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Attenuation of Coda Waves in the Nubra-Siachen Region, Himalaya, India

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ABSTRACT

The attenuation properties have been estimated in the Nubra-Siachen region situated in the highly mountainous region of Himalayan belt. Coda wave quality factor (Q_c) has been determined for this virgin region by using the single backscattering method. A total of thirty earthquakes recorded in this region, which fall in the epicentral distance range of 3 to 115km have been used for the present work. A 30 sec window length of coda waves at different central frequencies 1.5, 3.0, 6.0, 9.0, 12.0, 18.0 and 24.0 Hz have been studied to determine Q_c at different recording stations. The frequency dependent coda wave quality factor relationships of the form $Q_c(f) = Q_o f^n$, have been computed at each recording stations separately: BASE: $Q_c(f) = (137 \pm 4.2)\, f^{(0.99 \pm 0.12)}$, CHALUNKA: $Q_c(f) = (116\pm3.8)f^{(1.0\pm0.05)}$, PARTA: $Q_c(f) = (122\pm3.0)f^{(1.0\pm0.02)}$, and SASOMA: $Q_c(f) = (111\pm4.1)f^{(1.0\pm0.03)}$. A regional Q_c relation has been developed for the Nubra-Siachen region by using the average value of Q_c at different frequencies obtained at each recording station of the form $Q_c(f) = (121\pm7.2)f^{(1.0\pm0.04)}$. The average Q_c values vary from 183 at 1.5 Hz to 3684 at 24 Hz central frequencies. The present regional relation developed for Nubra-Siachen region indicates heterogeneous and tectonically active region.

INTRODUCTION

The Eurasian plate and the Indian plate started colliding about 55 Ma ago (Yin and Harrison, 2000) and is still continuing at the present time (Wang et al., 2001). This successive collision forms the Himalaya. The collision has also resulted into large scale thrusting and the same has progressed southward forming the Main Central Thrust (MCT) and Main Boundary Thrust (MBT). The Indus-Tsangpo Suture (ITSZ) located about 250 km, north of MCT marks the pre-collision boundary along which the Indian plate subducted below the Eurasian plate and the subduction ended in Eocene times (Gansser, 1964). Along the MCT, the higher Himalaya overthrusted the lesser Himalaya and along MBT, the lesser Himalaya thrusted over the Siwaliks. The Nubra-Siachen region is situated in the highly mountainous terrain of higher Himalaya. This region is of strategic importance for the countries sharing their borders in the region. This region is considered as virgin region as, till now no study has been made regarding the attenuation characteristics of this area. Attenuation characteristics of medium decide the decay of the amplitude of ground motion at various sites. The attenuation characteristics of a region can provide essential information, regarding earthquake hazard of that region. Various techniques have been developed to study the attenuation characteristic of seismic waves using different parts of the seismogram (e.g., Aki, 1969; Aki and Chouet, 1975; Hermann, 1980; Mitchell, 1995). Quantitatively attenuation characteristics have been studied by using a factor named as quality factor. The quality factor 'Q' is defined as the fractional loss of energy per cycle (Knopoff, 1964). In the present work, single back scattering method proposed by Aki and Chouet (1975) has been used to determine the coda wave quality factor (Q_c) for Nubra-Siachen region, India. In this method coda waves have been utilized to estimate the quality factor.

Ground motion in the vicinity of earthquakes often dies away slowly leaving a coda wave following the direct body waves and surface waves because of inhomogeneities in the earth. These seismic coda waves are backscattered waves from numerous randomly distributed heterogeneities in the earth (Aki, 1969; Aki and Chouet, 1975; Rautian, 1976; Rautian and Khalturin, 1976). The single backscattering model proposed by Aki and Chouet (1975) suggests that coda waves are interpreted as backscattered body waves generated by the numerous heterogeneities present in the Earth's crust and upper mantle. It implies that scattering is a weak process and outgoing waves are scattered only once before reaching the receiver. Under this assumption the coda amplitudes for a central frequency is related to the source function, lapse time and quality factor. In the present work, coda waves of 30 sec window length, filtered at six frequency bands centered at 1.5, 3, 6, 9, 12, 18 and 24 Hz, have been used to study the attenuation characteristics of Nubra-Siachen region, India.

TECTONIC SETTING AND DATA

Nubra region is tectonically disturbed (Rai, 1983). The prominent tectonic feature of this region is, approximately 800 km, dextral strike slip Karakoram fault. The Karakoram fault separates rocks of the Karakoram and Ladakh terrains. The Karakorum fault runs almost parallel to the main body of Siachen glacier. The other major tectonic features of this region are Karakoram shear zone, Shyok suture zone and Khalsar thrust. The intervention of strongly mylonitized granite gneiss, volcanic, conglomerate, slate, phyllite-limestone intercalations, amphibolites and serpentinite in the Shyok suture zone and the frontal Asian plate margin along the Nubra–Shyok valleys forms the Karakoram shear zone (KSZ) (Jain and Singh, 2009). This is very narrow in width (1-5Km) and extends for nearly 200 km in Nubra valley, Shyok suture zone (SSZ) is an association of dismembered ultramafics, gabbro, basalt and sediments having chert, shale and Orbitolina-bearing limestone (Jain and Singh, 2009). Karakoram batholith complex (KBC) comprises of various lithology such as biotite granite, leucogranite, metamorphics. Monotonous vertical cliffs of biotite-muscovite granite in upper parts of Nubra valley beyond Panamik constitute the main body of the Karakoram batholith (Jain and Singh, 2009).

The data of local seismological network comprising of four broad band recording station installed in Nubra region, Jammu & Kashmir has been used in the present work. Geographical coordinates of stations are given in Table 1. This network is situated in the highly mountainous

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Table 1. Geographical coordinates of stations used in the present work

Sr. No.	Station Name	Station Code	Latitude (Degree)	Longitude (Degree)	Elevation (m) MSL
1	Sasoma	SASO	77.49 E	34.92 N	3430
2	Parta	PTPR	77.41 E	34.61 N	3180
3	Base	BASE	77.20 E	35.18 N	3455
4	Chalunka	CHLK	77.12 E	34.82 N	3180

terrain of Ladakh Himalaya, where elevations of recording stations from mean sea level lie between 3180 to 3455 m. The four recording station used the same type of instrumentation i.e. the Trillium 120P broadband seismometer and Taurus 24 bit data acquisition system. These instruments are operational in continuous mode. Sampling interval of digital data is kept at 0.01 sec. A total of thirty earthquakes recorded at this network have been used in the present study. The location of earthquakes and recording stations is shown in Fig. 1. The parameters of the events used in the present work are given in Table 2. An example of the seismograms recorded at all the four stations is shown in Fig. 2.

METHODOLOGY

In the present work, single backscattering model proposed by Aki and Chouet (1975) has been used to estimate coda wave quality factor. According to this model the coda waves are interpreted as back-scattered body waves generated by the numerous heterogeneities present in the Earth's crust and upper mantle. Under this assumption the coda amplitude, A(f, t) in a seismogram can be expressed for a central frequency 'f' over a narrow bandwidth signal, as a function of the lapse time 't', measured from the origin time of the seismic event, as

$$A(f, t) = S(f)\, t^{-a} \exp(-\pi f t/Q_c) \tag{1}$$

where S(f) represents the source function at frequency 'f', and is considered a constant as it is independent of time and radiation pattern, and therefore, not a function of factors influencing energy loss in the medium; 'a' is the geometrical spreading factor, and taken as 1 for body waves, and Q_c is the quality factor of coda waves representing attenuation in a medium. By taking logarithm of equation (1), it is linearized as given below:

$$\ln[A(f,t)] = \ln S(f) - \ln(t) - (\pi f t/Q_c) \tag{2}$$

$$\ln[A(f, t)\, t] = C - b\, t \tag{3}$$

where in equation (3), the term 'b' and 'C' represent $\pi f/Q_c$ and ln S(f), respectively. Equation (3) is an equation of straight line. Hence, Q_c can be obtained from the slope of the ln[A(f, t) t] versus 't' curve.

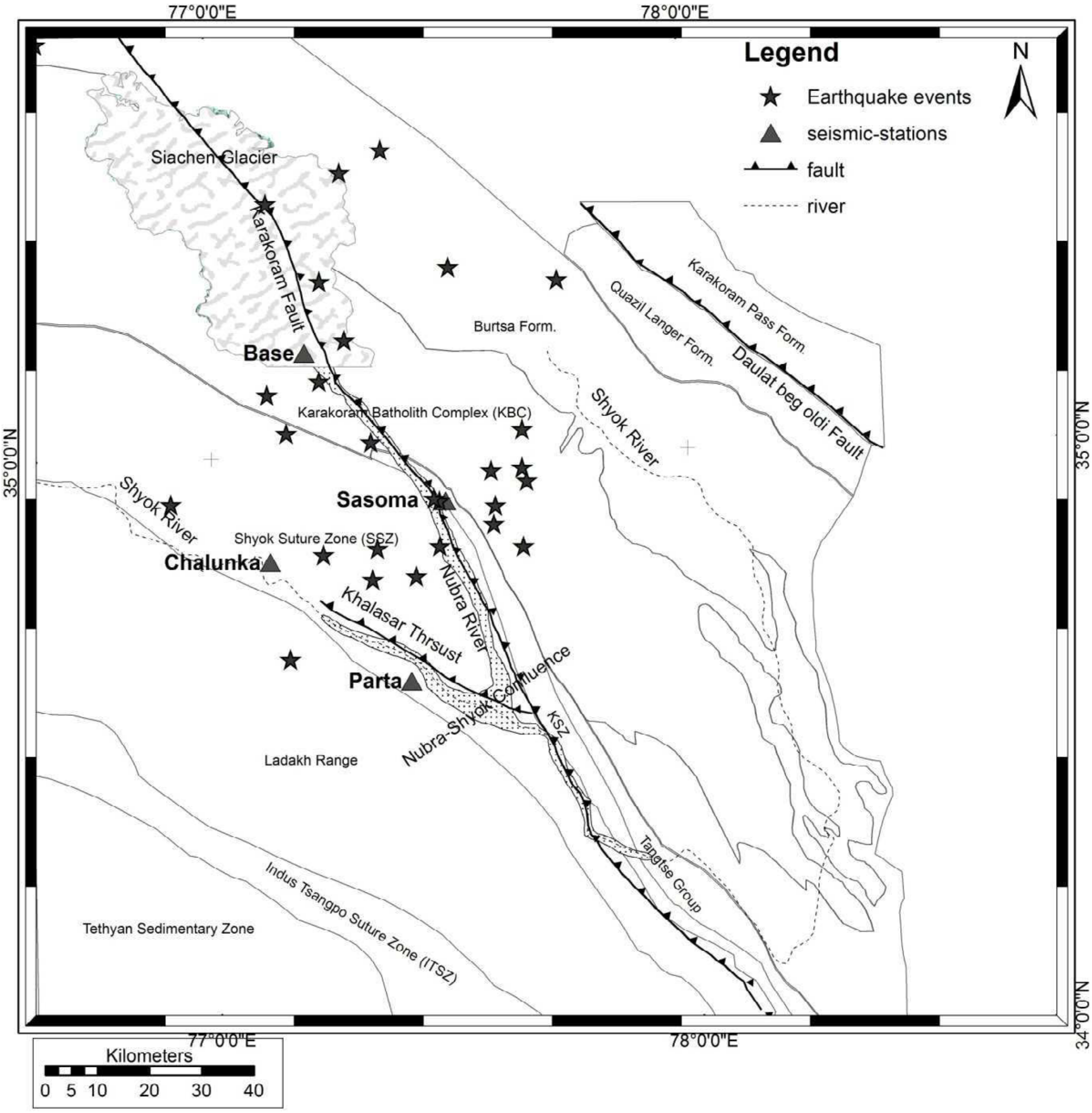

Fig. 1 The location of recording stations and epicenters of the events used in the present study along with the tectonic map of the region.

Table 2. The parameters of the events used in present work

Sr. No.	Hypocentral Parameters dd-mm-year	Origin Time Hr:Min:Sec	Long (degree)	Lat (degree)	Depth (km)	Mw	Waveform used for the stations (Station code)
1	01-01-2010	10:19:13	77.370	35.528	10	2.5	PTPR, BASE, CHLK
2	08-01-2010	13:24:10	77.230	35.131	10	3.7	PTPR
3	14-01-2010	08:32:51	77.425	34.791	10	3.8	SASO, PTPR
4	17-01-2010	07:09:52	77.232	34.831	10.3	2	SASO, PTPR
5	22-01-2010	02:51:07	77.466	34.924	3.2	2.6	PTPR
6	08-02-2010	04:14:22	77.477	34.920	10	4.2	SASO
7	10-02-2010	03:19:14	77.159	35.042	56.2	1.7	BASE
8	11-02-2010	01:42:44	77.507	35.323	10	1.8	SASO
9	11-02-2010	11:51:19	77.590	34.878	9	1	SASO, BASE
10	14-02-2010	06:09:34	77.651	34.838	80.6	1.7	BASE
11	23-04-2010	00:02:05	77.735	35.297	10	1.8	SASO, BASE
12	29-04-2010	12:28:33	77.654	35.040	12	2.6	SASO,BASE
13	14-05-2010	02:27:26	76.644	35.721	16.8	3.7	BASE
14	11-07-2010	13:40:10	77.125	35.439	120	2.1	BASE
15	16-07-2010	21:51:17	77.336	35.024	9.5	1.8	BASE
16	12-08-2010	03:06:03	77.594	34.910	14.2	2.5	PTPR, CHLK
17	16-08-2010	00:30:59	77.652	34.974	12.8	3.2	CHLK
18	24-08-2010	11:21:14	77.282	35.490	10.9	3.2	BASE
19	02-09-2010	03:04:03	77.476	34.842	45.7	4.4	BASE, CHLK
20	05-09-2010	04:15:02	77.587	34.970	8.7	2.7	PTPR, CHLK
21	06-09-2010	23:30:15	77.334	34.787	6.5	3.6	PTPR, CHLK
22	09-09-2010	16:13:12	77.345	34.840	12.3	4.5	PTPR, CHLK
23	11-09-2010	05:11:53	77.661	34.951	47.6	2.8	SASO, BASE
24	17-09-2010	14:11:16	77.661	35.926	13.2	4.1	SASO, PTPR, CHLK
25	19-09-2010	03:12:18	77.235	35.303	0.1	3.6	CHLK
26	01-10-2010	02:00:27	77.158	34.652	10.7	3	PTPR, CHLK
27	15-10-2010	01:34:38	77.158	34.652	46	2.6	SASO
28	28-10-2010	10:43:14	77.285	35.201	10	4	SASO, PTPR, BASE, CHLK
29	02-12-2010	12:21:24	76.914	34.923	10	3	BASE,CHLK
30	19-12-2010	11:18:21	77.120	35.109	10	3.4	BASE,CHLK

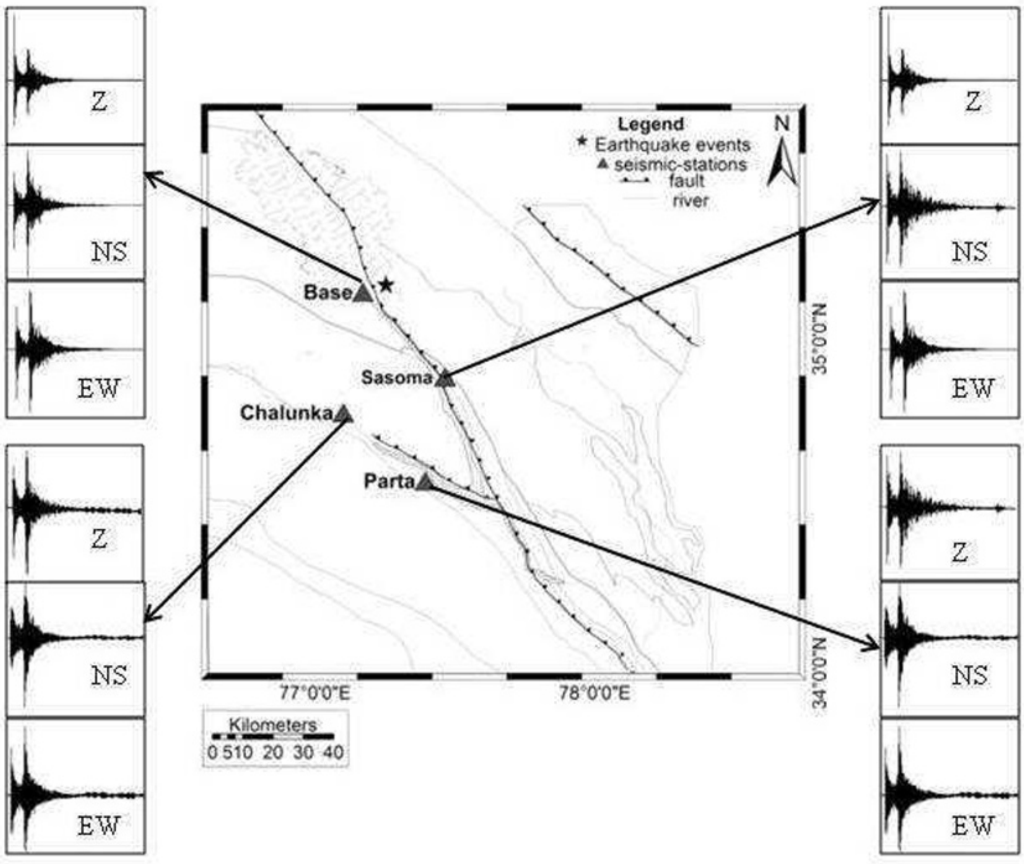

Fig. 2 Three component of seismogram of the event occurred on 28.10.2010 at all the four stations. The epicenter of the event and recording stations are denoted by star and triangle, respectively.

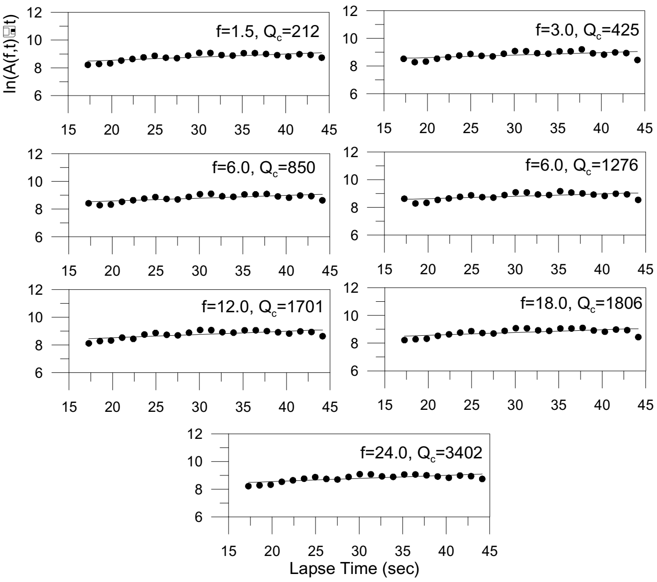

Fig. 3. Plot between logarithmic coda amplitudes and lapse time for difference central frequencies at Base station for the events occurred on 16-07-2010.

Table 3. Obtained Q_c relation at each recording station.

Sr. No.	Station Name	Station Code	Obtained Q_c Relation
1	BASE	BASE	$(137\pm4.2)f^{(0.99\pm0.12)}$
2	CHALUNKA	CHLK	$(116\pm3.8)f^{(1.0\pm0.05)}$
3	PARTA	PTPR	$(122\pm3.0)f^{(1.0\pm0.02)}$
4	SASOMA	SASO	$(111\pm4.1)f^{(1.0\pm0.03)}$

Table 4. Q(f) Relationship for Himalaya region, India.

Attenuation relation	Region	Reference
$Q(f) = 126f^{0.95}$	Garhwal Himalaya	Gupta et al. (1995)
$Q(f) = 30f^{1.21}$	Garhwal	Mandal et al. (2001)
$Q(f) = 86f^{1.02}$	NE Himalaya	Gupta and Kumar (2002)
$Q(f) = 92f^{1.07}$	Kumaon Himalaya	Paul et al. (2003)
$Q(f) = 158f^{1.05}$	NW Himalaya	Kumar et al. (2005)
$Q(f) = 112f^{0.97}$	Garhwal Himalaya	Joshi (2006)
$Q(f) = 87f^{0.71}$	Garhwal region	Sharma et al.(2009)
$Q(f) = 104f^{1.3}$	Kumaon Himalaya	Singh et al. (2012a)
$Q(f) = 61.8f^{0.992}$	Garhwal Himalaya	Singh et al. (2012b)
$Q(f) =119f^{0.99}$	Garhwal-Kumaon Himalaya	Mukhopadhyay and Sharma (2010)
$Q(f) = 28f^{1.2}$	Kumaon Himalaya	Parveen Kumar et al. (2015)

The coda waves of 30 sec duration, observed on all the event-station pairs, have been analysed in the present work. The starting time of this 30 sec window is considered by using the S-wave travel time (t_s) and it is taken as twice the t_s in the present work (Rautian and Khalturin 1978). At these window lengths all the seismograms are band pass filtered at central frequencies of 1.5, 3.0, 6.0, 9.0, 12.0, 18.0 and 24.0 Hz. The Q_c values corresponding to different central frequencies are used to calculate the frequency dependent coda-Q relation.

RESULTS AND DISCUSSION

Coda waves of 30 sec window length, at different central frequency of 1.5, 3, 6, 9, 12, 18 and 24 Hz, have been analyzed to estimate Q_c relation for the Nubra-Siachen region. In the present work, Q_c relation of form $Q_o f^n$ has been determined at four stations and the Q_c value obtained at each station is further used to determine regional Q_c relation for Nubra-Siachen region, NW Himalaya. The Q_c relation is estimated for all the three component i.e. North-South (NS), East-West (EW) and vertical (Z). The average value of Q_c from these three component provide us the final Q_c relation at a station as given in Table 3. The number of events used at BASE, SASOMA, CHALUNKA and PARTA stations are 15, 11, 13 and 12, respectively. The slope of linear equation (3) between logarithmic coda amplitudes and lapse time gives the Q_c values at different central frequencies and is shown in Fig. 3 at base station for the event occurred on 16-07-2010. Figure 3 shows value of Q_c obtained at different central frequencies for a particular event. Thus several values of Q_c are obtained at each central frequency

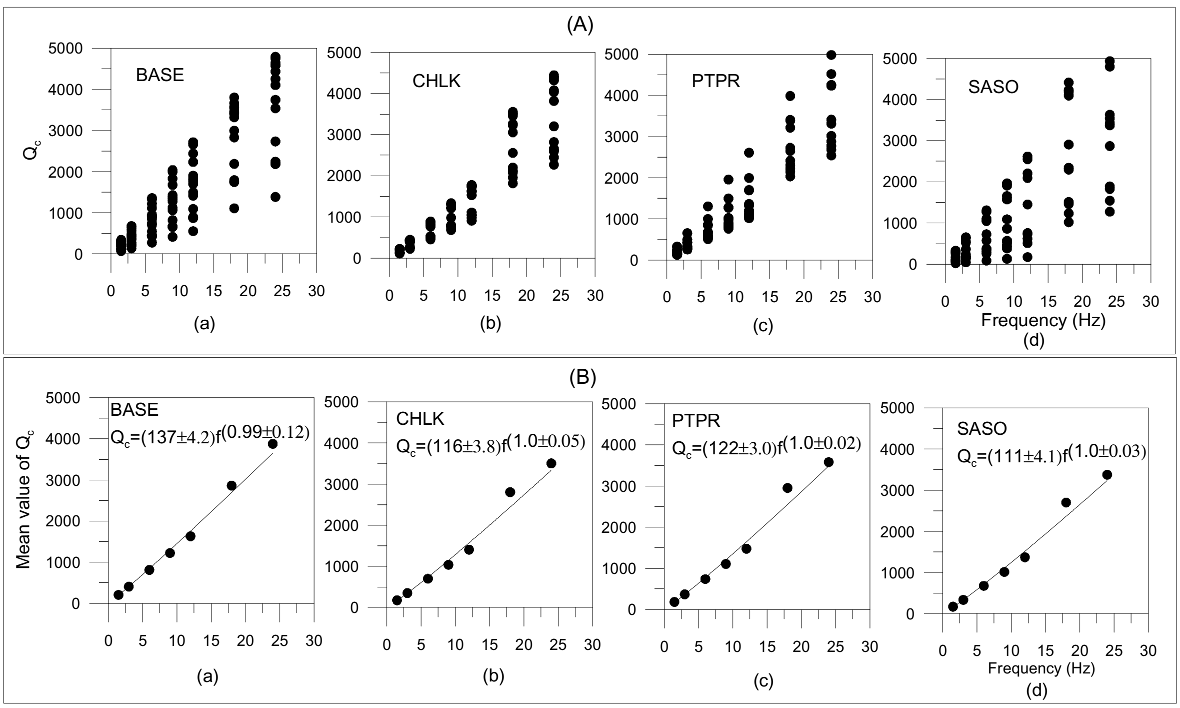

Fig. 4 (A) Plot of obtained Q_c values as a function of frequency and **(B)** Mean values of Q_c as a function of frequency at **(a)** BASE, **(b)** CHALUNKA, **(c)** PARTA and **(d)** SASOMA station, respectively.

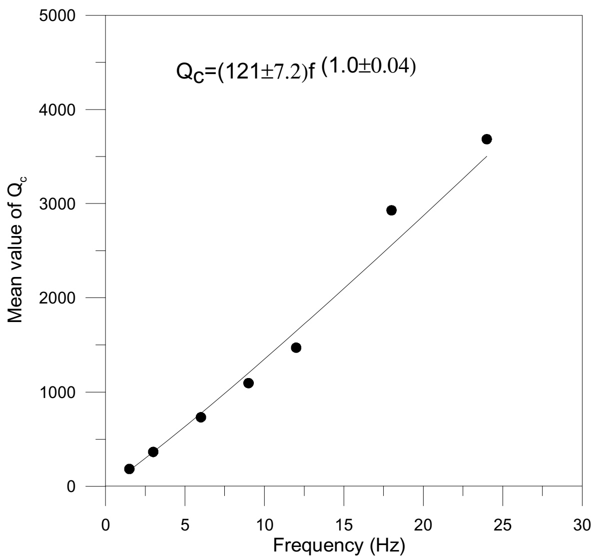

Fig.5. Regional Q_c(f) relationship for Nubra-Siachen region based on the obtained value of Q_c at different stations.

corresponding to several number of events i.e. Q_c values vary from 69 to 339 at 1.5 Hz and 1385 to 4789 at 24 Hz at BASE station; 113 to 222 at 1.5 Hz and 2269 to 4442 at 24 Hz at CHALUNKA station; 21 to 327 at 1.5 Hz and 1274 to 4934 at 24 Hz at SASOMA station; 127 to 326 at 1.5 Hz and 2540 to 4984 at 24 Hz at PARTA station as shown in Fig. 4(A). The mean value of Q_c is calculated at each frequency and it is further used to develop Q_c relation of form $Q_o f^n$ at each recording station as shown in Fig. 4(B). The Q_c relation computed

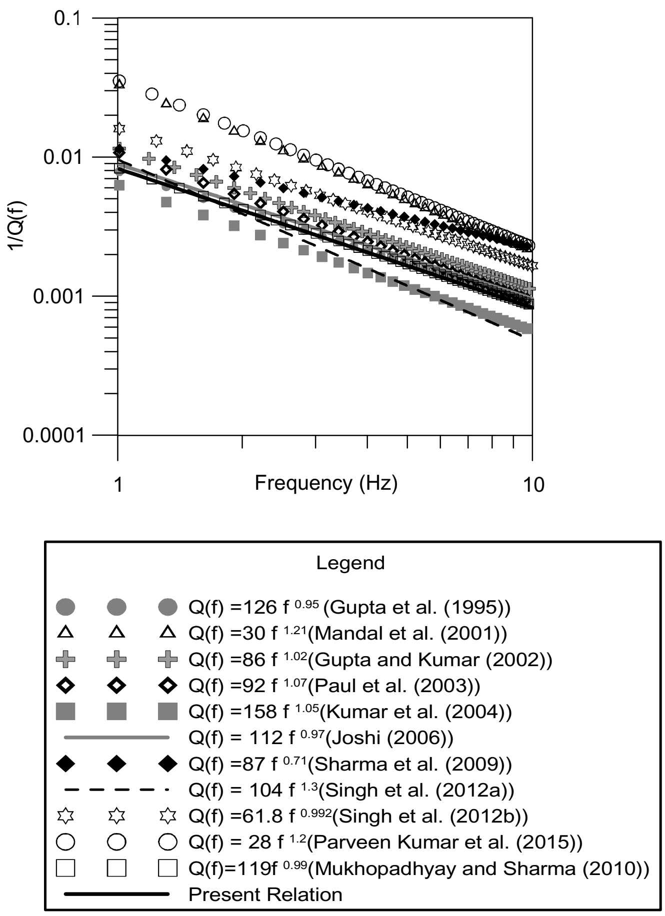

Fig.6. Comparison of Q_c(f) relation obtained in present work with the available relation of Himalaya region.

at each station is given in Table 3. The final values of Q_c obtained at each station is further used to calculate regional Q_c relation for Nubra-Siachen region and is plotted in Fig. 5. The best fit line gives (121±7.2)f $^{(1.0±0.04)}$, which represent regional attenuation characteristics of the Nubra-Siachen region of Himalaya. The $Q_o f^n$ relation is used for separating different regions into active and stable groups. The parameter 'Q_o' and 'n' in this relation represent heterogeneities and level of tectonic activity of the region, respectively. This relation propose low values of Q_o (<200) for tectonically and seismically active regions and high Q_o (>600) for seismically stable region and intermediate values for moderate regions (Kumar et al., 2005). Regions with higher 'n' (>0.8) value manifest local heterogeneities. It is seen that the calculated value of Q_o varies in between 121±7.2 and 'n' varies in between 1.0±0.04 indicating tectonically active and highly heterogeneous region.

A comparison of Q_c obtained in the present work has been made with available Q relations in Himalaya region. It is seen from Table 4 that for Himalayan region, 'Q_o' and 'n' varies from 28 to 158 and 0.71 to 1.3, respectively and the obtained relation for Nubra-Siachen region lies within this range. The relation provided by Mukhopadhyay and Sharma (2010) for Garhwal-Kumaon Himalaya i.e. Q(f) =119f $^{0.99}$ as tabulated in Table 4, gives the closest resemblance with the obtained Q_c relation for Nubra-Siachen region. As Mukhopadhyay and Sharma (2010) has also used the same method with similar lapse time ($2t_s$) and coda length (30s) and their study region is also not very far from present study area and these factors may be responsible for this resemblance. Comparison of present relation with available relations of Himalaya region is shown in Fig. 6 and it revealed that the relation obtained in present work falls within the range of values that are justified for tectonically active Himalaya regions.

CONCLUSIONS

In the present work, attenuation characteristics have been determined for Nubra-Siachen region, Himalaya, India as it is a virgin area regarding the attenuation studies. In this paper single back scattering method has been used to obtain regional Q_c relation for Nubra-Siachen region, Himalaya, India. Data of thirty events recorded at four stations in Nubra-Siachen region have been used in this study. In this work Q_c relation at each station is obtained individually. The values of Q_c obtained at four different stations further used to obtain a regional regression relation of form Q_c(f) = (121±7.2)f $^{(1.0±0.04)}$, which represent the attenuating property of rocks in the Nubra-Siachen region. Low value of Q_o and high value of 'n' obtained in the present Q_c(f) relation shows that the region is seismically active and characterized by local heterogeneities.

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References

Aki, K. (1969) Analysis of the seismic coda of local earthquakes as scattered waves. Jour.f Geophys. Res., v.74, pp.615-631.

Aki, K. and Chouet, B. (1975) Origin of the coda waves: source attenuation and scattering effects. Jour. Geophys. Res., v.80, pp.3322-3342.

Gansser, A. (1964) Geology of the Himalayas. Willey Interscience, London, 289p.

Gupta, S.C. and Kumar, A. (2002) Seismic wave attenuation characteristics of three Indian regions: a comparative study. Curr. Sci., v.82, pp.407-413.

Gupta, S.C., Singh, V.N., and Kumar A. (1995) Attenuation of Coda Waves in the Garhwal Himalaya, India. Physics Earth Planet. Inter., v.87, pp.247-253.

Hermann, R. (1980) Q estimates using Coda of local earthquakes. Bull. Seismol. Soc. Amer., v.70(2), pp.447-468.

Jain, A.K. and Singh, S. (2009) Geology and Tectonics of Southeastern Ladakh and Karakoram. Geol. Soc. India, Banglore, 181p.

Joshi, A. (2006) Use of acceleration spectra for determining the frequency dependent attenuation coefficient and source parameters. Bull. Seismol. Soc. Amer., v.96, pp.2165-2180.

Knopoff, L. (1964) Q. Rev. Geophys., v.2(4), pp.625-660.

Kumar, N., Parvez, I.A., and Virk, H.S. (2005) Estimation of coda wave attenuation for NW Himalayan region using local earthquakes. Phys. Earth Planet. Inter., v.151, pp.243-258

Kumar, P., Joshi, A., Sandeep, Kumar, A. and Chadha, R.K. (2015) Detailed Attenuation Study of Shear Waves in the Kumaon Himalaya, India, Using the Inversion of Strong-Motion Data. Bull. Seismol. Soc. Amer., v.105(4), DOI:10.1785/0120140053

Mandal, P., Padhy, S., Rastogi, B.K., Satyanarayana, V.S., Kousalya, M., Vijay-raghavan, R. and Srinvasa, A. (2001) Aftershock activity and frequency dependent low coda Qc in the epicentral region of the 1999 Chamoli earthquake of Mw 6.4. Pure Appld. Geophys., v.158, pp.1719-1735.

Mitchell, B.J. (1995) Anelastic Structure and Evolution of the Continental Crust and Upper Mantle from Seismic Surface Wave Attenuation. Rev. Geophys., v.33(4), pp.441-462.

Mukhopadhyay, S. and Sharma, J. (2010) Attenuation characteristics of Garhwal-Kumaon Himalayas from analysis of coda of local earthquakes. Jour. Seismol., v.14, pp.693-713.

Paul, A., Gupta, S.C., and Pant, C.C. (2003) Coda Q estimates for Kumaon Himalaya. Proc. Indian Acad. Sci., v.112, pp.569-576.

Rai, H. (1983) Geology of the nubra valley and its significance on the evolution of the ladakh Himalaya. *In:* Thakur, V. C. and Sharma, K.K., (Eds.), Geology of Indus Suture Zone of Ladakh. Wadia Institute of Himalayan Ggeology Dehradun, pp.79-97.

Rautian, T.G. (1976) The roles of source function and medium response in the model of formation of seismic vibrations, in Problems of Engineering Seismology, v.18, pp.3-14.

Rautian, T.G. and Khalturin, V.I. 1976: Spectral structure of the coda of local earthquakes as an instrument of investigation of the source radiation. Proc. USSR Acad. Sci., v.226, pp.566-569.

Rautian, T.G. and Khalturin, V.I. (1978) The use of the coda for the determination of the earthquake source spectrum. Bull. Seismol. Soc. Amer., v.68, pp.923–948.

Sharma, B., Teotia, S.S., Kumar, D., and Raju, P.S. (2009) Attenuation of P- and S-waves in the Chamoli Region, Himalaya, India. Pure Appld. Geophys., v.166, pp.1949-1966.

Singh, C., Singh, A., Bharathi, V.K.S., Bansal A.R., and Chadha, R.K. (2012a) Frequency- dependent body wave attenuation characteristics in the Kumaun Himalaya. Tectonophysics, v.524-525, pp.37-42.

Singh, P., Tripathi, J.N., Kumar, S. (2012b) Quality factor of seismic coda waves in Garhwal Himalayas. Internat. Jour. Civil Engg. Tech., v.3(2), pp.279-291.

Wang, Q., Zhang, P.Z., Freymueller, J.T., Bilham, R., Larson, K.M., Lai X., You, X., Niu, Z., Wu, J., Li, Y., Liu, J., Yang, Z., and Chen, Q., 2001: Present day crustal motion in China constrained by global positioning system Measurements. Science, v.294, pp.574-577.

Yin, A. and Harrison, T.M. (2000) Geologic Evolution of Himalayan-Tibet Orogen. Annual Rev. Earth Planet. Sci., v.28(1), pp.211-280.

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