Coda 파를 이용한 경상분지에서의 Q 값 추정

Q estimates using the Coda waves in the Kyeongsang Basin

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국문요약

이 연구의 목적은 경상분지에 설치되어있는 지진계에 기록된 자료를 이용하여 coda Q 값을 계산하고 그것이 어느 정도 주파수에 의존하는 가를 추정해 보는 것이다. 분석한 주파수 영역은 1.5 Hz에서 18 Hz 까지이다. 자료는 3 조로 나누어 처리하였으며, 단일 산란 이론을 적용하였다. 그리고 매질의 특성을 살펴보고자 minimum mean free path 와 비탄성 감쇠 계수를 계산했다. 계산 결과는 Q_0 값이 83.85～155.88 로 단층대를 지나는 경로를 가진 자료에서 비교적 낮은 Q 값이 결정되었고, n 은 0.7615～1.0466 이다.

***주요어** : Coda Q, 단일 산란 이론, minimum mean free path, 비탄성 감쇠 계수*

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1. Introduction

The retrieval of earthquake source parameters and the assessment of seismic hazards in a region both require knowledge of fundamental properties of the medium, such as attenuation and velocity, which affect the propagation of seismic waves.

Attenuation of seismic waves is customarily described by the parameter Q called the quality factor(1). Q is a dimensionless quantity that expresses the wave amplitude decay that occurs when a wave propagates through a medium, which cannot be attributed to geometrical spreading. It is a combination of intrinsic scattering, and other forms of energy decay due to randomly distributed inhomogeneities in the transmitting medium.

Since it is rather difficult to measure attenuation from short-period seismic waves (1 to 30 Hz) using a deterministic approach because of the large number of parameters required to adequately explain a high-frequency seismogram, Aki(2) initiated the application of a statistical approach to the attenuation of high-frequency seismic waves. He showed that the coda waves of local earthquakes could be separated

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to provide information about the source and the path effects, and applied it to get estimates of Q. Coda waves comprise of the part of seismograms after all the direct waves such as P, S, and surface waves.

The coda wave model of Aki(2), extended by Aki and Chouet(3), has been widely used since 1978, because of its simplicity and ease of application, to get estimates of regional Q (4)(5)(6). The subject of this study is to estimate seismic coda Q values and its dependence on the frequency range from 1.5 to 18 Hz in the Kyeongsang Basin, using the S-to-S single-backscattering model of Aki and Chouet(3). A large Cretaceous basin, the Kyeongsang Basin, developed in southeastern Korea in which the non-marine sediments, volcaniclastic and volcanic rocks of the Kyeongsang Supergroup were deposited. The Bulgugsa Granite Series were implaced in the southern part of the peninsula, mostly in the Kyeongsang Basin, in late Cretaceous times.

Since May 1994, the seismicity of the region has been monitored using short period seismographs by the Korea Institute of Geology, Mining & Materials (KIGAM). The data set consists of 22 microearthquakes, magnitudes ranging from 2.0 to 4.3, during December 29, 1996 and May 14, 1998, selected on the basis of spatial distribution and good signal-to-noise ratio. A sampling frequency is 100 Hz.

The earthquake epicenters and stations are plotted in Figure 1. Table 1 is a listing of the location parameters for these events.

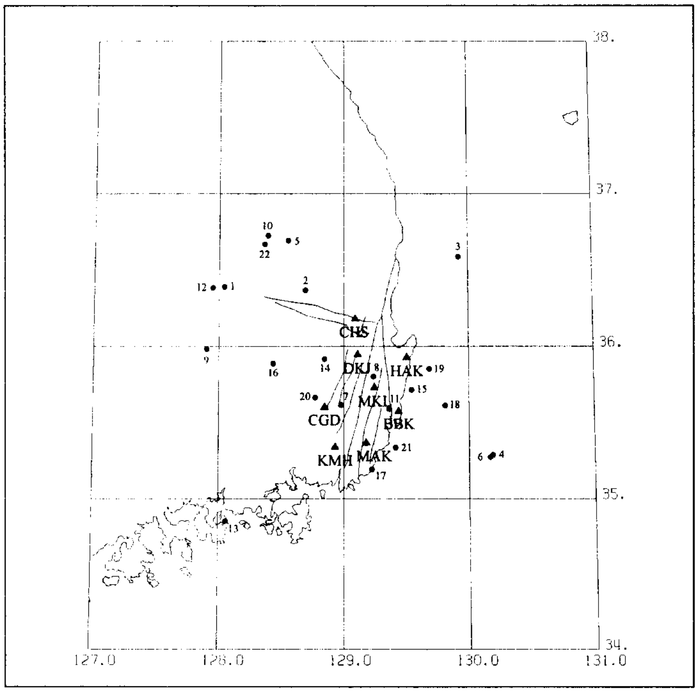

Figure 1. Study area in the Kyeongsang Basin. Triangles represent seismograph stations, and solid circles represent earthquakes used in this study.

Table 1. Earthquake Hypocenters, Magnitudes, Epicentral distances, and Number of data

Event #	Date	Time	Latitude (°N)	Longitude (°E)	Depth (km)	Local Magnitude	# of Data
1	96/12/29	01:55:03.82	36.39	128.04	4.45	2.8	2
2	97/01/08	13:06:22.31	36.37	128.69	12.46	2.6	1
3	97/03/17	11:11:48.23	36.59	129.92	4.78	3.0	1
4	97/03/26	04:38:08.62	35.29	130.19	17.73	2.6	2
5	97/05/19	08:29:06.73	36.69	128.55	12.19	2.4	1
6	97/06/04	01:48:05.29	35.28	130.17	14.75	2.5	2
7	97/06/16	22:51:13.96	35.61	128.98	1.42	2.9	3
8	97/06/26	03:50:23.19	35.80	129.24	14.66	4.3	1
9	97/06/30	23:48:47.48	35.98	127.90	10.55	2.8	4
10	97/08/05	12:45:53.29	36.72	128.39	4.49	3.3	6
11	97/09/17	09:33:18.46	35.59	129.36	10.69	3.1	4
12	97/09/26	21:16:37.27	36.38	127.95	2.14	2.6	1
13	97/10/02	23:47:16.94	34.85	128.06	6.09	2.8	4
14	97/10/11	19:50:28.76	35.92	128.84	10.93	2.7	7
15	97/12/04	14:02:52.71	35.72	129.54	10.00	2.0	1
16	98/01/13	10:08:03.28	35.89	128.43	14.96	2.8	3
17	98/01/20	02:06:09.59	35.19	129.22	4.05	2.5	2
18	98/04/11	16:21:13.08	35.62	129.81	23.22	2.6	2
19	98/04/15	07:28:28.82	35.85	129.68	15.53	2.8	4
20	98/04/24	04:39:55.79	35.67	128.77	14.60	2.4	2
21	98/04/29	01:23:04.87	35.34	129.41	14.67	2.2	1
22	98/05/14	14:23:10.05	36.67	128.36	7.88	2.6	1

2. Data Analysis

Attempts to explain the generation of coda waves have been made in terms of various models involving the scattering of primary waves. These can be grouped into single or weak scattering models(2)(3)(7), multiple scattering models(8)(9)(10), and very strong scattering or diffusion models(3)(8).

Single-scattering models assume that the scattered wavefield is weak and does not generate secondary scattering on encountering another scatterer(11). Also, the Born approximation which neglects the energy lost from the direct wave during the scattering process is often invoked.

The single-backscattering model of Aki and Chouet(3) considers coda waves as being composed of the superposition of backscattered body waves from numerous randomly distributed heterogeneities in the earth's crust and upper mantle. The model assumes that the earthquake and the seismic station are located at the same point in an unbounded, homogeneous, and isotropic medium containing a random but uniform spatial distribution of heterogeneities. Aki and Chouet(3) showed that the time dependence of coda wave amplitudes, $A(\omega \mid t)$, on a narrow bandpass filtered seismogram can be written as

$$A(\omega \mid t) = C(\omega)\, t^{-a} \exp(-\omega t/2Q_c) \qquad (1)$$

where $\omega = 2\pi f$ is the angular frequency, $C(\omega)$ is the coda source factor, a is a constant that depends on geometrical spreading and takes values of 1 and 0.5 for body wave and surface wave scattering, respectively, Q_c is coda quality factor, and t is lapse time, that is, the time measured from the origin time of the earthquake. In this study, $a=1$ is assumed.

Equating natural logarithms of both sides gives

$$\ln[A(\omega \mid t)\cdot t] = \ln[C(\omega)] - \omega t/2Q_c \tag{2}$$

Thus, left side is a linear function of t with slope equal to $(-\omega/2Q_c)$.

To process the data, an automated moving window computer code was developed to work interactively with the Seismic Analysis Code (SAC) created by Joe Tull at LLNL(12) .

Experience indicates that if $t_s - t_0$ is the time between the S-wave arrival time (t_s) and the origin time (t_0) , then often after $2(t_2 - t_0)$ and always after $3(t_s - t_0)$, the general form of the coda is established(13). Kvamme and Havskov(14) suggested that 30 sec time window is the best length of the time window. Thus in order to obtain the most stable results with a maximum number of observations, a fixed time window of 30 sec was chosen for most of the analysis. And start time of the coda window was selected at times equal to triple the S-wave travel time from origin.

To aid in the interpretation of an effect of the fault zone on the value of Q_c, data were sorted out 3 groups as follows.

Group I : Earthquake-Station paths don't pass through the fault zone (Inland)
Group II : Earthquake-Station paths pass through the fault zone
Group III : The same as Group I, but epicenter located in the coast and/or the sea

3. Results

A total of 385 Q_c measurements covering 55 different paths were made. Q_c values were determined using all events, but because of variable noise conditions, not all combinations of event/station/frequency band could be used.

Figure 2 is a plot of all Q_c measurements versus frequency for each group and shows that there is a definite frequency dependence of Q_c in the study area. The results for data from each group are summarized in Table 2 and Table 3. In all regions where coda Q measurements have been carried out, a positive correlation between Q_c and frequency of the form

$$Q_c = Q_0 f^n \tag{3}$$

has been noted.

In the context of the single-scattering theory, coda Q_c is an effective Q since the energy scattered away from the primary field is lost unless it is scattered towards the seismometer(15). Thus

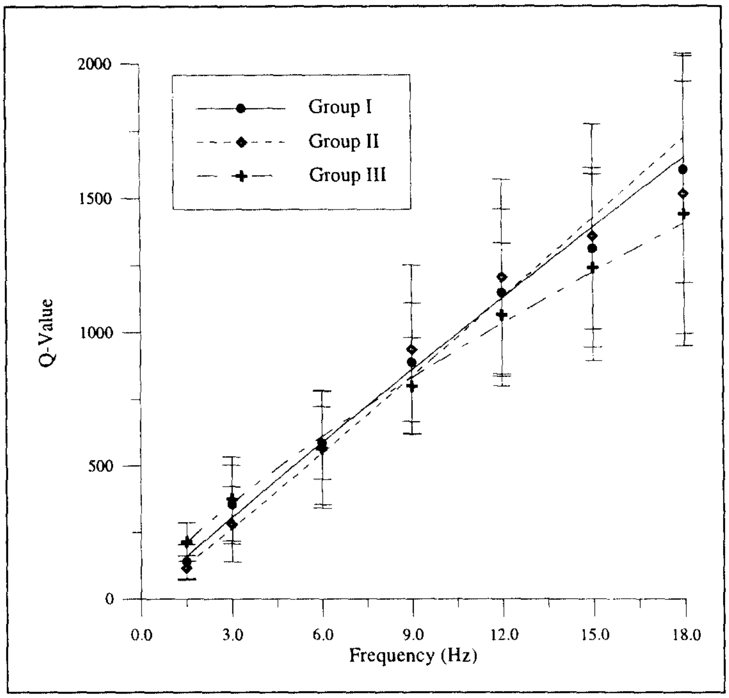

Figure 2. Summary of results for coda Q values with frequencies. Each 3 curve indicates the best fitting by linear regression. Numerical results are summarized in Table 2 and Table 3.

Q_c is a combination of both intrinsic attenuation, Q_i, and attenuation due to scattering, Q_s. From observations in various areas of a strong frequency dependence of Q_c, the value of Q_c at 1 Hz, and the intensity of current tectonic activity, Aki(15) concluded that scattering was the dominant contributor to the frequency dependence of Q_c. When scattering dominates over intrinsic friction, estimates of apparent Q made from backscattered coda vary with frequency(16).

Dainty(17) proposed that the observed Q_c can be expressed as

$$\frac{1}{Q_c(f)} = \frac{1}{Q_i} + \frac{1}{Q_s} = \frac{1}{Q_i} + \frac{v}{2\pi f L} \tag{4}$$

where v is velocity and L is the mean free path. The mean free path is a 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. The mean free path gives an idea of the distribution of scatterers in the earth thus providing useful information on the tectonic characteristic of the region.

However, assuming that scattering is the dominant contributor to attenuation in this study area, that is $Q_i \rightarrow \infty$, the minimum mean free path, $L_{\min} = vQ_c/2\pi f$ can be estimated using Dainty's(17) model.

Values of L_{min}, calculated from the mean values of Q_c and with an S-wave velocity of 3.5 km/sec(18), are shown in Table 2. The L_{min} are almost constant, irrespective of the frequency. Frequency-independent L_{min} from coda wave analyses at relatively short lapse times have also been observed in the Hindu Kush region of Afghanistan ($L_{min} \sim 40$ km)(4), in New England, United States ($L_{min} \sim 70$ km)(11), in Baja California, Mexico ($L_{min} \sim 16$ km)(19), and in the Dead Sea region ($L_{min} \sim 35$ km)(6).

In Table 2 we have also listed the corresponding values of the coefficients of anelastic attenuation, γ. The relationship between γ and Q is $\gamma = \pi f / QU$ (20), where f is the frequency and U is the group velocity. For the calculation in Table 2, we have also used a value of U equal to the S-wave velocity (3.5 km/sec).

Table 2. Mean values of Attenuation

Frequency (Hz)	Group I			Group II			Group III		
	Q	L_{min} (*km*)	γ (*km*$^{-1}$)	Q	L_{min} (*km*)	γ (*km*$^{-1}$)	Q	L_{min} (*km*)	γ (*km*$^{-1}$)
1.5	140.399 ±46%	52.25	0.0096	116.360 ±39%	43.21	0.0116	214.428 ±34%	79.63	0.0063
3	354.624 ±42%	65.85	0.0076	280.439 ±50%	52.07	0.0096	375.601 ±42%	69.74	0.0072
6	585.719 ±25%	54.38	0.0092	212.548 ±37%	52.68	0.0095	562.112 ±39%	52.19	0.0096
9	887.571 ±25%	54.94	0.0091	314.815 ±34%	57.94	0.0086	798.747 ±23%	49.44	0.0101
12	1147.72 ±27%	53.28	0.0094	1206.47 ±30%	56.00	0.0089	1066.26 ±25%	49.50	0.0101
15	1312.88 ±23%	48.76	0.0103	1360.48 ±31%	50.52	0.0098	1242.15 ±28%	46.13	0.0108
18	1606.51 ±26%	49.72	0.0101	1517.14 ±34%	46.95	0.0106	1442.03 ±34%	44.63	0.0112
Average		**54.17** ±5.22	**0.0093** ±0.0008		**51.34** ±4.69	**0.0098** ±0.0009		**55.89** ±12.38	**0.0093** ±0.0017

Table 3. Coefficients for $Q = Q_0 f^n$ and their Statistical values

	Q_0	n	$\sigma(Q_0)$	$\sigma(n)$	r *
Group I	**107.9550**	**0.9439**	1.0918	0.0415	0.9952
Group II	**83.8509**	**1.0466**	1.1000	0.0451	0.9954
Group III	**155.8770**	**0.7615**	1.0474	0.0219	0.9979

* Correlation Coefficient

4. Discussion

Measurements of the coda Q in the Kyeongsang Basin for 3 groups with the frequency range from 1.5 Hz to 18 Hz show a strong frequency dependence. Assuming that the attenuation is entirely due to the scattering loss, an almost constant minimum mean free path of about 54 km, 51 km, 56 km for Group I, Group II, Group III was found respectively.

Group II has relatively the low Q_c value (high attenuation) at 1 Hz, and strong frequency dependency ($n \approx 1.05$) to other ones. In general, this results agree with the phenomena that tectonically stable regions such as the central United States exhibited almost no frequency dependence, while active areas in which processes such as folding, faulting, and subduction are likely to introduce strong heterogeneity show significant frequency dependence of Q_c, and the low Q_0. There are however, some reservations as to the validity of these correlations; for example, the coda Q measurements in New England(15), which is a nontectonic region, show a very strong frequency dependence at lapse times less than 100 sec. If we assume that the above correlation is valid, then the Kyeongsang Basin region seems to be highly heterogeneous (at Group I, Group II).

In this study we get the Q_0 value in 83.9～108.0 range. These values of Q_0 appear higher than those obtained by other authors in the same region. Jun *et al.*(21) found a value Q_0=38.4609 by a different method (Sato's method(7)). Baag(22) estimated Q_0=42.4151 with the 20 sec window length. The increase in coda Q as a function of window length is thought to reflect an increase of Q with depth, because coda waves for a longer time window will sample deeper parts of the crust.

5. Conclusions

Using the single-scattering method, detailed attenuation parameters for the Kyeongsang Basin was obtained. The major findings of this study are as follows:

1. Absorption structure of the Kyeongsang Basin appears highly heterogeneous.
2. A frequency dependence of coda Q in the form of $Q_c = Q_0 f^n$ is observed in the range of frequencies. The value of n is not constant throughout the study area.
3. Group II (earthquake-station paths pass through the fault zone) have a relatively low Q_0 (≈ 83.9) value to other ones and strong frequency dependence ($n \approx 1.05$). Aki (1980) noted that the structural boundaries and faults can more effectively scatter waves propagating perpendicular to their planes.
4. $L_{\min}$ values are 51～56 km, and the values of the coefficient of anelastic attenuation γ are 0.0093～0.0098 km^{-1}.

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