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Seismotectonic Contours of Kashmir-Hazara Region and Seismological Aspects of October 08, 2005 Earthquake

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SEISMOTECTONIC CONTOURS OF KASHMIR-HAZARA REGION AND SEISMOLOGICAL ASPECTS OF OCTOBER 08, 2005 EARTHQUAKE

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ABSTRACT

During the wee hours of October 08, 2005, a devastating shallow focused (16.2 km) earthquake with moment magnitude of Mw 7.7 occurred in the Pakistan's Kashmir Hazara Region. Its tremors were felt in a radius of over 1000 km with damages taking place in an area of 36000 sq km. More than 0.1 million people died and the rehabilitation of infrastructures damages are estimated to cost around five billion dollars. The Kashmir Hazara terrain is located on the NW margin of lesser Himalaya. The KHS is one of the bold tectonic scars which physically isolate this terrain from rest of the Himalaya. Other major tectonic features sculpturing this terrain in the shape of folds and faults are: Main Mantle Thrust (MMT), Main Boundary Thrust (MBT), Panjal Thrust (PT), Hazara Thrust (HT) and the Indus Valley Faults. All these mega structures are the abode of variable seismicity and generate earthquakes of low to high (damaging) magnitude. The seismic zones of the mega-crustal deformations in the Kashmir Hazara terrain, from where the earthquakes emanate generally lies between 10 – 60 km surface depths. The earthquakes generated at this depth are categorized as shallow and are usually more hazardous. The earthquake resulted from the subduction of Indo-Pakistan plate beneath the Eurasian plate and it ruptured the southwest Jhelum Thrust (JT) fault. The fault was previously inferred to be as active in a region where the river incises directly into the Murree sandstones on the west side of the valley (footwall of JT), while it has abandoned large inset terraces along the east side (hanging wall of JT). The occurrence of Kashmir-Hazara earthquake confirms that the active Jhelum Thrust (JT) and Jhelum Fault (JF), in a region located well north of the Main Himalayan Frontal Thrust, accommodate roughly EW-oriented, present day shortening related to "zipper tectonics" within the part of the Kashmir Hazara Syntaxis (KHS). Maximum Modified Mercalli Intensity was X at Balakot, situated on the hanging wall side of the causative fault and the maximum ground motions in the same area were inferred to be 0.90 'g' from overturned vehicles in the direction parallel to the axis of valley.

INTRODUCTION

According to the Seismic Studies Program WAPDA, Pakistan, the earthquake originated from Lat. 34.53 E & Lon. 73.55 N and had a shallow focal depth of 16.22 km. The earthquake resulted from the subduction of Indian plate beneath Eurasian plate. Muzaffarabad and Balakot cities of Kashmir, Pakistan, where the Modified Mercalli Intensity reached a maximum of X were the most effected. The Kashmir-Hazara Syntaxis (KHS) is an anomalous folded structure which emanates from the Pir-Panjal Range in Kashmir and extends northwards till Balakot where its western limb takes a loop to the southwest and extends with this trend towards Muzaffarabad. The Jhelum Thrust (JT) is a terminal branch of Main Boundary Thrust (MBT). The mega earthquake and majority of its aftershocks are located on the western limb of KHS and is the product of release of energy stored in this zone by the convergence of KHS. The earthquake moment ranged between 2 and 3 x 10^{27} dyne.cm and rupture time was ≈ 30 sec. The patch of the fault that slipped during the earthquake may be approximated by an ellipse of 50-70 km. length in the NW-SE direction and 20-30 km. wide in the transverse direction. The Kashmir-Hazara terrain in Pakistan under the context of regional surface and sub-surface geology displays a composite seismotectonic scenario. Its earthquake-prone structures occur both exposed on the surface as major lineaments and also at depth beneath the surface as mega crustal deformations. Former are observable and can be brought within the fold of geological investigations by conducting geological mapping and their subsurface behavior can be confirmed by adopting various geophysical methods, whereas the deep crustal deformations occur at depth and their tectonic turbulences and pattern can be deduced by monitoring deep crustal seismicity.

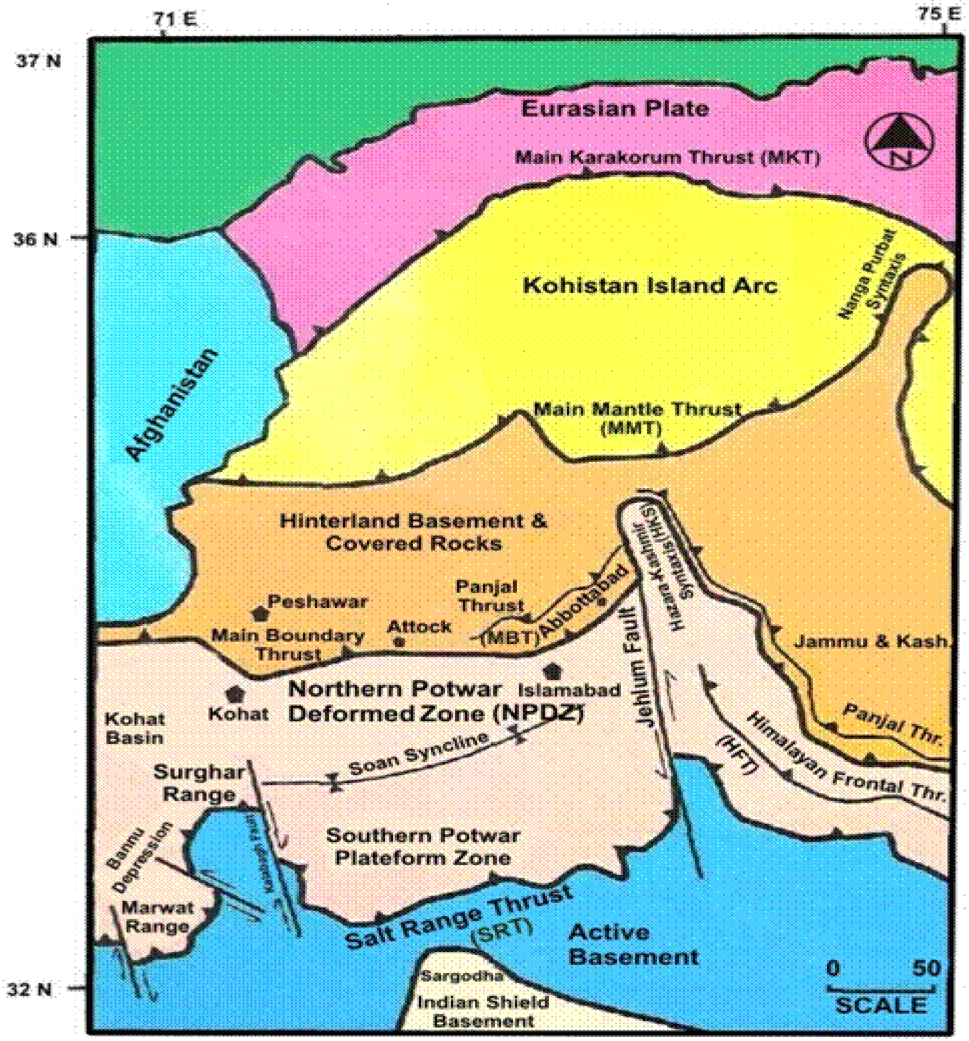


Figure 1- Regional tectonic map of northwest Himalayas of Pakistan.

SURFICIAL TECTONIC SCARS

The mega-geotectonic features exposed on the surface as faults (Fig. 1) in Kashmir-Hazara terrain are geologically mapped as: (i) Hazara-Kashmir Syntaxis, (ii) Main Mantle Thrust, (iii) Main Boundary Thrust, (iv) Panjal Thrust, (v) Hazara Thrust and (vi) the Jhelum Fault (JF). All these faults occur as major lineaments traversing the Kashmir terrain. Detailed investigations conducted on these faults had shown body movements in some but their contribution to seismicity were poorly known till the availability of seismic data monitored through the WAPDA Tarbela and Mangla Dam Seismological Observatories.

a. Hazara - Kashmir Syntaxis is an anomalous folded structure which emanates from the Pir-Panjal Range in Kashmir and extends northward till Balakot where its western limb takes a loop to southwest and extends with this trend towards Muzaffarabad. Calkin et al (1975) had reported a reversal movement on the faults along the western limb of the Syntaxis. He suggested that the amplified southwest pressure from the Himalayan boundary faults on the eastern limb of the Syntaxis is responsible for this reversal. This tectonic scenario in the Syntaxis point out to the main compress ional movements which are shifting to the west and northwest and stresses generated are stimulating its western limb, which is the abode of the Main Boundary Thrust. The earlier Muzaffarabad Fault, a terminal branch of MBT and the recent mega earthquake of October 08, 2005 are located on the western limb of HKS and are the product of release of energy stored in this zone by east-west convergence of the HKS. Based on the migration of the epicenters the rupture created by the devastating event is geologically extended between Bagh and Balakot in Kashmir. The latest information in hand reveals that seismologically this rupture is gradually extending towards northwest at shallow depth and resulted in eruption of over four thousand aftershocks of magnitude 3 - >5 so far which are concentrating on the northern ebb of the HKS.

b. Main Mantle Thrust (MMT) is the youngest suture of the Himalayan domain which buckles the Kohistan arc with the Indo-Pak and the Eurasian plates in the south and north respectively. The thrust after looping around the Nanga Parbat-Haramosh massif adopts its course along the northwestern fringe of Kashmir and Hazara, thus tectonically separating this terrain from the Kohistan Island arc. MMT is seismically active and beside being the source of continuous eruption of low to moderate seismic events within its zone, has also on its record some major earthquakes with their epicenters located at Malakand, Astore, and Pattan in Kohistan. In these events the seismicity ranged between magnitude 5.5 and 6.1. The Pattan earthquake of 1974 with magnitude 6.1 is the highest level of seismicity erupted in the MMT Zone adjacent to the Kashmir terrain.

c. The Main Boundary Thrust (MBT) is one of the youngest among the three mega shears of the Himalayas which runs all along its length for about 2500 km and in depth it is shallower than the others. MBT with its tangled roots in the Detachment, one of the Himalayan Boundary Faults well netted in the Himalayan orogeny will remain a major threat capable of generating earthquakes of October 08, 2005 level anytime and anywhere in the region which comes under its fold. It is competent to generate major events with large ruptures. Its seismic history reveals several great events spread all along its course in the Himalayan domain. To mention a few, Kangra (1905) and Bihar (1934) in the Middle and Eastern Himalayas are the ones which had generated magnitude> 8 level earthquakes. Some of the major towns which come under the seismic shadow of the MBT in Pakistan are Balakot, Muzaffarabad, Islamabad, Nathiagali, Murree, and Fateh Jhang and across the Indus is Kohat.

d. The Jhelum Fault (JF) is located at a distance of about 50 km East of Islamabad. This fault was reported by original researchers to extend along Jhelum River from north of Muzaffarabad to near Jhelum and further southward to Chaj Doab area. During recent studies it was investigated whether this fault extends southward up to Jhelum or not. Oil and Gas Development Company Ltd. (OGDCL), has mapped a fault parallel to Jhelum River up to Palala Mallah, beyond which it takes a southwest bend and extends parallel to other faults (Dil Jabba, Lehri) of the area as a thrust fault. The unexplained aftershocks of the Kashmir Hazara earthquake are in fact due to the stresses loading the JF. When adapted to the left lateral mechanism of this fault, the calculations indicate that its northernmost, north-south striking segment has indeed being brought considerably closer to the left-lateral strike-slip rupture, with a 15-20 bars increase in such stresses. This may be taken to specify that, in years to come, another ≈ 7.5 earthquake might nucleate near Muzaffarabad, with a dislocation propagating southwards on the JF.

DEEP CRUSTAL DEFORMATIONS

The locations and configurations of the deep crustal deformations of Hazara-Kashmir terrain were deduced from the seismic data collected from the Tarbela and Mangla Dam Seismological Observatories. The seismic observations revealed three zones of mega crustal deformations: (i). The Indus Kohistan Seismic Zone (IKSZ), (ii). The Hazara Lower Seismic Zone (HLSZ) and, (iii). The Tarbela Seismic Zone (TSZ).

i. The IKSZ is one of the most clearly defined deep crustal structure which extends northwestward beyond the nose of Hazara - Kashmir Syntaxis. In the northwest, it terminates in the vicinity of Pattan in Kohistan and its tectonic relationship with the Main Mantle Thrust, the southern Himalayan suture, buckling Kohistan Arc with the Indo-Pak Plate is not well defined. However, it is believed that the increase in its seismicity close to its northern termination may be due to its interference with the active part of the MMT. After the October 8, 2005 earthquake, with its epicenter located in the MBT zone on the western flank of Hazara-Kashmir Syntaxis, the post shock seismic events are migrating towards the northern ebb of the Syntaxis. It appears these shocks have activated the IKSZ; as a result the post shock seismic events are concentrating on its south-eastern termination in the vicinity of HKS. Among over 1800 post shocks events, quite a number of events ranging between magnitudes 4 and 5 have so far been recorded in this zone.

ii. The Hazara Lower Seismic Zone strikes southwest and runs at a distance of 70 km to the southeast of IKSZ. It is a vertical right lateral strike-slip fault and is interpreted as the western extension of the Main Basement Fault. The HLSZ passes underneath the Tarbela Dam network at a maximum 50 km depth and a part of this zone which is seismic occurs between 18 and 8 km below the surface. Its historical seismicity on its western extension reveals epicenters of low to moderate magnitude. Armbruster et al (1977) has described a north-east dipping fault which branch off the HLSZ and extends north-west at about 35 km depth. This offshoot has been found to be feebly active and its extension is recorded underneath the TDN. It has been tentatively interpreted by him as the Hazara Thrust. This interpretation brings the two structures; the surficial Mid. Valley Fault and the deep crustal Hazara Thrust more or less following the same trend under the Tarbela Dam Network. The seismicity on HLSZ basement fault is low relative to the seismicity on the IKSZ, although both the seismic crustal structures can be traced seismically for at least 100 km (Seeber and Armbruster, 1979A). They consider the Taxila event of 25 AD could be associated with the earthquake generated by the HLSZ.

iii. The Tarbela Seismic Zone (TSZ) constitutes sharply bounded clusters of hypocenters near the centre of the Tarbela Dam Network which overlies the north-south striking Hazara Lower Seismic Zone. The seismic zone is 25 km long, 15 km wide and 20 km deep lying below the Tarbela Dam Network and sharply truncated by the detachment at its lower boundary at 17 km depth. During 1973-76, out of the 8000 local events recorded at TDSO, 1495 were generated in the area lying within the fold of Tarbela Seismic Zone. Their hypocenters range from 0 to 20 km depth, with local events varying from magnitude 2 to 5.5. Seeber et al (1974) has considered this zone a potential source of the maximum credible earthquakes (M. 6.5) for the Tarbela site.

SOURCE & KINEMATICS OF KASHMIR HAZARA EARTHQUAKE

The epicenter of Kashmir-Hazara earthquake lies exactly on the JT-IKSZ, below the Pir-Panjal trace of the MBT. The

Kashmir Hazara Earthquake (KHE) of October 08, 2005, is thus clearly an event that activated only the JT, somewhat upwards and southwards of its inferred intersection with the Pir-Panjal MBT (Fig. 2). This may be taken as credible idea that the later is now inactive, having been superseded by the JT.

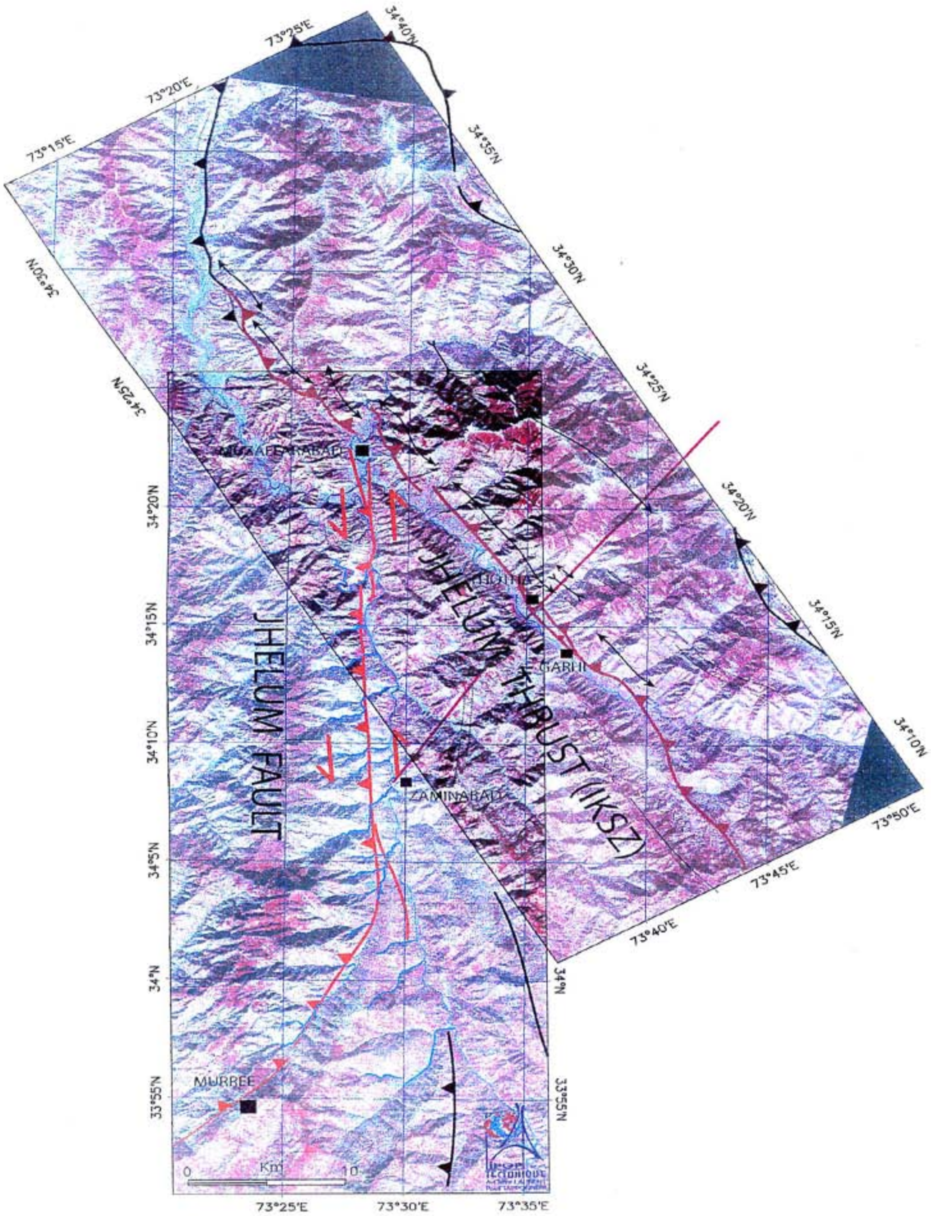


Figure-2 Orientation of Jhelum Thrust & Jhelum Fault.

Moment of the earthquake was projected to range between 2 and 3 x 10^{27} dyne.cm that match to a moment magnitude of Mw on the order of 7.7. The rupture time was computed as $\approx$ 30 sec. Seismic Studies Program (SSP) WAPDA, Mangla and several other groups (Figure 3) came up with fairly well constrained Fault Plane Solution. The best fit for the attitude of the nodal plane coinciding with the fault plane yield a rather well constrained azimuth of $\approx 330^0$, and somewhat less constrained dip of ≈ 35 -40^0 towards the NE. It is in amazing agreement with the JT surface trace mapped in the field. The scrap of fault that slipped during the earthquake may be approximated by an ellipse 50-70 km. long in the NW-SE direction, and 20-30 km. wide in the transverse direction. The length of this pair is in fair conformity, with the length of the fault along which major surface deformation is observed in the field, from Balakot to the mountains south of Hattian (50-60 km., up till 70 km). Fault Plane Solutions computed by various groups indicate thrust faulting with a slight lateral component. In view of the regional tectonics, aftershock activity, fault plane dipping to NE should be the causative fault, and the lateral strike-slip component of the faulting implies dextral motion of the fault. The unexplained aftershocks rupture of other faults having different focal mechanisms. Of particular interest the aftershocks that lie in the West of JT and on either side of Jhelum river valley downstream of Muzaffarabad, They lie in the area crossed by the other major active fault of the region, the Jhelum fault, which extends southwards of Muzaffarabad in the NS direction, before veering west towards Murree and Islamabad.

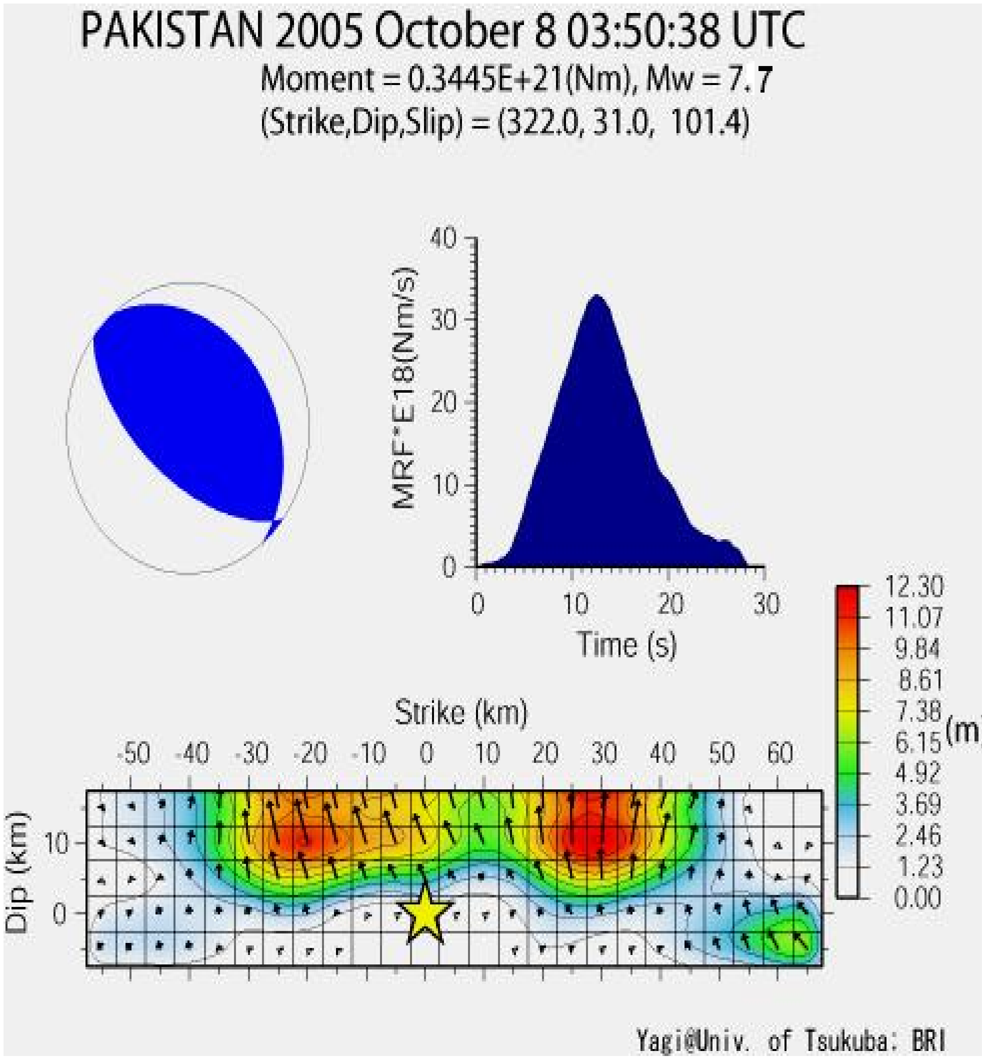
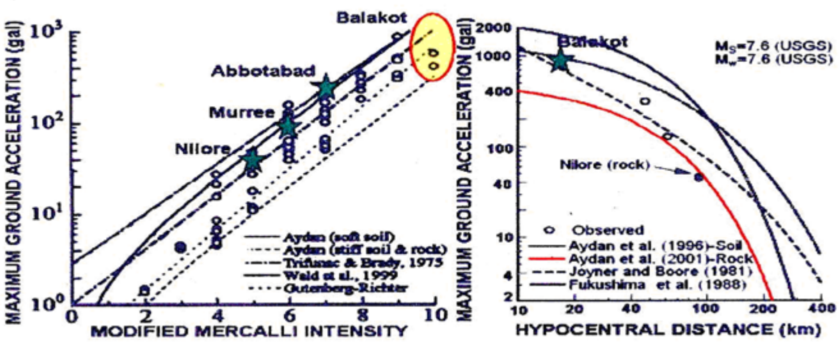


Figure 3. Focal Mechanism of Kashmir Hazara Earthquake

STRESS CHANGES INDUCED BY KASHMIR-HAZARA EARTHQUAKE

The occurrence of Kashmir-Hazara earthquake confirms that the active Jhelum Thrust and Jhelum Fault, in a region located well north of the Main Himalayan Frontal Thrust accommodate generally EW oriented, present-day shortening related to “zipper tectonics” within the tightest part of the KHS (Figure-2). Such EW shortening is an outcome of slip-partitioning at a much greater scale, co-involving the Chaman Fault to the west and Karakorum fault to the northeast. From the locations of aftershocks it is observed that greater part of the aftershocks of the Kashmir-Hazara earthquake presents increased stresses north of Balakot and south of Hattian. Shinkari seismic station installed by the WAPDA Seismic Observatory during 1973 effectively detected the IKSZ very close to its location during 1973-78. Since the October 08, 2005 earthquake and till date clusters of events are being recorded allover the IKSZ. Such stress increases may have brought the Kotli-Riasi Thrust, to the south, and the Indus Kohistan Seismic Zone ramp north of Balakot nearer to rupture. Many aftershocks remain unexplained because they fall in lobes of decreased Coulomb stress. These aftershocks thus most likely reflect rupture of other small faults with different focal mechanisms. Of particular interest is the concentration of aftershocks due west of Jhelum Thrust, along and both sides of Jhelum river valley downstream from Muzaffarabad. They lie in the area crossed by other major active fault of the region, the Jhelum Fault (JF), which extends southwestwards from Muzaffarabad in a NS direction, before veering west towards Murree and Islamabad.



(a) Relation between Amax and MKS (b) Attenuation of Amax with distance

Fig 4. Relation between MKS and maximum acceleration and its attenuation.

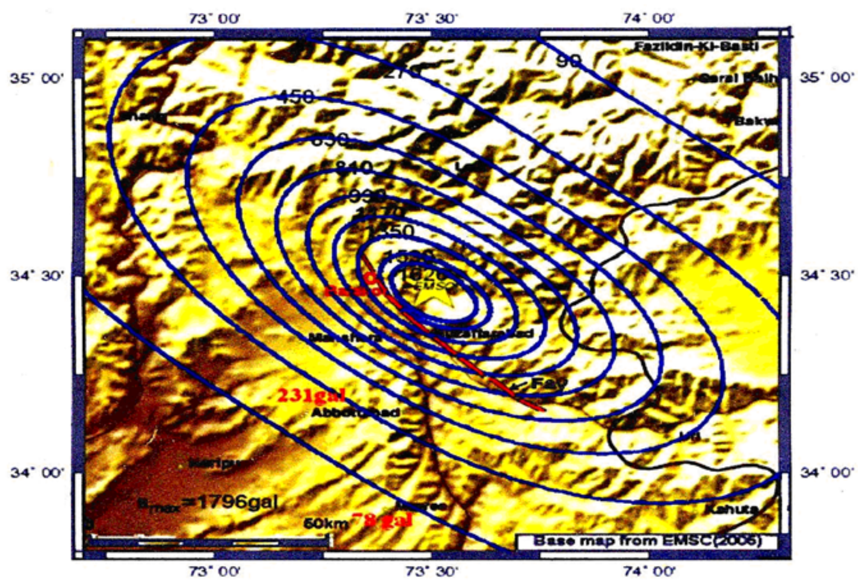


Fig 5. Estimated iso-acceleration contours for soft ground.

Table-1. Accelerations records on October 08, 2005.

SMA Location	Acceleration in 'g'			
	Vertical	Longitudinal	Transverse	Resultant
Abbottabad	0.087	0.231	0.197	0.316
Mirpur/Mangla	0.040	0.065	0.055	0.152
Tarbela	0.065	0.075	0.024	0.150
Diamer Basha Project	0.030	0.081	0.067	0.130
Ghazi (Barrage)	0.070	0.079	0.069	0.190
Attock (Power Complex)	0.061	0.074	0.070	0.120
Murree	0.069	0.078	0.075	0.128

STRONG GROUND MOTIONS

There are several Strong Motions Accelerograph (SMA) networks operated by different institutions of Pakistan. The institutions are Pakistan Water & Power Development Authority (WAPDA), Pakistan Atomic Energy Commission and Pakistan Geological Survey. It was possible to obtain the SMA records of seven stations in operation when the October 08, 2005 earthquake occurred.

The nearest station to the epicenter is Abbottabad and its response spectra are very flat for the natural period of 0.4 and 1.5 sec. As the distance increases, the longer period components become dominant as observed in the Nilore and Mangla record. Murree SMA is situated nearby the peak of the mountain and its response is likely to be influenced by the geometry and structure of the mountain. The signal from Abbottabad is the most usable of the three records presented, since it is obtained from an area where significant damage has occurred. Focusing the Abbottabad record the 5 % elastic spectrum shows a relatively broad range of high amplification, from 0.4 to 2.0 seconds. The highest amplification is about 4.0. This is compared to the value of 2.6, which is the 84 percentile amplification factor given by Newmark and Hall (1982), thus indicating the relative severity of Abbottabad record. Such a feature would result in relatively high demand imposed on both short and intermediate-long period structures. The maximum ground acceleration for Balakot was inferred at least 0.9 g from overturned vehicles in the direction parallel to the axis of valley. This probably represents the largest ground acceleration in the epicentral area. Balakot is situated on the hanging wall side of the causative fault. The attenuation of observed maximum ground accelerations are compared with some empirical attenuation relations in Figure-4. The contours of iso-acceleration on the ground surface for soft ground are shown in Figure-5. The ground acceleration on firm or rock ground would be 1/3 to 1/5 of those for soft ground. The maximum ground acceleration at the epicenter was estimated to be 1786 gal. Although this value seems to be quite high, it should be acceptable in view of the maximum ground acceleration recorded at Ojiya and Tookamachi during the 2004 Chuetsu earthquake. The surface extrapolation of the causative fault is also shown in the same figure. Furthermore the, the maximum ground acceleration recorded at Abbottabad is in accordance with the estimated iso-acceleration contours.

CONCLUSIONS & RECOMMENDATIONS

The October 08, 2005 Kashmir Hazara earthquake originated along the Jhelum Thrust (JT), which is a recent offshoot of the Pir-Panjal Thrust (PPT). Field rupture observations indicate that it is not a blind fault as known before. Location of abnormal number of aftershocks till date verifies that the mega earthquake imposed increased stresses on the Indus Kohistan Seismic Zone and Jhelum Fault Zone, which can result in another major earthquake in the near future. It is recommended that a detailed seismic hazard assessment is carried out in the affected areas prior to the commencement of reconstruction. This study should be comprehensive and should also incorporate the latest information on geology, tectonics and seismicity in the area. A detailed seismic hazard assessment would allow the ground motions to be estimated in order to be used for seismic design and the evaluation of the impacts by secondary hazards such as landslides. The future strain buildup, uplift rates, slip rates, recurrence intervals and seismicity in the area along JTZ, need to be monitored continuously, in order to avoid major human disasters like the Kashmir Hazara October 08, 2005 earthquake. It requires installation of seismic and accelerograph networks.

REFERENCES

A. A. Khwaja, Monalisa., S.A. Khan, M. C. Rafiq and A.T. Khan, Recent Seismic Activity along the western margin of the Nanga Parbat - Haramosh Massif, Pakistan. Islamabad Jour. Of Science Vol.13 (1).

A. Gansser, A., 1964. Geology of the Himalayas. Wiley, New York.

Ali. H. Kazmi, and M.Q. Jan, Geology and Tectonics of Pakistan. Graphic Publishers Karachi – Pakistan, (1997).

E.R. Gee, Pakistan Geological Salt Range Series ;(6 sheets, scale 1: 50,000). Directorate of overseas surves, UK for the Gov. of Pakistan & Geol. Surv. Pak, (1980).

I.P. Madin, R.D. Lawrence and S. Rehman, The northwestern Nanga Parbat-Haramosh Massif. M.Sc. thesis, Oregon State Univ., Corvallis, (1989).

Le Fort, Patrick and A. Pecher, An introduction to the geological map of the area between Hunza and Baltistan, Karakoram-Kohistan-Ladakh-Himalaya Region, Northern Pakistan (Scale 1: 150, 000). Geologica, Vol. 6, No.1, (2002).

L.L. Malinconico, 1989. Crustal thickness estimates for the western Himalaya. In Malinconico, L.L. & Lillie, R.J. (eds.). Tectonics of the western Himalayas. Geol.Soc.Ammer, Spec. paper.

L. Seeber, R.C. Quittmeyer and J.G. Armbruster, 1980, Seismotectonic of Pakistan: A review of results from network data and implications for the central Himalayas. Geol. Bull. Univ. Peshawar, Vol. 13

Mahdi, S. K., (1999 through 2005), "Annual Seismicity Reports for Tarbela & Mangla Dams Pakistan, (unpublished office files).

Mahdi, S. K., Et. Al., (2003), "FORTRAN Language Computer Program for the Seismotectonic Studies of Tarbela and Mangla Dams" (unpublished).

Mahdi, Syed Kazim, The Pir Panjal Earthquake & Aftershocks, Report on the October 08, 2005 Mega earthquake, Unpublished Office Files.

Monalisa et al., Seismic Hazard Assessment of NW Himalayan fold and thrust belt, Pakistan, using probabilistic approach, Proc. Pakistan Acad. Sci 42 (4) 2005.

Monalisa, A.A. Khwaja, and M. Qaiser, Focal Mechanism Studies of Kohat and Northern Potwar deformed Zone. Geological Bulletin, University of Peshawar, Vol.35, (2002).

Monalisa, S. A. Khan and A. A. Khwaja. Focal Mechanism Studies of North Potwar Deformed Zone (NPDZ), Pakistan. Acta Seismologica Sinica, China. Vol.17 No.3, (2004).

P.J. Treloar, D.C. Rex, P.G. Guise, M.P. Coward, M.P. Searle, B.F. Windley, M.G. Petterson, M.Q. Jan, and I.W. Luff, K-Ar and Ar-Ar geochronology of the Himalayan collision in NW Pakistan: Constraints on the Timing of collision deformation, metamorphism and uplift tectonic, Tectonics, Vol. 4, (1989).

R.A.K. Tahirkheli, M. Mattauer, F. Proust, and P. Tapponier, The India-Eurasia suture zone in northern Pakistan: Some new data for interpretation at plate scale. In: Farah, A. & DeJong, K.A., (eds.).Geodynamics of Pakistan. Geol. Surv. Pak., Quetta, (1979).

W.J. Sercombe, D.A. Pivnik, W.P. Wilson, M.L. Albertin, R.A. Beck and M.A. Stratton, Wrench Faulting in the northern Pakistan foreland. AAPG Bulletin, v. 82, (1998).