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Spatial variation of coda wave attenuation in the Southern Indian Shield and its implications

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┤ A B S T R A C T ├

During the recent past the Indian peninsular shield has experienced six damaging earthquakes of M 5.4-7.7 and compelled to readdress our understanding of the seismic attenuation characteristics for better evaluation of the seismic hazards in the so-called stable shield. We have performed the seismic attenuation study using coda waves of the broadband network from 1995 to 2009 for the shield region. About 400 local earthquakes M 2.5-4.0 within an epicentral distance of 250km are used in this study. The broadband seismic stations established are in different geological provinces, such as the Archaean Dharwar craton, the southern granulite terrain, the Proterozoic Cuddapah basin, the Godavari graben, the Cretaceous-Eocene Deccan volcanic province and in the Cambay basin. This allows us to understand the fluctuation of Q_0 in terms of spatial variations in the geologic and tectonic provinces. The results reflect a ubiquitous observation of frequency dependence of Q_c in the different geologic provinces. The rift basins exhibit lower Q_0, which suggests higher attenuation due to a more heterogeneous structure. Higher Q_0 in the western Dharwar craton infers lower attenuation. Similarly the Deccan volcanic province is characterized by significantly higher Q_0. The results show a good correlation with the observed heat flow. The study fills an important gap in knowledge about the Q factor as well as of crustal attenuation conditions in the whole southern peninsular shield of India.

KEYWORDS | Coda Q. Attenuation characteristics. Indian peninsular shield. Heat flow.

INTRODUCTION

The occurrences of several damaging earthquakes in the past few decades (1967 Koyna, M_b 6.3; 1969 Bhadrachalam, M_b 5.7; 1970 Broach M_b 5.4; 1993 Latur, M_b 6.1; 1997 Jabalpur, M_w 5.8 and 2001 Bhuj, M_w 7.7) have compelled to modify the seismic zoning map of India. Spatial distribution of these strong earthquakes indicates variations in the deformation pattern of the different crustal blocks of the shield area (Rao, 2000). This intraplate deformation plays a vital role in influencing the maximum compressive stress directions within the southern part of the peninsular shield (Agrawal and Pandey, 1999). The earthquakes of peninsular India are primarily of intraplate activities caused by crustal faults and epirogenic vertical movement of the crustal blocks. Major faults are shown in the Tectonic map of India by several authors (Naqvi *et al.*, 1974; Radhakrishna and Naqvi, 1986; Valdiya, 1993 and Ravi Shanker, 1995). Most of these faults were formed during the Precambrian.

The knowledge of regional values of the attenuation factor coda Q_c and its spatial variation attracts considerable interest in relation to tectonics and seismicity, being an important subject in seismic risk analysis and engineering seismology (Singh and Herrmann, 1983; Jin and Aki, 1988). The coda Q_c method is based on the following: 1) the coda wave is not affected by the source radiation pattern along the source-receiver direction, 2) path corrections are not necessary with the coda method since coda waves are scattered in the crustal volume, and 3) it can be applied successfully for single-station data (Aki, 1969, 1980; Aki and Chouet, 1975). It can be estimated using methods based on the single scattering model for coda wave generation (Aki and Chouet, 1975; Sato, 1977) which are based on the fit of the seismogram envelope, obtained at different frequency bands, to single-scattering theoretical models. Although single scattering is no longer taken to be a valid assumption (Gao *et al.*, 1983; Frankel and Wennerberg, 1987), it is still used as it is found that estimated Q_c are similar to the direct S-wave quality factor, and represent the attenuation characteristics of a given region. Aki (1985) observed agreement between Q_c and S-wave Q and concluded that the S coda is formed by single S-to-S backscattered waves in the 1–25Hz range. Sarker and Abers (1998) compared the coda Q with S-wave Q measured using seismograms recorded at two seismic arrays in the Caucasus and Kopet Dagh (Turkmenistan). Their results demonstrated that coda Q agrees with S-wave Q in both areas. Several studies have been carried out in varied geological terrains worldwide to investigate the seismic wave attenuation property of the medium, characterize the seismic activity and discriminate seismically active regions from stable ones (Aki and Chouet, 1975; Sato, 1977; Roecker *et al.*, 1982; Pulli, 1984; Wu, 1985; Jin and Aki, 1988, 1989; Havskov *et al.*, 1989; Ibanez *et al.*, 1990; Pujades *et al.*, 1991; Canas *et al.*, 1991; Akinci *et al.*, 1994; Zelt *et al.*, 1999; Biescas *et al.*, 2007). Phillips *et al.* (1988) found significant differences in Q_c related to variations in regional geology rather than variations in velocity between the two sides of the San Andreas fault in California. Seismic waves attenuate in amplitude *(A)* with both increasing travel time (*t*) and frequency (*f*), so that at a given *t* amplitudes decay with frequency A (f) $\sim\exp(-\pi ft/Q)$, where $1/Q$ describes the rate of attenuation in a given medium (Aki and Richards, 1980). Coda envelope shows a stable and similar time decay parameter for data from the same seismogenic area so the attenuation parameter $(1/Q_c)$ is often used to parametrize the tectonic characteristics. The heterogeneities responsible for the development of Q_c can be caused by velocity and/or density perturbations, and the presence of cracks and faults. Aki (1980) and Pulli (1984) have determined a correlation between the dependence of Q_c on frequency and the tectonic complexity of a region. Areas of strong tectonic heterogeneity show a strong frequency dependence of Q_c. Among many other physical phenomena that affect $1/Q$, temperature also probably plays a dominant role below the upper crust (Sarker and Abers, 1999). It is widely accepted that the Q_c value in high temperature or magma intrusion area is usually low. Sarker and Abers (1999) have shown that the $1/Q$ variations are a reasonable proxy for temperature variations. Gao (1992) suggested that, if coda mainly reflects the intrinsic Q, it should be very sensitive to temperature and the content of liquid within the detected body. However, if the activities are caused by small stress variations, consideration of coda Q may be less sensitive to the change in stress in comparison to temperature; it may thus be less sensitive to the stress-related precursors.

In this context, it is interesting to investigate whether the distinct geologic provinces of the Southern shield with differential heat variation show disparate attenuation characteristics. The attenuation of coda waves will be measured here as a function of frequency using about 400 local earthquakes during 1995-2009 (Fig. 1). Our investigation sites include three from the Archaean Dharwar craton, one from the southern granulite terrain, one from the Proterozoic Cuddapah basin of southern India, one from Godavari Graben, two from the southern part of the Cretaceous-Eocene Deccan volcanic province of central India and one site from the recent Cenozoic era (Fig. 2). This makes it interesting to study the influence of the geological structure on coda waves.
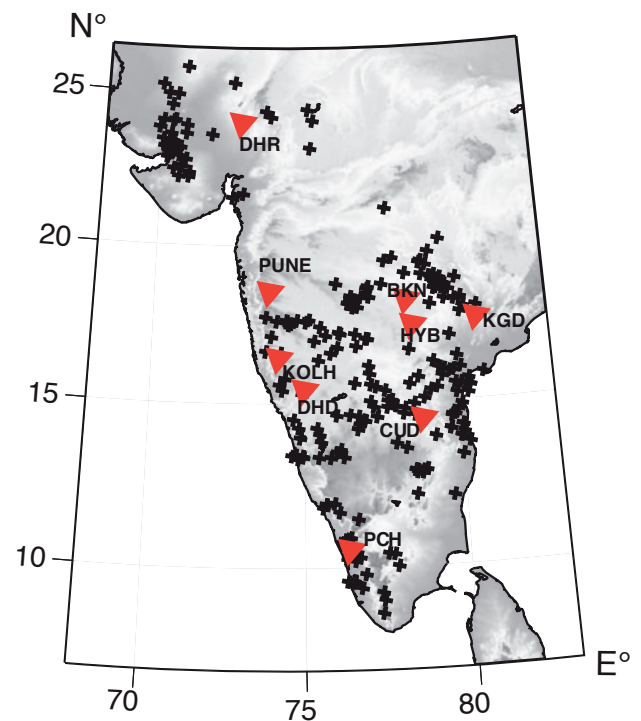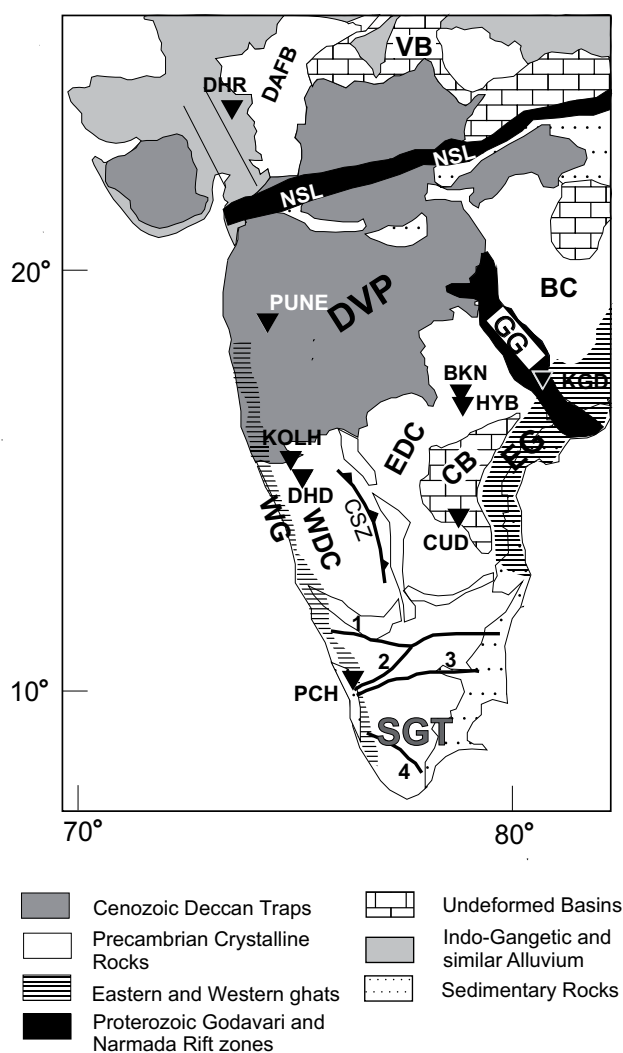

FIGURE 1 | Epicenter map of the events used for the analysis of Coda Q attenuation. Inverted triangles represent broadband seismic station locations.

GEOLOGICAL SETTING

India has a diverse geology. Almost the entire peninsular shield has been associated with continuous uplifting and destructive erosion since the early Tertiary until the present (Radhakrishna, 1993). The Indian craton was once part of the supercontinent of Pangaea. At that time, it was attached to Madagascar and southern Africa on the southwest coast, and Australia along the east coast. In the Jurassic, about 160Ma ago, rifting caused Pangaea to break apart into two supercontinents namely, Gondwana (to the south) and Laurasia (to the north). The

FIGURE 2 | Different geological provinces of peninsular India; WDC: Western Dharwar Craton; EDC: Eastern Dharwar Craton; GG: Godavari Graben; BC: Bhandara Craton; VB: Vindhyan Basin; DVP: Deccan Volcanic Province; SGT: Southern Granulite Terrain (Station PCH); CSZ: Chitradurga Shear Zone; EG: Eastern Ghats; WG: Western Ghats; CB: Cuddapah Basin; NSL: Narmada Son Lineament; FD: Foredeep; DAFB: Delhi-Aravalli Fold Belt; 1) Moyar; 2) Bhavani; 3) Palghat-Cavery and 4) Achan-Kovil Shear zones. The nine stations are located at different geological sites shown by inverted triangles.

Indian craton remained attached to Gondwana, until the supercontinent began to rift apart in the early Cretaceous, at about 125Ma.

The earliest phase of tectonic evolution was marked by the cooling and solidification of the upper crust of the Earth surface in the Archaean era (prior to 2.5 billion years) which is represented by the exposure of gneisses and granites especially on the Peninsula. It includes the oldest rocks of the Earth's crust that exhibit very complex structural deformations and petrological differentiation. These form the core of the Indian craton. The southernmost portion of the shield is constituted by the southern granulite terrain, which contains high-grade metamorphic rocks. The southern granulite terrain is a typical example of remobilization of one of the oldest crusts in the world (Bhaskar Rao et al., 2003). The Dharwar craton of southern India is a relatively typical Archaean "basement" assemblage of linear "schist belts" within widespread gneissic rocks, intruded by younger granites (e.g., Swami Nath and Ramakrishnan, 1981; Halls et al., 2007). Metamorphic grades increase from north (greenschist) to south (granulite) (Halls et al., 2007) and the northern block is again subdivided into the eastern and western Dharwar craton based on high temperature and low temperature metamorphic mineral assemblages respectively (Sarangi et al., 2007). The western Dharwar craton (age 3.5-3.0Ga) is made of old gneisses and green stones with few granites whereas the eastern Dharwar craton (age 3.0-2.6Ga) consists of younger rocks with widespread N-S elongate plutons of late Archaean granites. Early to Late Proterozoic calcareous and arenaceous deposits, which correspond to humid and semi-arid climatic regimes, were sedimented in the Cuddapah and Vindhyan basins. The Cuddapah basin rocks occupy an area of about 35000 square kilometers. The shape of the basin is crescentic, the concave side of which is oriented towards the east. These basins which border or lie within the existing crystalline basement were uplifted during the Cambrian (500Ma). The sediments are generally undeformed and have in many places preserved their original horizontal stratification. The Godavari valley basin is a NNW-SSE trending graben preserving the Gondwana sedimentary rocks. It is basically a younger rift zone, perhaps developed along a zone of weakness inherited from Archaean gneisses (Qureshy et al., 1968). This is a seismically active zone (Tandon and Srivastava, 1974). Towards the close of the Cretaceous, subsequent to the deposition of the Bagh and the Lameta beds, a large part of the Peninsula was affected by a stupendous outburst of volcanic energy, resulting in the eruption of a thick series of lava and associated pyroclastic materials. This great volcanic formation is known in Indian geology under the name of the Deccan Traps. The timing of these eruptions (65Ma) coincides with rifting of the Indian plate from the Seychelles. Because of the thick volcanic cover (maximum

thickness ~3000m), it is not easily possible to ascertain whether the basement rocks constitute those similar to the Dharwar craton. The origin of the Cambay rift basin, which is located in the northwest margin of the Indian platform, is connected with the northward movement of the Indian subcontinent after the break-up of Gondwanaland. This structure is occupied by a 3500m-thick pile of Tertiary and Quaternary sediments and bounded by north-northwest striking deep discontinuous normal faults.

DATA

In the aftermath of the many strong earthquakes in the southern peninsular shield region there has been an effort to monitor the seismic activity through the deployment of permanent broadband seismographs by various organizations like the Indian Meteorological Department, National Geophysical Research Institute, Center for Earth Science Studies, Indian Institute of Geomagnetism, Gujarat Engineering Research Institute, and Osmania University, supported by the Department of Science and Technology across the entire shield region. We have used nine stations from peninsular India like DHD, from the western Dharwar craton, which is situated in the core of the mid-Archaean craton; HYB and BKN are from the eastern Dharwar craton; PCH is from the southern granulite terrain; CUD is from the Proterozoic Cuddapah basin of southern India; KGD is from the Godavari graben; stations at KOLH and PUNE are on the Deccan volcanic province of central India and DHR is on the Cambay basin of the recent Cenozoic era (Fig. 2). All stations contain rocks of variable age, geological characters and different heat flow anomalies. These stations have been equipped with Broad-band three component seismographs. The HYB station is part of the GEOSCOPE global network with STS-1(360sec) and PUNE with STS-2(120sec). All the other stations are equipped with Guralp CMG-40T (30sec) and REFTEK-72A digitizers till the year 2006. From February 2007 onwards these stations are replaced with Nanometrics

Seismometer Trillium T240 (240sec) and Taurus digitizers. The details are given in Table 1. The locations of relatively higher magnitude earthquakes are taken from reporting agency Indian Meteorological Department, Maharashtra Engineering Research Institute, Nasik. Other very local earthquakes are located by using the single station method (Roberts *et al.*, 1989). The arrival times of P and S phases and back azimuth (from station to source) are used for the estimation of origin time and epicenter. The locations of the events are reported in Figure 1. Only waveforms with good signal-to-noise (S/N) ratio (≥ 2) are analyzed. Different stations have different sample/sec, from 100 to 20 sample/s. The stations (HYB, PUNE and DHR) with 20 samples/s records were used for the estimation of Q up to 5Hz. Data from other stations used up to 16Hz (Table 1). About 400 local earthquakes are used, the epicentral distances of which are within 250km and of M 2.5-4. (Fig. 1). These earthquakes were recorded with sufficient coda duration. The vertical component is chosen, the clipped or overlapped earthquakes are removed and finally correlation coefficients with greater than 0.50 are considered for the present analysis. Figure 3 shows a digital seismogram recorded at station KOLH whose data were used for this analysis and the box marks the position of coda window for start times 2ts.

METHODOLOGY

Aki and Chouet (1975) proposed a single backscattering model to explain the coda waves as a superposition of secondary waves from randomly distributed heterogeneities. Assuming that coda waves are composed of single backscattered waves, the coda amplitude can be approximately expressed by the following formula:

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

where $A(f, t)$ is the coda amplitude for a central frequency "f" over a narrow bandwidth signal at a lapse time "t" measured from the origin time of the seismic event and

Station (Place)	Agency	Sensor Type	Data used	No earth-quakes used	Frequency band used (Hz)	Geology
PCH (Peechi)	CESS	CMG-40T	12.2000 to 12.2007	51	1.5-16	South granulite terrain
DHD (Dharwar)	NGRI	CMG-40T (01-03-2007 onwards Trillium 240)	12.2001 to 08.2008	58	1.5-16	Western Dharwar craton
HYB (Hyderabad)	GEOSCOPE	STS-1	05.1995 to 01.2006	56	0.75-5	Eastern Dharwar craton
BKN (Bicknoor)	OU	CMG-40T (01-08-2007 onwards Trillium 240)	03.2000 to 01.2009	30	1.5-16	Eastern Dharwar craton
CUD (Cuddapah)	NGRI	CMG-40T (01-03-2007 onwards Trillium 240)	03.2000 to 07.2009	52	1.5-16	Cuddapah basin
KGD (Kothagudem)	NGRI	CMG-40T (18-02-2007 onwards Trillium 240)	12.2000 to 08.2009	45	1.5-16	Godavari graben
KOLH (Kolhapur)	IIG	Trillium 240	04.2008 to 07.2009	39	1.5-16	Deccan Volcanic province
PUNE (Pune)	IMD	STS-2	08.2005 to 10.2008	20	0.75-5	Deccan Volcanic province
DHR (Dharoi)	GEERI	CMG-40T	01.2000 to 10.2005	46	0.75-5	Western Cambay basin
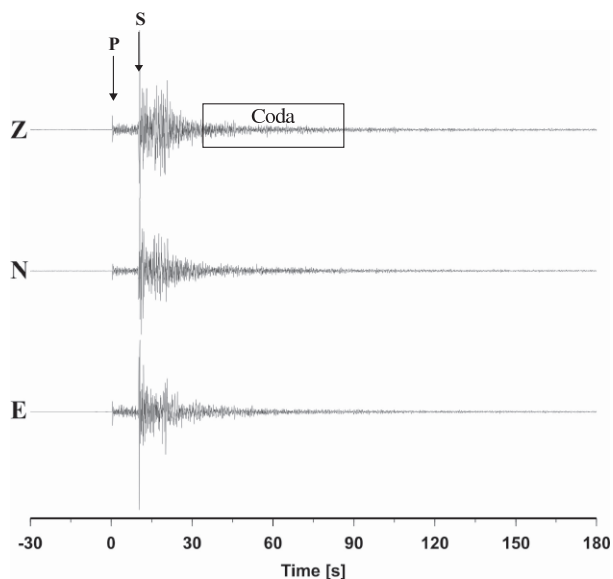
FIGURE 3 | An example of seismogram recorded at one of our stations (KOLH). P- and S-arrival times are shown with vertical arrows and coda window of 70s for $t_{start}=2t_s$ is shown with a box.

$C(f)$ is the coda source factor. This is used for the estimation of quality factor Q_c of coda waves representing the average attenuation properties of the medium for a given region. This is the most frequently used model and often chosen because it facilitates the comparison with other studies made elsewhere. Rautian and Khalturin (1978), however, found that equation (1) is valid only for the lapse time, t, greater than about two times the S-wave travel time, t_s. Assuming the source factor, $C(f)$, to be independent of time and radiation pattern and the geometrical spreading parameter (a) equals to 1 for body waves, the above equation can be rewritten as

$$\ln A(f,\, t)^* \, t = c - bt \qquad (2)$$

Where $b = \pi f t / Q_c$ and $c = \ln C(f)$. Equation (2) represents the equation of a straight line, slope of which $b = \pi f t / Q_c$ provides the Q_c, for the central frequency f. Sato (1977)

introduced the source receiver offset in a single scattering model so that the coda analysis begins after the arrival of the shear wave. The Q_c-values were calculated using the SEISAN software package (Havskov and Ottemoller, 2003). The time envelope for the coda decay observation is taken at twice the time of S-wave ($2t_s$) from the origin time of the event with fixed lapse time window length 70s. The coda of all the filtered seismograms from time t onwards are smoothed by using a root mean square (rms) technique which calculates the rms values of coda amplitude of the filtered seismograms with a sliding window of 5s length along the coda in steps of 2.5s and evaluates the value at each step in the same frequency band. Figure 4 shows the smoothed coda amplitude for the coda part of the filtered seismograms recorded at PUNE. The Q_c is calculated at different frequency bands from the slope of the least-square fit straight line of the plot between $\ln[A(f,\, t)t\,]$ and lapse time (t). Table 2 shows central frequency and bandwidth used for the estimation of Q_C. The calculated Q_c-values at given central frequencies were accepted only when correlation coefficients (C) for the best-fit line for the coda decay slope with respect to lapse time were greater than 0.5 and the signal-to-noise ratio (S/N) was greater than 2 for a given data set. In Figure 5(A, B), Q_c-values versus frequencies are plotted for the stations having 20 samples and 100 samples respectively. The power law in the form $Q_c = Q_0 f^n$ is fitted for the Q_C of each station, where Q_0 is the Q_C-value at 1Hz and n is the frequency relation parameter.

RESULTS AND DISCUSSION

Variation of Q_C with frequency

The location of the earthquakes and recording stations covers different types of geologic provinces. Estimates of coda Q_c for different frequencies are shown in Figure 5A, B. We have observed that in all cases Q_c increases with increasing frequency. This seems to be a general
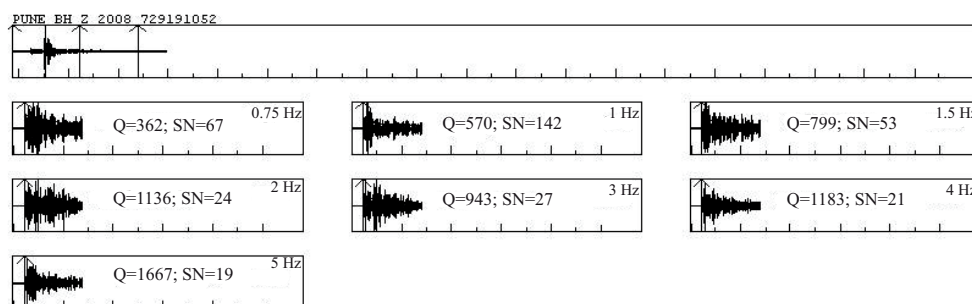
FIGURE 4 | The top panel of the figure shows the vertical component seismogram from station PUNE. The first arrow on the left side of the top panel shows origin time and the other two arrows indicate the coda duration. The lower panels in each set of figures show filtered coda windows for 7 central frequencies at $t_{start}=2t_s$. The number on the right-hand side within each panel represents central frequency in Hz. Tick marks on the x axes for all panels are at an interval of 30s. The y axis represents amplitude. In the lower nine panels amplitude scales are amplified with respect to that in the top panel to show the coda part more clearly. Abbreviations: Q–Q_c, SN – signal to noise ratio.

**TABLE 2** | Different central frequency components of band pass filter with low and high cutoff frequencies

High cutoff (Hz)	Central frequency (Hz)	Low cutoff (Hz)
1.05	0.75	0.45
1.5	1	0.5
2	1.5	1
2.66	2	1.34
4	3	2
5.34	4	2.66
6.5	5	3.5
8	6	4
10.66	8	5.34
16	12	8
21.34	16	10.66

feature of frequency dependence of Q_c (Aki, 1980). It depends on both degree of heterogeneity of a medium and level of tectonic activity in an area (Aki, 1980; Pulli and Aki, 1981; Roecker *et al.*, 1982). Aki (1980) postulated from these observations that scattering of seismic waves mainly controls the frequency dependence of Q_c. The low Q_c values (high attenuation) for lower frequencies may indicate a high degree of heterogeneity and the decrease in rock strength in the crust whereas the high Q_c values (low attenuation) at higher frequencies may be related to relatively more homogeneous deeper crustal layers. In the present study DHR and KGD show relatively low Q_c for the lower frequency band (Fig. 5A, B) indicating existence of heterogeneities due to significant influence of underplating and compressional tectonism at Cambay basin (Reddy *et al.*, 1999) and presence of a conjugate set of faults transverse to the Godavari Graben respectively. The high values at lower frequency ranges for CUD and KOLH indicate the crusts below both the stations are homogeneous. For frequencies above 8Hz the coda Q distribution is nearly uniform (Fig. 5B), indicating that the uniform distributions of smaller scale scatter over the study region (Jin and Aki, 2005).

Variations of Q_0 and frequency parameter *n* at different geologic regime

The Q_c frequency relation is given by $Q_c=Q_0f^n$ where Q_0 is Q_c at 1 Hz and *n* is the frequency relation parameter. At fixed lapse time, window length 70s the estimations of coda Q_0 and *n* are made for the comparison (Table 3). We have classified the obtained Q_0 values into four groups like $Q_0<250$, *i.e.* less values; $Q_0\geq250\leq300$, *i.e.* moderate; $Q_0\geq300\leq350$, *i.e.* high and $Q_0>350$, *i.e.* significantly high values. All values of Q_0 at different regimes indicate the area is moderately stable. The obtained Q_0 values of some parts of peninsular India are in close agreement with the values found by Ramakrishna *et al.* (1997) for the south Indian shield. Singh *et al.* (2004) have estimated a relation $Q(f)=800f^{0.42}$ for the Indian shield region. However, it gives a higher value of Q than estimated in the present study.

The higher estimate of Q value can be attributed to the fact that Lg coda wave averages over a broad region and they used the data at larger distances (240–2,400km), while the present study contains the data of smaller distances (≤250km). In the present analysis significantly higher values are found at station KOLH and those at CUD indicate low attenuation in the crust. Station CUD lies at the western part of the Cuddapah basin which has been relatively unaffected by tectonic activity as inferred by the near-horizontal bedding of the sedimentary rocks (Saha, 2002) and resulted as high Q_0 value. Within the Deccan volcanic province, PUNE exhibits quite a high value but a significantly high Q_0 value of KOLH indicates the south of the Deccan volcanic province is more stable than other parts of the Deccan volcanic province. In the western part of the Deccan volcanic province, the seismically very active Koyna region shows a lower value of Q_0 (Gupta and Kumar, 2002; Mandal and Rastogi, 1998). Thus, within the Deccan volcanic province there are abrupt variations of attenuation characteristics. The Deccan volcanic province is affected by the Reunion mantle plume activity and the associated Deccan volcanism which has a profound influence on the structure that varies spatially. The variations in Q_0 value for the western Dharwar craton (station DHD) and eastern Dharwar craton (stations BKN and HYB) are observed. The western Dharwar craton is made of older rocks and shows higher Q_0 values whereas the eastern Dharwar craton consists of younger rocks and exhibit lower values. It may be due to several reasons. The western Dharwar craton had evolved by the end of the Archaean and was largely stable thereafter. Moving from west to east in the Dharwar craton there is a variation in gravity field, heat flow and seismic images which suggest the existence of the different tectonic boundaries interfacing the domain of the western Dharwar craton and the eastern Dharwar craton (Harinarayana, 2007). According to Krishna and Ramesh (2000), there exists a scattering zone at upper crustal depths below the Gauribidanur seismic array in the eastern Dharwar craton. Tripathi (2001) reported the
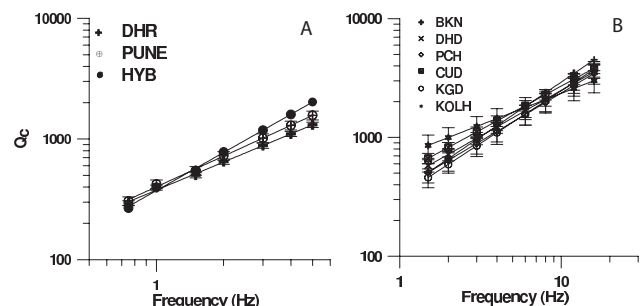
FIGURE 5 | Variation of average calculated Q_c value for different frequencies at 70s lapse-time windows starting at $2t_s$ in a log-log scale A) for stations having 20sample/s and B) stations having 100 sample/s. The bars represent standard deviation.

TABLE 3 | The observed Q_0 and n values with standard deviations at different stations

Stations	Coda Q_0-value	n value
BKN	268±55	0.92±0.09
HYB	254±21	1.1±0.09
DHD	342±41	0.76±0.05
PCH	290±54	0.81±0.08
CUD	400±40	0.74±0.04
DHR	288±20	0.81±0.05
PUNE	316±25	0.86±0.03
KGD	249±46	0.89±0.09
KOLH	594±125	0.53±0.09

presence of high heterogeneities beneath the Gauribidanur seismic array located at the western flank of the eastern Dharwar craton on the basis of differential attenuation at the array. Mohan and Rai (1992) suggested the presence of heterogeneities in the major geological contact between the eastern and western Dharwar cratons; this is prominent in the deeper crust and in the upper mantle. The station at the southern granulite terrain shows a moderate value of Q_0. The low value of Q_0 at the KGD suggests that the crustal part of the Godavari graben is heterogeneous. The Godavari graben represents a seismically active zone (Tandon and Srivastava, 1974), and in the northern side the faults associated with the Godavari graben show movement during the Holocene. The long and narrow Godavari rift oriented NW–SE, which forms the contact between the two major cratons, namely, Dharwar and Singhbhum cratons, is the source area that generated the April 13, 1969 earthquake (M 5.7) and its aftershock sequence (Gangrade and Arora, 2000). The Q_0 value at the DHR can be explained in terms of its underplating and compressional tectonism (Reddy et al., 1999).

A strong correlation between the degree of frequency dependence (n value) and the level of tectonic activity was observed by several authors in different parts of the world (e.g., Aki, 1980; Pulli and Aki, 1981; Roecker et al., 1982; Van-Eck, 1988; Akinci et al., 1994). They ascertained that the n value is higher for tectonically active regions compared to the tectonically stable regions. In the present study, "n" ranges from 0.5 to 1.1. The lowest value of "n" at KOLH suggests that the crust is more stable.

Q and Temperature

The ongoing intraplate deformation and the presence of large scale inhomogeneity within the Indian shield are well reflected in the geothermal heat distribution. Several studies on heat flow for southern peninsular India have been reported (Gupta et al., 1991; Agarwal and Pandey, 1999; Roy and Rao, 2000). Gao (1992) described that, if coda mainly reflects the intrinsic Q, it should be very sensitive to temperature and liquid content within the medium. Havskov et al. (1989) reported that coda Q at Mount St. Helens (volcanic region) is significantly lower than in the surrounding areas. The certain parts of peninsular India, Cambay basin and Godavari graben, which show higher heat flow, result in comparatively lower Q_0 than other parts of the stable shield. Measurements carried out in the Cambay basin indicate high heat flow values (75-93mW/m²) with an average value of 83mW/m² as compared to a normal heat flow value of approximately 46mW/m² for stable continental areas (Thiagarajan et al., 2001). This interpretation is corroborated by the moderate value of Q_0 at DHR. Heat flow is also found to be greater in the southern part of the Godavari graben where KGD is located (Roy and Rao, 2000). The Proterozoic Cuddapah basin, Dharwar craton and the Deccan volcanic province are characterized by low heat flow (Roy and Rao, 2000) that exhibit high Q_0 values. Rao (2000) has found a correlation between the seismically active zones and high heat flow areas in peninsular India. The coda Q_0 value obtained in the present study is comparable with the heat flow study in southern peninsular India.

Comparison of results with global observations

Some results of Q studies obtained worldwide in different geologic and tectonic provinces are shown in Table 4. In tectonically stable central United States, Singh and Herrmann (1983) found that the Q is nearly frequency independent while in our case it is strongly frequency dependent. Very stable areas such as mid-central North

TABLE 4 | A detailed comparison of coda-Q studies for different regions of the World

Places	Q_0	n	Sources
Active regions			
Aleutian	200	1.05	Scherbaum and Kisslinger (1985)
Washington State	63	0.97	Havskov et al. (1989)
South Spain	155	0.89	Ibanez et al. (1990)
West Anatolia, Turkey	183	0.76	Akinci et al. (1994)
Parkfield	79	0.74	Hellweg et al. (1995)
Koyna, India	169	0.77	Mandal and Rastogi (1998)
Bhuj, India	102	0.98	Mandal et al. (2004)
Stable regions			
Norway	120	1.09	Kavamme and Havskov (1989)
South Carolina	190	0.94	Rhea (1984)
South India	460	0.83	Ramakrishna Rao et al. (1997)
New England	460	0.40	Pulli (1984)
Eastern North America	680	0.36	Atkinson and Boore (1995)
North Iberia	600	0.45	Pujades et al. (1997)
B: From L_g spectral Amplitude method			
Active regions			
Western U.S.	150	0.4	Singh and Herrmann (1983)
NW U.S.	300	0.3	Singh and Herrmann (1983)
Stable regions			
Indian Shield	800	0.42	Singh et al. (2004)
NE U.S.	900	0.35	Singh and Herrmann (1983)
Central U.S.	1000	0.20	Singh and Herrmann (1983)
Canadian Shield	900	0.20	Hasegawa (1985)

America possess very high Q_0 values (*e.g.*>600), while tectonically active regions like western US and Japan have relatively low Q_0 values (*e.g.*<200). Intermediate Q_0 values in the range of 200–600 are associated with areas of moderate seismicity (Mak *et al.*, 2004). However, stable South Carolina and Norway have shown Q_0 values of 190 and 120, respectively, which are identical to those for active regions (Rhea, 1984; Kvamme and Havskov, 1989). Singh *et al.* (1999) have found that the Q value of the Indian shield is similar to that of the tectonically similar region of eastern North America. The Q_0 value in the present study is close to the values obtained by Ramakrishna Rao *et al.* (1997) for the south Indian peninsular shield. Although it is considerably lower than in other stable regions globally (Table 4), it is comparable to the intraplate regions with moderate seismicity, such as the rifted zone of the central Mississippi valley, which yielded a Q_0 of 210 (Dwyer *et al.*, 1984). Hence the Indian shield appears to be undergoing a large-scale rejuvenation and is more unstable than other shield areas worldwide. Rao (2000) has found the strain rate for the Indian shield as a whole is 6.01×10^{-10} per year, the second highest in SCR of the world, the highest being North America (6.80×10^{-10} per year) which also indicates that the Indian peninsular shield region is not very stable.

CONCLUSIONS

We calculated the coda Q_0 values for the entire south India peninsular shield based on the single-scattering theory. Our study area includes varied complex tectonic provinces that had undergone breakup and reassembly of the eastern Gondwana supercontinent. To improve the resolution of Q_0 for the entire southernmost part of India, we improved the resolution of Q_0 by subdividing the area based on the regional geology. A dataset of ~400 digital records from local earthquakes is analyzed. The estimated Q_c values show a systematic strong dependence on frequency range. The differences of Q_0 values are due to differences of the attenuative properties of the mediums. The long and continued geodynamic process of the entire peninsular shield has a considerable impact on the variation in Q_0 values. The relatively high value at the DHD infers low attenuation in the cratonic crust, which is expected since it has been stable for a longer time. The southern part of the Deccan volcanic province exhibits a significantly larger value of Q_0 that reflects the differential level of crustal heterogeneities within the province. The low value at the KGD of the Godavari graben could be a manifestation of the ancient rifting. A good correlation between coda Q_0 and heat flow across the entire peninsular shield is observed. The Q_0 values in the present study are much lower than in other stable regions globally.

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