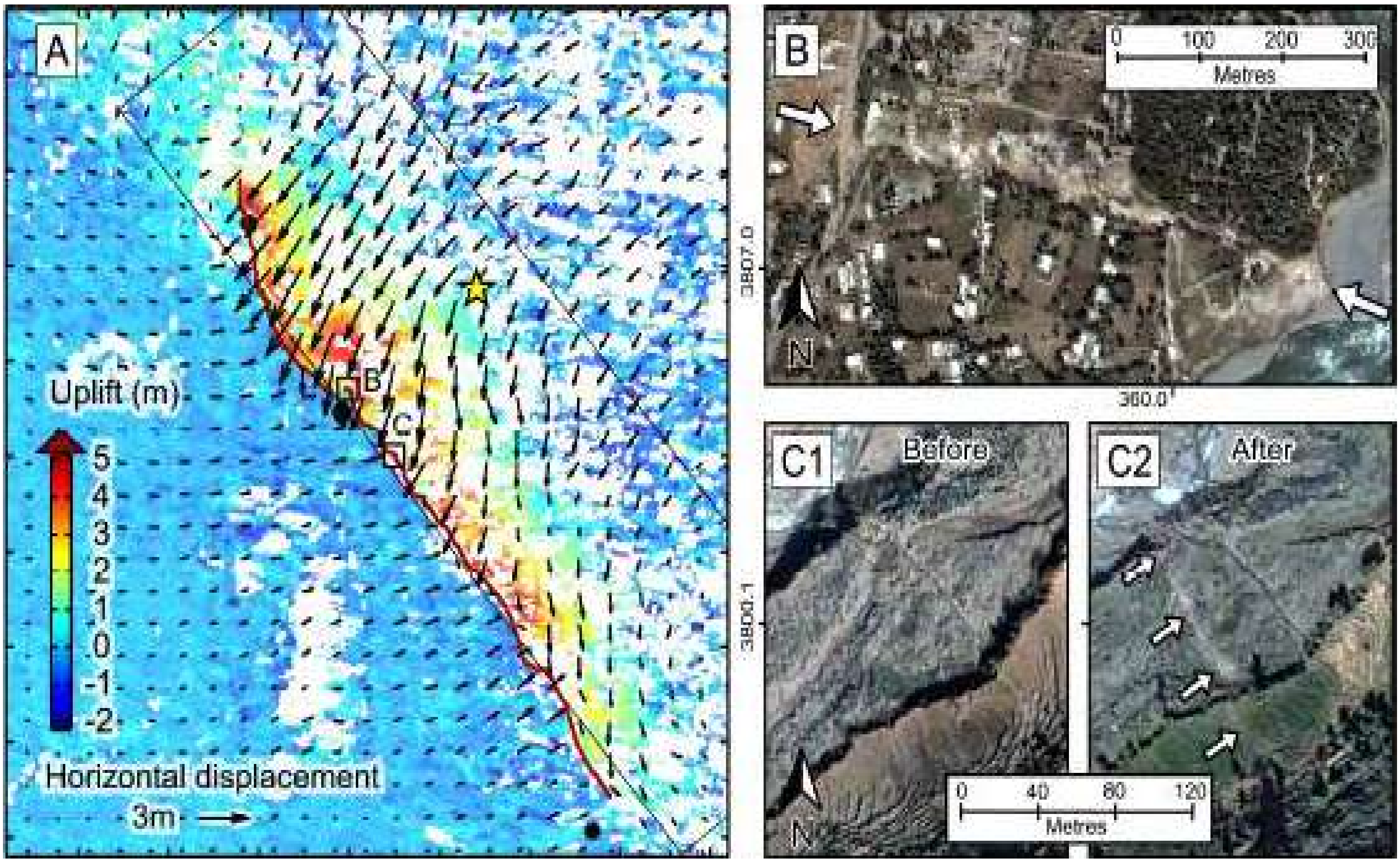
SEISMIC HAZARD ASSESSMENT OF MUZAFFARABAD

A Product of Earthquake Risk Reduction and Preparedness Programme



Pakistan

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SEISMIC HAZARD ASSESSMENT OF MUZAFFARABAD

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National Disaster Management Authority Pakistan

United Nations Development Programme Pakistan

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1. INTRODUCTION

The occurrence of the 7.6 M_w magnitude earthquake in north Pakistan on October 08, 2005 has brought into focus the realization that Pakistan is located in a seismically active region. It has also increased the urban earthquake risk in the area due to high rate of urbanization, faulty land use planning and construction, and inadequate infrastructure. The seismic hazard assessment (SHA), which can be conducted in connection with risk analysis in urban areas, can be carried out using the usually adopted methodologies of deterministic and probabilistic approaches. The present study focuses on the SHA determination of Azad Jammu & Kashmir (AJK) using both these conventional approaches. The SHA was carried out by considering the earthquake source zones, selection of appropriate attenuation equations, near fault effects and maximum potential magnitude estimation. The area is located tectonically in an active regime referred to the as Hazara-Kashmir Syntaxis. The Main Mantle Thrust, Mansehra Thrust, Oghi Fault, Banna Thrust, Balakot Shear Zone, Main Boundary Thrust, Panjal Thrust, Jhelum Fault and Muzaffarabad Fault and, further to the south, the Sanghargali, Nathiagali, and Thandiani Thrusts are the most critical tectonic features within the 50 km radius of Muzaffarabad (Capital of AK). Using the instrumental seismological data from 1904 to 2007, SHA has been carried out. Other reactivated critical tectonic features in the area have been investigated. Among them the Balakot-Bagh fault, with the fault length of 120 km from Balakot to Poonch, has been considered as the most critical tectonic feature on the basis of geological/structural/seismological data. The potential earthquake of maximum magnitude 7.8 has been assigned to the Balakot-Bagh fault using four regression relations. The peak ground acceleration value of 0.25g (10% probability of exceedance for 50 years) and 0.5g has been calculated with the help of the attenuation equation using probabilistic and deterministic approaches.

2. TECTONIC SETTING

2.1. REGIONAL

On the broader scale the area of Pakistan is encompassed by the alluvial covered peninsular shield of India on the east, the great Himalayan ranges towards the NE, the Pamir and Hindukush mountains to the north and northwest, the

Makran subduction zone in the southwest part of Pakistan, and the Arabian Sea on the south.

The area of Pakistan is under the influence of two plates i.e. the Eurasian plate in the north and the Indo-Pak Plate in the south. The active fold–and–thrust belt along the northwestern margin of the Indo–Pakistan plate is divisible into two parts–the Sulaiman belt and the NW Himalayan fold and thrust belt (Kazmi and Jan, 1997). The affected area in the recent earthquake –

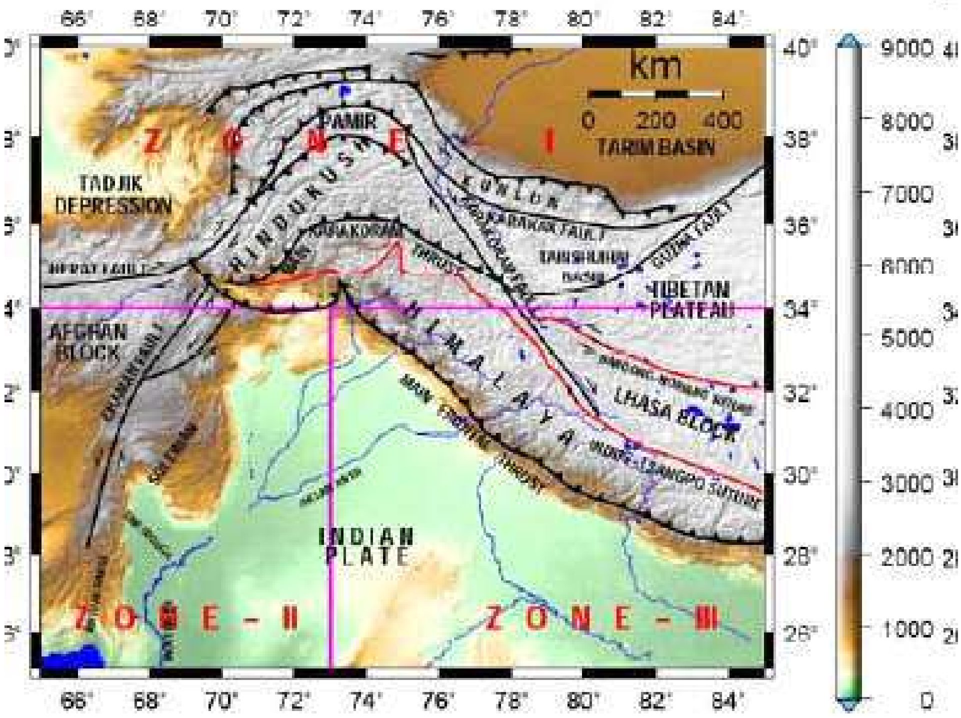

Figure 1. Tectonic setting of the study area.

activity belongs to the NW Himalayan Fold and Thrust Belts, which is associated with the main zone of Himalayan convergence (Jadoon, 1992). In the Himalayan zone of convergence (Fig.1), the Main Karakoram Thrust (MKT) also known as the Shyok Suture Zone; Main Mantle Thrust (MMT) also known as the Indus Suture Zone; Main Boundary Thrust (MBT) and the Salt Range Thrust (SRT) delineate the major subdivisions of the collision zone (Yeats and Lawrence, 1984; Tahirkheli et al., 1979).

It is believed that the Kohistan Island Arc (Tethyan tectonic domain, according to Kazmi and Abbas, 2001) situated between the MKT and MMT sutured in the north (along MKT with the Laurasian tectonic domain) about 100 Ma during the Cretaceous (Treloar et al., 1989). The collision at its southern extremity (along MMT with the Gondwanian domain) occurred about 50 Ma (Treloar and Rex, 1990). Following the cessation of movement along MMT (3 –15 Ma according to Zeitler et al., 1980), deformation shifted southwards to MBT. Here the Lower Tertiary rocks are thrusted over Miocene molasses. In the later phases, thrusting propagated south to the SRT. In the Salt Range, deformation as young as 0.5 Ma has been documented by Yeats and Lawrence (1984).

2.2. LOCAL

The NW Himalayan Fold-and-Thrust Belt covers an area between the MMT and SRT with its westward extensions (Surghar, Marwat, Bhittani and Manzai ranges). According to Gee (1980) and later workers, the southern sides of these ranges are also marked by thrusts. The tectonic domains of Hazara-Kashmir Syntaxis and the Nanga Parbat Haramosh Massif comprise its eastern boundary.

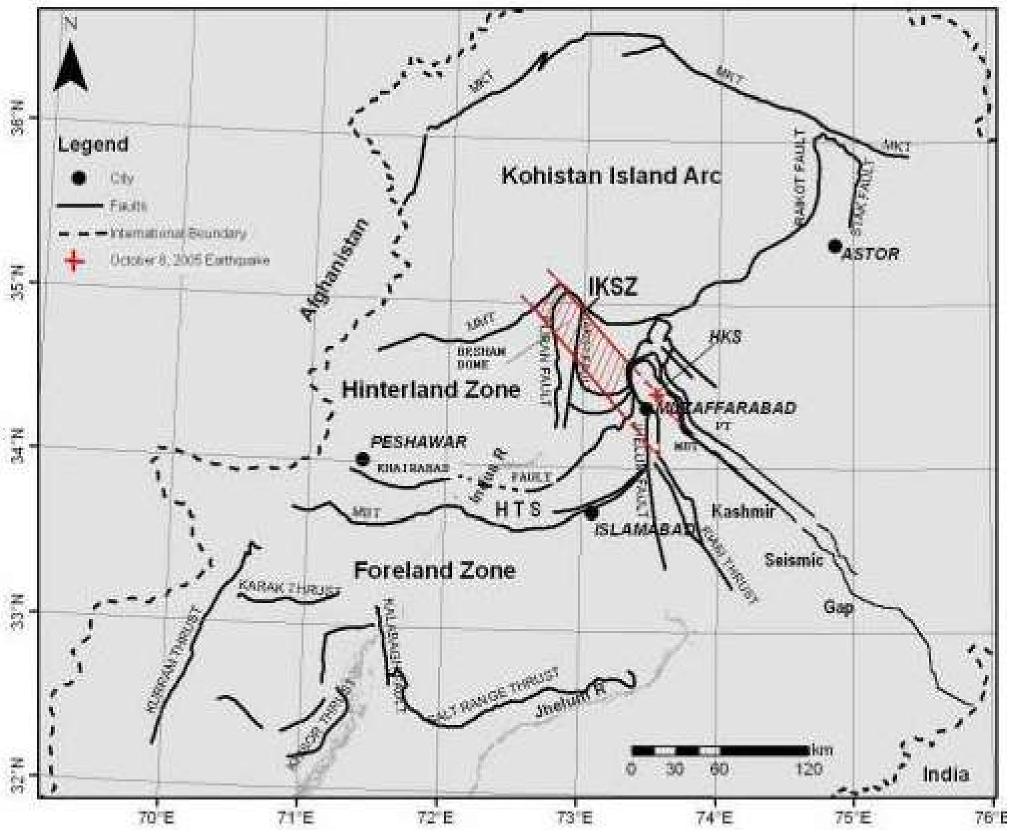

Figure 2. Tectonic Setting of northern Pakistan. Also shown are Hinterland and Foreland zones of the NW Himalayan fold-and-thrust belt. Area with diagonal lines represents the Indus Kohistan Seismic Zone, with its probable south-eastward extension shown in dashes. MKT: Main Karakoram Thrust, MMT: Main Mantle Thrust, MBT: Main Boundary Thrust, PT: Punjal Thrust, HTS: Hazara Thrust System (after MonaLisa et al., 2008).

The western limit is not clearly defined. Besides the Kurram Fault in the southwestern portion, series of thrusts beyond the borders of Pakistan (like the Sarobi Fault in Afghanistan) are considered to be delineating this boundary.

In this nearly 250 km wide and 560 km long fold and thrust belt, the Panjal-Khairabad fault (Fig. 2) divides it into a northern hinterland zone and the southern foreland zone. The hinterland zone is also referred to as the Hazara Crystalline Zone (Bender and Raza, 1995) and Himalayan Crystalline Zone (Kazmi and Abbas, 2001), whereas the Foreland zone consists of Kurram Cherat Margalla Fold-and-Thrust belt, Hazara Kashmir Syntaxis (HKS) and the Salt Range-Kohat-Potwar Fold-and-Thrust Belt.

The 8 Oct, 2005 Muzaffarabad earthquake occurred in HKS of foreland zone and its aftershocks are now proceeding towards the crystalline nappe zone of Hinterland zone. Recent activity has shown that at any one time more than one tectonic subdivision can be affected. This seems to have been the case in the present situation also where besides the tectonic subdivision referred to as the Hazara Kashmir Syntaxis, the crystalline nappe zone has experienced seismic activity.

In this large area of active convergence, transpressional tectonics seems to be operative in some parts also. Different workers have recognized a large number of active faults from the area. These include the faults of very large extent like the Main Mantle Thrust and Main Boundary Faults as well as many active faults of smaller length. About 45 faults are already known to be active in the fold and thrust belt (MonaLisa et al., 2008). Many new faults are still being delineated through geological mapping and use of remote sensing techniques. Further structural/tectonic complications arise due to the presence of a large number of blind faults as delineated by focal mechanism studies (MonaLisa et al. 2008).

3. METHODOLOGY

The overall study comprised of the following stages, which are described in detail below.

<u>Stage 1: Active and Quaternary Faults Identification (Preparation of Faults map)</u>

- **a)** Geological/Tectonic maps
- **b)** Satellite Images
- **c)** Field Studies

a) *Study of available Geological/tectonic maps*

Quite a large number of published work is available relevant to the tectonics of the study area either in the form of maps or in the form of the research

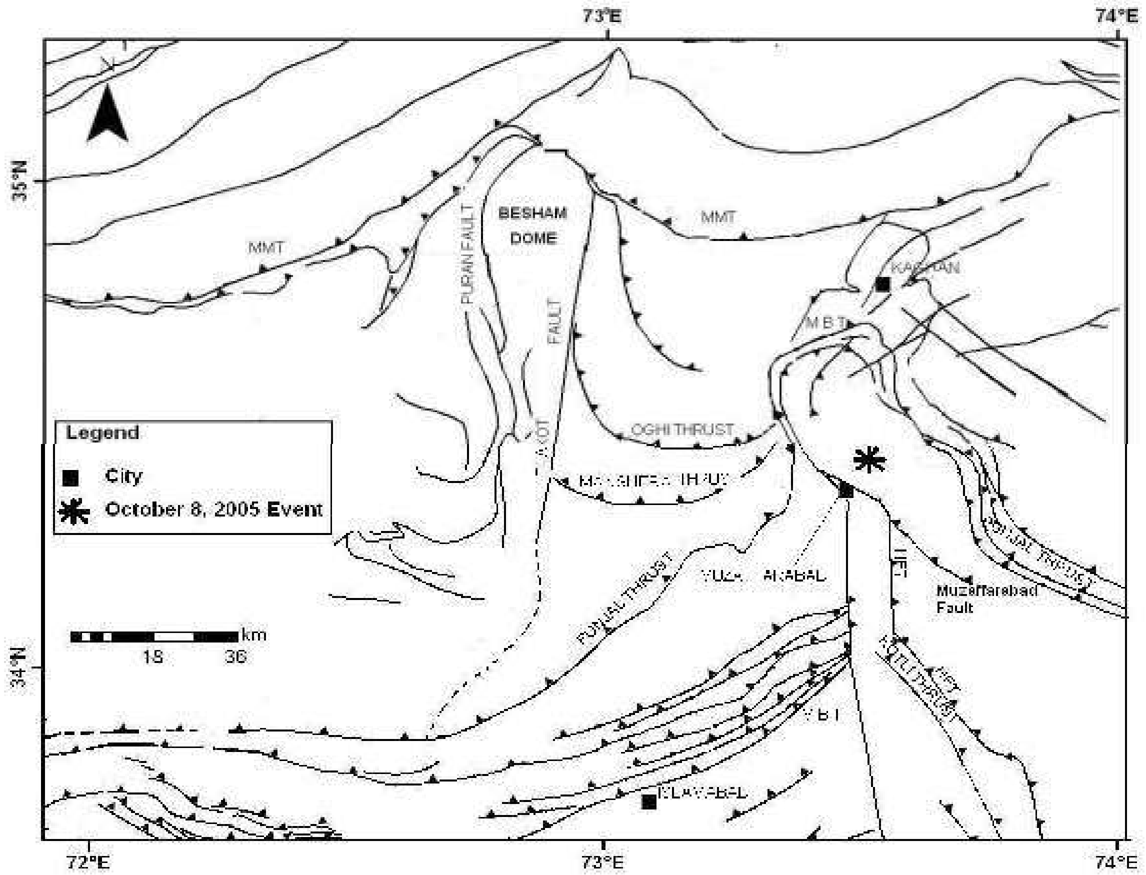

Fig.3. Structural map prepared in the present study (MonaLisa et al., 2008).

papers like Greco, 1991; Yeats and Hussain, 1989; Ashraf et al., 1980;

Treloar et al., 1989a; 1990; Coward et al., 1986; Baig and Lawrence, 1987; Lawrence and Ghauri, 1983; Baig et al., 1989; Treloar et al., 1989c,d; Seeber et al., 1980; Calkins et al., 1975; Seeber et al., 1980; Kazmi and Jan, 1997; Seeber and Armbruster, 1979; Kazmi, 1979a &b; Ghauri et al., 1991; Ghazanfar et al., 1986; Jadoon and Frisch, 1997; Johnson et al., 1986; Jaswal et al., 1997; Jadoon et al., 1999; Pennock et al., 1989; Sercombe et al., 1998; Gansser, 1964; Mirza et al., 1988; and several others. In the present case, using all above mentioned publications and the various other maps published by Geological Survey of Pakistan (GSP), and Oil and Gas Development Corporation Limited (OGDCL), Pakistan, a base map showing all the structural features of study area has been prepared and is shown in Fig.3.

b) ***Study of available Satellite Images***

The SPOT imagery, showing a part of the study area (curtosey of NESPAK, Lahore) and Landsat imageries (UNOSAT, 2005) were examined and analysed for regional structures and fault lineaments. From these satellite images of the area (Fig.2.3), all the mapped faults are very well depicted on the imagery and used in the preparation of faults map of the area (Fig.4).

c) ***Field Studies***

The field studies for the identification of Quaternary faults is the final but the most important step. It is beyond the scope of the present study to carry out the field studies of such a vast area; therefore the filed studies have been carried out for some parts.

On the basis of this Quaternary fault studies, a total of thirty-six faults have been selected as the features capable of generating the earthquakes. Also it has been recognized that although the entire study area is dominantly representing the thrust faulting but some strike-slip component is also present. This is the reason that out of 36 faults, 26 are thrusts and 10 are strike slips. All these faults are shown in Fig. 3 and a brief description of each critical feature is given below.

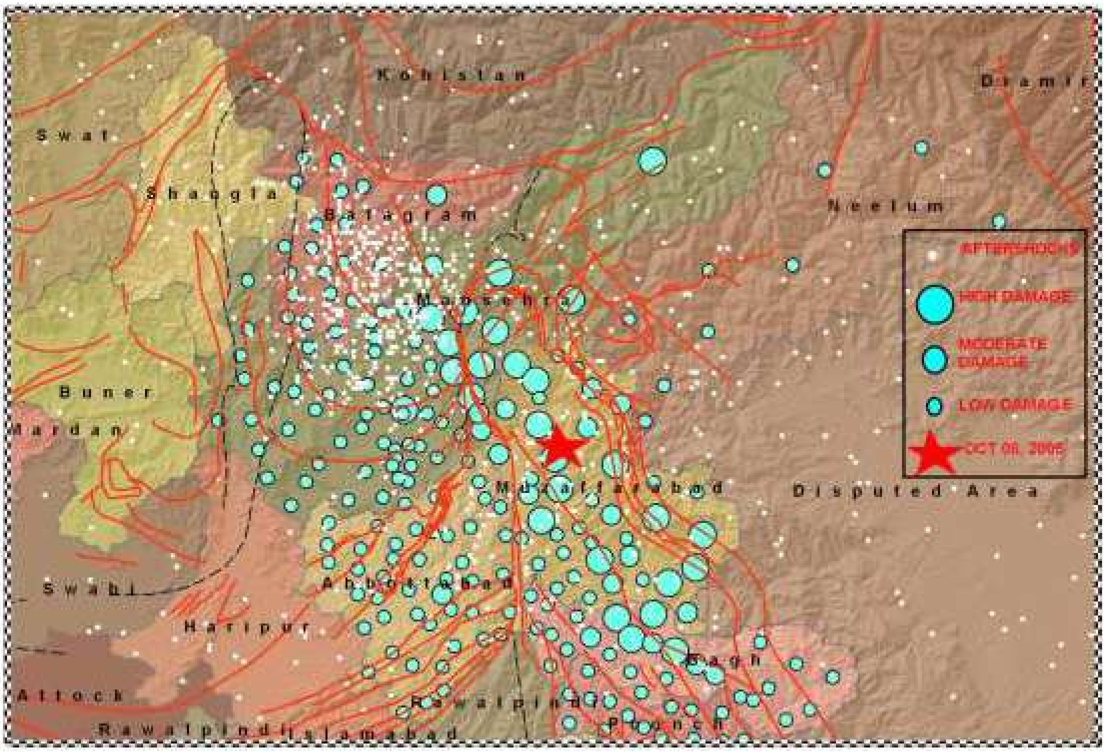

Fig.4. Major faults plotted on a satellite map, along with level of damage.

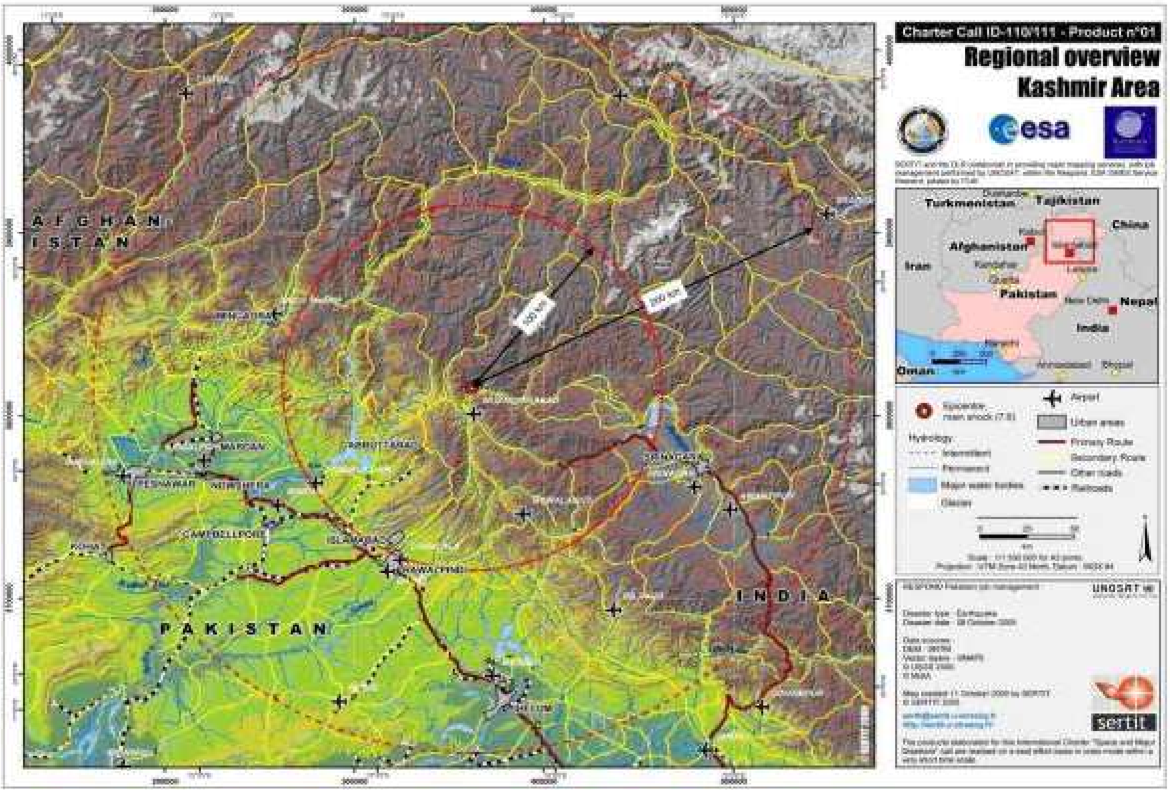

Fig.5. Regional overview of Kashmir area with Muzaffarabad Earthquake (UNOSAT, 2005).

None of the Himalayan Earthquakes have shown surface rupture before 1800-
DISTINCT RUPTURE associated with 2005 EQ

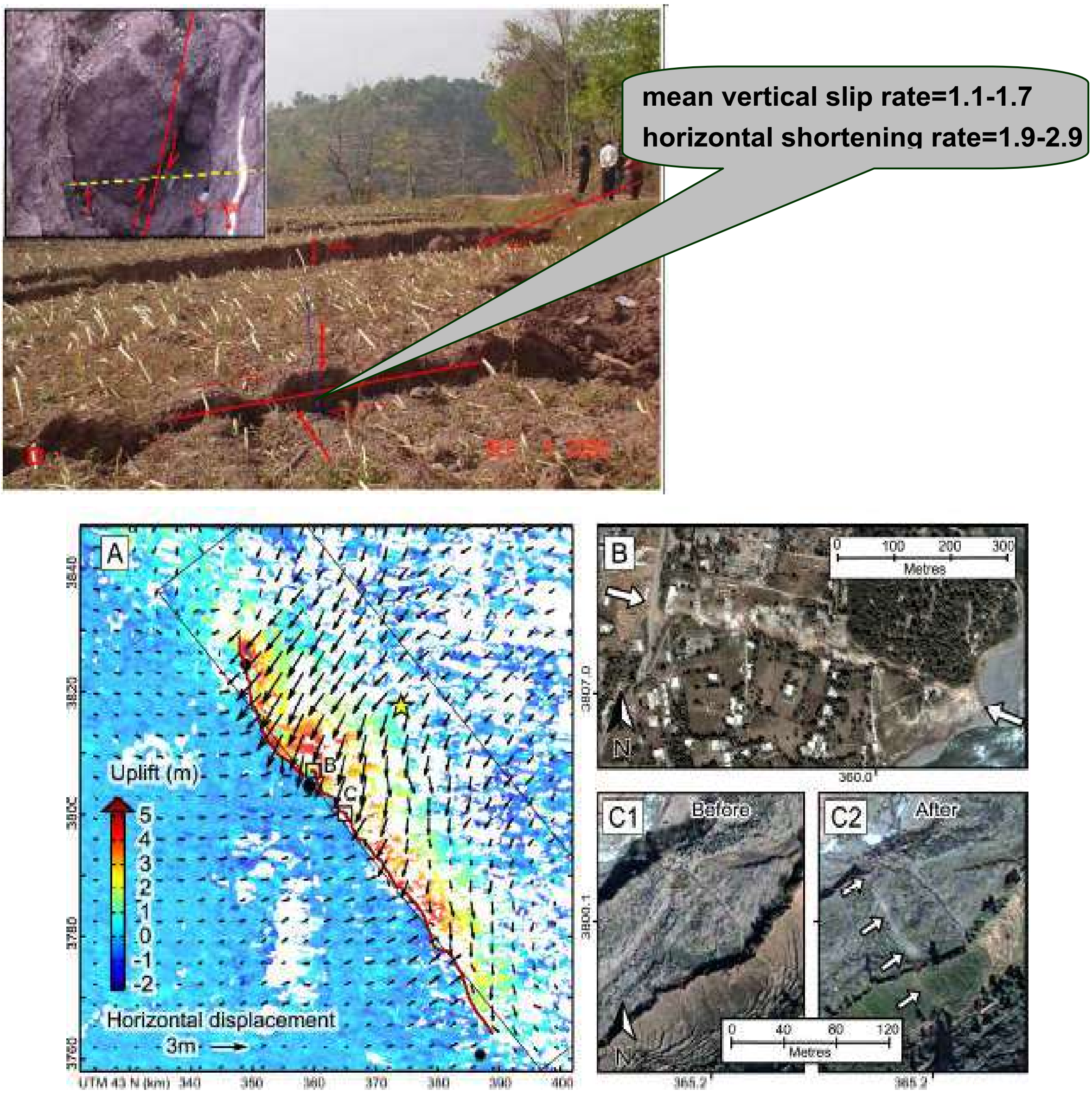

Fig.6. Field studies of the area surrounding Muzafarabad.

Stage 2: Collection of Seismological Data (Preparation of Seismicity Map)

For this purpose the data available from local seismic networks (like Pakistan Atomic Energy Commission, Pakistan Meteorological dept., Water and Power Development Authority), Geological Survey of Pakistan; Regional seismic networks like USGS (United States Geological Survey), ISC (International Seismological Centre of UK); JMA (Japan Metrological Association) has been utilized.

Seismicity data has been used for the following two purposes.

i) Preparation of seismicity map for the period of 1904-2007 for earthquakes with magnitude ≥4.5 M_w (Fig.6)

ii) For determination of Fault Plane Solutions (FPS)

In order to measure of ground motion (i.e. acceleration) by this ongoing seismic activity along the active tectonic features, two portable accelerometers have also been installed in the area.

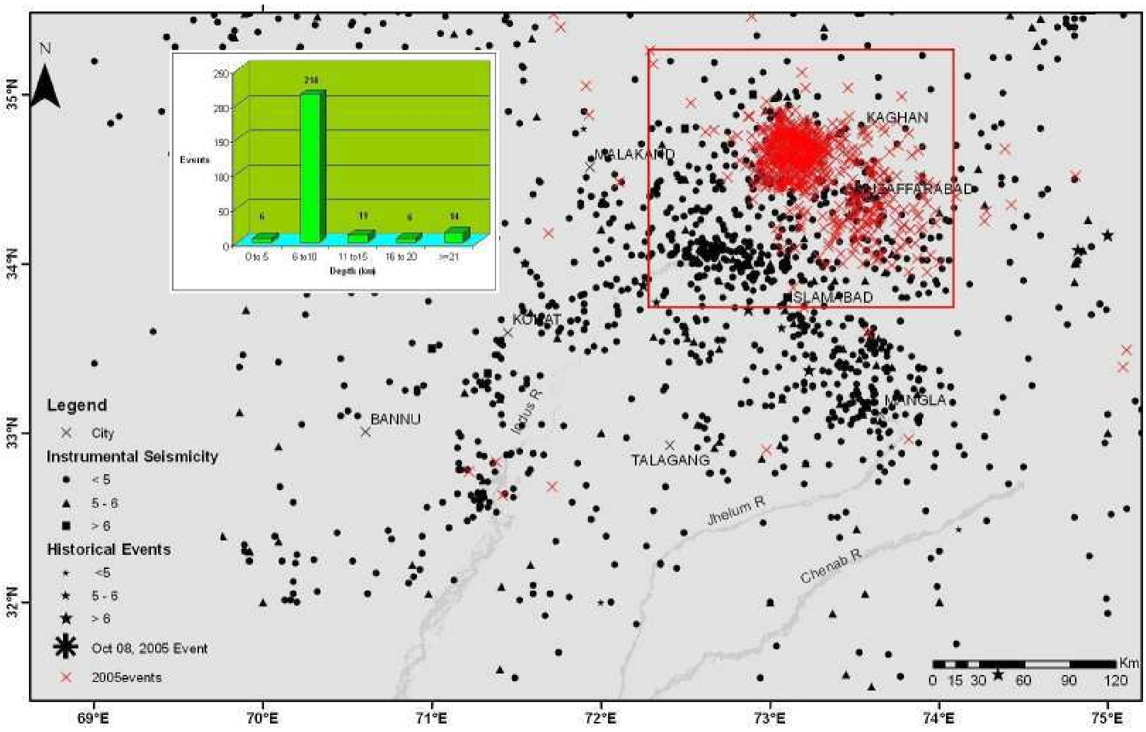

Fig.6.Seismciity map of the study area (MonaLisa et al., 2008).

Stage 3: Generation of Seismotectonic Map

On the basis of synthesis of the tectonic (Fig.3), seismological data (Fig.6) and FPS obtained from the above-mentioned studies, a "Seismotectonic Map" (Fig.7a and b) has been prepared (MonaLisa et al., 2008 submitted).

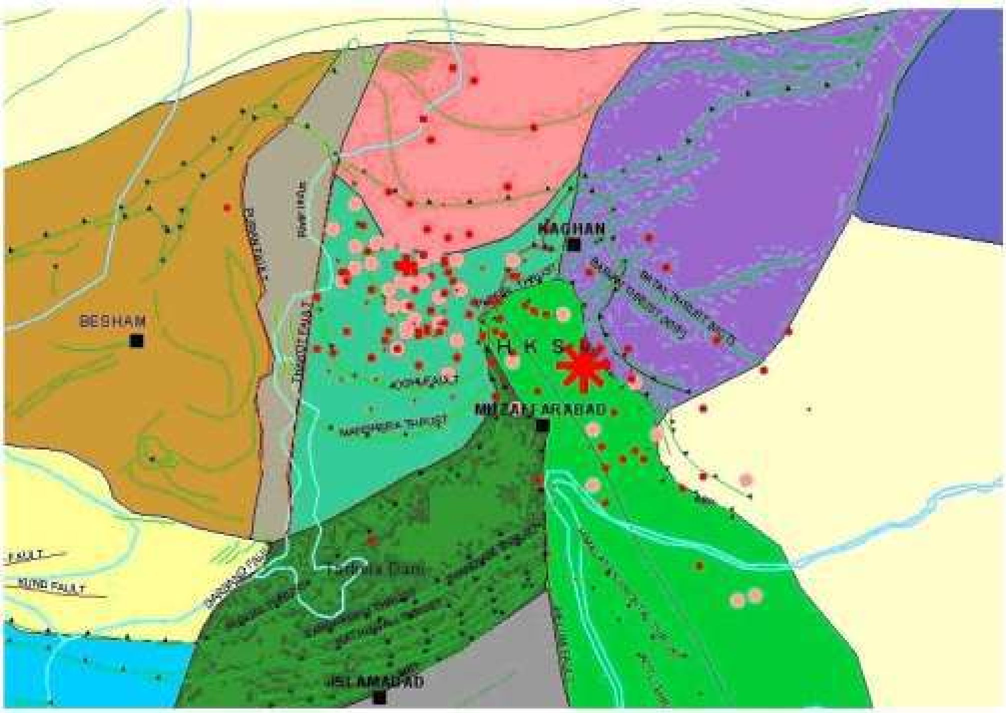

Fig7a.Seismotectonic map of the study area prepared in the present work (Closer view).

Stage 4: Seismic Hazard Assessment (SHA) of the area

The commonly used two approaches for the determination of seismic hazard assessment (SHA) are,

1. Deterministic Seismic Hazard Assessment (DSHA)
2. Probabilistic Seismic Hazard Assessment (PSHA)

The DSHA is comparatively simple and does not account for the uncertainties and probability of occurrence of an earthquake. The principle of analysis involved in the deterministic approach is to evaluate the critical seismogenic sources, like capable faults and the identification of a maximum magnitude assigned to each of these faults. Then with the help of suitable attenuation equations, peak horizontal accelerations are determined.

The PSHA is denoted by the probability that ground motion (acceleration) reaches certain amplitudes or seismic intensities exceeding a particular value within a specified time interval. Inverse of the probability of exceedance is known as the return period for that acceleration and is used to define the seismic hazard. In probabilistic hazard evaluation, the seismic activity of seismic sources (line or area) is specified by a recurrence relationship, defining the cumulative number of events per year versus their magnitude. Distribution of earthquakes is assumed to be uniform within the source zone and independent of time. Seismic hazard calculated for different sites can be used to generate maps or curves (hazard curves) with intensities or ground accelerations expected with a given probability for a specified interval of time. In the present work, PSHA has been carried out using the software EZ-FRISK (6.2 beta version, 2004 modified form). The program calculates earthquake hazard at a site under certain assumptions specified by the user.

I. DETERMINISTIC SEISMIC HAZARD ASSESSMENT (DSHA)

The deterministic method includes the following steps:

1. Identify all the critical tectonic features in the vicinity of the Muzaffarabad likely to generate significant ground motions.
2. Assign to each of these a maximum magnitude on the basis of key fault parameters.
3. Compute the ground motion parameters (Peak Ground Acceleration) at the site of Muzaffarabad associated with each feature as a function of magnitude and distance.

1. CRITICAL FEATURES

A total of thirteen faults (Table. 1) have been selected as the most critical tectonic features for the seismic hazard assessment for the site of Muzaffarabad. In addition to these faults, there are also other active features within NW Himalayan Fold-and-Thrust Belt but since their nearest segment is more than 40 km from the site, the rock motion from these features would not be as critical as for the features given in Table 1. Also this selection is primarily based upon the association of seismicity along each fault and the geological criteria such as the fault rupture length-magnitude relationships. The level of seismicity has been considered by observing both the historical and instrumental earthquake data along each feature.

Although the entire region is dominantly representing the thrust faulting but some strike-slip component is also present. All these faults along which earthquakes can produce the appreciable strong ground motions are shown in Fig. 3.

2. MAXIMUM EARTHQUAKE POTENTIAL

The methods assigning a maximum potential magnitude to a given active fault based on empirical correlations between magnitude and key fault parameters such as fault rupture length, fault displacement and fault area (Idriss, 1985). Selection of a maximum magnitude for each source, however, is ultimately a judgment that incorporates understanding of specific fault characteristics, the regional tectonic environment, similarity to other faults in the region and data on the regional seismicity. The peak horizontal accelerations calculated by deterministic approach is largely affected by the choice of the maximum magnitude of an earthquake that can occur within the certain critical feature. The procedure followed in assigning the maximum potential magnitude of an earthquake depends upon the maximum magnitudes of earthquakes experienced in the past, the tectonic history and the geodynamic potential for generating earthquakes. Thus in the present case, the maximum potential magnitudes of twelve faults calculated on the basis of 50 % of total length and using available relationship by Wells and Coppersmith (1994). Table.1 gives all these active faults present near Muzaffarabad, their total length, rupture length and maximum potential magnitudes calculated in the present study.

3. ATTENUATION EQUATION RELATIONSHIPS

The strong-motion attenuation relationship depicts the propagation and modification of strong ground motion as a function of earthquake size (magnitude) and the distance between the source and the site of interest.

In the present study, peak horizontal accelerations have been calculated using thirteen available attenuation equations as shown in Table 1. Among them the equation of Boore et al., 1997 have been preferred due to the two reasons. Firstly, this equation is based on a high quality data set and including the term specifying for reverse faulting, which is the dominant mechanism of earthquakes in this region. Secondly the same equation can also be used for earthquakes of focal depth > 30 km i.e. both for the shallow as well as for the intermediate earthquakes.

The equation is given below.

$$\ln(PGA) = -0.117 + 0.527\,(M-6) - 0.778\ln(r) - 0.271\ln(V_{s,30}/1396) + 0.52P$$

Here $r = (d^2 + 5.57^2)$

M = Moment Magnitude

d = Horizontal distance from the source to site (km)

P = dummy variable, takes the value of 0 for mean values of PGA and 1 for 84 percentiles.

$V_{s,30}$ = Average shear wave velocity over the uppermost 30m at the site with values of 750 m/s or greater for rock and values of less than 360m/s for soft soil.

Tectonic Features	Maximum Magnitude (Mw)	Closest Distance to Faults (Kms)	Computed Accelerations (g)											
			1		2	3		4	5		6		7	
			50%	84%		50%	84%		50%	84%	**50%**	84%	50%	84%
Punjal Thrust	7.2	1.61	0.51	0.93	0.56	0.41	0.78	0.39	0.32	0.57	**0.34**	0.57	0.46	0.85
MBT	7.8	0	0.59	1.07	0.7	0.58	1.1	0.41	0.47	0.84	**0.47**	0.79	0.62	1.16
Oghi Thrust	6.9	22	0.19	0.34	0.25	0.14	0.28	0.13	0.12	0.22	**0.15**	0.25	0.16	0.30
Mansehra Thrust	6.8	14	0.26	0.48	0.33	0.20	0.37	0.20	0.16	0.28	**0.18**	0.31	0.22	0.41
Thakot Fault	7.1	44	0.10	0.18	0.14	0.08	0.16	0.06	0.08	0.13	**0.08**	0.14	0.09	0.17
Puran Fault	7.2	65	0.06	0.12	0.09	0.06	0.11	0.03	0.06	0.10	**0.08**	0.13	0.06	0.12
Himalayan Frontal Thrust	7.6	1	0.56	1.02	0.63	0.52	0.98	0.41	0.42	0.73	**0.42**	0.71	0.56	1.04
Muzaffarabad (Balakot-Bagh Fault)	7.8	10	-	-	-	-	-	-	-	-	**0.21**	0.34	-	-
Jhelum Fault	7.1	0	0.51	0.92	0.55	0.39	0.75	0.32	0.31	0.55	**0.27**	0.45	0.44	0.82
Sangargali Thrust	6.9	32	0.13	0.23	0.17	0.10	0.19	0.08	0.09	0.16	**0.11**	0.19	0.11	0.21
Thandiani Thrust	6.8	34	0.11	0.20	0.15	0.09	0.17	0.07	0.08	0.14	**0.10**	0.18	0.10	0.19
Nathiagali Thrust	7	36	0.12	0.21	0.16	0.10	0.18	0.08	0.08	0.15	**0.11**	0.19	0.10	0.19
Balakot Shear Zone (BSZ)	6.8	30	0.13	0.23	0.18	0.10	0.20	0.08	0.09	0.16	**0.09**	0.16	0.11	0.21

Table.1. Thirteen most critical tectonic features (faults), their maximum potential magnitudes, closest distances and PGA's (%g) using the attenuation equations used in the study i.e.1. Joyner and Boore, 1982: 2. Sadigh et al., 1987: 3. Ambraseys and Bommer, 1991: 4. Campbell and Bozorgnia, 1993: 5. Ambraseys et al., 1996: 6. Boore et al., 1997:7. Tromans and Bommer, 2002

4. DISTANCE FROM THE SITE

Table. 1 represents the closest distances of all causative sources from the site of Muzaffarabad. Also the constant depth of 10 km has been taken for all these causative sources as the shallow earthquakes are of more concern to seismic hazard assessment.

5. PEAK HORIZONTAL ACCELARTIONS

The estimation of peak horizontal acceleration at the site depends upon the maximum potential magnitude, epicentral or hypocentral distance and local geological site conditions. Therefore on the basis of maximum potential magnitudes and shortest possible distance from the site, the peak horizontal accelerations have been determined using seven attenuation laws including the equation of Boore et al., 1997 (Table. 1).

The peak horizontal accelerations were computed assuming that maximum earthquake along a fault occurs at the shortest distance of this fault from the site. For attenuation laws, which take into account focal depth also, acceleration values have been computed for focal depth of 10 km.

6. MAXIMUM CREDIBLE EARTHQUAKE (MCE)

MCE i.e. the Maximum Credible Earthquake is the largest reasonable conceivable earthquake that appears possible along a recognized fault or within a geographically defined tectonic province, under the presently known or presumed tectonic framework (Mahdi, 2003). MCE can be calculated by both the deterministic or probabilistic approach. In the present work, it is calculated by the deterministic approach and is 8.0.

II. PROBABILISTIC SEISMIC HAZARD ASSESSMENT (PSHA)

The estimation of PGA has also been carried out using the Probabilistic Seismic Hazard Assessment (PSHA). The conventional approach has been adopted for the site of Muzaffarabad. PSHA is denoted by the probability that ground acceleration reaches certain amplitudes or seismic intensities exceeding a particular value within a specified time interval. The inverse of probability of exceedance is known as the return period for that acceleration and is used to define the seismic hazard. In PSHA, the seismic activity of seismic source (line or area) is specified by a recurrence relationship, defining the cumulative number of events per year versus their magnitude. Distribution of earthquakes is assumed to be uniform within the source zone and independent of time. Seismic hazard calculated for different sites can be used to generate maps or curves (hazard curves) with ground accelerations expected with a given probability for a specified interval of time. In the present work, the four seismic source zones and their seismic hazard parameters evaluated by MonaLisa et al, 2007 have been used for the estimation of PGA using PSHA. The calculation of PGA involves the use of an appropriate attenuation equation. In the present case the attenuation equation Boore et al 1997 have been used.

The PSHA results are in the form of the hazard curve that has been generated using the software EZ-FRISK (6.2 beta version, 2004 modified form). The range of values used as input parameters can account for multiple hypotheses and computation of uncertainty in the resultant hazard values. It uses the seismic hazard parameters such as annual activity rate, minimum magnitude, threshold magnitude and b-value characteristics of the region as the input parameters. Results obtained are in the form of hazard curve which represent the annual frequencies of exceedance of various ground motion levels at the site of interest. From these curves, acceleration values for different return periods can be determined.

Following the normal practice, the PGA values with 10% probability of exceedance in the 50 years, i.e., the return period of 475 years, are calculated (Figure 5). PGA values of 0.17g have been obtained using Boore et al., 1997 equations. The value of 0.17g is not so high for the next 50 years, but the site (Muzaffarabad) consists of poorly constructed structures and can experience appreciable damage as compared to other, less populated, sites in the surroundings.

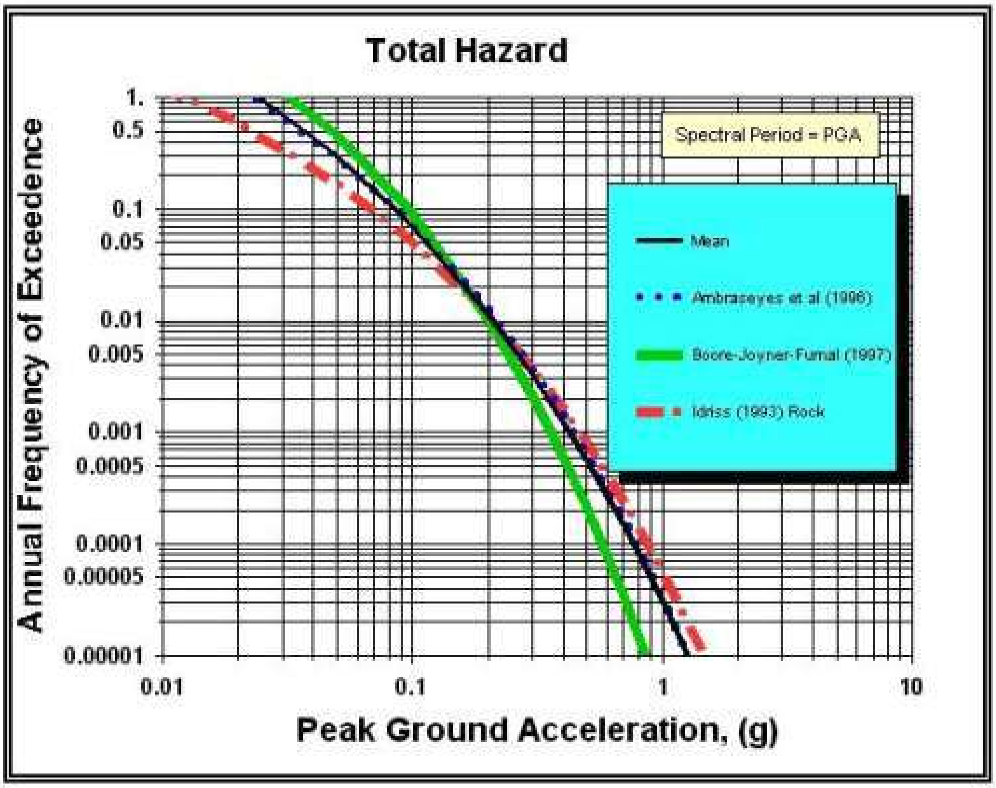

Fig. 8. Total seismic hazard curve for the site of Muzaffarabad for various return periods.

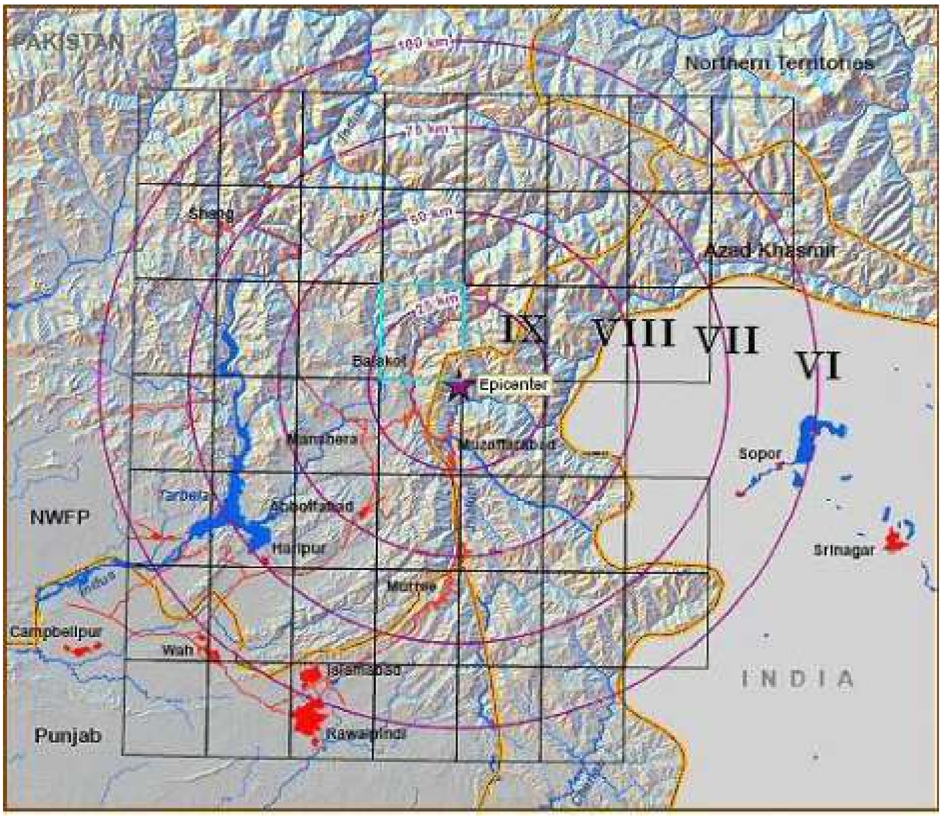

Fig. 9. Intensity map of Muzaffarabad and surrounding.

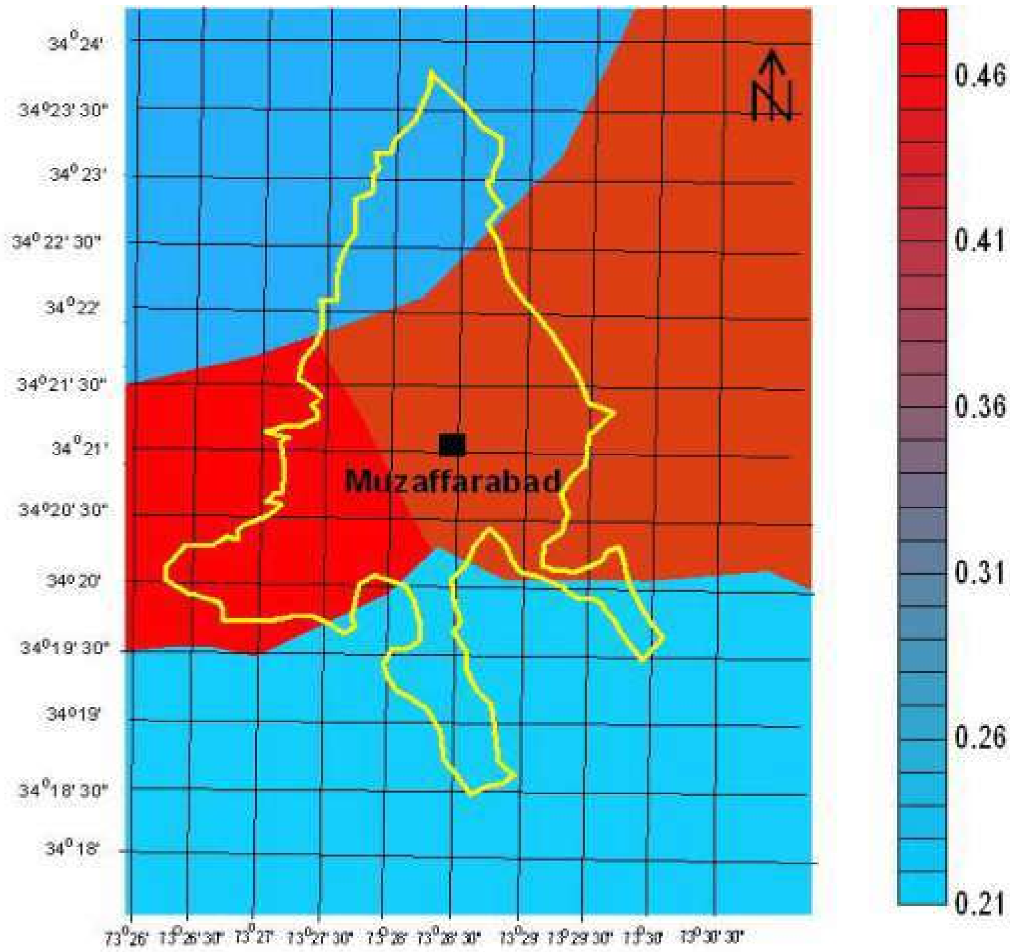

Fig. 10. Peak Ground Acceleration map for Muzaffarabad.

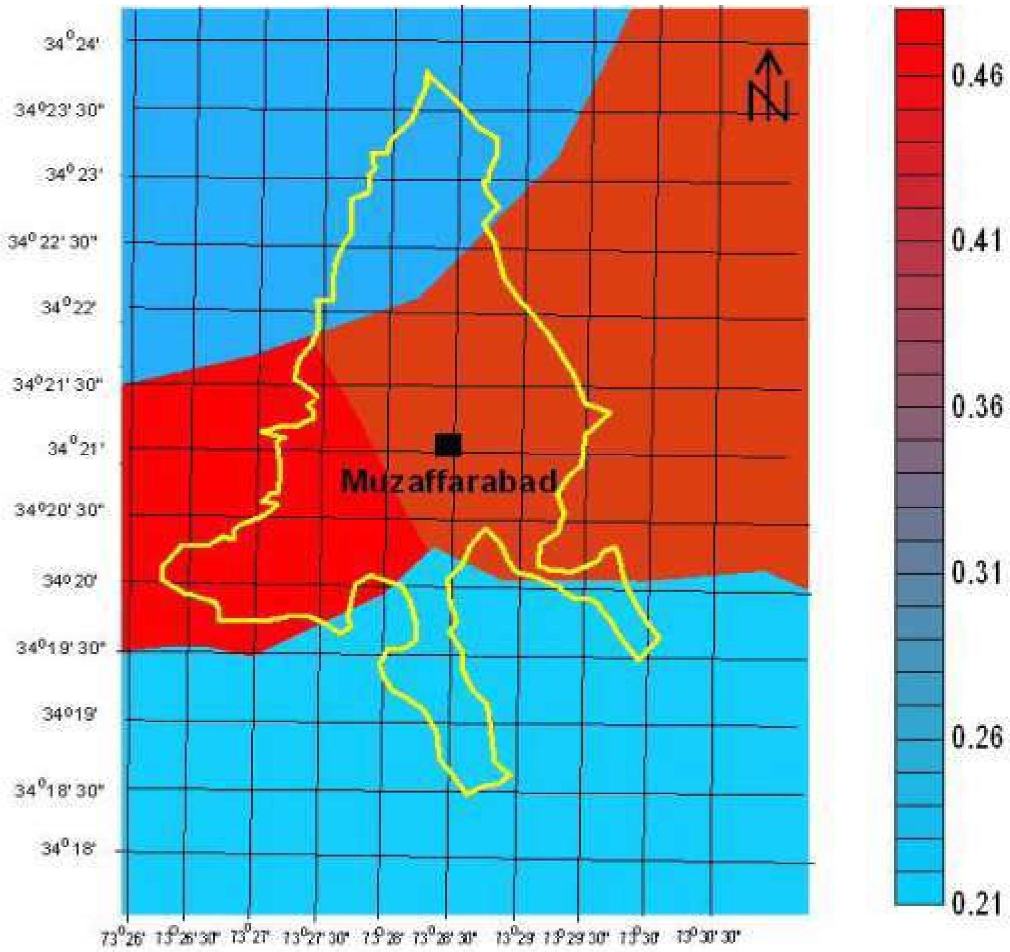

Fig. 11. Intensity based upon MMI scale, for Muzaffarabad.

Conclusions

The Seismic Hazard Assessment (SHA) of Azad Kashmir has been carried out using the conventional approaches of probabilistic and deterministic analysis. The SHA was carried out by considering the earthquake source zones, selection of appropriate attenuation equations, near fault effects and maximum potential magnitude estimation. The area is located tectonically in an active regime referred to the as Hazara-Kashmir Syntaxis. The Main Mantle Thrust, Mansehra Thrust, Oghi Fault, Banna Thrust, Balakot Shear Zone, Main Boundary Thrust, Panjal Thrust, Jhelum Fault and Muzaffarabad Fault and, further to the south, the Sanghargali, Nathiagali, and Thandiani Thrusts are the most critical tectonic features within the 50 km radius of Muzaffarabad (Capital of AK). Using the instrumental seismological data from 1904 to 2007, SHA has been carried out. Other reactivated critical tectonic features in the area have been investigated. Among them the Balakot-Bagh fault, with the fault length of 120 km from Balakot to Poonch, has been considered as the most critical tectonic feature on the basis of geological/structural/seismological data. The potential earthquake of maximum magnitude 7.8 has been assigned to the Balakot-Bagh fault using four regression relations. The peak ground acceleration value of 0.25g (10% probability of exceedance for 50 years) and 0.5g has been calculated with the help of the attenuation equation using probabilistic and deterministic approaches.