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Aftershock Activity and Frequency-dependent Low Coda Q_c in the Epicentral Region of the 1999 Chamoli Earthquake of M_w 6.4

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Abstract — On 28 March, 1999 (19:05:10.09, UT) a significant earthquake of M_w 6.4 occurred in the Garhwal Himalaya (30.555°N, 79.424°E). One hundred and ten well-recorded aftershocks show a WNW-ESE trending northeasterly dipping seismic zone extending from a depth of 2 to 20 km. As the main shock hypocenter occurred at the northern end of this seismic zone and aftershocks extended updip, it is inferred that the main-shock rupture nucleated on the detachment plane at a depth of 15 km and then propagated updip along a NE-dipping thrust plane. Further, the epicentral distribution of aftershocks defines a marked concentration near a zone where main central thrust (MCT) takes a significant turn towards the north, which might be acting as an asperity in response to the NNE compression due to the underthrusting of Himalayan orogenic process prevalent in the entire region. Presence of high seismicity including five earthquakes of magnitude exceeding 6 and twelve earthquakes of magnitude exceeding 5 in the 20th century is presumed to have caused a higher level of shallow crustal heterogeneity in the Garhwal Himalaya, a site lying in the central gap zone of the Himalayan frontal arc. Attenuation property of the medium around the epicentral area of the 1999 Chamoli earthquake, covering a circular area of 61,500 km^2 with a radius of 140 km, is studied by estimating the coda Q_c from 48 local earthquakes of magnitudes varying from 2.5–4.8. These earthquakes were recorded at nine 24-bit REFTEK digital stations; two of which were equipped with three-component CMG40T broadband seismometers and others with three-component L4-3D short-period seismometers. The estimated Q_o values at different stations suggest on average a low value of the order of (30 ± 0.8), indicating an attenuating crust beneath the entire region. The frequency-dependent relation indicates a relatively low Q_c at lower frequencies (1–3 Hz) that can be attributed to the loss of energy due to scattering on heterogeneities and/or the presence of faults and cracks. The large Q_c at higher frequencies may be related to the propagation of backscattered body waves through deeper parts of the lithosphere where less heterogeneities are expected. An important observation is that the region north of MCT (more rigid highly metamorphosed crystalline rocks) is less attenuative in comparison to the region south of MCT (less rigid slightly metamorphosed rocks (sedimentary wedge)). The acceleration decays to 50% at 20 km distance and to 7% at 100 km. Hence, even 1*g* acceleration at the source may not cause significant damage beyond 100 km in this region.

Key words: Attenuation, coda waves, scattering, Garhwal Himalaya, seismicity, aftershocks.

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Introduction

Since the Garhwal Himalaya has not experienced any earthquake of magnitude exceeding M_w 7.5 in its history (except perhaps the 1803 earthquake of intensity IX, Fig. 1), the recent occurrences of two M_w 6.0 earthquakes (Uttarkashi, M_w 6.6, 1991; Chamoli, M_w 6.4, 1999) drew the attention of earthscientists worldwide towards the reestimation of seismic hazard of the region. The 1999 Chamoli earthquake was caused by an approximately 9° north-dipping thrust at a depth of 15 km beneath the region north of MCT (30. 555°N, 79.424°E) in the Garhwal Himalaya. The aftershock activity of this earthquake was monitored for a period of about fifty days (03.04.99 to 21.05.99) with a close digital network (Fig. 2) consisting of seven short-period and two broadband stations, which enabled us to collect a good reliable data set for this earthquake. Thus, it would be important to reestimate the seismic hazard of the Garhwal Himalaya in the light of a new data set.

Understanding the attenuation property of the medium provides significant clues for designing suitable preventive measures to minimize seismic hazard in any region. Generally, damages result from the amplitudes of waves originating from the earthquake source, which are highly dependent on the attenuation property of the medium. The decay of seismic wave amplitudes with distance defines the attenuation of the medium which results from the conversion of elastic energy to heat (intrinsic attenuation due to sliding along grain boundaries and geometrical spreading) and the scattering of seismic waves resulting from heterogeneities of varied scale inside the

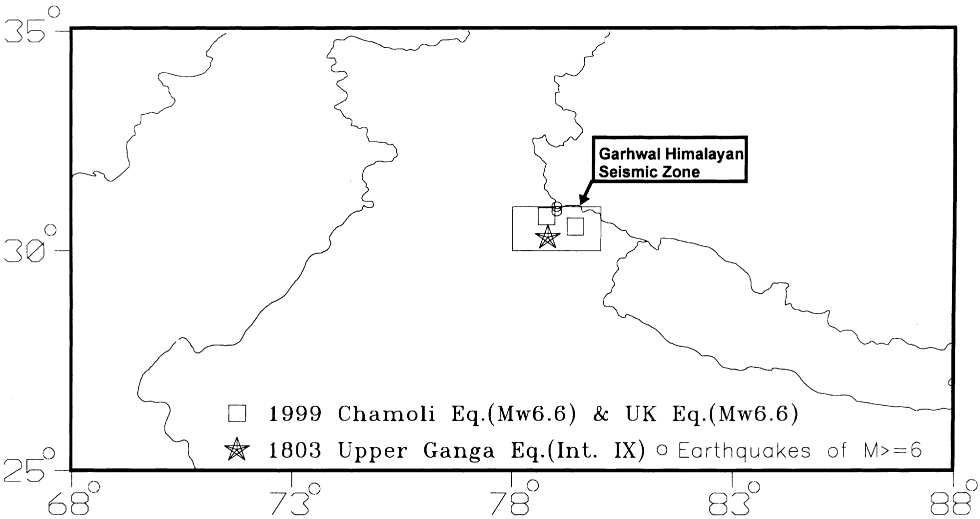


Figure 1
Location of earthquakes of magnitude $M \geq 6.0$ in the Garhwal Himalayan region (including the 1803 Upper Ganga earthquake of intensity IX).

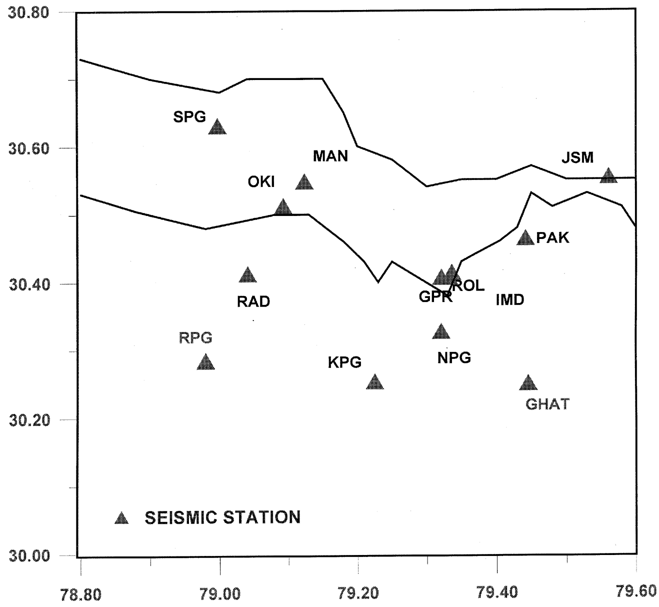


Figure 2
Location map of stations operated by NGRI in and around the Chamoli area.

earth's interior. There are different types of heterogeneities such as irregular subsurface geometry, velocity perturbations due to changes in rock types, cracks and faults. Further, attenuation is inversely proportional to the quality factor (Q) which is a combination of intrinsic quality factor, Q_i (due to internal heating), and scattering quality factor, Q_s (due to scattering). Several techniques have been proposed to estimate the Q_c by considering either a single or multiple scattering model (AKI and CHOUET, 1975; SATO, 1977; ROECKER *et al.*, 1982; FRANKEL and WENNERBERG, 1987; HELWEG *et al.*, 1995). In the single scattering model, attenuation of the backscattered body waves is considered to derive the intrinsic attenuation. It provides no estimate of the Q_s (PUJADES *et al.*, 1991).While the multiple scattering model gives estimates of both Q_i and Q_s (GAO *et al.*, 1983). However, FRANKEL and WENNERBERG (1987) found the same Q_i for Anza, California, using both single and multiple scattering techniques. Further, the single scattering model has been used widely to estimate Q_i due to its easier technique. Until today, few studies have been carried out to understand the attenuation of the medium in the Himalaya. These studies are for adjoining western and southwestern parts of the Garhwal Himalaya. CHANDRASEKARAN and DAS (1992) estimated Q_o from the decay of the fall of the recorded acceleration with distance and found a Q_o value of the order of 50 for the Uttarkashi earthquake of October 20, 1991. Nevertheless, based on coda-Q_c estimation using seven local earthquakes recorded in a network working in the adjoining southwestern part of the Garhwal Himalaya, GUPTA *et al.* (1995b) suggested a frequency-dependent coda-Q_c relation for the Garhwal Himalaya i.e., $Q_c = 126f^{0.95}$ indicating less pronounced attenuation at higher frequencies. The different Q_o estimations can be attributed to the different techniques used by them. It is important to estimate the attenuation property of the medium in the Chamoli region in order to understand the seismic hazard.

In this paper we present the results of the coda-Q_c study for the 48 well-located Chamoli aftershocks. A single scattering model of AKI and CHOUET (1975) has been applied on this reliable data set, to estimate a frequency-dependent coda-Q_c relation for the Chamoli area which would facilitate redesigning the preventive measures for minimizing the devastation possible from any significant earthquake in the Himalaya in general and the Chamoli area in particular.

Tectonic Setup

Himalaya, the highest mountain chain in the world, is mainly characterized by a marked concentration of interplate seismicity, a high rate of upliftment as well as convergence (MOLNAR and CHEN, 1983; NAKATA, 1989; DEMETS *et al.*, 1990). During the period 1897–1992 fourteen major earthquakes of magnitude ≥7.5, including five great earthquakes (including the 1912 Burma earthquake) of magnitude ≥8, have occurred in the Himalayan region (GUPTA *et al.*, 1995a; SATYABALA and GUPTA, 1996). Historically earthquakes have been recorded in this region which were mostly concentrated between main boundary thrust (MBT) and main central thrust (MCT) (SEEBER and ARMBRUSTER, 1984). The hypocentral depth plots of the Himalayan seismicity showed a low-angle northward-dipping seismic zone for moderate size earthquakes ($5 \leq m_b < 6$) beneath the region lying between the MCT and MBT (SEEBER *et al.*, 1981; NI and BARAZANGI, 1984). The focal mechanisms of selected regional and teleseismic Himalayan earthquakes using the polarity of first motion of *P* waves exhibited thrust faulting as the dominant deformation mode for the Himalaya (FITCH, 1970; RASTOGI, 1974; CHANDRA, 1978). Further, NI and BARAZANGI (1984) demonstrated that most of the thrust-type Himalayan earthquakes are concentrated at depths of 10 and 20 km. Additionally VALDIYA (1981) suggested that the neotectonics of the Himalaya manifests as movements along numerous thrusts. Several studies have been carried out to explain the mechanics of these thrust earthquakes, in terms of plate tectonic forces which revealed that the regional plate tectonic lithospheric compressive stresses resulting from the northward movement of the Indian plate were the prime factor in generating interplate seismicity in this region (FITCH, 1970; CHANDRA, 1978; NI and BARAZANGI, 1984; BURCHFIEL and ROYDEN, 1985). A region 200 km long, 100 km wide and about 20 km thick, based on local earthquake hypocentral parameters, has been identified as the Garhwal Himalayan seismic zone (GAUR *et al.*, 1985; KHATTRI *et al.*, 1989). To date, five earthquakes of *M*6 (including the 1803 Upper Ganga earthquake of intensity IX), twelve earthquakes of magnitude exceeding 5 and several earthquakes of magnitude ≤5.0 have occurred in the Garhwal Himalayan region (Fig. 1). The fault mechanism of the Kangra earthquake (1905) and the fault plane solutions of the Dharchula (1979), Uttarkashi (1991) and Chamoli earthquakes (1999) showed that the dominant deformation mode for the region is a low-angle northeasterly-dipping thrust faulting (THAKUR and ROHELLA, 1999). KHATTRI *et al.* (1989) indicated that these moderate earthquakes occur due to reactivation of detachment parallel, low-angle thrust faults in the upper crust. In the last two decades, small earthquakes of Garhwal Himalaya occurred in a narrow belt coinciding with the Himalayan seismic belt. However, GAUR *et al.* (1985) reported, based on the composite focal mechanism solution of selected local earthquakes of the Garhwal Himalaya which occurred at depths less than 10 km below the mean sea level (MSL), that strike-slip faulting can also occur in the region. These earthquakes have been explained in terms of reactivation of upper crustal faults, which are possibly slip surfaces of crustal shear zones facilitating the upliftment of lesser as well as higher Himalaya, and are a consequence of the same underthrusting Himalayan orogenic process prevalent in the entire region. Therefore, the presence of numerous thrusts and shear zones indicates that the crust beneath the region is quite heterogeneous.

Chamoli Earthquake

A significant earthquake of magnitude M_w 6.4 shook the Garhwal Himalaya during the early hours of 29 March, 1999 (19:05:10:10.09, UT of 28 March, 1999). It claimed 104 people deaths and several hundred people sustained injures. More than 10,000 houses were totally damaged and 42,000 houses were partially damaged in Chamoli, Rudraprayag and Tehri districts. The epicenter of the main shock was located north of main central thrust (MCT) with latitude 30.555°N and longitude 79.424°E by USGS, while the Indian Meteorological Department reported a different location for the main shock, i.e., latitude 30.408°N and longitude 79.416°E at a depth of 21 km. The magnitude of this earthquake was 6.4 as obtained by NGRI (M_s) and USGS (M_w and m_b) and 6.5 as reported by IMD (M_s). The focal depth of the earthquake was reported by the USGS, as 15 km from a waveform inversion whereas Harvard reported a focal depth of 12 km from a centroid moment tensor analysis. The isoseismals of this earthquake suggest a WNW-ESE trend with a 10 km × 5 km meizoseismal area westward of Chamoli. The intensity of the earthquake on the MM/MSK scale was estimated to be VIII. The focal mechanism solution for this earthquake was determined to be a low-angle thrust with strike 282°, dip 9° and slip 95° (as reported by USGS). Furthermore, we estimated the composite fault-plane solutions for shallower (<10 km) and deeper (>10 km) aftershocks, which also suggest a thrust mechanism along a NE-dipping (~30°) fault plane.

Aftershocks and Delineation of Aftershock Zone

The National Geophysical Research Institute, Hyderabad, India deployed a network consisting of nine 24-bit REFTEK recorders in the epicentral area of the 1999 Chamoli earthquake, of which seven were equipped with three-component short-period L4-3D sensors and two were equipped with three-component broad-band CMG40T sensors (Fig. 2). A total of 204 aftershocks were recorded during 03.04.99 to 21.05.99. The distance between station and epicentral area varies between 1.5 km to 47 km. The recording was done at 100 SPS (except 200 SPS for some near-by stations for some days). A realistic velocity model along with the station corrections for the region is obtained by inverting the *P*-arrival time for 110 selected events (Fig. 3). The velocity model of CHANDER *et al.* (1986) is considered as the initial model for velocity inversion. Next, the obtained model is used to relocate the aftershocks, resulting in significant improvement in the quality of hypocentral parameters. The relocated events showed ERH < 1.5 km, ERZ < 2 km and RMS < 0.4 s. The epicentral map of relocated events (Fig. 4) suggests a tight cluster trending NW–SE which corroborates well with the trend of fault plane as well as isoseismals of the 1999 Chamoli main shock (RASTOGI, 1999). The majority of events confine to a zone 3 km north of Gopeshwar where MCT has taken a significant turn north. The N–S and E–W hypocentral depth sections are shown in Figures 5(a) and 5(b), respectively. The N–S hypocentral depth section displays a

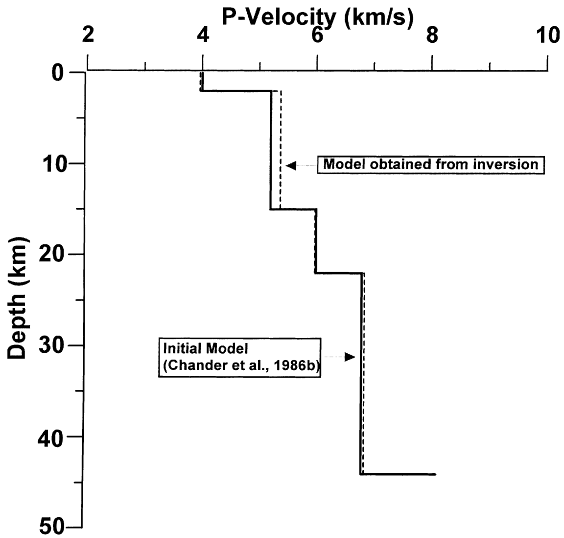


Figure 3
A plot showing the velocity model obtained from 1-D inversion of *P*-arrival time (dashed line) and initial velocity model (solid line).

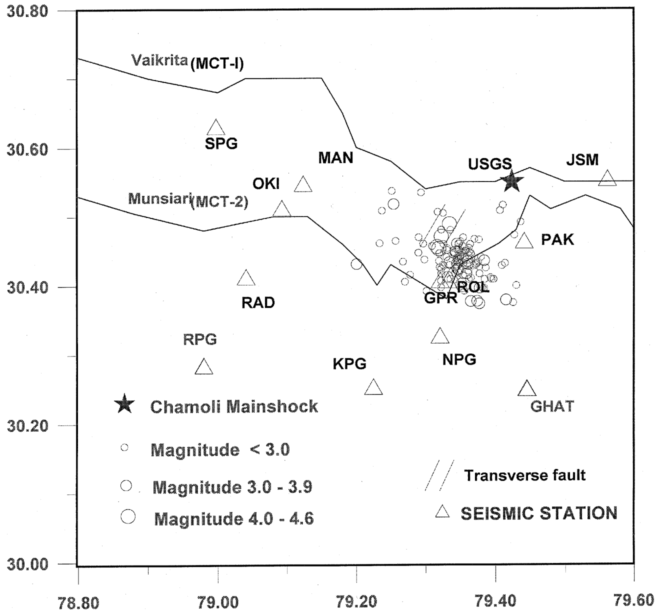


Figure 4
Epicentral plot for the selected Chamoli aftershocks.

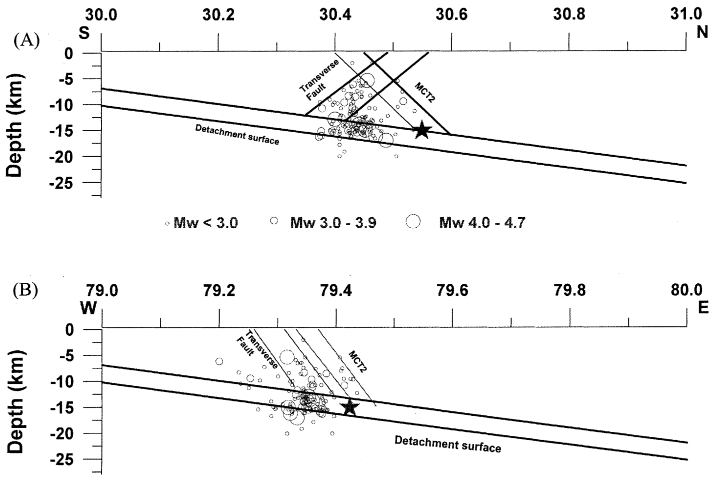


Figure 5
(a) E–W section of the hypocentral depth plot of Chamoli aftershocks, (b) N–S section of the hypocentral depth plot of Chamoli aftershocks.

north-dipping focal zone extending from a depth of 8 km to a depth of 16 km, where the estimated velocity model showed a significant jump (Fig. 3). Therefore, a combination of a gently north-dipping plane and a jump in P velocity at a depth of 8 to 16 km might be indicative of the detachment plane. It would be interesting to note that all aftershocks of magnitude exceeding 3 have occurred along the same plane except one aftershock, which occurred at a depth of 4 km. The E–W depth section (Fig. 5(b)) depicts an east-dipping focal zone. Thus, it can be inferred, based on the N–S and E–W depth sections, that the hypocenters of Chamoli aftershocks suggest a NE-dipping focal plane.

Methodology for the Calculation of Coda Q_c

In this paper we used the scattering method to compute the Coda Q_c for 48 small local earthquakes of magnitudes ranging from M_w 2.5–4.8 (Fig. 6). Utilizing this method, it is assumed that the coda wave is a combination of backscattered body waves generated by numerous heterogeneities present in the earth's crust and upper mantle (AKI and CHOUET, 1975). It is further assumed that the source and receiver are colocated, suggesting the scattering as a weak process; therefore the estimated Q_c would provide information regarding the intrinsic attenuation property of the medium. A narrow bandwidth signal with a central frequency F_m and coda wave amplitude $A(f,t)$ can be written as,

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

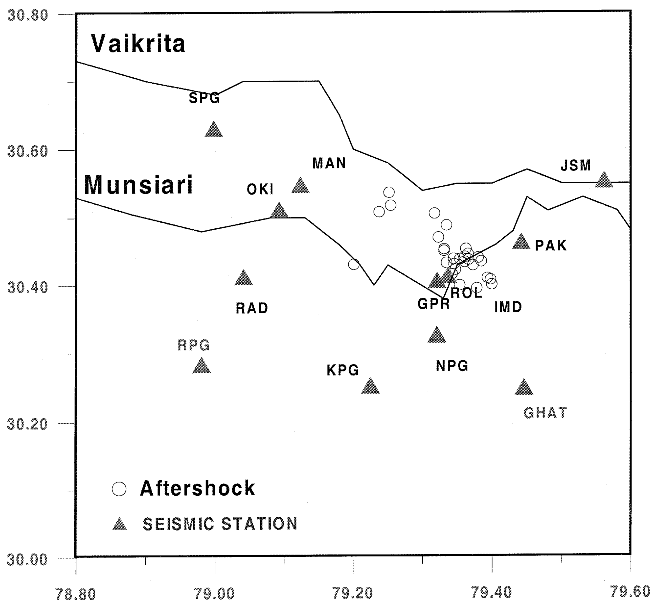


Figure 6
Epicentral map for the selected aftershocks (M_w 2.5–4.8) used in the estimation of coda Q_c.

where t represents the lapse time measured from the origin time of the event. $S(f)$ is the source function, which is assumed to be independent of time and radiation pattern. Therefore it behaves as a constant. The value a corresponds to the exponent for geometrical spreading and equals 1 for body waves, and Q_c represents the quality factor of the medium. The logarithm of the above equation provides

$$\ln[A(f,t)t] = c - bt \tag{2}$$

where b and c are equal to $-(f/Q_c)$ and $\ln(S(f))$, respectively. The slope of the above-mentioned equation gives $(1/Q_c)$. Since Q_c is dependent on frequency, the seismograms were filtered using a Butterworth bandpass filter for six different frequency bands (1–2, 2–4, 4–8, 6–12, 8–16 and 12–24) with central frequencies (F_m) of 1.5, 3, 6, 9, 12 and 18, respectively. The beginning of coda is considered at $2t_s$ where t_s is the S-wave travel time from the origin time as shown in Figure 7(a) (RAUTIAN and KHALTURIN, 1978). A time variable window of 30–80 sec, starting from $2t_s$ sec, has been used. For Q_c estimation a moving window (W) of $5/F_m*$ (SPS) sec is used to estimate the RMS average of the filtered coda amplitude which slides in steps of $0.5 * W$ sec. In this process a smoothed coda envelope is obtained. The logarithm of the product of the smoothed coda envelope and lapse time (t) is drawn (Fig. 7(b)). The slope of this line provides an estimate of $(1/Q_c)$ at every central frequency. Finally, the estimated Q_c values corresponding to different central frequencies are used to estimate the frequency-dependent coda-Q_c relation (Fig. 7(c)). A similar procedure is repeated for estimating similar coda-Q relations for different stations.

Results

The estimated average frequency dependent coda-Q_c relation for the region (Fig 8(a)) is mentioned below:

$$Q = (30 \pm 0.8)f^{(1.21\pm0.03)} \tag{3}$$

where iso-$Q(Q_o)$ and slope of the power-law fittng (n) are 30 and 1.21, respectively.

This relation suggests that the region beneath the Chamoli earthquake epicentral area is quite attenuated. It also indicates that the influence of the attenuation of the medium decreases with an increase in frequency. The low Q_c values at lower frequency range (1–3 Hz) might be attributed to the energy loss due to the presence of numerous heterogeneities. The estimated high coda Q_c values at greater than 12 Hz frequency band may be caused by the relatively homogeneous deeper layers in the lithosphere. The area for coda wave generation is assumed to be elliptical for the single scattering method, which can be represented as,

$$X^2/(vt^2) + Y^2/(vt^2 - R) = 1 \tag{4}$$

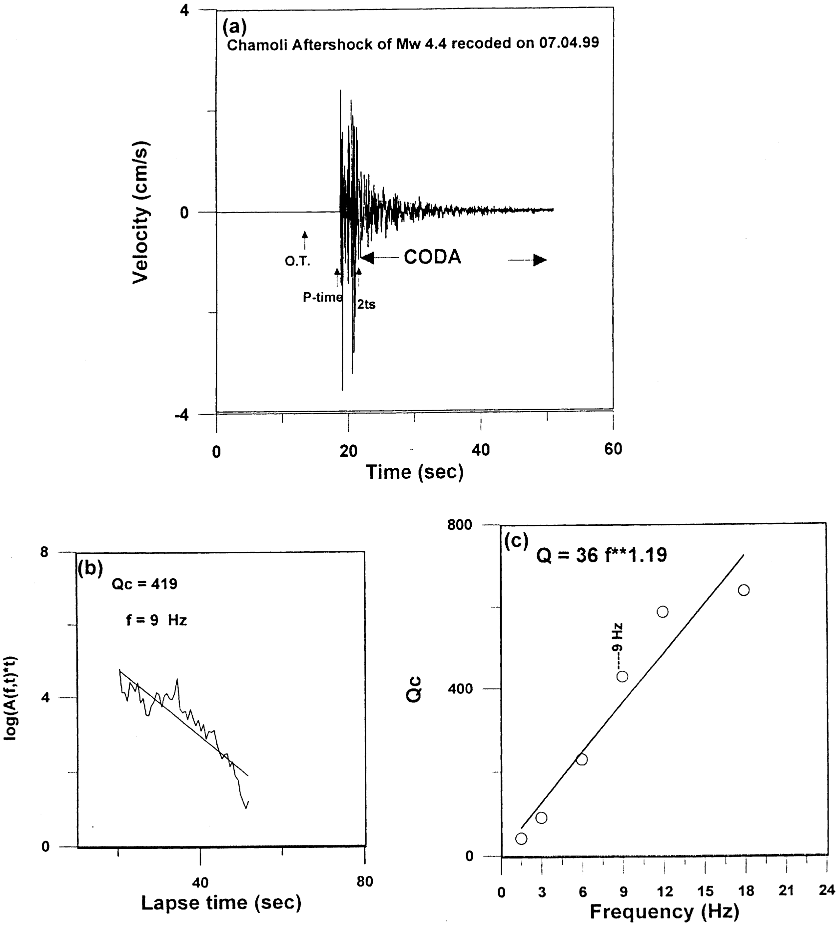
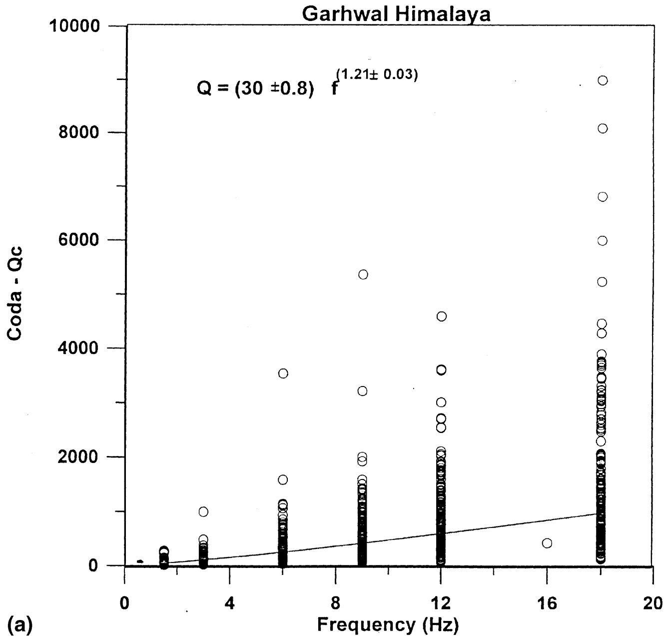


Figure 7
(a) Seismogram of a Chamoli aftershock. (b) A plot of lapse time $V_s \log[a(f,t) * t]$. (c) A plot of frequency V_s estimated Q_c values.

Additionally, AKI and CHOUET (1975) considered that source and receiver are colocated, therefore the above equation becomes an equation for a circular area with a radius, $vt/2$ (i.e., $R = 0$). The factors v and t represent velocity of S waves and lapse time, respectively. In this paper, an average lapse time duration of 80 sec has been used which corresponds to a circular area of 61,500 km^2 with a radius of 140 km.

The estimated frequency-dependent coda-Q_c relations at different stations suggest that the stations north of MCT indicate a larger iso-Q_o value in comparison to stations south of MCT (Fig. 8(b)). Therefore, the region south of MCT is inferred to be more attenuated in comparison to the region north of MCT. This difference in Q values can be explained in terms of sedimentary rocks beneath the lesser Himalaya



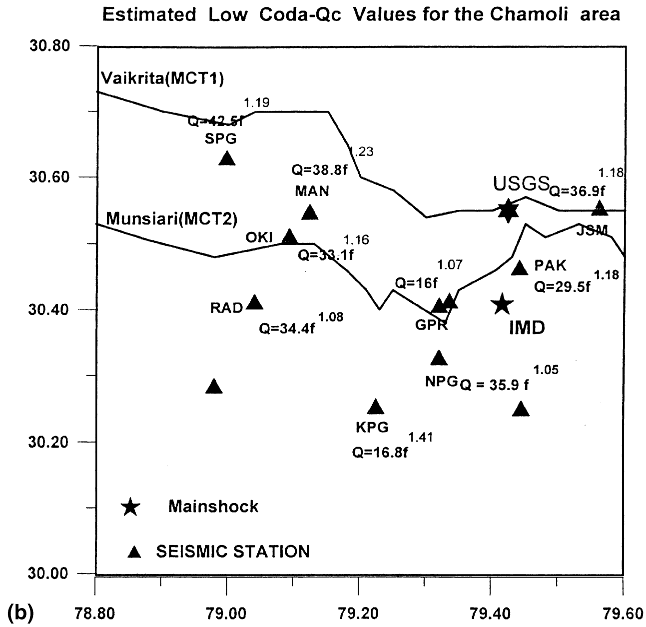


Figure 8

(a) Average frequency-dependent coda Q_c relation for the Garhwal Himalaya. All these estimates are included in obtaining the above-mentioned relationship. (b) Spatial distribution of the estimated frequency-dependent coda Q_c relation for different stations.

and crystalline rocks beneath the higher Himalaya, respectively. The frequency coda-Q_c relations obtained for different stations are listed below:

North of MCT

Sonprayag : $Q = 42.5f^{1.19}$ Mansona : $Q = 38.8f^{1.23}$
Okimath : $Q = 33.1f^{1.16}$ Joshimath : $Q = 36.9f^{1.18}$

South of MCT

Pakee : $Q = 29.5f^{1.18}$ Raidi : $Q = 34.4f^{1.28}$ Gopeshwar : $Q = 16.0f^{1.07}$
Nandaprayag : $Q = 35.9f^{1.05}$ Karnaprayag : $Q = 16.8f^{1.41}$

Decay of Acceleration with Distance

Numerous attempts have been made to predict the ground motion resulting from a severe earthquake (Kumar *et al.*, 1999; Irikura, 1983). The prediction of horizontal ground motion is a key factor in designing safe structures which, in turn, depend on understanding the attenuation property of the medium. The utilities of

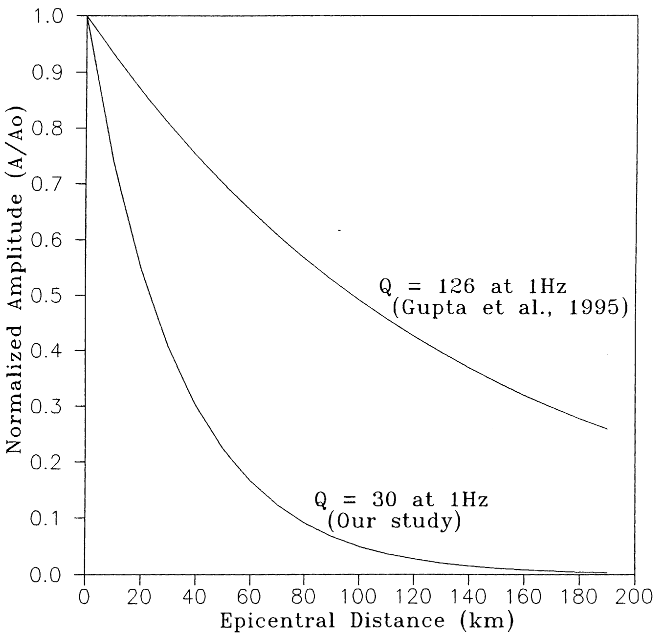


Figure 9
A plot of estimated normalized amplitude V_s distance for different Q_c values.

these kinds of studies are quite significant in estimating the seismic hazard of a region. The decay of amplitude with distance for different Q_o values (i.e., 30 from this study and 126 from GUPTA *et al.*, 1995b) is estimated (Fig. 9). Figure 9 suggests that the amplitude (A) becomes 7% at a distance of 100 km from the source where Q is considered to be 30 at 1 Hz. Thus, it can be inferred that even a great earthquake at Chamoli, which can cause a ground acceleration of the order of 1g, would produce no severe damage to engineered structures at distances beyond 100 km in the region.

A comparison study of estimated Q_c values for many seismically active sites worldwide suggests that sites like Guerrero (Mexico), Yugoslavia, Hindukush and Parkfield (US) are generally characterized by a low Q_o on the order of 60 and a 'n' value on the order of 0.9 as shown in Figure 10 (RODRIGUEZ *et al.*, 1983; ROVELLI, 1984; ROECKER *et al.*, 1982; HELLWEG *et al.*, 1995). This study reveals on an average Q_o of the order of 30 and 'n' of the order of 1.21 for the Garhwal Himalaya. Thus, in comparison to other active regions of the world, the Q_o is estimated to be quite low, whereas, 'n' is found to be slightly higher (Fig. 10). It would be worthwhile to mention that the earlier estimation of coda Q_c for the region suggested quite a high value of Q_o (126) which can be explained in terms of a constant 2.56 s RMS window for all the central frequencies (F_m) (where a time window of the order of $(5/f) * \text{SPS}$

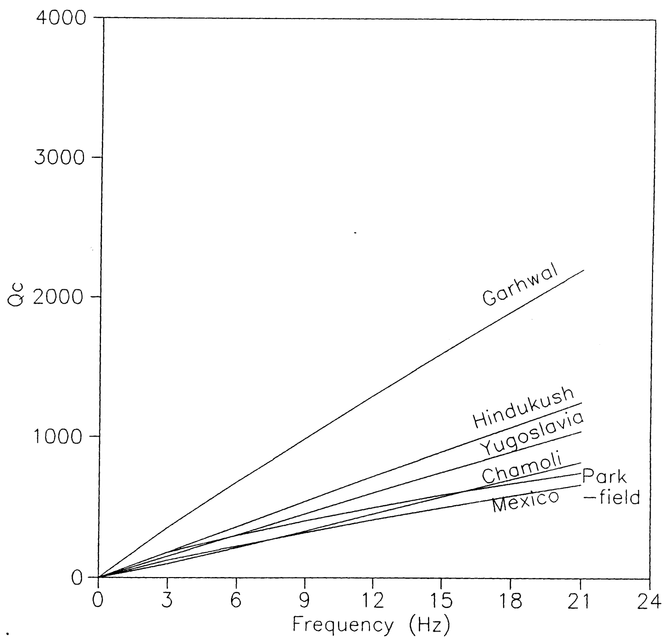


Figure 10
A plot showing a comparison between the estimated Q_c values for different seismically active regions of the world.

should be used) and only seven earthquakes considered for the study (GUPTA *et al.*, 1995b). In addition the study of KUMAR *et al.* (1999), based on earlier Q_c relation ($Q = 126f^{0.95}$), revealed inconsistencies between observed and synthetic peak values for the ground acceleration which can be attributed to the Q_c relation considered by them. It is important to note that Q_o estimated from the rate of fall of the recorded acceleration with distance was found to be approximately 50 for Uttarkashi of October 20, 1991 earthquake (as inferred from the decay curve shown by CHANDRASEKARAN and DAS, 1992) which is higher than our estimate of Q_o. This discrepancy can be explained by the fact that the coda-Q_c method provides an estimate for Q_i (due to intrinsic attenuation) but it does not account for Q_s (due to scattering attenuation). Hence, the multiple scattering techniques could provide a better estimate of Q for the region.

Discussion

The epicentral map and the hypocentral depth plots of 1999 Chamoli aftershocks define a $30 \times 10 \times 20$ km seismic zone trending NW–SE and dipping northeasterly. A marked concentration of large magnitude earthquakes is observed near a sharp bend of MCT. This bend might behave as an asperity or barrier in response to the NNE compression, due to the down going Indian plate. The progressive failure of the asperity or barrier on the detachment plane may be the vital factor in triggering the Chamoli earthquake sequence. Nevertheless, the hypocentral location of main shock on the NE side of the aftershock zone, the general northeasterly dip of the after-shock zone and the fault plane solution of the main shock suggested that the rupture most likely involved low angle NE-dipping thrust plane. It can be further inferred that rupture appears to have propagated up-dip.

The estimated coda-Q_c relations suggest that the region south of MCT (sedimentary) is more attenuative in comparison to the region north of MCT (crystalline). The Q_o and n value for the region are estimated to be (30 ± 0.8) and (1.21 ± 0.03), respectively, which hold good for a circular coda generation area of 61,500 km^2 with a radius of 140 km. It, in turn, indicates that the crust beneath the epicentral area is attenuative in comparison to the Indian Peninsula ($Q_o = 550$, $n = 0.84$, SINGH *et al.*, 1999). The Q_c values are found to vary from 30 at 1 Hz to 991 at 18 Hz. The low Q_c values at lower frequency range (1–3 Hz) can be attributed to the energy loss due to the presence of numerous heterogeneities. The high Q_c values for the higher frequency band (≥12 Hz) may be related to the relatively homogeneous deeper layers. Based on these results, it can be inferred that the displacement (A_o) due to any earthquake at Chamoli will be reduced to 0.07 A_o at distances beyond 100 km. Thus, an earthquake of magnitude exceeding 7.5 at Chamoli (which may be causing acceleration of the order of 1g at the source) would not be creating severe damage beyond 100 km.

Conclusions

The hypocentral and epicentral locations of the main shock as well as aftershocks of the 1999 Chamoli earthquake suggest that rupture nucleated at a depth of 15 km in the NE side of the aftershock zone and appears to have propagated up-dip along the detachment plane. The crust beneath the Garhwal Himalayan region is found to be attenuated. The estimated Q_o and 'n' for the region are estimated to be (30 $\pm$ 0.8) and (1.21 $\pm$ 0.03), respectively. Additionally, the region north of MCT is found to be more attenuative in comparison to the region south of MCT. This observation is in good agreement with the existing geology of the region. It is inferred, based on study of decay of amplitude with distance, that the occurrence of an earthquake of magnitude exceeding M_w 7.5 in the region would bring about slight damage beyond 100 km.

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