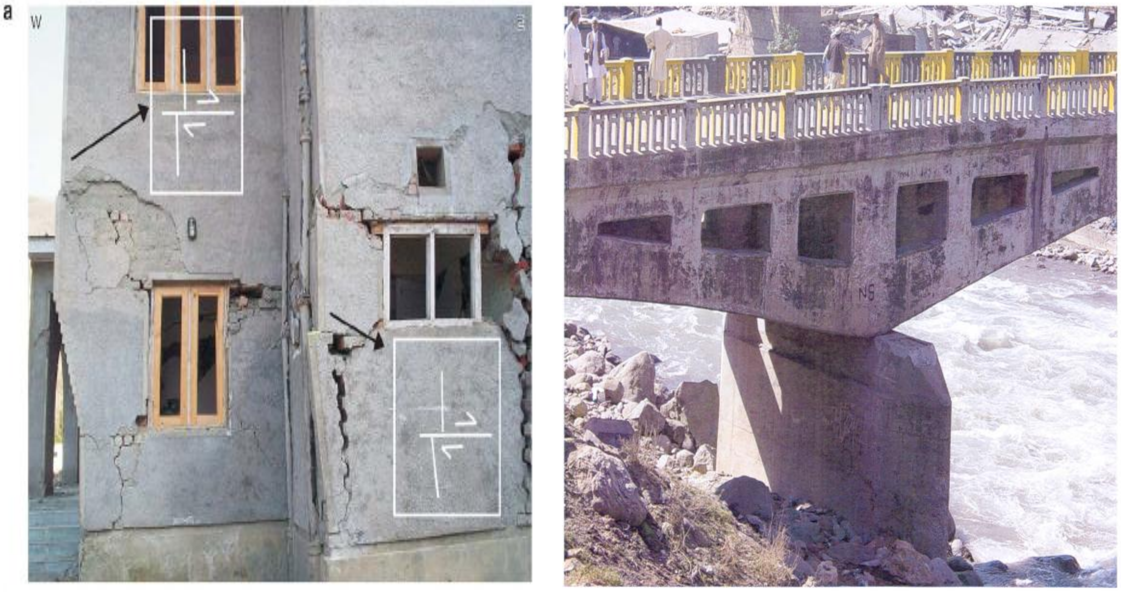
3. Summary and Discussion

The deadly Muzaffarabad Earthquake occurred in the HKS, an antiformal structure in a region where seismic activity is quite high (Oldham, 1883; Ambraseys et al., 1975; Quittmeyer et al., 1979; MonaLisa et al., 2007, 2008; MonaLisa 2009). The HKS is bounded by the Punjal Thrust and MBT which, along with the BBF, are truncated by the left-lateral strike-slip (LLSS) Jhelum Fault (Baig and Lawrence, 1987). Hussain et al. (2008) documented that the rupture associated with this earthquake passes through Balakot, Muzaffarabad, Sudangali and extends towards Bagh. Baig (2006) observed cumulative 2.5 meters reverse slip and 2 meters right-lateral slip along this active rupture. However, according to Tapponnier (2006), the exact locations of the active faults are ambiguous, as few surface ruptures have been mapped and paleo-seismological studies undertaken in the western syntaxis of the Himalayan thrusts.

In this paper, we attempted to seek the solution with the help of the available seismological data. The technique of focal mechanism solutions has already been widely used in the world in order to investigate the causative fault of an earthquake. Here also the FMS of 16 aftershocks and the main shock of Muzaffarabad Earthquake were reinvestigated using a large data set (Fig. 5 and Table 3) than that used by MonaLisa et al. (2008). The following observations can be made:

- On the basis of the nature, strike, dip and depths of these reinvestigated FMS, four types have been classified (Tables 1 and 3), i.e., Reverse/thrust with prominent RLSS component, Reverse/thrust with minor RLSS component, pure RLSS, and pure Normal.
- Among these the reverse/thrust with prominent RLSS component includes the FMS 2-6, 8-10, 12, 14, 15 and 17, whereas FMS 7 is a pure RLSS solution (Fig. 5). All these are NW striking, steeply dipping (> 45^0 NE) FMS and having depth ≤ 10 km.

These are considered to be due to the Balakot-Bagh Fault (BBF), surface trace of the IKSZ. We believe that either BBF is not a pure reverse fault but has a prominent RLSS component, or it is RLSS fault. The FMS 1, 13 and 16 are the reverse/thrust FMS with minor RLSS component.



(a) (b)

Fig. 6. (a) A deformed concrete house in Muzaffarabad. A right-lateral motion, west to east is indicated (from Avouac et al., 2006). (b) About one meter right-lateral movement in the Balakot Bridge immediately after the earthquake (Photograph courtesy of Iftikhar H. Baloch of the University of the Punjab, Lahore).

- These are the NW striking, shallow dipping < 45^0 NE, and have depths ≥ 10 km.
- These are associated with IKSZ, and we propose that IKSZ is not pure thrust/reverse blind zone as proposed by previous workers, but it comprises of some RLSS faults as well.
- Only one normal FMS (11) (Table 2 and Fig. 5) is considered to be an anomaly in the data, due to small number of FMS parameters.
- The horizontal principal stress axis (P-axis) for all the FMS follows NNE-SSE direction (Table 3) except for FMS 6, which is located on the northeastern tip of the HKS (Fig. 4), which is the same as observed by Burg et al. (2005).
- We observe no activation of the LLSS Jhelum Fault during this recent (October 08, 2005) seismic activity.
- Some evidences of right-lateral motion has also been observed in the man-made structures such as the deformed concrete houses (Fig. 6a), and in the Balakot Bridge immediately after the earthquake (Fig. 6b).
- As mentioned several times previously, serious limitations are involved in drawing conclusions on the basis of available seismological data in the country. Therefore, these results can be improved further by more geological field observations and reliable seismological data.

Acknowledgement

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