A Wall-Like Low- Q Zone beneath the Yakedake Volcano, Central Japan

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The structure of the seismic wave attenuation zone beneath the Yakedake Volcano in the Hida Mountain range of central Japan was disclosed by a temporary seismic observation array across the mountain range. The amplitudes of P waves from four distant offset explosions showed abrupt decay of seismic wave amplitude under the volcano. However, the amount of decay was dependent strongly on the azimuth. This suggests the existence of a very localized attenuation zone at a shallow depth. To explain consistently these observed data, a vertical wall-like attenuation zone that extends beneath the volcano in the strike of N33°W is suggested. The attenuation ratio that equals the product of the attenuation coefficient and the width of the zone is 0.6. The Q derived from this value is estimated as 30 at 15 Hz if we assume the width of the zone as 2 km. The estimated depth of the top of the zone is about 1 to 2.5 km below the surface. The location coincides well with not only a high geothermal belt near the volcano but also with the active fault that stretches southeast from the volcano.

1. Introduction

Many experiments and analyses in volcanic areas disclosed the existence of magma chambers, partial-melt or low- Q zones beneath the volcanoes and their geometrical structures. For example, Sanders (1984) mapped the shear wave attenuation body under the Long Valley caldera, California, by the wave amplitude analysis of small earthquakes. Achauer *et al.* (1988) determined the P-wave velocity structure at Newberry Volcano, Oregon, by the method of high-resolution seismic tomography. Clawson *et al.* (1989) determined the three-dimensional Q structure in the Yellowstone caldera by inversion analysis of the spectral decay of refracted P waves. Ueki (1990) summarized 29 seismic studies (70% of which were refraction surveys) on the shallow crustal structure beneath active volcanoes in Japan.

The Hida Mountain range, one of the highest mountain ranges in central Japan, includes several volcanoes such as Tateyama, Yakedake, Norikura, and Ontake. The Yakedake Volcano is the most active among them. They form a volcanic chain as shown in Figs. 1 and 2. Although the volcanic activity is relatively low in this area, the attenuation of seismic waves beneath the Hida Mountains is remarkably high. This has

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Fig. 1. Map showing the observation field. Solid triangles indicate the active volcanoes. The location of Agatsuma-Kanazawa profile and the shot points (squares) by RGES and the temporary observation stations (small circles) are also plotted. The shaded circle indicates the location of attenuation that Katsumata *et al.* (1995) suggested in the deeper part. Box in the center corresponds to Fig. 2. T, Tateyama Volcano; Y, Yakedake Volcano; N, Norikura Volcano; O, Ontake Volcano; YR, Yurigatake.

been suggested by a comparison of two epicentral maps made by two seismic networks in central Japan. One is a seismic network on the east side of the Hida Mountain range and the other on the west side (e.g., Mizoue *et al.*, 1983). We can recognize an apparent low seismic area beyond the mountain range in both epicentral maps. This is apparently due to some intense attenuation of seismic waves beneath the Hida Mountain range. Katsumata *et al.* (1995) have deployed a temporary seismic observation array across the northern part of the range. To find the location of the attenuation zone, they compared body-wave amplitudes from nearby earthquakes with those from the southern part of the range. They concluded that a very strong low- Q anomaly exists between the Ontake Volcano and Yurigatake at depths of 5–15 km. Their result, however, suggested only the extent of the area in which the attenuation zone exists, as plotted in Fig. 1. More precise position and distribution, especially in the shallow zone, and the features of the attenuation zone beneath the Hida Mountains remains to be investigated.

In 1991, the Research Group for Explosion Seismology (RGES) (1994) planned a large-scale seismic refraction experiment to probe the crustal structure in the northern part of central Japan. They deployed 169 seismic stations along a 180-km profile (the

Agatsuma to Kanazawa profile). It crossed the northern part of the Hida Mountain range east-west, as shown in Fig. 1. Four shot points (S-1 to S-4) were arranged along the profile. The charges of TNT at S-1 and S-4 were 700 kg each, and those at S-2 and S-3, 450 kg each.

To reveal the detailed attenuation structure beneath the Hida Mountain range, I planned an additional observation array near the Yakedake Volcano. The observation of P waves from these 4 shots provides us an azimuth-dependent seismic attenuation beneath the Hida Mountain range. In this paper, I present the results of the observation and propose an attenuation structure near the Yakedake Volcano.

2. Data Acquisition

Eighteen temporary seismic stations were aligned in the ESE direction along the road crossing the Hida Mountain range and an additional 3 in the NE direction, as shown in Fig. 2. The Abou pass, the center of the profile, is located 4 km south of the Yakedake Volcano. All the seismometers were set on the rocks or on concrete cemented on the rocks except those installed near the Abou pass. The rocks near the Abou pass are not so tight. The direction of the shot point S-1 from the Abou pass is N73.5°E. Those of S-2, S-3, and S-4 are N60.5°E, N32.5°W, and N61.7°W, respectively. As shown in Fig. 2, except for S-4, the shot points do not lie in the direction of the profile. The mean incident angles of the waves to the profile are about 45, 60, and 30 degrees for S-1, S-2, and S-3, respectively. S-4 is located in the direction of the profile. The distances

Fig. 2. Deployment of observation stations. Symbols indicate the type of recording system. Details are shown in Fig. 3. The mountain area higher than 2,000 m is shaded. Direction of 4 shot points from the center of this profile is shown in the lower left corner.

Fig. 3. Block diagrams of recording systems used in the observation. Three types of digital recording systems were used; the PRS-4 system (upper; circles in Fig. 2), the DTC-8000 system (middle; squares in Fig. 2), and the EAT-1000 system (lower; crosses in Fig. 2). The first system is driven by dry batteries, the second, by a DC power supply, and the last by an AC power supply. Wireless transmitters were used with the second and third systems and these systems recorded the data of several stations.

from the shot points are 97–133 km for S-1, 53–83 km for S-2, 30–59 km for S-3, and 62–102 km for S-4.

We adopted L-22D (Mark Products Inc.) vertical transducers with a natural frequency of 2.2 Hz and a damping constant of 0.7. Three types of digital recording systems were used (Fig. 3). PRS-4 (SCINTREX Inc.) is a compact, low-power, 4-channel data recorder with an accuracy of 12 bits, a dynamic range of 130 dB and with memory boards of 4–6 Mbytes. The recording schedule was programmed on a PC in advance and transferred to the recorder via the serial port. The stations equipped with PRS-4 are shown by circles in Fig. 2. DTC-8000 (Columbia Co., Ltd., DC power supply) and EAT-1000 (KINKEI System Corporation, AC power supply) are 6-channel data recorders of 16-bit accuracy and equipped with magneto-optical (MO)-disk drives. The former is also programmable and the latter can be controlled by telephone. They are

plotted in the same figure using squares and crosses, respectively. The sampling rate was set at 200/s and clocks were calibrated to JJY (broadcast service of Japan standard time) to within an accuracy of a few milliseconds.

The refraction experiment was conducted on October 17, 1991. The first shot was fired at 01h02m at S-1 and was followed in order by S-2, S-3, and S-4 at 10-min intervals. Recordings were made by setting the time windows for a 5-min duration. All the recording systems were installed in the daytime, and the data were collected on the next morning. The recorded digital data were transferred to a workstation for later analysis.

3. Observational Results

As motor traffic is significantly large on the road even in the middle of the night, ground noises were too high to record the seismic signals at some stations. Data from only 14 to 17 stations had a high S/N ratio. Figures 4 and 5 show the record sections and the travel-time diagrams of first arrivals from 4 shots with a reducing velocity of 6 km/s. The abscissa is shot-distance. No altitude correction in arrival times is treated

Fig. 4. Available recording sections with a reducing velocity of 6 km/s for shots S-1 to S-4. Amplitudes at all stations are shown in the same scale except for those at station-9 (Abou pass). Some record sections are not shown in these figures to avoid overlapping of traces.

Fig. 5. Travel-time diagrams. Travel times are reduced by a velocity of 6 km/s. Radius of circles indicates the reliability of first arrival readings. Bars indicate times and maximum amplitudes of the adopted data. Triangle: Abou pass.

in these figures. The maximum difference in height among the stations is 1.2 km and is estimated at nearly 0.2 s in time. A solid triangle on the abscissa marks the Abou pass, since it is located on the axis of the Hida Mountain range.

The distinctive features shown in the record sections are as follows:

(a) Except for the recording section for shot S-3, the amplitudes decay prominently when the waves pass through the axis of the mountain range. It suggests the existence of intense attenuation beneath the range.

(b) The apparent velocity in all record sections is almost 6 km/s, except for a 0.1–0.2 s delay of first arrival at stations near the Abou pass. However, there is no delay at stations beyond the Abou pass, as shown in Fig. 5. This delay may be due to the height difference between stations or due to a very shallow local low-velocity zone.

(c) The dominant frequency of the signals is nearly 15 Hz in all sections and does not change even when the waves pass through the axis of the mountain range.

To evaluate the amount of attenuation, maximum amplitudes of P waves are plotted against shot distance in Fig. 6. P-wave amplitude is generally expressed as decay inversely proportional to the n -th power of distance. In the Matsusiro explosion experiment conducted by RGES in 1981 (Ikami *et al.*, 1986), the data set of observed

Fig. 6. Maximum amplitudes of the main part of P waves plotted against epicentral distance. Open circles and triangles indicate the maximum amplitude of normal and attenuated waves, respectively. Crosses indicate omitted data which are considered to be affected by the local irregularities. Solid triangles are the same as in Fig. 5. The lines in the figures are the mean decay curves of the maximum amplitude that fit with the observed data of normally and of intensely attenuated waves. Notations a, c and e, and b, d and f indicate the normally and the intensely attenuated data near the mountain range axis, respectively.

maximum amplitudes indicates that the value of n is 2 for distances greater than 10 km. RGES adopted 2 as the typical value of n for the explosion data and described in their instruction for the explosion observation. This result is consistent with that of the refracted P-wave maximum amplitudes employed by Okada *et al.* (1979) if we assume that the epicentral distance equals the distance propagated by the critically refracted wave. Here, by adopting 2 as the value of n , the two lines in each figure are the least-squares curves fitted to the maximum amplitude decay at the west and east sides of the Abou pass, respectively. In the process of calculating the least-squares curves, I omit the amplitude data which are extremely or systematically out of range since such data are considered to be affected by local irregularities.

Here, we assume that a fitting is done with a single line as a standard decay curve

of maximum amplitude for each shot. If we fix the value of n at 2, the deviations of data from the normal attenuation become large and the obtained curve does not accord with the observed small amplitudes of P waves that passed through the mountain range. To avoid this discrepancy and to minimize the deviations of observed data, we need to adopt a value of n greater than 2. This case, however, does not meet the amplitude data observed by RGEs in this experiment. The amplitude extrapolated from the fitted curve becomes too large compared to those observed at short distances (Research Group for Explosion Seismology, 1994). A large value of n leads to this excessive estimation. It is obvious that these discrepancies described here come from the assumption that no abnormal attenuation structure exists beneath the mountain range.

From this figure, the following features are evident:

(a) Abrupt attenuation occurs only when the seismic waves pass through the main axis of the mountain range. The amount of attenuation or the offset between fitted lines depends on the direction of wave propagation. The amplitudes of waves from S-1 and S-2 are reduced by factors of 0.54 and 0.55, respectively. In contrast, it is 0.29 for S-4.

(b) No abrupt attenuation is recognized for S-3. The direction of wave propagation to this profile is southeast and differs from those of other shots. This means that the abnormal attenuation zone does not distribute continuously along the mountain range. If its distribution was continuous along the mountain range, all the amplitudes of waves that cross the range would attenuate intensely.

(c) Near the mountain axis, there is a zone of no abnormal attenuation for all the shots. The width of the zone was estimated to be around 5 km. This zone will be referred as the zone of no attenuation hereafter.

(d) The observed amplitudes at stations near the Abou pass are extremely large. This might be accounted for by geometrical effects such as focusing of the waves, and/or by the small elastic constants beneath the stations.

4. A Model for the Attenuation Zone

I propose a simple model of the wave attenuation structure that causes the above-mentioned observational results. In making the model, I take note of: 1) the azimuthal dependency of amplitude attenuation, 2) the absence of attenuation in the case of shot S-3, and 3) the abrupt decrease in amplitude when the P waves passed through the mountain range. The lack of the apparent delay in the first arrivals of attenuated waves was also taken into account.

The proposed model of the attenuation zone is as follows:

In the upper crust, a nearly vertical and thin wall-like shallow attenuation zone stretches underneath the Yakedake Volcano with a strike of about N33°W. Its direction coincides with the direction of the shot point S-3 (Fig. 8). In this model, the amount of attenuation depends on the length of the ray path in the attenuation zone. As mentioned in the previous section, the maximum amplitude of the waves outside the attenuation zone is expressed by

Fig. 7. A schematic model of the attenuation structure of the seismic waves. D , thickness of the attenuation zone.

Fig. 8. The proposed attenuation structure. The strike of the zone is about $N33^{\circ}W$. The shot point S-3 is located in the direction indicated by the arrow. The thickness of this zone is uncertain but it is smaller than the spacing of observation stations. The area filled with asterisks shows the high geothermal belt. Sakai-touge Fault (The Research Group for Active Faults of Japan, 1991) is indicated as a bold line. Open circles indicate the hot springs and cross marks indicate the observation stations. Solid and broken lines indicate ray paths of normally and intensely attenuated waves, respectively. The notations a to f are the same as in Fig. 6.

$$A = A_0 \Delta^{-2},$$

where Δ is the shot distance. The maximum amplitude of the waves passing through this attenuation zone is given by:

$$A = A_0 \Delta^{-2} \exp(-\lambda D / \sin \theta),$$

or

$$-\lambda D / \sin \theta = (\log_{10}(A/A_0) + 2 \log_{10} \Delta) / \log_{10} e,$$

where λ and D represent the attenuation coefficient per distance and the width of the attenuation zone, respectively, and θ the incident angle to the zone, as indicated in Fig. 7. The mean square error between the observed and the theoretical attenuation ratios for 3 shots (S-1, S-2, S-4) is obtained for various combinations of λD and the azimuth of the zone. They are plotted in Fig. 9. The mean square error becomes minimum when the strike of the modelled attenuation zone is N32.9°W and the attenuation ratio λD is 0.596 as shown in this figure. Figure 10 indicates the logarithmic attenuation ratio $\log(A/A_0)$ against the incident angle θ . Solid squares in the figure represent the mean attenuation for each shot in Fig 6.

If the width of the attenuation zone is narrower than the spacing of the stations for shot S-3, it is plausible that no waves pass through the attenuation zone. The absence of a delay in wave propagation also suggests that the attenuation zone is thin.

Fig. 9. Distribution of the root mean squares of difference between the observed and the theoretical attenuation factors for various directions and thicknesses of the model. Abscissa indicates the azimuth of the attenuation zone, and ordinate indicates the attenuation ratio (product of attenuation coefficient and thickness of the zone). Hatched area shows the range within 95% confidence interval.

Fig. 10. Attenuation ratio plotted against the incident angle of the wave propagation passing through the attenuation zone whose strike is $N32.9^\circ W$. Squares indicate mean values of the observed attenuated maximum amplitude for the 4 shots. Numerals denote shot numbers. Thick line indicates the theoretical attenuation value when the attenuation ratio of the zone equals 0.596. The assumed length of the attenuation zone affects the extent of the normally attenuated area in this figure.

The observation data do not give any information on the deeper structure and the total length of the attenuation zone except for its minimum length. The geometry of paths of attenuated waves indicates that the zone reaches at least about 8 km to the north-northwest and about 6 km to the south-southeast from the Yakedake Volcano.

Based on these features and on the observed apparent velocity, I suggest that the wall-like attenuation zone beneath the Yakedake Volcano is shallow but does not penetrate the uppermost surface layer. If it were deep, the zone of no attenuation would be wide on the surface, and if it was shallow the zone would be narrow or absent. Although the estimate of the depth of the anomalous structure depends a little on the crustal velocity structure, it is certain that its depth is less than several kilometers.

To estimate the depth of the attenuation zone, we have to know the P-wave velocity structure in this field. Mikumo *et al.* (1988, 1989) obtained a P-wave velocity model in and around the Hida Mountains. Taking into account their crustal model, I adopt two structure models for the profile near the Yakedake Volcano. They are slightly different. The ray paths are also shown to estimate the size of the abnormal attenuation zone. The upper model in Fig. 11 is based on a two-layer crustal model, and the lower is based on a continuous velocity model. The depth to the attenuation zone is estimated as 2.5 to 1 km from the surface depending on the crustal model.

To estimate the Q value in the zone, we have to determine the width of the zone, the P-wave velocity of the zone, and the frequency of the waves. It is plausible that the mean velocity in the zone is lower than 6 km/s, but, as no delay in travel time that depends on the velocity and on the width of the zone was observed, the velocity reduction is not so large when the width of the zone is of the order of a few kilometers.

Fig. 11. Velocity structure models and the ray paths of shots S-1, S-2, and S-4. A vertical section in the direction of S-4 is shown to indicate the width and the depth to the top of the attenuation zone. Abscissa indicates only the location of stations but not shot distances. Model-A (upper) indicates a deep attenuation zone and model-B (lower), a shallow one. The difference is mainly due to the thickness of the surface layer. Modelled P-wave velocities are shown in the right side. Solid and broken lines indicate ray paths of normally and intensely attenuated waves, respectively. The notations a to f are the same as in Fig. 6. Large triangle: the Yakedake Volcano. S07, S08, S11, and S13: observation stations. Note that this figure is a schematic one and the figured width of the attenuation zone is not the width itself (D) but the projected width along the direction of S-4 ($D/\sin\theta_4$), and it is not determinate value.

The dominant frequency of the observed waves is 10 to 20 Hz. So, for the Q -value estimation, I adopt 2 km, 5 km/s, and 15 Hz as the width, the velocity, and the frequency, respectively. In this case, the calculated Q value in the zone is nearly 30.

By using the estimated decay curves of the normally attenuated waves that propagated in the upper crust at the velocity of 6 km/s, we can evaluate the Q value. In the result of the rough estimation, Q value is determined as 350 to 1,200. These estimated Q values in the attenuation zone and in the 6 km/s layer are almost the same as those derived in the anomalous low- Q zone and in the surrounding regions in the Matsushiro earthquake swarm area by Suzuki (1972).

5. Discussion

The Hida Mountain range is characterized by a chain of active volcanoes. Therefore, the existence of the anomalous structure related to magma reservoirs is expected to lie in the shallow depth beneath the mountain range.

Harayama (1992) described the youngest exposition of the granitoid pluton in the Hida Mountains. He concluded that the major axis of this range upheaved and cooled at a very rapid speed and suggested the existence of young magma beneath the range. Using the inversion technique for P-wave travel time anomaly, Hirahara *et al.* (1989) found a low-velocity body at a depth of 100–150 km. At shallow depths, Mikumo *et al.* (1988) pointed out that the seismic events beneath the central and southern part of the range including the Yakedake Volcano are less than 8 km. They are significantly shallower than those in the Tohoku area, northeastern Japan (Hasegawa *et al.*, 1991). So, it is likely that the cause of the seismic wave attenuation is a type of volcanic structure.

As shown in Fig. 11, the observed data in this profile represent an anomalous structure shallower than those mentioned above. However, Katsumata *et al.* (1995) claimed that no anomalous attenuation exists in the uppermost crust shallower than 5 km. This discrepancy in depth can be explained as follows: The size of the anomalous structure is small and these anomalous zones distribute locally in the upper part of the crust. The observation stations developed by Katsumata *et al.* (1995) were not sufficiently dense to detect such an anomalous zone of small size, or there is no attenuation zone in the crust just beneath their field.

To detect the anomalous structure at shallow depths, the observation network above it is necessary. This anomalous structure may be due to volcanism beneath the mountain range. Routine seismic observation seems to suggest a more large-scale attenuation zone or a number of zones in this mountain range. I suggest that the same or conjugate shallow anomalous structures are distributed along the main axis of the Hida Mountains, especially near the active volcanoes.

A possible cause of the anomaly is the low- Q zone due to partial melting or hydrothermal intrusion. In this case, it is likely that the liquid intrudes into the fissures that developed parallel to the strike of the attenuation zone. If the zone has such a structure, it is possible to detect the amplitude anisotropy of the transverse waves that propagate from the depth passing through this zone using a high-density seismic network.

A marked geothermal belt stretches nearly N30°–35°W, beneath the Yakedake Volcano (Sakai *et al.*, 1991), and a number of hot springs are distributed in this belt. The location of the belt is just above the assumed attenuation zone and the strikes are the same. I suggest that both the geothermal belt and the attenuation zone in the upper crust are both the results of volcanic activity of the Yakedake Volcano.

An active fault named the Sakai-touge Fault extends to the southeast of the Yakedake Volcano with a strike of N30°–40°W (Nishina *et al.*, 1985; The Research Group for Active Faults of Japan, 1991). The position and the strike of the north-western part of this fault are almost the same as those of the proposed attenuation zone, as shown in Fig. 8. The tectonic activity of this faulting may excite the devel-

opment of the anomalous structure of wave attenuation. Nakamura (1984) claimed that the active volcanoes occur at the end of the active strike-slip faults. Examples include the Hakone Volcano and the Tanna Fault, the Tateyama Volcano and the Atotsugawa Fault. He suggested that the volcanoes as weak points in the crust are apt to deform under the tectonic shear strain concentration and create the stress concentration that causes the faulting activity. The Sakai-touge Fault and the Yakedake Volcano may be a similar case. The NW-SE or NNW-SSE trending plutonic activity that leads to an anomalous propagation of seismic waves might be caused by an NW-SE trending compressional tectonic field (Mikumo *et al.*, 1988) near the Yakedake Volcano.

6. Summary

To reveal the detailed structure of the attenuation zone of seismic waves beneath the Hida Mountains of central Japan, a temporary seismic observation array crossing the range near the Yakedake Volcano was installed. The observation of seismic wave attenuation utilized 4 explosive shots by Research Group of Explosion Seismology (1994). The observational results are as follows:

- (a) The apparent velocity of the first arrivals of all shots is almost 6 km/s.
- (b) The distinct amplitude decay of the waves that passed through the main axis of mountain range is apparent. The amount of attenuation was considerably dependent on the direction of wave incidence. The mean values of the abnormal attenuation factor for shots S-1 and S-2 located to the east side of the profile are 0.54 and 0.55. For shot S-4 located to the west side it is 0.29. However, no attenuation is recognized in the case of shot S-3. The direction of the wave propagation from S-3 is almost southeast.
- (c) The observed data indicate the existence of the abnormal structure at a shallow depth. A rough estimation of the width of the attenuation zone is as narrow as several kilometers. The top of the attenuation zone is about 1 or 2.5 km depending on crustal models.
- (d) The proposed model of wave attenuation is simple. The observation results support the existence of a wall-like shallow attenuation zone stretching beneath the Yakedake Volcano with a strike of N33°W. The length of this zone is estimated to be at least 14 km.
- (e) The attenuation ratio λD (the product of the attenuation coefficient and the width of the zone) is 0.6. The Q value estimated from this result is about 30 at a frequency of 15 Hz if we assume the width of the zone to be 2 km. On the other hand, that of the normal upper crust is evaluated as 350 to 1,200.
- (f) The model is supported not only by the existence of a geothermal belt in the same area, but also by the existence of an active fault stretching to the southeast.

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