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Seismic attenuation in two geologically distinct regions of central Greece

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Abstract - The attenuation parameters Q and n in the frequency range of 1-12 Hz was studied. The single isotropic scattering model was applied in the analysis of coda waves using seismic data of small local events. The slope of the coda envelope and the mean Q_c with respect to lapse time and frequency dependence was estimated in two stations which belong to the VOLNET seismological network, operating in central Greece. The seismological stations are situated in two regions characterized by different geological and neotectonic features. The clear frequency dependence of Q_c follows the power law relation $Q_c = Q_o f^n$. The Q_o values were found ranging from 32 to 108 and n from 1.06 to 0.65 for 10s to 40 s lapse time window at the Erythres station and from 25 to 70 and 1.08 to 0.94 at the Pavliani station for the same lapse time window. The difference, of the attenuation parameters Q_o and n values, between the two examined areas were interpreted in terms of different scattering environments present in the two investigated areas. The age of geological formation and their folding grade seem to be important factors in this interpretation.

1. Introduction

The attenuation of seismic coda waves is customarily described by the so-called quality factor Q_c estimated from seismic coda waves, (Aki, 1969; Aki and Chouet, 1975). The seismic coda consists of reverberations in geological structures under the receiver (the site response), and surface waves scattered by lateral heterogeneities (Aki, 1969; Malin, 1980). In addition, coda can be generated by the conversion of body waves into surface waves either by topography at the free surface or at buried interfaces (Hill and Levander, 1984).

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Measurements of Q_c are obtained by means of the single backscattering model (Aki and Chouet, 1975) or its later extension (Sato, 1977a, 1977b), which is the single isotropic scattering model. These models interpreted coda waves as singly scattered S-waves from random heterogeneities.

This study was accomplished by using the single isotropic scattering model, which assumes a spherical radiation of energy and an isotropic scattering, due to the homogeneous and isotropic distribution of scatterers. Our knowledge about the mode of scattering, single or multiple or about the exact nature of scatterers is rather limited. Nevertheless, cracks, faults, folds, density and velocity anomalies could be considered as heterogeneities, which can effectively work as scatterers in the earth medium. Much of the scattering appears to be localized in the crust and lithosphere, which is the most heterogeneous part of the earth, and also the only part available for geological and neotectonic observation.

Although the single scattering model is simple, we believe that it is useful for relating the characteristics of coda waves to geotectonical observations. Many investigators have measured Q_c in a large number of areas and some of them correlated the results with the degree of seismotectonic activity. (Aki 1980; Roecker et al., 1982; Singh and Herrmann, 1983; Gagnepain-Beyneix, 1987; Jin and Aki, 1988; Phillips et al, 1988; Sato, 1988; Matsumoto and Hasegawa, 1989; Correig et al., 1990; Spudich and Ida, 1992; Baskoutas, 1996, 1998).

The aim of this paper is to estimate Q_c in two areas, around Pavliani and Erythres stations, which have different geological and neotectonic characteristics, and to determine whether Q_c distinguishes between these two regions. For this purpose, we used small local events from two stations situated in the above mentioned areas. The events of each station are distributed within the extent of the area under consideration.

2. Method

A variety of models have been proposed to explain the decay of S-wave coda of local earthquakes. The progress of theoretical studies on coda waves is reviewed by Herraiz and Espinosa, 1987. Due to inhomogeneities, which are present in the crust and upper mantle, a stochastic approach seems to be better adapted than a deterministic one, to describe the shape of high frequency seismograms from local earthquakes. Coda waves can be described by their envelope as a function of frequency f, and lapse time t. Assuming a single isotropic scattering and a uniform distribution of observed scatterers (Sato, 1977a, 1977b) and introducing attenuation Q_c, distribution of coda energy density is given by:

$$E_{SIS}(f,t) = [W_0 g_o / (4\pi r_o^2)]\, K(x) \exp(-\, Q_c^{-1}\, 2\pi f t) \tag{1}$$

where W_0 is S-wave source energy; g_o, total scattering coefficient; r_o hypocentral distance; f frequency; and t, lapse time measured from earthquake origin time. Considering the asymptote of function $K(x) = (1/x) \ln[(x+1)/(x-1)]$, Eq. (1) becomes:

$$E_{SIS}(f,t)\ \alpha\ [W_o g_o / (2\pi\beta_o^2 r_o^2)]\ \exp(-\,Q_c^{-1}\,\pi f t) \quad \text{for } \beta_o^2\, t > r_o \tag{2}$$

which coincides to the Aki and Chouet (1975) single back-scattering model. The energy density of the coda wave is proportional to the mean square of the velocity amplitude of the coda wave, $A(f,t)$:

$$A(f,t)\ \alpha\ (1/t)\ \exp(-\,Q_c^{-1}\,\pi f t) \quad \text{for } t > 2ts \tag{3}$$

Taking the logarithm of that relation we obtain:

$$\log(t\,A) = -\,[Q_c^{-1}\,\pi f \log e]\ t + \text{const} \quad \text{for } t > 2ts \tag{4}$$

Applying the relation to the observed data, we can directly evaluate Q_c from the linear regression of log $(t\,A)$ against lapse time.

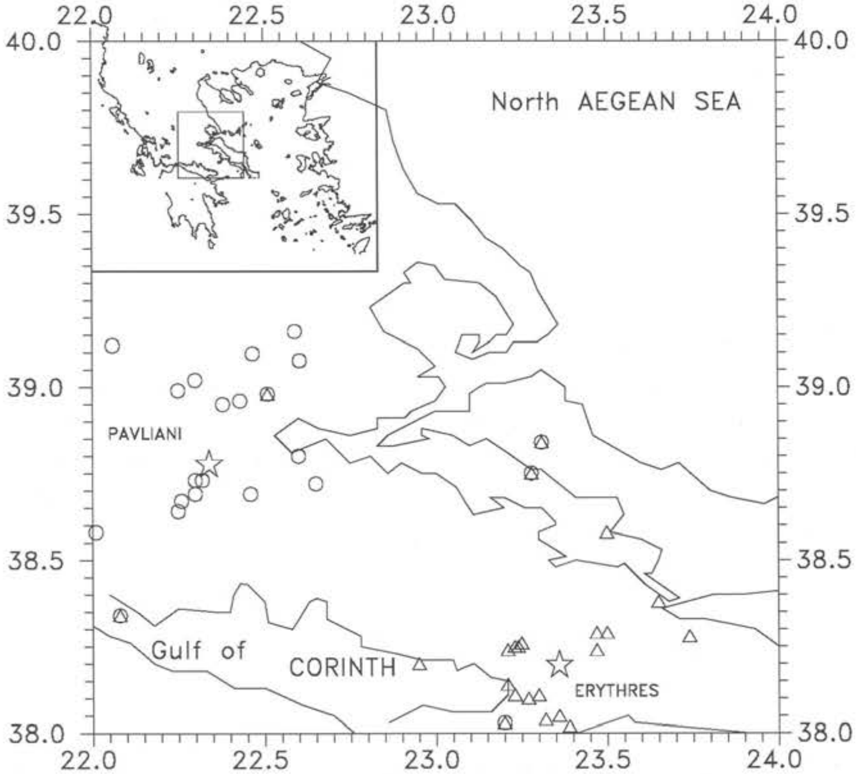

Fig. 1 - Epicenter distribution of the events used in this analysis, and the location of the stations (open stars).

3. Data and analysis

Seismograms used in this study were recorded during the year 1984 at Pavliani (VPA) and Erythres (VTH) stations (22.34° E, 38.78° N and 23.36° E, 38.20° N respectively), which belong to the VOLNET seismic network. Each station is equipped, with a Willmore-II, velocity type and short period seismometer, with a natural period of 1s. Seismic signals were originally recorded on analogue magnetic tapes and subsequently digitized at a sampling frequency of 50 Hz.

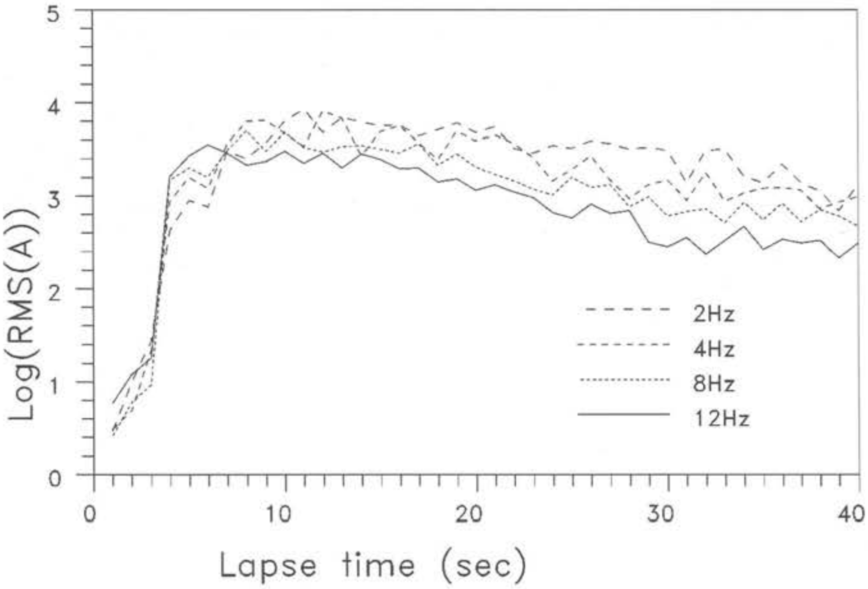

Fig. 2 - Example of the quantity log(RMS(*A*)) at each frequency band.

The number of events used is 23 for VPA station and 25 for VTH. Figure 1, shows the epicenter distribution of those earthquakes. Local magnitude ranges from 2.0 to 3.0. Hypocenter parameters are taken from the monthly bulletin of VOLNET network. The depth of all the events is less than ~20 km.

In order to evaluate Q_c, filtered seismograms were analyzed from the vertical-component; each seismogram was band-pass filtered by using a phase-less eight-pole Butterworth filter with four pass-bands of 1-3, 2-6, 4-12 and 8-16 Hz. Then, the RMS of the filtered amplitudes was calculated at 1.0 s intervals for each frequency band, Fig. 2. To investigate the lapse time dependence, we calculated Q by shifting the time of the data window in steps of 10 s. Thus, lapse time window lengths were defined 10, 20, 30 and 40 s, limit, which in all cases, lies before the end of the coda. The analysis was started at time 1.5 t_s, where ts is the S-wave travel time and end of coda were considered the point where the signal - to - noise ratio falls below 2.

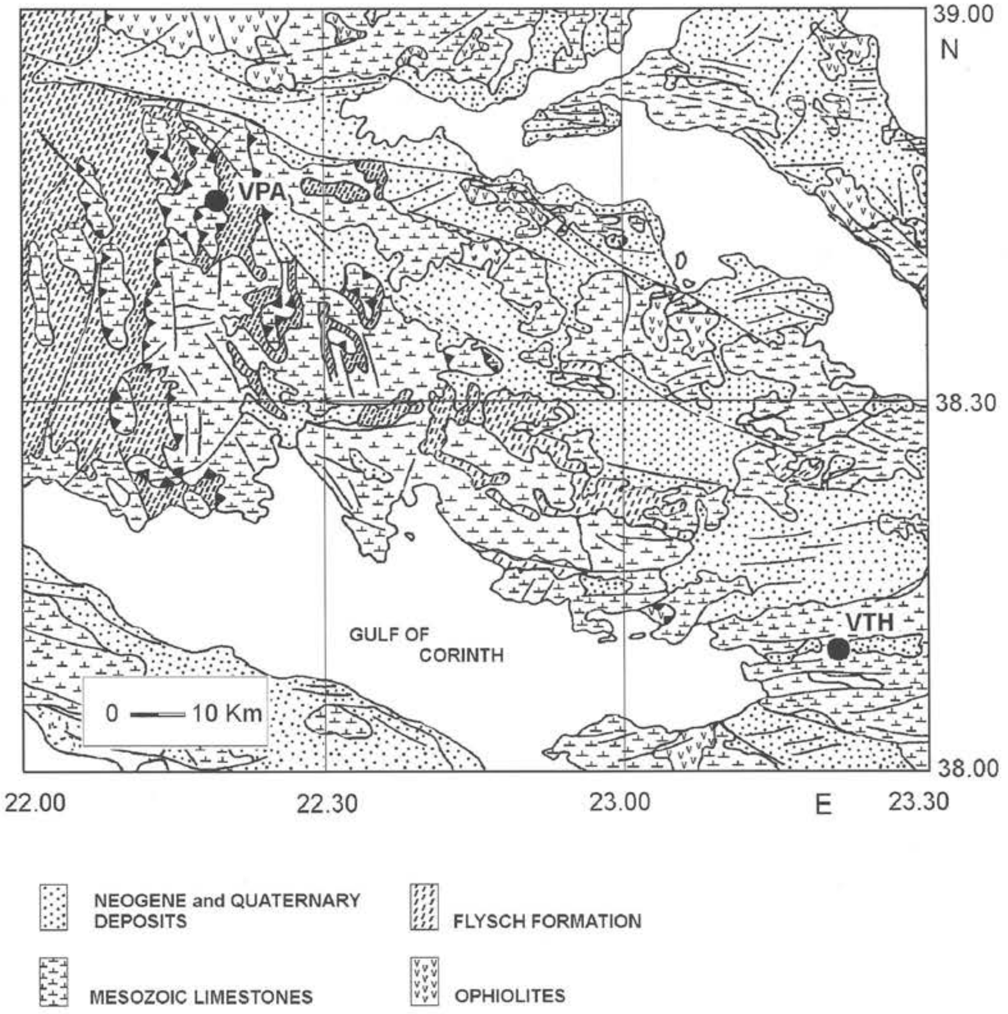

Fig. 3 - Geological map of the examined area. Solid circles show the location of the stations.

4. Geological and Neotectonic outline

Although both seismic stations are situated in central Greece, the geological and tectonic structure of their surrounding areas is quite different, (Pegoraro, 1972; Lemeille, 1977; Rontoyanni, 1984). The Pavliani station is located on the flysh formation of the Parnassos geotectonic zone, which consists mainly of shales, siltstones, sandstones, conglomerates and locally thin limestone intercalations. Usually they are intensively folded and fissured particularly in the area of the Pavliani station. The mechanical strength of this formation is low and high heterogeneity and dissimilar mechanical behavior generally characterize them. Furthermore, the extent of the area in consideration has a rather complicated structure composed of geological formations of three different geotectonic zones. The surface geology near in the vicinity of the station is the overthrusted limestone of the Pelagonian zone, while at a distance of about some kilometers to the west, the flysch of Pindos is the dominant surface formation. Most deep structures of the area sampled by coda are composed of limestone of Eocene, Cretaceus, Jurassic and Triassic age, schist and ophiolites. These latter formations, usually thick with high cohesion, constitute the geological basement. The presence of recent formations is generally limited. The relation between the formations of the area is expressed by numerous thrusts and overthrusts which characterize the tectonics of the region. The existing faults of Preneogene age have mainly NW-SE and N-S directions.

Table 1 - Observed geological and tectonic differences in Pavliani and Erythres stations.

PAVLIANI STATION	ERYTHRES STATION
Presence of the formations of three distinct geological zones	Presence of the Pelagonic zone
Presence of recent age formations are limited	Presence of extended basins with Neogene and Quaternary faults
Presence of numerous thrust and overthrusts	Presence of numerous normal faults

The Erythres station and the surrounding area is essentially composed of the Pelagonic limestone of the Triassic-Jurassic age. Neogene and Quaternary sediments located in extended basin cover the limestone. The region is characterized by numerous normal faults, some of which are large towards E-W and NE-SW. A geological map can be seen in Fig. 3. The above mentioned observed geological and tectonic differences are shown in Table 1. The main differences can be summarized as follows: firstly, the Pavliani station is located in a region of complex structure composed of three different geological zones, while the Erythres station is located at geological formations, belonging to the Pelagonic zone. Furthermore, differences are also observed in the ages of the formations, and in the character of the faulting.

5. Results and discussion

Using the method and the data outlined in the previous sections, we obtained Q_c for each event-frequency pair, then averaged in each frequency band. The value of average Q_c are listed in tables 2a and 2b. The results show a definite frequency dependence of Q_c, despite the length window. The frequency dependence has been observed in many previous studies in Greece, (Martin, 1988; Hatzidimitriou, 1993; Tselentis, 1993; Baskoutas, 1996), and also in several other region of the world. Generally, this behavior, can be expressed by a power law of the form:

$$Q_c = Q_o f^n$$

where f is frequency in Hz, and parameters Q_o and n obtained by the least squares determination. Previous studies (Biswas and Aki, 1984; Havskov et al., 1989) have shown that both Q_o and n indicate regional variation often related to tectonic features.

Tables 2 and 3 show Q_o and n values at each station, respectively, with respect to the lapse time window. Same results are shown in Figs. 4 and 5. From these figures can be seen the clear

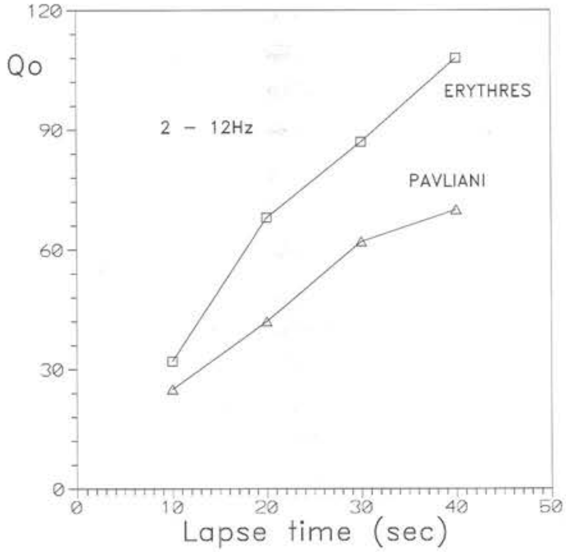

Fig. 4 - Lapse time dependence of the parameter Q_o.

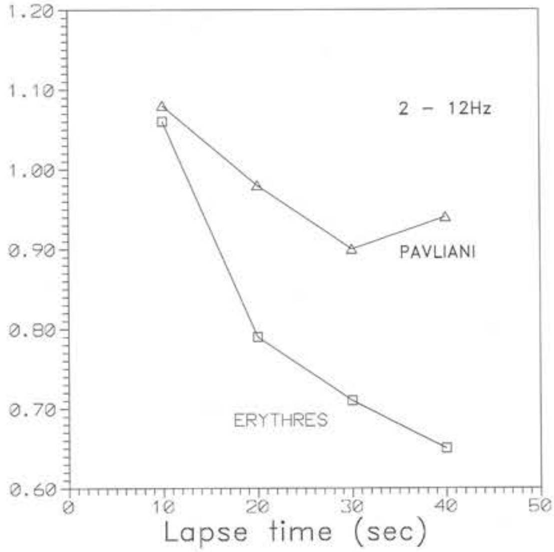

Fig. 5 - Lapse time dependence of the parameter n.

the lapse time dependence of Q_o and n values at each frequency band for both stations and for lapse time window analysis 10 to 40 s. Besides, there is a clear difference of the observed Q_o and n values for two stations, which grow more different with increasing lapse time, which contradicts to the Aki model.

Q_o increases with lapse time in both stations and ranges from 32 to 108 at the Erythres station and from 25 to 70 at the Pavliani station. On the other hand, the exponential factor n decreases with lapse time at both stations and the obtained values range from 1.06 to 0.65 in the Erythres station and from 1.08 to 0.94 in the Pavliani station.

According to Sato's (1984, 1990) model, the general decrease in n with lapse time reflects the dominance of the short wavelength component of heterogeneity for long lapse times. Probably such behavior suggests a decrease in large-scale heterogeneity.

The general increase in Q_o and decrease in n, is attributed to a depth dependent attenuation but their difference in the two examined areas may reflects the regional variation between them. According to the observed geological and tectonic data, the differences of Q_o and n values between the two stations, can be interpreted in terms of the different scattering environments,

Table 2 - Q_c, Q_o and n values and respective errors for VTH (Erythres).

Hz	**10 s**	**20 s**	**30 s**	**40 s**
2	71 ± 15	115 ± 27	149 ± 30	178 ± 36
4	129 ± 40	215 ± 61	222 ± 51	260 ± 55
8	335 ± 114	351 ± 77	383 ± 86	407 ± 55
12	437 ± 113	484 ± 97	534 ± 155	588 ± 133
Q_o	32 ± 7	68 ± 19	87 ± 15	108 ± 36
n	1.06 ± 0.05	0.79 ± 0.02	0.71 ± 0.05	0.65 ± 0.01

Table 3 - Q_c, Q_0 and *n* values and respective errors for VPA (Pavliani).

Hz	10 s	20 s	30 s	40 s
2	53 ± 18	80 ± 19	111 ± 28	140 ± 35
4	105 ± 42	170 ± 55	231 ± 70	247 ± 51
8	258 ± 107	390 ± 185	471 ± 181	510 ± 173
12	350 ± 95	430 ± 120	530 ± 124	721 ± 203
Q_0	25 ± 9	42 ± 10	62 ± 17	70 ± 16
n	1.08 ± 0.01	0.98 ± 0.05	0.90 ± 0.01	0.70 ± 0.02

which characterize the two investigated areas. Consequently, the nature, the age of the geological formations and their tectonic features seem to be important factors in this interpretation.

On the other hand the mean free path is the parameter that controls the energy transferred from the primary to the scattered waves throughout the traveled path. The scatterers reduce the mean energy flux density of the incident plane wave by exp(-*x*/L), where *x* is the distance along the propagation direction, thus the mean free path L gives an idea of the distribution of the scatterers in the earth. According to Pulli (1984), if we assume intrinsic attenuation, Q_i

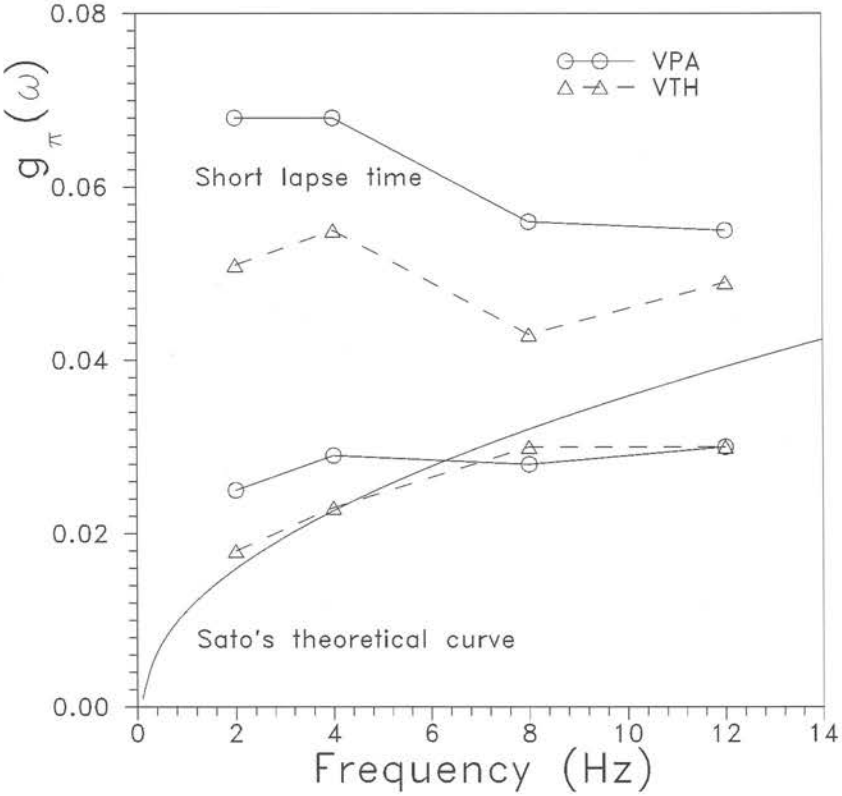

Fig. 6 - Scattering coefficient versus frequency for short (10 sec) and long lapse time (up to 40sec) window analysis. Sato's theoretical curve also shown.

frequency independent or Q_i not decreasing substantially between 30 and 1 Hz and $\upsilon = 3.5$ km/sec, then mean free path can be estimated visually by fitting the resulting Q_c values after choosing a high frequency Q_i value, (Q_i=1800). Assuming Q_i infinite leads to a minimum mean free path of $\upsilon Q_c / \omega$. Applying the scattering coefficient, $g_\pi(\omega)$ to the both stations data, shows a weak frequency dependence at short lapse rime window (10 s). Absolute values of mean free path are larger in the VPA station than in VTH and they present a trend to converge gradually at 12 Hz. This result may reflect the differences of the geological and tectonic characteristics of the upper crust around these stations. For a longer lapse time window (10 to 40 s), values are similar and agree with Sato's theoretical curve, shown in Fig. 6.

6. Conclusions

The purpose of this paper is to estimate Q_c in two distinct geological and neotectonic regions, and determine whether Q_c distinguishes between these two regions. We have calculated the Q_c in these two regions, and we conclude that the differences of Q_0 and n values distinguish between the different geological and neotectonics of the regions. The differences of the age of the geological formation and their folding grade, seems to be important factors in this interpretation.

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