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## RESEARCH ARTICLE

### Matlab codes (Qbody) to study attenuation of seismic body-waves

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### Abstract

The main disasters of geological origin are earthquakes, landslides, tsunamis and volcanic eruptions. Earthquake is the most dangerous among the disasters of geological origin. The destruction caused by an earthquake is directly related to its source (size) and indirectly related to the path travelled by the seismic waves. In order to mitigate the destruction, the knowledge of its source and path travelled by seismic waves is very important. The understating of these attributes of earthquakes is important for carrying various development activity such as, river valley projects, bridges and other construction works in the Himalayan region.

Matlab codes ( $Q_{body}$ ) have been developed to study the seismic wave attenuation characteristics. The frequency dependence relationships of quality factors for P-wave ( $Q_\alpha$ ) and S wave ( $Q_\beta$ ) have been estimated by using extended coda wave normalization method in the frequency range 1.5 Hz to 24 Hz. A data set of 104 local earthquakes from Lower Siang region of Arunachal Himalaya has been investigated using these codes. The average variation in the estimated value of  $Q_\alpha$  and  $Q_\beta$  are from 49 at 1.5 Hz to 1421 at 24 Hz and 118 at 1.5 Hz to 2335 at 24 Hz respectively. The frequency dependent relations for P and S-waves are  $(25 \pm 3) f^{(1.24 \pm 0.04)}$  and  $(62 \pm 9) f^{(1.13 \pm 0.04)}$  respectively. The value  $Q_\alpha$  and  $Q_\beta$  obtained in the present study are comparable with the other seismically active regions of the world as well as of India. The obtained attenuation relations in the present study will be useful for simulation of strong ground motion and for estimation earthquake source parameters which have been further required for seismic hazard assessments in this region.

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### Introduction:-

Study of seismic wave attenuation is considered as one of the fundamental requirements for understanding the seismo-tectonics setup of a seismic region, for the estimation of earthquake source parameters and for the simulation of strong ground motion at a site due to probable earthquake source zones.

The basic physical mechanisms which are responsible for the loss of energy of propagating seismic waves are intrinsic absorption from inelasticity of rocks and scattering due to heterogeneities present in the path of seismic waves. The seismic energy is converted into the heat by intrinsic absorption and redistributed due to the internal heterogeneous medium through which the seismic wave passes. The higher frequency component of seismic waves attenuates more rapidly than the low frequency components resulting in resolution loss in seismograms. Therefore, the attenuation of seismic waves in the lithosphere is an important property for studying the regional earth structure

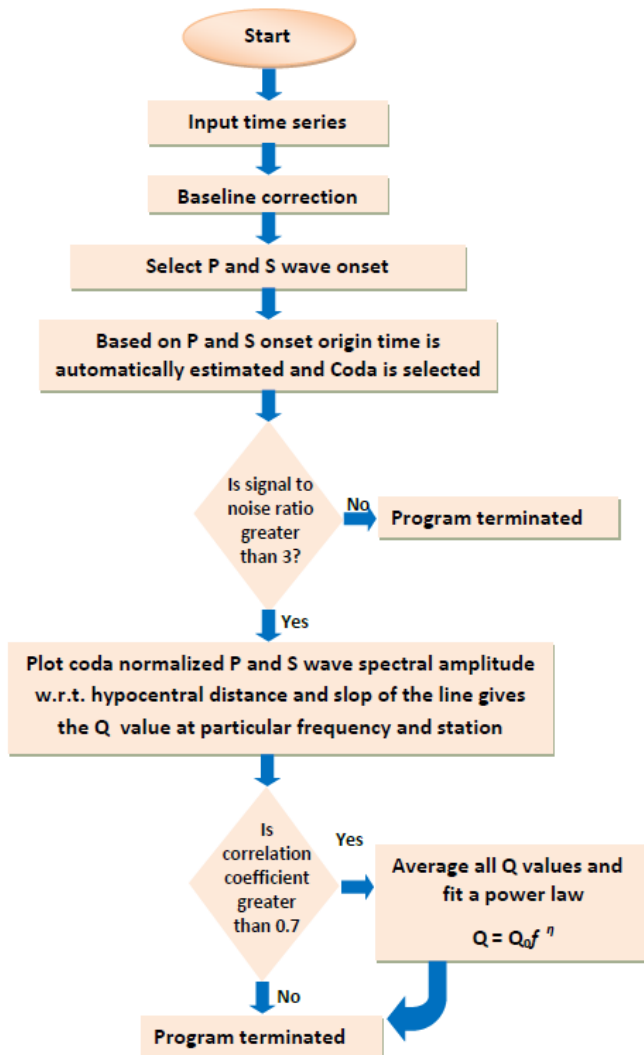
in relation to seismicity (Mandal et al., 2004). On the earthquake ground motion the effect of traveled path is mainly due to the attenuation of propagation seismic waves. The efficiency of seismic energy propagation through a medium is commonly expressed by the inverse of dimensionless quantity called quality factor  $Q$  (Knopoff, 1964).

$$Q^{-1} = -\Delta E / 2\pi E,$$

Where  $E$  is the total energy available in a harmonic wave and  $\Delta E$  is the energy lost in one cycle. An essential property of the earth reflecting its composition and thermal state is described by the attenuation parameter. Wave attenuation is one of the most important parameter which is directly related to medium properties of study region and essential for many studies such as exact determination of earthquake source parameters (Abercrombie, 1997), prediction of earthquake ground motions (Chopra et al., 2010), monitoring nuclear explosions (Mayeda et al., 2003) and the assessment of seismic hazards in a region (Anderson et al., 1996, Gupta et al., 1998). Also, attenuation parameter  $Q^{-1}$  is essential for understanding the physical mechanism of seismic wave attenuation in relation to the composition and physical condition of the earth's interior (Liu *et al.*, 1976; Sato, 1992). As seismic wave attenuation is effected by the tectonic activity so in tectonically active region it is also used to investigate tectonic properties and structure in the region (Aki, 1980). The seismic wave attenuation can be estimated using P-wave ( $Q_\alpha$ ), S-wave ( $Q_\beta$ ) and/or coda waves ( $Q_c$ ) observed on a seismogram which is recorded at local or regional distances.

In a region, seismic wave attenuation can be estimated by a number of techniques and different parts of the seismogram (Aki, 1969; Aki and Chouet, 1975; Hermann, 1980; Mitchell, 1995). Aki (1980) proposed the coda normalization method to estimate the frequency-dependent relation for  $Q_\beta$ . Yoshimoto et al. (1993) extended this method for simultaneous measurement of  $Q_\alpha$  and  $Q_\beta$  which is successfully applied in the various regions of India and world, e.g., Koyana, India (Sharma et al. 2007); Bhuj, India (Padhy, 2010); Kanto, Japan (Yoshimoto et al. 1993); Western Nagano, Japan (Yoshimoto et al. 1998); South-Eastern Korea (Chung and Sato, 2001); central South Korea (Kim et al., 2004); East-Central Iran (Ma'hood et al., 2009) and Cairo metropolitan area (Abdel-Fattah, 2009). The attenuation characteristics vary from one region to another. It has been observed that in the seismically active regions, the  $Q$  factor is low as compared to stable regions (Sekiguchi, 1991; Fedotov and Boldyrev, 1969; Masuda, 1988; Sato and Fehler, 1998). As per the requirement of engineering seismology the attenuation characteristics of S waves have been studied more intensively than P wave. In the same region, the  $Q_\alpha$ , and  $Q_\beta$  are different another (Rautian et al., 1978). A very few studies have been done for the simultaneous estimation of frequency dependent  $Q_\alpha$  and  $Q_\beta$  (Hough and Anderson, 1988; Masuda, 1988; Campillo and Planet, 1991; Yoshimoto et al., 1993; Sharma et al., 2007, 2008, 2009). The attenuation of high frequency P and S waves in the earth has been summarized by Der (1998).

In the present study attempt has been made to understand the seismic body wave's attenuation characteristics in lower Siang region of Arunachal Himalaya. The region is one among the highest seismically active regions and undergone many deformations and reactivation of some of the faults, thrusts etc. For this purpose Matlab codes (Qbody) as shown by flow chart in Figure 1, have been developed to study  $Q_\alpha$  and  $Q_\beta$  using extended coda normalization method (Yoshimoto et al., 1993).



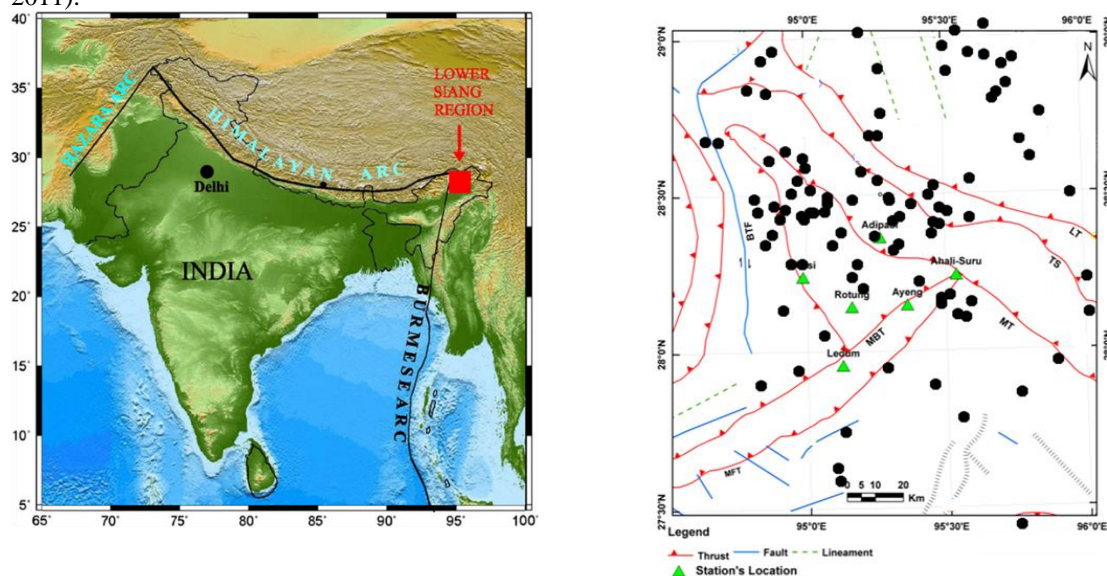
**Fig 1** The flow chart depict the various steps of estimations of  $Q\alpha$  and  $Q\beta$ .

Waveform data of 104 local earthquakes (Fig 2) recorded by local seismological network deployed in lower Siang region (Table 1) of Arunachal Himalaya have been used for the analysis.

### **Geology and Seismotectonic of the Region:-**

The Lower Siang region belongs to major antiformal tectonic unit called Eastern Syntaxis, which show a bend in their regional strike from ENE–WSW to NW–SE. The regional stratigraphy of this zone has been established by various researchers (Singh, 1993; Kumar, 1997). The Eastern Syntaxis is built up of Proterozoic to Cenozoic rocks arranged in distinct litho-tectonic belts. The Eastern Syntaxis is a belt where two distinct tectonic domains with ENE-WSW trend in the west and NW-SE trend in the east are juxtaposed (Singh, 1996). The Eastern Syntaxis is composed of three major thrust sheets, namely Siang, Siyom and Rikor in descending tectonic order. A complex Para autochthonous zone is exposed in the central part which contains the Abor Volcanic, the Yingkiang Formation and the Dalbuing Formation. Rocks exposed in the Eastern Syntaxial region belong to three major units of Himalaya; the Sub-Himalaya (Siwaliks), the Lesser Himalaya (including the Gondwana Group) and the Higher Himalaya (Gansser, 1964). In addition, central part of the syntaxial structure is occupied by a sequence of sedimentary rocks of Eocene age, associated with basic volcanic rocks (Singh, 1993).

From the tectonic point of view, Arunachal Pradesh is unique and is much different than the other parts of Himalaya. It is situated at the junction of three plates; Indian plate, Indo-Burmesen plate and Eurasian plate. The most important elements of Himalayan domain in this region are Tsangpo Suture, Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT) (Narula et al., 2000). The Lohit Thrust separating the moderately metamorphosed sequence from Granitoid massif of Tuting Group and Mishmi Thrust is also an important structural element of the area. The Bame Fault bears evidences on right lateral sense of movement. Rejuvenation of a conjugate set of faults encompassing Po Chu Fault and one parallel to Bame Fault, during historical past, has been interpreted. There are several sets of neotectonic faults in the Brahmaputra Basin, at the south of Arunachal Himalaya. Of these faults, those trending NE-SW and E-W are the most important (CISMHE, 2011).



**Fig 2** Map depicts topographic features along with major tectonic fronts of the Indian Plate on north edge along the Himalaya, i.e. Hazara Arc, Himalayan Arc and Burmese Arc. The area of study is also shown as a red box in the map. Map showing epicenters of events recorded during July 2011 to May 2012 (solid circles) in the Lower Siang Region. Tectonics after GSI (2000).

The region (Fig 2) is, seismologically, one of the most active zone of Himalayan terrains. In the Seismotectonic architecture of the Arunachal Himalaya the main river Tsangpo, follows a Suture zone in Tibet. This river, named Siang in Arunachal Pradesh, is controlled by the axis of Siang Antiform. As per seismic zoning map of India as incorporated in Indian Standard, (Criteria for Earthquake Resistant Design of Structure IS 1893 (part-I), 2002, 2014: General provision and Buildings), the study area lies in the seismic zone V. The zone V is broadly associated with a seismic intensity of IX or above on modified Mercalli scales (M.M. Scale). The earthquake activity in this region is due to the Indian plate diving beneath the Eurasian plate in the north and subduction below the Burmese plate in the east. Earthquakes here are generally shallow (depth < 40Km) but in the Naga Hills some intermediate focus events have also been occurred (CISMHE, 2011).

**Table 1:** Site characteristics and epicentral locations of the recording stations.

Sl. No.	Name of Station	Station Code	Lat. (°N)	Long. (°E)	Elev. (meters)	Type of Soil/Rock
1.	Adi-Pasi	ADI	28.36°	95.26°	997	Reddish Sandstone with Shale
2.	Ahali-Suru	AHO	28.24°	95.54°	571	Quartzite
3.	Ayeng	AYE	28.15°	95.36°	272	Boulder Bed
4.	Ledum	LED	27.96°	95.13°	385	Boulder bed
5.	Rotung	ROT	28.14°	95.16°	410	Quartzite
6.	Yeksi	YEK	28.24°	94.98°	401	Conglomerate

**Methodology:-**

Aki (1980) proposed the coda normalization method based on the empirical observation to derive frequency dependent attenuation relationship for shear waves ( $Q_\beta$ ). Yoshimoto et al. (1993) extended this method for simultaneous measurements both body waves ( $Q_\alpha$  and  $Q_\beta$ ). For the local earthquakes recorded at distances less than 100 km, the spectral amplitude of the coda at lapse times greater than twice the S wave travel time is proportional to the source spectral amplitude of the S waves (Yoshimoto et al., 1993; Kim et al., 2004). The normalization of S wave spectra to coda removes the effects of source, site and the recording instrument. The Q is estimated under the assumption that P- to S-wave radiations have the same spectral ratio within some magnitude range within narrow frequency range (Yoshimoto et al., 1993). Even if the spectral shapes of P and S waves are different, the assumption holds good (Molnar et al., 1973; Rautian et al., 1978; Sharma et al., 2009). The method is based on the following proportionality between the coda spectral amplitude  $A_c(f, t_c)$ , the source spectral amplitude of S waves  $S_s(f)$  and the source spectral amplitude of P waves  $S_p(f)$ :

$$A_c(f, t_c) \propto S_p(f) \propto S_s(f) \tag{1}$$

Where  $S_p(f)$  is the source spectral amplitude of P waves,  $S_s(f)$  is the source spectral amplitude of S waves,  $f$  is the frequency in Hz and  $t_c$  is the reference lapse time measured from the source origin time.

The  $Q_\alpha$  and  $Q_\beta$  can be calculated based on the above proportionality with the analysis of earthquakes of various hypocentral distances.

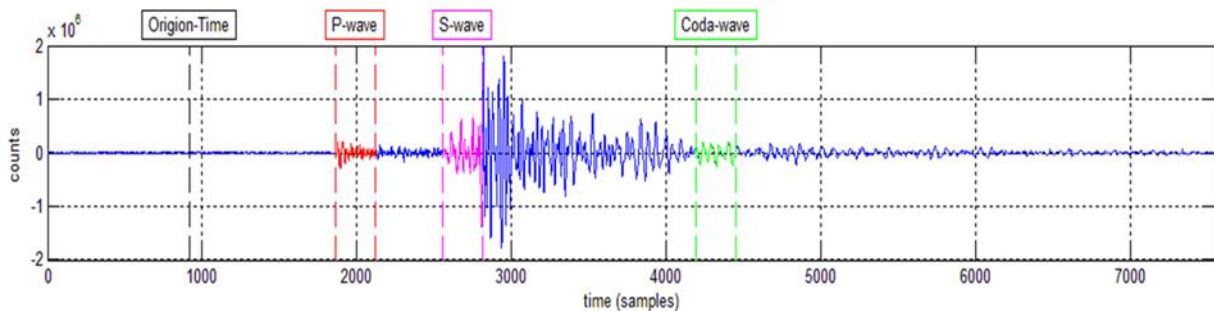
$$\ln \frac{A_p(f,r)r}{A_c(f,t_c)} = -\frac{\pi f}{Q_\alpha V_p} r + cont(f) \tag{2}$$

$$\ln \frac{A_s(f,r)r}{A_c(f,t_c)} = -\frac{\pi f}{Q_\beta V_s} r + cont(f) \tag{3}$$

Where  $A_p(f, r)$  and  $A_s(f, r)$  represents the amplitude spectra of the direct P and S waves at the hypocentral distance  $r$  (km) respectively.  $V_p$  is the P-wave velocity and  $V_s$  is the S-wave velocity. The vertical (Z) components of seismograms and horizontal components (N-S) are analyzed for the estimation of  $Q_\alpha$  and  $Q_\beta$  respectively. The Butterworth band pass filter has been used for filtering the data at seven different central frequencies (Table 2).

**Table 2:** Central frequency components of bandpass filter with low and high cut-off frequencies

Low cut-off (Hz)	Central frequency (Hz)	High cut-off (Hz)
1.00	1.50	2.00
2.00	3.00	4.00
4.00	6.00	8.00
6.00	8.00	12.00
8.00	12.00	16.00
12.00	18.00	24.00
16.00	24.00	32.00

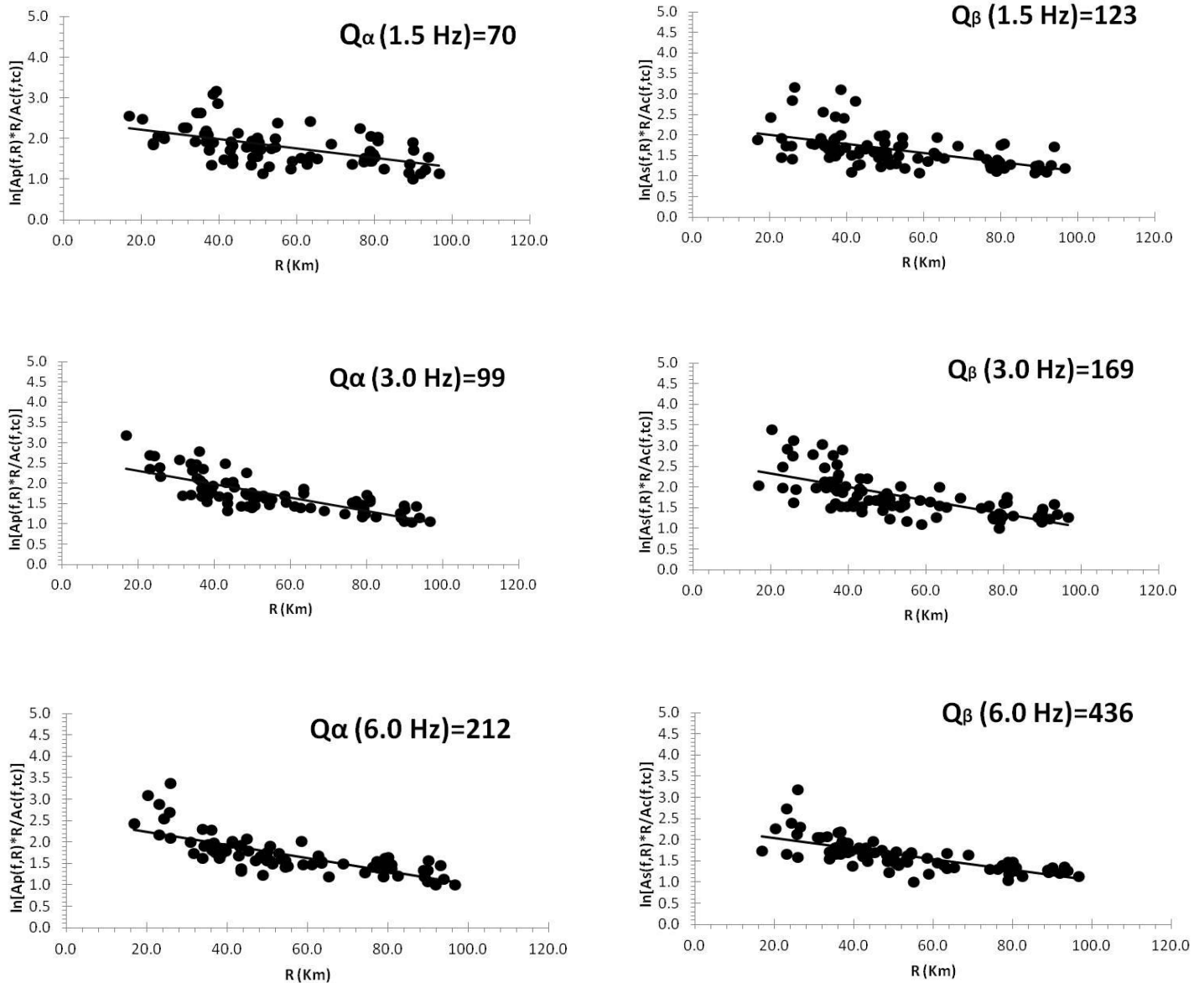


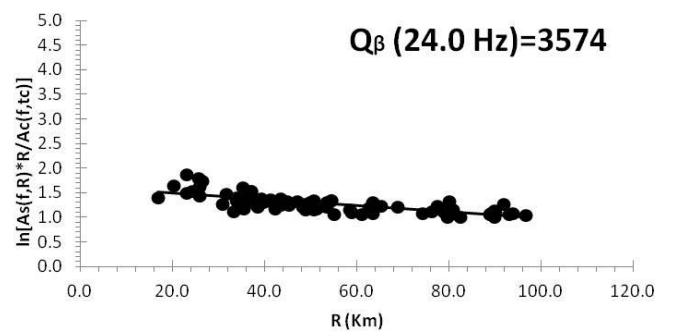
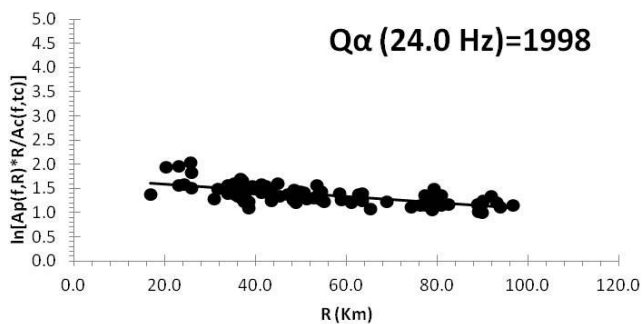
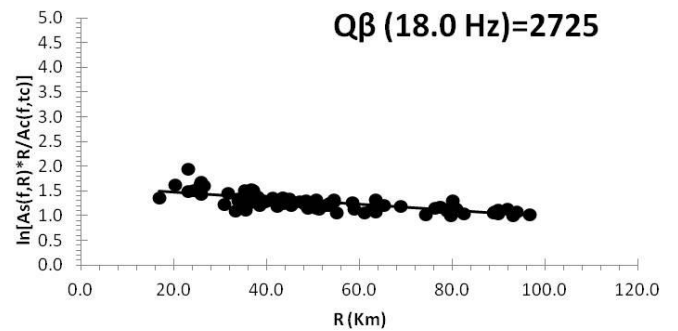
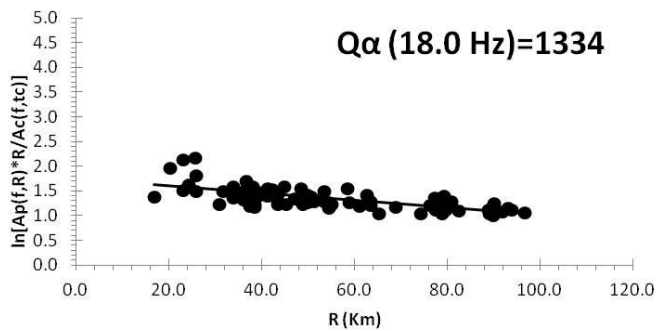
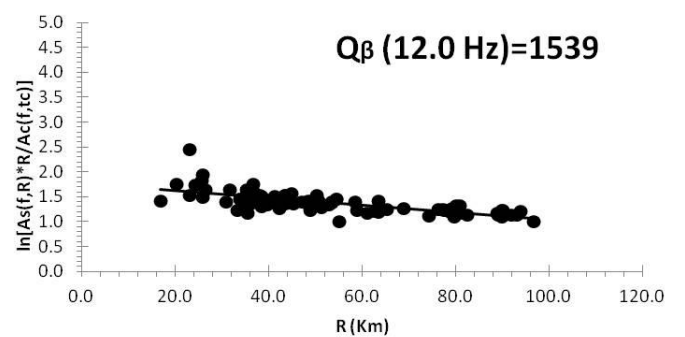
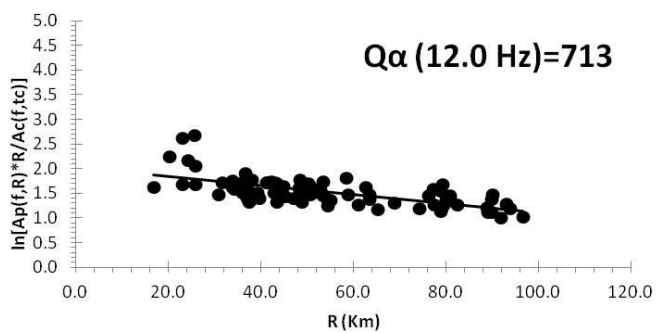
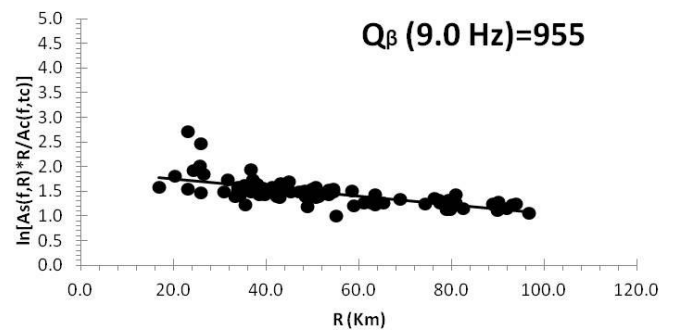
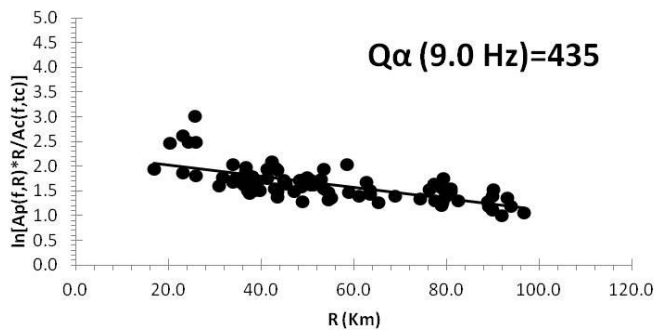
**Fig 3** Example of a horizontal (N-S) component seismogram recorded at station LED with. The time of P, S and Coda waves are marked. Coda is measured for a time window of 2.56 sec with a lapse time greater than twice the travel time of S-wave.

The Fig.3 represents the seismogram recorded at LED. The spectral amplitude of the direct P and S waves are measured using 2.56 sec time window. The spectral amplitude of the Coda  $A_c(f, t_c)$  is calculated using a lapse time window of 2.56 sec and the lapse time for the analyzed portion of the coda wave is taken as twice the travel time of

S-wave (Aki and Chouet, 1975; Rautian and Khalturin, 1978). The geometrical spreading is  $r^{-1}$  and  $\frac{1}{\sqrt{r h_{moh}}}$  for the epicentral distance of  $r \leq h_{moh}$  and  $r \geq h_{moh}$ , respectively where  $h_{moh}$  is twice the Moho depth (Herrmann and Kijko, 1983; Mahood et al., 2009). In the study region the Moho depth is 46 km (Khattri, 1983) so  $h_{moh}$  approximately can be taken as 90km. the hypocenter of the earthquakes considered for the analysis is less than 90 km. Therefore inverse power law of hypocentral distance  $r^{-1}$  has been considered for geometrical spreading.

The values of  $Q_\alpha$  and  $Q_\beta$  are obtained from the slope of best fitted line derived by fitting linear regression line after applying the least square method (Fig 4).





**Fig 4** Coda normalized peak amplitude decay of P and S waves with hypocentral distance for five central frequencies at LED station and the regression lines from the least-squares best-fitted lines are also shown. The slope of best fitted line can be obtained by using equation (2) and (3):

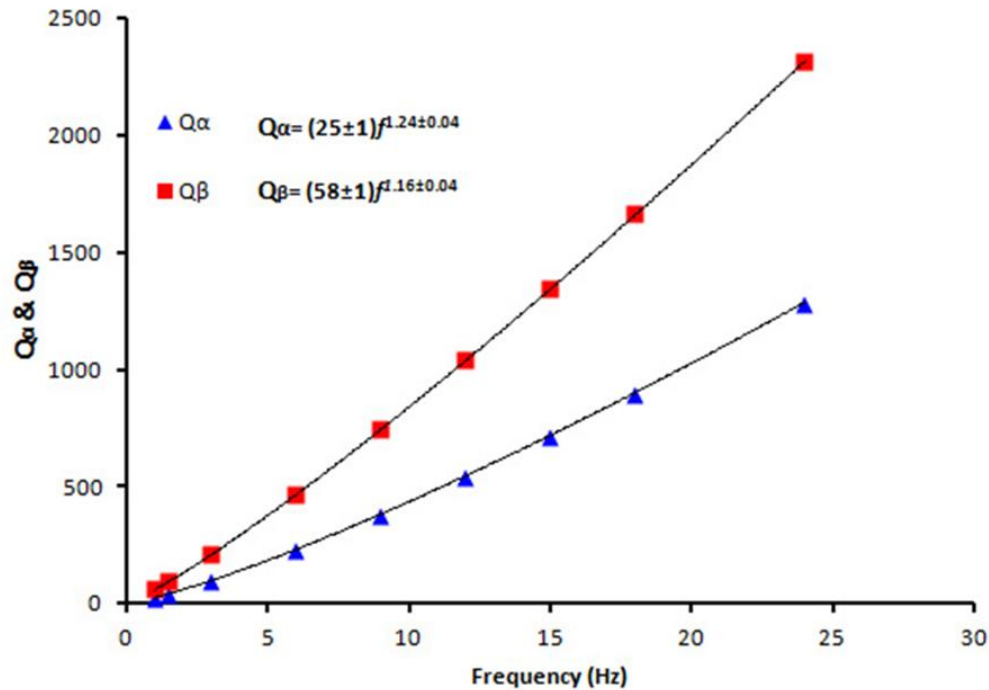
$$Q_{\alpha} = -\frac{\pi f}{\text{Slope} \times V_P} \text{ for P-wave} \quad (4)$$

$$Q_{\beta} = -\frac{\pi f}{\text{Slope} \times V_S} \text{ for S-wave} \quad (5)$$

### Results and discussions:-

For Lower Siang region of Arunachal Himalaya the estimated values of  $Q_{\alpha}$  and  $Q_{\beta}$  at various frequencies shows increase with the increasing frequency. The average values of  $Q_{\alpha}$  vary from 49 at 1.5 Hz to 1421 at 24 Hz, the average values of  $Q_{\beta}$  vary from 118 at 1.5 Hz to 2335 at 24 Hz (Fig. 4).

Average values of  $Q_{\alpha}$  and  $Q_{\beta}$  along with their standard deviations at different central frequencies (Fig 5).



**Fig 5** Average values of  $Q_{\alpha}$  and  $Q_{\beta}$  at different central frequencies.

The frequency dependence is comparable with the other seismically active regions of India and world such as Kanto, Japan (YOSHIMOTO et al., 1993), Garda, Italy (CASTRO et al., 2008), South, Eastern Korea (CHUNG and SATO, 2001), Northern Italy (Console & Rovelli, 1981), Central Italy (Castro et al., 2002), South Central Alaska (Dutta et al., 2004), Central South Korea (Kim et al., 2004), Kuchchh region (Chopra et al., 2008), Chamoli region (Sharma et al., 2009), NE Himalaya (Padhy and Subhadra, 2010), NW Himalaya (Imtiyaz et al., 2012), Koyna region, Gujrat (Sharma, 2009), Mainland region, Gujarat (Chopra et al., 2010), Saurashtra region, Gujarat (Chopra et al., 2010), Marche, Italy (Castro, 1999), Central South Korea (Kim et al., 2004) and France (Campillo and Planet, 1991). For each station the power law  $Q=Q_0f^n$  (where  $Q_0$  is the Q value at 1 Hz and n is the frequency dependence factor) has been fitted to estimate the frequency dependence of Q (Table 3).

**Table 3:** Average values of  $Q_\alpha$  and  $Q_\beta$  along with their standard deviations at different central frequencies at five stations.

Frequency (Hz)	ADI ( $Q_\alpha$ )	( $Q_\beta$ )	AHO ( $Q_\alpha$ )	( $Q_\beta$ )	AYE ( $Q_\alpha$ )	( $Q_\beta$ )	LED ( $Q_\alpha$ )	( $Q_\beta$ )	ROT ( $Q_\alpha$ )	( $Q_\beta$ )
1.5	46±4	101±5	56±4	130±6	33±4	109±5	71±6	123±7	42±4	128±7
3.0	91±4	135±3	92±3	132±4	75±3	199±4	99±3	169±3	106±3	180±4
6.0	253±6	346±5	200±4	404±5	206±4	416±4	212±3	436±4	222±3	490±5
9.0	412±6	606±4	360±4	654±5	383±4	722±4	435±5	955±6	374±3	698±4
12.0	580±6	808±3	488±4	955±4	590±5	1097±5	714±6	1939±8	585±4	1007±4
18.0	1025±7	1240±3	743±4	1471±4	1070±6	1867±6	1335±7	2725±8	937±4	1713±4
24.0	1528±9	1654±3	984±4	1996±5	1273±5	2194±5	1999±9	3574±8	1325±5	2261±4

**Table 4:** Frequency dependent relationships for five stations.

Station code	Relation for p waves	Relation for s waves
ADI	$Q_\alpha = (19\pm 2)f^{(1.31\pm 0.03)}$	$Q_\beta = (55\pm 4)f^{(1.07\pm 0.02)}$
AHO	$Q_\alpha = (34\pm 3)f^{(1.06\pm 0.02)}$	$Q_\beta = (56\pm 5)f^{(1.12\pm 0.03)}$
AYE	$Q_\alpha = (31\pm 5)f^{(1.19\pm 0.02)}$	$Q_\beta = (72\pm 7)f^{(1.09\pm 0.03)}$
LED	$Q_\alpha = (17\pm 2)f^{(1.44\pm 0.04)}$	$Q_\beta = (67\pm 4)f^{(1.24\pm 0.05)}$
ROT	$Q_\alpha = (25\pm 1)f^{(1.24\pm 0.02)}$	$Q_\beta = (60\pm 5)f^{(1.14\pm 0.03)}$

The average power spectral relation (Table 4) for the Lower Siang region of Arunachal Himalaya region is  $(25\pm 3) f^{(1.24\pm 0.04)}$  for P-wave and is  $(62\pm 9) f^{(1.13\pm 0.04)}$  for S-wave. It has been observed that the value of  $Q_\alpha$  and  $Q_\beta$  in the stable regions of is low as compared to that of seismically active regions. The frequency dependent relationships for  $Q_\alpha$  and  $Q_\beta$  are comparable with the other seismically active regions of the world and India such as Kuchchh region (Chopra et al., 2008), NE Himalaya (Padhy and Subhadra, 2010), NW Himalaya (Imtiyaz et al., 2012), Kanto, Japan (YOSHIMOTO et al., 1993), Kumaun Himalaya (Singh et al., 2012), Marche, Italy (Castro, 1999), Central Italy (Castro et al., 2002), Garda, Italy (Castro et al., 2008) and Koyna region, Gujrat (Sharma, 2009), low Q values are observed. However, for comparatively stable regions such as Central South Korea (KIM et al., 2004) and Baltic Shield (Kvamme and Havskov, 1989), their Q value is high.

### Conclusion:-

For Lower Siang region of Arunachal Himalaya, the attenuation characteristics of body waves ( $Q_\alpha$  and  $Q_\beta$ ) have been obtained using extended coda normalization method. The obtained values of  $Q_\alpha$  and  $Q_\beta$  have been found strongly frequency dependent. The frequency dependence relationships are  $(25\pm 3) f^{(1.24\pm 0.04)}$  and  $(62\pm 9) f^{(1.13\pm 0.04)}$  for P and S-wave respectively. The results obtained in the present study are comparable with the other seismically active regions of the world and India. The higher frequency dependence of attenuation describes the region highly seismically active. Also low value of  $Q_\alpha$  and  $Q_\beta$  in the Lower Siang region indicate the high tectonic activity. The  $Q_\alpha$  is higher than the  $Q_\beta$  for entire frequency range which indicate the crust of the Lower Siang region of Arunachal Himalaya is highly heterogeneous. The obtained attenuation relations in the present study will be useful for

simulation of strong ground motion and for estimation earthquake source parameters which have been further required for seismic hazard assessments in this region.

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