Int. J. Econ. & Environ. Geol. Vol:1(1) 1-5

Pre and Post Earthquake Seismo-Tectonic Scenario of Hazara–Kashmir Terrain of Pakistan

R. A. KHAN TAHIRKHELI

Gandhara University, Peshawar, Pakistan (vicechancellor.gu@hotmail.com)

Abstract. The Hazara-Kashmir (HK) terrain is located on the northwestern margin of the Lesser Himalaya. The Hazara-Kashmir Syntaxis (HKS) is one of the bold tectonic scars, which physically seperate this terrain from rest of the Himalaya. The major tectonic features sculpturing this terrain in the shape of folds and faults are: Hazara-Kashmir Syntaxis (HKS), Main Mantle Thrust (MMT), Main Boundary Thrust (MBT), Panjal Thrust (PT), Hazara Thrust (HT) and Indus Valley Faults (IVF). All these mega-structures are the abode of variable seismicity and generate earthquakes of low to moderate magnitude. Among them, the MMT, MBT, PT and the IVF have hazardous seismic history. The earthquake of October, 8, 2005 of magnitude 7.6 with its epicenter, located south of Balakot is linked with one of these faults, the MBT, which traverses the eastern and western flanks of the HKS. The deep mega-crustal deformations beneath the Hazara-Kashmir terrain monitored through seismicity are: Indus-Kohistan Seismic Zone (IKSZ), Hazara Lower Seismic Zone (HLSZ) and Tarbela Seismic Zone (TSZ). The epicenter of earthquakes generally lies between 10-60 km depth in the seismic zone of the mega-crustal deformations in the HK terrain. The earthquakes generated at this depth are categorized as shallow and usually more hazardous. The successive events in the seismic profile between years 2003-2005 were a reliable precursor to predict accumulation of energy, which ultimately caused the earthquake on October 8, 2005.

Introduction

The Hazara-Kashmir terrain in the context of regional surface and sub-surface geology displays a complex seismo-tectonic scenario (Tahirkheli, 1970, 1982, 1983; Ali, 1975; Tahirkheli et al., 1977, 1979; Armbruster, et al., 1978; Quittmeyer et al., 1979; Tahirkheli and Mattauer, 1984; Yeats and Lawrence, 1984).

The earthquake-prone structures occur both on the surface as major lineaments and also at depth beneath the surface as mega crustal deformations. These features are visible and can be brought within the fold of geological investigations by conducting geological mapping.

Their subsurface behaviour can be verified by adopting various geophysical methods, whereas the deep crustal deformations occur at depth and their tectonic turbulence or configuration can be deduced by monitoring deep crustal seismicity.

The mega-lineaments (Himalayan Boundary Faults) running parallel to the Himalayan front play an active role in geotectonic evolution of its frontal domain. Seebar et al. (1981) 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 that separates the under thrusting Indo-Pakistan 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, the faults in the Hazara-Kashmir 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 earthquakes. In case of Detachment, a rupture occurs in vast area in a single event causing sever earthquakes.

Surficial Tectonic Scars

The mega-geotectonic features exposed on the surface as faults in Hazara-Kashmir 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) Indus Valley Faults. All these faults occur as major lineaments traversing the Hazara–Kashmir terrain. Detailed investigations conducted on these faults had shown movements in some, but their contribution to seismicity was poorly known, till the availability of seismic data monitored through the Tarbela Dam Seismological observatory (Fig. 1).

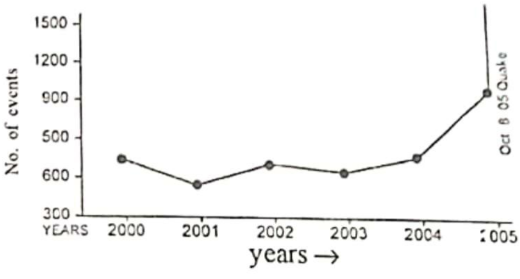

Fig. 1. Critical Seismic Phase Scenario at Terbela Seismological Observatory.

a) Hazara-Kashmir Syntaxis (HKS) 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. The eastern flank of HKS is traversed by two parallel thrusts, the Panjal Thrust and the Main Boundary Thrust. The former is older and involves Precambrian rock formations, whereas, the latter is young and involves the Muree Formation of Oligo-Miocene age. Hypocenters of relocated earthquakes indicate that HKS is about 30 km wide and most of its earthquakes emanate at 12-14 km depth. Calkins et al. (1975) had reported a reversal movement on the faults along the western limb of the syntaxis and suggested that the increased 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 points out to the main compressional movements, which are shifting to the west and northwest and stresses generated are energizing the western limb of the syntaxis, which is the abode of the Main Boundary Thrust. The Muzafffarabad Fault, a terminal branch of MBT and the epicenter of Hazara-Kashmir earthquake are located on the western limb of HKS and are the products 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 this earthquake is geologically extended between Bagh in Kashmir and Balakot in (Hazara).

b) Main Mantle Thrust 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. Sutures constitute the plate boundaries and are the sites of intense geological activities. 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 magnitudes 5.5 and 6.1 on the Richter scale. The Pattan earthquake of 1974 with magnitude 6.1 is the highest level of seismicity recorded in the MMT Zone adjacent to the Hazara Kashmir terrain (Tahirkheli, 1983).

c) The Main Boundary Thrust is one of the youngest among three mega-shears of the Himalayas, which runs along its length for about 2500 km and in depth it is shallower than others. The stresses generated due to convergence movements are migrating to the Himalayan front in the south, which is being accommodated by the multiple shear zones. Among these shears one of the major recipients is the MBT. Thus, the MBT with its tangled roots in the Detachment, one of the Himalayan Boundary Faults and well netted in the Himalayan orogeny will remain a major threat with potential of generating earthquakes of October, 2005 intensity, any where in the region, which comes under its fold. It has also the potential to cause major events with large ruptures. Its seismic history reveals several major 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.

d) Panjal Thrust constitutes an important tectonic boundary, which played an active role in the tectonic evolution of Hazara–Kashmir terrain. The thrust emanates in Pir Panjal range in Kashmir and extends northward along the eastern flank of the Hazara–Kashmir syntaxis. It lies at the base of Precambrian metamorphic rocks and tectonically separates the Salkhala unit of Precambrian age from the younger Panjal imbricate zone of Palaeozic–Mesozoic age (Tahirkheli, 1982). The Panjal Thrust is located on the receiving end of northwest pressure caused by the Himalayan boundary faults and the resulting stresses are being transported to the west through Hazara–Kashmir syntaxis and getting accumulated along its western limb targeting the MBT. Along the eastern limb of the synatxis, PT shows cluster of epicenters ranging in magnitudes between 4 and 5 on the Richter scale. Several events of magnitudes >5 and two of 6-6.4 as the post-shocks of October, 2005 earthquake are new addition to the seismic domain of the eastern limb of syntaxis, which is traversed by both PT and MBT. Quite a number of these events as a result of aftershocks might have emanated from the Panjal Thrust seismic zone.

e) The Hazara Thrust seismically merges together three isolated thrusts namely, Thandiani, Sangargali and Nathiagali thrusts and extends westward from the Hazara-Kashmir syntaxis. In this thrust in the west, the Precambrian Hazara slates, Cambrian dolomitic limestones of Abbottabad Group and Palaeocene–Eocene limestone formations are involved in the thrust zone, the former two formations thrust over the latter. The thrust strikes east-west and from Nathiagali in Hazara passes through Abbottabad, Hassan Abdal and after crossing the Indus river emerges in the Attock-Cherat range where it merges with the Khairabad Fault. A high level shallow seismicity occurs along the Hazara Thrust, west of the Indus river, which is reflected by cluster of epicenters with 2.5 magnitudes distributed in the eastern part of Peshawar plain. Among the historic events, there are some events of magnitudes 4–4.9, spanning the Khairabad Fault. The shallow seismicity of the thrust on the eastern side of the Indus in Hazara, is low or absent. Seeber and Armbruster (1979) consider that the inactive part of the Hazara Thrust in its eastern part is locked and stresses generated are being accumulated for a greater event. Most of these events in Hazara Thrust are not deeper than 40 km.

f) The Indus Valley Faults incorporate three parallel running faults, which crop out along the Indus valley upstream and downstream of Tarbela Dam. The system includes three shears namely: i) Dal Fault, ii) Darband Fault and iii) the Mid-Valley Fault.

Deep Crustal Deformations

The locations and configurations of deep crustal deformations of Hazara–Kashmir terrain were deduced from the seismic data collected from the Tarbela Dam Seismological Observatory. The seismic observations revealed three zones of mega crustal deformations: i) Indus Kohistan Seismic Zone (IKSZ) ii) Hazara Lower Seismic Zone (HLSZ) and iii) Tarbela Seismic Zone (TSZ). None of these deep crustal deformations indicate relation with the thick surficial geological or topographic features (Fig. 2).

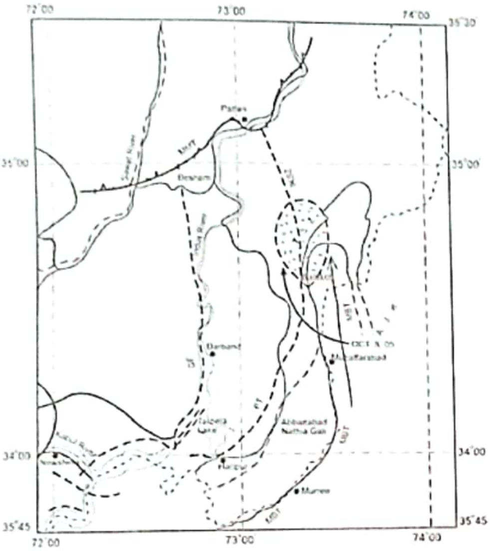

Fig. 2. Surficial seismotectonic contours of Hazara-Kashmir. MMT-Main Mantle Thrust, MBT-Main Boundary Thrust, PT-Panjal Thrust. HKS-Hazara-Kashmir Syntaxis, DF-Darband Fault, DA-Dal Fault. MF-Mid. Valley Fault, IKSZ-Indus Kohistan Seismic Zone, HT-Hazara Thrust. KF-Khairabad Fault and CF-Cherat Fault.

i. ***The Indus Kohistan Seismic Zone*:** It is one of the most clearly defined deep crustal structures, which extends north-westward beyond the nose of Hazara–Kashmir syntaxis. In the northwest, it terminates in the vicinity of Pattan in Kohistan. Its tectonic relationship with the Main Mantle Thrust, the southern Himalayan suture and 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. The IKSZ is a Basement Thrust, where the basement material penetrated deeper beneath the Higher Himalaya. On the basis of focal mechanism interpretation (Seeber et al., 1981), the IKSZ is a thrust dipping to the north-west and covers an area of about 120 km long and 25 km wide. Its seismicity extends to about 70 km depth. Majority of the epicenters along this zone have focal depth of 12 to 24 km. 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 that 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, quite a number of events ranging between magnitudes 4 and 5 on the Richter scale have so far been recorded in this zone.

ii. ***The Hazara Lower Seismic Zone*:** It 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. It passes underneath the Tarbela Dam Network at a maximum depth of 50 km 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. However, this fault remained much less active during the period of Tarbela network operations. Armbruster et al. (1978) have described a northeast dipping fault, which branches off the HLSZ and extends northwest 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 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. However, the structural relationship between these two faults is not yet clear. 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. According to Seeber and Armbruster (1979) the Taxila event of 25 AD could be associated with the earthquake generated by the HLSZ.

iii. ***The Tarbela Seismic Zone*:** It is 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 Tarbela Dam Seismic Observatory, 1495 seismic shocks were generated in the area lying within the fold of Tarbela Seismic Zone. Their hypocenters range from 0 to 20 km depth, with varying magnitudes of 2 to 5.5. Seeber et al. (1981) have considered this zone a potential source of the maximum intensity earthquakes (M. 6.5) for the Tarbela site. Most of the larger events in this zone are located at about 12-14 km depth and cover an area of about 500 sq.km.

Seismic Potential of Mega Structures

Details of the turbulences generated by seismically active structures of the Hazara–Kashmir terrain, have been obtained by three previous studies: one is supplied by TDSO seismic record for years 2000 to 2005, published by NESPAK in 1990, which covers seismic events between 1904 and 1989 and a recent publication by Lisa et al. (2005) with seismo-tectonic details of northwest Himalaya. Based on the available information, one can delineate five isolated seismic zones on the map of Hazara-Kashmir terrain, where large concentrations of epicenters are noted. These are: i) In the vicinity of Pattan, north and south of MMT (M. 3-5.9), ii) Northern and northwestern tips of Hazara-Kashmir Syntaxis (M. 3-5), iii) West of the HKS covering the area around Nathiagali, Murree, Abbottabad, Havelian and Haripur (M. 3-5.9), iv) around Tarbela Dam Network and northwest of Darband (M. 3–5.9) and v) west of the Attock–Cherat Range across the Indus river (M. 2.5-4.5). All these seismic zones fall within the domains of the surficial and deep crustal mega-structures. A major part of the seismicity is erupted by the Basement faults, which are continuous, yielding low to moderate magnitude events. Five families of faults, which have significant seismic record of contribution to the seismo-tectonic domain of Hazara-Kashmir terrain are: MBT, PT, HKS and MMT which are surficial structures, whereas IKSZ and TSZ are deep crustal structures.

The seismic history of MBT, besides generating the October 8, 2005 earthquake is associated with several large events in the middle and eastern Himalayas. Earlier this Balakot–Muzaffarabad belt in Hazara–Kashmir terrain has witnessed a major seismic eruption, leading to creation of a rupture named as Muzaffarabad fault, which is considered an offshoot of MBT. The factors responsible to activate MBT in Balakot–Muzaffarabad belt are: northern tip of the Hazara–Kashmir syntaxis, where three tectonically active faults: Indus Kohistan Seismic Zone, Panjal Thrust and Main Boundary Thrust converge and constitute a very active seismic source zone, which displays a cluster of epicenters of variable magnitudes (Fig. 2). This zone based on the exposed seismotectonic contours may be delineated at 15-20 km radius from Balakot and is distinguished as Triple Seismic Junction. This seismic zone is critical to the area around, specifically the western flank of the Hazara-Kashmir syntaxis, which due to stress accumulation is already under constant strain. The MBT traverses this flank after it loops around the northern tip of the syntaxis at Balakot. Thus, a slight tectonic upheaval created in this zone can destabilize the MBT for larger events. Beside this factor, the inherent linkage of the MBT with the Detachment, one of the active boundary faults of the Himalaya can be more devastating and may lead to large seismic hazards and great ruptures.

All the shears are seismically active and among them the deep crustal Indus Kohistan Seismic Zone shows a large number of epicenters distributed all along its domain, exceeding in concentration from the others. The seismicity in its zone varies from magnitudes 3.5 to 5.5 and the higher level concentrations occur in the vicinity of its terminations near MMT and HKS, located in the north and south. The Panjal Thrust along its course on the eastern limb of Hazara–Kashmir syntaxis indicates a large number of isolated epicenters in the range of magnitudes 3 to 3.9, with some events culminating in 4.9 magnitude. West of the syntaxis along its course through Balakot, Chitta Batta, Mansehra and Bassu Maira in Haripur plain, the epicenters of magnitudes 3.5 to 5.9 are associated within its zone. One of the latter events is located not far from the eastern flank of the Gandghar Range.

The Tarbela Seismic Zone covers 500 sq.km area underlying the Tarbela Dam network and lies about 20 km deep beneath the surface. This deep crustal structure is also one of the major irritants for the Tarbela Dam. It is a source of maximum number of local events, the larger ones in the range of magnitudes 4–5.5. After MBT, this structure is the second in the Hazara–Kashmir domain, which is tagged with the Detachment and has potential of generating large seismic events. According to Seeber et al. (1981), it can be the source of sever earthquakes for Tarbela Dam.

Pre and Post Hazara-Kashmir Earthquake

Prediction of earthquakes is still far from achieving an authentic scientific base to forecast time and location of occurrence. However, there are some earthquake precursors, which are being followed and one of them is based on historical and prevailing seismic events. In case of Hazara–Kashmir terrain, the detail of year-wise distribution of foreshocks reveals that from year 2003 onwards till October 7, 2005, one day before the main event, there appeared progressive increase in the seismic activity, which culminated in 916 events, when the earthquake of magnitude 7.6 occurred. Subsequent to this catastrophe, the shocks continued with upward trend, adding 448 shocks, increasing the total number to 1364 events at the end of year 2005. This progressive increase in frequencies of seismic events from year 2003 onward was a strong signal to remain alert for any untoward incident. A serious exercise could have helped to forecast the seismic upheaval, which paved way for Hazara-Kashmir earthquake (Ambraseys, 1995). Most of the earthquake precursors are still considered an academic exercise, but studies of some can help to predict the level of energy built-up in an area to forecast seismic upheaval without pinpointing intensities, location and the time of arrival of the major events.

Mitigation Measures

Hazara–Kashmir has emerged as the most vulnerable seismic zone after the devastating earthquake. This seismic scenario necessitates preparedness from grass-root level to mitigate such hazards in future. Seismic zoning at macro and micro levels are a pre-requisite to assess the vulnerability of the earthquake-prone structures and to delineate the high risk zones.

The upgradation of the current network for the earthquake probe in the country is important step, which should be undertaken without delay. In this program, seismologists and geologists need to develop and streamline their facilities in the Observatory which will enable them to produce technical data compatible with the modern technology during field work. More observatories may be established in the high risk seismic zones. A periodic report may be prepared by each observatory and data gathered should be exchanged among geologists and geophysicists working in the universities and research institutes.

Development of manpower resource is necessary to run the sophisticated labs and observatories. Hence, scientists should have an opportunity for periodic training in the observatories abroad to update their technical know-how and get abreast with the modern trends in the earthquake technology.

References

Ambraseys, N.N. (1995) The prediction of earthquake peak ground accelerations in Europe. *Earthquake Engineering and Structural Dynamics*, **24**, 1179-1202.

Armbruster, J; Jacob, K. H; Seeber, L. (1978) Tectonics of the Lesser Himalayas in northern Pakistan based on microquake observations. *J. Geophysics. Research*, **83**, 269-282.

Ali, S.T. (1975) Geology of the southern Himalaya in Hazara, Pakistan and adjacent areas. *U.S. Geol. Surv., Prof. Paper*, **716**-C.

Calkins, J. A; Offield, T.W; Abdullah, S.K.M; Tayyab, A. S. (1975) Geology of southern Himalaya in Hazara, Pakistan and adjacent areas. *U.S. Surv. Prof. Paper*, **716** C, 29 p.

Lisa, M; Khwaja, A. A; Javed, M; Ansari, Y. S; Jan, M.Q. (2005) Seismic hazard assessment of NW Himalayan Fold and Thrust Belt, Pakistan, using probabilistic approach. In: *Proc. Pak. Acad. of Science*, **42** (4).

Quittmeyer, R.L; Farah, A; Jacob, K.H. (1979) The seismicity of Pakistan and its relation to surface faults. In: *Geodynamics of Pakistan*. A. Farah and K.A. DeJong (eds.), 271-284.

Seeber, L; Armbruster, J; Quitmeyer, R.C. (1981) Siesmicity and continental subduction in the Himalayan Arc. In: *Zagros, Hindu Kush, Himalaya-Geodynamic Evolution, Geodyn.* Ser., **3**. H. K. Gupta and F.M. Delany (eds.), 215-242.

Seeber, L; Armbruster. J. (1979) Seismicity of Hazara Arc in northern Pakistan: Decollement vs. Basement Faulting. In: *Geodynamics of Pakistan*. A. Farah and K.A. De Jong (eds.), 131-142.

Tahirkheli, R.A.K. (1970) The geology of the Attock-Cherat Range, West Pakistan. *Geol. Bull. Univ. Peshawar*, **5**, 1-26.

Tahirkheli, R.A.K; Mattauer, M; Proust, F; Tapponnier, P. (1977) Some new data on the India-Eurasia convergence in the Pakistani Himalayas. College Intern. CNRS (Himalaya, Sci. de la Terre), **268**, 209-220.

Tahirkheli, R.A.K. (1982) Geology of the Himalaya, Karakoram and Hindukush in Pakistan. *Geol. Bull Univ. Peshawar*, **15**, 1-51.

Tahirkheli, R.A.K. (1983) Geological evolution of Kohistan island arc on the southern flank of the Karakoram-Hindukush in Pakistan. *Bull. Geofis. Teorica Applicata*, **25**, 351-364.

Tahirkheli, R.A.K; Mattauer, M. (1984) The geographic and geologic domains of the Karakoram. In: *International Karakoram Project*, **2**. K.J. Miller (ed.), Royal. Geogl. Soc. London, 57-70.

Tahirkheli, R.A.K; Mattauer, M; Proust. F; Tapponnier, P. (1979) The India-Eurasia suture zone in northern Pakistan: Synthesis and interpretation of data at plate scale. In: *Geodynamics of Pakistan*, A. Farah and K.A. DeJong (eds.). Geol. Surv. Pak., Quetta, 125-130.

Yeats, R.S; Lawrence, R.D. (1984) Tectonics of the Himalayan thrust belt in northern Pakistan. In: *Marine Geology and Oceanography of Arabian Sea and Coastal Pakistan*, B.U. Haq and J.D. Milliman (eds.), 177-200.