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Kaghan Valley (Pakistan) earthquakes of February 14, 2004: source mechanism, intensity distribution and their impact

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Abstract

Two moderate earthquakes of magnitude M_L 5.6 and 5.4 occurred in the Kaghan Valley of northern Pakistan on February 14, 2004. The events were located in Mansehra District near the town of Paras, about 30 km NNW of Muzaffarabad. The seismic and geologic data of the area suggest that the tectonic movement was concentrated in upper crust down to a depth of about 10 km. The composite focal mechanism solution of the earthquakes, using combined polarity data of a local network and global stations, indicates dominantly thrusting with orientation striking 335^o NNW-SSE and dipping 55^o in NE direction. The isoseismic map shows that the lateral extent of the intensity contours did not extend significantly far from peak intensity VIII on Modified Mercalli Intensity scale near Paras trending in NW-SE direction. Most of the damage took place along the strike of the seismogenic fault. Sharp relief and loose/thin fluvial filled narrow valleys further added to the damage. After about 20 months of these earthquakes, on October 8, 2005, a devastating earthquake occurred about 10 km north-west of Muzaffarabad at a depth of about 13 km. The orientation of the Kaghan Valley earthquakes is similar to the orientation of the main shock of the Muzaffarabad earthquake and coincides with that of the Kashmir Thrust.

1. Introduction

Two moderate earthquakes with Local Magnitudes 5.6 and 5.4 occurred in the north of Mansehra District on February 14, 2004 in the Kaghan Valley, about 20 months before the Muzaffarabad earthquake of October 8, 2005. The locations of the two earthquakes were about 80 km east of Mingora and about 125 km north of Islamabad, respectively. The main shock (M_L = 5.6) resulted by thrusting close to the Main Boundary Thrust (MBT) as well as to the northern extent of the Hazara – Kashmir Syntaxis. It was followed by a large number of aftershocks distributed mainly in the west and southwest of the MBT. Some aftershocks were large enough to increase the damage caused by the main shock. Focal mechanism solutions of these earthquakes were determined. Since the epicenters were located outside a local seismic network, with all its stations lying in the south, global data were added in order to achieve better results. Intensity distribution in the region was also estimated.

2. Physiography

The study area lies within the lower Himalayas about 20 km north of Manshera. The mountains are of relatively low altitude not exceeding 5000 meters above sea level. High relief and steep cliffs are the main geomorphologic features of the area (Fig. 1). The Kaghan and Siran Rivers, after emerging from springs and large glaciers of northern mountains, pass through the study area. High peaks of the region remain snow-covered throughout the year. Geographical data (Molnar, 1984) indicates that the continental crust in this region is 50 to 80 km thick which is about twice the normal crustal thickness. This feature has been attributed to continuous under-thrusting of the Indian plate beneath the Eurasian plate. The Himalayas form a mountain belt that is about 2500 km long and 160-400 km wide. This belt comprises a series of mountain ranges, with extensive transverse valleys. These ranges contain thick piles of intensively deformed Paleozoic sediments, interspersed with ripped up and thrusted masses of Precambrian basement, intruded by a series of magmatic rocks and affected by various metamorphic events (Kazmi and Jan, 1997). The Main Mantle Thrust (MMT) and the Main Karakorum Thrust (MKT) form the suture zone between the Indian and the Eurasian plates which separates Kohistan-Ladakh magmatic arc in the north from the Himalayan fold- and-thrust belts in the south.

2.1. Seismotectonics of the area

Northern Pakistan is characterized by extensive zones of high seismicity and contains several seismotectonic features generated by a large system of active faults. The prominent tectonic features of the study area are the Hazara-Kashmir Syntaxis, the Hazara Thrust System of the MBT, the Kashmir Thrust, the Balakot-Bagh Fault (MonaLisa et al., 2008; Hussain et al., 2008), and the Oghi, Thakot, Alai, and Daraband faults (Fig. 1). The MBT surrounds the Hazara Kashmir Syntaxis and forms a system of differentially oriented faults in the region. The main surface trace of the MBT in Pakistan starts from Kashmir continues northward, turns westward near the apex of the Hazara- Kashmir Syntaxis and then bends southward to Balakot. The Panjal Thrust runs parallel to the MBT on the eastern limb of the Syntaxis. It is an active fault and generates southeastern tectonics of the area (Seeber et al., 1979; Seeber and Armbruster, 1980; MonaLisa et al., 2008; MonaLisa, 2009; Hussain et al., 2008; Tahirkheli, 1996; Ali et al., 2009).

3. Kaghan Valley earthquakes and aftershocks

The Micro Seismic Studies Programme (MSSP) operates a local seismic network in northern Pakistan. The seismic activity recorded by this network reveals that five to ten shallow earthquakes of Local Magnitude 3 to 4.5 occur every year in this area. A few events have a magnitude close to 5. The Kaghan Valley itself had not experienced significant earthquakes earlier. However, some prominent earthquakes in the surrounding regions were the Pattan earthquake of December 28, 1974 (magnitude 6.0 m_b) and Astor Valley earthquakes of November 1 and 20, 2002 (magnitudes M_L 5.3 and 6.2, respectively). The earthquakes of this area, as recorded by the local network for the period 1976-2008, are shown in Fig. 2. Hypocenters of events having magnitude $M_L \geq 4.5$ were determined by using local as well as global seismic data. A Computer Code SEISAN (Havskov and Ottemoller, 2001) was used for this purpose. The main shock and aftershocks occurred at an average depth of 10 km. These events are listed in Table 1. Although the main shock was located in the southern part of the Kaghan Valley, the aftershocks were scattered southward along the MBT. The hypocentral parameters of significant earthquakes were compared with those reported by the United States Geological Survey (USGS) and are given in Table 2.

4. Focal mechanism solutions

Focal mechanism solutions of the two earthquakes (M_L=5.6 and 5.4) were determined by using the onset polarity of locally recorded data. Polarities at a few global stations were added for better results. For the first event, a total of 23 seismic stations were available, out of which only one was inconsistent. For the second event, with 38 data points, only three were inconsistent. Focal mechanism solutions and composite fault plane solution are given in Fig. 3(a, b, c). Computer programs PMAN and FOCAL (Suetsugu, 1997) were used for this purpose. The orientations of the fault planes of the two events correspond to the general trend of local tectonics. Distribution of aftershocks also supports this orientation. The source parameters are given in Table 3. It is worth noting that the composite source mechanism of these events is similar to the Muzaffarabad earthquake of Oct. 8, 2005, having NNW-SSE orientation, striking 338^o and dipping 60^o NE (Ali et al., 2009).

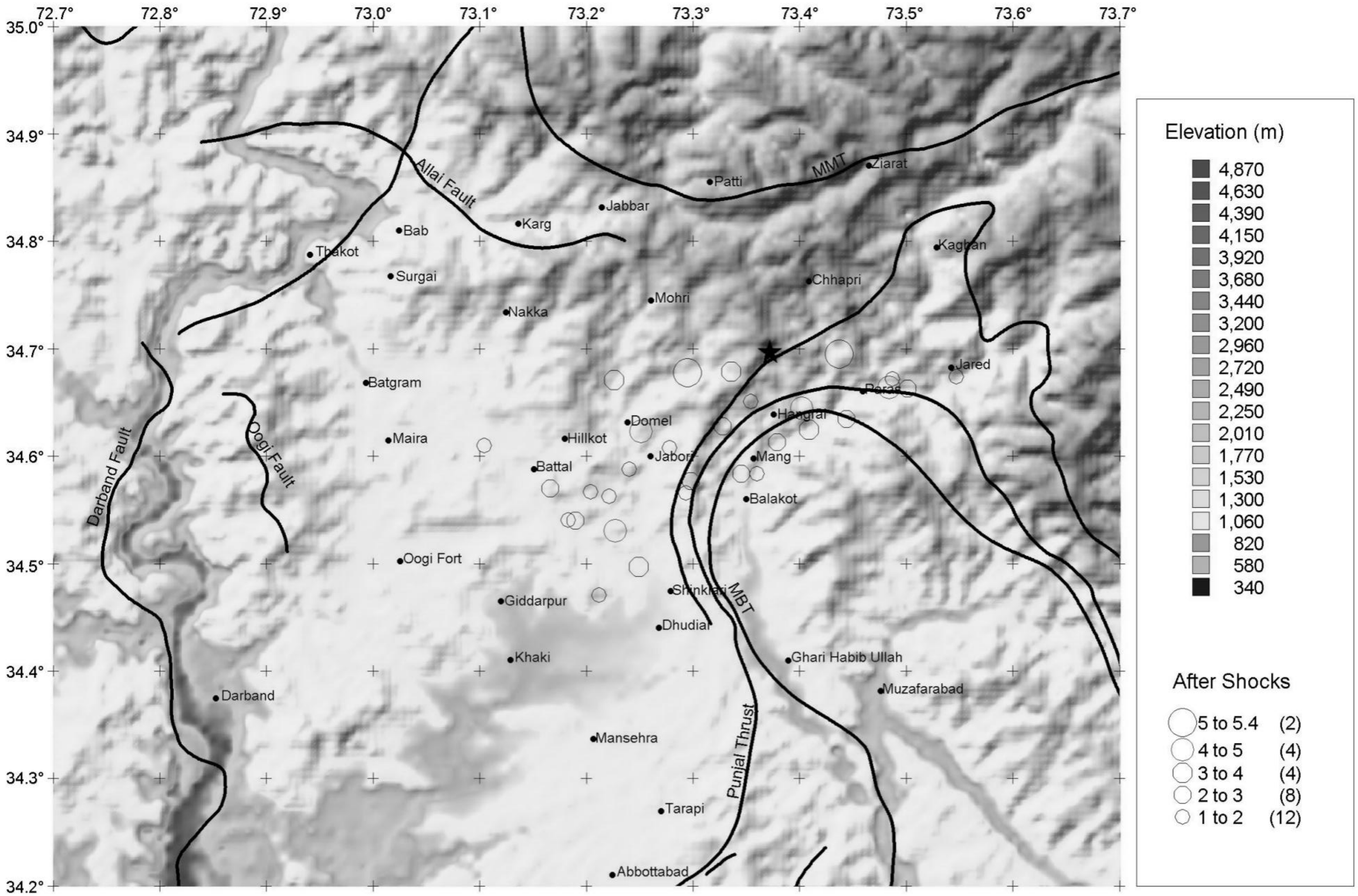

Fig. 1. Geomorphologic and prominent tectonic features of the study area with main shock (Star) and aftershocks of the Kaghan Valley earthquake.

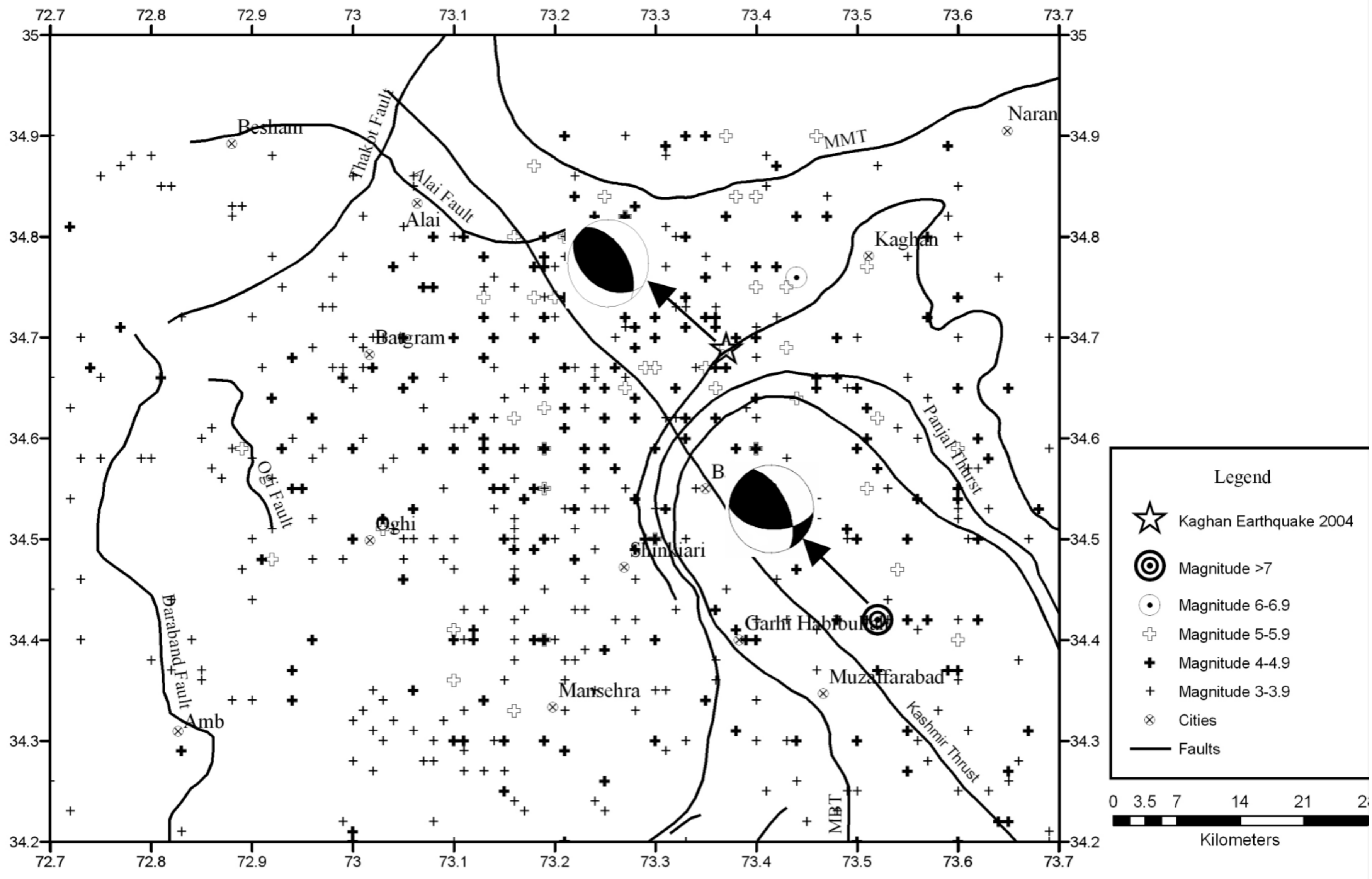

Fig. 2. Seismicity of the study area (1976-2008) recorded by local network.

Table 1. Hypocenters of the main shock and aftershocks of the Kaghan Valley earthquakes.

Sr. No.	Date	Time	Lat (N)	Long (E)	Mag. (Local)
1	14-02-2004	10:30:22.9	34.698^o	73.372^o	5.6
2	14-02-2004	10:56:57.5	34.577^o	73.298^o	2.7
3	14-02-2004	11:15:16.5	34.623^o	73.251^o	4.0
4	14-02-2004	11:28:22.6	34.671^o	73.226^o	3.2
5	14-02-2004	11:56:58.6	34.678^o	73.295^o	5.4
6	14-02-2004	12:20:33.4	34.608^o	73.278^o	1.5
7	14-02-2004	12:30:14.2	34.651^o	73.354^o	1.5
8	14-02-2004	13:11:03.2	34.679^o	73.336^o	3.0
9	14-02-2004	13:12:24.9	34.570^o	73.166^o	2.7
10	14-02-2004	15:10:14.6	34.584^o	73.360^o	1.4
11	14-02-2004	15:11:34.9	34.567^o	73.204^o	1.4
12	14-02-2004	15:47:01.6	34.613^o	73.379^o	2.5
13	14-02-2004	21:41:19.9	34.628^o	73.328^o	2.9
14	14-02-2004	22:02:24.2	34.584^o	73.345^o	2.0
15	15-02-2004	03:29:34.7	34.563^o	73.221^o	1.5
16	15-02-2004	03:33:54.5	34.588^o	73.240^o	1.6
17	15-02-2004	03:44:46.0	34.645^o	73.402^o	4.6
18	15-02-2004	04:03:19.0	34.663^o	73.501^o	2.5
19	15-02-2004	04:44:30.2	34.610^o	73.104^o	1.5
20	15-02-2004	04:50:56.4	34.635^o	73.444^o	2.0
21	15-02-2004	05:42:12.6	34.625^o	73.409^o	3.4
22	15-02-2004	05:47:50.2	34.471^o	73.212^o	1.6
23	15-02-2004	08:35:07.0	34.541^o	73.183^o	1.5
24	15-02-2004	08:51:56.5	34.566^o	73.293^o	1.5
25	15-02-2004	11:34:12.9	34.672^o	73.487^o	1.6
26	15-02-2004	14:30:35.7	34.674^o	73.547^o	1.5
27	16-02-2004	02:45:15.6	34.497^o	73.249^o	3.0
28	16-02-2004	08:59:42.2	34.531^o	73.227^o	4.0
29	16-02-2004	10:12:06.4	34.540^o	73.190^o	2.0
30	16-02-2004	19:11:51.6	34.664^o	73.484^o	4.2
31	22-02-2004	08:03:54.4	34.695^o	73.437^o	5.0

All depths<10 km

Table 2. Comparison of hypocenter parameters reported by MSSP and USGS.

Date		MSSP		USGS	
14-02-2004	Time (GMT)	10:30:27.2		10:30:22.2	
	Location	34.698^{o}N	73.372^{o}E	34.77^{o}N	73.22^{o}E
	Depth (km)	<10 km		11 km	
	Magnitude	M_L=5.6		m_b=5.5	
14-02-2004	Time	11:56:58.6		11:56:57.44	
	Location	34.678^{o}N	73.295^{o}E	34.80^{o}N	73.21^{o}E
	Depth (km)	<10 km		11 km	
	Magnitude	M_L=5.4		m_b=5.4	
	Time	03:44:46.0		03:44:44.26	
15-02-2004	Location	34.645^{o}N	73.402^{o}E	34.80^{o}N	73.17^{o}E
	Depth (km)	<10 km		10 km	
	Magnitude	M_L=4.6		m_b=4.3	
	Time	08:03:54.4		08:03:56	
22-02-2004	Location	34.695^{o}N	73.437^{o}E	34.82^{o}N	73.32^{o}E
	Depth (km)	<10 km		10 km	
	Magnitude	M_L=5.0		m_b=4.7	

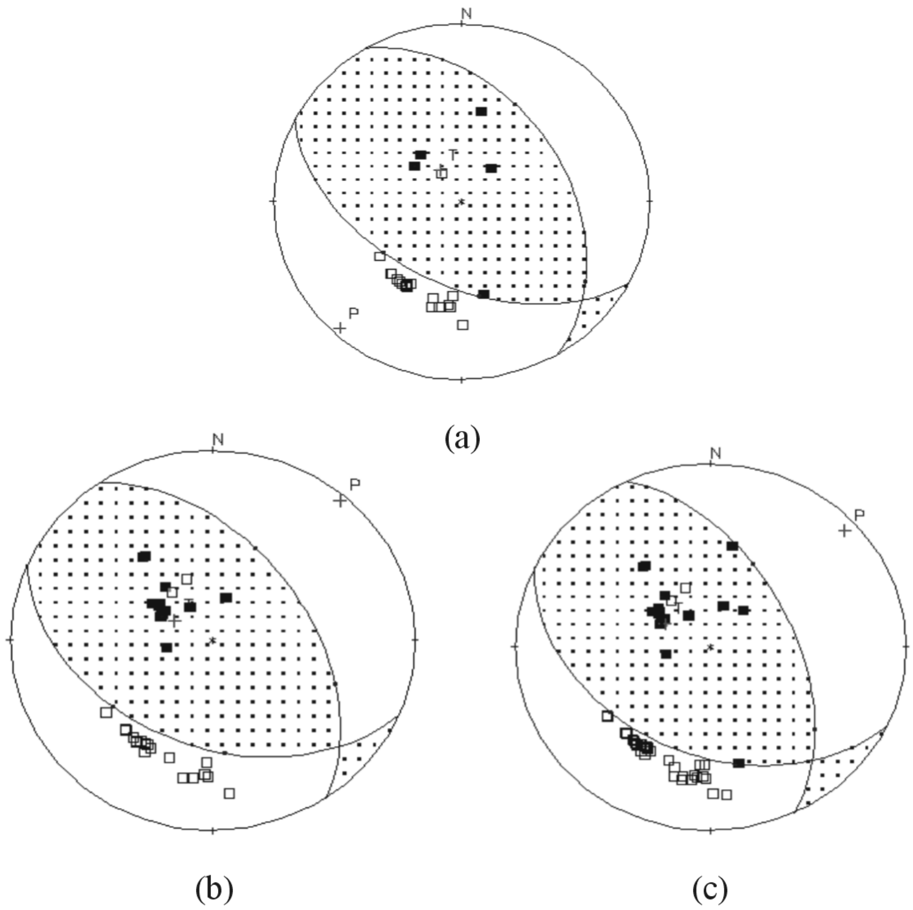

Fig. 3. Focal mechanism solutions of the Kaghan Valley Earthquake of February 14, 2004, (a) Main Shock, (b) Aftershock, (c) Composite Solution of (a) and (b).

Table 3. Source parameters of the two earthquakes of the Kaghan Valley.

Sr. No.	**Nodal plane I**		**Nodal plane II**		***P* axis**		***T* axis**		**Fault type**
	Strike	**Dip**	**Strike**	**Dip**	**Pl**	**Az**	**Pl**	**Az**	
1	118^o	52^o	329^o	43^o	5^o	-138^o	73^o	328^o	Thrust
2	113^o	44^o	326^o	51^o	4^o	41^o	73^o	299^o	Thrust
3	116^o	42^o	335^o	55^o	7^o	47^o	69^o	299^o	Thrust (composite)

5. Field studies

A field survey of the area was undertaken. Data were collected for understanding the nature of the earthquakes and related hazard in the area and, also, for compiling isoseismic and intensity maps. All villages located in the area were visited with a view to examining the nature of damage and to record impressions of inhabitants in order to assess variations in the earthquake affected area in relation to geological conditions. The sites of ground cracks were also studied to determine their mode of formation. The margins of the Kaghan Valley and, especially, the valley interfaces were examined in many places to detect recent tectonic activity and fault rupture, if any, due to the earthquakes.

Recent buildings in the valley area used cement blocks or brick-cement masonry and had reinforced structures. Almost all the residential houses in far-flung areas of the valley were, however, constructed by primitive methods using mud mortar and timber as construction materials. Many houses were constructed on less stable slopes and unconsolidated ground which tended to enhance damage due to earthquakes. Most of the damage took place in narrow valleys, particularly where the man-made structures were built on thin (<10 m) fluvial deposits with underlying deformed metasedimentary-sedimentary rocks. The earthquakes caused moderate damage in the Kaghan Valley where some causalities also occurred due to collapse of a house built with mud mortar. Most of the houses remained intact but some of them sustained partial damage, such as falling of walls and development of cracks. The exposed Mansehra Igneous Complex area, even with steep slopes (particularly Battal and Battagram), received lesser shaking that resulted in lesser damage.

According to our survey, snow clad Kaghan valley, Knosh and Bhogarmang valleys of the Mansehra District and Alai Tehsil of Battagram were the worst hit by the two tremors. About 206 houses were affected, with 6 structures collapsing completely and some 200 damaged partially. About 70 % houses were partially damaged in the Tangai area. In the Alai Tehsil, the earthquakes caused a landslide which buried a Datsun wagon killing all 17 passengers and the driver on the spot. In Shamlai area of the Battagram District, a 10 year old boy was killed under the collapsed wall of his house. Over 100 houses collapsed in the Kaghan Valley, 75 in Hangrai, 20 in Paras and five in village Jigan. The Kaghan road from Jaraid onwards was blocked due to heavy snowfall and landslides which hampered relief efforts in the area.

In Balakot area, 86 houses were reported destroyed and 145 partially damaged; four children were killed, and seven men, six women, and seven children were injured. About 20 percent of water wells were damaged in the Mansehra District. In Manda Gucha area of Knosh Valley, two women were killed when the roof of their house collapsed. In Battal area of this Valley, seven houses were destroyed and 53 damaged. Meanwhile, two earthquakes of mild intensity jolted Mansehra and its adjoining areas again the next day, causing panic among people. No loss of life or property was, however, reported. The events were felt as far as Gulmerg, Srinagar and Jammu to the east and Kabul, Afghanistan to the west.

According to field investigations, the area of significant damage covered about 1230 km^2, while the felt area of the earthquakes was about 79750 km^2. At a few places, on margins of valleys, ground cracks appeared in unconsolidated material generally adjacent to bedrock but apparently with no rupture or displacement of contiguous parts. It may, thus, be concluded that the earthquakes did not cause primary surface faulting. Small scale landslides were reported at numerous places in the valley. Close examination of the crack zones in their geological and geomorphologic perspective suggested that severe shaking of unconsolidated material on the slopes gave rise to cracks and fissures. The villages Paras, Jabbori, Hillkot, Mohri and Karg received heavy damage (Fig. 4 and Fig. 5) both of life and property.

(a)

(b)

Fig. 4. Photographs showing damage in Paras.

(a)

(b)

(c)

Fig. 5. Photographs showing damage in Jabbori.

6. Intensity distributions

In addition to field investigations in the area of maximum damage, various nearby places were visited in order to obtain information about variations in intensity of the earthquake with distance. The maximum intensity VIII on the MMI scale was observed around the town of Paras which is located about 15 km NE of Balakot and about 16 km SW of Kaghan. The intensity values reduced sharply in the north-south direction and contours formed an elongated shape trending NWW to SEE (Fig. 6). The earthquakes were accompanied by heavy rumbling sound in the meizoseismal areas (Paras town), which may be attributed to the transmission of high frequency seismic energy into the air. Civil structures built on the valleys filled by alluvial deposits were damaged, whereas, localities founded on hard rock (granite), received lesser damage even though lying at close distances from the epicenter. Some observations regarding intensity and its distribution at some towns are described below.

6.1. Paras

It is a sparsely populated town, located in a steep valley, about 9 km from the epicenter. The MBT passes through the town. Inter-bedded sedimentary rocks (shale, sandstone, limestone) of Salkhala Formation, and Galiat Group are exposed in the area. These rock groups put the upper crust in high seismic attenuation zone. The observed intensity in this area was about VIII on the MMI scale. Intensive shaking was experienced both indoors and outdoors. This caused heavy damage to poorly constructed mud-stone masonry (about 75%) and partial damage to concrete structures (about 30%). The concrete structures founded on steep slopes and/or on fluvial deposits received more damage particularly at the basements while the structures built on hard rocks received lesser damage (Figs. 4 a, b).

This town in Siran Valley is densely populated. It is located about 15 km from the epicenter. The MBT passes about 4 km in the east. Most structures in this town are founded on fluvial deposits of the Siran River that overlie the Mansehra granites. The observed intensity in this area was about VII on the MMI scale. Severe damage to loose masonry construction and some damage to concrete structures was reported (Figs. 5 a, b, c).

6.2. Jabbori

This town in Siran Valley is densely populated. It is located about 15 km from the epicenter. The MBT passes about 4 km in the east. Most structures in this town are founded on fluvial deposits of the Siran River that overlie the Mansehra granites. The observed intensity in this area was about VII on the MMI scale. Severe damage to loose masonry construction and some damage to concrete structures was reported (Figs. 5 a, b, c).

6.3. Karg

This densely populated town in Alai Valley is located about 25 km from the epicenter. The geomorphologic and geologic conditions of the site are nearly the same as that of Jabbori.

6.4. Domel

This town is located in Siran Valley about 14 km from the epicenter. The construction is mostly founded on bed rocks of Salkhala Formation where the Siran Valley is relatively narrow and steep. The area, though located closer to epicenter, sustained lesser damage obviously due to structures founded on hard rock.

6.5. Shinkiari

This densely populated town is situated about 26 km from the epicenter. Here the Siran Valley is relatively wide and more flat. The fluvial deposits are significantly deep. These deposits accompanied with relatively long distance from the epicenter may have reduced the surface shaking considerably. The observed intensity was about V to VI on the MMI scale.

6.6. Kawai

It is a sparsely populated town situated in Kunhar Valley, about 10 km from the epicenter. Slates, limestone, rhyolite, dacite, andesite and basalt are exposed in the area. Most civil structures are founded on hard/bed rocks. Thus, though located closer to the epicenter, the area received much less or no damage.

6.7. Other towns

The observed intensity in other towns around the epicenter area of the earthquakes is shown in isoseismic map in Fig. 6.

7. Geotechnical phenomena

The main shock was accompanied by some geotechnical phenomena such as landslides and subsidence.

7.1. Landslides

As shown in the geological map of the area, except granites, the lithologies are sensitive to landslides particularly in high slope areas. The landslide prone zone is limited to the mountains and channel banks. As a result of high surface shaking caused by earthquakes at Paras and its vicinity, the stability of natural channels was reduced and many landslides occurred in the area (Fig. 7 a). In addition, several tensional cracks and separation of blocks from main body were observed in the area.

7.2. Subsidence

This phenomenon was observed mainly in soft rock areas particularly on Kunhar Valley slopes cut along the road. This obviously resulted due to poor slope protection of civil structures (Fig. 7 b).

8. Conclusions

The study of the Kaghan Valley earthquakes and their aftershocks shows that they lie in an area where earthquakes with local magnitude ML low to moderate intensity less than 5 occur. Focal mechanism solutions of these earthquakes indicate dominantly thrusting with minor right-lateral strike- slip component (Fig. 3) along the fault planes of northeast-southwest orientation which corresponds to the general trend of local tectonics. Treloar et al. (1989) documented the dominance of strike-slip as compared to thrust/reverse faulting for shallow focus earthquakes (Table. 3). This is in agreement with fault plane solutions obtained in the present study. However, more work is needed to confirm this contention.

Observations made during the intensity survey indicated that the intensity contours converged around the town of Paras in Kunhar Valley trending northwest-southeast, which is in accordance with the trend obtained from the presently derived fault plane solutions (Figs. 3 and 6). The isoseismic map shows that the lateral extent of the intensity contours did not exceed peak intensity VIII on the MMI scale near Paras. Most of the damage took place along the strike of the causative fault. Sharp relief and loose/thin fluvial filled narrow valleys further added to the damage. Heavy damage to civil structures in Jabbori town is a typical example of fluvial enhanced seismic damage. On the other hand, Domel and Dadar towns, located nearly at the same distance from the main shock, received less damage because the structures were founded on hard rocks. Narrow valleys and sharp relief enhanced the seismic hazard as they act as barrier for seismic wave propagation and deposit most of the seismic energy at the valley face. Damage at Karg (Alai Valley) and Jabbori (Siran Valley) supports this concept.

The similarity of orientation and source mechanism solutions of the Kaghan Valley earthquakes with that of the Muzaffarabad earthquake of 2005, indicate that they were, most probably, the foreshocks of the Muzaffarabad earthquake. This coincides well with the slip nature of the Kashmir Thrust and is also supported by the surface evidence recorded during the present study. This, however, needs to be confirmed with more work and data.

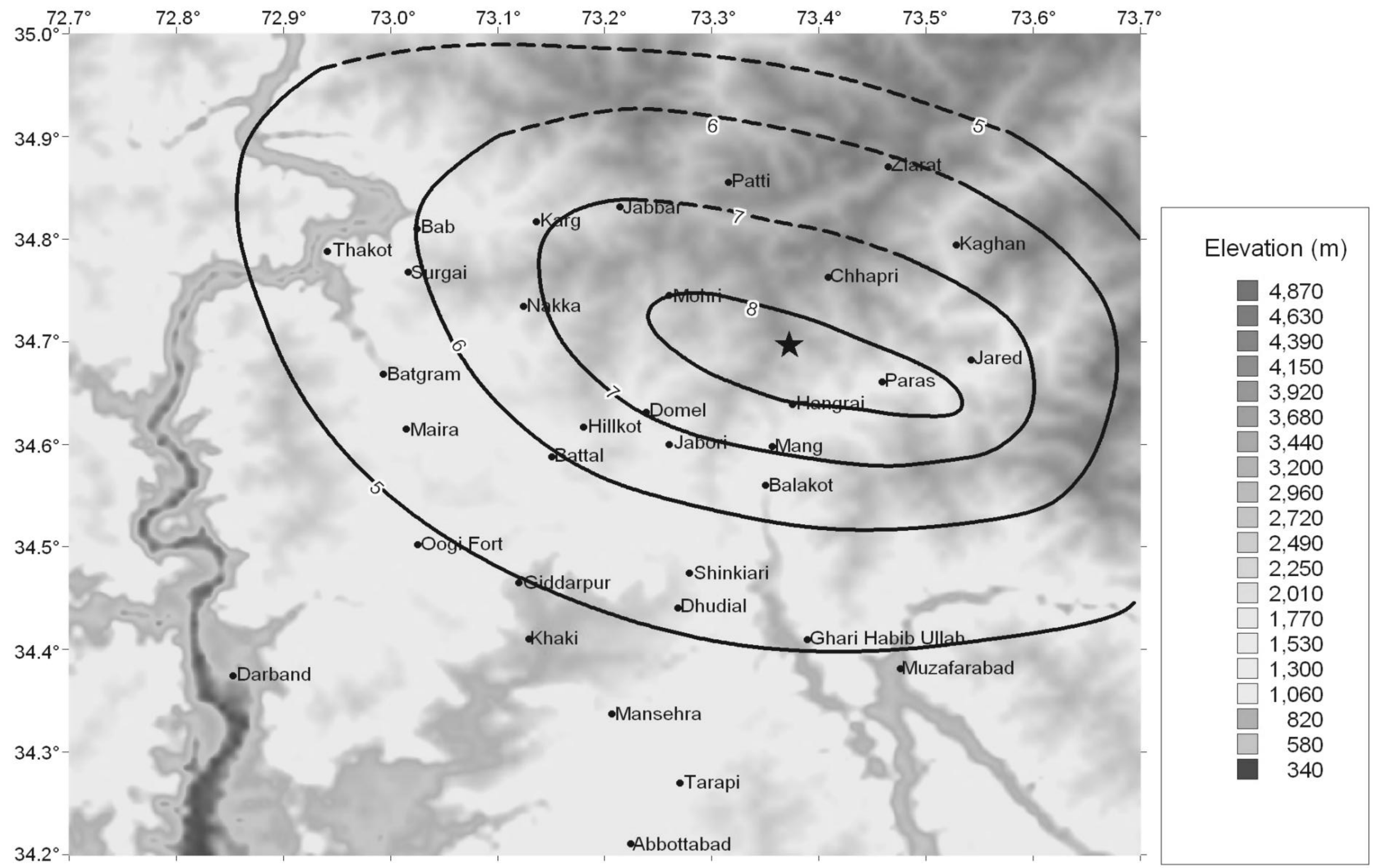

Fig. 6. Isoseismic map of the study area. The star shows the epicenter.

(a)

(b)

Fig. 7. Photographs showing (a) land sliding in the Kaghan Valley, and (b) subsidence along the road in Paras.

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