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Title	A study on the enhancing earthquake frequency in northern Pakistan: is the climate change responsible?
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Citation	Natural Hazards, 82, 921-931 https://doi.org/10.1007/s11069-016-2226-z
Issue Date	2016-02-17
Doc URL	http://hdl.handle.net/2115/64426
Туре	article (author version)
File Information	NHZ_RevisedPaper_AcceptedVersion.pdf



# A Study on the Enhancing Earthquake Frequency in Northern Pakistan: Is the Climate Change Responsible?

#### Abstract

In northern Pakistan, the collision between Indian and Eurasian plates has resulted in the formation of many faults. The concentration of ruptures, in this regime, probably makes it sensitive to the localized changes in the stress. The current climate changes have caused an increase in the rainfall and variation in the mass of glaciers, present in the northern Pakistan. The rainfall and glacial runoff has potential to erode and transport sediments thus can change the balance of load across faults. On the other hand, glacial mass loss or gain also has potential of iso-static rebound or compression of crust, respectively. All these factors have been observed in the northern Pakistan. The seismic data of the duration 1965 to 2004 has been obtained from Pakistan Meteorological Department (PMD) and the sedimentation data has been acquired from Tarbela Dam Project (TDP). The study indicates a gradual increase in the earthquake frequency for the magnitudes 4.1-5.0(Mb). The epicental distributions show that these events gradually cluster in the central Karakorum and Hindukush areas. The depth analysis suggests the earthquakes with the foci 0-60km are gathering in the central Karakorum and shocks with depth 0-120 are clustering in the Hindukush areas. The FMS study exhibits the dominance of normal faulting in the central Karakorum after 1999 and these characteristics do not correspond with behavior of previous mapped Raikot Fault, lying in the vicinity. The known significant variables during the study period are the different geological processes associated with climate change, which have potential to alter the load across faults and can possibly result in enhancing earthquake frequency by changing stresses at some local scale.

Key words: Climate change, glacial mass change, rising earthquake frequency

#### 1 Introduction

In the present days it is an established fact that the climate is changing due to global warming. The alterations in the glacial mass, resulting from climate change, depend upon their spatial distribution through the world. Since the industrial revolution in 1750, human activities are mostly responsible for accelerated global climate changes and giving rise to other globally and locally environmental changes and alteration in land use cover and soils (Iqbal and Goheer 2008).

After Alaska and Arctic regions, the Karakorum-Himalaya (K-H) area constitutes the second largest glacial cover of the Earth (Dyurgerov and Meier 2005). On the basis of mapping done by using the recent satellite images in K-H region, the estimated glacial mass covers around 40,800 square kilometers: Himalaya 22800 and Karakoram 18000 square kilometers (T. Bolch et al. 2012). The Karakoram glaciers are fed by precipitation and avalanche. An increase in precipitation has been observed in the heights around 2500 and 4800 meters while maximum precipitation occurs at the altitude between 5000 to 6000 meters (Hewitt 2005).

- 14 A few larger glaciers are expanding in the Karakoram and adjacent areas (Smiraglia et al. 2007; Hewitt
- 15 2005). Around 5% decline has been observed in the Karakorum glaciers in the early 20<sup>th</sup> century (Hewitt
- 16 2011). However, the loss in mass was slowed down in 1970s (Mayewski and Jesche 1979) and in 1990s
- the glaciers stabilized and started advancing in the high Karakoram (Hewitt 2005; Immerzeel et al. 2009).
- 18 A net gain in the glacial mass has been studied in the higher Karakoram (Naz et al. 2009). The GRACE

19 satellite gravimetric observations, during 2003 to 2009, suggest a net loss in mass of glaciers across high

20 Asian mountains, however this trend is highly variable in the space and time and northwestern part

21 including the Karakorum mountain range show a gain in mass and in Hidukush areas there is a slight loss

in mass (Matsuo and Heki 2010). During the early twentieth century i.e. 1999-2008, based on the Digital

23 Elevation Model (DEM) data acquired from Shuttle Radar Topographic Mission (SRTM) and Satellite

24 Pour l'Observation de la Terre (SPOT5) optical stereo imagery, J. Gardelle et al (2012) observed a slight

25 gain in the mass, in the central Karakorum glaciers.

The snout of Baltoro glacier, one of the largest glaciers in the Karakoram, is oscillating back and forth a couple of hundred meters (Mayer et al. 2006). In the central Karakoram, there are strong indications of glacial meltdown along the northern flank of Rakaposhi Mountain and over all slight loss in the glacial mass, in the Bagrot valley (Mayer et al. 2010). As wasting ice sheets and caps unload the solid Earth, stresses released can both deform the Earth's surface (Pagli and Sigmundsson 2008) and decompress the Earth's mantle (Sigvaldason et al. 1992). The cumulative stress on the Earth's crust results from tectonic background stress, overburden pressure and pore-fluid pressure. The fault movement is controlled by the

superposition of first two and variation in the third one (Twiss and Moores 2007; Steffen et al. 2013).

34 Along with the change in the glacial size, the stresses on the earth crust and across faults can also be 35 altered by erosion and transport of the sediments associated with the rainfall and water runoff. To have an 36 insight about the amount of sediments being eroded and transported from northern Pakistan, Tarbela Dam 37 is located in ideal position. It is one of the largest rock-fill dams in the world that is built on the Indus 38 River (Tate and Farquharson. 2000). Although it can collect some part of the rain and melt water coming 39 from the northern Pakistan. In an average year the river Indus can carry around two hundred million tons 40 of sediments from Himalaya and Karakoram ranges and deposits it in the Tarbela Dam (Project Monitoring Organization 1996). The sediment longitudinal profile for the Tarbela dam shows that the 41 reservoir capacity is decreasing considerably with the each passing year (Fig. 2) due to the large amount 42 43 of sediments deposited each year. The glacial mass loss and gradual increase in the rainfall would 44 possibly result in increase discharge rate with the passage of time. So the potential of water to erode, carry, transport and deposit the sediments may also increase. The imbalance of load can have potential to 45 46 change the stress regime across faults and may possibly trigger some earthquakes. Ekstro"m et al. (2006) 47 observed an increase in the seismic activity in Greenland for the long-period seismic magnitudes in the range 4.6 to 5.1, which cannot be associated with the advancement of the instruments. The research 48 49 indicated that some glaciers and ice streams periodically lurch forward with sufficient force to generate 50 emissions of elastic waves that are recorded on seismometers worldwide.

51 As the northern Pakistan is thickly populated with faults, which make it sensitive to the localized changes (Usman et al. 2010b). So, this region is good to study and analyze the possible correlation between 52 53 change in mass and earthquakes. Jadon (1992) proposed that the tectonically northern Pakistan is 54 associated with the convergence resulting from the collision between Indian and Eurasian Plates and has 55 the dominance of various types of thrust faults (Fig. 1b). The major delineated structures of the collision 56 zone, present in the study area, are the Main Karakoram Thrust (MKT) also known as the Shyok Suture 57 Zone, the Main Mantle Thrust (MMT) also known as the Indus Suture Zone, the Main Boundary Thrust 58 (MBT). (Yeats and Lawrence 1984; Tahirkheli et al. 1979). The Hazara-Kashmir Syntaxis is supposed to serving as junction mainly for different types of thrust faults. The zone of about 250 km wide and 560 km 59 60 long fold-and-thrust belt surrounding The Panjal-Khairabad fault (Fig. 1b) has been divided into the

61 northern hinterland zone and southern foreland zone (Lisa et al. 2007). The studies also suggest that

62 strike slip faulting is also active in this compressional zone (Verma and ChandraSekhar 1986, Sercombe

63 et al.1998, Lisa et al. 2002, 2004).

During the probabilistic seismic hazard assessment of the northern Pakistan, Lisa et al. (2007) has observed a consistent increase in the earthquakes having moment magnitude 4.0 to 5.0. Usman et al. (2010a) proposed that the increase in the earthquake activity may possibly be the result of isostatic rebound of the earth resulting from the expected glacial mass loss due to climate change. Also, the sediment load across faults may alter the balance of load to generate earthquakes (Usman et al. 2011).

69 As the study area is mostly covered with glaciers and also due to the unavailability of satellite data during the study period, it is not possible to establish a direct correlation between the crust movement and the 70 71 resulting seismic activity. However, it is essential to study the changing earthquake activity from every possible aspect. A revised earthquake catalog (catalogue completeness test was perfumed and unreliable 72 events were excluded) along with sedimentation data of Tarbela Dam Project and FMS data of Global 73 Centroid Moment Tensor (GCMT) has been used to further understand and analyze this possible 74 75 relationship. The earth's climate model projections suggest that global surface air temperature will considerably increase in future due to radioactive effects of atmospheric gases (Delworth et al. 1999) 76 77 which will further complicate the problem of glacier melting and associated geological hazards.



(1) Main Karakorum Thrust (2) Surghar Range Thrust (3) Raikot Fault (4) Main Mantle Thrust (5) Puran Fault (6) Batal Thrust (7) Oghi Fault (8) Mansehra Thrust (9) Panjal-Khairabad Fault (10) Darband Fault (11) Nowshera Fault (12) Kanet Fault (13) Karak Fault (14) Jehlum Fault (15) Himalayan Frontal Thrust (16) Kotli Thrust (17) Riasi Thrust (HKS) Hazara-Kasmir Syntaxis; (ATR) Astor (ISB) Islamabad (PWR) Peshawar (TDP) Tarbela Dam Project



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Fig. 2 Sediment Longitudinal Profile of Tarbela Dam. The horizontal axis shows the distance in miles (Tarbela Dam
 Project 2010).



89 Fig. 3 Magnified view of the FMS clustered areas. MKT is Main Karakorum Thrust and RF is Raikot Fault

## 94 **2. Materials and Methods**

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96 The seismological data was acquired from Pakistan Meteorological Department (PMD) and study 97 duration was from 1965 to 2004 as the Pakistan has not installed new seismological stations from 1965-98 2004 in study area. Only PMD catalog was used and in this catalog every other seismological value 99 shared from different sources like International Seismological Center (ISC), Indian Meteorological 100 Department (IMD) etc was excluded. After performing the catalogue completeness tests (detail of the process is given in the supplementary file) the earthquakes having body wave magnitude 4.1-6.0 were 101 102 selected. Although, in the northern Himalaya (including the northern Pakistan) the recurrence interval for 103 the earthquakes having magnitude  $\leq 6.0$  is less than a year (Shankar et al. 2007); but the change in load, 104 due to climate change, is a slow geological process. So, decadal frequency has been used to make a clear conclusion. Dadson et al. (2003) also used the decal erosion rates in the eastern Central Range and 105 southwest Taiwan, and found that the rate was the maximum in the active thrust fault regions. It means 106 107 that the contribution of sediment transport in the mass change, for the active thrust region of northern 108 Pakistan, cannot be ignored. To have an insight about the sediment transport rate and amount the sediment longitudinal profile data was acquired from Tarbela Dam Project. To examine the behavior of 109 the earthquakes the Focal Mechanism Solutions data for the duration 1976 to 2004 was acquired from 110 111 GCMT.

**Table 1** Different body wave magnitude and its average frequency (AF) and cumulative frequency (CF)

114	Magnitude						
115	Duration	4.1-5.0	AF	5.1-6.0	AF	Total	ACF
116	1965-74	99	9.9	24	2.4	123	12.3
117	1975-84	127	12.7	5	0.5	132	13.2
118	1985-94	139	13.9	11	1.1	150	15
119	1995-04	166	16.6	11	1.1	177	17.7
120	Total	531	13.3	51	1.3	582	14.6
121		•					







123



- **Fig. 5** Epicenteral plot for different magnitudes in the corresponding decades.
- 127 Table 2 Different depth ranges (in kilometers) and their corresponding average frequency (AF) and average
- 128 cumulative frequency (ACF)

Depth Duration	0-60	AF	61-120	AF	121-180	AF	181 <u>&gt;</u>	AF	Total	ACF
1965-74	76	7.6	32	3.2	5	0.5	10	1	123	12.3
1975-84	91	9.1	36	3.6	4	0.4	1	0.1	132	13.2
1985-94	75	7.5	45	4.5	25	2.5	5	0.5	150	15
1995-04	104	10.4	51	5.1	20	2	2	0.2	177	17.7
Total	346	8.7	164	4.1	54	1.4	18	0.45	582	14.6





Fig. 6 Depth plot. ACF is Average Cumulative Frequency



137 Fig. 7 Epicenteral plot for different depths in the corresponding decades.

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## 3. Results and Discussion

Table 1 and Table 2 show the magnitude and depth wise earthquake frequency for northern Pakistan respectively. The corresponding epicenter plots for the magnitude and depth have been shown in Figs. 5 and 7. While Figs. 4 and 6 depict the average earthquake frequency for the magnitude and foci ranges, respectively.

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146 The satellite data study of around 19 glaciers in the Hindukush area has shown that around 73% glaciers are retreating at slower rate and the study of 42 glaciers in the Karakoram areas has suggested that around 147 58 % of the glaciers are advancing (Scherler et al. 2011). The grace gravimetric observations also indicate 148 a slight gain in the mass of Karakoram glaciers but loss in mass has been detected in the Hindukush areas 149 (Matsuo and Heki 2010). In the Karakoram area from 1920 to early 1990s most the glaciers have lost 150 mass this period was punctuated with a small advancement phase in the 1970s and in the late 1990s the 151 glaciers of Karakorum started advancing (Hewitt 2005). In the central Karakorum area, there is around 152 153 200 meters oscillation in the terminus of Baltoro glacier (Mayer et al. 2006). In the central Karakoram, 154 there are strong indications of glacial meltdown along the northern flank of Rakaposhi Mountain and over all slight loss in the glacial mass, in the Bagrot valley (Mayer et al. 2010). 155

Apart from the current changes in the mass of glaciers the rain fall also has a strong potential for erosion and transportation of load across faults. In the upper Indus basin, from 1961-1999, statistical analysis shows that precipitation has increased in summers, winters and annually at several stations (Fowler and Archer 2005). Around two hundred million tons of sediments from Himalaya and Karakoram ranges are carried by Indus and deposited it in the Tarbela Dam in an average year (Project Monitoring Organization 1996) the sediment longitudinal profile is shown in Fig. 2.

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163 So, there are strong evidences of change in mass across Karakorum and Hindukush area. As wasting ice

sheets and caps unload the solid Earth, stresses released can both deform the Earth's surface (Pagli and

165 Sigmundsson 2008) and decompress the Earth's mantle (Sigvaldason et al. 1992). For the activation of

- 166 faults, the change in load over the earth crust is one of the major factors (Twiss and Moores 2007; Steffen
- the et al. 2013). Some glaciers and ice streams periodically lurch forward with sufficient force to generate
- 168 emissions of elastic waves that are recorded on seismometers worldwide (Ekstro"m et al. 2006).

In this area as the source, stations and seismograph have remained same during the study period. The increasing temperature is causing the glaciers of study area to melt and as the glaciers melt their load on plate lessens and there is a greater likelihood of an earthquake to happen to relieve the large strain underneath (Usman et al. 2010).

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174 The epicentral plot for different magnitude earthquake frequencies (Fig. 5) shows a 'clustering response' 175 for the magnitude ranging from 4.1-5.0 (Mb) with passage of time in the Hindukush areas where there are 176 reports of glacial mass loss. In the central Karakoram area where are studies indicating the change in 177 mass and also the concentration in the earthquake epicenters for the magnitude 4.1-5.0 have been observed. Probably the combined with localized changes in the stress on the crust the glacial run off and 178 179 rainfall has also the potential to erode and transport sediments across faults thus can change the balance of 180 load and may probably trigger seismic activity. While studying the cause for the rise of Andes, Lamb and 181 Davis (2003) concluded that climate controlled sediment starvation can possibly cause high sheer stresses along the plate boundary. The Fig. 4 shows an increase in the seismic activity for the magnitude of 4.1 to 182 5.0 however no such increase has been observed for 5.1-6.0 magnitude shocks. This rise in earthquake 183 184 frequency was also observed by Lisa et al. (2007).

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186 The focus plot of the epicenter (Fig. 7) also shows the clustering of earthquakes for the depth 0-60 km in 187 the central Karakorum and around 0-120 km for the Hindukush areas. Also the Fig. 6 shows the 188 increasing trend in the earthquake frequency for the depth range of 0-60 and 61-120 km. No such clear 189 increase in earthquake frequency has been observed for the greater depths.

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191 The Focal Mechanism study (Fig. 1b) also indicates the clustering of the events in two zones (Fig. 1 a,b). 192 Two previously studied faults are passing through these areas: Main Karakorum Thrust (MKT), strikes in 193 strikes east-west to south-west direction; and Raikot Fault which strikes in north to north east direction (Fig. 1b). On the basis of stress directions, Seeber and Pêcher (1998) proposed that the RF is the mainly a 194 195 reverse fault, although dextral and sinistral components are found locally (Seeber et al. 1997). Based on 196 the behavior of FMS and the characteristics of MKT which is passing close, it is reasonable to believe 197 MKT as a possible source fault in this region (Fig. 3a). From 2000 the FMS behavior seems interesting 198 (Fig. 3b). Out of six focal mechanisms, 5 exhibit normal and one show that the strike-slip faulting. However, these characteristics do not correspond with the features of RF. Also, there is always an 199 200 uncertainty about the location of FMS and they cannot be associated accurately with any under 201 observation fault based on seismological or even the GPS data, especially in a complex tectonic regime. 202 During the study of the October 28, 2008 shock sequence, in Baluchistan (Pakistan) based on the seismological and GPS data numerous researchers proposed that previously studied Urghaghai Fault as a 203 204 possible source (Lisa and Jan 2010; Khan et al. 2008; Yadav et al. 2012). However, on the basis of 205 synthetic aperture radar data, it became clear that a new complex geometry of conjugate faults was the 206 responsible source (Pezzo et al. 2014; Puyssegur et al. 2014; Usman and Furuya 2015).

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In the intraplate compression regime, various parts of plates experience different style of deformation and exhibit corresponding strain partitioning of reverse, normal and strike slip faulting. The FMS serve as finger prints to identify the stresses accommodation in different parts (Figs 1b, 3). The possible load change driven enhancing earthquake frequency resulting from climate change might be factor for the

change of stresses at some local scale. Consequently, resulting from the increase in tremors ranging from

- 4.1 to 5.0, the landslides and avalanches would possible become more frequent.
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## 215 Conclusions

In the northern Pakistan an increase in the earthquake frequency has been observed for the magnitude 4.1 to 5.0 and epicenter plot show that they are mostly concentrated in the central Karakoram and Hindukush areas where there are reports of glacial mass change and increase in the rainfall. The depth plot indicates that the earthquakes ranging from 0-120 km are increasing with the passage of time while 0-60 km earthquakes aggregate in the central Karakorum and 0-120 km shocks show a gradual increase in the concentration in the Hindukush areas. Regardless of the fact that there is a high population of reverse faults in the central Karakorum, the FMS study indicates that from year 2000 the normal faulting is

dominant in the study area and its characteristics do not correlate with the Raikot Fault passing nearby.

## 225 Acknowledgments

226 I am thankful to anonymous reviewers for their comments that helped to improve the manuscript. I am

- also incepted to Prof. Kosuke Heki and Prof. Junji Koyama for their valuable suggestions. I am very
- thankful to Seismic Section of Pakistan Meteorological Department and Tarbela Dam Project officials for
- 229 providing the necessary data and information.
- 230

#### 231 **References**

- Al-Tarazi E. (1992) Investigation and assessment of seismic hazard in Jordan and its vicinity Ph.D. thesis, Berichte
   Reihe A, Inst. f. Geophysics, Ruhr-Univ. Bochum, Vol. 34.
- Archer DR, Fowler HJ (2004) Spatial and temporal variations in precipitation in the Upper Indus Basin, global
   teleconnections and hydrological implications. Hydr & Eart Sys Sci. 8 (1):47-61. doi: 10.5194/hess-8-47-2004
- Bolch T, Kulkarni A. Kääb A, Huggel C, Paul F, Cogley JG, Frey H, Kargel JS, Fujita K, Scheel M,
   Bajracharya S, Stoffel M (2012) The State and Fate of Himalayan Glaciers. Sci. 336, 310:310-314. doi: 10.1126/science.1215828
- 241 Dadson SJ et al. (2003) Links between erosion, runoff variability and seismicity in the Taiwan orogen. Nature. Vol:
   426
   243
- 244
  245 Delworth T, Mahlman JD, Knutson TR (1999) Changes in summer temperature and heat related mortality since
  246 1971 in North Carolina, South Finland, and Southeast England.Environ Res. 91:1-7.doi: 10.1016/S0013247 9351(02)00002-6
- 248
   249
   249 Dyurgerov MB, Meier MF(2005) Glaciers and the Changing Earth System: A 2004 Snapshot.
   250 http://instaar.colorado.edu/uploads/occasional-papers/OP58\_dyurgerov\_meier.pdf. University of Colorado at Boulder. Accessed April 2011
- 252
   253 Ekstro"m G, Nettles M, Tsai VC (2006) Seasonality and Increasing Frequency of Greenland Glacial Earthquakes.
   254 Science.336:1756-1758. doi: 10.1126/science.1122112
   255
- Fowler HJ, Archer DR (2005) Hydro-climatological variability in the Upper Indus Basin and implications for
   water resources. Regional Hydrological Impacts of Climatic Change—Impact Assessment and Decision

- Making. Proceedings of symposium S6 held during the Seventh IAHS Scientific Assembly at Foz do Iguaçu, Brazil.
   Gardelle J, Berthier E, Arnaud Y (2012) Slight mass gain of Karakoram glaciers in the early twenty-first century.
- 261 Nat Geosci. 5:322-325.doi:10.1038/NGEO1450
- Hewitt K (2005) The Karakoram Anomaly? Glacial Expansion and 'Elevation Effect,' Karakoram Himalaya. :Mount Res and Devel. 25:pp332-340. doi; <u>http://dx.doi.org/10.1659/0276-</u>
  4741(2005)025[0332:TKAGEA]2.0.CO;2
- Hewitt K. (2011) Glacier Change, Concentration and Elevation Effects in the Karakoram Himalaya, Upper Indus
   Basin.Moun Res and Devel. 31:188-200.doi: http://dx.doi.org/10.1659/MRD-JOURNAL-D-11-00020.1
- Iqbal MM, Goheer MA (2008) Greenhouse Gas Emission from Agro-Ecosystems and Their Contribution to
   Environmental Change in the Indus Basin of Pakistan. Adv in Atm Sci. 25: 1043-1052.
- Immerzeel WW, Droogers P, de Jong SM, Bierkens MFP (2009) Large-scalemonitoring of snow cover and
   runoff simulation in Himalayan river basins using remote sensing. Rem Sen of Env.113:40–49. doi:
   10.1016/j.rse.2008.08.010
- Jadoon IAK. (1992). Thin-skinned tectonics on continent/ocean transitional crust, Sulaiman Range, Pakistan. Ph.D.
   thesis, Oregon State University, USA.
- Khan MA et al (2008) Preliminary geodetic constraints on plate boundary deformation on the western edge of the
   Indian plate from TriGGnet (Tri-University GPS Geodesy Network). J Himayan Geoscience. 41:71–87
- Kazmi AH, Jan MQ (1997) Geology and Tectonics of Pakistan . In: Neotectonics. Graphic Publishers,
   Karachi.Pakistan

- Lamb S, Davis P, (2003) Cenozoic climate change as a possible cause for the rise of the Andes. Nature. Vol: 425.
   pp 792-797. doi:10.1038/nature02049
- Lisa M, Jan MQ (2010) Geoseismological study of the Ziarat (Balochistan) earthquake (doublet?) of 28 October
   2008. Current Sciences. 98(1):50–57
- Lisa M, Khwaja AA, Javed M, Ansari YS, Jan MQ (2005) Seismic Hazard Assessment of NW Himalayan Fold
   and Thrust Belt, Pakistan, Using Probabilistic Approach. Proceedings of Pakistan Academy of Sciences. 42(4).
   pp 287-295
- Lisa M, Khwaja AA, Qaiser M. (2002) Focal Mechanism Studies of Kohat and Northern Potwar Deformed
   Zone.Geo.l Bul. Univ. of Peshawar 35 85–95.
- Lisa M, Khan SA, Khwaja AA. (2004) Focal Mechanism Studies of North Potwar Deformed Zone (NPDZ)
   Pakistan. Acta Seismol. Sinica. 17(3), 255–261.
- Lisa M, Khwaja AA, Jan MQ (2007) Seismic Hazard Assessment of the NW Himalayan Fold-and-Thrust Belt,
   Pakistan, Using Probabilistic Approach. Journal of Earthquake Engineering. DOI:
   10.1080/13632460601031243
- 301 Mahmood N, Hara T (2008) Travel time residuals from the new and old networks of Pakistan and preliminary
   302 hypocenter determination. International Institute of Seismology and Earthquake Engineering.(Japan).
   303 Available at http://iisee.kenken.go.jp/syndb/?action=abstr&id=MEE07163&est=S&year=2008
   304
- 305 Matsuo K, Heki K (2010) Time-variable ice loss in Asian high mountains from satellite gravimetry. Ear and Planet
   306 Sci Let. 290:30–36. doi:10.1016/j.epsl.2009.11.053

307	
308	
309	Makropoulos KC, Burton PW (1981) A catalogue of seismicity in Greece and adjacent areas. Geophysical Journal
310	International. 65. pp 741-762.
311	
312	
313	Mayer C. Lambrecht A.Belo M. SmiragliaC. Diolainti G. (2006) Glaciological characteristics of the ablation
214	and a function of the former participation of the state o
514	zone of Balloro glacier, Karakoram, Pakistan. Annais of Glaciology 45:125-151
315	
316	Mayer C, Lambrecht A, Mihalcia C, Belo M, Diolaiuti G, Smiraglia C, Bashir F (2010) Analysis of Glacier
317	Melt Water in Bagrot Valley Karakoram, Mou Res and Devel 30(2):169-
318	177 doi - http://dx doi org/10 1659/MRD-IOURNAL-D-09-000431
319	Tritor map and to the t
320	Mayaweki PA Jacobka PA (1070) Himalayan and trans Himalayan glaciar fluctuations since AD 1812 Arc and
220	Nayewshi 1A, Jestine 1A (1979) Inmanayan and trans-filmanayan glacier fluctuations since AD 1012. Are and
221	Alp Kes. 11.207–287.
322	
323	Naz BS, Bowling LC, Diffendaugh NS, Owens P, Ashfaq M, Shafiqur-Renman S (2009) Hydrological
324	sensitivity of the Upper Indus River to glacier changes in the Karakoram Himalaya region. Poster no. C31C-
325	0455 presented at the American Geophysical Union Meeting. San Francisco, CA, November 2009.
326	
327	Pakistan's Water and Power Development Authority (WAPDA) (Project Monitoring Organization, 1996)
328	Project Monitoring Organization: 1996, Reservoir Sedimentation Report, Tarbela, Pakistan.
329	
330	Pakistan Meteorological Department (PMD) NOSAR (Norway) (Report 2007) Seismic Hazard Analysis and
331	Zonation for Pakistan, Azad Jammu and Kashmir, Available at http://www.pmd.gov.pk/seismicreport_pmd.pdf
332	
222	Pagli C. Sigmundsson F (2008) Will present day glacier retreat increase volcanic activity? Stress induced by recent
331	algorier retreat and its effect on magnetism at the Vatneikull ice can Iceland Geophy Res Let 35:15 doi:
225	10 1029/2008GI 033510
336	10.1027/20000E055510
330	Pezzo C. Bancori IPM Atroz S. Antonioli A. Salvi S. (2014) Deformation of the western Indian plate boundary:
338	insights from differential and multi aparture InSAP data inversion for the 2008 Baluchistan (Western Pakistan)
220	sistence Goophysical Journal International doi:10.1002/gii/gm106 Piral
222	seisine sequence. Geophysical Journal methational. doi:10.1093/gji/ggu100 Filei-
340	Puysségur B. Crandin B. Ballinger I. Baudry C (2014) Multifaulting in a tectonic syntaxis rayaaled by InSAR:
341	the case of the Zierzt earthquele sequence (Patietan) Journal of Geophysical Pasearch Solid Earth 110:5838
2/2	5854 doi:10.1002/2013ID010564
243 244	5854. doi:10.1002/ 2015JB010504
345	
346	Sercombe W J, Pivnik DA, Wilson, WP, Albertin ML, Beck RA, Stratton MA (1998) Wrench Faulting in the
347	northern Pakistan foreland. AAPG Bulletin <b>82</b> , 2003–2030.
348	
349	Sarwar F, Iqbal S, Kamal S (2011) An Analysis of Pakistan's Local Network Catalog of Earthquake for the
350	Period of 1905-2007. Science International, 23(1), 13-18.
351	
357	Scharler D. Rookhagan R. Strackar MP (2011) Spatially variable response of Himalayan glaciars to climate
252	Scherer D, Bookhagen D, Stecker WK (2011) Spatially variable response of finital yan gladers to chinate
222	change affected by debits cover. Nature Geoscience. <b>vol: 4. pp 150-159.</b> doi: 10.1058/NGEO1068
354	
355	Seeber L, Armbruster JG, Meltzer AS, Beaudoin BC, Zeitler PK (1997) Extension above shortening from
356	earthquakes in the Nanga Parbat massif [abs.]: Eos Transactions, American Geophysical Union, v. 78, p. F651.
357	
358	Seeber L, Pecher A (1998) Strain partitioning along the Himalayan arc and the Nanga Parbat antiform. Geology. v.
359	26; no. 9. pp 791–794
360	
361	Smiraglia C. Mayer C. Mihalcea C. Diolajuti G. Belò M. Vassena G (2007) Ongoing variations of Himalayan
362	and Karakoram glaciers as witnesses of global changes: Recent studies of selected glaciers. Devel in Ear Surf

- 363 Proc. 10:235–248. doi: <u>doi:10.1016/S0928-2025(06)10026-7</u>
- Shankar D, Yadav RBS, Singh HN (2007) On the seismic risk in the Hindukush-Pamir-Himalaya and their
   vicinity. Current Science. Vol:92 pp 1625-1630
- 368 Sigvaldason GE, Annertz K, Nilsson M (1992) Effect of glacier loading/deloading on volcanism: postglacial
   369 volcanic production rate of the Dyngjufjöll area, central Iceland. Bull of Vol 54: 385–392.
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  374
- Stepp JC (1973) Analysis of completeness of the earthquake sample in the Puget Sound area. Contributions to seismic zoning, NOAA Tech. Report, ERL 267-ESL 30, Washington, D.C. pp. 16–28.
  377
- Tarbela Dam Project (2010) Sedimentation Profile. Courtesy: Hydrological and Sedimentation (H&S) Department.
   379
- Tate EL, Farquharson FAK (2000) Simulating Reservoir Management under the Threat of Sedimentation: The
   Case of Tarbela Dam on the River Indus. Water Resources Management 14: 191–208,
- **Twiss RJ, Moores EM (2007)** Structural Geology, 2nd ed. W.H. Freeman and Company, New York, USA.
- Usman M, Zafar M, Murata M, Amir NA (2010b) Effects of Temperature Increase on Earthquake Frequency and
   Depth in Northern Pakistan. International Conference on Biology, Environment and Chemistry. IPCBEE vol.1.
   IACSIT Press, Singapore
- Usman M, Asghar ZA, Saeed A, Rafi Z (2011) A Study on Enhancing Earthquake Frequency in the Glacial and
   Planar of Areas of Pakistan with Emphasis on Magnitude. Am Jour of Sci Res: July :155-156
- Usman M, Qureshi SN, Amir NA (2010a) Effects of Global Warming on the Frequency of Earthquakes in
   Northern Areas of Pakistan. Sci Vis. 15:39-50
- Usman M, Furuya M (2015) Complex faulting in the Quetta Syntaxis: fault source modeling of the October 28,
   2008 earthquake sequence in Baluchistan, Pakistan, based on ALOS/PALSAR InSAR data. Earth, Planets and
   Space. DOI 10.1186/s40623-015-0303-2
- Tahirkheli RAK, Mattauer M, Proust F, Tapponier P. (1979) The India-Eurasia suture zone in northern
  Pakistan: Some new data for interpretation at plate scale. Geodynamics of Pakistan. Farah A. DeJong KA. Eds.
  Geol. Surv. Pak. Quetta, pp. 125–130.
- Verma RK, ChandraSekhar C (1986) Focal mechanism solutions and nature of plate movements in Pakistan.
   Jour. Geodyn 5. 331–351.
- Yadav RBS, Gahalaut VK, Chopra S, Shan B (2012) Tectonic implications and seismicity triggering during the
   2008 Baluchistan, Pakistan earthquake sequence. Journal of Asian Earth Sciences. 45:167–178.
   doi:10.1785/0120120133
- Yeats RS, Lawrence RD (1984). Tectonics of the Himalayan thrust belt in northern Pakistan. Marine Geology and
   Oceanography of Arabian Sea and Coastal Pakistan, Haq, BU & Milliman, J. D. Van Nostrad Reinhold Co.,
   New York, pp. 177–200.

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