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Pakistan's Kashmir-Hazara Zone and the October 08, 2005 Earthquake

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PAKISTAN'S KASHMIR-HAZARA ZONE AND THE OCTOBER 08, 2005 EARTHQUAKE

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ABSTRACT

A mega shallow depth earthquake originated from the Pakistan's Kashmir Hazara Zone (KHZ). The KHZ under the context of regional surface and sub-surface geology displays a complex seismotectonic scenario. Its earthquake prone structures occur both exposed on the surface as major faults/folds and also at depth beneath the surface as mega crustal deformations. Former are visible and have been investigated geologically by mapping and their surface behaviour verified by various geophysical methods, whereas the deeper ones interpreted by the monitoring of seismotectonic events.

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) and the recent shallow depth (16 km.), Mw = 7.7 earthquake of October 08, 2005 and aftershocks are located on the western limb of KHS and are 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 length of this patch is in fair agreement with the length of the fault along which significant surface deformation is observed in the field, from Balakot to the mountains south of Hattian.

INTRODUCTION

A large devastating earthquake of Mw = 7.7 occurred in the Pakistan's Kashmir-Hazara zone on October 08, 2005 at 0350 UTC, killing over 0.1 million people. According to the Seismic Studies Program WAPDA, Pakistan, the earthquake occurred at 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, and the faulting mechanism solutions indicated that the earthquake resulted due to thrust faulting. Muzaffarabad and Balakot cities of Kashmir, Pakistan, where the Modified Mercalli Intensity reached a maximum of X were the most effected. Epicenter of the Kashmir-Hazara earthquake was located at the western periphery of the Himalaya (Figure-1), where the arc meets the Karakorum, Pamir, and Hindukush ranges. The physiography of the range, as well as tectonic structure defines a syntaxis, called the Kashmir Hazara Syntaxis (KHS), outlined by the hairpin rotation of the Main Boundary Thrust (MBT). The MBT is a most important fault bounding the Himalayan range that has thrust metasediments of the Lesser Himalaya over the Tertiary molasses of the Himalayan foreland. Active deformation in the area results from the 3 cm/yr northward notch of the northwestern Indian Peninsula into Eurasia. Along the northwestern Himalaya, a fraction of that junction, estimated to about 1.4 cm/yr, is absorbed by thrusting.

REGIONAL GEOLOGY

In Kashmir-Hazara region of Northern Pakistan the orogen is composed of three main tecton-ostratigraphic terrains, the Asian plate to the north, the Indo-Pakistan plate to the south, and the Kohistan island arc sandwiched between (Figure-2). The Kohistan arc can be divided from the Asian plate by the Northern or Shyok Suture and from the Indian plate by the Main Mantle Thrust (MMT). The Asian plate Karakorum is divided into the Northern Sedimentary terrain of Paleozoic and Mesozoic Formations, the Karakorum Batholiths of Cretaceous to Miocene age, and the Kohistan arc, consist of

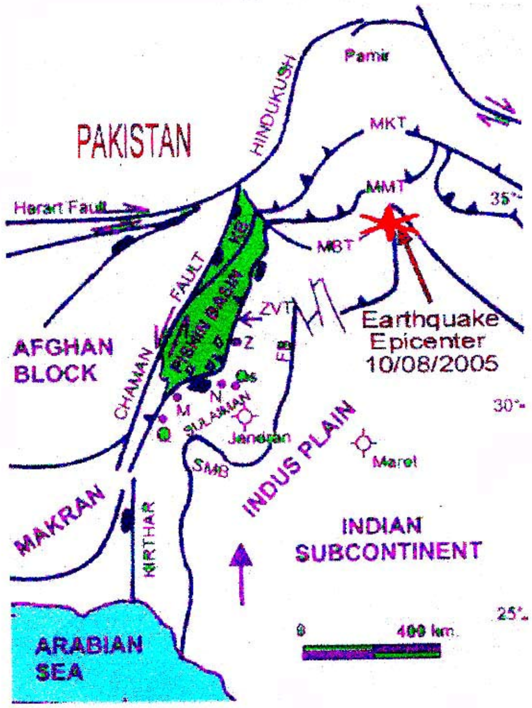


Fig. 1 Map of the Main Active Fault in Pakistan. Main Karakorum Thrust (MKT), Main Mantle Thrust (MMT), Main Boundary Thrust (MBT) & Location of October, 08, 2005 Earthquake

Late Cretaceous and Eocene plutonic belts, and pyroxene granulites, calc-alkaline volcanic, amphibolites, and minor metasediments. The Indian plate can be sub-divided into three tectonic unit's viz. (from north to south these are) (1) an internal metamorphosed unit, (2) an external un-metamorphosed or low grades metamorphosed unit, and (3) the foreland basin sediments. The internal unit consists of cover and basement rocks. The basement rocks are predominantly high-grade gneisses; the cover rocks are predominantly greenschist to amphibolites grade metapelites and metapsammites metamorphosed during the Himalayan orogeny. The internal zone is separated from the external zone un-metamorphosed to low-grade metamorphic Precambrian sediments and dominantly Mesozoic to Eocene Tethyan shelf sediments by the Panjal Thrust (PT). Farther to the south, the MBT separates these rocks from the Tertiary foreland basin deposits. The Main Frontal Thrust (MFT) delineates the southernmost extent of the foreland basin fold and thrust belt.

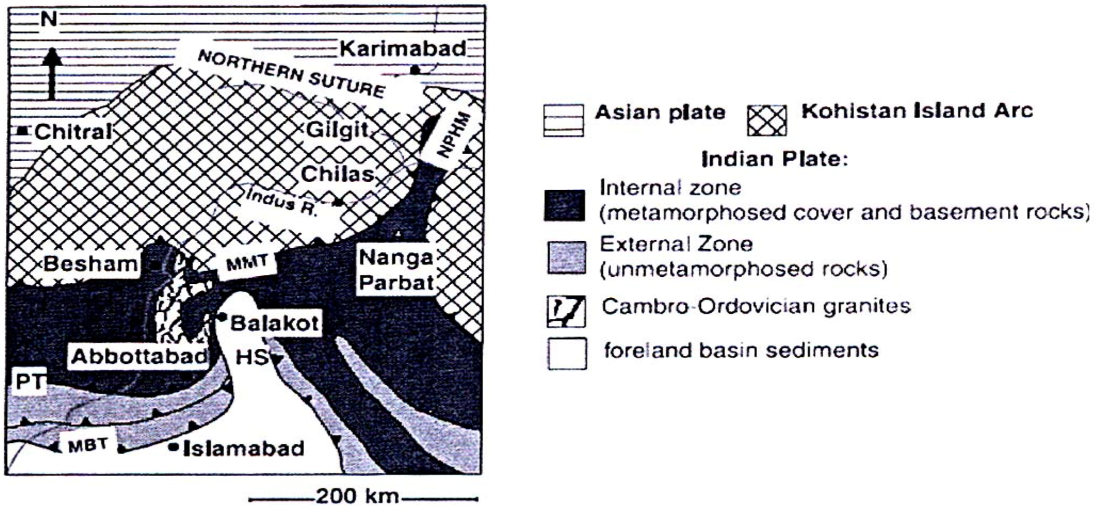


Figure 2. Regional Geology of Kashmir

The more than 8 km thick red bed Balakot Formation in the KHS as a steeply north dipping, normal homoclinal stratigraphic succession, conformably overlying the Paleocene-aged shallow marine Patala Formation and Lockhart Limestone. The Balakot Formation is truly variably deformed and folded by a series of tight folds (wavelengths and amplitudes of I km). The Patala and Lockhart Formations unconformably overlie the Late Precambrian to Cambrian Abbottabad Formation, which forms the core of the Muzaffarabad anticline. The lower part of the Balakot Formation is structurally imbricated and isoclinally folded with the Patala Formation, which in turn is in thrust contact with the overlying Abbottabad limestones. The entire package is complexly faulted, with systematic top to the southwest thrust shear sense. Therefore, in summary, the Balakot Formation red beds lie in thrust contact with the Paleocene aged shallow marine Patala Formation and Lockhart Limestone below, and are tectonically intercalated with an underlying dark gray marl formation (Mahdi 2007).

Jhelum Fault is a NE dipping strike-slip fault following the western margin of HKS bend. Rocks belonging to Miocene, Cambrian and Pre-Cambrian periods exposed along its trace are highly deformed due to recurring shear zones. Individual blocks of the Panjal Volcanic and Triassic limestones have been found dragged for several kilometers southward. An accumulative left-lateral offset of about 31 km is indicated on the western limb of the Syntaxis. It apparently dislocates from the Main Boundary Thrust and terminates at the eastward continuation of some of the geological structures of North West Himalayan Fold and Thrust Belts. These tectonic relationships indicate Jhelum fault as the youngest major tectonic feature in the syntaxial zone (Mahdi et. al. 2006).

KASHMIR HAZARA TERRAIN

The Kashmir Hazara terrain lying in the lesser Himalayan belt constitutes the NW segment of the Indo Pakistan plate. This part of the plate has been grilled by two continental accidents; the earlier one 100-75 my ago when the Indo-Pakistan Plate collided with Eurasia, annihilating the Palaeotethys. The second accident occurred about 55 – 60 my ago when the Kohistan Arc created by the intraoceanic subduction ahead of northward drifting Indo-Pak Plate again collided with Indo-Pak Plate and annihilated the Neo-Tethys.

After the initial collision, the Indo-Pak plate started under-thrusting the Eurasian Plate and according to an estimate over 700 km of the Indo-Pakistan Plate has been consumed under Eurasian plate. The uplift of the Tibetan Plateau and Himalayan Belt and their attaining higher elevation is considered as a result of under-thrusting the Indo-Pak Plate underneath Eurasia. Even now the northward subduction is continuing at the rate of 3-4 cm per year and stresses generated by this convergence movement have given rise to extensive southward directed thrust system which is successively migrating to the south and being accommodated by the major shear zones including those of Kashmir and Hazara.

The active tectonics created by the plate movements or deep crustal disturbances induce body waves which are seismic and travel through the earth's interior, spreading outward from the epicenters in all directions. These waves are capable of triggering the dormant faults and could transform an Aseismic zone into seismic.

The Kashmir Hazara terrain under the context of regional surface and sub-surface geology displays a complex 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 visible and can be brought within the fold of geological investigations by conducting geological mapping and their subsurface behaviour can be verified by adopting various geophysical methods, whereas the deep crustal deformations occur at depth and their tectonic turbulences and configuration can be deduced by monitoring deep crustal seismicity (Armbruster et. al. 1978).

The mega-lineaments (Himalayan Boundary Faults) running parallel to the Himalayan front play an active role in geotectonic evolution of its frontal domain. Seeber et al (1983) based on seismic data delineated two major deformational anomalies at crustal level called Detachment Fault and Basement Fault. The Detachment is nearly a horizontal fault and separates the under thrusting Indo-Pak shield from the overlying metamorphic and sedimentary rock formations. The Basement marks the line separating the shallow dipping Detachment Fault from the steeper dipping Basement. Thus under this context the fault in the Kashmir-Hazara terrain are categorized either being the offshoots of Basement or Detachment.

The seismicity associated with the Basement Thrust is relatively continuous with a reduced upper magnitude limit in the earthquake. In case of Detachment a rupture occurs in vast area in a single event and it generates great earthquakes.

The earthquakes are categorized as shallow at depth range up to 70 km beneath the surface, intermediate between 70 -350 km and deep between 350 – 670 km. Following Quittmeyer et al (1979) as qualifier for the earthquake sizes, an earthquake is considered moderate with magnitude 6 – 7, major between 7 – 7.8 and great > 7.8.

SEISMOTECTONIC

Seeber, et. al. (1983) has used microseismic data from the Pakistan's Tarbela and Chasma microseismic networks to develop a seismotectonic model for the KHS region in Pakistan. According to them there exist a sub-horizontal decollement as an interface between the sedimentary and meta-sedimentary wedge and the basement. However, they have also discerned two parallel clusters of epicenters associated with the basement faults, extending towards NW from the KHS, which they interpreted as the deeper level NW extensions of the structural trends in the Kashmir Himalaya, east of Syntaxis. Out of the two zones/clusters the NE one, which they preferred to call Indus Kohistan Seismic Zone (IKSZ), is currently more active and indicates predominantly thrust type movement. The other zone towards SE, named as Hazara Lower Seismic Zone (HLSZ), indicates basement faults with predominantly strike-slip right lateral movement.

Monitoring by the local Tarbela seismic network around the KHS has revealed an alignment of seismicity, called the Indus Kohistan Seismic Zone (IKSZ). The IKSZ strikes parallel to the north-western Himalaya, but extends beyond the HKS. This seismicity extends northwestwards the belt of seismic activity that follows the front of the entire Himalaya. This is an indication that northwest-trending Himalayan basement structures extend beyond the syntaxis and that the change in the strike of the MBT is a rather superficial feature, probably related to the infrac-ambrian salt.

The fault that ruptured during the October 08, 2005, Mw 7.7 earthquake is a thrust has been identified characteristically along the Jhelum valley from Muzaffarabad to Garhi and farther south. Before the earthquake this south-west vergent thrust was not accurately mapped on the 1/50,000 scale geological maps (trace mostly along the Jhelum, with a dip towards west!), except in the instant vicinity of Muzaffarabad where it evidently emplaces Precambrian (mostly white-grey dolomites) capped by early Eocene nummulitic limestone on top of the schistosed Murrees (Figures 3 & 4). When visited in the field the JT stands out undoubtedly in the geomorphic landscape of the middle-Jhelum valley. Thus it is more justified to be called as Jhelum Thrust (JT). Previously it has been mapped and identified as Tanda-Muzaffarabad fault. However, at that time just the northern stretch of the fault was assumed to be active.

It is certainly the west directed thrusting on the JT that has made the Jhelum valley strongly asymmetric: the river incises

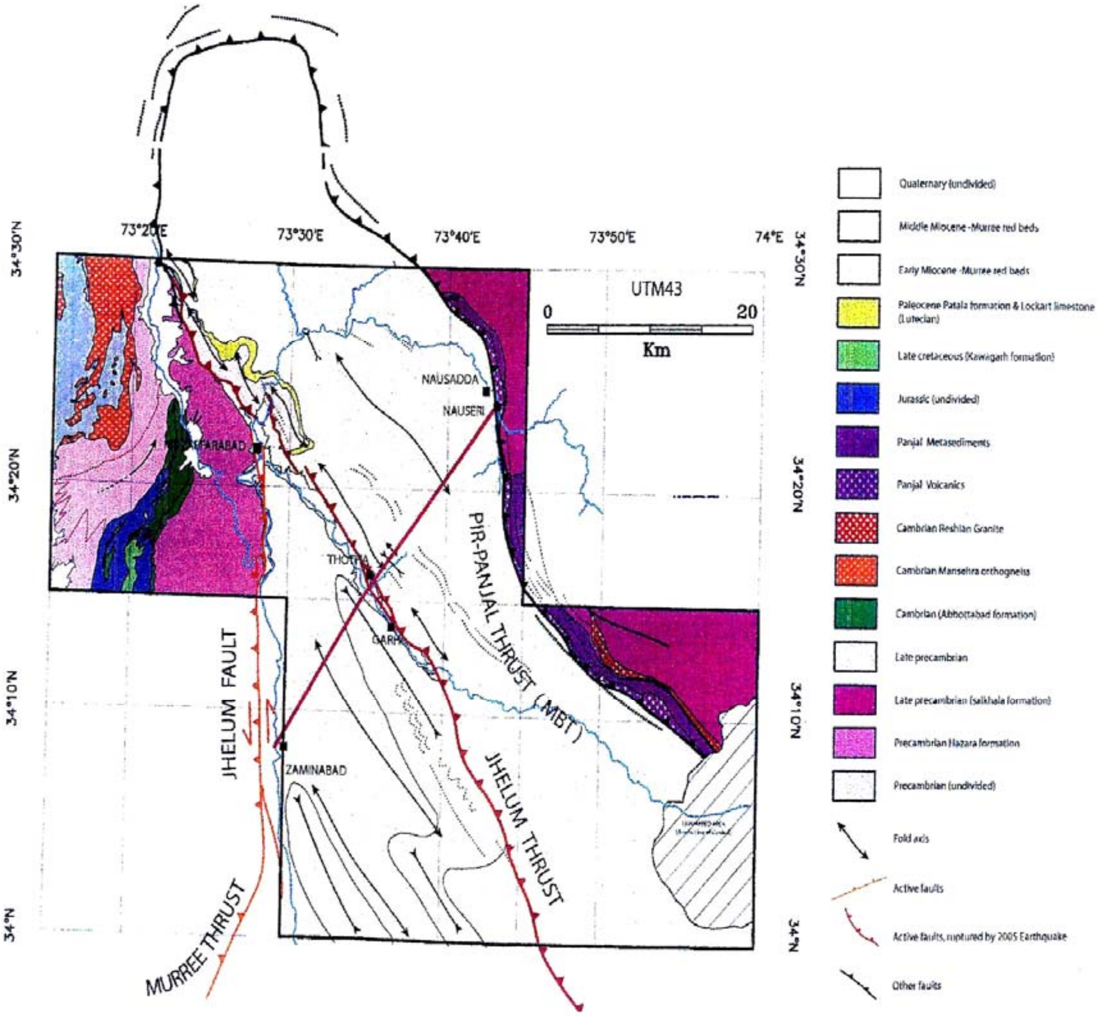


Fig. 3. Geology and Seismotectonic of Kashmir Hazara Region.

in a straight line 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) because it keeps being enforced southwestwards by the rise of hanging wall. Near Thotha, such fluvial terraces, which include far-traveled boulders, stand more than 200 meters over the riverbed. Tributary catchments east of the river, where mountain heights reach 3200 meters, are well developed, while they are nearly insignificant along the west bank, where there is a less relief (≤ 1400 meters). This is because deep incision is promoted by the rise of the JT's hanging wall. Just north of Muzaffarabad, the thrust steps leftwards across the Neelum, continuing into the Kunar valley alongside high faceted spurs to no less than Balakot. It might extend farther than west, north of Manshera. As discussed later, the steps at the Jhelum crossing is one place where some of the most remarkable cumulative seismic displacements (uplifted terraces) on the JT are observed. These steps (Figure-2) are interpreted to reflect offset of the JT by the Jhelum Fault (JF), which is a confirmed active fault (Mahdi 2007).

The JT is less well-known geological than geomorphic feature, because it cuts mostly across rocks of similar age. This may explain, in part, why it had not been clearly documented and mapped up till now. In cross section, it dips eastwards below a large hanging wall anticlinorium of schistosed Murree red-beds, whose escalation it has orchestrated. Only in the vicinity and than scarcely, dose this anticlinorium's core exhumes the Precambrian substratum of the red beds, near Muzaffarabad. This indicates that the JT is very youthful feature (possibly only a few million years old).

Undoubtedly the JT match up neither to the Main Frontal Thrust (MFT), Main Boundary Thrust (MBT), Main Central Thrust (MCT) and nor to other "Dun" thrusts which have been mapped farther West. Somewhat it coincides with a segment of the well known Indus Kohistan Seismic Zone (Figure 4), lateral equivalent of the principal ramp of the Main Himalayan Thrust (MHT) in Nepal. As confirmed by the outstanding evidence of surface rupture, described in the later topics, it is now definite that at the discussed location (unlike in Nepal), the JT reaches the surface instead of remaining blind. The idea that thrusts like JT should be blind everywhere, is so deep-seated in most minds, that till date no surface rupture had yet been realistically mapped, and most landscape disturbances had been interpreted to reflect slope instability and mass-wasting.

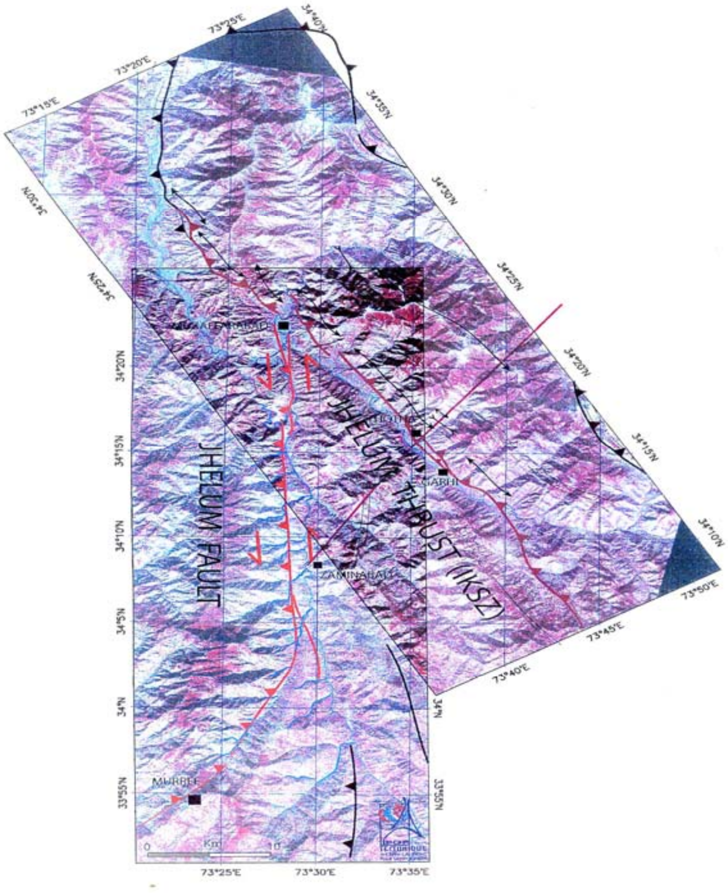


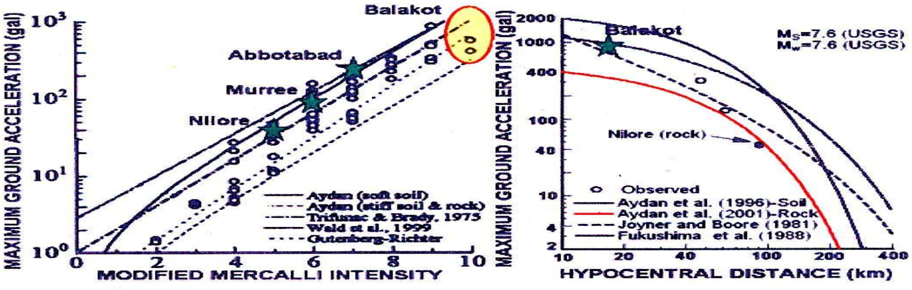
Fig. 4 Orientation of Jhelum Thrust & Jhelum Fault.

Actually, it is now clear that the JT provides a typical example of the foreland thrust migration. It is a recent offshoot of the Pir-Panjal Thrust (PPT), which jumped southwestwards by about 20 km possibly in the last five million years only. The geometry is consistent with this interpretation and depicted in the section of Figure-3. Due to this reason the Seismic Studies Program (SSP), WAPDA Mangla Project, named the earthquake on the very first day (October 08, 2005) as Pir-Panjal Earthquake (Mahdi 2005). However, later owing to the vast deaths/destructions in whole of the Kashmir-Hazara region it was afterwards named as the "Kashmir Hazara Earthquake" (Mahdi et. al. 2006).

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 1.5s. 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. Compared with the records of Abbottabad and Nilore stations, it seems that there is also a dominant natural period of about 0.2 - 0.25s (Figures 8, 9, 10 & 11).

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 constant ductility spectra shown in Figure-12 indicate rather low strength demand for highly ductile structures (of ductility of 4.0 or more), and average demands for intermediate ductility structures (of ductility around 2.0).



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

Fig 5. Relation between MKS and maximum acceleration and its attenuation.

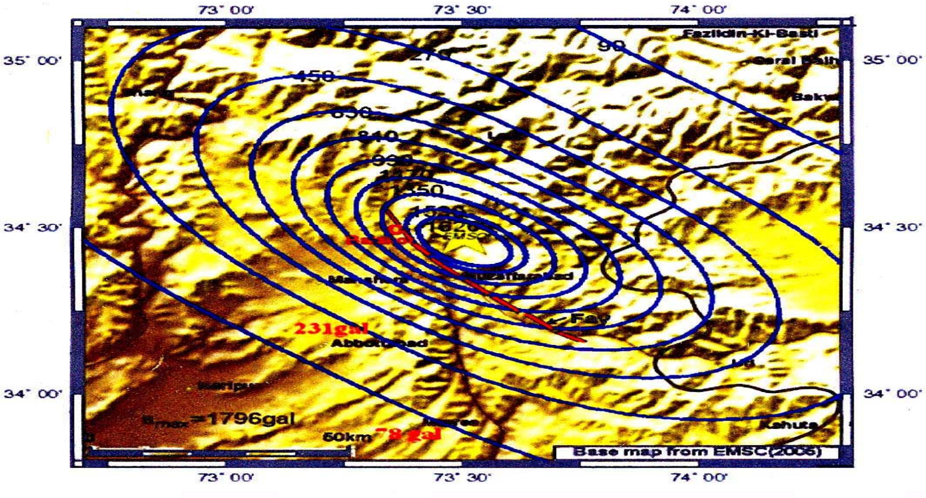


Fig 6. Estimated iso-acceleration contours for soft ground.

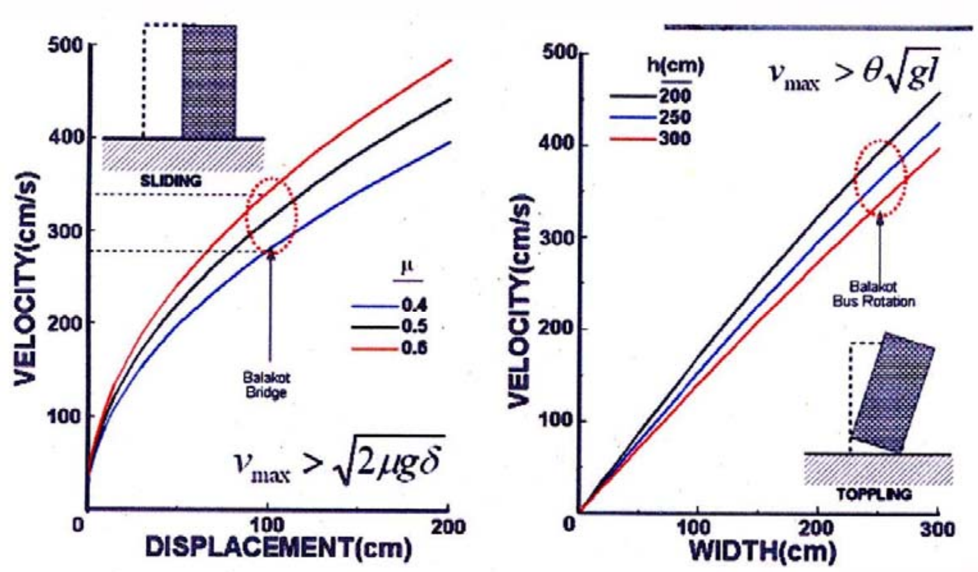


Fig 7. Theoretical relations between maximum ground velocity and displacement or size of structures.

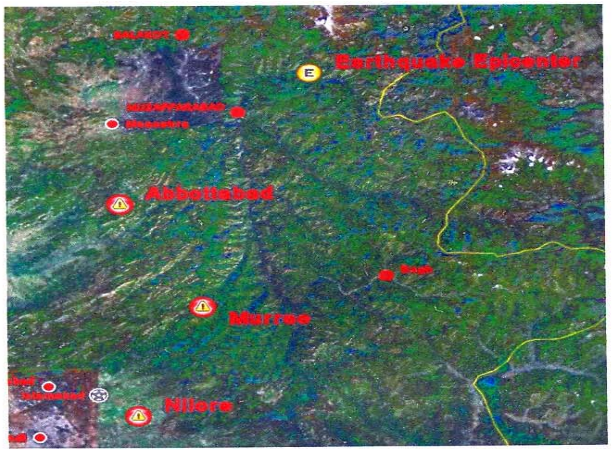


Fig. 8 Location of recorded data

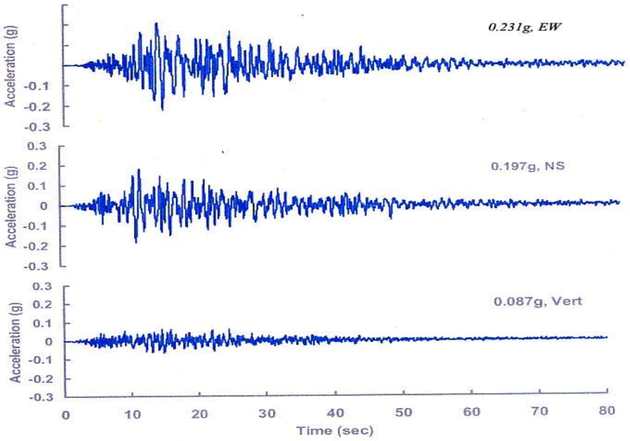


Fig. 9 Strong Motion Records at Abbottabad

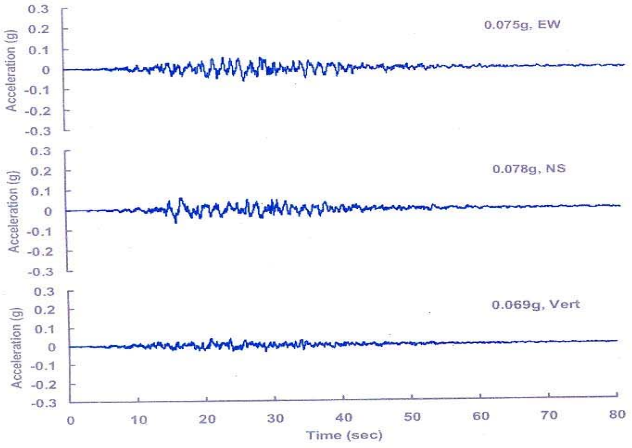


Fig. 10 Strong Motion Records at Murree

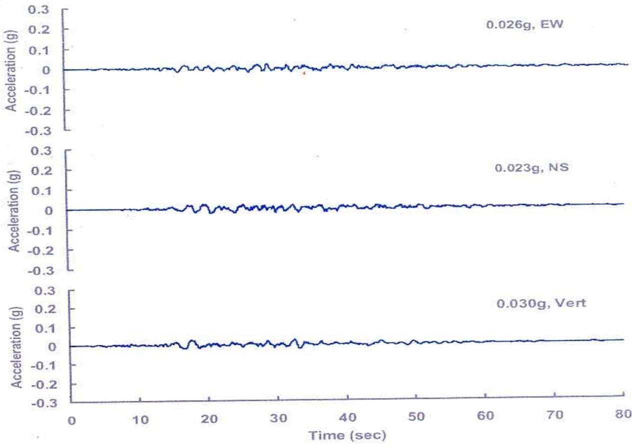
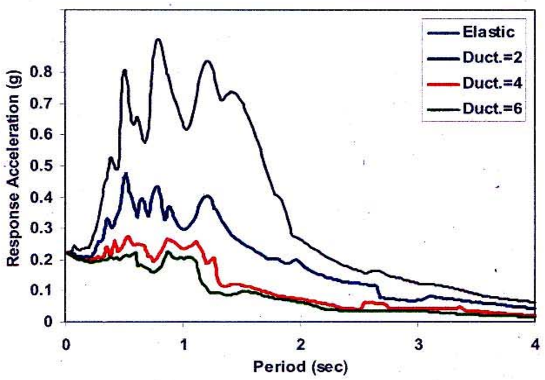


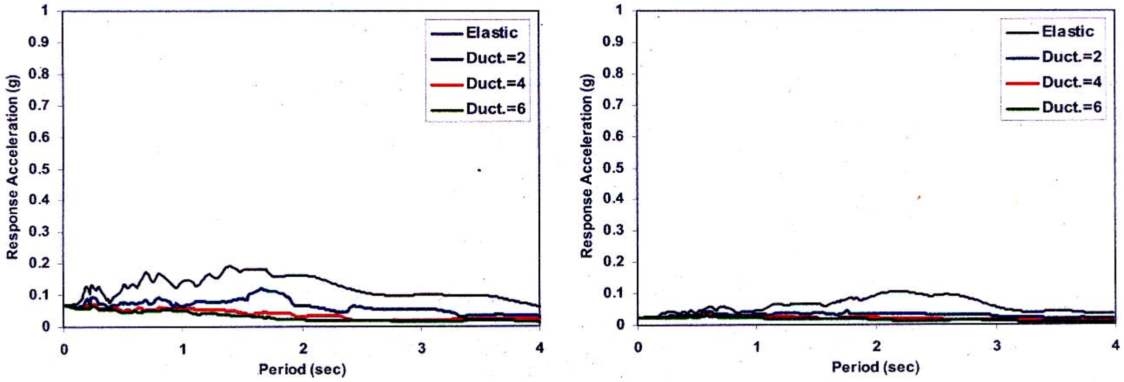
Fig. 11 Strong Motion Records at Nilore

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



(a) Abbottabad, EW component



(b) Murree, NS component

(c) Nilore, NS component

Fig. 12 Spectra for horizontal component of each record

The above shown Figure 5 (a) compares the observed maxi. MKS Intensity together with some observations from past earthquakes. 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 5 (b). The contours of iso-acceleration on the ground surface for soft ground are shown in Figure-6. The ground acceleration on firm or rock ground would be 1/3 to 1/5 of those for soft ground. As noted from the figure, the maximum ground acceleration at the epicenter was estimated

Table-2. Computed values of Attenuation Equations.

Location Distance From Fault	Krinitzsky (1988)		Dahle et al (1995)		Campbell (1997)		Schmidt (1997)		Ambraseys et al (2005)	
	Stiff	Soft	Stiff	Soft	Stiff	Soft	Stiff	Soft	Stiff	Soft
Muzaffarabad (4 km.)	0.079	0.968	0.458	0.635	0.720	0.800	0.751	0.835	0.659	0.805
Balakot (10 km.)	0.078	0.964	0.345	0.478	0.471	0.548	0.531	0.591	0.486	0.594
Abbottabad (39 km.)	0.073	0.903	0.160	0.221	0.124	0.155	0.210	0.234	0.194	0.237
Islamabad (98 km.)	0.056	0.692	0.079	0.110	0.031	0.040	0.094	0.104	0.094	0.115
Attock (140 km.)	0.046	0.563	0.057	0.079	0.017	0.023	0.065	0.072	0.071	0.087
Mirpur (140 km.)	0.046	0.563	0.057	0.079	0.017	0.023	0.065	0.072	0.071	0.087
Mangla (145 km.)	0.042	0.558	0.052	0.072	0.012	0.020	0.060	0.064	0.065	0.085

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.

In addition to the inference of maximum ground accelerations, maximum ground velocity are inferred from the displaced or overturned structures. Figure-7 also presents the theoretical relations between maximum ground velocity and the displacement or size of the structure. In the same figure, the inferred results for the displaced Balakot Bridge and overturned bus next to the bridge are shown. The results indicate that the maximum ground velocity in the same location should have been more than 300 cm/s.

GROUND MOTION RELATIONS

Ground motion relations are key element in seismic hazard evaluations. They provide the link between the occurrence of earthquake and the resulting ground motion at a particular site, which a structure must be able to withstand. At present there is no attenuation equation derived for Pakistan. More SMA's are required to be installed in important cities/towns and along critical structures, such as dams and big buildings, in order to develop data base for attenuation equations. Till the data base is available, an attempt is done to select attenuation relations that can be used to arrive at some conclusions. Keeping in view the seismological parameters of October 08, 2005 earthquake, the candidate attenuation relations and results for important sites are given in Table-2. Based on this table, two attenuations equations i.e. Campbell (1977) and Ambraseys et al (2005) can be feasible for Northern Pakistan tectonic conditions. It is emphasized that constructions may be carried out keeping in view these values, until the new Buildings Codes for Pakistan are prepared (These are under preparation till date). However, the Critical Structures require special studies and geotechnical investigations.

GEOTECHNICAL EVALUATION OF INDUCED FAILURES OF NATURAL & CUT SLOPES

One of the most distinct characteristics of the Kashmir-Hazara earthquake is the widespread slope failure all over the epicentral area. The devastating earthquake particularly caused extensive damage to housing and structures founded on sloping soil deposits. Extensive natural and cut slope failures occurred along Neelum, Jhelum and Kunhar valleys, which obstructed both river flows and roadways. Furthermore, many slope failures associated with highly sheared and weathered dolomitic limestone occurred along the presumed surface trace of the earthquake fault. The failures nearby Muzaffarabad were spectacular in both scale and their areal distributions.

<u>Classification and Examples of Slope Failures:</u> Slope failures caused Kashmir-Hazara earthquake may be classified into three categories, namely, 1) Soil slope failures, 2) Weathered and/or sheared rock slope failures, and 3) Rock slope failures.

<u>Soil Slopes</u> Soil slope failure occurred in either plane sliding mode or circular sliding. Planner sliding modes are generally observed on soil slopes over the bedrock. Deep-seated circular type soil slope failures observed when the soil thickness was large. Some peculiar soil slope failures were observed in both

Balakot and Muzaffarabad. These slope failures occurred in conglomeratic soil deposits with rounded large cobbles, which are products of past glaciation's period. Since the slope angles were quite steep (60 – 80^0), these slopes failed on surface involving partly vertical tensile cracks and several shear plane. The residual slope angles (response angle) ranges between 40 and 45^0, which may be considered to be equivalent to its friction angles.

Embankment: The embankments of roadways failed along the rivers. Stone masonry or gabions are commonly used for supporting the embankments of roadways in steep terrains as well as along rivers. However, the embankments of roadways are not generally protected by retaining walls or gabions for a great length, which may make them prone to failures as a result of toe erosion due to the river currents. They may also suffer from heavy rainfalls in long term. No support or protection measures for most of the slope cuts along roadways are undertaken. Furthermore, the slopes cuts are generally very steep and there are no catchment pockets in the case of rock falls and small scale slope failures.

Rock Slopes: Rock units in the epicentral area are schists, sandstone, shale, and dolomitic limestone. Particularly red shale of Balakot formation is prone to weathering and the thickness of the weathered rock seems to be about 2 – 5 meters. Dolomitic limestone rock unit is intensively sheared and this unit is thought to constitute the fault fracture zone. The surficial slope failures in dolomitic rock unit were spectacular and continued for several kilometers as they are clearly noticed in the satellite images.

Except granite, all rock units have at least one thoroughgoing discontinuity set, namely, bedding plane or schistosity plane. Since rock units had been folded, they also include joint sets and fracture plane as a result of tectonic movements. The rock slope failures are mainly planar or wedge sliding failure, flexural or block topping failure. Planar sliding failures were observed mainly in schists, sandstone and shale while flexural topping failure was observed in intercalated sandstone and shale depending upon the inclination of bedding planes with respect to slope geometries. The inclination of layers ranges between 30 – 65^0, which implies the sliding failure can be easily caused by small intensity of disturbing forces resulting from such an earthquake, heavy rainfall or both.

Rock falls in the epicentral area generally resulted from the topping of rock blocks due to excitation of the earthquake. Numerous rock falls were observed for a great length of roadways. Rock falls were particularly common in sandstone slopes. Some flexural fall were also observed in intercalated sandstone and shale formation with undercutting. The satellite images indicated that there was a large scale slope failure nearby Hattian in the vicinity of the SE tip of the causative fault. The slope failure was at Hattian and it is an asymmetric wedge sliding type. The estimated wedge angle is about 100^0.

CONCLUSIONS AND RECOMMENDATIONS

In this paper an overall view of geology, tectonics, and seismicity of October 08, 2005 Kashmir Hazara earthquake was presented. The maximum ground acceleration and velocity at Balakot were inferred to be, at least, 0.9 g and 300 cm/s, respectively. The computational results indicated that the failure of soil slope containing large cobbles was imminent under such strong ground motions. Furthermore, the loose surficial and talus deposits were laterally spreaded, which resulted in further damages in Balakot and as well as in Muzaffarabad. Inspite of the translation of the girder of Balakot Bridge more than 1 meter, the bridge could stand against high ground motions and forces imposed by ground due to slope failures. Although some damages to several bridges were observed, it may be stated that large bridges with good engineering design and construction did stand against high ground motions.

Slope failures were observed along entire Neelum and Jhelum valleys. Particularly slope failure associated with heavily fractured dolomitic rock unit was spectacular in both scale and its areal distribution. However, these slope failures were aligned on locations, which may be interpreted as the surface expression of the causative fault.

The important recommendations are summarized as follows:

i. Description of the local tectonic features suggest that the whole of the Northern Pakistan lies in the collision zone of the northern part of Indo-Pakistan Plate, with associated faults that show evidences of fault movement during Quaternary period and should therefore be considered seismically active.

ii. The October 08, 2005 earthquake was caused by the movement due to rupture along a thrust fault named "Jhelum Thrust" a main branch of MBT.

iii. The both sides of steep valleys should be connected to each other at certain intervals in order to facilitate by-pass routes in case of emergencies resulting from bridge collapses and/or viaducts when there is a high risk of slope failures.

iv. Embankment slopes are highly steep and they are prone to fail either by ground shaking or heavy rainfalls. It is recommended to either reduce slope angle of embankments or to introduce support, reinforcement or protection measurements. Furthermore, measures should be introduced to eliminate the toe erosion problems.

v. Landslides were a major secondary hazard due to the earthquake. The slides varied from major slides to disrupted slides, which pose a major danger in future earthquakes or during heavy rainfalls. It was estimated that the landslides may have occurred to a distance of about 200 km from epicenter.

vi. The slope angle and slope height of slope cuts should be such that the slope is stable under its natural resistance. If such a condition is difficult to be fulfilled, some measures for supporting and reinforcement should be undertaken. Since the valleys are very steep, there is a high possibility of surficial slope failure risk. The design of slopes and assessment of failure risk must be based on the guidelines of modern slope engineering.

vii. 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.

viii. The substantial damage to building stock in the area suggests lack of seismic resistance design and construction practice in the region. It is therefore important that the reconstruction is carried out in accordance with proven seismic methods.

ix. A large proportion of buildings damaged were residential and hence their reconstruction is now being locally driven. There is need for a good education program in seismic resistance construction practices using local available technologies.

x. 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.

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