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Intrinsic and Scattering Seismic Attenuation in W. Greece

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Abstract—Intrinsic (Q_i^{-1}) and scattering (Q_s^{-1}) attenuation parameters have been determined in the seismically active region of W. Greece, which is continuously monitored by the University of Patras microearthquake network. One hundred and twenty-three local and shallow earthquakes close to the recording stations have been used and WENNERBERG's (1993) approach has been adopted. Results for 1 to 12 Hz range show that Q_i^{-1} is higher than Q_s^{-1} and coda Q values are close to Q_i, indicating that coda Q can be a reasonable estimate of intrinsic Q.

Key words: Intrinsic, scattering, attenuation, Greece.

1. *Introduction*

The attenuation of short-period S waves, expressed by the inverse of the quality factor (Q^{-1}), is of particular importance in understanding the physical laws according to which the elastic energy of an earthquake propagates through the earth's lithosphere.

Among the many influential factors on the propagation path are attenuation due to scattering, i.e., deviation of energy from the general propagation direction, and attenuation due to intrinsic losses or anelasticity, i.e., conversion of energy into heat.

Intrinsic attenuation is conveniently described by the quality factor Q_i of the medium which depends, among others, on viscous processes between the rock matrix and liquid inclusions (GORICH and MULLER, 1987), such as pore fluids and on movements of dislocations through the mineral grains.

Since scattering has the same effect as anelasticity, namely a reduction of amplitudes, it is also described by a quality factor Q_s which depends on the spatial structure of the scattering heterogeneities in the medium, on the size of the velocity and density fluctuations.

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Attenuation inferred from the decay rate of the coda (AKI and CHOUET, 1975; SINGH and HERRMANN, 1983; SATO, 1988) is also a combination of scattering and intrinsic attenuation.

During recent years, many researchers have tried to separate the contribution of scattering and intrinsic attenuation. TSUJIURA (1978) and AKI (1980) stated that scattering attenuation plays a more significant role than intrinsic attenuation, while FRANKEL and WENNERBERG (1987) stated the opposite.

WU (1985) developed a method, based on the radiative transfer theory, allowing an estimation of the relative amounts of scattering and intrinsic attenuation from the dependence of the entire S-wave energy on hypocentral distance (TÖKSÖZ *et al.*, 1988; MAYEDA *et al.*, 1992; HATZIDIMITRIOU, 1994). HOSHIBA (1991) proposed a multiple lapse time window analysis method to estimate scattering and intrinsic attenuation by considering energy for three consecutive time windows as a function of hypocentral distance (FEHLER *et al.*, 1992).

GUSEV and ABUBAKIROV (1987) and HOSHIBA (1991) found that for short lapse times the single-scattering model (AKI and CHOUET, 1975) is adequate and for long lapse times the diffusion model is appropriate. FEHLER *et al.* (1992) and MAYEDA *et al.* (1992) applied HOSHIBA's (1991) method, based on Monte Carlo simulations, to estimate both intrinsic and scattering quality factors.

ZENG (1991) extended WU's work and developed a coda model based on multiple scattering. Obviously, neither the single nor the multiple scattering hypothesis can completely describe the complexities of the earth's crust, however the latter is probably the most relevant to the physical processes which control the shape of the coda envelope.

WENNERBERG (1993) proposed a methodology to estimate Q_i and Q_s from measurements of the direct S-wave Q (Q_d) and coda Q (Q_c), based on the approximation given by ABUBAKIROV and GUSEV (1990) to the model developed by ZENG (1991).

According to WENNERBERG (1993) the lapse-time dependence of Q_c cannot be fully explained with a deficiency of the single-scattering model but it is more reasonably interpreted in terms of a non-uniform medium. A possible explanation of the observed lapse-time dependence of Q_c could be attributed to depth decreasing intrinsic attenuation in the lithosphere (DEL PEZZO *et al.*, 1995) and could be plausibly related to depth-decreasing intrinsic attenuation in the lithosphere.

The goal of this study is to separate the contributions to the apparent decay, namely, the intrinsic and scattering attenuation, Q_i^{-1} and Q_s^{-1} in the crust of W. Greece by applying WENNERBERG's (1993) methodology.

2. *Method of Analysis*

Comparing single-backscattering (AKI and CHOUET, 1975) and multiple-scattering (ZENG, 1991) attenuation models and assuming that the intrinsic attenuation is increased as a common overall exponential factor ($\exp - \omega t/2Q_i$), WENNERBERG (1993) indicated that it is possible to express the observed value of Q_c in terms of the intrinsic and scattering Q as follows

$$\frac{1}{Q_c} = \frac{1}{Q_i} + \frac{1 - 2\delta t}{Q_s} \tag{1}$$

where

$$\delta(\tau) = \frac{0.72}{4.44 + 0.738\tau} - 0.5 \tag{2}$$

$$\tau = \frac{\omega t}{Q_s} \tag{3}$$

and ω, t are the angular frequency and the lapse time, respectively.

Let Q_d be the quality factor for direct S waves, corresponding to an earth volume equivalent to the volume sampled by coda waves and assuming that it describes the total attenuation, we can write

$$\frac{1}{Q_d} = \frac{1}{Q_i} + \frac{1}{Q_s}\,. \tag{4}$$

Following DEL PEZZO *et al.* (1995) we express Q_s and Q_i as

$$\frac{1}{Q_s} = \frac{1}{2\delta(\tau)}\left(\frac{1}{Q_d} - \frac{1}{Q_c(\tau)}\right) \tag{5}$$

$$\frac{1}{Q_i} = \frac{1}{2\delta(\tau)}\left(\frac{1}{Q_c(\tau)} + \frac{2\delta(\tau) - 1}{Q_d}\right). \tag{6}$$

Considering (1), (2) and (3) Q_s is given as the positive root of the following equation

$$4.44\left(\frac{1}{Q_d} - \frac{1}{Q_c}\right)Q_s^2 + \left[0.738\left(\frac{1}{Q_d} - \frac{1}{Q_c}\right)\omega t - 5.88\right]Q_s - 0.738\omega t = 0. \tag{7}$$

The above relations indicate that if we measure Q_c as a function of lapse time t, then we can estimate Q_i and Q_s as a function of lapse time for different frequencies.

In the present investigation we use short-period seismic data and calculate Q_c as a function of lapse time for short epicentral distances. To estimate Q_c, we use the well-known method of AKI and CHOUET (1975), a brief outline of which follows.

Assuming that coda waves are composed of single-scattered wavelets, the coda envelope can be approximately expressed by the following formula

$$A(\omega|t) = A_0(\omega)t^{-1}\exp[-\omega t/(2Q_c)] \tag{8}$$

where $A(\omega|t)$ is the moving Fourier spectrum of the coda, depending on lapse time

t, $A_0(\omega)$ is the so-called coda source and ω is the angular frequency. Rewriting (8) as

$$\ln[A(\omega|t)t] = \ln[A_0(\omega)] - \omega t/(2Q_c) \tag{9}$$

we can calculate Q_c by applying a linear regression analysis between $\ln[A(\omega|t)t]$ and lapse time t for each frequency.

Q_d is estimated following the spectral ratio method (TSUJIURA, 1966; FERRUCCI and HIRN, 1985). In this method, the observed amplitude $A(f)$ of body waves is expressed as

$$A(f) \propto \frac{A_0(f)R(f)\exp(-\pi ft/Q_d)}{r} \tag{10}$$

where $A_0(f)$ is the spectral amplitude at the source and $R(f)$ the site response. By assigning two frequencies f_1 and f_2 and taking the logarithm of the ratio of the corresponding amplitude, we can write

$$\ln\frac{A(f_1)}{A(f_2)} = \ln\ \frac{A_0(f_1)}{A_0(f_2)} + \ln\frac{R(f_1)}{R(f_2)} - \frac{\pi(f_1-f_2)}{Q_d}\,t. \tag{11}$$

We can estimate Q_d by applying a linear regression between the function $\ln[A(f_1)/A(f_2)]$ and time t. All the above are based on the assumption that Q_d can be considered constant over the frequency band studied and that source spectrum is similar for the events analyzed. The later assumption may hold if we use shocks relating to small focal volumes and lying in a small magnitude range. Next, by substituting in (5) and (6) equation (3) we can estimate Q_i and Q_s.

3. Data Used

The data used in the present investigation are 136 digitally recorded seismograms corresponding to local earthquakes at epicentral distances less than 50 km, recorded by the University of Patras seismological network. All records chosen exhibit excellent signal to noise and were free from glitches and spurious signals. Figure 1 shows the distribution of events and stations used.

The network commenced operation in 1990 and the data used cover the period 1993–1996. The network consists of 17 stations equipped with (Teledyne S-13 1 Hz) seismometers operating at 90 dB dynamic range in a low-noise environment. The signals are radio-telemetered via FM subcarriers to the central recording site at Patras seismological center in real time. There, each channel signal is filtered for aliasing with a 30-Hz Butterworth low-pass filter, sampled at 100 sps and converted to digital form with a resolution of 16 bit.

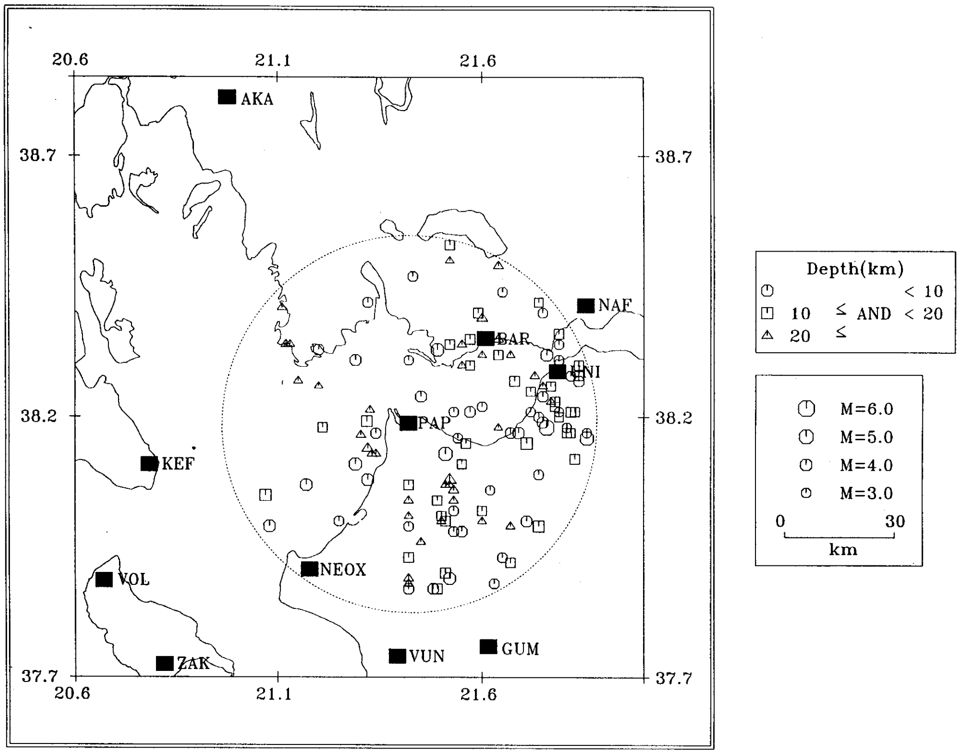


Figure 1
Map showing the location of the events used in the present analysis. Filled rectangles show the seismological stations.

For estimating Q_c, only the vertical components of the seismograms have been used. Beginning at times $t > 2rV_s$, where r and V_s are the hypocentral distance and shear-wave velocity respectively, values of $A(\omega|t)$ were calculated using successive overlapping time windows, corrected for instrument response and averaged over octave frequency bands centered at 1.0, 2.0, 4.0, 8.0 and 12.0 Hz. The effect of noise

Table 1
Measures of Q_c, Q_d, and estimates of Q_i and Q_s.

Freq. (Hz)	Q_d	Q_c	Q_i	Q_s
1	119	175	157	487
2	130	223	190	407
4	178	337	278	494
8	246	511	406	623
12	337	752	580	803

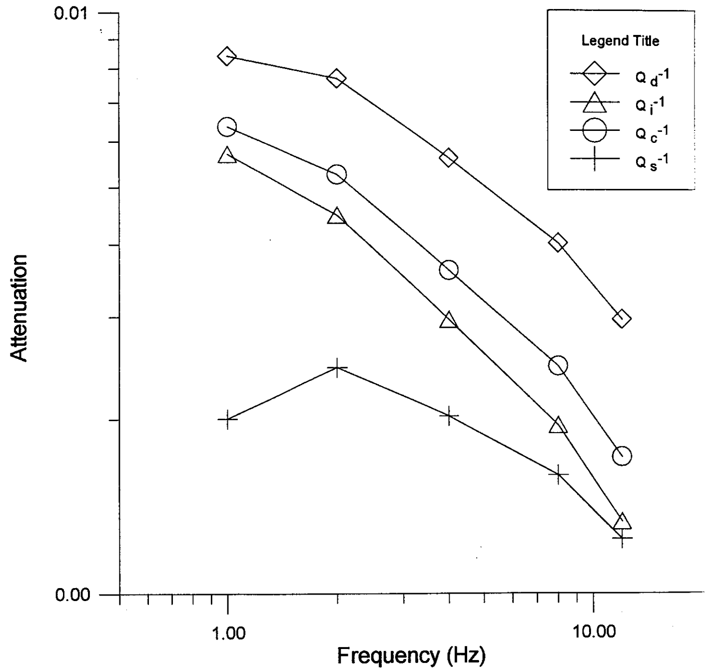


Figure 2
Plot showing the total, scattering and intrinsic attenuation determined in the present study, versus frequency together with coda attenuation.

was removed from each seismogram $S(t)$ in the following way (assuming the general case of uncorrelated signals $s(t)$ and noise $n(t)$)

$$\langle s(t)\rangle_T^2 = \langle S(t)\rangle_T^2 - \langle n(t)\rangle_T^2 \tag{12}$$

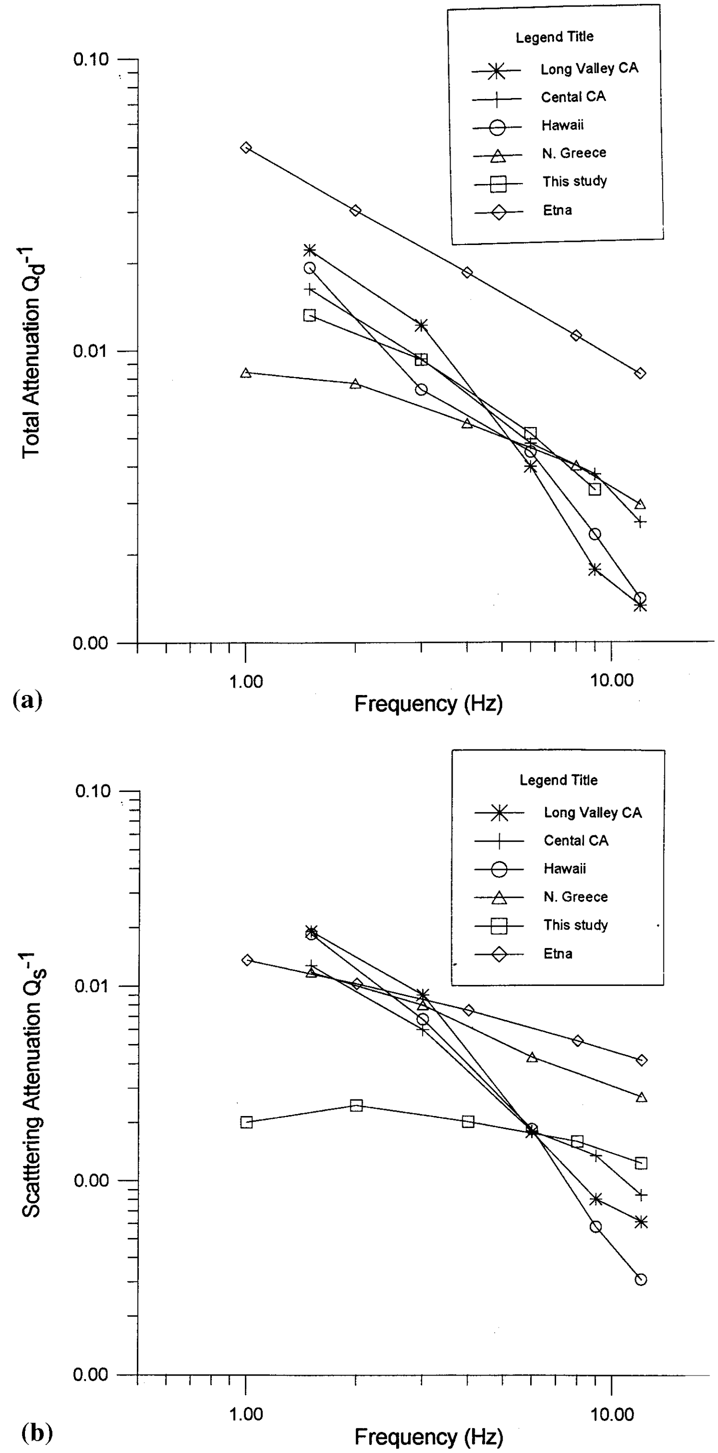
where the quantity between brackets refers to the mean over the time interval T. Thus, the rms amplitude of the signal is derived as:

$$A(r, \omega|t) = [\langle s(t)\rangle_T^2]^{1/2}. \tag{13}$$

4. Results and Discussion

By applying eq. (9), Q_c values were calculated in all the frequency bands. Values corresponding to regression coefficients less than 0.80 were not considered. Averaged Q_c values are depicted in Table 1.

For estimating Q_d, we follow the method of TSUJIURA (1966) as described above. Spectral amplitudes were estimated over 2 Hz wide bands centered at f_1 and f_2. With f_2 set equal to 1 Hz and allowing f_1 to vary in 2 Hz steps between 2 and 12 Hz. Averaged Q_d values over all the measuring stations are depicted in Table 1.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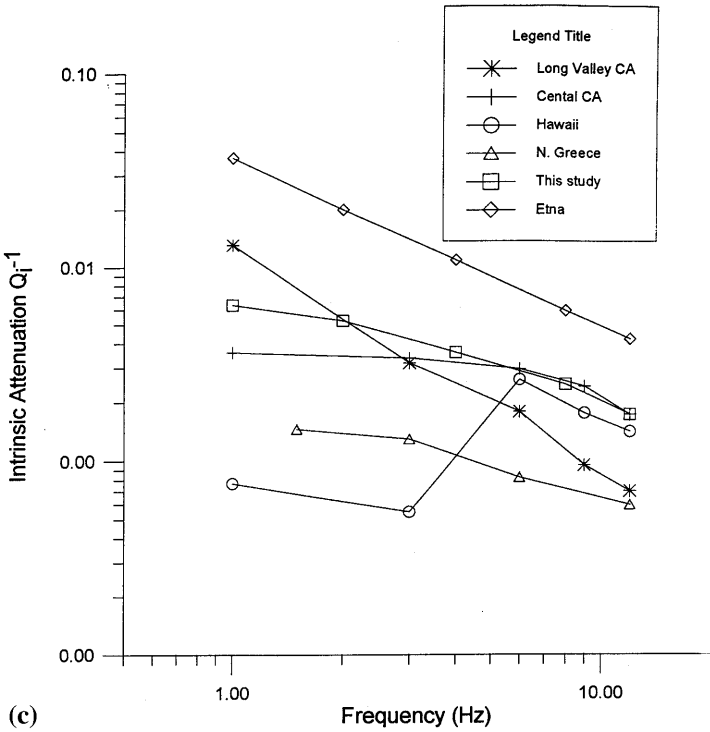
Hawaii
N. Greece
This study
Etna
0.10
0.01
0.00
Total Attenuation Q_d^{-1}
1.00
10.00
Frequency (Hz)
(a)
Legend Title
Long Valley CA
Cental CA
Hawaii
N. Greece
This study
Etna
0.10
0.01
0.00
0.00
Scattering Attenuation Q_s^{-1}
1.00
10.00
Frequency (Hz)
(b)

Figure 3(a,b)



(c)

Figure 3
Plot of the total (a), scattering (b) and intrinsic (c) attenuation calculated in the present study, versus frequency. The values of the same parameters calculated for Hawaii, Long Valley and Central California (Mayeda *et al.*, 1992), N. Greece (Hatzidimitriou, 1994), and Etna (Del Pezzo *et al.*, 1995) are also shown for comparison.

The next step was to evaluate Q_s and Q_i by solving eq. (7) and eq. (6), respectively and using the previously computed values of Q_d and Q_c. Table 1 lists the corresponding values for scattering and intrinsic attenuation for the five frequency bands examined.

In order to compare the scattering and the intrinsic attenuation with that inferred from the coda waves, Figure 2 depicts the Q_d^{-1}, Q_s^{-1}, and Q_i^{-1} values versus frequency, together with the obtained Q_c^{-1} values. Judging from this diagram we clearly see that the observed Q_c^{-1} is close to Q_i^{-1}, in agreement with finite-difference simulation results of Frankel and Wennerberg (1987) and laboratory experiments of Matsunami (1991). The analytical results of Shang and Gao (1988) point that in a highly scattering medium, coda decay is identical to Q_i^{-1}.

Similar observations have been published by Töksöz *et al.* (1988) for North America, Wu and Aki (1988) for Hindu-Kush, while Mayeda *et al.* (1991) for South California and McSweeney *et al.* (1991) for Alaska have reported Q_c^{-1}

values close to Q_s^{-1}. HATZIDIMITRIOU (1994) reported Q_c^{-1} values very close to Q_s^{-1} for short lapse times and intermediate between Q_s^{-1} and Q_i^{-1} for longer lapse times for North Greece.

In Figure 3 we plot for comparison the total scattering and intrinsic attenuation estimated in the present study versus frequency together with the results obtained from other regions. Judging from this figure we can see that both the total and intrinsic attenuation estimates for W. Greece agree well with those obtained for Central California, while the scattering attenuation estimate in this study displays a different behavior. The difference between the results from N. Greece and the present work can possibly be attributed to the higher tectonic activity and consequently higher heterogeneity present in the region of W. Greece. The coda Q values obtained are in good agreement with those obtained for the same region by TSELENTIS (1993) using a different data set.

From Table 1 we can obtain the frequency dependence of Q_i^{-1}, Q_s^{-1} and Q_c^{-1} for the region of W. Greece. The results show that Q_i^{-1} has a frequency dependence of $f^{-0.52}$, Q_s^{-1} has a frequency dependence of $f^{-0.36}$ and Q_c has a frequency dependence of $f^{0.58}$ which is similar to that of Q_i. This might imply that the frequency dependence of the coda wave attenuation in this region is due to the frequency dependence of intrinsic attenuation.

5. Conclusions

WENNERBERG's (1993) methodology has been applied to seismological data from Central Greece, in order to study the relative contribution of scattering and intrinsic attenuation to the total S-wave attenuation for frequencies 1, 2, 4, 8 and 12 Hz. Results show that both Q_i^{-1} and Q_s^{-1} have a frequency dependence with higher variations for Q_i^{-1}. Also that coda wave attenuation is very close to the intrinsic attenuation. The patterns of Q_i^{-1} and Q_s^{-1} with frequency are comparable to other estimates obtained from other areas.

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