J. Ind. Geophys. Union (November 2018)
v.22, no.6, pp: 571-584

Seismic attenuation in Indian shield and Himalayan regions and its implications

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ABSTRACT

Seismic attenuation is a key parameter to elucidate the properties of the Earth's internal structure and is defined in terms of Quality factor Q, a dimensionless quantity which is the relative energy loss per oscillation cycle. Various studies have been carried out in the Indian shield and Himalayan regions to understand the risks and hazards due to the earthquake, using attenuation studies. Here, we provide a bird's eye view on the attenuation studies carried out using Qp, Qs and Qc, which are the attenuation values of P, S and coda wave respectively in the Indian shield and Himalayan regions by combining the available published works by various researchers. Based on the available data set, four broad classifications have been suggested i.e. shield and cratonic regions, rift zones, orogenic belts, and sedimentary basins. Further, an attempt has been made to correlate these values with the geological provinces. It is found that the attenuation value, which has a large variation, agree very well with the geology of the region. The entire Indian shield has in general Qs/Qp > 1, implying that the scattering is a predominant factor which causes the attenuation. Interestingly, in sedimentary basins and rifted regions of India, Q values have been found less, indicating more attenuation of seismic waves. Qs/Qp < 1, would also imply that the underlying rocks are partially fluid-saturated. In addition, we also found that the attenuation values have an anti-correlation with the surface heat flow values, suggesting that the attenuation of seismic waves in the Indian shield and Himalayan region, is not only controlled by the temperature, but also influenced by the other factors such as composition to a large extent.

Keywords: Seismic attenuation, P- wave, S- wave, Coda wave, Indian shield, Himalayan regions, Heat flow, Crustal composition.

INTRODUCTION

Seismic attenuation is attributed to the energy loss experienced by seismic waves as they propagate through a medium. The rate of loss is mostly controlled by the temperature, composition, melt and volatile contents of the rocks, through which the seismic waves travel. For these reasons, seismic attenuation has great potential to be a valuable parameter to understand the Earth's interior, complementing seismic velocity and allowing more definite conclusions to be drawn. Seismic attenuation of a region is also a key parameter to understand the earthquake hazard assessment and the source processes (Anderson et al., 1996; Abercrombie, 1997). It is a ubiquitous characteristics of the medium and can largely be associated with the geometrical spreading, absorption (intrinsic attenuation) due to the anelastic nature of the rock mass and scattering or elastic attenuation due to inhomogeneities of the medium (Aki and Chouet, 1975). Absorption occurs when an elastic wave travels through any medium, where its mechanical energy is progressively converted to heat through friction and viscosity. This conversion causes the amplitude to decrease and the pulse to broaden. In fact, the scattering is wavelength dependent and controlled by the ratio of the characteristic scale length of the heterogeneity of the medium to the wavelength.

The most common measure of seismic wave attenuation is the dimensionless quality factor Q and its inverse (dissipation factor) Q^{-1}. Thus Q measures relative energy loss per oscillation cycle (Knopoff, 1964), which can be given as

$$Q=2\eta\ (E/\delta E)$$

where, δE is the amount of energy dissipated per cycle of a harmonic excitation in a certain volume and E is the peak elastic energy in the system in the same volume.

It has been generally observed that the colder regions have lesser attenuation compared to the tectonically active region, where the heat flow is likely to be higher. Lay and Walace (1995), suggested that the Q correlates with the travel-time variations, i.e. fast travel-times are typically associated with high Q and vice-versa. All these properties made Q a suitable parameter for practical uses. The knowledge about the Q is also of fundamental interest in groundwater, engineering, environmental studies, and hydrocarbon exploration. As the propagation of seismic wave suffers the reduction in amplitude and this reduction is frequency dependent and can therefore characterize the lithology, physical state, saturation and rheology of the rock mass (Toksöz and Johnston, 1981). Since Q is a frequency dependent parameter, it obeys a power law relation (Mitchell, 1981) as,

$$Q=Q_o f^{\eta}$$

where, Q_o is the quality factor at frequency of 1Hz, η is a measure of the frequency dependence. Its values are generally close to 1, but varies depending upon the heterogeneity of the medium (Aki, 1981).

To decipher the attenuation parameters, the commonly used phases are P, S, coda-wave, Lg, surface waves etc (e.g. Yoshimoto et al., 1993; Kim et al., 2004; Mitchell, 1981; Savage, 1965; Baruah et al., 2016 etc). In recent past, globally, a number of studies have been conducted on attenuation by various researchers in diverse geological regimes. In Indian shield and Himalayan region also a number of works have been published, but they are mostly region specific (e.g. Mukhopadhyay and Sharma, 2010; Mukhopadhyay, S. et al., 2008; Padhy, 2009; Padhy and Subhadra, 2010 a, b; Padhy et al., 2011; Paul et al., 2003; Gupta et al., 2012; Gupta et al., 1998; Hazarika et al., 2013, Baruah et al., 2016; Sharma et al., 2007; Sharma et al., 2008, 2009; Singh et al., 2012a, b; Chopra et al., 2010; Mandal et al., 2001; Bora and Biswas, 2017; Vedanti et al., 2018 etc). There is no unified view exist on attenuation for the Indian shield and Himalayan region. Therefore, the objective of this work is to present a bird's eye view of the attenuation picture of the Indian shield and Himalayan region by compiling the large number of available information through various studies. The results are interpreted in term of the prevalent tectonics of the region and also the rheological state of the Indian lithosphere.

Tectonics of Indian shield and Himalayan region

The Precambrian Indian shield is a mosaic of number of cratons, which preserves the oldest geological history from Paleoarchaean to the present era. As the Indian shield has undergone various tectonic and geochemical changes, it has evolved as distinct terrain of complex geology and tectonic history. Grossly, the Indian shield is composed of five major cratons i.e. Bundelkhand Craton (BhC), Eastern Dharwar Craton (EDC), Western Dharwar Craton (WDC), Bastar Craton (BC) and Singhbhum Craton (SC), which are demarcated by mobile belts and rift zones (Figure 1).

The Bundelkhand craton, in Central Indian shield, is characterized by various Proterozoic extrusive and intrusive events. The isotopic data indicate that the three generations of gneisses are thought to have formed in this region at around 3.2-3.3 Ga, 2.7 Ga and 2.5 Ga (Sarkar et al., 1996, Mondal et al., 1998, 2002; Rao et al., 2005; Gopalan et al., 1990).

Similarly, the Archaean Dharwar craton, concocted of granite-gneiss-greenstone belts, has been divided into Western Dharwar Craton (WDC) and Eastern Dharwar Craton (EDC), separated by the Closepet Granite (Radhakrishna, 1956). Several diamond and non-diamond bearing kimberlites, and lamproites of Proterozoic age (~1.1 Ga) have been discovered in the EDC and around Cuddapah basin (CB) (Chalapathi Rao, 2008; Griffin et al., 2009). The WDC is an Archaean continental fragment with a continuously exposed crustal section from low-grade gneisses and greenstone basins in north, to granulites in the south. Southern part of the WDC consists of one of the oldest (3.36 Ga) crustal nuclei in form of the greenstone belt (Taylor et al., 1984; Peucat et al., 1995).

Similarly, the Bastar craton (BC), popularly known as the Bastar-Bhandara craton, lies to ENE of the Dharwar craton (DC), separated from the latter by the Godavari rift. The Bastar craton is essentially made up of orthogenesis with enclaves of amphibolites, vestiges of banded Tonalite-Trondhjemite-Granodiorite (TTG) gneisses (3.5–3.0 Ga), and low to high grade metasediments as supracrustals (Sarkar et al., 1993).

In comparison, Singhbhum Craton (SC) lying NE of Bastar craton (BC), basically an Archaean nucleii of triangular crustal block, has recorded an age span as old as 4.2 Ga to 0.9 Ga (Mondal et al., 2007; Mukhopadhyay, J. et al.,2008; Meert et al., 2010; Mazumder et al., 2012, Chaudhuri et al., 2018).

Further, the central and western parts of Indian shield are covered by the Deccan Volcanic Province with an area extending 50,0000 sq.km. It is considered one of the largest Igneous Province, where the eruption of basalts took place rapidly (< 1Ma) at around 65 Ma (Mezger and Cosca, 1999, Courtillot et al., 1988). The eruption occurred while India was situated in the Indian Ocean where Reunion hotspot is presently located (Mahoney 1988) and coincides with the Cretaceous–Tertiary boundary (e.g., Mahoney, 1988; Duncan and Pyle, 1988; Courtillot et al., 1988). Pb-Pb dating of the porphyritic granitic basement rocks concealed below Deccan basalt at Killari, yielded in an age of 2.57 Ga (Zachariah et al., 1995), which is similar to the ages found in the EDC.

The southernmost portion of the Indian shield is occupied by the Southern Granulite Terrain (SGT) which consists of high grade metamorphic rocks, sutured together by the shear zones. Zircon dating suggests it to be 3.46 Ma old in the Trivandrum block, the southernmost part of SGT that represent relics of the early continental crust formation (Zeger et al., 1996; Rao and Prasad, 2006).

The eastern margin of Indian coast is mostly controlled by the Eastern Ghat Mobile belt (EGMB) evolved during the Proterozoic times. The geochronological data suggest major charnockite formation event that occurred between 1.17 and 0.95 Ga (Paul and Sarkar., 1995).

Aravalli-fold belt, specifically Proterozoic Aravalli mountain belt, which is a prominent geotectonic feature of western India, is made up of the supracrustal rocks of the Aravalli Supergroup and Delhi Supergroup, both of which were laid upon the Archaean basement - the Banded Gneissic Complex (BGC), including the Berach granite.

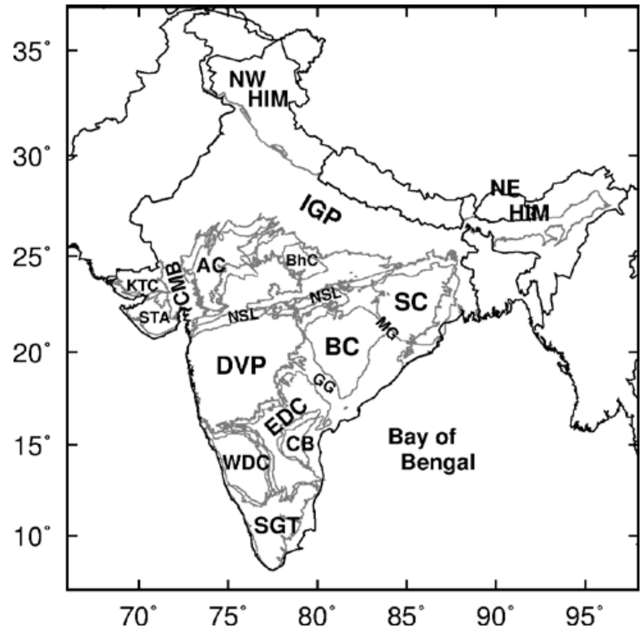

Figure 1. Geological map of India marked with different major tectonic provinces and study area. NW HIM: Northwest Himalaya, NE HIM: Northeast Himalaya, IGP: Indo-Gangetic Province, AC: Aravalli craton, CMB: Cambay basin, KTC: Kachchh, STA: Saurashtra, BhC: Bundelkhand craton, NSL: Narmada-Son lineament, DVP: Deccan volcanic province, BC: Bastar craton, SC: Singhbhum craton, GG: Godavari graben, MG: Mahanadi Graben, EDC: Eastern Dharwar craton, WDC: Western Dharwar craton, CB: Cuddapah basin and SGT: Southern Granulite terrain.

A mega lineament is known to extend from west to east in the central part of the Indian shield, popularly known as Narmada-Son Rift zone. It is a zone of weakness that separates the regions of Meso-Neoproterozoic deposits to the north from the Gondwana (Permo-Carboniferous-lower Cretaceous) deposits to the south.

The Paleoproterozoic Cuddapah basin is another important geotectonic entity of EDC, which is situated close to the eastern boundary. This basin contains thick sediments (up to ~6 km) with ages ranging between 1.33 and 0.79 Ga (Chaudhuri, 2003; Chandrakala et al., 2013). One hypothesis suggests that the basin was formed due to a mantle induced thermal trigger (Chatterjee and Bhattacharji, 2001), while, the other one suggests that the deep basin margin faults played a major role in controlling the evolution of the basin (Chaudhuri et al., 2002). Apart from the above, there are several deltaic sedimentary basins that were created due to drainage of the major rivers into the Bay of Bengal. The Gondwana rift basins in the central and eastern India (Godavari, Mahanadi and Damodar grabens) (Figure 1) were formed due to the break-up of the east Gondwanaland during the upper Carboniferous-lower Cretaceous period. Similarly, three peri-continental rift basins (Kutch, Cambay and Narmada) originated in the western part of India after break-up of the Gondwanaland. Northward movement of the Indian subcontinent, between the early Jurassic and Tertiary period, was possibly responsible for the origin of such rift basins (Biswas, 1987).

In comparison to the relatively stable Indian shield, Himalayas are formed by the closure of Tethys Sea, by the continent-continent collision of Indian and Eurasian plate. The collision process which started as early as in Early Eocene is still continuing. Two major thrusts, The Main Boundary thrust (MBT) and The Main Central thrust (MCT), separate three geologically distinct zones of Outer Himalaya, the Lesser Himalaya and the Higher Himalaya (Srivastava and Mitra, 1994). The Indo-Gangetic plain came into existence by the filling up of the sediments from the Himalaya and partly from the northern Peninsular India, in the foredeep basin in front of the rising Siwalik Ranges. Basin was transformed later into vast plains filled by the Quarternary Alluvium (Valdiya, 2016).

Attenuation parameters of various geological provinces

Himalayan region

Until recent past, the seismological studies along the Indian side of Himalaya are not much done, compared to the Tibetan side. Along the Himalayan arc, the attenuation studies are mostly conducted utilizing the data from small network of stations. The significant works on seismic attenuation in the area have been carried out by various researchers. Sharma et al (2009) using P and S-waves in Chamoli Region of northwestern Himalayan region obtained the frequency dependent quality factors as

$Qp=44f^{0.82}$ and $Qs=87f^{0.71}$. They further suggest that the Qs/Qp is greater than 1, interpreting the dominant role of scattering due to the presence of faults and fractures in the region. In the same region, Mandal et al., 2001 computed the attenuation using the coda pulse and established the relation as $Qc=30f^{1.21}$ for the epicentral region of the 1999 Chamoli earthquake and relatively low Qc at low frequencies which is attributed to the loss of energy due to the scattering by heterogeneity or the presence of faults and cracks in the region. High Qc at high frequencies is attributed to the propagation of back-scattered body waves through deeper parts of the lithosphere, where the amount of heterogeneity is less. However, Kumaun Himalayan region as a whole exhibits bit of lower coda wave attenuation with the frequency dependent relation as $Qc=92f^{1.07}$ (Paul et al., 2003). Another study in the same region for body waves reveal the relationships as $Qp=22f^{1.35}$ and $Qs=104f^{1.3}$ (Singh et al., 2012b). Also the ratio Qs/Qp is greater than 1 indicating the crust is heterogeneous and possibly due to the presence of partially saturated rocks.

The attenuation relation using the coda wave in Garhwal Himalaya is estimated to be $Qc=126f^{0.95}$ (Gupta et al., 1995). Whereas, the body waves and coda attenuation values by Banerjee and Kumar (2017) are found to be marginally different coda Q with $Qp=76f^{1.06}$, $Qs=155f^{0.92}$ and $Qc=101f^{1.05}$ respectively. Almost similar values have been reported by Tripathi et al., 2014 using body waves in Garhwal Himalayas, with $Qp=36f^{1.16}$ and $Qs= 124f^{0.93}$. The Garhwal region also exhibits Qs/Qp ratio greater than 1, possibly due to the highly heterogeneous rocks.

Similarly, Mukhopadhyay et al., 2010 brought out the relative contribution of intrinsic and scattering attenuation from the S-wave for Garhwal-Kumaun Himalaya. They found out contribution of scattering attenuation to total attenuation, is more around low frequency (1 Hz), and as frequency increases, the scattering part annihilates. Also, Qc is estimated to be $119f^{0.99}$ for the region. By comparing the values of Kumaun Himalaya and Garhwal Himalaya, we could observe the Qp and Qs values are less for the former compared to the Garhwal regions.

Parvez et al., 2012 also studied the attenuation in north-west Himalayan region and established the relations, $Qp=97f^{1.06}$ and $Qs=127f^{0.96}$, with $Qs/Qp > 1$. In this region, scattering attenuation contributes more to the total attenuation. The coda-attenuation comes from the study of Kumar et al., 2005 and they found it to be $Qc=158f^{1.05}$ for the same region. The Qc values is dependent on frequency and lapse time in the region, implying upper lithosphere is more heterogeneous and active, compared to the lower lithosphere. From these studies, it is observed that $Qc > Qs$, which is due to the enrichment of coda waves due to the prevalent heterogeneities. Also it indicates that the scattering attenuation has a great effect to the total attenuation. Another study by Mukhopadhyay et al., 2006 have estimated intrinsic and scattering attenuation using Qc and direct Qs in the northwestern Himalayas and established the relations as $Qc=113f^{1.01}$ and Qd (direct S-wave) $=69f^{1.18}$. The effect of intrinsic(Qi) and scattering(Qsc) which constitute the coda wave, is much larger than Qsc, and the values of Qi is close to Qc, which indicates intrinsic attenuation has more contribution to the Qc.

For the northeastern region, which is one of the most active zones in the world, Hazarika et al., (2009) have estimated an average $Qc=52f^{1.32}$. At lower frequencies such as 1 HZ, Qc for the region is much higher. In another study by Hazarika et al., (2013) in Sikkim Himalaya, the quality factors are found to be $Qp=96f^{0.94}$, $Qs=100f^{1.16}$ and $Qc=189f^{1.2}$ for body and coda waves respectively. Also they have separated individual effects of intrinsic and scattering attenuation as $Qi=160f^{1.5}$ and $Qsc=298f^{1.2}$, which indicates Qsc is more. But Qi value is closer to Qc, indicating intrinsic attenuation is dominating over scattering attenuation, further implying that the attenuation is mainly controlled by the composition. In this region the values of η is greater than 1 indicating the crust is highly heterogeneous in the region. Kumar et al., (2014) provided the quality factors of $Qp=25f^{1.24}$ and $Qs=62f^{1.13}$ for the lower Siang region of Sikkim Himalaya with Qs/Qp ratio is estimated to be greater than unity and high frequency dependence of Q values to frequency denotes that the region is seismically active.

For the Kopili region of northeast India, Bora and Biswas (2017) found out body wave attenuations as $Qp=42f^{1.2}$ and $Qs=98f^{1.3}$. Estimated values of Q show high frequency dependence indicating that it is also an active region. Padhy and Subhadra (2010a) have found out $Qs=96f^{1.03}$ and Qc at 1 Hz (Qo) as 213 to 278 and η as 0.89 to 0.79 for northeast India with the increase in lapse time from 40 to 60 s. In another study, Padhy and Subhadra (2010b) provided body wave values as $Qp=28f^{0.96}$ and $Qs=71f^{0.94}$.

All the attenuation parameters obtained from the studies are low values, agreeing the fact that the crust attenuates the seismic signals in the Himalayan region because of the highly heterogeneous structure due to the presence of subsurface faults. These higher attenuation values also indicate that the region is tectonically complex due to the Indian-Eurasian plate collision associated with high seismicity.

Cratonic regions

Cratons are usually considered cold and stable, therefore, it may have low attenuation or higher Q values than the other geological regimes. Kumar, C.H.P. et al., (2007) have brought out the differences in coda Q-attenuation characteristics for three distinctive features in the Indian Shield; Dharwar craton, Cuddapah basin and the Godavari graben, essentially utilizing single scattering method. The

Qc values estimated for the stations in the western Dharwar craton is $730.62f^{0.54}$ and for the station at Cuddapah basin is found to be $535.06f^{0.59}$ and suggested that these are basically associated with the crustal heterogeneities with varying degrees. The western Dharwar craton has highest Qo values, compared to the Cuddapah basin which lies within the Eastern Dharwar craton.

In the southern Indian shield which is mostly covered by cratonic part with exposed mid-lower crustal rocks exhibit the mean Q values lower compared to the other parts of the shield. Sivaram et al., 2017 estimated the mean Q values using body waves for the Southern Indian region, which comprises of EDC, WDC and SGT to be $Qp=95f^{1.32}$, $Qs=128f^{1.49}$. However, the individual estimates for EDC are $Qp=97f^{1.40}$, $Qs=116f^{1.48}$, for WDC as $Qp=130f^{1.20}$, $Qs=103f^{1.49}$ and for SGT as $Qp=68f^{1.4}$, $Qs = 152f^{1.48}$. For EDC and SGT, Qp is lesser than Qs, suggesting P-wave attenuation is more than S-wave attenuation. Low values of Qp may be attributed to the presence of numerous fractures or lineaments, which may contain fluid. Low Qs values may also attribute to the high upper lithospheric temperatures, as suggested by heat flow measurements (Ray et al., 2003). According to the laboratory studies, for dry rocks, the Qs/ Qp ratio is close to unity, for partially fluid-saturated rock it is greater than unity and for fluid saturated rock it is less than unity (Vassiliou et al., 1982). Hence the estimated values for $Qs/Qp >> 1$ may indicate that some of the regions in the southern region may be characterized by the presence of partially fluid-saturated rocks.

Studies in the southern Indian shield has reported attenuation of coda wave Q for various stations in Eastern Dharwar craton as $268f^{0.92}$ and $254f^{1.1}$ and in Western Dharwar craton as $342f^{0.76}$. For station in SGT, Qc value is calculated to be $290f^{0.81}$ and in DVP stations it is $316f^{0.86}$ and $594f^{0.53}$ (Singh et al., 2012a).

Koyna-Warna earthquake region which falls in the western part of Indian shield, show the attenuation values resembling to active region i.e. $Qc=169f^{0.77}$ (Mandal and Rastogi, 1998). They have further reported that the Qc has lower values for low frequency and higher for high frequency, implying that the shallow part of the crust is more heterogeneous and, as we go deeper the crust is becoming homogeneous. Sharma et al., (2007) have also reported similar but some-what lower values of Qc for Koyna region i.e. $117f^{0.97}$. The body waves quality factors have been estimated to be $Qp=59f^{1.04}$ and $Qs=71f^{1.32}$. It shows that the ratio of Qs/ Qp is greater than one, indicates scattering, is a predominant factor which brings about the attenuation of body waves in the region.

Sedimentary basin

A large part of the north Indian shield is covered by Tertiary, Mesozoic and Gondwana sediments like Cambay, Godavari, Mahanadi, Damodar valley grabens and Bengal basin. In some sedimentary basins, the thickness of sediment is upto 10 km. The attenuation parameters in these regions are significantly affected by such sedimentary layer thicknesses.

It has been found that the attenuation parameter Q increases with frequency in the northeastern part of Indo-Gangetic Plain (IGP) i.e. Delhi and surrounding regions (Sharma et al., 2015). The reported frequency dependent parameters are $Qp=52f^{1.03}$, $Qs=98f^{1.07}$ and $Qc=158f^{0.97}$. Qc, which depends on the effect of intrinsic and scattering attenuation, is found to be greater than Qs. Also while separating Qc values in terms of Qsc (scattering) and Qi (intrinsic values), the value lies in between the Qi and Qsc. In the frequency range of 1.5-9 Hz, intrinsic absorption is predominant over scattering attenuation. Here, Qs/Qp ratios are found to be greater than 1, which implies the presence of partially fluid-saturated rocks. Also, the Qc values are lesser than 200, suggesting that the region is seismically active.

In the eastern part of the IGP, which comprises parts of south Bihar, north Orissa, south-western part of West Bengal and Jharkhand, the Qc values for three coda windows 30, 40 and 50 s and average Qc to be $313.2f^{0.73}$ (Khan et al., 2016). They have also reported increasing values of Qo with increasing lapse time attributing to the depth dependency of attenuation due to the decrease in heterogeneity with depth. The η value suggests that the region is prone to moderate-higher level of tectonic activity. The eastern Indian shield region attenuates more, compared to the other shield regions, which is attributed to the deformation and faulting of the Gondwana graben.

Baruah et al., 2016 have found out Qp and Qs for various tectonic regions for the India. Their results for entire Indo-Gangetic basin suggest low Qp values (<350) and Qs values (< 150).

In comparison, the coda waves attenuation studies in the basins of the Southern Indian Shield, have resulted in observed coda Qo values at the stations in Cuddapah basin and Cambay basin to be $400f^{0.74}$ and $288f^{0.81}$ respectively (Singh et al., 2012a).

Region covering Rift valleys

Most of the attenuation studies are concentrated in the Kachchh region of Gujarat (Sharma et al., 2008, Chopra et al., 2010, Gupta et al., 2006). The attenuation study in Kachchh suggests $Qp=77f^{0.87}$, $Qs=100f^{0.86}$ and $Qc=148f^{1.01}$, using coda normalization method utilizing single backscattering model (Sharma et al., 2008). Combined effects of intrinsic and scattering attenuation, results in Qc more than Qs. Qc values are found to be in between Qi and Qsc, but closer to Qi at lower frequencies. Qi dominates over Qsc, which is due to the presence of faults and fractures.

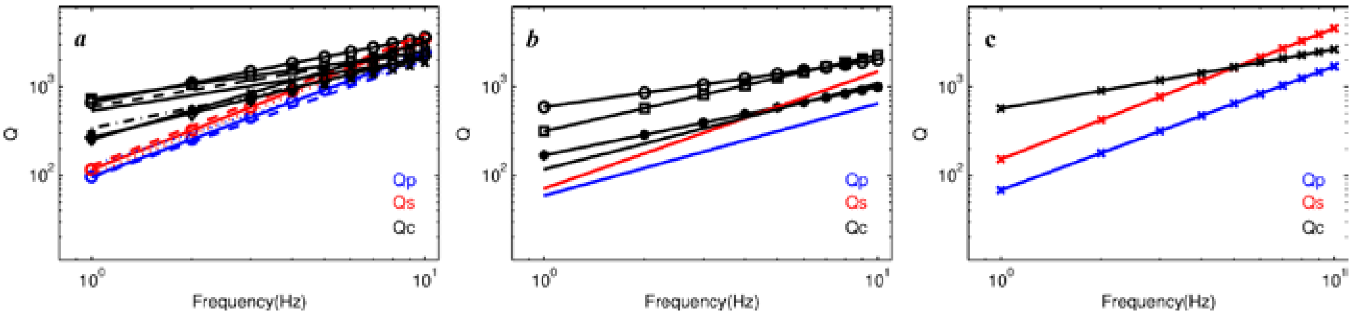

Figure 2. Plot depicting the relation between Q and frequency dependence η for the shield and cratonic regions. Figure 2a is for the regions EDC (Sivaram et al., 2017, Singh et al., 2012a), WDC (Sivaram et al., 2017, Kumar, C.H.P. et al., 2007, Singh et al., 2012a), Southern Indian Region (Sivaram et al., 2017), Cuddapah (Kumar, C.H.P. et al., 2007) and SGT (Singh et al., 2012a). Figure 2b is for the regions Koyna-Warna Region (Mandal and Rastogi., 1998, Sharma et al., 2007), DVP (Singh et al., 2012a) and Figure 2c for SGT (Sivaram et al., 2017). Qp, Qs and Qc values are shown by Blue, Red and Black lines, respectively.

The Qc values obtained in Kachchh is similar to the values obtained for other active regions around the world. Also Qs/Qp is greater than one, which means the crust is composed of partially fluid saturated rocks. The lower Q values and higher frequency dependent η values obtained in the largest intracontinental rift zone in India, is explained by the presence of thick layer of sediments, in which energy gets attenuated fast.

Chopra et al., 2010 in their study in the regions of Kachchh, Saurashtra and Mainland Gujarat, estimated $Qp=105f^{0.82}$, $Qs=74f^{1.06}$ for Kachchh region, $Qp=148f^{0.92}$, and $Qs=149f^{1.43}$ for Saurashtra, and $Qp=163f^{0.77}$, $Qs=118f^{0.65}$ for Mainland Gujarat. Kachchh region has the lowest Q value compared to the other two regions possibly due to high attenuative heterogeneous crust. Qs/Qp ratio obtained for Kachchh region is less than 1, which implies the presence of fluid saturated rock. But in contrary, Sharma et al (2008) have obtained ratio to be greater than unity, which might be due to the different dataset or because of the distance between stations. For mainland Gujarat, the ratio is less than one similar to Kachchh region and it is almost equal to unity for Saurashtra region.

The Qc values provided by Mandal et al (2004) is $102f^{0.98}$ for the epicentral region of the 2001 Bhuj earthquake. The results obtained agree with the fact that the region is active, and composed of heterogeneous crust. Similar study in the Kachchh basin using the aftershock data of Bhuj earthquake 2001 has been reported the frequency dependent attenuation to be $106f^{1.11}$ in the lapse time window of 30–60 sec (Gupta et al., 2006).

Another study that has been carried out by Sharma et al., (2012) in the areas of Jamnagar and Junagarh regions of Saurashtra, Gujarat. They have estimated values of Qc as $158\ f^{0.99}$ for lapse time 20s, $170f^{0.97}$ for 30s and $229f^{0.94}$ for 40 s for Junagarh and for Jamnagar area as $178f^{0.95}$ for 20s, $224f^{0.98}$ for 30 s and $282f^{0.91}$ for 40s. The numerical values suggest that the Junagarh area is more attenuative compared to Jamnagar. It is also observed that when lapse time is increased, Qc also increases due to the depth dependence of attenuation.

Similarly for Kothagudem region, which is surrounded by Godavari Graben, Kumar, C.H.P. et al., 2007 estimated the attenuation relation to be $150.56f^{0.91}$, which can be attributed to the ancient rifting and faulting of the Gondwana basin. Whereas, Singh et al., 2012a has reported coda Qo values for the Kothagudem region to be $249f^{0.89}$.

DISCUSSION

Attenuation characteristic of the Indian lithosphere

The attenuation data show wide variations for diverse geological provinces in the Indian shield and Himalayan region. In order to have a quantitative assessment for each geological province, here, we group the entire available attenuation values into four major divisions corresponding to craton, rift/active, orogenic and sedimentary provinces. The frequency dependent plots for each province has been re-plotted for entire frequency range. It has been clearly seen that the coda wave quality-factor obtained for the shield/cratonic regions (Figure 2a) is always higher than Qp and Qs, indicating that the cratonic crust is less attenuative for high to moderate frequency compared to the other regimes. In other words, cratonic parts can be characterized by low intrinsic attenuation region. The observation also reveals that the southern Indian shield has higher-P wave attenuation and frequency dependent exponent (η), possibly due to the presence of faults, fractures. In other words, the crust of the cratonic lithospheres are heterogeneous, might have been caused by the alteration in past. Such observation is also supported by the recent receiver function studies which support the thinner Indian plate vis-a-vis to other Gondwanaland (Kumar, P. et al., 2007; 2013). Such degeneracy has resulted due to the passage of the Indian plate over four major hotspots. Thermal modeling based on the intersection of the mantle solidus with the peridotite

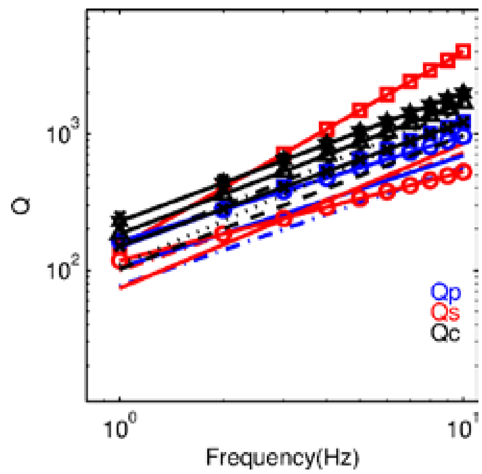

Figure 3. Plot depicting the relation between Q and frequency dependence η for the rift/active regions of Kachchh (Sharma et al., 2008, Chopra et al., 2010, Gupta et al., 2006), Saurashtra (Chopra et al., 2010, Sharma et al., 2012), Mainland Gujarat (Chopra et al., 2010), Bhuj (Mandal et al., 2004), Godavari Graben(Kumar, C.H.P. et al., 2007, Singh et al., 2012a). Qp, Qs and Qc values are shown by Blue, Red and Black lines, respectively.

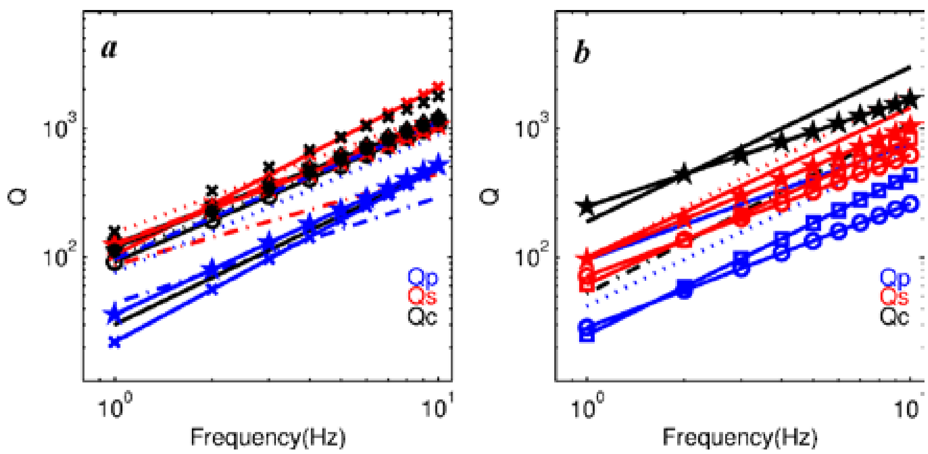

Figure 4. Plot depicting the relation between Q and frequency dependence η for the orogenic regions. Figure 4a is for the regions Chamoli (Sharma et al., 2009, Mandal et al., 2001), Garhwal Himalaya (Gupta et al., 1995, Banerjee and Kumar., 2017, Mukhopadhyay et al., 2010, Tripathi et al., 2014), Kumaun Himalaya (Paul et al., 2003, Singh et al., 2012b, Mukhopadhyay et al., 2010), NW Himalaya (Parvez et al., 2012, Kumar et al., 2005, Mukhopadhyay et al., 2006). Figure 4b is for Northeastern Himalaya (Hazarika et al., 2009, Padhy and Subhadra, 2010a,b), Sikkim Himalaya (Hazarika et al., 2013), Arunachal Himalaya (Kumar et al., 2014), Kopili Region (Bora and Biswas., 2017). Qp, Qs and Qc values are shown by Blue, Red and Black lines, respectively.

incipient melting curve reveals similar values of thermal lithospheric thickness (Pandey and Agrawal, 1999). All these results suggest large scale alteration of the Indian plate in geological time. Further, the Qs/Qp ratio obtained is very much greater than unity for EDC and SGT signifying that the region is laterally heterogeneous.

Figure 2b, depicts the attenuation values for the Koyna-Warna region, which is a classic example for reservoir induced seismicity (Guha et al., 1970; Gupta et al., 1969). A number of studies have been conducted here and suggests that the region has low values of Q, similar to the other active regions. The region is mostly interpreted to be dominated by scattering attenuation. It has also been seen that with increase in frequency, the attenuation values are increasing, implying, that the homogeneity of the crust is increasing with depth. Qc values plotted in Figure 2b show large variation within the regions, that may be attributed to the varying heterogeneities in the upper part of the crust.

The attenuation-frequency relation for the rift region (e.g. Kachchh) is displayed in Figure 3, it shows that the Qp, Qs and Qc values are quite variable in the entire region. The region is covered by thick layer of Jurrasic, Tertiary and Quaternary sediments. The region is also controlled by active faults which might have caused the high Q and high frequency dependent η values. Several studies have suggested that the faults in this seismic active regions

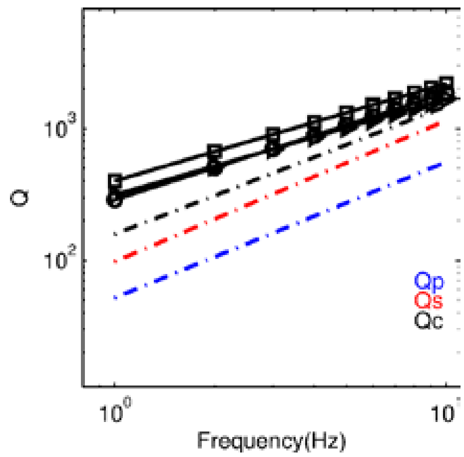

Figure 5. Plot depicting the relation between Q and frequency dependence η for the sedimentary basins of Delhi (Sharma et al., 2015), Eastern Indian Shield (Khan et al., 2016), Cuddapah basin (Singh et al., 2012a) and Cambay basin (Singh et al., 2012a). Qp, Qs and Qc values are shown by Blue, Red and Black lines, respectively.

are acting as conduit for fluids (e.g. Pavan Kumar et al., 2017) which may facilitate the seismicity in intraplate and interplate settings. Godavari Graben also shows a strong frequency dependence of Qc (Kumar, C.H.P. et al., 2007), indicating the upper part of the crust is more attenuative and attributed to the ancient rifting and faulting occurred in the Gondwana basins.

The attenuation relations are summarized in Figure 4, which shows variation of Q with frequency dependent η for Himalayan region. Low Qc values are obtained for low frequencies, which is due to scattering because of heterogeneities and due to the presence of faults and cracks. At higher frequency, the increased Qc values are due to the back-scattered body wave through the deeper part of the lithosphere. The high Q in the Himalayan region could also be due to the presence of partially molten or aqueous fluid-rich layer in the mid-lower crust as revealed by various geophysical studies (Klemperer, 2006; Caldwell et al., 2009). Study from the Garhwal Himalayas, reported a contrasting low Lg Qo value 30-60 in High Himalayan segment and high values of 700 in the lower Himalayas. The low Qo values, have been attributed to the presence of a low viscosity channel and partial melt in the crust due to the Indo-Asian collision (Ashish et al., 2009). The frequency dependent parameter η is almost similar for all the studies in the region, which ranges from 0.7 to 1.3 for P, S and coda waves.

The comparison of values in the sedimentary basins of India (Figure 5), i.e. Indo- Gangetic Plain (IGP), parts of the eastern Indian Shield, Cambay and Cuddapah basins show that the frequency dependent Q has almost similar trend. It has been suggested that the intrinsic attenuation is predominant over Delhi region compared to its surroundings that may be attributed to the presence of submerged ridges by the thick sedimentary cover (Arora and Singh, 1992).

Comparison with the heat-flow measurements

It is widely accepted that the temperature has a significant role in estimated attenuation anomalies in regions. However, other possible causes of attenuation anomalies can include compositional variations, partial melts and/ or fluids. Numerous seismic and laboratory studies have addressed the question of the correlation between seismic elastic and anelastic properties, and temperatures. On the continents, studies of seismic shear wave attenuation revealed a qualitative correlation between regional attenuation anomalies in the crust and upper mantle and tectonic provinces (e.g. Nakanishi, 1978; Canas and Mitchell, 1978; Roult, 1982; Dziewonski and Steim, 1983; Chan and Der, 1988; Mitchell et al., 1997; Sarker and Abers, 1998; Selby and Woodhouse, 2002). Here, we compare geological province-wise to the available surface heat flow values to that of the attenuation values. Studies about the Surface heat flow in India has been done by different researchers (Roy and Rao, 2000; Ray et al., 2003; Roy et al., 2007, 2008; Podugu et al., 2017), however the coverage is still far from complete in all the geologic provinces.

The attenuation studies in the shield and craton region (Figure 1) which consists of EDC, WDC, Koyna, SGT, DVP and Southern Indian region as a whole, had obtained similar values of Qp and Qs from various studies as Qp in the range 59-130 with a frequency dependence of 1.04-1.4 and Qs 71-152 and η as 1.32-1.49 respectively. But the Qc values obtained have large variation for the region which is in the range of 117 for Koyna region and as high as 730 for Dharwar craton and values in between for other regions. The average value of ~90 for P-wave Quality factor, ~114 for S-wave and ~420 for Coda wave is obtained. According to the heat flow values, it has been seen that the Archaean Dharwar province has lower heat-flow values in western Dharwar craton (29-30 mWm^{-2}) compared

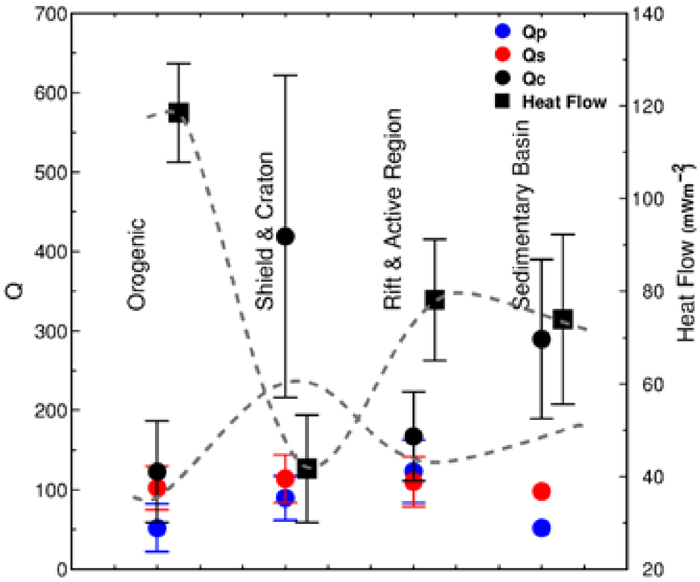

Figure 6. Comparison of Qp, Qs and Qc for the regions classified, i.e., Orogenic, Shield and craton, Rift and active region and Sedimentary basins, along with the heat flow values. Solid circles (blue=Qp, red=Qs and black=Qc) represent attenuation values and solid black square heat flow values with the error bar.

to the eastern Dharwar Craton (25-50 mWm-2) of ~36 mW m^{-2}. However, Singbhum and Bastar cratons have relatively higher values ranging from 59-63 mW m^{-2} and 51-63 mWm^{-2} respectively. Also the northern and southern block of Southern Granulitic terrain is characterized by different heat values of average 28-42 mW m^{-2} and 40-55 mW m^{-2} respectively (Ray et al., 2003; Roy et al., 2007). The recent studies by Podugu et al., 2017 suggest that the Bundelkhand craton, in north central India, has heat flow value of 32-41 mW m^{-2}, which is slightly lower compared to the values reported from Dharwar craton. Therefore, the average heat flow values in cratons are somewhat normal to lower range corresponding with the higher quality factor values which in turn implies for lower attenuation (Figure 6).

For the rift and active regions (Figure 1), which covers various parts of Gujarat such as Kachchh, Saurashtra, Jamnagar, Junagarh, suggested average values for Qp, Qs and Qc are 123, 110 and 167 respectively (average Qp, Qs and Qc value ranges from 77-163 with η ranging between 0.77 and 0.92, Qs values as 74-149 and η as 0.65-1.43 and Qc 102-249 with η as 0.8-1.08). The most significant change in heat flow values occur in rifted regions. Roy and Rao (2000) observed higher heat flow values in the regions of rifted continental crusts such as mobile belts, having high strain rates and seismicity. In the relatively stable regions of continental crusts such as Bundelkhand and western Dharwar craton, characterized by low strain rate and low seismicity, are associated with lower heat flow values, whereas the rifted margin zones such as Kachchh, Godavari, Damodar-Mahanadi, Aravalli and Saurashtra-Narmada-Son lineaments, are characterized by higher heat flow from 50-140 mWm^{-2}. These regions might be associated with the intraplate deformation. Delhi fold belt (Aravalli region) also has similar range of heat flow from 56 to 96 mW m^{-2}. Figure 6 shows a very good correlation with the average heat flow values and average attenuation values for the different geological provinces of India. It clearly reveals that the high heat flow regions will be having more attenuative crust.

The orogenic regions in India, which are most active, have very low Q values (Figure 4), compared to other regions. This region which comprises of northwest (Figure 4a) (Kumaun, Garhwal) and northeast (Figure 4b) (Sikkim, Arunachal Himalaya etc), have a combined average of 51 for Qp, 102 for Qs and 123 for coda wave quality factor. In terms of heat flow, orogenic belts are usually associated with the higher heat flow values. However, till date no thermal studies have been undertaken in Indian side of Himalaya. If we take the heat flow values for Himalayan region similar to the other orogenic belts of world, then we could infer that higher heat flow values are correlated with the observed lower Q values with larger scatter. It should be emphasized that the attenuation in such neo-tectonic province is not only controlled by the subsurface temperature distribution, but other factors also such as presence of melt/fluid or composition, as suggested by the dispersion (Caldwell et al., 2009) and magnetotelluric (Gokarn et al., 2002; Harinarayana et al., 2004, 2005; Arora et al., 2007) studies.

The IGP which includes Delhi region which is categorized under sedimentary basins (Figure 5) have an average Qp value of 52, Qs as 98 and Qc 290. Although the average obtained here are from sparse studies. In sedimentary basin, an average heat flow of 75 mWm^{-2} is suggested. The Qp and Qs values are similar to the rift regions, but the Qc is high for sedimentary basins which is comprised of IGP compared with the rift region.

Further, we could observe an inverse relationship between the heat flow and the Q values, when the heat flow is less, Q value is high and vice versa (Figure 6). Qp values are lesser than Qs, for all the suggested divisions, with an exception of rift-active zone, where we observed a low Qs, suggesting higher S-wave attenuation than P-wave, which may be attributed to the presence of volatile liquids in the rift basins.

On the other hand, the Gondwana basins which are developed on the Precambrian crust are distinguished by an average higher heat flow values of 69-79 mWm^{-2} (Rao and Rao 1983). Deccan Volcanic Region, which spans a larger part of the Indian shield, is associated with similar heat flow values as Archaean Dharwar province, with an average of 35-50 mW m^{-2} (Roy and Rao, 2000). This region is underlain by the Archaean Dharwar crust. Such regions are also associated with the lower Q values compared with the cratons (Figure 6).

CONCLUSIONS

A comprehensive study on the attenuation character using P, S and coda waves combining various studies has been provided to get a bird's eye view of crustal structure and its relationship with tectonic and heat flow studies in the Indian shield and Himalayan region. The average values suggest that average Qp and Qs are ~90 and ~114 for the shield and cratonic regions, which are tectonically lesser active, where the heat flow is also lesser than 40 mW m^{-2}, whereas the Qc values are very high with an average of ~420. Rift and active region are recorded with high heat flow values of average of 80 mWm^{-2}, and the attenuation values Qp as 123, Qs as 110 and Qc as 167. It is clearly understood that high heat flow regions will be having more attenuative crust. In Himalayan region, there is no heat flow data available, however comparing with other regions like Tibet where we have obtained heat flow values of 91 and 146 mW m^{-2} which was measured at two different points (Francheteau et al., 1984) is taken to be the representative for entire Himalayan orogenic belt. It is clearly seen that it correlates more or less well with the obtained less average attenuation values of 51 for Qp, 102 for Qs and 123 for coda wave. Apart from the temperature, other factors such as presence of melt/fluid and the ongoing orogenic activity may reinforce the obtained attenuation values. Similarly, in sedimentary basins, an average heat flow of 75 mWm^{-2} is obtained whereas estimated attenuation values are 52 for Qp, 98 for Qs and 290 for Qc. The Qp and Qs values are similar to the rift regions, but the Qc is high for sedimentary basins which is comprised of IGP compared with the rift region.

The anti-correlation exists between the heat flow and the Q values, however with a larger scatter i.e. low correlation coefficient implying that the attenuation scenario in Indian shield and Himalayan region is not only controlled by temperature alone but also the presence of volatile liquids, melts, etc which may have a greater role.

ACKNOWLEDGEMENTS

We thank Dr. O.P. Pandey, chief editor for his invitation to contribute this research article. The Director, CSIR-NGRI, kindly permitted to publish this article. KSR is an Inspire Fellow supported by Department of Science and Technology, Govt. of India. Plots are generated using Generic Mapping Tool (Wessel and Smith, 1995). The article has Ref. No. NGRI/Lib/2018/Pub-82.

Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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Received on: 14.8.18; Revised on: 25.9.18; Accepted on: 28.9.18