Attenuation of S Waves and Coda Waves in the Inner Zone of Southwestern Japan

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Abstract

The attenuation properties of S and coda waves were studied in the northern Kinki district by analyzing local earthquakes, recorded at 21 stations of the Tottori, Abuyama and Hokuriku micro-earthquake observatories, Kyoto University. The data consist of four datasets of shallow events in the crust, and deep events in the upper mantle which occurred near Wakayama and Nagoya. Quality factors of S waves (Q_s) were determined by the maximum RMS amplitude ratio method, and by the single station method. The decay of the maximum amplitudes of S waves with distances was analyzed within the hypocentral distance range of 50～250km at five frequencies of 2, 4, 8, 16 and 32Hz for the transverse component seismograms. Quality factors of coda waves (Q_c) were also determined for the same data on the basis of the single scattering model of coda generation in the same frequency range. The result of Q_s by the maximum RMS amplitude ratio method and Q_c for local earthquakes are considered to be reliable. Q_s and Q_c approximately agree with each other within their standard deviations. The values are, for example, about 600 at 8Hz. Therefore, the attenuation properties of S waves and their coda parts are considered to be almost the same in this district. The frequency dependence of Q_s also agrees well with that of Q_c for the datasets in this analysis. The exponent of frequency n, in the formula $Q=Q_0 f^n$, has values of 0.5～1.1, which are the typical values in the seismic active regions such as island arcs. Q_s indicates regional variations more clearly than Q_c. Q_s values derived from the deep events near Wakayama are larger than those from the other events. This suggests that the attenuation is smaller in the upper mantle in the southern Kinki district relating to the subduction of the Philippine Sea plate.

1. Introduction

The attenuation of S waves has been extensively studied using the decay of amplitudes with hypocentral distance or by using the decay of coda part amplitudes with time. A simple method to determine quality factors of S waves (Q_s) is to examine the decay of amplitude with hypocentral distance in the same direction from an epicenter. Noguchi[18] derived the regional differences in Q_s in the Kanto and Tokai districts by this method. It is better to analyze the transverse component of S waves because SH waves are their dominant compositional element of them[28]. From analyzing the ratio of spectrum at two stations, Okamoto *et. al*[19] determined Q_s on the assumption of a fixed source spectra. Matsuzawa *et. al*[16] determined Q_s from the double spectrum ratio of two stations in the same direction from the epicenters. These methods, however, assume the frequency independence of the quality factors[29,30].

The effects of site amplification cannot be neglected in the above methods. In order to eliminate the site effects, Aki[7] introduced the ratio of the maximum amplitude of S waves to the amplitude of coda waves at a fixed reference time (hereafter referred to as the single station method). Iwata and Irikura[13] tried to separate site effects from source and path effects in the frequency domain, and they obtained Q_s with frequency dependence.

On the other hand, coda parts of seismograms are considered to consist of S waves scattered by many heterogeneities distributed randomly in the lithosphere[5, 6, 23, 24]. The quality factors (Q_c), which indicate the apparent attenuation containing both scattering effects and intrinsic absorption, have been determined by the decay of coda amplitudes with time (Q_c). Q_c has been determined by many authors[8, 10, 11, 22, 25]. The regional differences in Q_c have also been revealed at various regions in the world, including tectonic active regions such as fault zones[17] and inactive regions such as Antarctica[4]. Moreover, the relationship between Q_c and site effects has also been derived with reference to geological differences[21].

Recently, Campillo[9] measured Q values of the L_g phase (Q_{Lg}), which are S waves trapped in the crust, and indicated that Q_{Lg} was the same as Q_c and also that the frequency dependence of Q_{Lg} agreed with that of Q_c.

In the Kinki district, Okano and Hirano[20] measured Q_s by using the ratio of S–wave maximum amplitudes recorded with short and long period seismograms at one station, Abuyama. Akamatsu[2] took a different approach to derive frequency dependence of Q_s. He used the ratios of maximum amplitudes of S waves to the source factors of coda waves in order to reduce the effect of magnitude dependence. The resultant formula of frequency dependence of Q_s is approximated as $Q_s = 110f^{0.5}$.

As for Q_c, Akamatsu[1, 3] determined Q_c from the data of one observation station for the earthquakes that occurred at various regions in and around the Kinki district. Kanao and Ito[14] determined Q_c for different time lapses by using the data of 12 stations in the middle and northern parts of Kinki district.

In this paper, both Q_s and Q_c are determined in the area of the inner zone of southwestern Japan, from the Hokuriku through northern Kinki to Chugoku districts. The four datasets analyzed consist of earthquakes which occurred near Wakayama and Nagoya in two different focal depth ranges (3～29 km, 35～57 km), recorded at 21 stations of micro–seismic observation networks. The deep earthquakes are considered to be caused by the subduction of the Philippine Sea plate. It is the first analysis to use such a large number of observation stations in the Kinki district. The obtained results are compared to examine the differences between Q_s and Q_c. Moreover, the regional differences in Q_s are also examined in comparison to Q_c values.

2. Data and Analysis

Epicenters of local earthquakes and the observation stations used in this study are shown in **Fig. 1.** The earthquakes are also listed in **Table 1.** The analyzed earthquakes consist of four datasets, 1) shallow events near Wakayama, which occurred in the upper crust with magnitudes 2.6～3.6 (*WAKAYAMA SHALLOW*), 2) deep events near Wakayama which occurred in the upper mantle with magnitudes 3.3～4.1 (*WAKAYAMA*

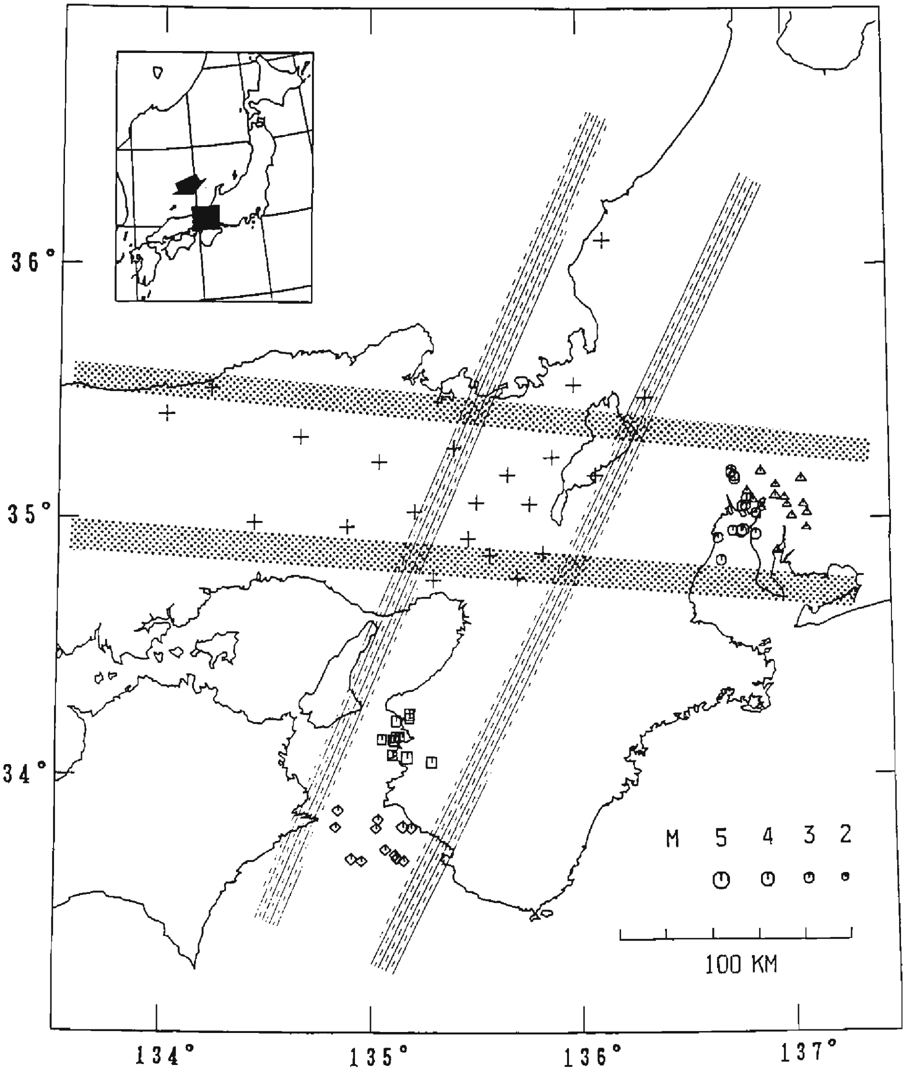

Fig. 1. Epicenters and stations (*plus*) used in this study. Seismic data consists of four groups of earthquakes; *1. WAKAYAMA SHALLOW* (*square*), *2. WAKAYAMA DEEP* (*diamond*), *3. NAGOYA SHALLOW* (*octagon*) and *4. NAGOYA DEEP* (*triangle*).

DEEP), 3) shallow events near Nagoya with magnitudes 2.6~3.5 (*NAGOYA SHALLOW*) and 4) deep events near Nagoya with magnitudes 2.9~3.8 (*NAGOYA DEEP*). The locations of hypocenters and magnitudes are after J. M. A..

The analyzed seismograms were recorded with short period (1 Hz) high-gain horizontal-component velocity-type seismometers at the stations of the micro-earthquake observation networks of the Research Center for Earthquake Prediction, Disaster

Table 1. List of the earthquakes for the four datasets analyzed in this study. The hypocenters and magnitudes are determined by J.M.A.. The number of stations for each event and the total number(N) for each dataset are also listed. The lapse time for coda analysis and the reference time from origin to measure coda amplitudes are also shown for the four datasets.

REGION NO.	DATE Y	D	M	TIME H	M	LAT D	M	LONG D	M	H km	MAG	STATION NO.
1. WAKAYAMA SHALLOW (LSPSE TIME : 50～60s REFERENCE TIME : 40～45s)												N=40 (total)
1	1985	5	20	1	51	34	9.2	135	8.5	10	2.6	2
2	1985	5	20	2	35	34	9.1	135	7.4	10	3.1	3
3	1985	5	20	3	41	34	8.2	135	7.0	10	3.2	5
4	1985	5	20	6	12	34	9.3	135	8.0	10	2.8	2
5	1985	5	20	22	20	34	8.4	135	6.6	8	3.3	4
6	1986	12	22	4	3	34	9.3	135	8.6	5	2.9	2
7	1986	12	22	17	8	34	4.8	135	6.3	12	3.1	3
8	1986	12	24	19	11	34	12.9	135	7.4	6	3.0	3
9	1986	12	24	20	6	34	13.5	135	11.3	8	3.0	4
10	1987	12	27	6	33	34	8.5	135	3.3	3	2.8	3
11	1987	12	27	7	9	34	4.2	135	10.5	11	3.6	3
12	1987	12	28	23	6	34	14.4	135	11.3	5	3.4	3
13	1987	12	29	3	2	34	14.7	135	11.1	5	2.6	2
14	1988	12	23	16	17	34	3.1	135	17.5	11	3.2	1
2. WAKAYAMA DEEP (LAPSE TIME : 60～70s REFERENCE TIME : 55～60s)												N=32 (total)
1	1985	2	3	7	2	33	40.2	135	54.5	48	3.7	1
2	1985	3	31	19	14	33	39.7	134	57.5	44	3.3	2
3	1985	7	15	22	1	33	40.3	135	7.5	47	3.7	7
4	1985	10	27	1	1	33	47.5	135	11.8	57	3.6	3
5	1985	12	23	23	43	33	47.7	134	50.1	52	3.3	2
6	1986	5	25	2	15	33	49.5	135	2.3	53	3.4	4
7	1987	4	9	6	41	33	41.1	135	7.1	40	3.3	1
8	1987	7	18	7	37	33	47.4	135	1.7	41	3.3	3
9	1987	11	6	2	32	33	51.7	134	50.7	49	3.6	3
10	1988	1	25	23	22	33	47.7	135	9.3	56	4.1	1
11	1988	9	10	5	26	33	42.4	135	4.2	54	3.4	3
12	1988	9	22	16	57	33	39.7	135	9.6	51	3.4	2
3. NAGOYA SHALOW (LAPSE TIME : 50～60s REFERENCE TIME : 45～50s)												N=47 (total)
1	1985	4	10	18	37	35	10.2	136	44.6	10	2.8	6
2	1985	4	11	3	22	35	10.9	136	43.6	6	2.8	3
3	1985	4	12	4	53	35	9.6	136	44.7	7	3.2	5
4	1985	4	29	0	56	34	57.2	136	43.9	10	2.7	3
5	1986	7	17	5	1	34	55.6	136	39.6	16	2.9	4
6	1986	8	7	9	2	35	1.5	136	50.9	9	2.7	2
7	1986	8	7	9	11	35	1.4	136	50.5	11	2.6	2
8	1986	12	27	1	24	35	3.1	136	46.8	19	2.9	4
9	1986	12	27	9	23	35	4.8	136	48.1	25	3.0	3
10	1987	2	17	2	29	35	3.3	136	47.8	12	2.9	2
11	1987	7	10	7	45	35	11.4	136	43.8	15	3.1	4
12	1987	11	14	9	39	34	57.4	136	46.9	13	3.5	3
13	1987	11	14	15	20	34	57.0	136	46.4	14	3.3	3
14	1987	12	17	8	23	34	56.4	1336	50.5	29	3.0	1
15	1988	1	24	18	30	34	50.3	136	40.5	14	3.0	2
4. NAGOYA DEEP (LAPSE TIME : 55～65s REFERENCE TIME : 50～55s)												N=33 (total)
1	1985	3	7	7	54	35	9.4	137	4.0	44	3.7	4
2	1986	1	19	18	17	34	57.8	137	5.3	52	3.0	5
3	1986	3	3	8	32	35	5.1	136	59.0	47	3.1	3
4	1986	6	2	13	59	35	6.7	136	48.3	52	3.0	3
5	1986	8	19	14	0	35	5.5	136	56.4	43	3.8	3
6	1986	8	20	5	18	35	8.1	136	56.5	35	2.9	1
7	1986	10	15	1	14	35	4.6	136	50.0	43	3.1	3
8	1987	2	5	21	45	35	1.4	137	5.6	39	3.1	1
9	1987	4	25	20	16	35	3.4	137	4.5	51	3.1	2
10	1987	9	7	20	31	35	0.7	137	1.0	43	3.2	2
11	1987	9	15	10	39	35	11.3	136	52.3	40	3.3	1
12	1988	1	28	18	9	35	3.3	136	59.8	39	2.9	1
13	1988	3	11	12	25	34	52.5	136	56.7	49	3.3	4

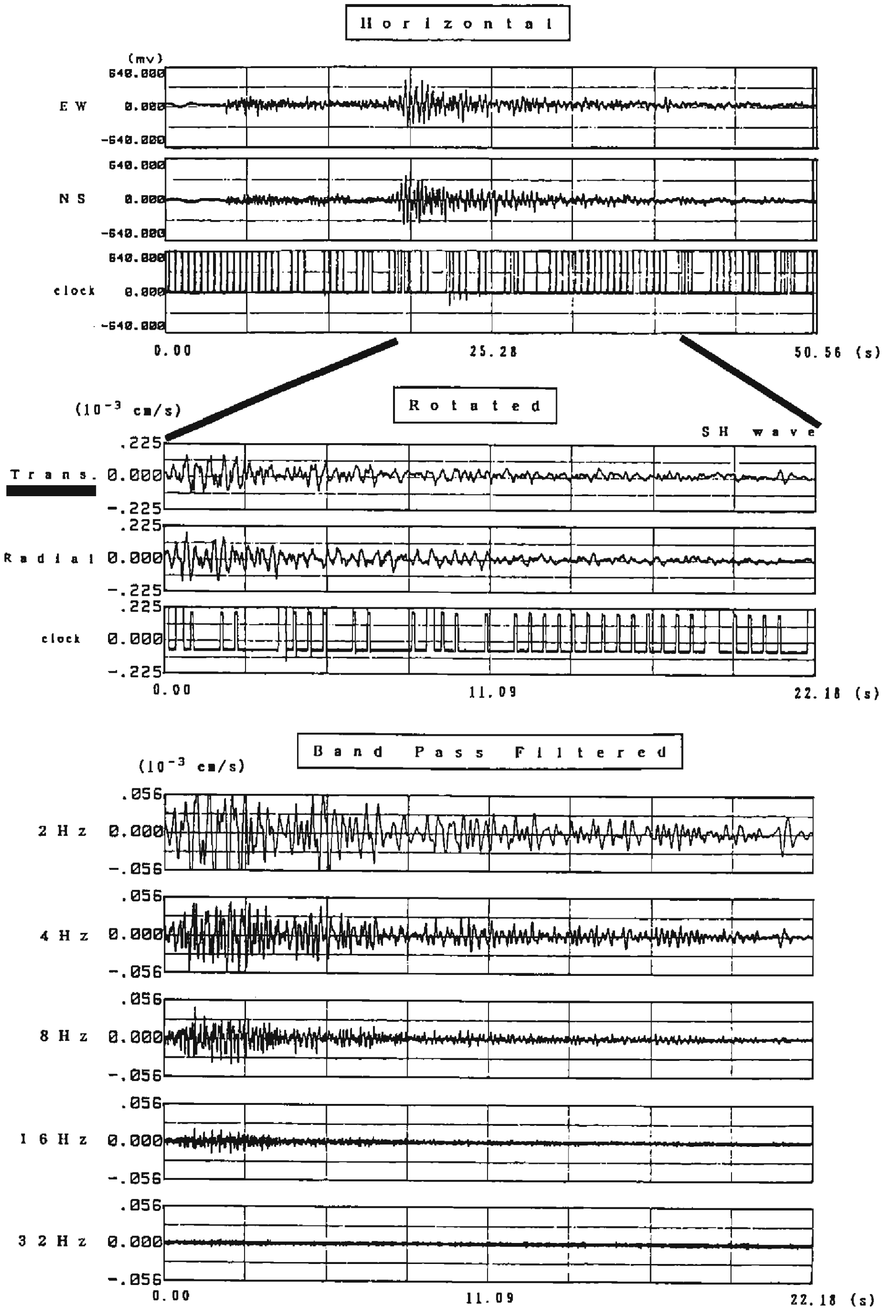

Fig. 2. An example of seismograms of horizontal components (*upper traces*), its transverse and radial components of S wave part (*middle traces*), and band-pass filtered traces with central frequencies of 2, 4, 8, 16, 32 Hz (*lower traces*).

Prevention Research Institute of Kyoto University. The frequency response of telemetered systems is flat in a range of 0.5 ~ 25 Hz. The seismograms of 15 stations of the Abuyama and the Hokuriku Observatories were used for the events near Wakayama, (*Datasets 1, 2*) to cover a sufficient range of hypocentral distances. Likewise, the seismograms at 18 stations of the Abuyama and the Tottori Observatories were used for the events near Nagoya, (*Datasets 3, 4*). The combinations of the datasets and stations are shown in **Fig. 1** by two pairs of near parallel lines. The number of stations used for the analyses of an event are from 1 to 7 (**Table 1**). Q_s and Q_c were determined by averaging the overall results of the events. The total number of stations used to determine Q_s and Q_c ranges from 32 to 47 for each dataset (**Table 1**).

The procedure of waveform analyses is as follows: First, records were digitized at a sampling frequency of 200 Hz. Next, seismograms of horizontal components of EW and NS were converted into transverse and radial components (**Fig. 2**). A part of the transverse component seismograms after S wave arrival was used for the following analyses, because the amplitude decay with hypocentral distance is simpler for the transverse component than for the radial component[26,28]. The seismograms were band-pass filtered at five central frequencies of 2, 4, 8, 16, 32Hz with a fall off of 48dB/oct. Examples of band-pass filtered traces are shown in the lower figure in **Fig. 2**. Furthermore, root mean square (RMS) amplitudes were generated for the filtered outputs in each frequency band (**Fig. 3**). Then the RMS amplitudes were moving averaged for a few periods (1~3(s)) for each frequency band. The RMS amplitudes were used for the following analyses. The positions of the maximum RMS amplitude (A_s) and of the reference time (t_o) to measure the amplitude level of the coda part, which is used to determine Q_s. These are shown in **Fig. 3** together with the lapse time used to determine Q_c.

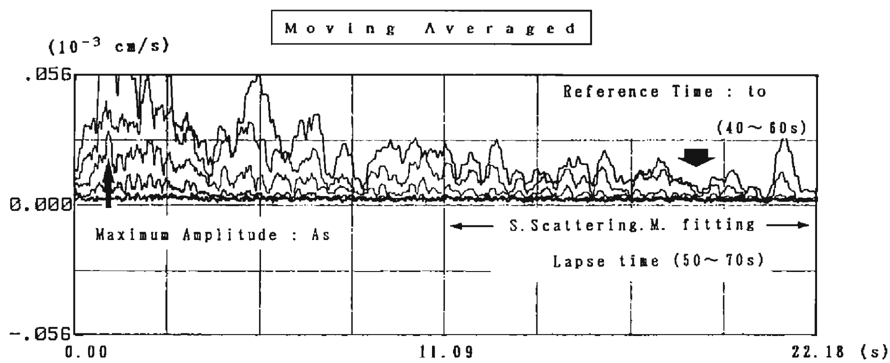

Fig. 3. Examples of moving-averaged root-mean-square (RMS) amplitudes of the event shown in **Fig. 2** at 5 frequency bands, 2, 4, 8, 16 and 32 Hz. The amplitude decreases with increasing frequencies. Two arrow heads mark the positions of the maximum RMS amplitude (A_s) and the reference time (t_o) used for the maximum RMS amplitude ratio method and the single station method. The lapse time fitting the single scattering model is also indicated. The reference time and the lapse time are measured from the origin time.

3. Determination of Q_s and Q_c

Three different methods were used to determine the quality factors. Two of them are to give the quality factors Q_s of direct S waves using the attenuation of RMS amplitudes with distance. In contrast, the third method gives Q_c based on the model of coda generation from measuring the amplitude decay of coda parts of seismograms with time.

The procedures of these methods and the results are described in this section and the discussion on the resultant Q_s and Q_c is presented in section 4.

3. 1 Maximum RMS Amplitude Ratio Method

The first method is to determine Q_s from the maximum amplitude decay of S waves with hypocentral distances. In the actual analyses, instead of raw amplitudes, maximum RMS amplitudes (A_s) mentioned in the previous section were used for the stability of amplitude decay. The maximum amplitude of direct S waves (As) is written as,

$$A_s = Cr^{-1}\exp(-\pi f_0 r/\beta Q_s), \tag{1}$$

where C is the source factor, r is the hypocentral distance, β is the velocity of S waves, (assumed as 3.5 km/s), f_0 is the central frequency of band pass filter (2, 4, 8, 16, 32 Hz) and Q_s is the quality factor of S waves. Taking the ratio of maximum amplitudes between two stations in the same azimuth[16] from an earthquake, the source factor (C) is canceled and the amplitude ratio is,

$$\frac{A_{s1}}{A_{s2}} = \frac{r_2}{r_1}\exp\left\{-\frac{\pi f_0(r_1 - r_2)}{\beta Q_s}\right\}, \tag{2}$$

where subscripts 1, 2 denote station numbers.

The maximum RMS amplitudes are plotted against hypocentral distances at five frequencies for four datasets of earthquakes in **Figs. 4-1~4-4**. The stations within 20 degrees in azimuth from an epicenter are selected in this analysis and are linked by solid lines in **Fig. 4**. The amplitudes decrease as a whole with increasing distances and are approximated by the formula (1), although the amplitudes of a few events do not decay with increasing distance as shown in **Fig. 4**. The amplitudes at the frequency of 32 Hz are small, but their decay with distance have the same pattern as do the other frequency bands.

Q_s values were obtained by averaging all the combinations of stations for each event. Frequency-dependent Q_s values were determined for four datasets by averaging all the resultant values calculated for every event. Q_s^{-1} values thus obtained and their standard deviations are listed in **Table 2**.

Frequency dependence of Q(Q_s or Q_c) in a frequency range higher than 1Hz is roughly given as[7],

$$Q = Q_0 f^n, \tag{3}$$

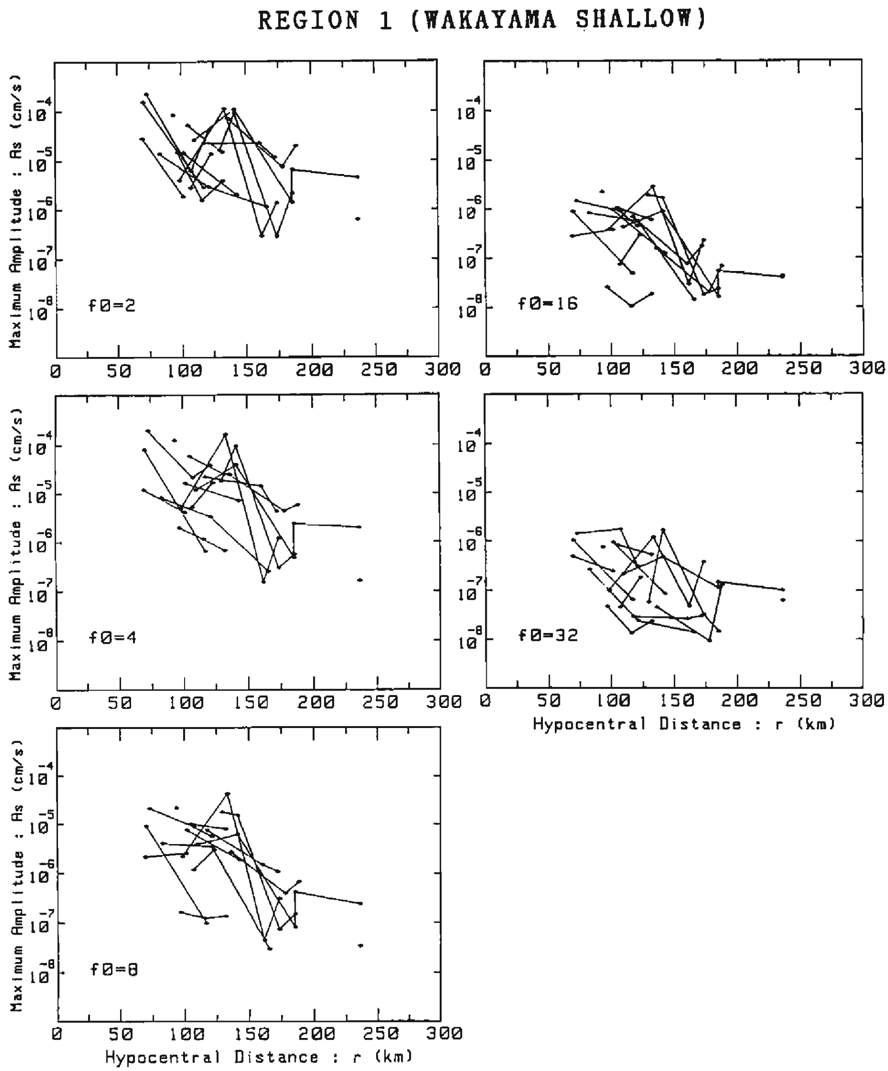

Fig. 4–1. Attenuation of maximum RMS amplitudes with hypocentral distance at each frequency band for dataset *1* (*WAKAYAMA SHALLOW*). The data for the same events are linked by a line.

Table 2. The values of $Q_s^{-1}(\times 10^3)$ and the exponent of frequency n determined by the maximum RMS amplitude ratio method for the four datasets at five frequencs bands.

REGION	2Hz	4Hz	8Hz	16Hz	32Hz	n
1. WAKAYAMA SHALLOW	11.90±5.14	4.69±1.90	2.15±0.98	1.19±0.47	0.62±0.24	1.05
2. WAKAYAMA DEEP	2.58±1.55	2.15±1.01	1.09±0.53	0.82±0.33	0.62±0.23	0.55
3. NAGOYA SHALLOW	6.49±3.04	3.75±1.73	2.15±0.97	1.32±0.51	0.59±0.24	0.84
4. NAGOYA DEEP	7.04±3.06	3.52±1.85	1.81±0.84	0.91±0.46	0.55±0.24	0.93

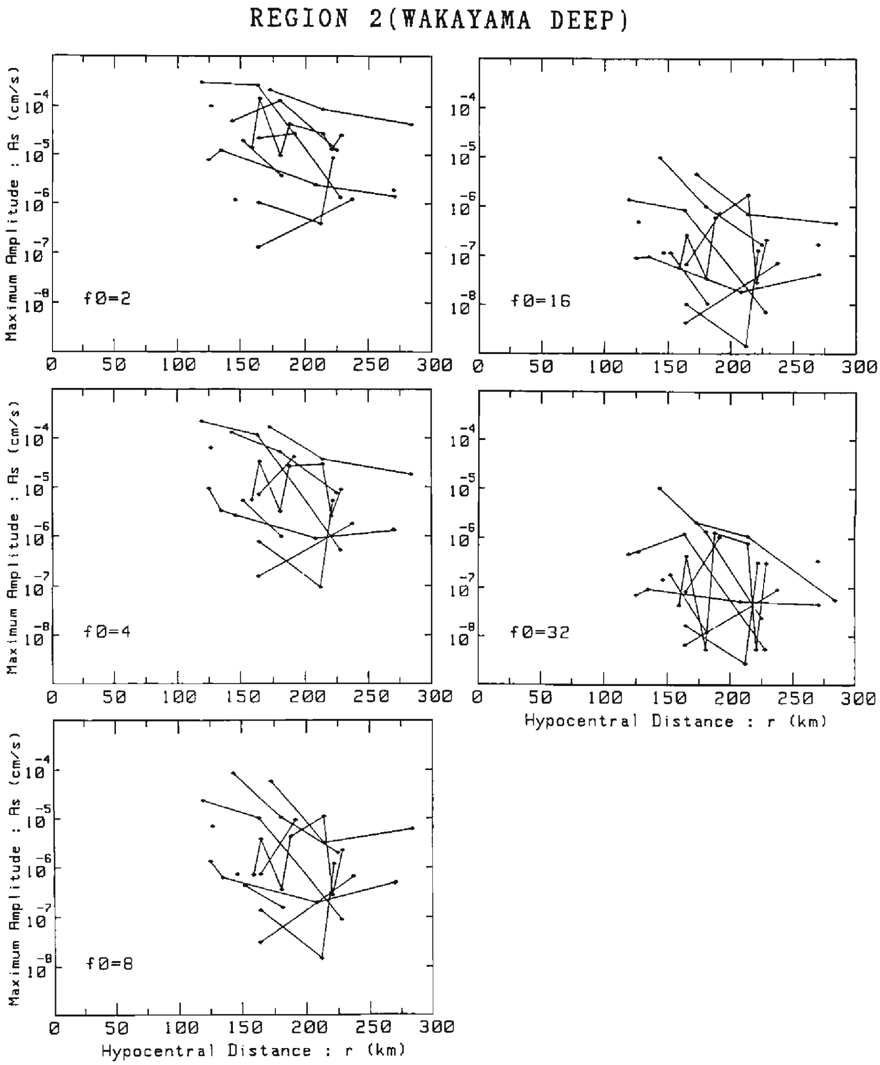

Fig. 4–2. The same for dataset *2* (*WAKAYAMA DEEP*).

where Q_0 is the Q value at 1Hz. The values n are determined by the least squares method and listed in **Table 2.**

3. 2 Single Station Method

The second method to determine Q_s is to use both the maximum RMS amplitudes and coda amplitudes at a fixed reference time[7]. The maximum RMS amplitude (As) at each frequency is written in the formula (1). The RMS amplitudes of coda waves (A_c) for the central frequency f_0 at the time t after twice the travel time of S waves (t_s) are approximated as,

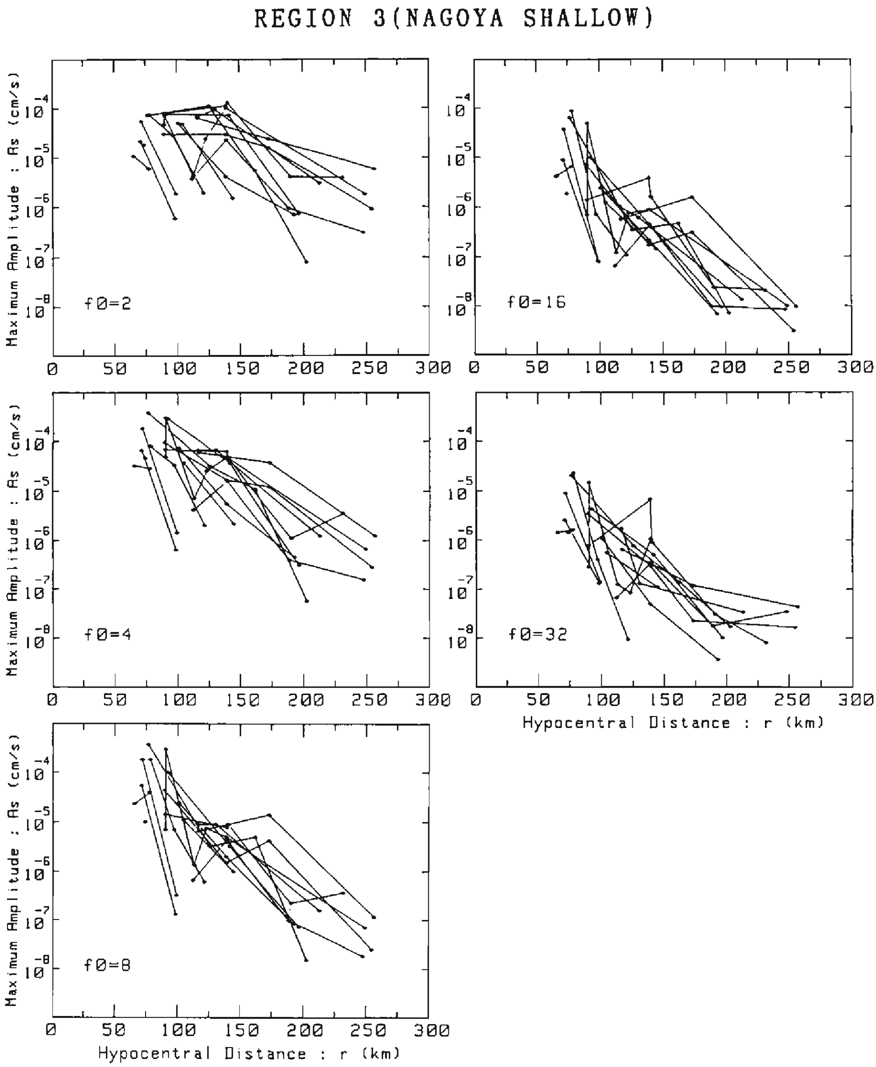

Fig. 4-3. The same for dataset 3 (*NAGOYA SHALLOW*).

$$A_c = Ct^{-1}\exp(-\pi f_0 t/Q_c), \qquad (t > 2t_s), \tag{4}$$

where C is the source factor of coda, Q_c is the quality factor for coda waves and t is the lapse time. Since C/A_c value is a function of only the lapse time t, when we take coda amplitude at a reference time $(t=t_o)$ measured from the origin time, C/A_c takes a constant value. Besides, when the maximum RMS amplitude (A_s) is divided by a coda amplitude (A_c) at a reference time (t_o), the amplitude ratio is thought to be free from site effect, because site amplification to S waves and coda waves is nearly the same at a station[27]. Examples of A_s and t_o are indicated in **Fig. 3** (arrow heads). The ratio of

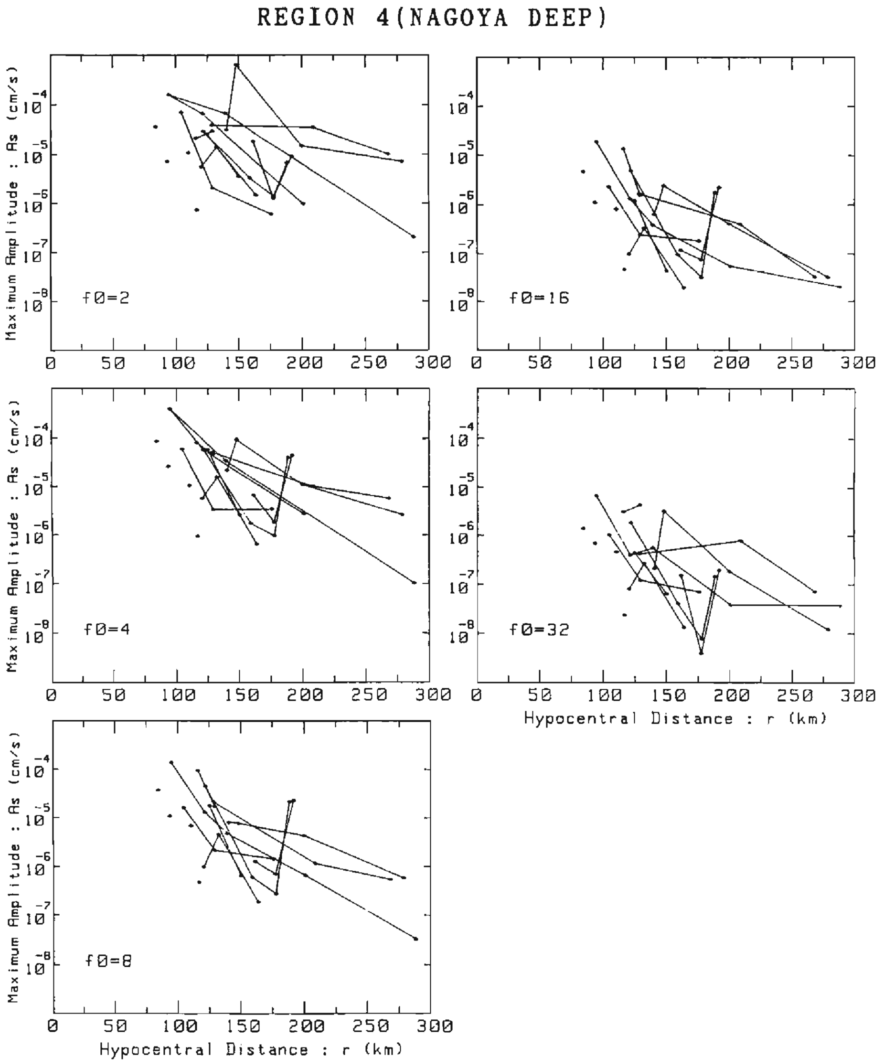

Fig. 4-4. The same for dataset *4* (*NAGOYA DEEP*).

the maximum RMS amplitudes of S waves to coda amplitude is written as follows,

$$\frac{A_s}{A_c} = \frac{C}{rA_c} \exp\left(-\frac{\pi f_0 r}{\beta Q_s} \right). \tag{5}$$

Taking the logarithm of both sides of the formula (5), we obtain

$$\ln\left(\frac{rA_s}{A_c}\right) = -\frac{\pi f_0 r}{\beta Q_s} + Constant, \quad (6)$$

Q_s values at each frequency f_o can be determined by the least squares analysis using formula (6) for each dataset.

In the present analyses, the reference times (t_o) were taken to be from 40 to 60 s for each dataset (**Table 1**). **Figs. 5-1~5-4** show the relations between the amplitude

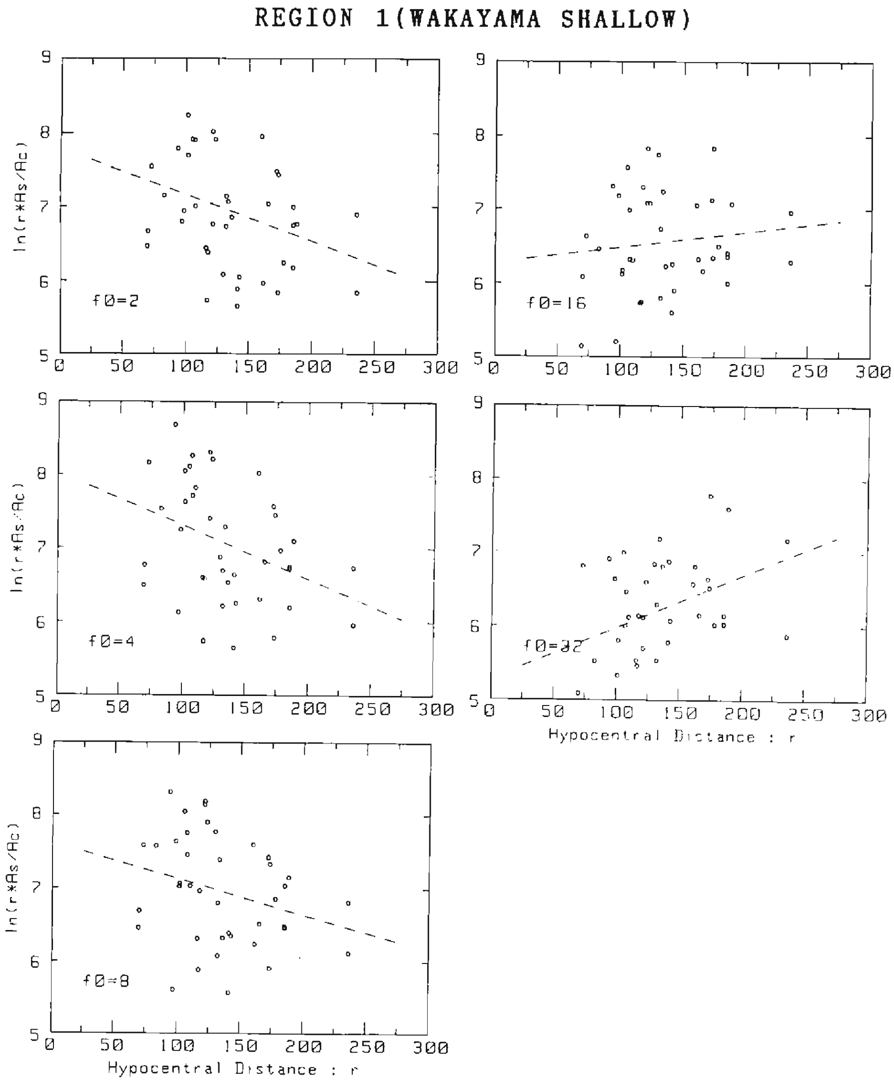

Fig. 5-1. Plots of the maximum RMS amplitude ratios to coda amplitude against hypocentral distances, and the regression line at each frequency band for the events in dataset 1 (*WAKAYAMA SHALLOW*).

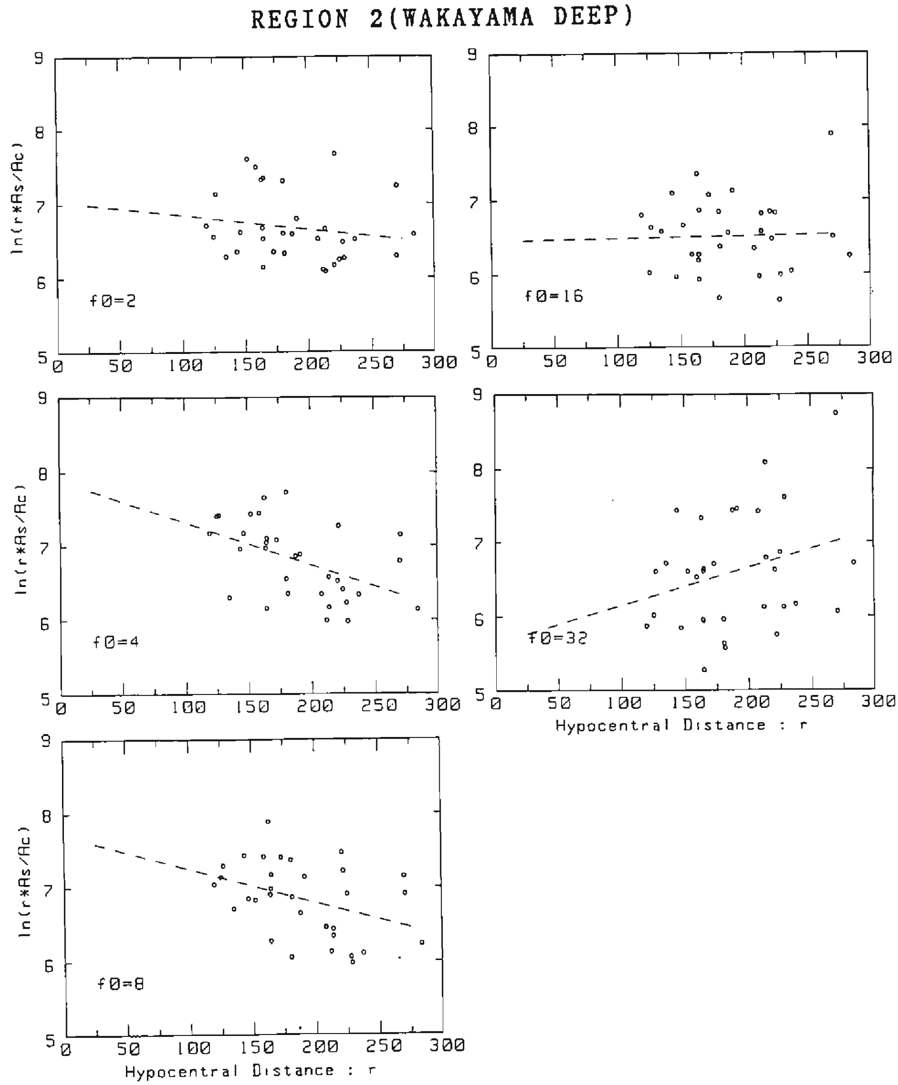

Fig. 5-2. The same for dataset 2 (*WAKAYAMA DEEP*).

ratios on the left hand side of the formula (6) to the hypocentral distances for four regions at each frequency band. The regression lines are also shown by broken lines. The resultant Q_s^{-1} and the exponent of frequency n for four datasets are listed in **Table 3.** Q_s values for four datasets at the frequency of 32 Hz, and those for one dataset at the frequency of 16 Hz cannot be determined to be positive values, because of small S/N ratios of coda amplitudes at far stations.

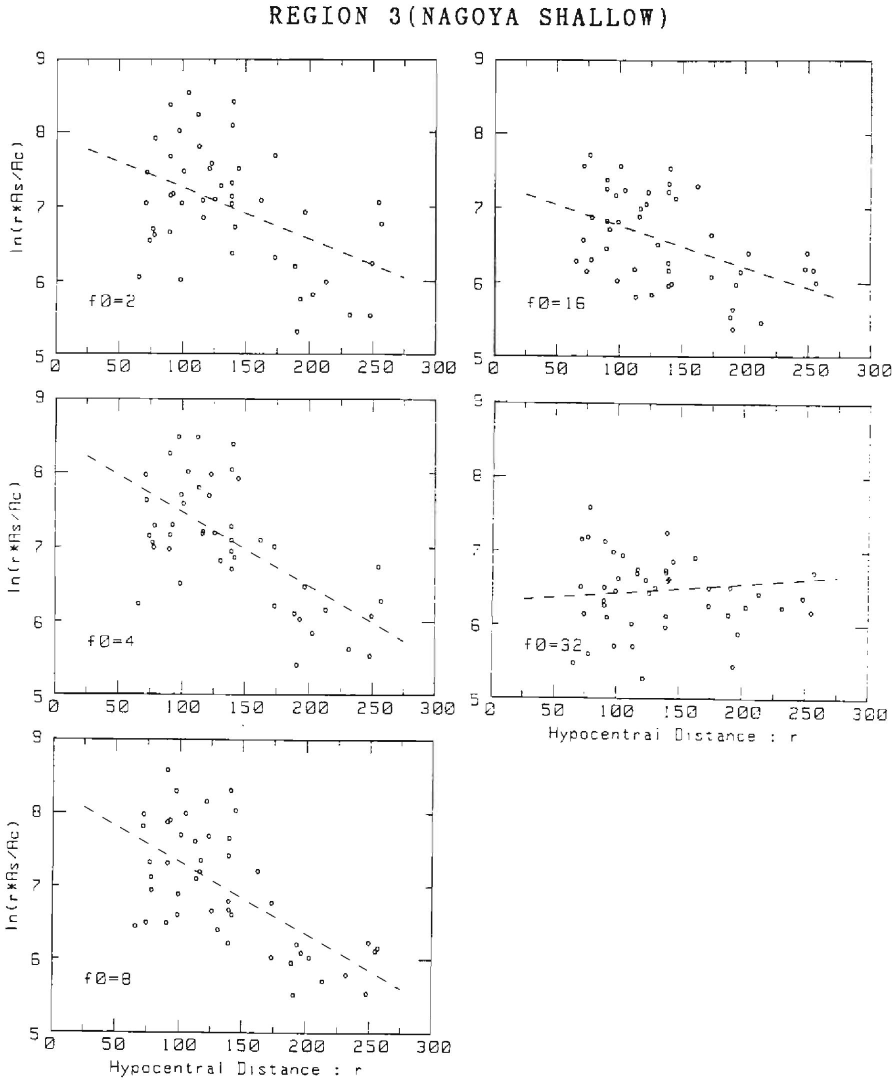

Fig. 5-3. The same for dataset 3 (*NAGOYA SHALLOW*).

Table 3. The values of $Q_c^{-1}(\times 10^3)$ and the exponent of frequency n, determined by the single station method for the four datasets at four frequency bands.

REGION	2Hz	4Hz	8Hz	16Hz	32Hz	n
1. WAKAYAMA SHALLOW	3.53±0.44	2.02±0.23	0.68±0.08	—	—	1.19
2. WAKAYAMA DEEP	1.07±0.14	1.62±0.23	0.64±0.09	0.16±0.03	—	0.95
3. NAGOYA SHALLOW	3.83±0.31	2.77±0.23	1.38±0.12	0.39±0.03	—	1.09
4. NAGOYA DEEP	2.57±0.27	1.29±0.14	0.68±0.10	0.19±0.02	—	0.93

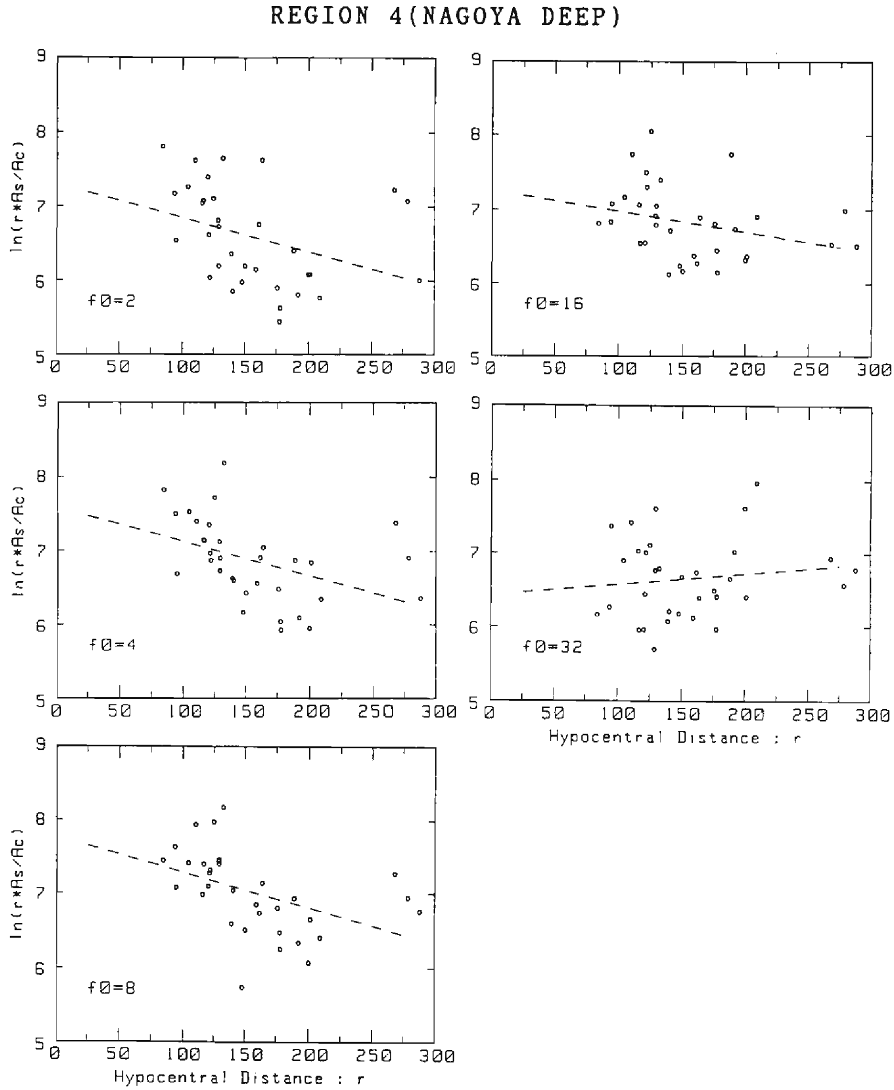

Fig. 5–4. The same for dataset 4 (*NAGOYA DEEP*).

3. 3 Single Scattering Model

The third method is to use the single scattering model of coda generation, which has been widely used to determine Q_c from the decay of coda amplitudes (A_c) with time[5, 6] using the formula (4). In most studies, the formula (4) is applied to the coda part of seismograms in the time window from twice the travel time of S waves to the time at which the coda amplitude is twice ground noise. However, in the case of this study, the times twice the S wave arrival are sometimes later than the end time of data acquisition, or the amplitudes at the lapse time of twice the S arrival become less than the ground noise level, because the hypocentral distances are longer than 60km.

Table 4. The values of $Q_c^{-1}(\times 10^3)$ and the exponent of frequency n determined by the single scattering model for the four datasets at five frequency bands.

REGION	2Hz	4Hz	8Hz	16Hz	32Hz	n
1. WAKAYAMA SHALLOW	7.69±3.34	4.81±1.57	2.02±0.71	0.54±0.16	—	1.27
2. WAKAYAMA DEEP	7.04±4.50	2.94±1.37	1.62±0.61	0.60±0.19	—	1.15
3. NAGOYA SHALLOW	5.75±2.93	3.40±1.40	1.43±0.59	0.64±0.21	0.24±0.06	1.15
4. NAGOYA DEEP	4.78±1.86	2.83±1.03	1.88±0.27	0.49±0.15	—	1.05

An example of the coda part of the seismogram is shown in **Fig. 3**. The beginning point of the time window was taken at 20~30s from the origin time of the event and the end point of the window (the lapse time) was taken at 50~70s for each dataset (**Table 1**). The obtained Q_c^{-1} and n using the formula (4) are listed in **Table 4**. Q_c for three datasets at the frequency of 32 Hz cannot be obtained as positive values, because of small S/N ratio coda amplitudes at far stations.

4. Discussion

4. 1 Quality Factor of S Waves

The obtained Q_s^{-1} values are plotted against frequency for four datasets by the maximum RMS amplitude ratio method (**Fig. 6A**), and by the single station method (**Fig. 6B**). The numbers attached to the four datasets in both figures refer to **Table 1**, showing the shallow and deep events near both Wakayama and Nagoya.

The method for determining the quality factors should be discussed before examining the regional variations of their values. The results of the maximum RMS amplitude ratio method (**Fig. 6A**) are larger than those by the single station method (**Fig. 6B**). The former seem better than the latter because the correction of source factors by coda amplitudes may not be efficient. At far stations from epicenters, coda amplitudes at reference time (t_o) are very close to or immediately after S arrivals. In this case the wave parts at the reference time are not coda waves but a part of direct S waves. When Q_s is determined from data in a large range of hypocentral distances and of limited dynamic range of 40 dB, such as the present data, the maximum RMS amplitude ratio method is better than the single station method.

4. 2 Quality Factor of Coda Waves

The obtained Q_c^{-1} values for the single scattering model are plotted against frequency for four datasets (**Fig. 7A**). Broken lines in **Fig. 7A** show the results by formula (4). The region numbers in the left side of each line correspond to those in **Fig. 6** and **Table. 1**. For comparison, the results of Q_c after Kanao and Ito[15] are shown in **Fig. 7B**. These values are determined in the middle and northern parts of Kinki district by using local earthquakes which occurred near the observation stations. These results are obtained for the same lapse times (55 and 70s) as those of the present study. Therefore,

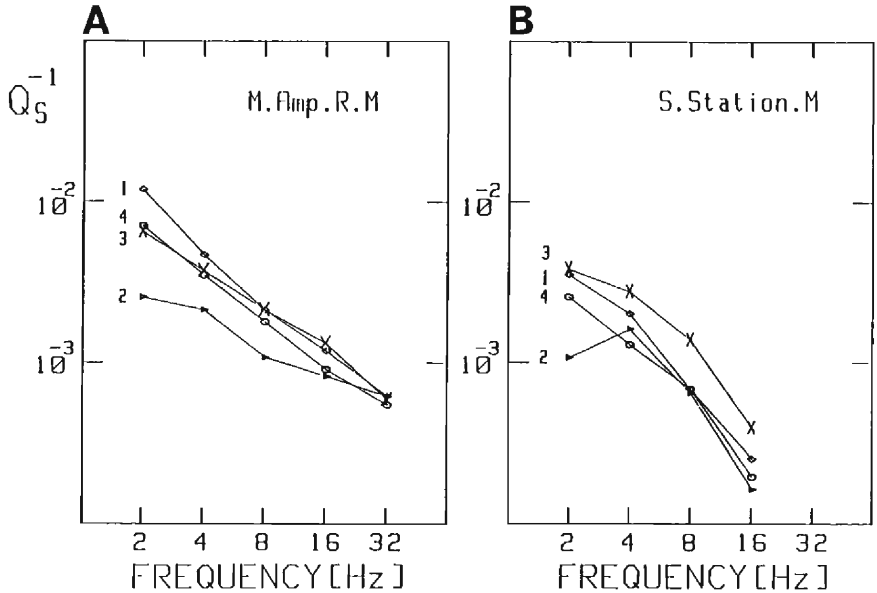

Fig. 6. Frequency dependence of Q_s for four datasets by the maximum RMS amplitude ratio method (*A*), and by the single station method (*B*). The numbers 1~4 in both figures indicate the numbers of datasets, corresponding to those in *Table 1*.

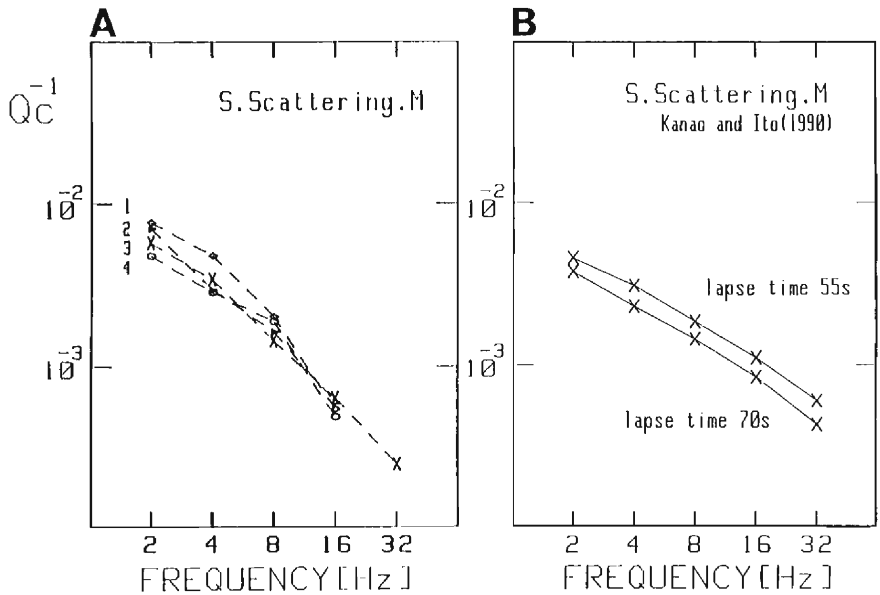

Fig. 7. *A*: Frequency dependence of Q_c for four datasets by the single scattering model (*dashed lines*). The numbers 1~4 indicate numbers of datasets, corresponding to those in *Table 1*. *B*: Q_c values in the middle and Kinki district using the local earthquakes with lapse time of 55 and 70s (after Kanao and Ito[15]).

the scattering areas affecting coda generation are nearly the same in both studies.

4. 3 Comparison between Q_s and Q_c

From the above consideration, Q_c values by the single scattering model represented by formula (4) or from the result by Kanao and Ito, and Q_s by the maximum RMS amplitude ratio method shown in **Fig. 6A** are used to discuss the differences between Q_s and Q_c and their regional variations. The results by Akamatsu[2, 3] are also used for the comparison of Q_s with Q_c.

(1) *Q* values

For comparison, Q_s^{-1} obtained by the maximum RMS amplitude ratio method (**Fig. 8 A**), Q_s^{-1} and Q_c^{-1} after Akamatsu[2, 3] (**Fig. 8B**) and Q_c^{-1} after Kanao and Ito (1990) (**Fig. 8C**) are shown. In **Fig. 8B**, marks *a* and *b* show Q_c^{-1} determined by the single scattering model at a station in the middle Kinki district from the events in the Tokai and Wakayama districts, respectively. Mark *c* indicates the range of Q_s^{-1} with the correction of the source term at origin time in the middle part of the Kinki district. Comparing the results shown in **Fig. 8** with each other, that is, **Fig. 8A** with *c* in **Fig. 8 B**, and also **Fig. 8C** with *a, b* in **Fig. 8B**, Q_s and Q_c appear to be nearly the same. Q_s determined for a long hypocentral distance of more than 60 km approximately agrees with Q_c determined for long lapse time (50~70(s)), which gives enough scattering area to cover the ray path of direct S waves. This means that the attenuation properties of S waves and of their coda parts are roughly the same in the Kinki district.

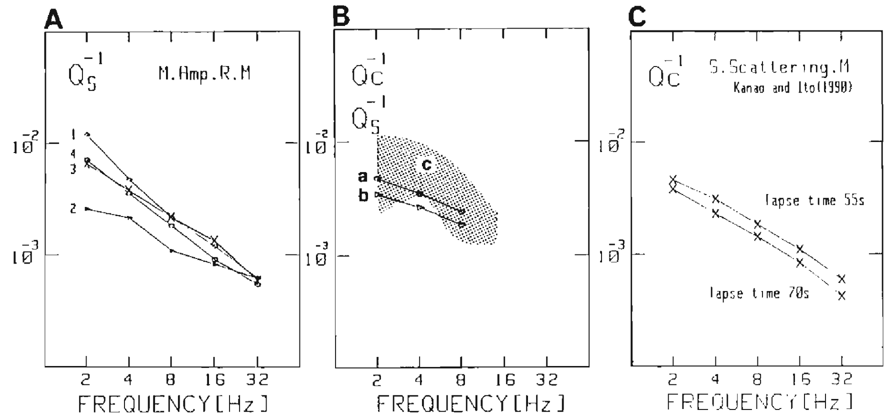

Fig. 8. *A*, Frequency dependence of Q_s by the maximum RMS amplitude ratio method (the same as shown in **Fig.6A**). The numbers 1~4 attached to each line indicate the numbers of datasets, corresponding to those in *Table 1*. *B*, Q_c determined for events in the Tokai (*a*) and Wakayama (*b*) districts after Akamatsu[3]. Shadow area shows Q_s in the Kinki district *(c)* from the result of Akamatsu[2]. *C*, Q_c determined by the single scattering model after Kanao and Ito[15] in the Kinki district (the same as shown in **Fig.7B**).

(2) Frequency Exponent, *n*

The exponents of frequency, n for S waves by the maximum RMS amplitude ratio method have values ranging from 0.55 to 1.05 (**Tables 2**), while n values are 0.72～0.83 for Q_c determined by Kanao and Ito (1990). Thus the frequency dependence is also nearly the same in Q_s and Q_c. Further, these n values belong to relatively high values compared with those at various regions in the world[14]. This supports the argument that n values are large in tectonically active regions, since seismicity is high in the Kinki district.

(3) Regionality and Depth Dependence

The difference in Q_s for four datasets are seen more clearly than that in Q_c. This is because Q_s reflect the attenuation property only along the ray path of S waves, although Q_c are averaged values over a widely scattered area. The regional difference is obvious only for deep events near Wakayama, which appears to have larger Q_s values than the other regions (**Fig. 8A**). Since seismic rays from shallow and deep events pass through the shallow crust and the upper mantle, respectively, the large Q_s values for deep events near Wakayama suggest that the attenuation is larger in the shallow crust than in the upper mantle in the southern Kinki district.

From details shown in **Fig. 4**, the decay rate of maximum amplitude gradually becomes smaller with increasing distance. This suggests that Q_s may depend on the hypocentral distance, relating to the variations in Q_s with depth. A similar attenuation property with depth has been derived for Q_c in the northern Kinki district[15] with different time lapses.

5. Conclusion

The quality factors of S waves (Q_s) and coda parts of seismograms (Q_c) were determined for the earthquakes near Wakayama and Nagoya, using waveform data recorded at 21 stations of three micro-earthquake observation networks in the Kinki district. The methods and the model of the present analysis are the maximum RMS amplitude ratio method and the single station method for Q_s, and the single scattering model of coda generation for Q_c. The results are as follows:

1. The maximum RMS amplitude ratio method in determining Q_s is better than the single station method for the datasets with a wide range of hypocentral distances, because the correction of site effects by coda amplitude may not be efficient for the seismograms with limited dynamic range.
2. The values of Q_s agree approximately with Q_c within their errors in the frequency range of 2～32Hz. This indicates that the attenuation property of S waves and their coda parts are roughly the same in the crust and the upper mantle.
3. The frequency dependence of Q_s and Q_c is represented by the formula $Q=Q_0f^n$ for all the datasets in these analyses. The n values for S waves are 0.55～1.1, which agree with those for Q_c determined by the single scattering model. The values of n are relatively high compared with those determined in other regions. This supports the argument that n is high in seismic active regions.

4. The differences in quality factors among four datasets are clearer in Q_s than in Q_c. The reason is that Q_c values are affected by the attenuation property over a wide area of the lithosphere, while Q_s values reflect the attenuation property of the medium only along the ray path.
5. Q_s values for the deep events near Wakayama are larger than those for other datasets. This suggests that Q_s is larger in the southern Kinki district and related to the Philippine Sea plate.

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