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Seismic Wave Attenuation in the Vicinity of Kyoto

By Kennosuke OKANO and Isamu HIRANO

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Abstract

A method is devised to examine inelastic properties from maximum amplitude data obtained by two types of seismographic instruments with different frequency responses. As a result of the present analysis based on data obtained at Abuyama, attenuation characteristics of the seismic body waves in the vicinity of Kyoto are found to be different between two distance ranges, that is, at distances less than about 40 km and those greater.

At greater distances, the specific dissipation factor Q of P and S waves can be estimated to be about 500 and 800 respectively. At distances less than 40 km, the inelastic properties could not be extracted by the present method. This indicates that various causes, including intrinsic attenuation, are related to the amplitude variation at near distances. It is, however, safely concluded that the specific dissipation factor at distances less than 40 km is much smaller than that at those greater.

1. Introduction

One of the present authors[1] has recently pointed out that the aftershock activity in the vicinity of Kyoto varies with focal zones. The regional variation of aftershock activity may be considered to reflect the regional difference in the physical and geophysical properties of the earth's crust in question. This paper examines attenuation of seismic waves transmitted in various zones near Kyoto as the first step toward clarifying the relation between the physical properties of the crust and seismic activity.

2. Method of Analysis

At Abuyama Seismological Observatory, two types of seismographic systems with different overall frequency responses have been used for the routine observation of microearthquakes in the vicinity of Kyoto. A method was devised in the present paper to extract useful information concerning the inelastic properties from maximum amplitude data obtained by these two seismographic instruments.

The ratio of the maximum amplitudes obtained by these two instruments with different frequency responses is considered as independent from the radiation pattern and also from the earthquake magnitude if the source spectra are considered as being white. Furthermore, this ratio is not affected by geometrical spreading. Therefore the maximum amplitude ratios, if corrected for the instrumental responses, may provide us information concerning the inelastic properties of the crust where seismic waves are transmitted.

Let us designate the amplitude recorded by the instrument of which the frequency response is $I_i(f)$ by $A_i(f)$, where f is the frequency. $A_i(f)$ can be written as

$$A_i(f) = A_o(f)\ exp(-\pi fr/Qv)\ I_i(f)\ G(r) \quad \text{.................................(1),}$$

where $A_o(f)$ is the amplitude at the source, Q is the specific dissipation factor, $G(r)$ is geometrical spreading, v is the velocity of seismic wave and r the focal distance. The instrument with the response $I_1(f)$ is designated by instrument-1, and the instrument with response $I_2(f)$ by instrument-2. The ratio of the maximum amplitude obtained by instrument-1 to that by instrument-2 can be written as

$$A_1(f_1)/A_2(f_2) = exp\ \{-\pi kt(f_1 - f_2)/Qv\}\ I_1(f_1)/I_2(f_2) \quad \text{...........(2),}$$

where the focal distance is expressed in terms of *P-S* time t and Omori's Constant k, f_1 and f_2 are the frequency of the maximum amplitude recorded by instrument-1 and that by instrument-2 respectively. f_i's are given by

$$(\partial ln\ I_i/\partial f)_{f=f_i} = \pi kt/Qv \quad \text{..(3).}$$

Another assumption implied in equations (2) and (3) is the independence of Q from frequency.

The curve representing the dependence of the maximum amplitude ratio to *P-S* times can be calculated from equation (2) if Q is given. The observed ratios of the maximum amplitudes are compared with theoretical curves calculated for various Q-values from equation (2) to determine Q-value. A plot of the observed frequencies of maximum amplitudes vs. *P-S* times can also be used for an estimation of Q-value by being compared with theoretical curves calculated for various Q-values by the use of equation (3).

3. Instrument and Data

As mentioned above, the amplitude data obtained by the two instruments are used for the present study. The response curves of these instruments are shown in Fig. 1. Instrument-1 consists of a 1.00-sec pendulum and a 0.02-sec galvanometer, with a flat response for particle velocities in the 3–25 Hz band. The peak system magnification is about 65,000 at about 33 Hz. Instrument-2 consists of a 0.70-sec pendulum and a 0.35-sec galvanometer, with the peak system magnification of about 16,000 at about 2.5 Hz.

Some of the seismic records by the two instruments are reproduced in Fig. 2. Each pair records the same event. The paper speed of instrument-1 is twice as high as that of instrument-2. The seismic records are arranged in order of the *P-S* times of the events. As is easily found from Fig. 2, the indications are generally that the amplitudes of the records by instrument-1 are larger than those by instrument-2 for events with short focal distances and become comparatively smaller with the increase of the focal distance.

A total of about 150 earthquakes with magnitude of 1.0 ca. to 3.0 ca. occurring in the vicinity of Kyoto is examined for an estimation of the seismic wave attenuation.

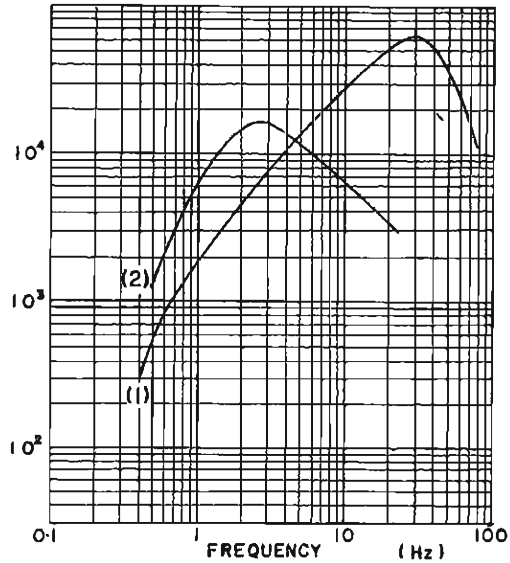

Fig. 1. Frequency response curves of instruments:
(1) Instrument-1 (T_1 = 1.00 sec, T_2 = 0.02 sec),
(2) Instrument-2 (T_1 = 0.70 sec, T_2 = 0.35 sec).

In the following, we denote the maximum amplitude for instrument-1 by A_S, and that for instrument-2 by A_L.

4. Results

(4–1) Attenuation of *P* Waves

The observed ratios of the maximum amplitudes for *P* waves A_S/A_L are plotted against *P-S* times in Fig. 3. Also in this figure are shown the theoretical curves calculated from equation (2) by assuming Q=100, 300 and 500. As is known from Fig. 3, the observed ratios are widely scattered in the range of 0.5 to 6.0 for events with focal distances less than about 40 km. On the contrary however, observed amplitude ratios are little scattered at distances greater than about 40 km. The plot of the amplitude ratios vs. *P-S* times at great distances is well represented by the theoretical curve for the *Q*-value of 500. It is difficult to determine *Q*-value accurately at distances less than 40 km from the variation of observed amplitude ratios with *P-S* times because of the wide scatter, although the theoretical curve representing Q=100 would be approximatedly fitted to the plot over a short distance.

The frequencies of the maximum amplitudes obtained by the two instruments are plotted against *P-S* times in Figs. 4 and 5. Fig. 4 shows the result for instrument-1 and Fig. 5 that for instrument-2. The curves drawn in Fig. 4 show the dependence of the frequency of the maximum amplitude to *P-S* times calculated from equation (3) for the *Q*-values of 100, 300, 400 and 500 respectively.

It is found from Figs. 4 and 5 that the frequencies of the maximum amplitudes

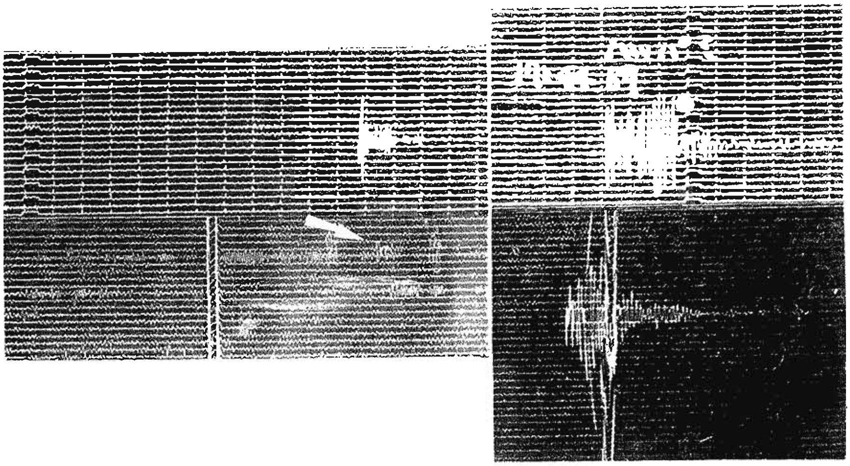

Fig. 2-I

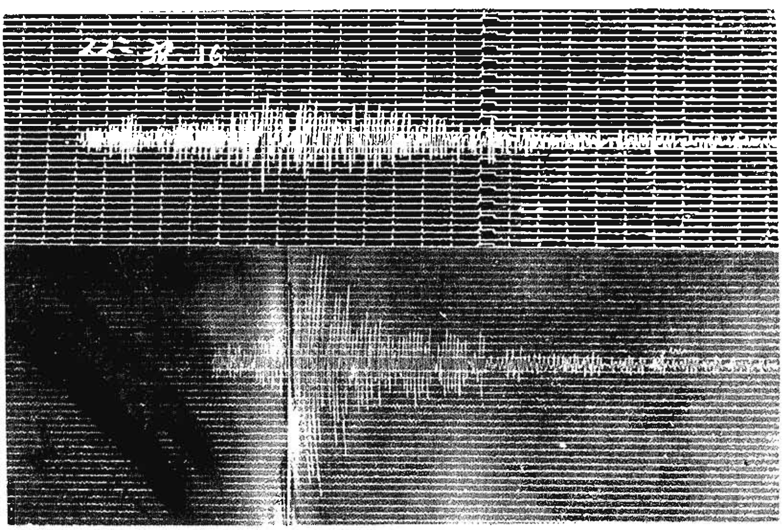

Fig. 2-II

are also widely scattered at distances less than about 40 km. For instance, the frequencies are ranged from 10 to 30 Hz in the case of instrument-1 over short distances. At distances greater than 40 km frequencies higher than 15 Hz are not observed. As is estimated from Fig. 4, Q-value is about 100 for distances less than 40 km, and 400 to 500 for those greater.

In the case of instrument-2, the frequency of the maximum amplitude is calculated from equation (3) to be about 2.5 Hz independently of focal distances for the Q-values of 100 to 1000. The observed frequencies shown in Fig. 5 are ranged from 8 to 30 Hz, which do not agree with the calculated value. The disagreement might

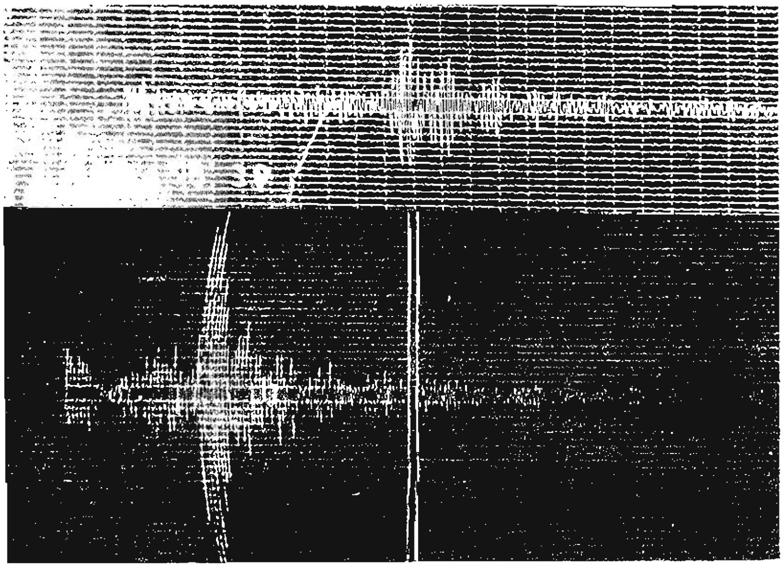

Fig. 2-III

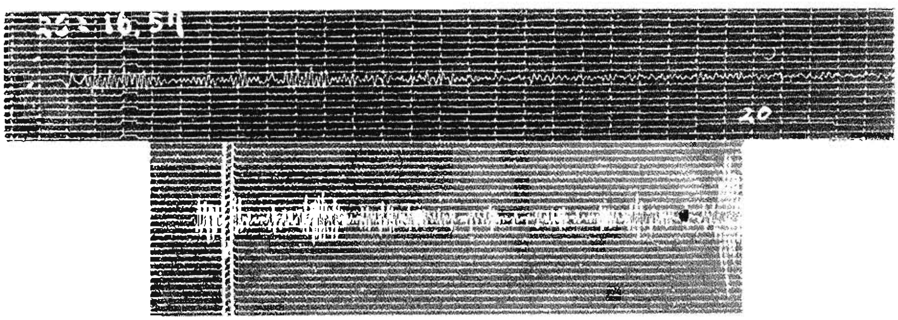

Fig. 2-IV

Fig. 2. I-IV Seismic records obtained by imstrument-1 and instrument-2. Each pair records the same event; the upper is the record of instrument-1 and the lower that of instrument-2. The paper speed of instrument-1 is twice as high as that of instrument-2.

be due to either the assumption of the white spectrum at the source or the assumption of the independence of Q from frequency or both. Actually, under both assumptions the frequency of the maximum amplitudes does not exceed the frequency giving the peak system magnification as is known from equation (3).

Figs. 3, 4 and 5 show that the variation of the maximum amplitudes with distances is caused by various mechanisms depending on the distance range. It may be reasonably considered from the above results that the decrease of the maximum amplitudes at distances greater than about 40 km is accounted for by the intrinsic attenuation. In a range less than 40 km, however, not only the intrinsic attenuation but other

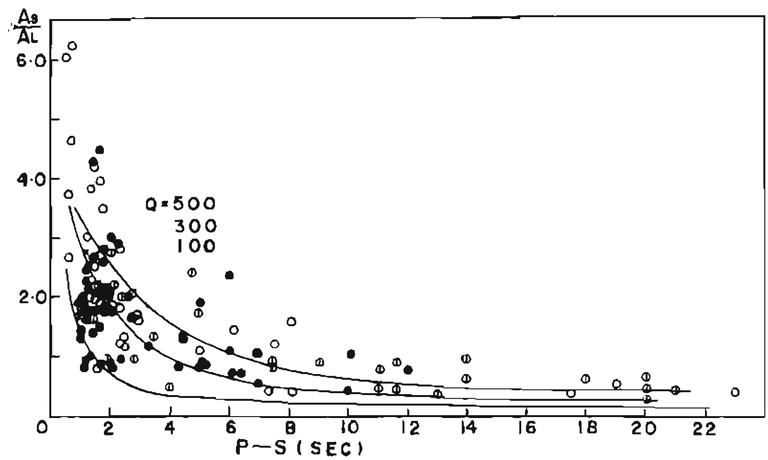

Fig. 3. Ratios of the P maximum amplitude obtained by instrument-1 to that by instrument-2 (A_S/A_L). Solid curves show the theoretical variations calculated from equation (2). In abscissa is taken P-S time.

factors such as the inhomogeneity of the earth's crust are associated with the amplitude decrease. In this connection, details are discussed again in Section 5.

(4–2) Attenuation of S waves

The observed ratios of the maximum amplitudes for S waves A_S/A_L are plotted against P-S times in Fig. 6. In this figure are also shown the theoretical curves calculated from equation (2) for the Q-values of 100, 400 and 850 respectively. The observed ratios of the maximum amplitudes, if compared with the theoretical ones, indicate that Q-value is 600 to 850 at distances greater than about 40 km. The most probable value is computed to be 850. Over shorter distances Q-value cannot be uniquely determined because of the wide scatter of the amplitude ratios, which may suggest that various causes are associated with the amplitude decrease at distances near focus.

As is known from Figs. 3, 4, 5 and 6, attenuation characteristics can be considered as different between two regions, that is, the distance range less than about 40 km and those greater, for S wave as well as for P wave. This tendency can be seen in the observed frequencies of the maximum amplitudes of S waves.

Fig. 7 shows the relation between the observed frequencies of the S maximum amplitudes and the P-S times for the two instruments used. The upper figure is the result for instrument-1 and the lower that for instrument-2. The curves drawn in the upper figure show the dependence of the frequencies of the S maximum amplitudes to P-S times calculated from equation (3) for the Q-values of 100, 400 and 600 respectively. Fig. 7 shows that attenuation characteristics may be considered to be different between two regions, that is, at distances less than about 40 km and at those greater. At distances greater than about 40 km the observed frequencies, if compared with the theoretical ones, indicate that the probable Q-value is about

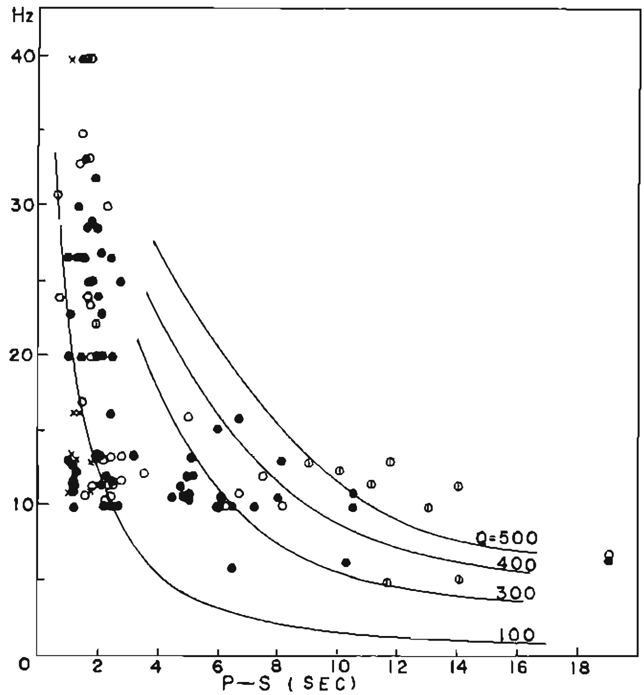

Fig. 4. The observed frequencies of the P maximum amplitudes obtained by instrument-1 plotted against P-S times. The theoretical frequencies as a function of P-S times are also shown by solid curves.

400 to 600. Over shorter distances, the frequencies of the S maximum amplitudes are widely scattered, so that it is difficult to estimate Q-value. It is however safely concluded that Q-value at distances less than 40 km is smaller than that at those greater. In the case of instrument-2, the frequency of the maximum amplitude of S

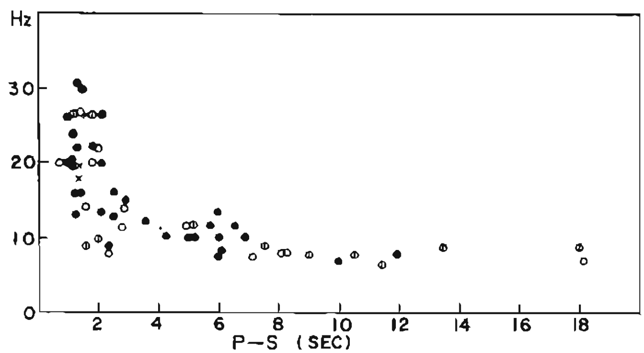

Fig. 5. The observed frequencies of the P maximum amplitudes obtained by instrument-2 plotted against P-S times.

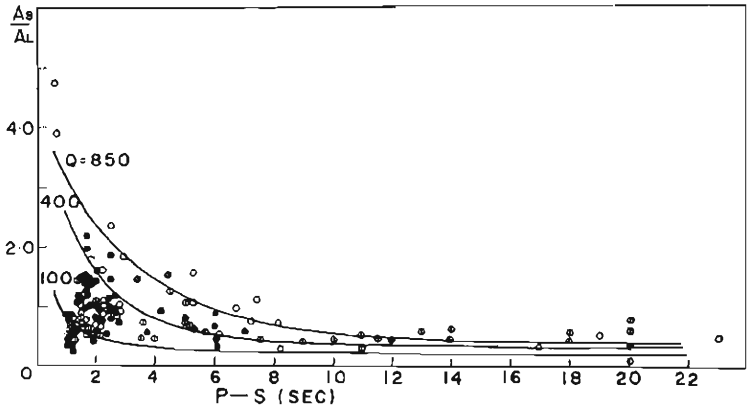

Fig. 6. Ratios of the S maximum amplitude obtained by instrument-1 to that by instrument-2 (A_S/A_L). Solid curves show the theoretical variations calculated from equation (2). In abscissa is taken P-S time.

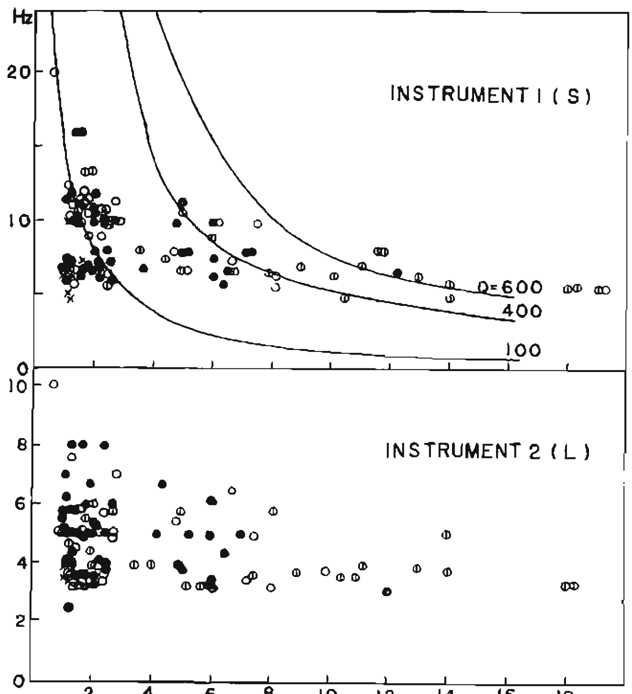

Fig. 7. The observed frequencies of the S maximum amplitudes obtained by instrument-1 (the upper figure) and those by instrument-2 (the lower figure). Solid curves in the upper figure show the theoretical variation of the frequencies with P-S times calculated from equation (3).

waves calculated from equation (3) for probable Q-values is 2.5 Hz independently of P-S times. The disagreement of the observed frequencies with the calculated ones may be due to either of the two assumptions mentioned in (4–1) or both.

It is noted that 'the maximum amplitude of S wave' means here the maximum amplitude of the waves arriving after the S wave onset, although the majority of them belong to S wave. The theoretical curves in Figs. 6 and 7 are calculated by the use of the velocity of S wave.

Concerning attenuation of S waves, Umeda (1969)[2] has obtained similar results to ours based on the seismometric observation in Matsushiro District. He found that the attenuation constant of S waves is abruptly decreased at focal distance of 30 to 40 km.

Solid circles and open circles in Figs. 3, 4, 5, 6 and 7 denote the first motions of the events corresponding to Push and Pull respectively. Crosses and circles with a vertical line denote explosions and events with unidentified first motion. The above classification is advanced in order to find any difference of attenuation respectively among the propagation directions of the seismic waves. However any significant feature concerning the difference of attenuation could not be found in the present study. It is intended to study this problem further in following papers.

5. Summary and Discussion

In the preceeding sections, attenuation of P and S waves was examined by the use of the maximum amplitude data recorded by the two seismographic systems with different frequency responses. As a result, the characteristics of attenuation are conceived to be different between two distance ranges, that is, at distances less than 40 km and those greater. The observed values of the maximum amplitude ratios and the frequencies of the maximum amplitudes for respective instruments are widely scattered at distances less than 40 km for both of P and S waves. This fact seems to suggest that various causes are related to the amplitude variation in the short distance range. On the other hand, at greater distances they are little scattered, permitting us to evaluate the Q-value by comparison with the theoretical curves. The Q-values of P and S waves in the distance range greater than 40 km are, as already shown, about 500 and 800 respectively.

The present study assumes that the source spectra are constant over a wide range of frequencies and that the specific dissipation factor Q is independent from frequency. On these two assumptions, as is mentioned in Section 4, the theoretical frequency of the maximum amplitude does not exceed the value of the frequency giving the peak system magnification of the instruments used. But Figs. 5 and 7 show that the observed frequencies are greater than 2.5 Hz, at which the peak system magnification is given in the case of instrument-2, especially for the events with short P-S time. This contradiction cannot be explained without considering that either of Q or the source spectra or both increase with frequency for a frequency range higher than 2.5 Hz. In other words, either of the two assumptions or both may be invalid. Therefore the Q-values obtained above are no more than the approximate values.

One of the factors pertaining to the source spectra may be the magnitude of the event. If the source spectra depend severely on magnitude, the present method is not applicable to an estimation of seismic dissipation. However the magnitudes of the events treated here are subject to restriction due to the dynamic range of the recording system. Consequently the magnitude range is limited in 2 or so for the events used in the present study. It may therefore be considered that the present estimation of Q-value is not severely affected by the use of events with different magnitudes.

It is difficult to evaluate the intrinsic attenuation at distances less than 40 km because of the wide scatter of the maximum amplitude ratios. Possible causes of the wide scatter are the difference of the focal depths and the regional difference of the crustal structure besides the magnitude difference. It is considered that the various causes are related to the variation of the amplitudes at near distances. For events with great P-S times, the transmission path is not much varied with focal depths. Therefore the amplitude variation at great distances is little affected by the crustal structure. On the contrary, for events with short focal distances the transmission path varies very much with focal depths. In other words, the variation of amplitudes at distances near focus is considered to be very sensitive to the lateral variation as well as to the vertical variation of the crustal structure. It is therefore difficult to extract information on only intrinsic attenuation from the amplitude variation data near focus. It is however very useful from the viewpoint of clarifying the relation between the properties of the crust and the seismic activity to investigate the amplitude variation and attenuation by the use of earthquakes with short focal distances.

Only the data obtained at Abuyama Seismological Observatory were used in the present study. Seismic records from three stations besides Abuyama are also available for us. The present authors intend to make further study on the attenuation of seismic waves based on all the data available for the purpose of making clearer the relation between the physical and geophysical properties and the seismic activity. Further, the authors plan to examine the characteristics of the source spectra and the dependence of seismic attenuation to frequency.

The numerical computations in the present study were run on a FACOM 230–60 at the Data Processing Center of Kyoto University.

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