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Estimation of Coda Waves Attenuation for NW Himalayan Region using Local Earthquakes

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Abstract

The attenuation of seismic wave energy in NW Himalayas has been estimated using local earthquakes. Most of the analyzed events are from the vicinity of the Main Boundary Thrust (MBT) and the Main Central Thrust (MCT), which are well-defined tectonic discontinuities in the Himalayas. The time-domain coda-decay method of a single backscattering model is employed to calculate frequency dependent values of Coda Q (Qc). A total of 36 local earthquakes of magnitude range 2.1 to 4.8 have been used for Qc estimation at central frequencies 1.5, 3.0, 6.0, 9.0, 12.0 and 18.0 Hz through eight lapse time windows from 25 sec to 60 sec starting at double the time of the primary S-wave from the origin time. The estimated average frequency dependence quality factor gives the relation, Qc=158f^{-1.05}, while the average Qc values vary from 210 at 1.5 Hz to 2861 at 18 Hz central frequencies. The observed coda quality factor is strongly dependent on frequency, which indicates that the region is seismic and tectonically active with high heterogeneities.

The variation of the quality factor Qc has been estimated at different lapse times to observe its effect with depth. The estimated average frequency dependent relations of Qc vary from 85f^{-1.16} to 216f^{-0.91} at 25 sec to 60 sec lapse window length respectively. For 25 sec lapse time window, the average Qc value of the region varies from 131±36 at 1.5 Hz to 2298±397 at 18 Hz, while for 60 sec lapse time window its variation is from 285±95 at 1.5 Hz to 2868±336 at 18 Hz of central frequency. The variation of Qc with frequency and lapse time shows that the upper crustal layers are seismically more active compared to the lower lithosphere. The decreasing value of the frequency parameter with increasing lapse time shows that the lithosphere acquires homogeneity with depth.

Key words: Coda wave, attenuation, lapse time, scattering, North-West Himalayas.

Introduction

A seismogenic region can be characterized by tectonic, seismic and volcanic activities in
addition to geological formation and geological history. All these properties quantify the behaviour of the seismic energy propagation in the lithosphere and can be utilized for seismic hazard mitigation. As the seismic energy propagates through the earth medium, its energy (amplitude) decays due to geometrical spreading, intrinsic attenuation and scattering attenuation. Intrinsic attenuation converts the seismic energy to heat due to anelastic absorption and scattering attenuation redistributes the energy at random heterogeneities present in the upper earth medium. Therefore, the attenuation of seismic waves in the lithosphere is an important property for studying the regional earth structure and seismotectonic activity. This attenuation is measured by a dimensionless parameter called the quality factor \( Q \) (Knopoff, 1964), which is inversely proportional to the decay of amplitude (energy) with passage of time or source-receiver distance. The inverse of quality factor is known as the attenuation factor, \( Q^{-1} \). Jin and Aki (1988) state that the quality factor of coda waves at a frequency of 1 Hz can be useful to quantify the seismicity of regions.

After the advent of coda wave theory (Aki, 1969), these short-period secondary waves are utilized for crustal studies near the source in a laterally heterogeneous upper lithosphere, the seismicity of the region and earthquake source mechanism. Coda waves are secondary waves generated by the scattering of primary body waves at small-scale heterogeneities present in the lithosphere. These waves have been estimated as backscattered superposition waves from randomly distributed heterogeneities in homogeneous medium (Aki, 1969; Aki and Chouet, 1975; Rautian and Khalturain, 1978). The scattering is produced by irregular topography, complex surface geology, heterogeneous elastic property of the rocks, faults and cracks, which are more near the surface and less in the deep region. The spatial variation of regional coda quality factor has been utilized for a better understanding of tectonics, seismicity, seismic risk analysis and engineering seismology (Singh and Herrmann, 1983; Jin and Aki, 1988). It has been observed that the coda spectrum of small earthquakes (M<5) close to the source is independent of earthquake size, epicentral distance and the path between station and epicentre but depends on lapse time from the origin time of the earthquake. This suggests that the coda part of the seismogram is due to an average scattering effect of the medium in the region near the source and station (Aki and Chouet, 1975; Sato, 1977).

Aki and Chouet (1975) proposed the single scattering model only for backscattered body
waves to calculate the coda quality factor, $Q_c$. Pujades et al. (1991) described that this quality factor is estimated mainly due to intrinsic quality factor, $Q_i$, while Gao et al. (1983) suggested a multiple scattering model for primary as well as secondary waves to estimate both $Q_i$ and $Q_s$ (scattering) quality factors. These two methods have been successfully used to estimate coda wave attenuation in different regions of the world (Aki and Chouet, 1975; Sato, 1977; Roecker et al., 1982; Pulli, 1984, Wu, 1985, Jin and Aki, 1988, 1989; Havskov et al., 1989). These observations indicate that the multiple scattering model is not suitable for coda Q because in this model $Q_i$ and $Q_s$ are estimated separately, while in coda Q these must be observed simultaneously. Wu and Aki (1988) suggested that simultaneous estimation of $Q_i$ and $Q_s$ lead to unacceptably large errors for both parameters. Therefore, the single backscattering model is preferred for coda Q calculation and according to Jin and Aki (1989), the first Born approximation of this model includes both the attenuation due to intrinsic absorption and the loss due to scattering. In this study the single scattering model is used and different lapse time envelopes are taken to observe multiple scattering effects (Peng et al., 1987; Su and Aki, 1990).

The coda-Q has been estimated at different parts of the world by Roecker et al. (1982), Pulli (1984), Jin and Aki (1988), Havskov et al. (1989), Ibanez et al. (1990), Pujades et al. (1991), Canas et al. (1991), Akinci et al. (1994), Gupta et al. (1995), Latchman et al. (1996), Gupta et al. (1998), Mandal and Rastogi (1998), Zelt et al. (1999) to observe the ongoing seismic activity and polarize the active regions from the stable regions. These studies generally show low value of $Q_0$ (e.g. <200) for tectonic and seismic active regions, high $Q_0$ value (e.g. >600) for seismic inactive stable regions and intermediate value for moderate regions. Jin and Aki (1989) strongly correlated the coda-Q $^{-1}$ with the degree of fracture in the lithosphere associated with current seismicity.

**Tectonic setting and Seismic activity**

The Himalayas is the youngest mountains range formed by the convergence of the north dipping Indian plate under the southward movement of the Eurasian plate. This convergence has caused structural faults and folds, great height of the Himalayan peaks and recurrence of large earthquakes. High levels of tectonic activity resulted due to these opposite convergence movements,
which have developed ISZ (Indian Tsangpo-suture zone), MCT (Main Central Thrust), MBT (Main Boundary Thrust) and HFT (Himalayan Frontal Thrust) as prominent thrusting (faulting) boundaries in the Himalayas in addition to many localized thrusts, faults, folds and minor lineaments. These main thrusts divide the NW Himalayan mountains into five tectonic zones as the Indus Suture (IS), the Tethys Himalaya (TH), the Higher Himalaya (HH), the Lesser Himalaya (LH), and the Sub Himalaya (SH) (Thakur et al., 2000). In the present study region, the Jawalamukhi thrust (JMT), Drang thrust, Panjal thrust, Vakirita thrust, Sundernagar fault, Kistwar fault and Ropar fault are well known tectonic features. The Drang thrust, Panjal thrust and Vakirita thrust are very close to the MBT in Chamba-Sundernagar region (Kumar et. al. 2001). North ward underthrusting of the Indian plate created the geological structures through EW compression, tear faulting, strike-slip and reverse block movement and stacking of crust separated by major basement tear faults. They suggest that the continued stress movement postulates seismicity in the thrust emergence zones of the NW Himalayas. The tectonic movement of NW Himalayas and prominent discontinuities are shown in figure 1.

The MBT was formed as a normal fault during an extensional phase in NW Himalayas, prior to the Himalayan orogeny (Dubey et. al. 2001). The reactivation of MBT and HFT during the Quaternary has been inferred from a variety of geological features, which is still active. Subsequent evolution of the foredeep marked by intra-basin boundary faults during this period reveals that the Himalayan foothill region has been experiencing neotectonic activity. In this process large scale thrusts and young strike slip faults occurred, together with normal faults of small magnitude. In NW Himalayas the thrust faulting with strike-slip motion along gently dipping planes towards north, south west and southeast have been observed from the fault plane solutions by Ni and Barazangi, 1984. The reverse faulting focal mechanism indicates that the Indian plate underthrusts the Eurasian plate at a shallow angle in the NS to NNE-SSW direction and there is a surface of decollment at which most of the seismicity concentrates. The depth of decollment is about 15 km and in the present study about 60% seismic activity has been observed around this depth. The tectonic features of NW Himalayas have been shown in figure 1, in which the direction of shortening in Quaternary period is indicated by a black arrow and azimuth of insitu stress are indicated by white arrows. It is clear from the figure that the major tectonic thrusts are EW and minor faults are oblique to these thrusts and support NS.
underthrusting of the Indian plate. Seismic activity is observed on the basis of the integrated fault surface area of earthquakes (Rao et. al., 2003), which indicate different deformation patterns in the Himalaya and adjoining Tibetan plateau region. These findings suggest that in the NW Himalayas the seismicity is dominated by reverse faulting (93%), while in Tibetan plateau the reverse-faulting is a mere 2% and is dominated by strike-slip and normal faulting (59% and 39% respectively). Strain rates indicate predominant crustal thinning in the Himalayas and crustal thickening with EW extension in Tibetan plateau region, just across the Indus-Tsangpo suture zone.

The Himalayas is one of the most seismic active regions of the world, which has experienced micro, moderate and high-sized shallow focus (mainly $10 \leq h \leq 20$ km) seismic activity (Ni and Barazangi, 1984). Past and present studies in this region explore the high seismic activity in Chamba-Dharamshala region between MBT and MCT. This seismicity is associated with active faults and folds trending normal or oblique to the mountains, which is the direction of underthrusting blocks. Prominent past earthquakes of the region are great the Kangra earthquake (1905), the Kinnuar earthquake (1975), Dharamshala earthquakes (1978, 1986), the Sundarnagar earthquake (1997) and some other earthquakes of 1945, 1947 and 1950. Micro seismicity reveals that the area is geodynamically unstable and seismically active. The Chamba-Sundarnagar region is a part of the active belt of NW Himalayas, which falls under seismic zone V as per the Bureau of Indian Standards (BIS, 2000). There are two types of movement in the Chamba-Sundarnagar region, firstly due to regional tectonic activity in the basement not exceeding 40 km and secondly due to neotectonic activity in the sedimentary sequence confined mostly upto 10 km depth (Ni and Barazangi, 1984). Most of the present study area falls under seismic zones IV and V. The seismic events analyzed in this study are mostly located between the MBT and the MCT and two oblique faults as Sundarnagar fault in the east and of same trend parallel to Kistwar fault in the west. The reason may be that in this small region the MBT and MCT are very close to each other than in the rest of the NW Himalayan region.

In the present study, the micro seismic events originate from very a shallow origin (less than 15 km), while big events of magnitude more than 3.5 come from a deeper origin having focal depth more than 33 km. Three events having focal depth (82, 72 and 65 km) are located NW to Chamba and are very close to each other (i.e. from one small region). The epicentres of most of the earthquakes are in the
vicinity of the MBT; there is only one event to the north of the MCT and three events are from the Gangetic plain (Fig. 1).

**Coda Q calculation**

The coda waves have been estimated as a superposition of secondary waves through single backscattering of primary body waves at randomly distributed heterogeneities (Aki, 1969, Aki and Chouet, 1975). The decrease of coda wave amplitude with lapse time at a particular frequency is only due to energy attenuation and geometrical spreading but independent to earthquake source, path propagation and site amplification (Aki, 1969). The attenuation of seismic waves is the sum of intrinsic and scattering attenuation, where in the first case the energy is converted to heat through anelastic absorption and in second case it is redistributed through refraction, reflection and diffraction at random discontinuities present in homogeneous medium. Generally, the Q factor increases with frequency (Mitchell, 1981) through the relation

\[ Q = Q_0 \left( \frac{f}{f_0} \right)^n \]

Where \(Q_0\) is the quality factor at reference the frequency \(f_0\) (generally 1Hz) and \(n\) is the frequency parameter, which is close to 1 and varies from region to region on the basis of heterogeneity of the medium (Aki, 1981). This relation indicates that the attenuation of seismic waves with time is different for different frequencies. Hence, the seismic data is first bandpass filtered to calculate the attenuation. In the present study, the attenuation of coda waves is calculated at six central frequencies after bandpass filtered using Buterworth six pole filters as given in table 2.

The amplitude of the coda wave at lapse time \(t\) seconds from the origin time for bandpass filtered seismogram at central frequency \(f\) is given by the attenuation method of the single backscattering model as

\[ A(f, t) \propto t^{-\alpha} e^{-\pi f t / Q_c} \]

or

\[ A(f, t) = K(f) t^{-\alpha} e^{-\pi f t / Q_c} \]

----------- (1)
Where $K(f)$ is the coda source factor at frequency $f$, which is independent of time and radiation pattern, $\alpha$ is the geometrical spreading parameter having one value out of 1.0, 0.5 or 0.75 for body waves, surface waves or diffusive waves respectively (Sato and Felher, 1998), $Q_c(f)$ is the quality factor of coda waves. As coda waves are backscattered body waves, therefore putting $\alpha=1$ in eq. (1) and taking the logarithm,

$$\ln A(f,t) = \ln K(f) - \ln(t) - \frac{\pi f}{Q_c(f)} * t$$

or

$$\ln(A(f,t) * t) = \ln K(f) - \frac{\pi f}{Q_c(f)} * t$$

-------- (2)

Hence $Q_c$ is determined from the slope, $b$ of least squares fit straight line plotting $\ln(A(f,t) * t)$ versus $t$ using the relation.

$$Q_c(f) = \frac{\pi f}{b}$$

-------- (3)

The calculation of $Q_c(f)$ from the RMS values of amplitude with time is shown in fig (2) along with the plot of the coda window selected. According to Rautian and Khalturain (1978), the above relation is valid for lapse time greater than twice the S-wave travel time for avoiding the data of the direct S-wave and for validation of the model that the source of the earthquake and receiver are coincident. Sato (1977) introduced the source receiver offset in single scattering model so that the coda analysis begins after the arrival of the shear wave. In the present study, the time envelope for coda decay observation is taken at twice the time of the S-wave (2ts) from the origin time of the event.

Data Analysis

The digital events data utilized for coda Q calculation were recorded during 1997 to 1999 at the regional seismograph network of three seismic stations by Earthquake Research Centre, Guru Nanak Dev University, Amritsar. As shown in Fig. 1, the first seismic station, PTK (Pathankot) is on the top of the Siwalik hills, the second one, HOS (Hoshiarpur) is at Siwalik foothills, while third one,
ASR (Amritsar) station is located on the Gangetic plain. The station PTK is situated on hard bedrock in the vicinity of high tectonic and seismic activity at high altitude. The station HOS is situated at alluvium near recent tectonic and moderate seismic activity, and the station ASR is on a thick alluvium of the Gangetic plain away from tectonic and seismic activities. All the stations were equipped with portable high quality three component short-period (1Hz natural frequency) L4-3D seismometers of Mark products (USA) and high dynamic range 24 bit recording apparatus of REF TEK (USA). The instruments were setup to digitize the signal at 100 sps and an antialiasing filter was applied to get the flat velocity spectrum between 1 and 40 Hz. During the given period, more than 300 seismic events were recorded from different epicentral ranges. Out of these, 36 local events with epicentral distance up to 200 km are analyzed for coda Q calculation. The epicenters of these selected events, the seismic stations, prominent discontinuities and the topography of the region are shown in figure 1.

A total of 126 seismograms of good S/N ratio are used in this study. The detailed epicentral information of seismic events is listed in table 1, which indicates that the maximum events are recorded at PTK station while minimum events at HOS station. A few more local events are discarded due to low signal to noise ratio and other set criteria for coda Q calculation. We restrict the epicentral distance of PTK station up to 160 km for getting strong signal to noise ratio. The magnitude range of earthquakes is 2.1 to 4.8 and most of the events, nearly 60 percent are of shallow focal depth ($4 \leq h \leq 15$ km). The average focal depth of all the events is 23 km. Only four earthquakes have focal depth more than 35 km, in which the deepest earthquake is 82 km deep. Three deeper events are only from one small region, which is north to PTK station. On the basis of epicentral distance, 31 events of PTK station are further divided into three groups as $R \leq 55$ km, $55 < R \leq 100$ km and $100 < R \leq 160$ km. All the nine events of ASR station used here are from $100 \leq R \leq 200$ km of epicentral distance and in case of Hoshiarpur station both events are from $50 \leq R \leq 100$ km epicentre range. Most of the seismic events are located between MBT and MCT bounded by two other transverse faults as the Sundernagar fault to the east and of same trend the Kistwar fault to the west. This region is very close to the PTK station in the northeast direction. The events of PTK station are also analyzed in three groups of focal depth as
very shallow (h≤15 km), medium (15<h≤35 km) and deeper (35<h≤82 km) to observe the attenuation factor with varying depth of the lithosphere. Further, 18 events of Pathankot station lying between the MBT and MCT from 0º to 100º azimuths are analyzed separately to estimate the effect of seismic activity.

The Q values are calculated through the CODAQ subroutine of SEISAN (Havskov and Ottemoller, 2003). The S-wave time is calculated through the P-wave time using \( V_p/V_s = 1.74 \). The lapse times are selected at 2ts to avoid the data of the direct S wave and to utilize the minimum possible sampling volume for Qc values (Havskov et al., 1989). The observations by Roecker et al., 1982, Havskov et al., 1989, Gupta et al., 1998, Giampiccolo et al., 2002 from different regions of the world indicate increased value of Qc with lapse time, which is due to greater penetration of waves in the deeper part where the attenuation is less. Therefore, eight window lengths are taken from 25 sec to 60 sec with a variation of 5 sec to estimate the attenuation at different lapse times for observing the effect with crustral depth. 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 and 18.0 Hz with bandwidths of 1.0, 2.0, 4.0, 6.0, 8.0 and 12.0 respectively. An increasing frequency band is used for increasing central frequency to avoid ringing and to take constant relative bandwidths for getting equal amount of energy into each band as suggested by Havskov and Ottemoller (2003). The RMS amplitude of the last 5 sec data of lapse time window is divided by noise data of same length before the onset of P wave to calculate the S/N ratio. All the seismograms having S/N ratio below 2 are rejected for better Qc values. In the same manner the criteria of correlation coefficient = 0.48 are applied to obtain reliable Qc values. The comparison of the number of values selected for each frequency and lapse time to observe the average Qc is described by the factor N in table 2. The logarithm of product of RMS amplitude and lapse time is plotted against lapse time as shown in figure 2 for calculating Qc from slope of the linear regression curve of \( \ln(A(f,t)*t) \) and t.

**Results and Discussion**

The quality factor, Qc has been estimated to assess the effect of tectonic and seismic activity in the NW Himalayas. The region is in a deforming stage as it contains many discontinuities and is
highly seismic active. 126 local digital seismograms are analyzed through a single backscattering model at eight lapse time windows of 25 sec to 60 sec duration. Six frequency bands have been applied at central frequencies of 1.5, 3, 6, 9, 12 and 18Hz. The data is analyzed in nine groups to observe the attenuation factor at different epicentral range, depth range and for a small high seismic region. Figure 3 shows the comparison of $Q_0$ (quality factor at 1 Hz) and frequency parameter, $n$ for all the groups. Figure 4 shows the plot of $Q_c$ and central frequencies with linear regression fit for all the stations. Average values of $Q_0$, $Q_c$ and frequency parameter, $n$ are plotted in figure 5, while $Q_c^{-1}$ values of NW Himalayas are compared with other regions of the world in figure 6. The detailed results of these figures are discussed below.

The estimated attenuation of coda waves is the average decay of amplitude due to seismic waves scattering on the surface of ellipsoid volume having earthquake source and station as foci (Pulli, 1984). On this basis the approximate ellipsoidal volume for nine groups of seismic events is estimated, which shows average attenuation properties of the region. The observed $Q_c$ reflects the average attenuation properties of the volume of ellipsoid at an average depth, $h = h_{av} + a_2$, where $h_{av}$ is the average focal depth of the events and $a_2 = \sqrt{a_1^2 - \Delta^2}$ is the small semi axis of the ellipsoid for $\Delta$ as average epicentral distance. The large semi-axis of the ellipsoidal volume is $a_1 = ct/2$ for lapse time, $t$ and velocity, $c$ of the Lg wave ($c=3.5$ km/s). The average lapse time is taken as

$$t = t_{start} + \frac{WN}{2}$$

$t_{start}$ is the starting time of the lapse time window and $WN$ is the lapse time window length.

The maximum depths calculated for the ellipsoidal volume for different groups of data are given in table 4.

The station Pathankot is in the vicinity of high seismic and tectonic activity. The data recorded at this station is analyzed in detail to differentiate the attenuation factor laterally, vertically and seismotectonically. PTK1 group contains the data of Pathankot station for epicentre distance less than 55 km. In this group nine events of high S/N ratio and greater correlation coefficients are analyzed. The average focal depth of the earthquakes is 13.5 km and the average epicentral distance is 44.5 km. As shown in fig 1, the region of this data group is in and around Sub-Himalaya containing
the MBT and the JMT as major tectonic features. Figure 3(a) indicates the low value of iso-$Q_0$ for this group as compared to other data groups. Its variation with lapse time is small for 25 to 50 sec window lengths. After 50 sec there is some increase in the $Q_0$ value, which indicates that the deeper region is homogenous with some drastic change. The effect of the frequency parameter is given in fig 3(b), which shows that the frequency parameter effect to this group of data is high. The value of this parameter is almost constant for all lapse times with standard deviation merely 0.02. The average quality factor at 1.5 Hz is 144.5, while its value at 18 Hz is 2829. The average frequency relationship for this data is $98.6f^{1.19}$. The maximum depth of the ellipsoidal volume is 76.6 km. As expected the calculated values of quality factor are lower than the values of other data groups. The low value of $Q_0$ and nearly constant high value of frequency parameter indicate that the region around this data group is seismically active and contains more heterogeneities.

In PTK2 group of data, sixteen events of epicentral range 55 to 100 km and average focal depth of 25.6 km are analyzed for the coda attenuation factor. In this group most of the data is from the subduction zone and the subcrustal movement is along JMT, MBT and MCT tectonic features. The estimated quality factor relationship is $148f^{1.05}$. The average $Q_c$ value is 207 at 1.5 Hz and 2795 at 18 Hz of central frequencies. The attenuation of coda waves for this data group is less as compared to PTK1 data group. The reason may be the epicentral range, which increases the depth of ellipsoidal volume. It is clear from fig 3(a) that the $Q_0$ value at 25 lapse time is slightly more than PTK1 and it increases rapidly with the increase of lapse time. The frequency parameter is high at lower lapse times and its value decreases sharply for lapse times more than 50 sec but even then the overall variation is still low with a standard deviation of 0.08. This shows that upper part of the crust is heterogeneous and seismically active while the lower crust is more homogeneous and less active. The maximum depth from which the coda waves are scattered is 122 km.

The data of PTK3 group is from 100 to 160 km of epicentral distance. Six seismic events are selected for this group. The S/N ratio is low and most of the seismic data is rejected due to set criteria. Only 10% of the calculations for central frequency 12 Hz are chosen and all the data above 12 Hz is rejected. From figs 3(a) and (b), it is clear that quality factor of this data group does not show any particular pattern as seen in the case of PTK1 and PTK2. Generally, $Q_0$ increases and $n$ decreases with
increasing lapse time. This variation of $Q_c$ might be due to large variations in subcrustal tectonics, as
the seismic waves were scattered in high tectonic and seismic active region to the north of Pathankot
station and by less active region covered through thick alluvium in the south. The average frequency
dependent relationship for this data is $147f^{1.06}$, which is nearly equal to PTK2. The magnitude of
events for Pathankot station in epicentre range $100 < R \leq 160$ (PTK3) is low and attenuation is high,
therefore, the frequencies higher than 12 Hz are so severely attenuated, that $Q_c$ values for central
frequencies higher than 12 Hz could not meet the selection criteria and are rejected. This may be one
reason for its quality factor similar to PTK2. The other reason of analogous quality factor may be the
inclusion of three deeper events (more than 50 km) in PTK2.

The events data for HOS Station is from 50 to 100 km of epicentral range with average focal
depth of 14.75 km. The station is on the Siwalik foothills having the north part tectonically active,
while the southern part is a foredeep covered with Gangetic alluvium and is less deformed. In this
data group the recorded events are few but the data contains high S/N for all selected lapse times. As
it is clear from fig 3(a) the iso-$Q_0$ values of HOS are comparable with PTK2 but fig 3(b) shows that
frequency parameter is more varying and shows high value for PTK1 and low value for PTK2 than
HOS. It indicates that the region is seismically less active but more heterogeneous. This may be due to
greater deformation of the region through recent Himalayan orogeny e.g. HFT. The frequency
dependent relationship for this data is $138f^{1.12}$ and $Q_c$ varies from 183 at 1.5 Hz to 2924 at 18 Hz.

The ASR (Amritsar) station is located on the alluvium and which is far from the Himalayas.
The seismic sources are relatively distant from this station, the data of nine events in epicentre range
of 100 to 200 km are analyzed but due to low S/N ratio about 40% values of these events are rejected.
The iso-$Q_0$ value of this station is relatively high and frequency parameter is low for all the lapse
times. The figures 3(a) and (b) show that the values of these parameters are reversed as compared to
the values of the other data groups. The frequency dependent relationship is $205f^{0.95}$, the high $Q_0$
value of 205 and low n value of 0.95 show that the region is intermediate active and less
heterogeneous. The calculated $Q_0$ and n values of all the stations are given in Table 3.

The data of Pathankot station is further analyzed at different focal depths i.e. very shallow
focus (h≤15 km) in PTK4 data group, intermediate depth (15<h≤35 km) in PTK5 data group and deep focus (35<h≤82 km) in PTK6 group. Moreover, the data of high seismic active sub-region of the current study towards the northeast of Pathankot station are analyzed in the ACT (active region) group. The iso-$Q_0$ and $n$ values of these data groups are shown in figures 3(c) and (d). In all the groups the iso-$Q_0$ increases with increasing lapse time but the increment is more as focal depth increases. The pattern of iso-$Q_0$ is more or less similar for PTK1 and ACT data groups with slightly more values for ACT for lapse time more than 50 sec. The $Q_0$ for PTK5 increases almost linearly but for deep focus earthquakes (PTK6) it increases nonlinearly. The variation of $n$ value is minimum for PTK1 and ACT. For these data groups its value is almost constant upto lapse time 50 sec and after that it drops. For PTK5 the value of $n$ decreases linearly and for PTK6 nonlinearly with lapse time. 

The maximum depth of ellipsoidal volume for these data groups is given in Table 4, which shows that the coda waves for shallow focus depth and active region are scattered in the upper lithosphere mainly in heterogeneous medium. In the case of intermediate focus, the scattered waves are from somewhat greater depth giving the indication that the seismic activity decreases and homogeneity increases with depth. In the case of deep focus the $Q_0$ values for lapse time less than 40 sec are very low showing an active upper lithosphere. For this data the average frequency parameter is 0.96 and nearly equal to 1 for lower lapse times so that the upper region is heterogeneous. The frequency parameter for shallow focus and active region is greater than 1 for all lapse times with nearly constant value for lapse times less than 50 sec, which is the clear indication that upper lithosphere is more heterogeneous.

The trend of quality factor, $Q_0$ and frequency parameter, $n$ for the data of PTK1, PTK4 and ACT (active region) is similar for all the lapse times. The data of these groups have different sources near to Pathankot station but the maximum depth of ellipsoidal volume is almost same around 100 km. These values indicate that the upper lithosphere near MBT and MCT is seismically active and highly heterogeneous. The heterogeneous effect is greater compared to the seismic effect. Along with these groups the data of HOS group also indicate that frequency parameter is more effective for the upper lithosphere. This low value of $Q$ and high frequency parameter has been suggested due to more seismic activity and heterogeneities in the upper part of lithosphere in brittle-ductile zone, which is
the effect of tectonic stress loading in brittle-ductile transition (Aki, 2003). If we compare the values of these groups with the values of ASR data then the results are not similar. Therefore, we can say that the fordeep Gangetic plain covered with alluvium is less active and less heterogeneous. Recently Mandal et al. (2004) have studied the coda attenuation factor in the epicentral region of devastating 2001 Bhuj earthquake using aftershocks data to estimate Qc effect with seismicity and heterogeneity. Their findings reveal low Qc values in aftershock zone as compared to adjoining regions, therefore attenuation is more near seismically active and heterogeneous region. They also attribute high value of frequency parameter with heterogeneous upper lithosphere and homogeneous deeper part. The average Q values along with individual values of all the stations are plotted in Figs. 4(a), (b), (c), and (d). These figures show the pattern of quality factor with central frequencies and best least square fits are interpolated to get the frequency dependent relationship of quality factor. The average frequency dependent relationship for NW Himalayan region is $158f^{1.05}$.

The difference in Qc values between Amritsar and other two stations is greater, which may be considered probably due to real crustal differences in coda Q. This indicates that the average attenuation properties and the scatters in the study area are not of the same pattern. The attenuation of seismic waves is more towards the Himalayan belt but comparatively less towards the Gangetic plains. This variation may be due to differences in seismotectonic, geotectonic, epicentral distance and focal depths in the subregions. To observe the effect of focal depths the events are divided in three groups but the number of events of shallow focus depths were more (65%) and deep focus depth less (10%). The estimated relation of Qc gives an average strong frequency dependent relationship of $Q_c = Q_0 f^n$, with mean value of $n$ as 1.05 and varies for different parts of the region. The quality factor is also lapse time dependent and from 25 sec to 50 sec window length, its value increases with lapse time for all the frequencies (fig 4). This means that for ellipsoidal volumes upto a tentative depth of 85 km the attenuation decreases with depth and medium homogeneity increases. After 50 sec lapse time there is still a small increment of Qc for lower frequencies (less than 10 Hz) but no variation for higher frequencies. This suggests that there is not much effect of small heterogeneities after lapse time 50 sec or after depth 85 km. We also tried to find out the variation in coda quality factor laterally and vertically to observe the subcrustal heterogeneities and seismotectonics through different groups of
data. The results show the variation for different parts but these variations can not be taken as sharp
division of the region because in the S-S backscattering model the scattering is the average property
of the region. Also all the stations did not record enough data used for Qc calculation and the
maximum selected events are clustered in a small subregion. Therefore, to observe all these effects in
detail, we may require more data. High dependence of Qc with frequency than its low value at 1Hz
indicates more effect of heterogeneities and tectonics in the upper crust as compared to seismic
activity.

The coda attenuation, Qc⁻¹ values estimated at different frequencies in this study, are
compared with other tectonic and seismic active regions of the world in figure 6. The Qc⁻¹ values of
this region are comparable to other Indian regions but less than most of the other available values of
the world. The coda attenuation of this region is similar to California as given by Nuttli (1981).
Parvez et al. (2001) also observed that the attenuation low of NW Himalayas is comparable to other
seismogenic zones in the world including California. Our results also agree with other Indian active
regions but are less than other observed active regions of the world. The frequency parameter of this
region is greater compared to the other regions, which indicates that the region is more heterogeneous.
The frequency parameter is nearly constant for data groups having epicentre distances less than 55
km, focal depths less than 15 km and active subregion as given in fig. 3. Also in some other regions of
the world no significant variation of frequency parameter has been observed for smaller lapse time
windows and shallow focus depths (e.g. Ibanez et al., 1990; Akinci et al., 1994). The attenuation
properties of the Indian lithosphere have been estimated earlier by coda Q methods for some regions
by Gupta et al., 1995 for Garhwal Himalays, Mandal and Rastogi, 1998 for Koyna region, Gupta et
al., 1998 for Koyna region, Tripathi and Ugalde, 2004 for southern Indian region and Mandal et al.
2004 for Kutch area. The coda Q¹ values observed by this study are comparable to other Indian
regions but more sensitive to frequency, which shows that this region is more heterogeneous as
compared to other parts of the country.
Conclusion

The estimated coda Q value of NW Himalayas indicates that the attenuation is greater towards high tectonic and seismic active areas. The estimated average frequency dependent relationship of the region is $158f^{1.05}$, while this relationship varies from $138f^{1.1}$ for mountains and its foothills to $205f^{0.95}$ for the plains. The observed quality factor is strongly dependent on frequency and lapse time, which indicates that the upper lithosphere, is more heterogeneous and seismo-tectonically active, while the lower lithosphere is homogeneous and relatively less active. The seismic data for the regions of epicentral distances less than 55 km, focal depths less than 15 km and highly seismic active subregions of current study indicate low values of $Q_0$ and high values of frequency parameter. The frequency parameter of these selected data groups is high and almost constant upto 50 sec lapse time window length, which indicates that upper lithosphere is highly heterogeneous. The frequency dependent quality factor indicates that the seismic energy of high frequency waves is attenuated more in upper lithosphere than in the lower lithosphere. The coda attenuation factor of NW Himalayas is comparable to other seismic active regions of India but the frequency parameter is somewhat more sensitive than the other regions. The trend of coda energy attenuation is similar to other seismic and tectonic active regions of the World. The subregional variation of $Q_0$ and frequency parameter indicates that seismic activity and heterogeneity of the lithosphere affect the attenuation behaviour of seismic waves.

Acknowledgement

We are very thankful to Prof. K. Aki for his encouragement and constructive suggestions to improve the quality of the manuscript. We thank Dr. Gangan Prathap, Scientist-in-Charge, CMMACS for his permission and to provide the facilities to complete this work. We also thank the Department of Science & Technology, Government of India to provide the fellowship to N. K. under DST project R-0-134.
References

Ni, J., Barazangi, M., 1984. Seismotectonics of the Himalayan collision zone: Geometry of the
interdependence among strong-motion amplitude, earthquake magnitude and hypocentral
interdependence among strong-motion amplitude, earthquake magnitude and hypocentral
interdependence among strong-motion amplitude, earthquake magnitude and hypocentral
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Fig. 1: General seismotectonic and topographical map of NW Himalayas and adjoining area. MCT: Main Central Thrust; MBT: Main Boundary Thrust; HFT: Himalayan Frontal Thrust; JMT: Jawalamukhi Thrust; KWF: Kisatwar Fault; SNF: Sundarnager Fault; Earthquake epicentres are plotted by circles, triangles represent the recording stations (PTK: Pathankot; HOS: Hoshiarpur; ASR: Amritsar) and cities are shown by squares.

Fig. 2: Plot of event recorded at Pathankot station on 16/01/1999 from 66 km epicentral distance. (a) Unfiltered data trace with coda window, (b) and (c) bandpass filtered displacement amplitudes of coda window at 2-4 Hz and 12-24 Hz respectively, (d) and (e) the RMS amplitude values multiplied with lapse time along with best square fits of selected coda window at central frequencies of 3.0 Hz and 18.0 Hz respectively. The Qc is determined from the slope of best square line. Abbrevations are: O.Time: Origin Time; P: P-wave Time; S: S-wave Time.

Fig. 3: Plots of $Q_0$ (quality factor at 1 Hz) and n (frequency parameter) with lapse time for different groups of data. PTK1 ($R \leq 55$), PTK2 ($55 < R \leq 100$), PTK3 ($100 < R \leq 160$) are different epicentre ranges for Pathankot; ASR, Amritsar; HOS, Hoshiarpur; PTK4 ($h < 15$), PTK5 ($15 < h \leq 35$), PTK6 ($35 < h \leq 82$) are data groups of different focal depths, ACT, Active region data. $Q_0$ and n are plotted with lapse time in (a), (b), (c) and (d) for these data groups.

Fig. 4: Plots of quality factors and central frequencies for all station with linear regression for frequency dependent relationship, $Q_c = Q_0 f^n$. (a) $Q_c$ with $f$ for all epicentre distances of Pathankot ($Q_c = 136 f^{1.07}$), (b) $Q_c$ with $f$ for Hoshiarpur ($Q_c = 138 f^{1.12}$), (c) $Q_c$ with $f$ for Amritsar ($Q_c = 205 f^{0.95}$), (d) Average $Q_c$ with $f$ for all the stations ($Q_c = 158 f^{1.05}$).

Fig. 5: Plot of average values of $Q_c$, $Q_0$ and n with lapse time for all the stations. (a) average $Q_0$ and n with lapse time, (b) Average $Q_c$ with lapse time at different central frequencies.

Fig. 6: Comparison of Coda-$Q_c$ of NW Himalayan region with reported coda-$Q_c$ of other regions of the world.
Table 1: Earthquake Data used for CODAQ calculation.

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Station: Pathankot Latitude: 32.45° N Longitude: 75.76° E Elevation: 600 m

Station: Amritsar Latitude: 31.64° N Longitude: 74.82° E Elevation: 218 m

Station: Hoshiarpur Latitude: 31.50° N Longitude: 75.94° E Elevation: 284 m
Table 2: Average quality factor at different frequencies and lapse times.

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<td>3119±397</td>
<td>30</td>
</tr>
<tr>
<td>55</td>
<td>266±82</td>
<td>71</td>
<td>637±193</td>
<td>55</td>
<td>1262±171</td>
<td>52</td>
<td>1716±235</td>
<td>46</td>
<td>2303±238</td>
<td>37</td>
<td>2953±442</td>
<td>29</td>
</tr>
<tr>
<td>60</td>
<td>285±95</td>
<td>68</td>
<td>656±177</td>
<td>51</td>
<td>1352±208</td>
<td>52</td>
<td>1715±221</td>
<td>43</td>
<td>2225±238</td>
<td>35</td>
<td>2869±335</td>
<td>27</td>
</tr>
</tbody>
</table>

Table 3: Q_0 (Quality factor at 1Hz) and n values for all the stations.

<table>
<thead>
<tr>
<th>Lapse Time (sec)</th>
<th>Pathankot R≤55</th>
<th>55&lt;R≤100</th>
<th>100&lt;R≤160</th>
<th>Average</th>
<th>Amritsar 100≤R≤202</th>
<th>Hoshiarpur 50≤R≤100</th>
<th>Avg. of all Stations R≤202</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>77</td>
<td>1.18</td>
<td>87</td>
<td>1.13</td>
<td>82</td>
<td>1.24</td>
<td>82.00</td>
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<tr>
<td>30</td>
<td>81</td>
<td>1.18</td>
<td>98</td>
<td>1.13</td>
<td>100</td>
<td>1.17</td>
<td>93.00</td>
</tr>
<tr>
<td>35</td>
<td>90</td>
<td>1.18</td>
<td>117</td>
<td>1.11</td>
<td>131</td>
<td>1.03</td>
<td>112.67</td>
</tr>
<tr>
<td>40</td>
<td>100</td>
<td>1.18</td>
<td>139</td>
<td>1.07</td>
<td>141</td>
<td>1.06</td>
<td>126.67</td>
</tr>
<tr>
<td>45</td>
<td>98</td>
<td>1.21</td>
<td>158</td>
<td>1.04</td>
<td>133</td>
<td>1.15</td>
<td>129.67</td>
</tr>
<tr>
<td>50</td>
<td>103</td>
<td>1.22</td>
<td>169</td>
<td>1.04</td>
<td>167</td>
<td>1.02</td>
<td>146.33</td>
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<tr>
<td>55</td>
<td>119</td>
<td>1.17</td>
<td>204</td>
<td>0.94</td>
<td>195</td>
<td>0.95</td>
<td>172.67</td>
</tr>
<tr>
<td>60</td>
<td>121</td>
<td>1.17</td>
<td>214</td>
<td>0.94</td>
<td>234</td>
<td>0.85</td>
<td>189.67</td>
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</table>

Table 4: The maximum depth of ellipsoidal volume.

<table>
<thead>
<tr>
<th>Data Group</th>
<th>Average D</th>
<th>Average t</th>
<th>Average hav</th>
<th>a_1=v/t/2</th>
<th>a_2=√(al^2−Δc)</th>
<th>Max. Depth h=hav+a_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTK1</td>
<td>44.5</td>
<td>13.5</td>
<td>44.10</td>
<td>77.2</td>
<td>63.1</td>
<td>76.6</td>
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<tr>
<td>PTK2</td>
<td>74.5</td>
<td>25.6</td>
<td>69.93</td>
<td>122.4</td>
<td>97.1</td>
<td>122.7</td>
</tr>
<tr>
<td>PTK3</td>
<td>131.3</td>
<td>20.0</td>
<td>103.20</td>
<td>180.6</td>
<td>124.0</td>
<td>144.0</td>
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<tr>
<td>ASR</td>
<td>168.7</td>
<td>25.3</td>
<td>120.98</td>
<td>211.7</td>
<td>127.9</td>
<td>153.2</td>
</tr>
<tr>
<td>HOS</td>
<td>93.6</td>
<td>14.8</td>
<td>75.80</td>
<td>132.7</td>
<td>94.0</td>
<td>108.7</td>
</tr>
<tr>
<td>hs15</td>
<td>71.8</td>
<td>9.7</td>
<td>66.01</td>
<td>115.5</td>
<td>90.5</td>
<td>100.2</td>
</tr>
<tr>
<td>15&lt;hs≤35</td>
<td>91.3</td>
<td>29.7</td>
<td>72.96</td>
<td>127.7</td>
<td>89.3</td>
<td>119.0</td>
</tr>
<tr>
<td>35&lt;hs≤82</td>
<td>71.3</td>
<td>73.2</td>
<td>77.05</td>
<td>134.8</td>
<td>114.4</td>
<td>187.6</td>
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<tr>
<td>ACT</td>
<td>68.5</td>
<td>13.7</td>
<td>65.10</td>
<td>113.9</td>
<td>91.0</td>
<td>104.7</td>
</tr>
</tbody>
</table>
Figure 1
Figure 2
Figure 3
Figure 4
Figure 5
Figure 6

Koyna (Gupta, 1998)
Koyna (Mandal, 1998)
Garhwal (Gupta, 1995)
GBA, India (Jayant, 2004)
Hindu Kush (Roecker, 1991)
Erzincan (Akinci, 1996)
Washington (Havskov, 1989)
California (Nuttli, 1981)
NW Himalayas (This study)