Bull. Disas. Prev. Res. Inst., Kyoto Univ., Vol. 22, Part 2, No. 203, February, 1973

Seismic Attenuation in Relation to the Tectonic Force in the Vicinity of Kyoto

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(Received February 5, 1973)

Abstract

This paper discusses seismic wave attenuation in the seismically active region in the vicinity of Kyoto based on the regional and azimuthal distributions of the ratios of short- to long-period amplitude recorded by two types of seismographic instruments with different frequency responses. One of the most interesting results shows that seismic wave attenuation differs with propagation directions. Attenuation is small for seismic waves propagating in the direction of EW which coincides with the direction of the global tectonic force acting in the region concerned. A possible cause to diminish attenuation for waves propagating in the EW direction might be a high strain accumulation caused by the tectonic compressional force. The results also show that attenuation of seismic waves in the northern part of the region is low if compared with that in the southern part. Low attenuation in the northern part can be interpreted as caused by the in situ stress added to the global one. The regional distribution of the ratios of P- to S-maximum amplitude, the data concerning earth quake magnitudes and the regional difference of the aftershock activity seem to support the above interpretation.

1. Introduction

The variation of seismic attenuation with region as well as with depth is a very important source of information regarding the composition, physical properties and dynamics of the earth's crust and mantle (Press, 1964[1]; Asada, 1967[2]). It is, however, rather recently that sufficient precision has been achieved which makes possible the inversion of the observational data, especially for the study of the crust. Thus, in contrast to much literature concerning the anelastic properties of the mantle (e.g. Jackson and Anderson)[3], there is relatively a small amount of results relating to the regional and depth-dependent variation of Q in the crust which have been published. Clowes and Kanasewich (1970)[4] constructed a model for Q of the crust in Alberta of Canada by comparing near-vertical incidence deep-reflection seismograms with synthetic ones generated with frequency- and depth-dependent attenuation. According to one of the models proposed by them, the Q values in the upper 2 km and the lower 40 km are approximately 300 and 1500 respectively. Recently Suzuki (1971)[5] studied the lateral variation of Q in the Matsushiro earthquake swarm area to draw an interesting result that Q of the seismically most active region is extremely lower, 30 to 50, than that of the surrounding region. His estimation of Q is based on the ratios of spectral amplitude at 10 Hz to that at 20 Hz of P waves generated by the explosion experiments.

In a previous paper (Okano and Hirano, 1971)[6], the present authors have investigated seismic wave attenuation of the crust of the seismically active region in the vicinity of Kyoto. They estimated Q values by using the ratios of amplitudes obtained by two types of seismographic instruments with short- to long-period responses. The variation of these ratios with distance was compared with the theoretical variation. As a result, the average Q values for P and S waves travelling for more than 30 km were estimated to be roughly 500 and 800 respectively. Fig. 1 reproduced

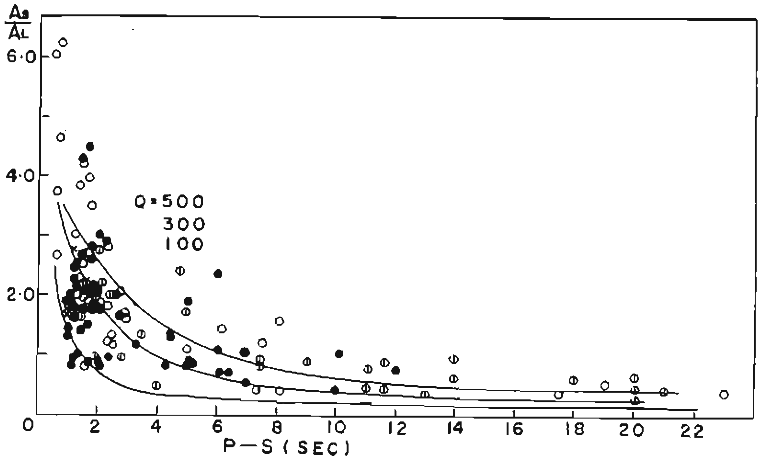

Fig. 1. Ratios of short- to long-period amplitude vs. P–S times for P waves (Reproduced from a previous paper, Okano and Hirano, 1971)[6].

from the previous paper[6] shows the ratios for P waves vs. P–S times with the theoretical curves. This indicates that the observed ratios are widely scattered for distances less than 30 km. The variation of the ratios for S waves is similar to that for P waves shown in this figure, the ratios being also widely scattered for the same distance range. It is, therefore, difficult to determine uniquely a value of Q by using seismic waves travelling short distances. This paper intends to study what such a wide scatter arises from. For this purpose, we will examine the regional variations of attenuation characteristics based on the ratios of short- to long-period amplitude obtained by two systems of seismographic instruments for P and S waves, the ratios of P- to S-maximum amplitude and the station deviation of earthquake magnitudes.

2. Data

Fig. 2 shows the micro-earthquake observation stations in the vicinity of Kyoto. At four of these stations — Abuyama (AB), Yagi (YG), Kyohoku (KH) and Kamigamo (KG) — two systems of seismographic instruments are installed. Seismic records from the four stations are used for the present study. The response curves of the two instruments are shown in Fig. 3. Instrument-1 consists of a 1.00-sec pendulum and a 0.02-sec galvanometer. The peak magnification is about 60,000 at about 15 Hz. Instrument-2 consists of a 0.75-sec pendulum and a 0.35-sec galvanometer with the peak magnification of about 30,000 at 2.5 Hz. Instrument-1 installed at AB has a little different frequency response from that shown in Fig. 3 due to the use of the different high-cut filter (see Fig. 1 in the previous paper)[6]. This difference of frequency response, however, does not seriously influence arguments put forth.

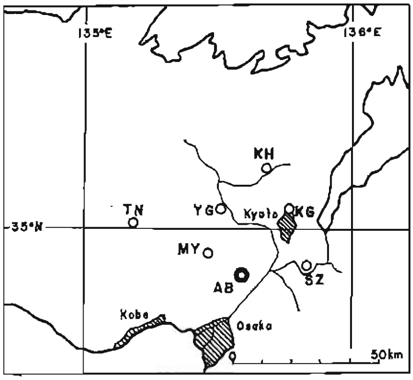

Fig. 2. Map showing the observation stations.

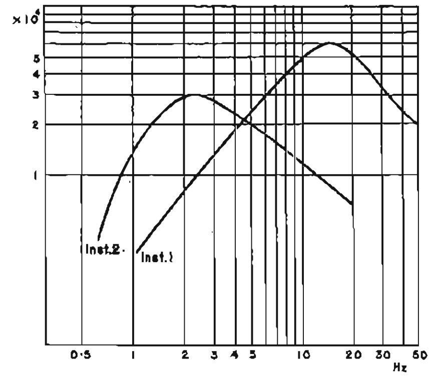

Fig. 3. Frequency response curves of Instrument-1 and Instrument-2.

A total of about 200 earthquakes with magnitude 1.0 to 3.0 occurring in the vicinity of Kyoto are analyzed in this paper. In the following, the maximum amplitude recorded by Instrument-1 will be referred to as short-period amplitude, A_S, and that by Instrument-2 as long-period amplitude, A_L. The maximum amplitudes of P and S waves are denoted by P_m and S_m respectively.

3. Regional variation of the ratios of short- to long-period amplitude and its implications

Figs. 4, 5 and 6 schematically show the regional distributions of the ratios of short- to long-period amplitude (A_S/A_L) for P and S waves recorded at YG, AB and KH respectively. Events with high, intermediate and low frequencies are plotted by open, semi-solid and solid circles respectively in these figures.

It is found from Fig. 4 that events located east and west of YG give higher frequency seismograms than those located north and south. This means that the difference in the frequency contents of seismic signals for P waves as well as for S waves is related to epicenter azimuth. Possible causes which make the difference of frequency contents may be characteristics of source or source region and/or transmission path. If this difference is caused only by characteristics of source or source region, the ratios A_S/A_L would not be related to epicenter azimuth but to epicenter location, hence the regional distributions of the ratios observed at AB (Fig. 5) and KH (Fig. 6) would be similar to the distribution at YG. Although events are not uniformly distributed around AB, as is known from Fig. 5, the events located in the west quadrant of AB give higher frequency seismograms than those in the north quadrant for P waves as well as for S waves. As seen in Fig. 6, only a few events occurred in the northern part of KH. However, the ratios A_S/A_L observed at KH indicate that the events located in the east and west quadrants give higher amplitude ratios than those in the south quadrant. It may be, therefore, considered from Figs. 4–6 that seismic waves propagating in the EW direction are less attenuated than those propagating in the NS direction. As has been already studied by the present authors by use of composite first motions of P and S waves (Okano and Hirano, 1965, 1966)[7),8)], the

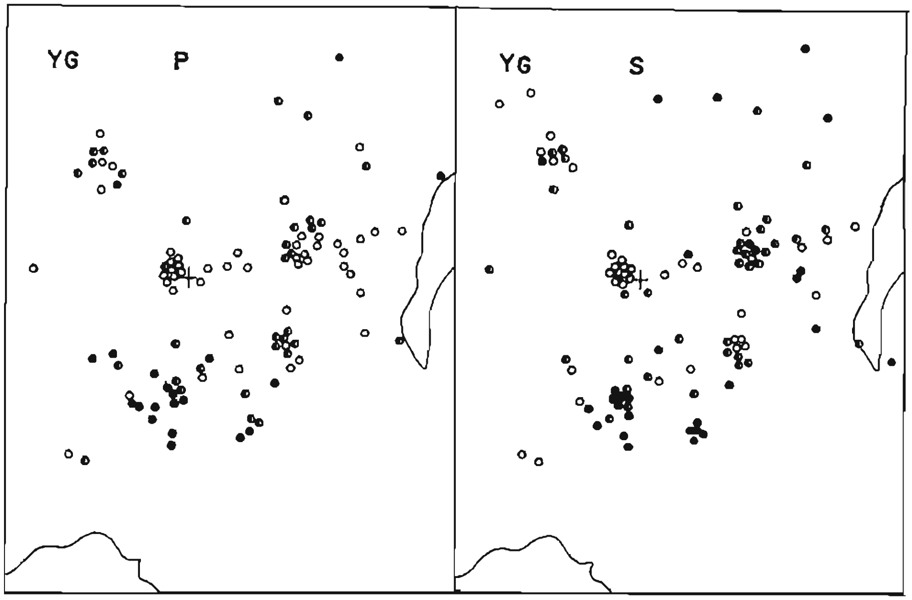

Fig. 4. Relations between epicenter locations and frequency contents of events observed at YG for P and S waves. Events with high, intermediate and low frequencies are denoted by open, semi-solid and solid circles respectively.

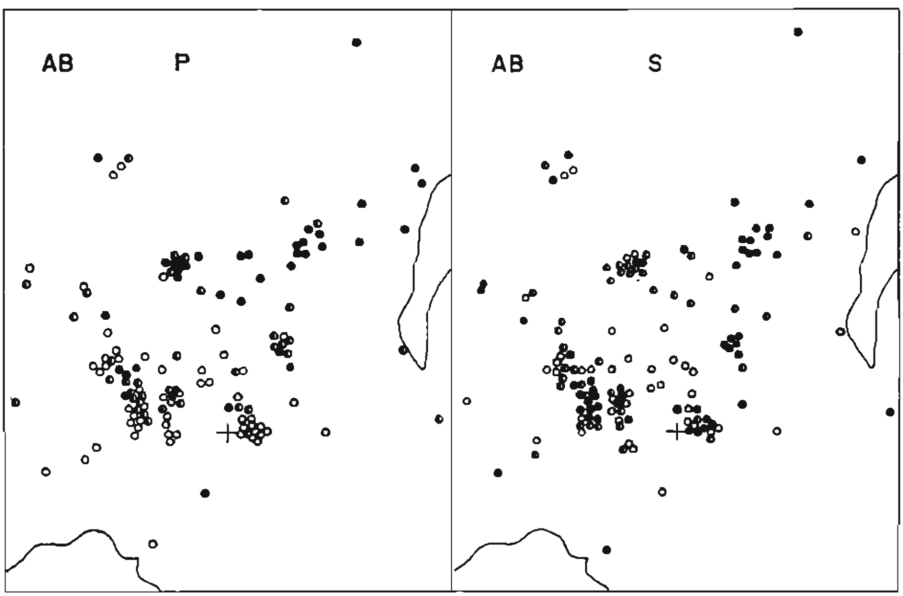

Fig. 5. Relations between epicenter locations and frequency contents of events observed at AB for P and S waves. Symbols are the same as those in Fig. 4.

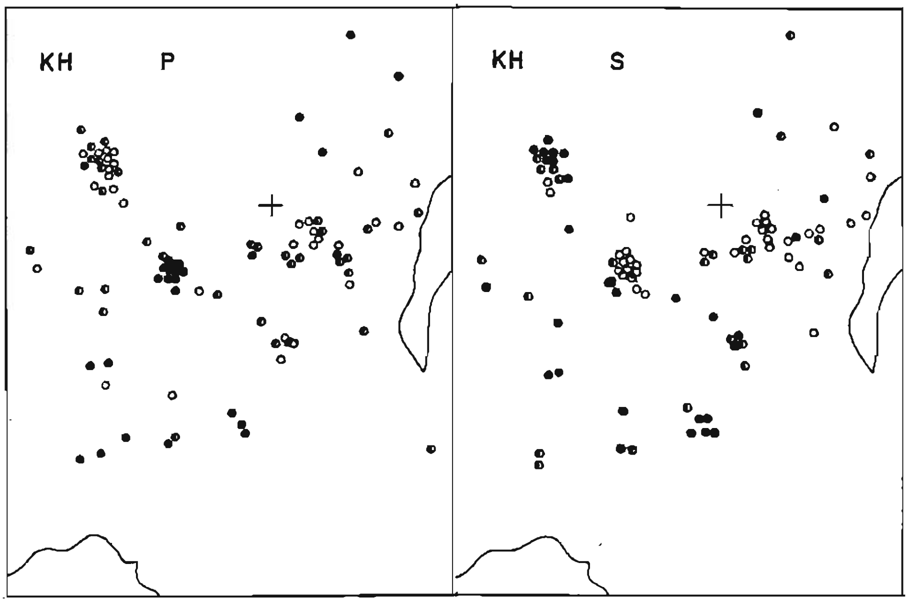

Fig. 6. Relations between epicenter locations and frequency contents of events observed at KH for P and S waves. Symbols are the same as those in Fig. 4.

principal axis of compression in the vicinity of Kyoto lies in the EW direction. Therefore, the regional distributions of A_S/A_L's observed at YG, AB and KH indicate that seismic waves propagating in the direction of compressional force (EW) are less attenuated than those in the direction perpendicular to the compressional axis (NS).

Figs. 7, 8 and 9 show the azimuthal distribution of amplitude ratios of A_S/A_L's

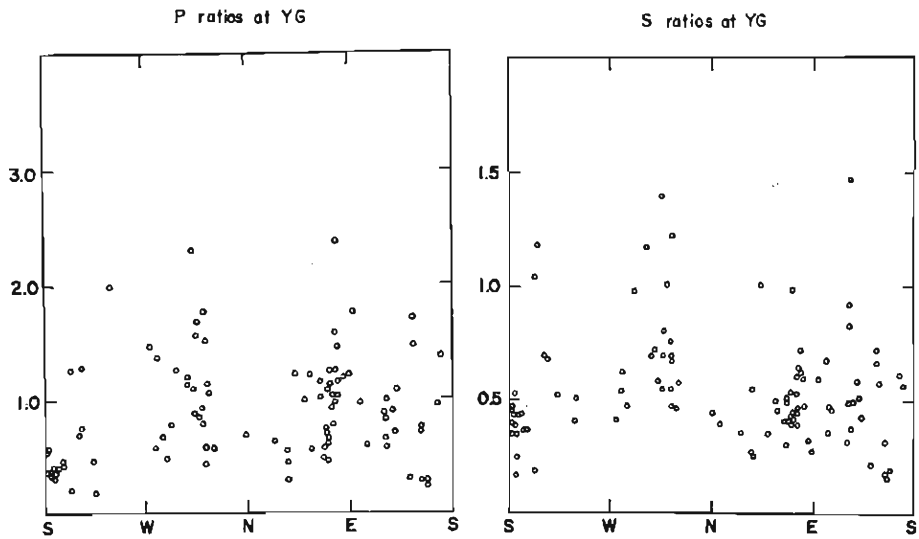

Fig. 7. Azimuthal distributions of the ratios of short- to long-period amplitude observed at YG for P and S waves.

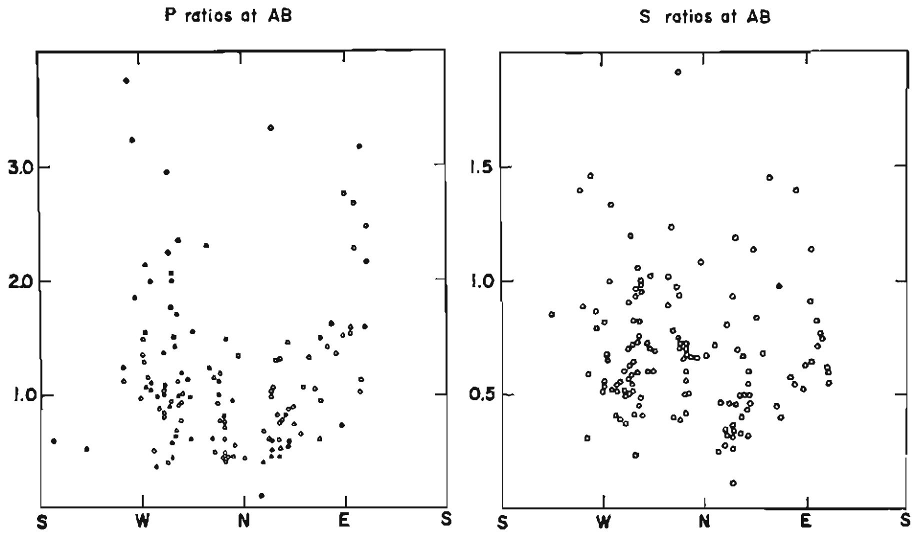

Fig. 8. Azimuthal distributions of the ratios of short- to long-period amplitude observed at AB for *P* and *S* waves.

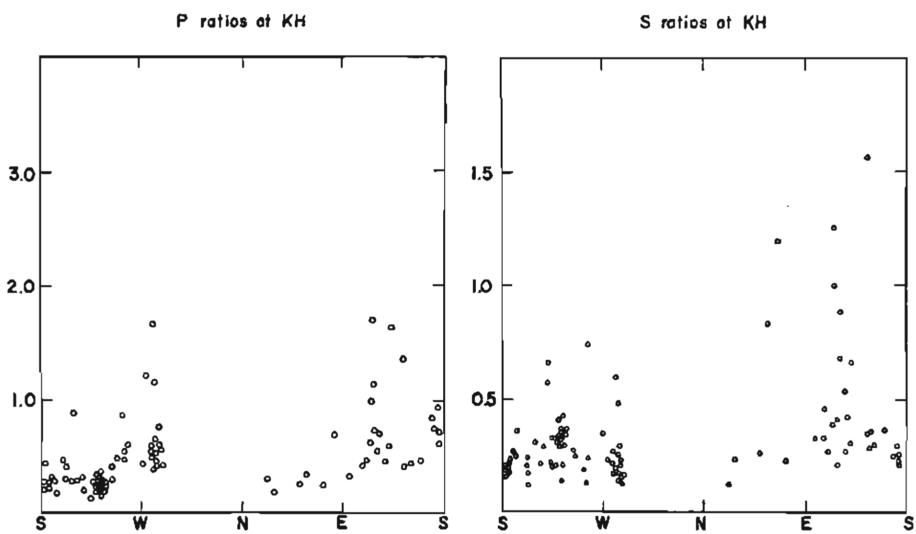

Fig. 9. Azimuthal distributions of the ratios of short- to long-period amplitude observed at KH for *P* and *S* waves.

observed at YG, AB and KH respectively. As is found from Fig. 7, the amplitude ratios at YG seem to vary sinusoidally with azimuth, with two peaks at the direction of maximum compression (EW) and two troughs at the direction of the minimum compression (NS). The azimuthal variations of the amplitude ratios observed at AB and KH, as is known from Figs. 8 and 9, are similar to the variation at YG, although events are not uniformly distributed around AB and KH. Therefore, it may be considered that all the data from YG, KH and AB indicate that the regional variation of attenuation of short-period amplitude is closely related to the global tectonic stress of the region concerned. It is suggested from the sinusoidal variation of the ratios with respect to azimuth that a magnitude of attenuation depends on a magnitude of the compressional stress. One of the most probable causes of the diminishing attenuation for seismic waves propagating in the direction of compressional stress may be higher strain accumulation caused by compressional force. However the data from KG located in the northern part of the region concerned are against the facts mentioned above. Fig. 10 schematically shows the regional variation of amplitude ratios for *P* and *S* waves observed at KG. Symbols are the same as those in Figs. 4–6. The azimuthal variation of these ratios is shown in Fig. 11. Fig. 10 and 11 indicate that the amplitude ratios are independent of epicenter azimuth. Thus, KG data indicate that the regional variation of attenuation cannot be explained by the difference of propagating direction of seismic waves. The amplitude ratios observed at KG, as is known from Fig. 10, are generally large independently of epicenter azimuths for events occurring near KG. This suggests that seismic waves are less attenuated near KG than near the other stations. Therefore, it is reasonable to consider that less significant attenuation near KG shown by the ampli-

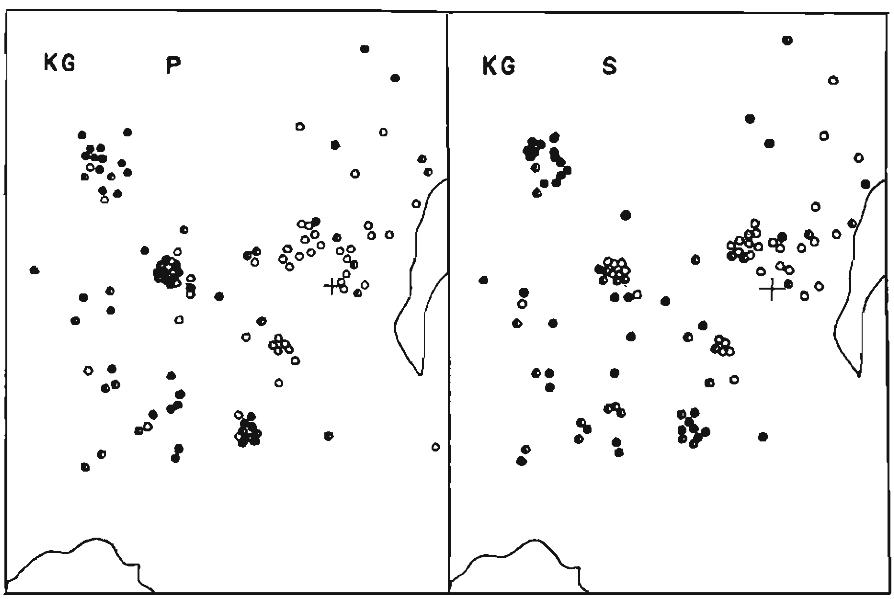

Fig. 10. Relations between epicenter locations and the frequency contents of events observed at KG for *P* and *S* waves. Symbols are the same as those in Fig. 4.

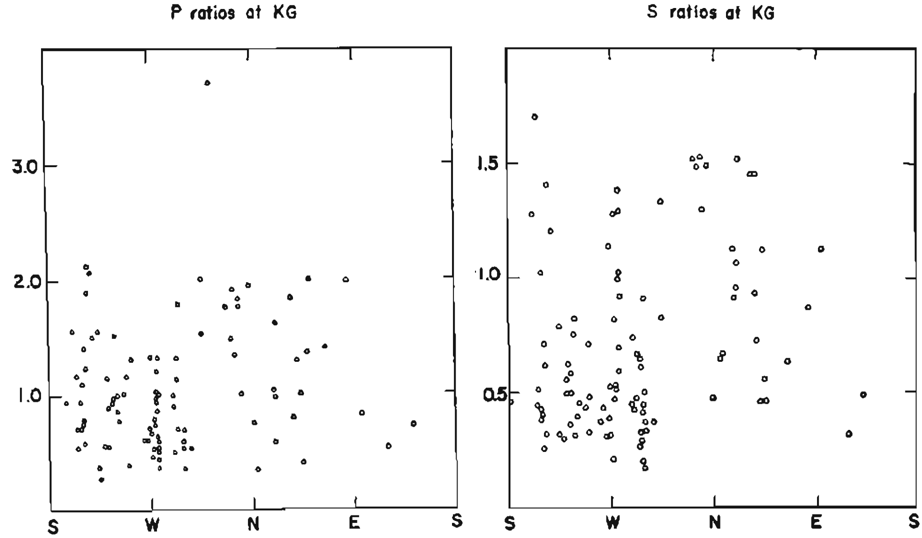

Fig. 11. Azimuthal distributions of the ratios of short- to long-period amplitude observed at KG for P and S waves.

tude ratios is caused by the in situ characteristics. As is mentioned above, the data from YG, AB and KH indicate that seismic wave attenuation is closely related tothe global stress. On the contrary, according to the data from KG, the relation between the regional variation of the seismic attenuation and the global stress is not so clear as shown by the data of the other stations. If less attenuation of seismic waves results from higher strain accumulation, it is reasonable to consider that strain accumulation is higher in the region near KG than in the other regions. The high strain accumulation is probably caused by the in situ stress in the vicinity of KG or in the northern part of the region concerned. It is speculated from the above considerations that strain accumulation in the northern part of the region concerned reaches a higher degree than that in the southern part. This implies that strain is difficult to accumulate near AB and YG compared with the region near KG.

Another evidence for the above speculation is the behavior of aftershock occurrence in the region concerned. As for events occurring in the vicinity of Kyoto, the number of aftershocks depends rather on the location of mainshock than its magnitude (Okano, 1970)[8]. According to Okano's study, the events occurring in the southern part are followed by more aftershocks than those in the northern part. The regional variation of the aftershock activity can be interpreted as a reflection of the difference in the properties of the crust between the northern and southern parts. One of the properties of the crust relating to the regional variation of the aftershock activity may be the relative difficulty of strain release. In other words, strain is apt to be accumulated in the northern part to a higher level than in the southern part, which results in the difference of the aftershock activity mentioned above. This interpretation is just the same as is speculated based on the attenuation characteristics of seismic waves.

It may be concluded from the above considerations that the regional variation of attenuation characteristics found in the vicinity of Kyoto is closely related to the global stress known from the radiation pattern, and that the attenuation characteristics found in the northern part of the region reflect the in situ stress field added to the global one.

4. Regional variation of the ratios of *P*- to *S*-maximum amplitude

If the period of *S* waves, as is generally accepted, is longer than that of *P* waves as for an earthquake, the maximum amplitudes of *P* and *S* waves can be considered as a measure of attenuation of high and low frequencies respectively. Of course, the amplitude and period of seismic wave are probably more strongly affected by various factors such as earthquake magnitude, source parameters, radiation pattern and so on. These effects are discussed later. For the present, we assume that the ratios of *P*- to *S*-maximum amplitude (P_m/S_m) are a measure of attenuation. It is expected on this assumption that the regional distribution of P_m/S_m's resembles to that of A_m/A_m's, discussed in the preceding section.

Figs. 12–17 show the regional variations of P_m/S_m's observed at YG, AB, KH, TN, SZ and KG respectively. Events with the ratio of 2.0 or greater are plotted by open circles, and those with the ratio of 0.5 or smaller by solid circles. These ratios were obtained by the records of Instrument-1 for all stations. As is found from Figs. 12–16, P_m is larger than S_m for events located in the east and west quadrants with respect to the respective observation stations, and vice versa for those in the north and south quadrants. Therefore, it can be considered that seismic wave attenuation is smaller

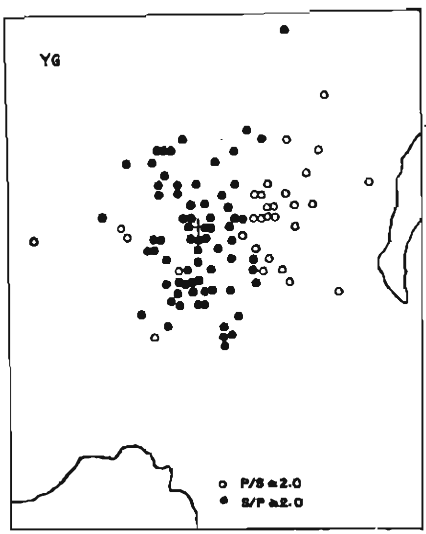

Fig. 12. Regional variation of the ratios of *P*- to *S*-maximum amplitude obtained from YG data. Events with ratios greater than 2.0 and smaller than 0.5 are plotted by open and solid circles respectively.

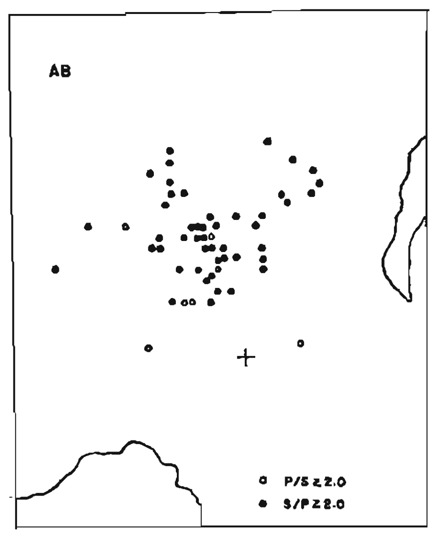

Fig. 13. Regional variation of the ratios of *P*- to *S*-maximum amplitude obtained from AB data. Symbols are the same as those in Fig. 12.

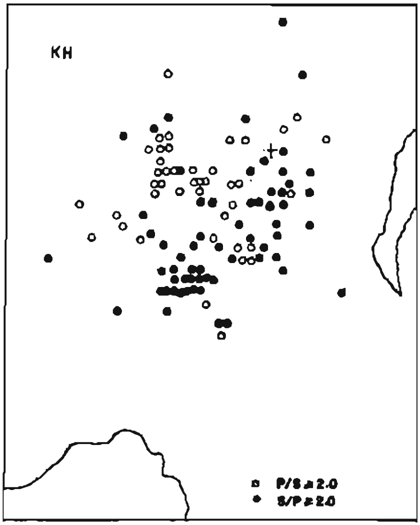

Fig. 14. Regional variation of the ratios of *P*- to *S*-maximum amplitude obtained from KH data. Symbols are the same as those in Fig. 12.

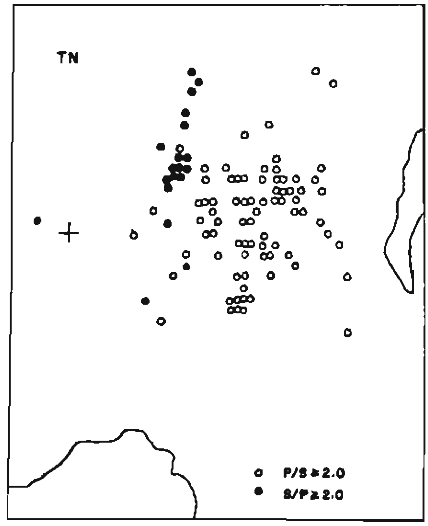

Fig. 15. Regional variation of the ratios of *P*- to *S*-maximum amplitude obtained fromTN data. Symbols are the same as those in Fig. 12.

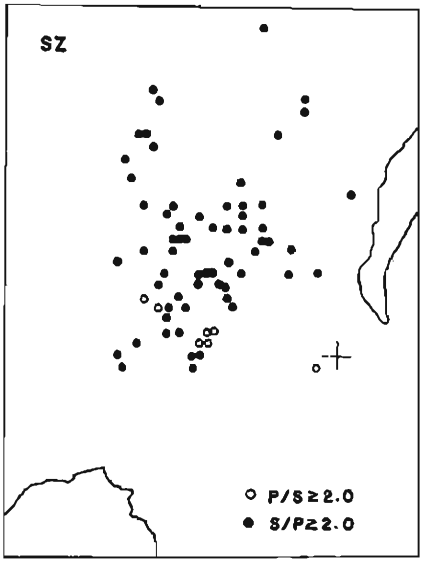

Fig. 16. Regional variation of the ratios of *P*- to *S*-maximum amplitude obtained from SZ data. Symbols are the same as those in Fig. 12.

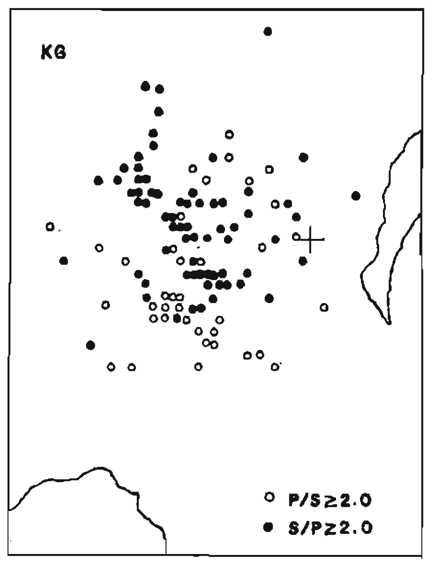

Fig. 17. Regional variation of the ratios of *P*- to *S*-maximum amplitude obtained from KG data. Symbols are the same as those in Fig. 12.

in case of propagating along the EW direction than in case of propagating in the NS direction, if we accept that the frequency of P wave is higher than that of S wave. It is known from Fig. 17 that the regional variation from KG data is a little different from the variations of YG, AB, TN, SZ and KH. This difference probably arises from the characteristics of the region near KG. The values of P_m/S_m may be also possibly affected by the stress or strain inherent to the region near KG, as is discussed in the preceding section. Thus, it is implied that the regional distribution of P_m/S_m's is very similar to that of A_S/A_L's for the respective stations.

In Fig. 18, the ratios of P- to S-maximum amplitude obtained from the data of all

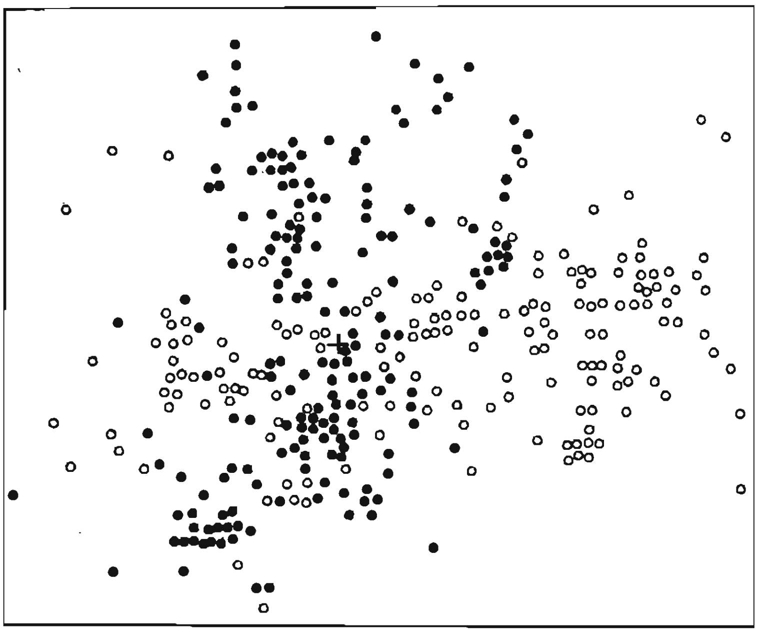

Fig. 18. Regional variation of the ratios of P- to S-maximum amplitude obtained from the data of AB, MY, YG, KH and TN.

stations except KG are composed in order to show clearly the azimuthal distribution of the ratios. Symbols are the same as those in Figs. 12–17. As is very clearly indicated from this figure, the maximum amplitude ratios of P and S waves are larger for events occurring in the east and west quadrants than for those in the north and south quadrants. Fig. 18 looks as if it were the composite first motion diagram for events occurring in the region concerned (Okano and Hirano, 1968)[10]. The events with large and small ratios of P_m/S_m correspond to the events with compressional and dilatational first motions respectively. If we accept that P_m/S_m is a measure of attenuation of seismic waves, we may conclude that attenuation of seismic waves is small when propagating along the direction of large compressional stress.

The above consideration based on the distribution of P_m/S_m's is less reliable if these ratios are strongly affected by radiation pattern. According to the study of first motions of P and S waves (Okano and Hirano, 1966)[8], the axes of the maximum and minimum stresses lie in the EW and NS direction respectively. Motion on a fault would be approximated by a vertical strike slip for most events in the region concerned. Therefore, if the radiation pattern strongly affects the ratios of P_m/S_m's, four peaks would appear in their azimuthal distributions. Fig. 19 shows the azimuthal distribution of these ratios observed at YG. As is found from this figure, although

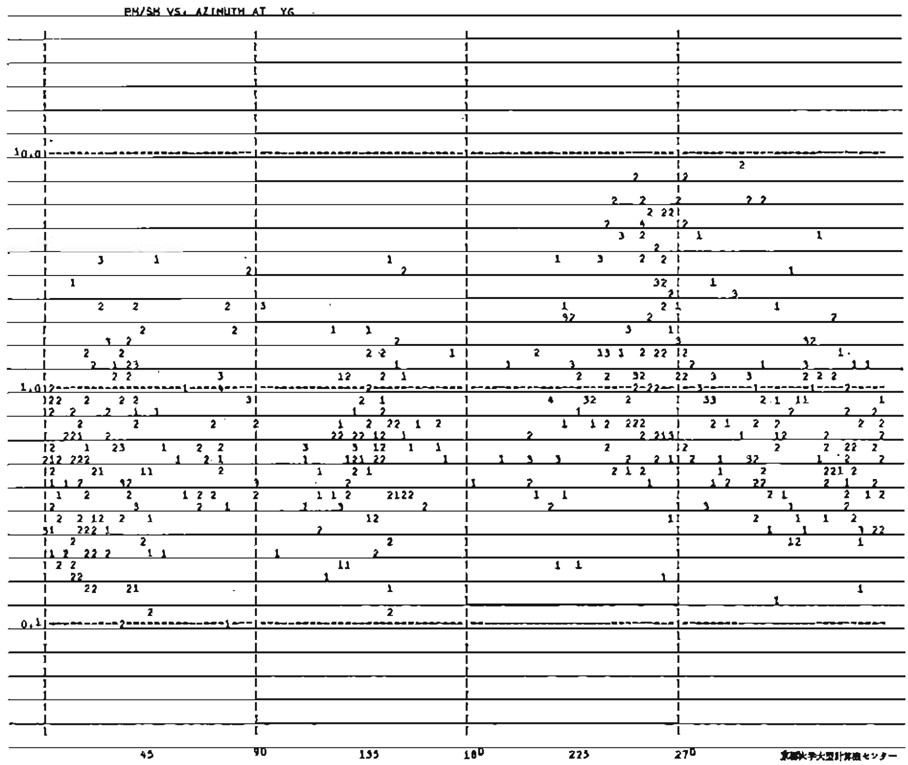

Fig. 19. Azimuthal distribution of the ratios of *P*- to *S*-maximum amplitude obtained from YG data.

the values of the ratios are widely scattered, the upper bounds of the ratios have two peaks at about 90° and 270° respectively. As for the lower bounds, the peak is seen at 0°, 90°, 180° and 270°. The peaks at 90° and 180° are more remarkable than those at 0° and 270°. This seems to indicate that the effect of radiation pattern on the maximum amplitude ratios is less significant than the effect of attenuation. The azimuthal distributions of $P_m/{}_mS$'s observed at AB and KH are similar to the distribution at YG. However the number of peaks cannot be known since the azimuthal distributions of events with respect to these stations are not uniform. Therefore a definite conclusion concerning the effect of a radiation pattern cannot be drawn from the data of AB and KH. So far as the data of YG are concerned, it can be considered that the ratios of P_m/S_m's are not seriously affected by the radiation pattern.

Finally, earthquake magnitudes are discussed briefly with relation to seismic wave attenuation in the region concerned. Routine data processing determines the magnitudes of events by use of maximum amplitudes recorded at all stations. In determining magnitude, two attenuation constants depending on epicentral distance ranges are used, but the site amplification or heterogeneity and lateral variation of attenuation is not taken into consideration. Therefore, deviation of magnitude determined by use of one station data from the averaged value of magnitudes determined from all station data, if any, is considered to result from the characteristics inherent to the station concerned and its vicinity. Fig. 20 shows the frequency distributions of magnitude deviations of the four routine stations. $M-\bar{M}_0$ denotes

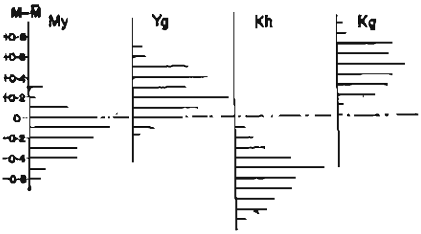

Fig. 20. Deviations of magnitudes obtained from the data of MY, YG, KH and KG from the averaged magnitude.

the magnitude deviation. As is found from Fig. 20, magnitude estimated from the data of KG located in the northern part are larger than the averaged magnitude. This indicates that attenuation near KG is smaller than the overall attenuation used for the routine determination of magnitude. Oppositely, magnitudes estimated from the data of MY located in the southern part are smaller than the averaged magnitude. This suggests that attenuation near MY is large compared with the other regions. The regional difference of attenuation, if compared with the regional difference of the aftershock activity, indicates that the regions with high and low attenuations coincide with the regions showing high and low aftershock activities respectively. The regional variation of attenuation might result from the difference of the relative difficulty of strain accumulation. Furthermore, it is not too unreasonable to speculate that the high strain accumulation in the northern part may be caused by the in situ stress added to the global one.

According to the frequency distribution of $(M-\bar{M})$'s of KH, the magnitude determined by use of the maximum amplitude recorded at KH located in the northern part is very small. Such a high attenuation cannot be found from the regional variations of A_S/A_L's and P_m/S_m's. Furthermore, events occurring near KH are followed by a comparatively small number of aftershocks[9]. Magnitudes obtained from KH data might be underestimated due to the local characteristics of the station itself. However the inconsistency shown by the KH data will be solved by further studies.

5. Summary and discussion

The results of the present study show that, in the seismically active region in the vicinity of Kyoto, seismic wave attenuation differs with propagation direction as a whole. The attenuation is small for waves propagating in the EW direction which corresponds to the direction of the global tectonic stress acting in the region concerned. Thus, a possible cause of diminished attenuation is speculated to be high strain accumulation caused by the compressional force acting in the EW direction. The results also show that attenuation in the northern part is small compared with that in the southern part of the region. This seems to suggest that there is a regional difference of strain or stress field between the northern and the southern part of the region concerned. It is not too unreasonable to consider that, in the northern part, the in situ stress is added to the global tectonic stress, causing higher strain accumulation compared with the other parts of the region. On the contrary, lower strain accumulation found in the southern part might be a reflection of low stress. Furthermore, it can be considered that the regional difference of aftershock activity might be related to the relative difficulty of strain accumulation. Relation between attenuation and stress will be made clearer by determination of stress drops or the tectonic effective stresses and their regional distribution based on amplitude data of earthquakes. If attenuation characteristics, as accepted in the above discussion, are very sensitive to either strain or stress field, an investigation of regional distribution of seismic attenuation may be one of the most important tools for earthquake prediction.

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