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S - WAVE ATTENUATION IN NORTHERN GREECE

P. Hatzidimitriou*

ABSTRACT

The attenuation of shear waves in the crust is estimated, for frequencies between 1.5 to 12.0 Hz by applying a single station method based on the rate of decay of the S to coda waves amplitude ratio with distance. The data used come from local earthquakes that occurred in the Thessaloniki area in northern Greece during the period 1983-1989 and recorded by the telemetered network of the Geophysical Laboratory of the University of Thessaloniki. The esimated Q_s values are very close to the coda Q values estimated for the same area using the S to S single scattering model for lapse times between 30 to 100 sec but they are higher than the coda Q of earlier times (10 to 30 sec). The estimated Q_s is found to be strongly frequency dependent, proportional to $f^{0.91}$, which is very close to that of the coda Q. These results suggest that coda Q is a good measure of the S wave Q and that both scattering and anelastic attenuation are important with neither completely dominating in the area of northern Greece.

ΣΥΝΟΨΗ

Στην παρούσα εργασία υπολογίζεται ο παράγοντας ποιότητας Q_s των S κυμάτων στο φλοιό για συχνότητες μεταξύ 1.5 Hz και 12.0 Hz. Η Μέθοδος που εφαρμόστηκε βασίζεται στο ρυθμό ελλάτωσης με την απόσταση του λόγου του φασματικού πλάτους των S κυμάτων προς το φασματικό πλάτος των κυμάτων ουράς. Χρησιμοποιήθηκαν δεδομένα τοπικών σεισμών της περιόδου 1983-1989 που καταγράφηκαν από το τηλεμετρικό δίκτυο του Εργαστηρίου Γεωφυσικής του Πανεπιστημίου Θεσσαλονίκης. Οι τιμές του Q_s που υπολογίστηκαν βρίσκονται σε συμφωνία με τι τιμές Q που υπολογίστηκαν από τα κύματα ουράς για χρόνους μεταξύ 30sec και 100sec για την ίδια περιοχή, με την εφαρμογή του μοντέλου της απλής οπισθοδιασποράς, αλλά είναι υψηλότερες από τις τιμές του Q που υπολογίστηκαν από τα κύματα ουράς σε χρόνους μεταξύ 10sec και 30sec. Βρέθηκε επίσης ότι οι τιμές του Q_s εξαρτώνται από τη συχνότητα f, ανάλογα με $f^{0.91}$, που βρίσκεται σε συμφωνία με την εξάρτηση από τη συχνότητα του Q των κυμάτων ουράς. Από τα παραπάνω συμπεραίνεται ότι ο παράγοντας ποιότητας Q που προκύπτει από τα κύματα ουράς εκφράζει την απόσβεση των S κυμάτων και επίσης ότι η απόσβεση λόγω διασποράς και η ενδογενής απόσβεση συνεισφέρουν το ίδιο στην ολική απόσβεση των S κυμάτων στην περιοχή της βόρειας Ελλάδας.

ΕΙΣΑΓΩΓΗ - INTRODUCTION

The attenuation of seismic waves, expressed by the inverse of the quality factor (Q^{-1}), is one of the most important geophysical parameters which characterizes the materials through which the seismic waves propagate. There are two basic methods of measuring the attenuation of seismic waves, namely by

* Aristotle University of Thessaloniki, Geophysical Laboratory, 54006 Thessaloniki, Greece.

using the direct waves or the coda waves of the seismograms. Aki (1969), Aki and Chouet (1975) and Sato (1977) interpreted the coda waves as single backscattered S- to S- waves from heterogeneities in the crust and upper mantle. Since then, the rate of time decay of coda waves amplitude has been widely used (Herraiz and Espinoza, 1987) for the estimation of the coda attenuation (Q_c^{-1}). The equality of Q_c and S-wave Q (Q_s) estimated from direct waves or Lg waves has been reported in some studies (Rautian and Khalturin, 1978; Aki, 1980a; Herrmann, 1980; Roecker et al., 1982; Campillo et al., 1985). This observational result states that the use of coda waves is the easiest way to estimate Q_s (Nonelo-Casanova and Lee, 1991). However there is still some ambiguity of how the apparent attenuation inferred from coda waves is related to the attenuation of the direct S waves and what is the relative contribution of scattering attenuation and intrinsic attenuation to the coda and S wave attenuation (Frankel and Wennergerg, 1987; Sato, 1990; Frankel, 1991).

The scope of the present paper is to estimate the attenuation of S-waves for different frequencies using local earthquake data from the Thessaloniki area, northern Greece. We applied the single station method based on the rate of decay of the S- to coda waves amplitude ratio over distance for different frequencies (Aki and Chouet, 1975; Rautian and Khalturin, 1978, Aki, 1980a). For the same region the coda attenuation Q_c^{-1}, has been estimated (Hatzidimitriou, 1993a) for frequencies between 1.5 and 12.0 Hz and lapse times between 10sec and 100sec using the single S to S backscattering model of Aki and Chouet (1975) and a comparison is made between Q_c^{-1} and Q_s^{-1} values.

ΔΕΔΟΜΕΝΑ ΚΑΙ ΜΕΘΟΔΟΣ ΑΝΑΛΥΣΗΣ - DATA AND METHOD OF ANALYSIS

The absolute value of the Fourier transform $A_s(\omega)$ for direct S-waves can be written as

$$A_s(\omega)=S(\omega,\theta)R(\omega,\theta)D^{-1}\exp(-\omega D/2Q_s\upsilon) \qquad (1)$$

where $S(\omega,\theta)$ represents the source spectrum, θ is the source receiver direction, $R(\omega,\theta)$ is the site effect at the receiver, D is the source-receiver distance, õ is the velocity of wave propagation and Q_s is the S-wave transmission Q (Aki, 1980a).

According to the single S to S backscattering model proposed for the generation of coda waves (Aki, 1969; Aki and Chouet, 1975) the spectral amplitude $A_c(\omega,t)$, for lapse times t greater than about twice the S-wave travel time (Rautian and Khalturin, 1978) can be written as

$$A_c(\omega,t)=S_c(\omega)R(\omega)C(\omega,t) \qquad (2)$$

where $S_c(\omega)$ and $R(\omega)$ are the source factor and the site effect at the receiver, respectively, and $C(\omega,t)$ depends on frequncy and lapse time and is independent of the source-receiver distance and direction.

From equations (1) and (2), after averaging over many events which lie in a distance range ($D-\Delta D, D+\Delta D$) and keeping the time t, that coda wave amplitude is measured the same for all the events we get

$$<\ln\{DA_s(\omega)/A_c(\omega)\}>_{D+\Delta D} = a - bD \qquad (3)$$

where $b=\omega/2Q_s\upsilon$ and $<\chi>$ means the average over $D+\Delta D$. Thus we can estimate Q_s from a least squares fit of (3).

The major assumption in the above formulation is that averaging over many events at different azimuths in a distance range diminishes both the radiation

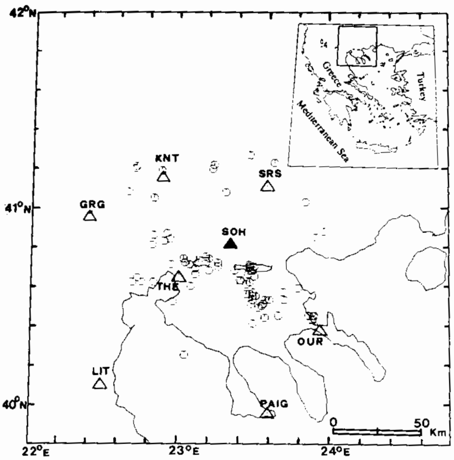

Fig. 1: Map showing the seismological stations of the network (triangles) and the epicenters of the events (circles) used in the estimation of Q_s from the SOH records.

Σχ. 1: Χάρτης των σταθμών του δικτύου (μαύρα τρίγωνα) και των επικέντρων των σεισμών δεδομένα των οποίων χρησιμοποιήθηκαν για τον υπολογισμό του Q_s από εγγραφές στο σταθμό SOH.

pattern and the directionally dependent site effects (Aki, 1980a; Roecker et al., 1982).

The data used in the present study come from local earthquakes recorded by the telemetered network which is operated by the Geophysical Laboratory of the University of Thessaloniki at northern Greece. The network started its operation in 1981 and the data we used cover the period 1983-1989. During that time the network had eight stations, all of them located on unweathered crystaline rocks, each one equipped with one vertical and two horizontal short period (1 Hz, S-13 Teledyne Geotech) seismometers. The signals from all stations are transmitted via telephone lines to the central station of Thessaloniki, (THE), digitized at 50 samples/second and the detected events are stored on magnetic tapes by a PDP 11/34 for later off-line processing.

The seismograms of all the well located events (more than one thousand earthquakes) were visually examined to find un clipped records and to check whether there were any recording problems such as noise, missed recordings, overlapping (a second earthquake at the coda of the first one) or early cut off 'the seismogram recording was terminated too early to have well developed coda 'aves).

For the estimation of $A_s(\omega)$ and $A_c(\omega)$ a time window of 256 points (5.12 sec) as taken for the S-waves from the vertical components and the same window ength, centered at time t=50sec from the origin time , was also taken for the oda waves. The selected time windows were tappered by a 10% Hanning window, ourier transformed, corrected for instrument gain and the average was taken ver octave frequency bands centered at 1.5, 3.0, 6.0 and 12.0 Hz. The time =50sec for the estimation of the coda amplitude was chosen because at that ıpse time all the records had well developed coda waves above the noise level Iatzidimitriou 1993a). We avoided to calculate the coda amplitude at different .mes and then to extrapolate at a common time (Aki, 1980a) in order to avoid lditional errors which would be introduced by this extrapolation.

Unfortunately, because of the low dynamic range of the network many records re clipped and therefore the S-wave amplitude could not be determined. In dition to that, the spatial distribution of the events for which the S to da wave amplitude ratio was estimated was confined inside the network and erefore only one station had good azimuthal coverage and the peripheral ations were also lacking data at close distances. For these reasons Q_s values re estimated only for the station, SOH, located in the center of the network using data of 184 earthquakes. In Figure 1 we show the epicenters of these rthquakes (circles) , the seismological stations of the network (open .angles) and station SOH (black triangle). The local magnitudes of these

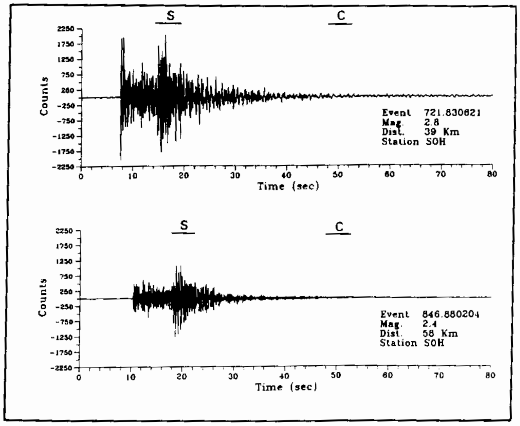

Fig. 2: Seismograms at SOH of two events with M_L magnitudes of 2.8 and 2.4 and epicentral distances of 39 and 58 Km, respectively. The time is measured from the erthquake origin time. The horizontal bars show the time windows used for the estimation of the S- and coda wave spectral amplitudes.

Σχ. 2: Εγγραφές στο σταθμό SOH δύο σεισμών με μεγέθη M_L 2.8 και 2.4 και επικεντρικές αποστάσεις 39 Km και 58 Km, αντίστοιχα. Ο χρόνος μετρείται από το χρόνο γένεσης του σεισμού. Οι οριζόντιες γραμμές δείχνουν τα παράθυρα που χρησιμοποιήθηκαν για τον υπολογισμό του φασματικού πλάτους των S κυμάτων και των κυμάτων ουράς.

events are between 2.0 and 3.5 , while the focal depths are between 8 and 20 km and the location errors are all less than 3 Km. SOH is located on unweatherd gneisses and a study on the relative site amplification based on the coda wave method (Phillips and Aki, 1986) showed no amplification for frequencies between 1.5 and 12.0 Hz (Hatzidimitriou, 1993b).

Figure 2 shows the seismograms at SOH of two events with M_L magnitudes of 2.8 and 2.4 and epicentral distances of 39 and 58 Km, respectively. The time is measured from the erthquake origin time. The horizontal bars show the time windows used for the estimation of the S- and coda wave spectral amplitudes.

RESULTS AND DISCUSSION

According to eq. 3, the natural logarithm of the ratio $D.A_s(\omega)/A_c(\omega)$ was plotted versus hypocentral distance D and averaged over a window of 10 Km with 50% overlapping. We had no data for distances less than 10 Km while at epicentral distances greater than 70 Km the data were rejected in order to avoid the refracted waves. Therefore the linear regression according to (3) was constrained between 10 and 70 Km. In Figure 3 we show the plots of $<\ln\{DA_s(\omega)/A_c(\omega)\}>_{D+\Delta D}$ versus distance D for the four frequency bands. Vertical bars indicate one standard deviation of the mean and the straight lines are the least wquares fit to the data with slope equal to b. In Table 1 the calculated values of the parameters a and b with their standard errors for each frequency are given. The values of Q_s have been estimated by $Q_s = \pi f/bu$, assuming the S-wave velocity u=3.5 Km/sec. We see that the values of b do not change with frequency, while the Q_s values show a clear increase with frequency. A least squares fit of the Q_s values to the relation $Q_s=Q_o f^n$, where f is the frequency, gave Q_o=85 and and=0.91.

The Q_s values found in the present study using the single station method are in good agreement with the Q_s values estimated from strong motion accelerograms of earthquakes occurred in this area, using the spectral decay of the log spectrum (Hatzidimitriou et al. 1993). These strong motion Q_s values are between 82 and 364, for epicentral distances between 16 and 119 Km and have been estimated for the frequency range between 4 and 10 Hz by assuming that Q is frequency independent.

The attenuation coefficient c = ω/2Qυ has been estimated by Papazachos (1992) by inverting a large amount of macroseismic data and modeling the anisotropic radiation pattern of the sources. The average c for the whole area

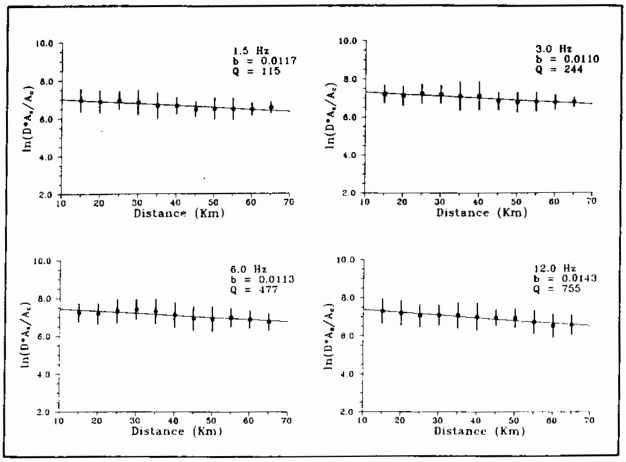

Fig. 3: Plots of the average of natural logarithm of S to coda amplitude ratio multiplied by the source-receiver distance D, versus distance, for frequencies 1.5, 3.0, 6.0, and 12.0 Hz. Vertical bars indicate one standard deviation of the mean and the straight lines are the least squares fit to the data.

Σχ. 3: Χαρτογράφηση του λογαρίθμου του γινομένου της απόστασης επί το λόγου του φασματικού πλάτους των S κυμάτων προς το φασματικό πλάτος των κυμάτων ουράς, σε συνάρτηση με την απόσταση D, για συχνότητες 1.5, 3.0, 6.0 και 12.0 Hz. Οι κατακόρυφες γραμμές δείχνουν την τυπική απόκλισηαπό το μέσο όρο. Οι ευθείες γραμμές έχουν υπολογιστεί με τη μέθοδο των ελαχίστων τετραγώνων.

of Greece was found equal to 0.0026 . If we assume that the macroseismic field represents S waves at frequencies between 1 and 2 Hz we get Q between 344 and 690. These values are considerably higher than the Q_s values obtained in the present study . However, the use of macroseismic data involves much larger epicentral distances than 70 Km which was the maximum distance in this study and therefore the high Q values obtained by the macroseismic field may represent the average Q of the crust and the upper parts of the mantle.

For the same area and using the same data, Hatzidimitriou (1993a) estimated the coda Q values by applying the single backscattering model of Aki and Chouet (1975) for the frequency bands of 1.5, 3.0, 6.0 and 12.0 Hz, and for lapse time windows of 10-20sec, 15-30sec, 20-45sec, 30-60sec and 50-100sec. In Figure 4 we plotted these Q_c^{-1} values for different lapse times and the Q_s^{-1} values estimated in the present study, versus frequency. As we can see from this plot the Q_s^{-1} values are very similar with

Table 1: Values of a and b in eq. 3 with their standard errors. The values of Q_s have been estimated by $Q_s = \pi f / b\upsilon$, assuming the S-wave velocity υ=3.5 Km/sec.

Frequency	a	b (Km^{-1})	Q_s
1.5 Hz	7.143±0.076	0.0117±0.0018	115±18
3.0 Hz	7.415±0.071	0.0110±0.0016	244±36
6.0 Hz	7.557±0.098	0.0113±0.0023	477±96
12.0 Hz	7.524±0.067	0.0143±0.0016	755±83

the Q_c^{-1} values estimated for the longer lapse times between 30 and 100 sec but there is considerable discrepancy between the two at the short lapse time range 10 to 30 sec.

The dependence of the coda Q on the lapse time has been observed in many studies (Rautian and Khalturin 1978; Roecker et al., 1982; Gagnepain-Beyneix, 1987; Kvamme and Havskov,1989; Ibanez et al., 1990). This dependence has been attributed to the change from single scattering to multiple scattering as time increases (Gao et al., 1983), to an increase of Q with depth (Roecker et al.,

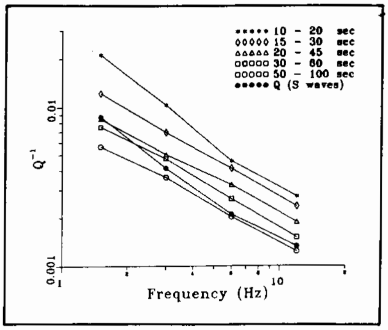

Fig. 4: Plots of the Q_c^{-1} values for different lapse times and the Q_s^{-1} values estimated in the present study versus frequency.

Σχ. 4: Χαρτογράφηση των τιμών Q_c^{-1} που υπολογίστηκαν από τα κύματα ουράς για διάφορα παράθυρα χρόνων από το χρόνο γένεσης του σεισμού και των τιμών του Q_s^{-1} που υπολογίστηκαν στην παρούσα εργασία σε συνάρτηση με τη συχνότητα.

1982; Pulli, 1984), to changes in the modal content of coda with lapse time (Phillips and Aki, 1986), to incorrect or time-variable geometrical spreading coefficient (Wang and Herrmann, 1988) or to an increase of the wave velocity with depth (Herak, 1991). The discrepancy observed in Figure 4 between the shear wave attenuation and the coda attenuation for very short times supports the interpretation that the lapse time dependence of the Q_c values is mostly due to a real increase of Q with depth since the early coda sample the shallower and more attenuative parts of the crust while at later times the sampling volume increases and thus the estimated Q_c values approach the Q_s values which represent the whole crust.

The similarity of apparent Q^{-1} of S-waves or Lg waves with Q_c^{-1} determined by the single scattering method, in agreement with the results of the present study, has been noted in several other cases (Rautian and Khalturin, 1978; Herrmann, 1980, Aki, 1980a, Roecker et al., 1982,; Rovelli, 1982; Campillo et al., 1985). In these studies the detailed lapse time dependence of coda Q has not been presented but in general the Q_c values were derived for times later than 10 to 30 sec. However, Q^{-1} values obtained from the first arrivals of seismic pulses in seismograms should represent the total attenuation caused both by scattering and intrinsic losses (Frankel and Wennerberg, 1987; Gao et al. 1993) in contrast with the attenuation deduced from the coda waves. Finite difference simulation results (Frankel and Wennerberg, 1987; Frankel, 1989), laboratory experiments (Matsunami, 1991) and analytic results (Shang and Gao, 1988) have shown that coda Q^{-1} should be identical or very close to the intrinsic attenuation. Thus it seems that there is a discrepancy between theoretical predictions and observations (Sato, 1990). Mayeda et al., (1992) calculated the expected Q_c^{-1} by fitting the single scattering formula of Aki and Chouet (1975) to theoretical codas obtained by using the integral equation of Zeng et al., (1991). The theoretical Q_c^{-1} were very close to the intrinsic attenuation but the observed Q_c^{-1} values were intermediate between the total Q^{-1} and the theoretical Q_c^{-1}. This discrepancy was attributed to a depth dependent intrinsic Q that increases with depth which causes the observed attenuation deduced from the coda waves to be closer to the total attenuation than to the intrinsic attenuation, even in strong scattering environments.

Observations have shown that Q_s is frequency dependent proportional to f^n, where n is between 0.5 and 0.9, in high frequencies from 1 to 30 Hz (Fedotov and Boldyrev, 1969; Aki, 1980; Console and Rovelli, 1981; Sato, 1990), so the value of 0.91 found for northern Greece is in very good agreement with these studies and further supports the applicability of the method which we used for the estimation of the Q of shear waves. Additionaly, the frequncy dependence of the Q_s values is similar with that of the coda Q (Hatzidimitriou, 1993a). For lapse times between 10-20sec Q_c show a frequncy dependence proportional to $f^{1.0}$ and for the other time windows proportional to $f^{0.75}$.The similarity in the frequency dependence of the Q_s and Q_c values as the one observed here has been also reported in other regions (Aki, 1980; Roecker et al., 1982; Rovelli et al., 1988) and support the concept that coda waves are generated by the S to S scattering and that the attenuation mechanism for coda waves is similar to that of the direct S waves (Aki, 1980b). The results obtained in the present study suggest that both scattering and anelastic attenuation are important, with neither completely dominating (Dainty and Toksoz, 1977; Dainty et al., 1987) and that the relation between scattering and anelastic attenuation in the coda is a complex one.

ΕΥΧΑΡΙΣΤΙΕΣ - ACKNOWLEDGMENTS

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