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Attenuation of P and S waves in the Kachchh Region

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ABSTRACT
The quality factor Q has been estimated using spectral amplitudes of P and S waves from earthquakes recorded by the seismic network of Institute of Seismological Research (ISR) in Kachchh region. The earthquakes recorded at two stations – Lakadia (LAK) and Suvai (SUV) have been used. The spectral amplitude ratios have been calculated between 2 - 25 Hz and single station spectral ratio method has been applied for this purpose. The results show that the quality factors for both P and S waves (Q_p and Q_s) increase as a function of frequency according to law $Q = Q_0 f^n$. The frequency dependent relations estimated for the Q_p and Q_s at the two stations are : $Q_p = (111\pm1.5)f^{1\pm0.01}$, $Q_s = (107\pm4)f^{0.76\pm0.03}$ for Lakadia and $Q_p = (72\pm1.4)f^{1.22\pm0.01}$, $Q_s = (193\pm3)f^{0.86\pm0.01}$ for Suvai. The average frequency dependent relations for Q have been estimated as $Q_p = (89\pm1)f^{1.12\pm0.004}$ and $Q_s = (121\pm1)f^{0.92\pm0.004}$ in the region. The ratio Qs/Q_p is close to one at Lakadia and greater than one at Suvai. The reported coda-Q (Qc) for this region has been found to be more than that of average Qs value estimated here. This supports the Zeng's model of attenuation in the region. The results of this study have been found to be consistent with the findings of other studies in this region using different methods. The frequency dependent relations for Q estimated here have been compared with those of other parts of the world. These relations are useful for the estimation of source parameters of earthquakes and simulation of earthquake strong ground motions.

INTRODUCTION

The attenuation characteristics of seismic waves in a region is required to understand the source process, to simulate the earthquake ground motion and for the seismic hazard analysis. The amplitudes of seismic waves at various distances from an earthquake source are affected by the attenuation properties of the medium. The factors contributing to the overall attenuation include geometrical spreading, scattering due to in homogeneities and inelasticity. The geometrical spreading controls the amplitudes of seismic waves in the homogeneous and purely elastic earth. As the real earth is not perfectly elastic the net loss of energy during seismic wave propagation is symbolized by absorption. The absorption of seismic waves is partly controlled by intrinsic physical loss mechanisms such as internal friction and partly by in homogeneities along the travel path that can cause scattering. Due to the non-elastic nature of the medium, a part of the energy in the wave is dissipated instead of being transferred through the medium. This type of attenuation of seismic waves, known as intrinsic/inelastic attenuation or damping, is described by a parameter called quality factor, Q.

The quality factor, Q, which measures the deviation from perfect elasticity is defined as (Knopoff 1964):

$$2\pi/Q = -\Delta E/E$$

where ΔE is the energy lost in one cycle and E is the total energy available in a harmonic wave.

The objective of this study is to understand the attenuation of body waves in the Kachchh region of Gujarat by estimating the frequency dependent relationships of Q for P waves (Qp) and for S waves (Qs). The spectral ratio method has been used for this purpose. This method has been used frequently in seismological literature to separate the effects of attenuation and site response (e.g. Borcherdt 1970; Bakun & Bufe 1975; Frankel 1982; Ferrucci & Hirn 1985; Frankel & Wennerberg 1989). The results obtained in this study have been compared with those of obtained in other regions of the world.

METHOD

The spectral ratio method, also known as single station method, has been used in the present study. In this method, the observed amplitude at the frequency f, A(f), of body waves is given by (Tsujura, 1966):

$$A(f) \propto [A_0(f)R(f)\exp(-\pi f t/Q)]/r \quad (1)$$

Where $A_0(f)$ is the spectral amplitude at the source, R(f) is the response function of the site, t is travel time, Q is quality factor and r is source to receiver distance.

The ratio of the amplitudes at two different frequencies, f_1 and f_2, using equation (1) can be written as:

$$A(f_1)/A(f_2) = [A_0(f_1)R(f_1)\exp(-\pi f_1 t/Q)]/[A_0(f_2)R(f_2)\exp(-\pi f_2 t/Q)] \quad (2)$$

Taking natural log the above equation becomes:

$$\ln[A(f_1)/A(f_2)] = \ln[A0(f_1)/A0(f_2)] + \ln[R(f_1)/R(f_2)] - \pi(f_1 - f_2)t/Q \quad (3)$$

If $A_0(f_1)/A_0(f_2)$ and $R(f_1)/R(f_2)$ are constant and independent of time then the equation (3) becomes:

$$\ln[A(f_1)/A(f_2)] = C - \pi(f_1 - f_2)t/Q \quad (4)$$

which represents the equation of straight line between $\ln[A(f_1)/A(f_2)]$ and t with slope (θ) given by:

$$\theta = - \pi(f_1 - f_2)/Q \quad (5)$$

Equation (5) gives the estimates of Q between f_1 and f_2.

The assumptions of this method are: (i) Q is constant over the frequency band f_1 and f_2 (ii) the source spectrum is same for all the earthquakes analyzed. The second assumption is satisfied for the earthquakes lying in small magnitude range and having a small focal volume. For estimating the Q the average radiation pattern is assumed to be isotropic and therefore negligible contribution in equation (3). The link between high frequency amplitude and double couple radiation pattern has been found to be negligible (Hanks & McGuire 1981; Fletcher et al., 1984).

SEISMOTECTONICS OF THE STUDY AREA

The Kachchh region is a rift basin which opened up in early Jurassic and continued till early cretaceous. The rifting ended with change in stress direction due to rotation of Indian plate (Biswas 1987). Geologically, Quaternary/Tertiary sediments, Deccan volcanic rocks and Jurassic sandstones resting on Archean basement mainly characterize the Kachchh region (Gupta et al., 2001). Kachchh is bounded by Nagar Parkar ridge in the North, Radhanpur arch in the East and Kathiawar uplift in the South. Major tectonic features in Kachchh are series of EW trending uplifts along master faults. The uplifts comprise of blocks tilted towards south. The uplifts comprise of Mesozoic and Tertiary rocks and Quaternary sediments are deposited in the depressions between the uplifts (Biswas 1987). The major faults are Nagar Parkar fault, Allah Bund fault,

Table 1. Details of earthquakes used in the present study

SR No	Year	MMDD	HRMIN	SEC	Latitude(N)	Longitude (E)	Depth (Km)	Magnitude
1	2006	0724	1808	20.85	23.510	70.689	6.1	2.7
2	2006	0725	0959	31.26	23.672	70.271	38.1	3.1
3	2006	0725	2222	57.97	23.508	70.69	0.2	2.7
4	2006	0727	0052	15.97	23.453	70.429	16.3	3.4
5	2006	0727	2354	4.26	23.376	70.42	14.4	2.4
6	2006	0731	2016	36.26	23.454	70.277	11.2	3.1
7	2006	0803	0602	3.56	23.528	70.126	30.7	3.3
8	2006	0804	2034	29.93	23.456	70.294	9.3	3.0
9	2006	0805	0716	52.15	23.458	70.29	3	3.2
10	2006	0805	1036	8.83	23.492	70.399	6.3	3.5
11	2006	0806	1049	25.88	23.541	70.397	15.3	2.9
12	2006	0809	1209	21.06	23.807	70.763	22.8	2.1
13	2006	0810	0646	28.12	23.398	70.442	16.6	2.6
14	2006	0810	1613	32.73	23.376	70.402	21.6	3.0
15	2006	0812	0554	33.44	23.47	70.421	21	2.8
16	2006	0812	0741	15.97	23.381	70.287	3.5	2.1
17	2006	0813	1705	6.08	23.344	70.249	7.3	3.4
18	2006	0819	2340	12.81	23.743	70.89	10	2.5

19	2006	0820	0126	16.5	23.451	70.297	15.4	2.4
20	2006	0820	0237	21.3	23.530	70.508	15	4.3
21	2006	0828	0547	26.4	22.182	69.731	25	3.1
22	2006	0828	0800	36.3	23.672	70.443	25.9	2.6
23	2006	0828	1335	2.2	24.416	71.357	25	2.8
24	2006	0828	2156	42	23.754	70.712	5	2.7
25	2006	0829	1416	41.9	22.366	70.223	20	3.2
26	2006	0830	1600	10.3	24.696	70.979	10	2.5
27	2006	0903	1747	26.9	23.697	70.753	6.5	4.1
28	2006	0904	1722	1	24.77	69.538	40	3.2
29	2006	0909	0247	47.3	23.349	70.207	25	2.9
30	2006	0910	1920	56.7	23.501	70.212	18.6	2.7
31	2006	0915	2322	51	23.924	71.466	20	2.9
32	2006	0920	0048	11.9	21.299	70.515	10	3.3
33	2006	0921	1523	30	23.694	70.755	20.9	2.6
34	2006	0927	0045	33.1	22.285	70.338	19	3.1
35	2006	0929	0803	17.3	22.831	70.459	5	2.9
36	2006	0929	1034	30.3	22.828	70.429	5	3.1
37	2006	0929	1042	52.2	22.278	70.078	8.1	3.4
38	2006	0930	0010	11.8	22.291	70.111	5	3.0
39	2006	0930	0016	2.1	22.197	71.227	18.1	4.1
40	2006	1006	0017	14.8	22.321	70.214	5	3.5
41	2006	1006	1441	15.9	22.121	70.282	10.1	3.0
42	2006	1006	1511	25.4	22.337	70.233	3.1	3.4
43	2006	1008	1034	10.6	22.282	70.265	6.1	3.1
44	2006	1008	2244	37.2	23.327	70.38	20.8	3.2
45	2006	1010	0153	52.4	23.395	70.168	17.9	2.3
46	2006	1010	2152	20.8	23.463	70.032	15.4	2.2
47	2006	1012	0732	29.7	23.165	70.654	3.3	3.9
48	2006	1013	0102	13.5	23.509	70.233	20	3.0
49	2006	1014	0538	26.4	23.487	70.157	20	3.1
50	2006	1014	1423	27.9	23.49	70.183	20	3.1
51	2006	1015	2338	1.9	23.459	70.421	15.4	3.0
52	2006	1017	0011	4.8	23.5	70.378	25	2.9
53	2006	1018	1909	32.5	23.307	70.26	24.8	2.9
54	2006	1018	2335	4	23.329	70.277	20.1	3.1
55	2006	1019	1911	2.3	23.4	70.089	10.5	2.8
56	2006	1020	0214	43.1	23.484	70.308	19.2	2.6
57	2006	1022	0301	32.9	23.402	70.112	15.8	2.0
58	2006	1023	2001	13.1	23.422	70.224	20	2.5
59	2006	1025	2121	12.3	23.612	70.095	25	2.6
60	2006	1026	0808	11.9	21.299	70.515	10	3.3
61	2006	1027	1307	13.4	23.407	70.479	20.5	3.0
62	2006	1028	0636	4.9	23.315	70.189	22.4	3.3
63	2006	1028	1620	29.3	23.314	70.597	28.2	2.8
64	2006	1030	0143	49.4	23.414	70.386	22.7	2.6
65	2006	1030	0653	25.8	23.296	70.121	20	2.8
66	2006	1031	0317	5.2	23.333	70.102	20	3.2
67	2006	1031	0728	29.3	23.46	70.226	25	2.2
68	2006	1031	1050	11	23.735	70.659	22.8	3.1

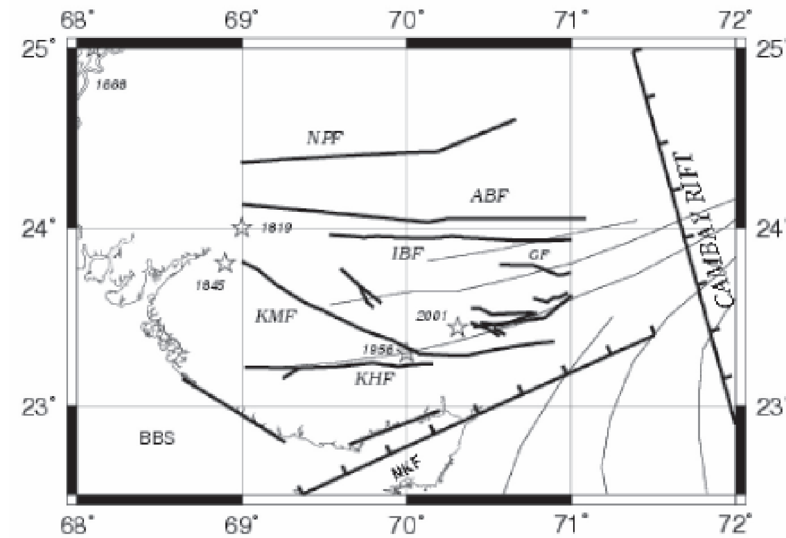

Figure 1a. Tectonic map of Kachchh region along with the locations of epicenters and recording stations.

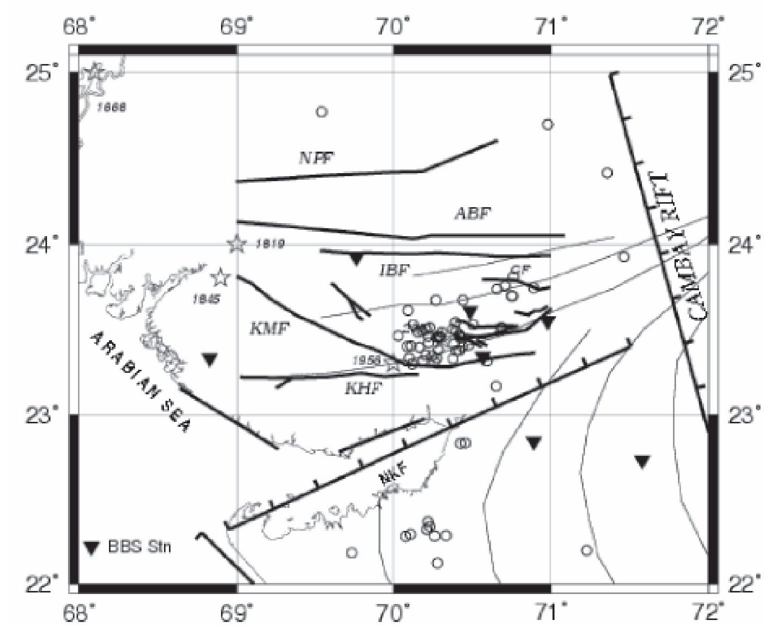

Figure 1b. Epicenter location of earthquakes used in present study.

Island Belt fault, Kachchh Mainland fault and Katrol hill fault (Fig. 1a). In addition, several NE and NW trending small faults/lineaments are observed (Biswas 1987). Seismic, gravity and magneto-telluric surveys indicate undulated basement with 2–5 km deep sediments and Moho depth at 35–43 km in the southern Kachchh region (Gupta et al., 2001; Reddy et al., 2001). In general, this region is very complex, as it contains faults of multiple orientations and different natures.

Major earthquakes that occurred in the historical past are 1668 Indus delta (MM X), 1819 Kuchchh (Mw 7.8), 1845 Lakhpat (MM VIII), 1956 Anjar (Mw 6.0) and 2001 Bhuj (Mw 7.7).

DATA SET

The Institute of Seismological Research (ISR), Gandhinagar has instrumented the entire Gujarat region with state of the art 18 permanent

Table 2. Frequency dependent relationships estimated in this study

Station Code	Q_p	Q_s	Average
LAK	$(111\pm1.5)f^{(1\pm0.01)}$	$(107\pm4)f^{(0.76\pm0.03)}$	$Q_p = (89\pm1)f^{1.12\pm0.004}$
SUV	$(72\pm1.4)f^{(1.22\pm0.01)}$	$(193\pm3)f^{(0.86\pm0.01)}$	$Q_s = (121\pm1)f^{0.92\pm0.004}$

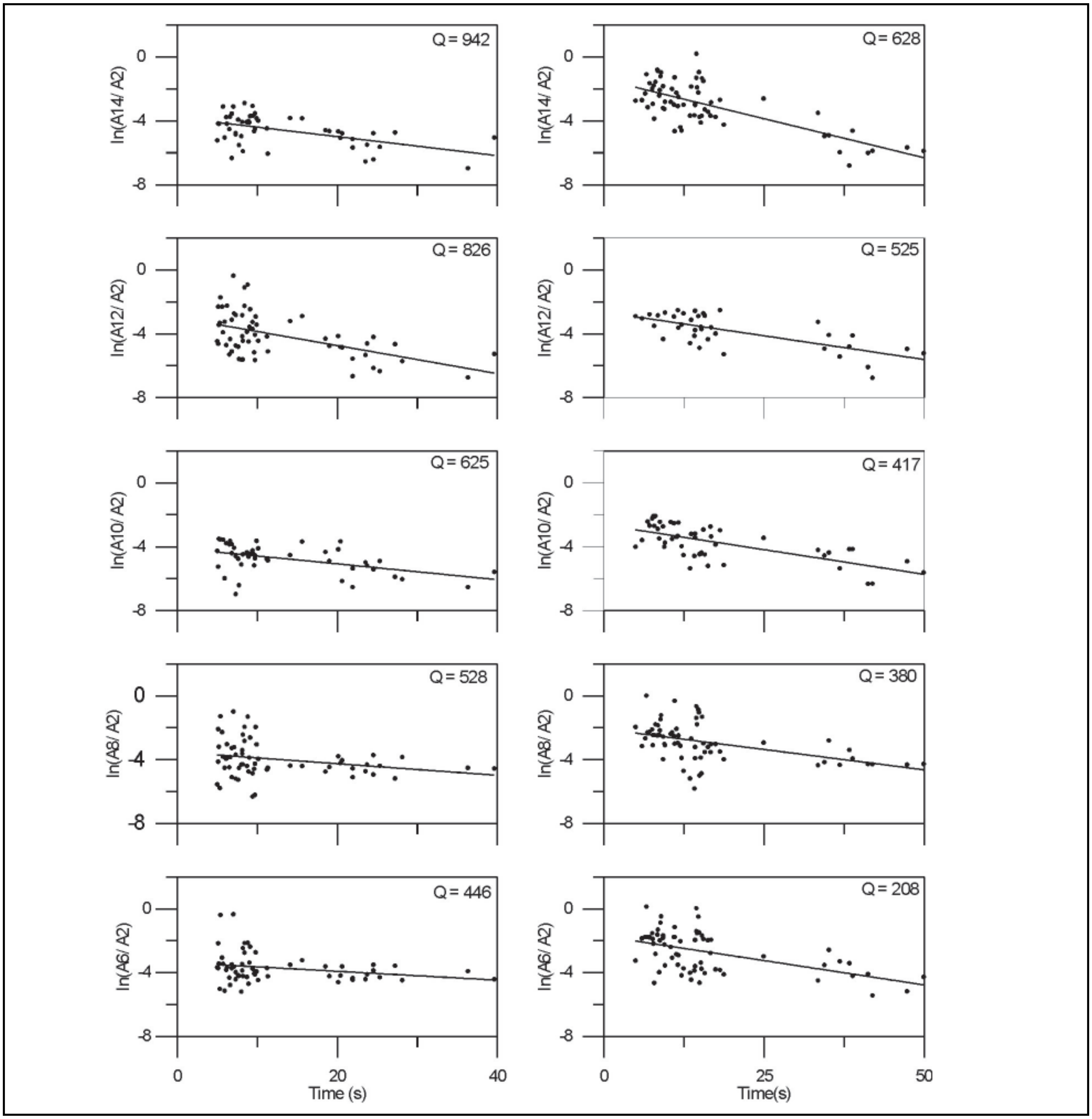

Figure 2. Plots of log of spectral ratios versus time along with the best least square fitted line for the station LAK (a) for Q_p (b) for Q_s

seismological observatories equipped with broadband seismographs. These permanent observatories are linked via VSAT with central station at Gandhinagar. Of these, two namely Khavda and Naliya are in Kachchh. Besides this three temporary stations are established at Lakadia, Suvai and Adesar. These are equipped with 120 sec broadband sensor of Guralp make (CMG-3T) with 24 bit digitizer working on continuous mode at 100 sps and continuous GPS time synchronization. In this study, we utilize data from two broadband stations namely Lakadia and Suvai. We have used the waveforms of earthquakes occurred between Lat 21.1 – 24.5 ^{0}N and Lon 69.5 – 71.5 ^{0}E and the epicentral distance range 20 – 170 Km from the stations. The location of stations and epicentres of earthquakes are shown in Figure 1b. The details of earthquakes used in the study are shown in Table-1.

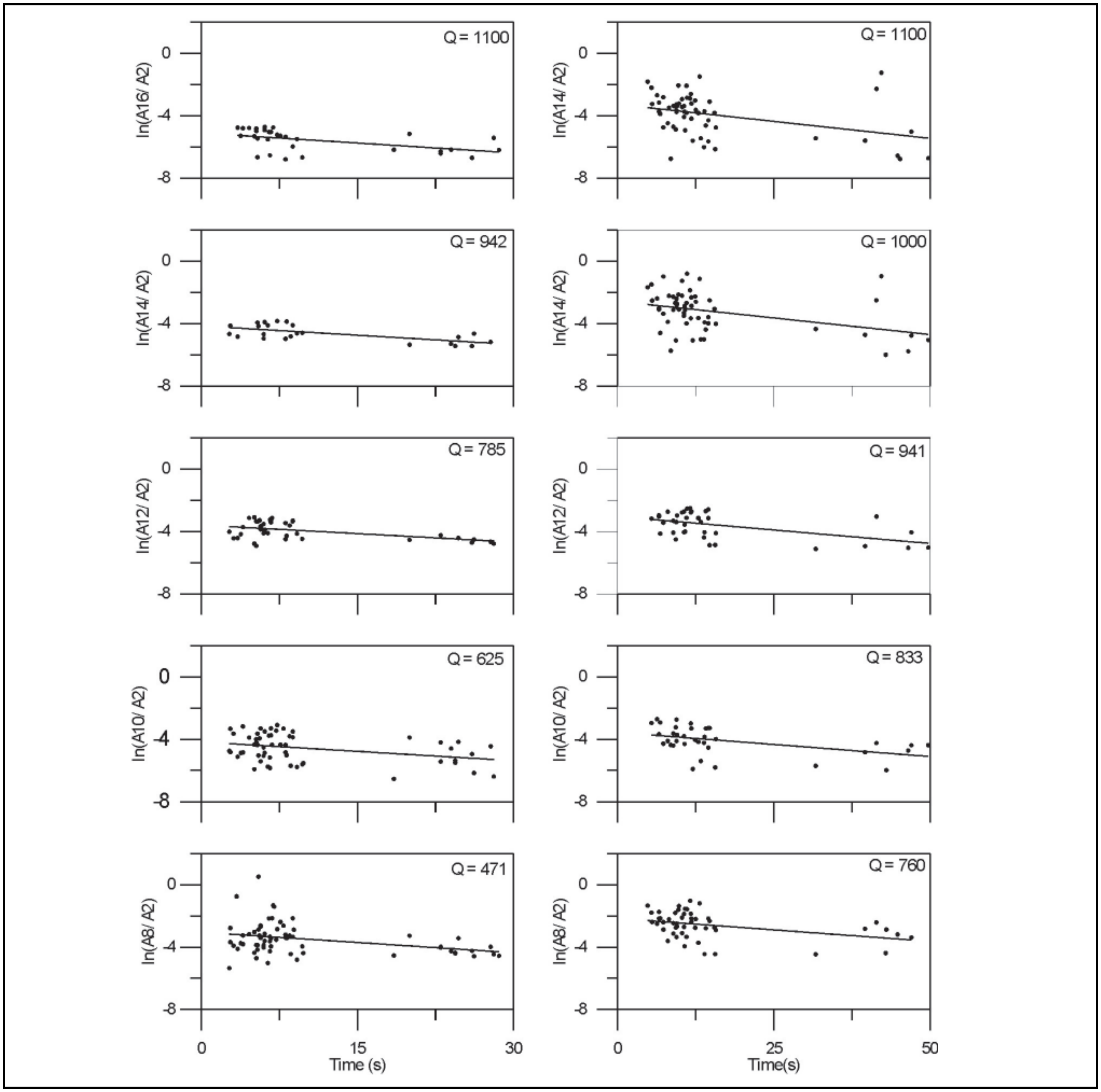

Figure 3. Plots of log of spectral ratios versus time along with the best least square fitted line for the station SUV (a) for Q_p (b) for Q_s.

RESULTS AND DISCUSSION

The seismograms recorded at Lakadia and Suvai have been used in this analysis. The spectral amplitudes have been estimated over a wide band centered at f_1 and f_2. We set f_2 = 2 Hz and f_1 = 4, 6, 8, 10, 12, 14, 16 and 20 Hz respectively. The log of spectral ratio is plotted against P-wave and S-wave travel time. Figures 2 and 3 shows few of these plots along with the least square fitted line for Lakadia and Suvai respectively. From the slope (θ) of these best fitted lines, the Q has been estimated using the expression Equation 3 and 4):

$$Q = -\pi(f_1 - f_2)/\theta \quad (6)$$

The behavior of Qp and Qs versus frequency at two stations is shown in Figures 4 and 5 respectively. We note that Q value increases with increase in frequency for two types of waves at both the stations. This indicates the frequency dependent nature of Q estimates in the region. The fitting of power law $Q = Q_0 f^n$ to these plots gives the frequency dependent relation for two stations. The estimated relations are: $Q_p = (111\pm1.5)f^{1\pm0.01}$, $Q_s = (107\pm4)f^{0.76\pm0.03}$ for Lakadia and $Q_p = (72\pm1.4)f^{1.22\pm0.01}$, $Q_s = (193\pm3)f^{0.86\pm0.01}$ for Suvai. The average frequency dependent relations for Q have been estimated as $Q_p = (89\pm1)f^{1.12\pm0.004}$ and $Q_s = (121\pm1)f^{0.92\pm0.004}$ in the region (Table 2).

The average attenuation relations for P and S waves estimated here have been compared with those of other regions in Figure 6a and 6b respectively. We observe from figure 6a that rate of increase of Q(f) for P waves obtained here is similar to other regions like Kanto region, Japan and South Eastern Korea but more close to later in absolute values. The rate of increase of Q(f) for S waves is comparable with other regions of the world (Figure 6b). Singh et al. (2004) have estimated a relation $Q(f) = 800f^{0.42}$ for the Indian shield region. This gives higher Q estimates than in the present analysis. This difference may be attributed to the data used in these two studies. The present study is based on the earthquakes recorded at smaller distances while the relation developed by Singh et al. (2004) is based on the earthquakes recorded at larger distances (240 – 2400 km). This observation shows the dependence of attenuation on distance as the waves penetrate to deeper parts of the crust when propagating longer distances. The dependence of Q on distances has been shown in other studies also (e.g. Modiano & Hatzfeld 1982; Dinesh Kumar 2005, Dinesh Kumar, Sri Ram & Khattri 2006).

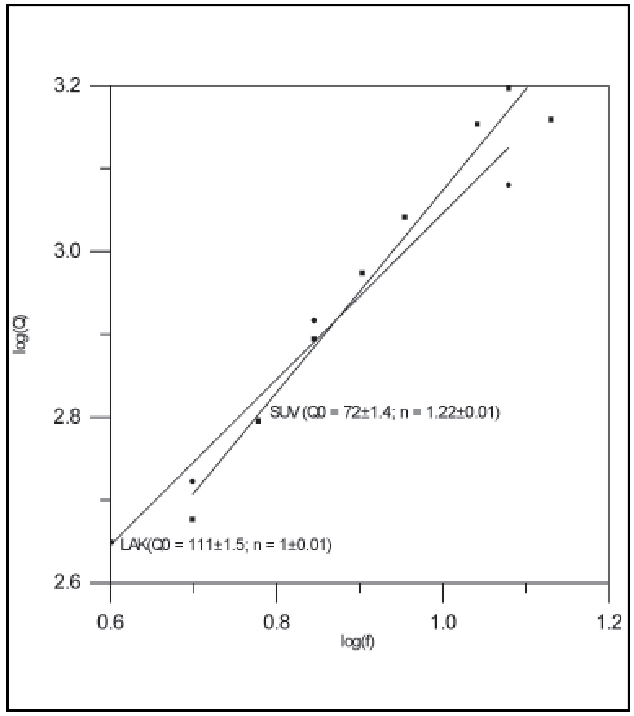

Figure 4. Behavior of Q_p versus frequency at LAK and SUV along with best least square fitted line.

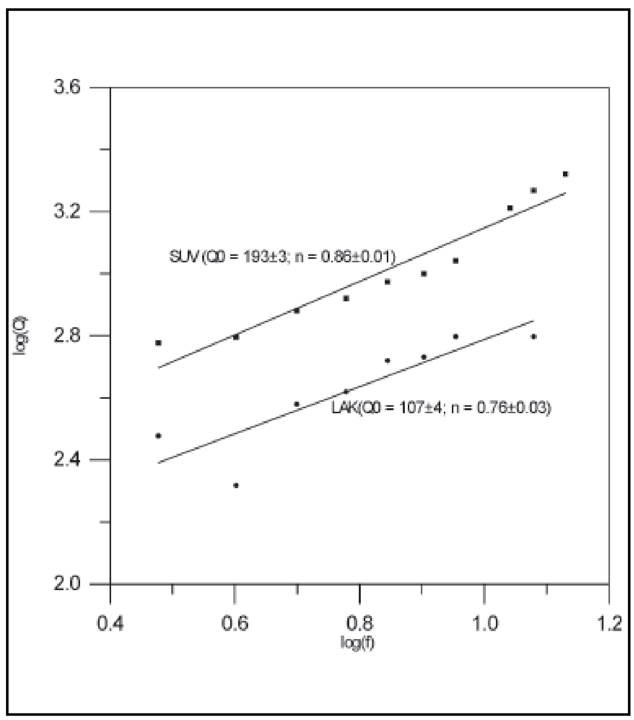

Figure 5. Behavior of Q_s versus frequency at LAK and SUV along with best least square fitted line.

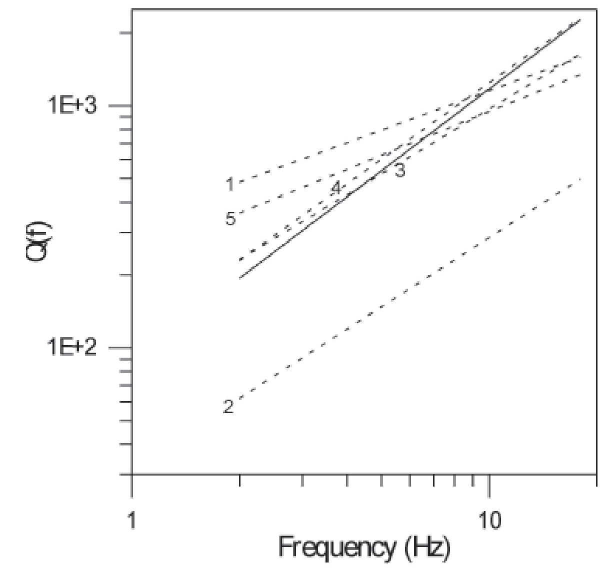

Figure 6a. Comparison of average Q(f) for P-waves of the Kuchchh region obtained in this study (solid line , $Q(f) = 89f^{1.12}$) with those of other regions of the world.(dash lines). line 1: Central South Korea, $Q(f) = 333f^{0.54}$, Kim, Chung & Kyung. (2004); line 2: Kanto, Japan, $Q(f) = 32f^{0.95}$, Yoshimoto, Sato & Ohtake (1993); line 3: Baltic Shield, $Q(f) = 125f^{0.89}$, Kvamme & Havskov (1989), line 4: South Eastern Korea, $Q(f) = 111f^{1.05}$, Chung & Sato (2001); line 5: France, $Q(f) = 238f^{0.6}$, Campillo & Planet (1991).

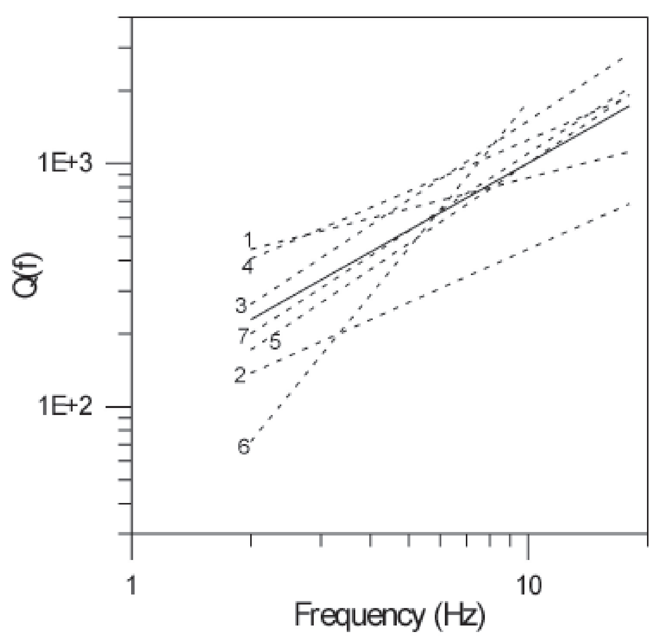

Figure 6b. Comparison of average Q(f) for S-waves of the Kuchchh region obtained in this study (solid line , $Q(f) = 121f^{0.92}$) with those of other regions of the world.(dash lines). line 1: Central South Korea, $Q(f) = 333f^{0.42}$, Kim et al. (2004); line 2: Kanto, Japan, $Q(f) = 83f^{0.73}$, Yoshimoto et al. (1993); line 3: Baltic Shield, $Q(f) = 125f^{1.08}$, Kvamme & Havskov (1989), line 4: South Eastern Korea, $Q(f) = 250f^{0.70}$, Chung & Sato (2001); line 5: Northern Itlay, $Q(f) = 80f^{1.1}$, Console & Rovelli, (1981); line 6: Central Itlay, $Q(f) = 18f^{2.0}$, Castro et al. (2002); line 7: South Central Alaska, $Q(f) = 96f^{1.06}$, Dutta et al. (2004).

We note from the values of Q for P and S waves (Table 2) that the ratio Qs/Q_p is close to one at Lakadia and greater than one at Suvai. Using the accelerograms recorded in Kachchh region, Mandal (2007) revealed that the ratio Qs/Qp varies from 0.41 to 2.99 in this region. The ratio Qs/Qp estimated in this study may be verified further using more data at large number of recording stations.

A few studies have been done to estimate the frequency dependent relationships for coda-Q for the region adjacent to the region considered in the present study. The estimated relations in these studies are: $Q_c = 102f^{0.98}$ (Mandal et al., 2004); $Q_c = 106f^{1.11}$ (lapse time window 30-60 sec) (Gupta et al., 2006). The data of aftershocks of 2001 Bhuj earthquake have been used in these two studies. Sharma et al. (2006) have obtained a relation $Q_c = 148f^{1.01}$ (lapse time window 30 sec) for the same region considered here and using the similar data set used here. This relation gives higher value of Q_c as compare to average Q_s estimated from the relation obtained here ($Q_s = 121f^{0.92}$). Aki (1980) argued that Q_c and Q_s are comparable as coda waves are backscattered S waves. On the other hand Zeng's (1991) model predicts that the effects of intrinsic and scattering attenuation combine in a manner that Q_c should be more than Qs. The observation made in this study supports the Zeng's (1991) model for the region considered here. However, this finding can be verified by using the data at more number of stations. We note that Sharma et al., (2007) have made the same observation using coda normalization method for this region. The observation that $Q_c > Q_s$ may be due to the relative weakness of scattering attenuation (Wennerberg 1993). It has been found that the intrinsic absorption is predominant over scattering in this region (Ugalde et al., 2006; Sharma et al., 2007). Thus the results of this study are in agreement with the findings of other studies for this region using different methods.

CONCLUSIONS

The single station spectral method has been used to estimate the quality factors of P and S waves of the earthquakes recorded at Lakadia and Suvai in the Kachchh region. The frequency dependent relations estimated for the Q_p and Q_s at the two stations are : $Q_p = (111 \pm 1.5)f^{1 \pm 0.01}$, $Q_s = (107 \pm 4)f^{0.76 \pm 0.03}$ for Lakadia and $Q_p = (72 \pm 1.4)f^{1.22 \pm 0.01}$, $Q_s = (193 \pm 3)f^{0.86 \pm 0.01}$ for Suvai. The average frequency dependent relations for Q have been estimated as $Q_p = (89 \pm 1)f^{1.12 \pm 0.004}$ and $Q_s = (121 \pm 1)f^{0.92 \pm 0.004}$ in the region The average Qs value estimated here has been found to be less than that of reported Qc value for this region. This supports the Zeng's model of attenuation. The obtained relations have been compared with those of other regions of the world. The results of this study are in consistent with the findings of other studies for Kachchh region using different methods. The frequency dependent relations developed here may be useful for the near source simulation of earthquake strong ground motion as well as to estimate the source parameters of the earthquakes in the study area.

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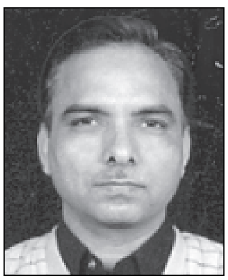

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