SEISMIC WAVE ATTENUATION BENEATH GEOTHERMAL AREAS IN CENTRAL KYUSHU, JAPAN

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ABSTRACT

Three tripartite and one linear array were installed at geothermal areas in central Kyushu, where many active and other Quaternary volcanoes exist and many fumarolic activities and hot springs also exist in connection with the volcanoes. Seismograms were analyzed using the spectral ratio technique to determine the seismic wave attenuation factor Q. Seismic waves through the crust and upper mantle of central Kyushu attenuate more than those through its surroundings. This fact may be due to many water-filled fractures in the upper crust (surface to c a. 15 km deep) and partial melting of the upper mantle. Local anomalies of seismic wave attenuation were also detected beneath the Kuju area in the eastern half of central Kyushu. This fact may also show that there exist not only much more water-filled structures in the shallower crust (surface to 4.2 km) but also heat sources in the lower part (4.2 km to 14.2 km) in the Kuju area.

INTRODUCTION

The most important characteristic structures of geothermal areas are an existence of fracture zones filled with hot water in the shallow crust and that of heat sources beneath them. Laboratory studies show that the attenuation of elastic waves in rocks strongly depends on the physical state and saturation condition (Toksöz et al., 1979) . A seismological study for the earthquake swarms which occurred at Matsushiro, central Japan in the period of 1965 to 1967, clarified that the seismic wave attenuation factor Q beneath where many earthquakes occurred was much lower (1 /20) than that beneath where no earthquake occurred (Suzuki, 1971) . In this case, the relation between the occurrence of the cracks and the peameation of the underground water was discussed (Ohtake, 1974) . Furtheremore, the well-known low Q zone in the upper mantle beneath island arcs is interpreted by the existence of partial melting of rocks. Therefore, we consider that the observation of seismic wave attenuation is extremely useful in the detection of water saturated fracture zones and partial melting. In this paper, we show the differences in Q values between geothermal areas and their surroundings in Kyushu.

GEOTHERMAL MANIFESTATIONS

There are many active and other Quaternary volcanoes in central Kyushu, Japan. Many fumarolic activities and hot springs also exist in connection with the volcanoes and they are in a high heat flow zone than 2 HFU (84 mw /m²) as shown in Fig. 1 (EHARA, 1984a) . The above geothermal manifestations concentrate especially in the eastern half of central Kyushu. Shallow seismic activity is generally high in the western half of central Kyushu (EHARA, 1984b) and gravity anomaly is low in the eastern half of it (KUBOTERA et al., 1969) . Therefore, there may be great differences in underground structure between beneath central Kyushu and its surroundings. Also, there may exist local anomalies in central Kyushu.

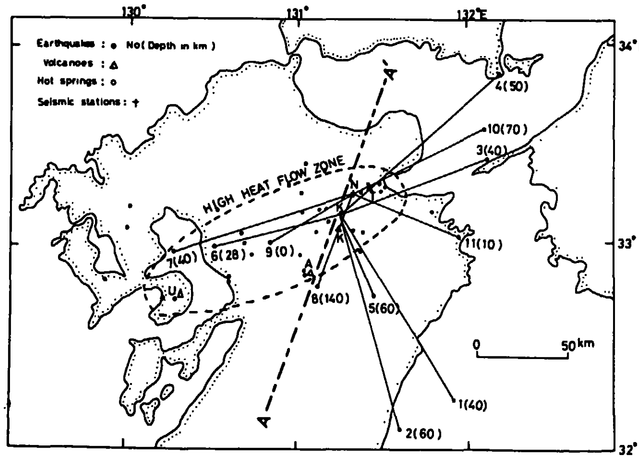

Fig. 1 Tectonic map in central Kyushu and seismic arrays. solid circle : earthquakes, No (Depth in Km) , open triangle : active volcanoes, open circle : hot springs, cross : tripartite arrays (K : Kuju and N : Noya) .

OBSERVATION

Three tripartite and one linear arrays were installed in the eastern half of central Kyushu. Seismic events were recorded on magnetic tape for about one to three months in the respective arrays. The hypocenters of small earthquakes ($M = 3$ to 5) were determined by the Japan Meteorological Agency and those of microearthquakes were determined by the seismic array of the Kyushu Electric Power Company and by our tripartite nets.

DATA ANALYSIS

The spectral ratio technique was used to infer the Q value. The amplitude spectrum of a seismic wave observed at a station can be written as

$$A(f) = O(f) \cdot C(f) \cdot S(f) \cdot G \cdot e^{-\pi \frac{T}{Q} f},$$

where $O(f)$ is the source spectrum, $C(f)$ the crustal transfer function, $S(f)$ the instrumental transfer function, G the geometrical spreading, T the travel time, Q the quality factor, and f the frequency (MORIYA, 1976). The spectral ratio of S wave to P wave is expressed as

$$R(f) = (Os/Op)\, e^{-\pi \left(\frac{Ts}{Qs} - \frac{Tp}{Qp}\right) f} .$$

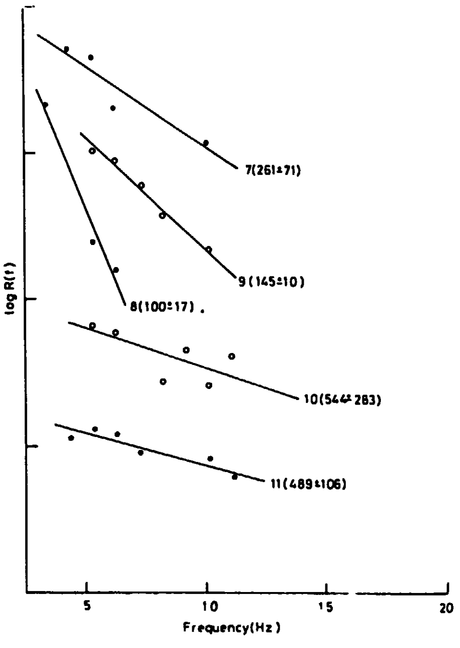

Fig. 2 Examples showing spectral ratio.

Therefore, we can obtain the Qs (Q value for S wave from the gradient of the straight line d (ln R (f))/df, assuming that Os (f)/Op (f) =const. and Qs/Qp=4/9 〔Anderson et al., 1965〕.

The earthquakes analyzed are shown in Fig. 1. At first we get Fourier spectra of the P and S-wave first arrivals of events. After that, spectral ratios are obtained. Some examples of them are shown in Fig. 2. From each straight line in the figure, we can get each Q value, using travel times of the P- and S- waves.

LARGE SCALE Q STRUCTURE

Qs values along the respective wave paths are shown in Fig. 3, which are obtained using the small earthquake data. "Low Q" and "High Q" in the figure show the large scale Q structure inferred from other seismological studies 〔Utsu, 1969〕. From the figure, we can point out the following three features ;

1) Qs values in the crust and uppermost mantle are several hundreds in general. The Qs values beneath geothermal areas are about 250. However, the Qs value beneath non-geothermal areas is 470 on the average. Therefore, the Qs value beneath geothermal areas is lower than that beneath non-geothermal areas.

2) The Qs value in the upper crust beneath geothermal areas is about 150.

3) The Qs value in the upper mantle beneath geothermal areas is extremely low, i.e., 70.

The value was calculated, assuming that the Qs values of the upper and lower crust are 150 and 500, respectively. As a result, a model of the Qs structure in the profile across Kyushu island from SE to NW was suggested as shown in Fig. 4. The low Qs value in the upper crust beneath geothermal areas in central Kyushu is interpreted as having more water filled fracture zones. In the lower crust, the cracks in rocks are closed

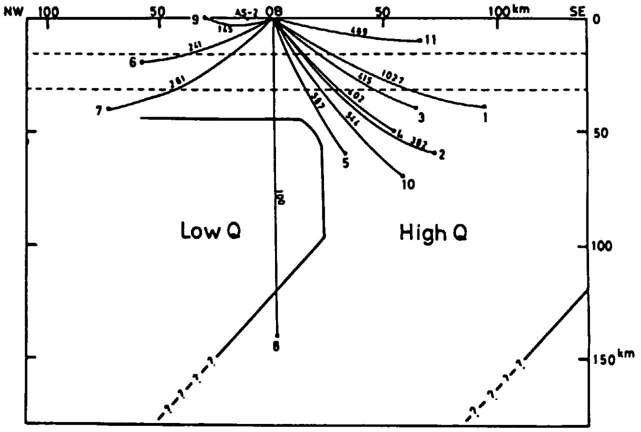

Fig. 3 Qs value along each path. This vertical section is perpendicular to A - A′ in Fig. 1.

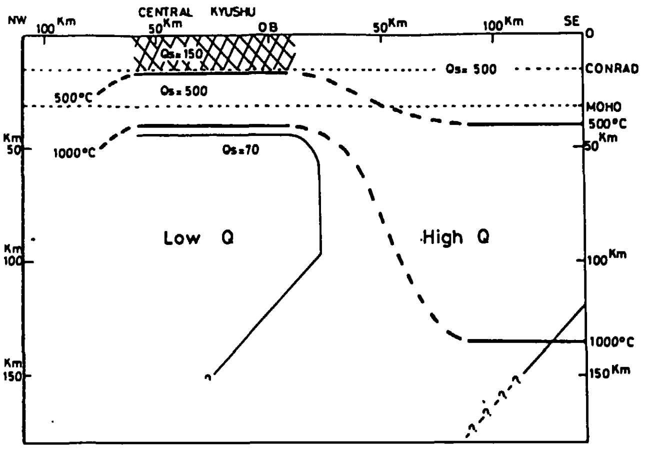

Fig. 4 Qs and temperature model beneath Kyushu.

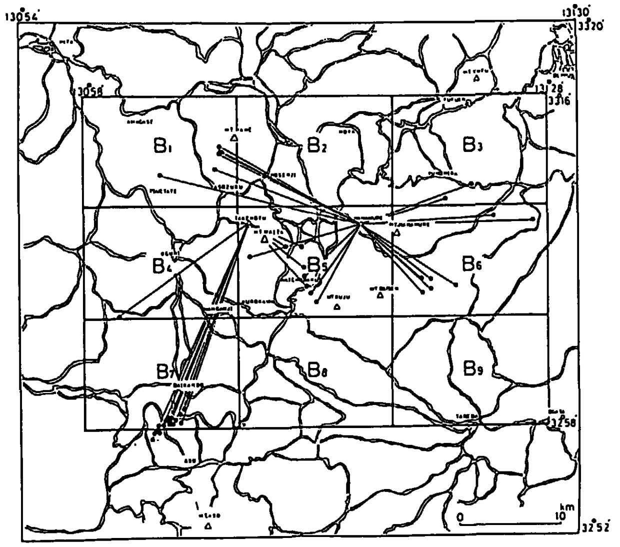

Fig. 5 Epicenters and paths of earthquakes used for analysis in the Kuju area.
solid circle : epicemters, open circle : seismic arrays, open triangle : active and other Quaternary volcanoes.

by high pressure and liquid water does not exist because of high temperature inferred from the heat flow data (EHARA,1984a) . Therefore, in the lower crust beneath geothermal areas, the Qs value should not be so low and the difference between geothermal and non geothermal areas must be small. The low Qs value in the upper mantle beneath geothermal areas may originate from partial melting which is inferred from the heat flow data (EHARA, 1984a) .

SMALL SCALE Q STRUCTURE

The detailed Qs structure in the Kuju area, where many geothermal manifestations concentrate, was analyzed using the microearthquake data. Seismic wave paths used for analysis are shown in Fig. 5. Rectangular grids in Fig. 5 outline cell boundaries on the earth's surface. The three-dimentional Qs model contains two layers with thickness of 4.2 km and 10 km, respectively. Each cell covers an area of about 15 km × 10km. The total number of cells is eighteen (3 ×3 ×2) . Therefore, generally if we use the total number of Qs observations more than nineteen, we can find an optimal solution by minimizing the square error between the calculated Qs and the observed one. However, seismic waves do not necessarily pass through the respective cells equally. Furthermore, all the Q values obtained do not always have high accuracy. In such a case, we often obtain unreasonable solutions by the above mentioned least square method. Accordingly, we made the following method ; At first, we determine an average Qs value (Q1) of a cell (CELL 1) using the seismic waves which pass through the cell only. Next, using the Qs value (Q1) , we can determine a Q value (Q2) of another cell (CELL 2) from the equation

$$T / Q = T1/Q1 + T2/Q2,$$

where T is the total travel time, T1 the travel time in the CELL 1, T2 the travel time in the CELL 2, Q the average Qs value along all the paths, Q1 the Qs value in the CELL 1 and Q2 the Qs value in the CELL 2. We apply such a method to the cells with unknown Qs values one by one. When several Q2 values were obtained, we adopted an average value as the Qs value of the CELL 2. By such a treatment, we obtained a three-dimentional Q model as shown in Fig. 6. The figure (9) in a parenthesis of the upper layer shows that the value is obtained using only one wave path. The figure (150) in a parenthesis of the lower layer is assumed using the typical value in central Kyushu. The cells with no figures could not be resolved by the observed data, since no ray passed through them. From Fig. 6, we can point out the following features ; The Qs values in the upper layer range from 50 to 80 and those in the lower layer from 20 to 150. The upper layer does not show significant high attenuation. However, in the lower layer, there are zones (B1, B2 and B5) of significantly high attenuation, where many geothermal manifestations exist. Especially, in the CELL B5, the Qs value shows the lowest value in the Kuju area. Kuju volcano and related many fumarolic activities and hot springs exist and two geothermal power plants (Otake and Hatchobaru) are operated at present there. We deduce that the significantly high attenuation in the lower part of the CELL B5 may be related to not only many hot water filled fractures but also heat sources, i. e., unsolidified magma.

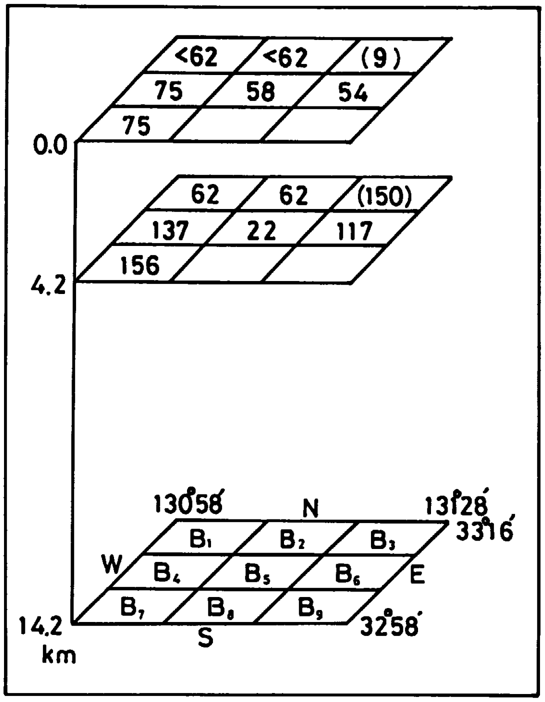

Fig. 6 Three-dimensional Qs model beneath the Kuju area.

CONCLUSION

The underground structures in central Kyushu were discussed using the seismic wave attenuation factor Q. We showed the significantly high attenuation in the upper crust and upper mantle beneath geothermal areas of central Kyushu and deduced that the former was related to many water filled fractures and the latter to partial melting of rocks. The three-dimensional Q model was constructed in the eastern half of central Kyushu. As a result, a zone of significantly high attenuation was found in the lower layer (4.2 km to 14.2 km deep) of a cell, where an active volcano and related many fumarolic activities and hot springs exist. Such high attenuation may be related to not only hot water filled fractures but also heat sources. We consider that the detection of seismic wave attenuation is very useful to delineate the underground structures beneath geothermal areas.

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