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Regional Differences in Absorption of Seismic Waves in the Upper Mantle as Inferred from Abnormal Distributions of Seismic Intensities

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Abstract

According to the idea that the abnormal distributions of seismic intensities observed in Japan are mainly due to the effect produced by regional differences in absorption of seismic waves, a region of increased absorption has been located in the upper mantle under Japan outside the zone of abnormal intensity. This absorptive region appears to be related to the distributions of topography, earthquake foci, volcanoes, gravity anomalies, heat flow, etc. A preliminary estimate of the Q value contrast between two paths crossing highly absorptive and less absorptive regions indicates that the maximum ratio of mean Q values between two paths reaches 10.

1. Introduction

Many papers[1)-22)] have been published in Japan about the abnormal distribution of seismic intensities since it was first discovered in 1913. This phenomenon is most clearly observed in connection with deep-focus earthquakes, an example being shown in Figure 1. This earthquake which occurred at a depth of about 240 km in central Japan was only barely perceptible near the epicenter, but it was felt strongly at Onahama and its vicinity and the felt area extended on the Pacific side of Tôhoku and Hokkaidô districts as far as Kushiro about 1000 km from the epicenter. Other three examples of deep earthquakes which exhibited this phenomenon are presented in Figures 2, 3, and 4.

Some shallow earthquakes also show such a phenomenon, but they have not been investigated systematically so far. In this paper data on both shallow and deep earthquakes are utilized and the main cause of this phenomenon is explained by regional differences in absorption of seismic waves (especially S waves) due to nonelastic process in the upper mantle under a part of Japanese area. Since seismic intensities are the main materials in this study, the discussions are somewhat qualitative. A more detailed quantitative

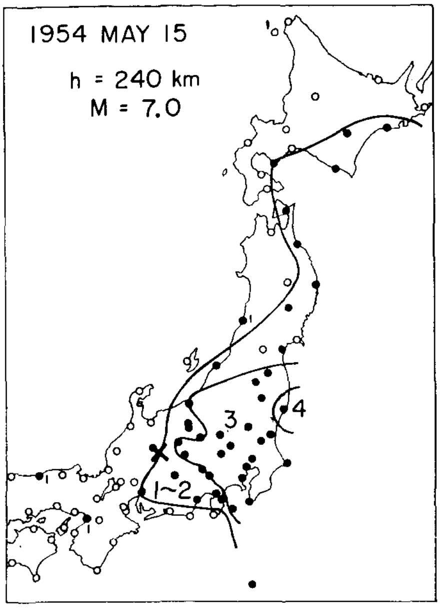


Fig. 1.

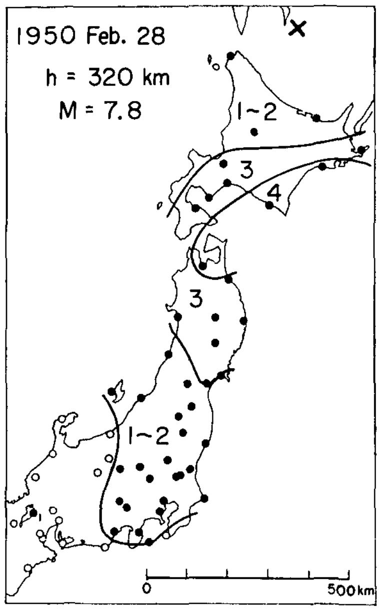


Fig. 2.

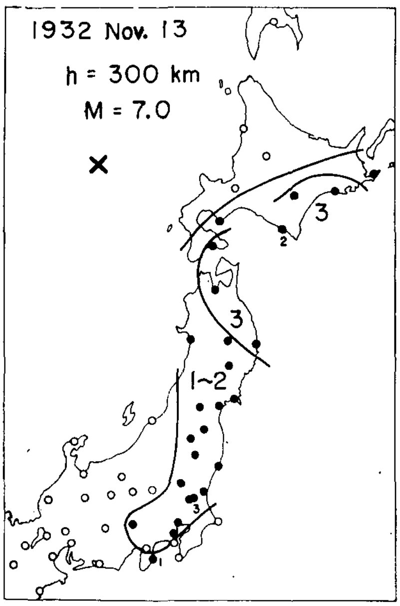


Fig. 3.

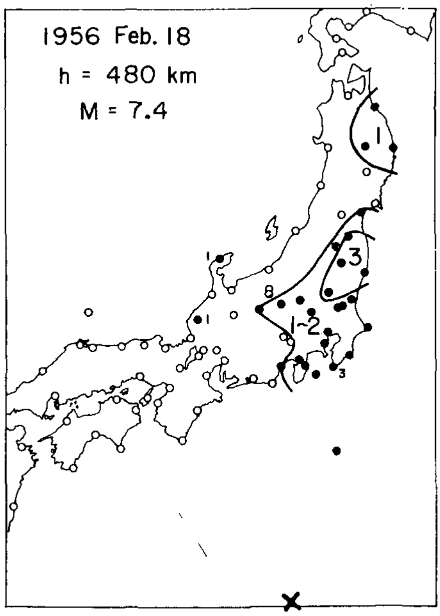


Fig. 4.

Distributions of seismic intensities. ×: epicenter.

study by means of spectral analysis of seismograms from various stations in Japan will be made in the following paper.

The seismic intensities used in this study are based on the the Japanese scale of seven grades. The relationship between the modified Mercalli scale and the Japanese scale is shown in Figure 5.

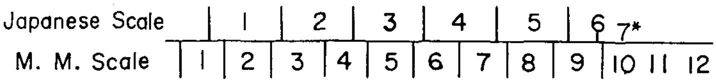


Fig. 5. Relationship between the Japanese and the modified Mercalli intensity scales. * Intensity 7 in the Japanese scale was introduced in 1949.

2. Summary of the past studies

The main conclusions from studies of the abnormal intensity distributions published hitherto are summarized as follows.

(1) The zone where abnormally high seismic intensities are observed extends on the Pacific side of Hokkaidô, Tôhoku, and Kwantô districts. This anomalous zone includes seismograph stations, Nemuro, Kushiro, Obihiro,

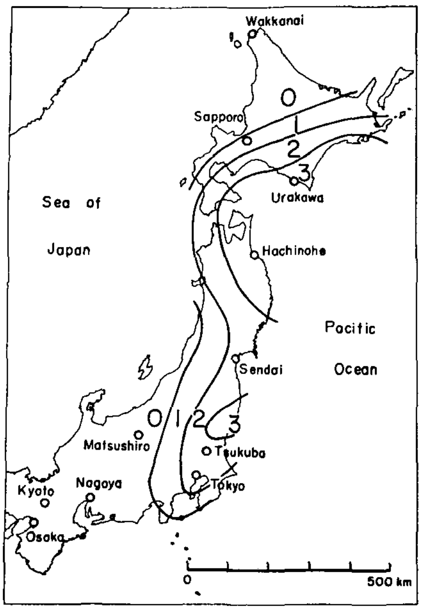


Fig. 6. Map showing the average intensity anomalies.

Hiroo, Urakawa, Hakodate, Aomori, Hachinohe, Morioka, Miyako, Ishinomaki, Sendai, Fukushima, Onahama, Shirakawa, Mito, Kakioka, Tsukuba, Utsunomiya, Tôkyô, Yokohama, etc.

To show the relative intensity anomalies in the case of deep-focus earthquakes, the author prepares a map shown in Figure 6 which represents how the intensities are increased in the anomalous zone as compared with the normal intensity area marked with 0 in Figure 6. The zones marked with 3, 2, and 1 in Figure 6 indicate that the intensities are higher than the normal value by 3, 2, and 1 respectively. This zoning has been obtained by comparing intensities between adjacent stations observed in deep-focus earthquakes. Of course this map represents only average conditions. The individual intensity distribution varies considerably from earthquake to earthquake.

(2) In the case of earthquakes which exhibit the abnormal intensity distribution, the seismograms recorded in the anomalous zone are characterized by P and S phases containing high-frequency waves as compared with the seismograms recorded outside the anomalous zone.

(3) In northeastern Japan and the surrounding areas fairly close relationships are apparent between distributions of the topography of island arc and ocean trench, earthquake foci, volcanoes, gravity anomalies, anomalies of seismic wave travel times, and heat flow. The anomalous zone of seismic intensity seems to have some connection with these geophysical phenomena.

(4) Two kinds of possible explanations for the cause of the abnormal intensity distributions have been provided hitherto.

i) In the anomalous zone short period waves are exicted due to multiple reflections in thin surface layer(s) having low wave velocity and density.

ii) Absorption of the seismic waves in the crust or upper mantle varies regionally and the seismic waves reaching the anomalous zone have propagated through regions of comparatively small absorption, suffering less attenuation of short period waves.

3. Preliminary remarks on the cause of the abnormal intensity distributions

The first explanation as to the cause of the phenomenon described above may correspond to the idea that the differences in earthquake motions are due to ground conditions. The amplitude, period, and duration of ground motions, and also seismic intensity and earthquake damage are strongly affected by local ground conditions. It is well-known that earthquake damage is quite different at two places which are very close but on different ground. The distributions of seismic intensities naturally depend on the ground conditions at the observing points. However, it seems unreasonable to attribute the main cause of the abnormal intensity distributions to the differences in ground conditions for the following reasons.

(1) The anomalous zone extending more than several hundred kilometers includes many stations under various ground conditions. Some stations such as Tôkyô and Aomori are on the soft alluvium, whereas some stations such as Tsukuba and Nemuro are on the hard igneous rock. This circumstance is the same for stations outside the anomalous zone. There are no common differences in ground conditions between stations inside and outside the anomalous zone.

(2) If the correlation between the anomalous intensity distribution and the distributions of topography, earthquake foci, volcanoes, gravity anomalies, heat flow, etc. have a geophysical significance, the cause of the abnormal intensity distributions lies in the deeper part of the earth, because such geophysical phenomena are believed to be related to the structure of the crust and upper mantle system.

(3) If the abnormal intensity distributions are due to the effect of surface layers, the effect must be the same for two earthquakes with the same epicentral distance and focal depth but with different azimuth. However, observations indicate strong azimuthal effects. For example, in the eastern part of Kwantô district (including Tôkyô) abnormally increased intensities are recorded for shallow earthquakes occurring off the Pacific coast of Hokkaidô and Tôhoku districts but such abnormal intensities are not observed for shallow earthquakes in southwestern Japan. The former earthquakes produce high frequency S waves on Tôkyô seismograms, but the latter ones do not.

For these reasons the author adopts the second explanation as the main cause of the phenomenon in question, and investigates where the regions of increased absorption are distributed in the crust and upper mantle.

It is difficult to support an idea that the regional changes in the thickness of the highly absorptive crustal layer cause the abnormal intensity distributions, because the third reason (3) described above is also applicable to this idea. Furthermore, the crustal thickness in Japan from seismic refraction and surface wave studies falls in the range from 20 km to 40 km. From equation (7) in Chapter 6, it is found impossible that the difference in thickness of only 20 km causes the observed intensity anomalies for deep earthquakes even if very small Q value is assumed in the crust.

4. Earthquakes which exhibit the abnormal intensity distributions

The maps showing the distribution of seismic intensities have been prepared for all the earthquakes with magnitude 7.0 and larger which occurred in Japan and its vicnity (the area limited by 126°E and 152°E cricles and 26°N and 50°N parallels — see Figure 7) during 1926–1965. The total number of earthquakes reaches 66. The observed intensities at all weather stations are used but the intensities reported from climatic stations (*kunai-kansokusho*) were neglected. Some climatic stations sometimes fail to report an felt earthquake, therefore absence of a intensity report from these

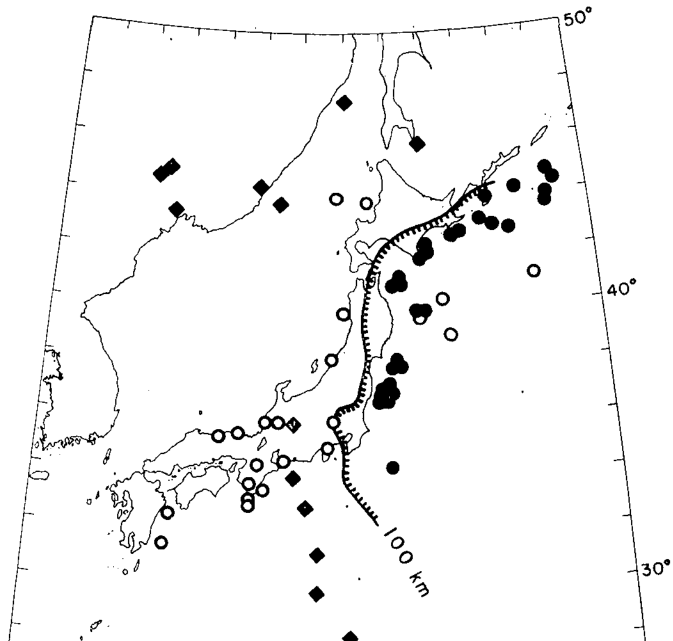


Fig. 7. Distribution of earthquakes with magnitude 7.0 and larger during 1926–1965. Solid cricles and squares denote shallow and deep earthquakes which exhibited remarkably abnormal intensity distributions respectively. Open circles denote the other earthquakes.

stations does not necessary mean that the shock was not actually perceptible there. It is important to know at which station the shock in question is actually unfelt in order to determine the limits of the felt area.

The epicenters of these earthquakes are shown in Figure 7 in which a line marked with "100 km" represents the 100 km iso-depth line of earthquake foci as estimated from the data in "Earthquake Catalogue" published by the Japan Meteorological Agency in 1958. It is seen that the east side of this line agrees approximatly with the anomalous zone shown in Figure 6.

Several examples of the intensity distributions are reproduced in Figures 1–4 and 8–15. Open circles indicate the station where the shock was reported unfelt. Isoseismal lines separate the areas of intensity 0, 1 ~ 2, 3, 4, and 5. Small numerals attached to solid circles refer to an exceptionally high or low intensity in each area. Other solid circles indicate the stations with intensity expressed by large numerals between isoseismal lines.

The examinations of 66 isoseismal maps reveal the following facts.

(1) All deep-focus earthquakes (indicated by squares in Figure 7) show quite abnormal intensity distributions without exception.

(2) Some shallow earthquakes show the similar phenomenon as illsutrated in Figures 8–13. The epicenters of such earthquakes are indicated by solid circles in Figure 7 which show a distinctive geographical distribution. For these earthquakes the epicentral distance to the furthest point in the felt area is more than twice of the epicentral distance to the nearest point in the unfelt area. For all shallow earthquakes occurring in the area west of "100 km line", isoseismal lines are very roughly concentric circles as shown in Figures 14–15. Most of these earthquakes have a focal depth of 0 to 30 km, therefore they occur in the crust. Four earthquakes indicated by open cricles off the Pacific coast of northern Japan are not classified as ones exhibiting the abnormal intensity distributions as judged by the criterion explained above.

An additional fact has been brought out from the investigation of intensity distributions for earthquakes with magnitude smaller than 7.0.

(3) Some earthquakes with small magnitude occurring on the east side of "100 km line" show normal intensity distributions as illustrated in Figure 16. These shocks are usually shallower than 30 km. Earthquakes with a depth of 50 km or deeper in this zone exhibit the abnormal intensity distributions as illustrated in Figure 17.

Above three facts provide a basis for the discussion of the location of regions with increased absorption as will be done in next chapter.

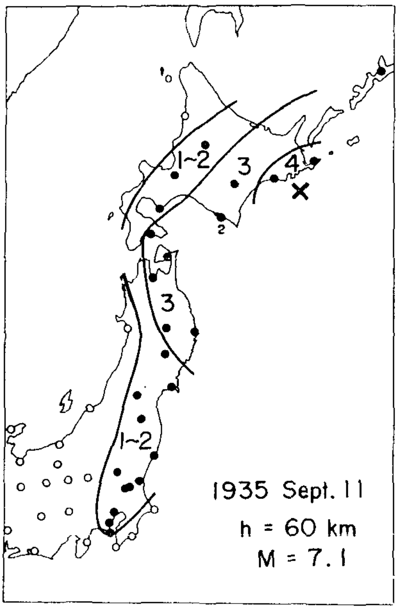


Fig. 8.

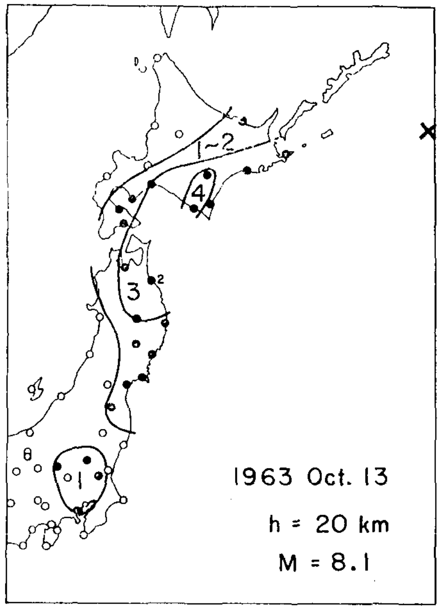


Fig. 9.

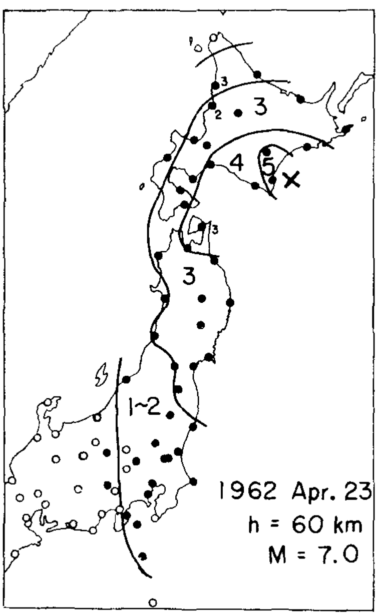


Fig. 10.

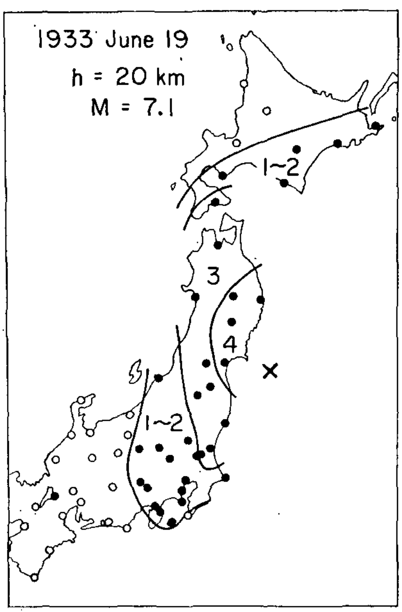


Fig. 11.

Distributions of seismic intensities.

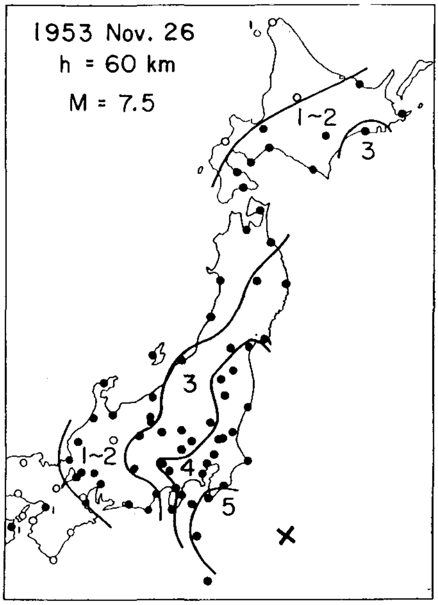


Fig. 12.

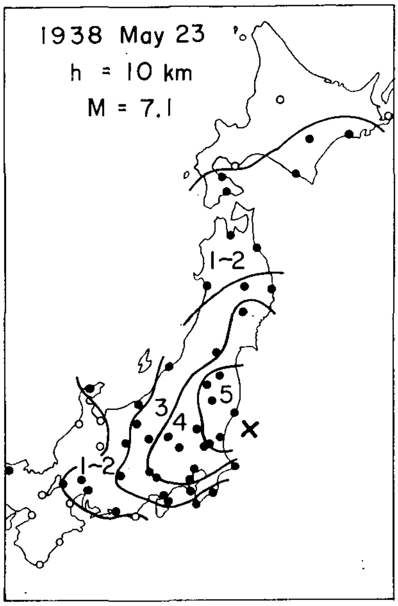


Fig. 13.

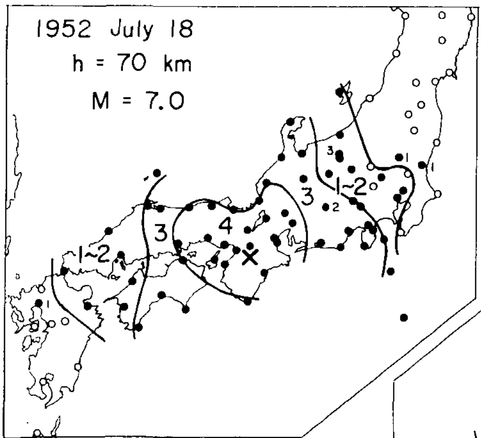


Fig. 14.

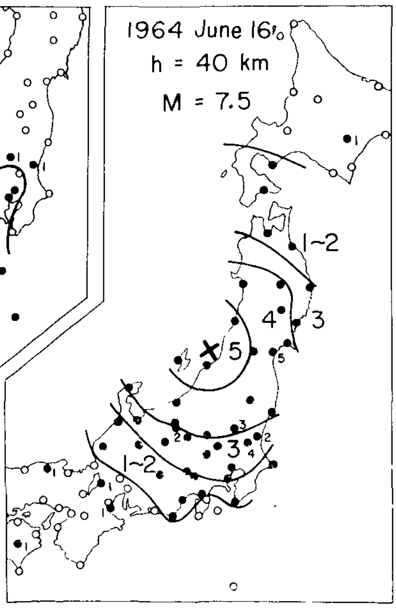
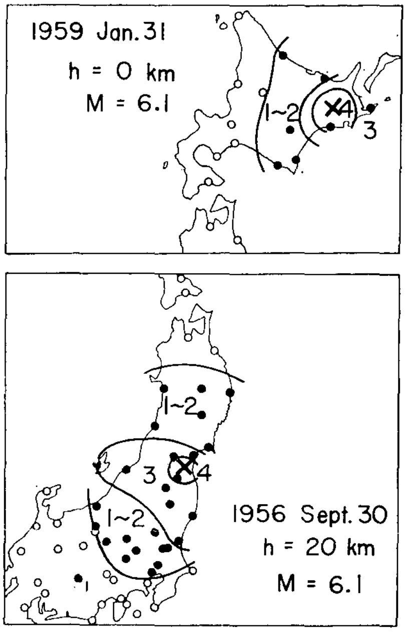


Fig. 15.

Distributions of seismic intensities. Figs. 14 and 15 represent "normal" intensity distributions.



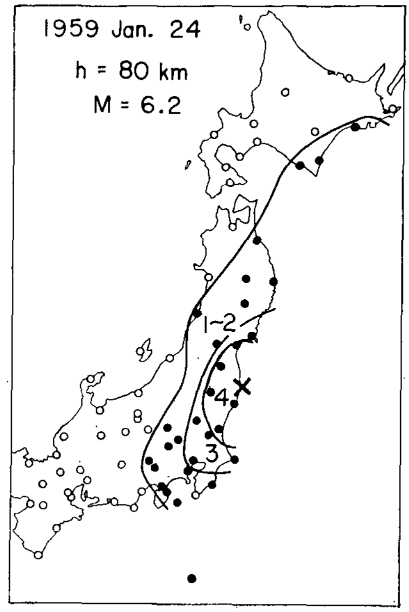


Fig. 16. Fig. 17.

Distributions of seismic intensities for shocks with magnitude about 6. Note that shocks occurring in the crust (Fig. 16) do not show abnormal intensity di tributions.

5. The location of the highly absorptive layer

It seems most reasonable to assume that a region of relatively high absorption exists in the upper mantle just below the Mohorovičić discontinuity under the Japanese area excluding the anomalous zones. Figure 18 is a schematic representation of a vertical cross-section normal to the extension of the Japanese islands and the anomalous zone. In this figure solid cricles indicate earthquake foci which show a well-known systematic distribution. Hatched region A is assumed to be highly absorptive as compared with other regions at the same depth. Upper limit of this region cannot be fixed definitely, but it may be close to the Mohorovičić discontinuity, since the anomalous intensities can occur for earthquake-station combinations for which the deepest point of the seismic ray is only 60 km deep. The regions with question marks cannot be specified from the present data. It should be emphasized that the seismically active parts in the upper mantle is non-absorptive[21,22], whereas no earthquakes originate in the absorptive region.

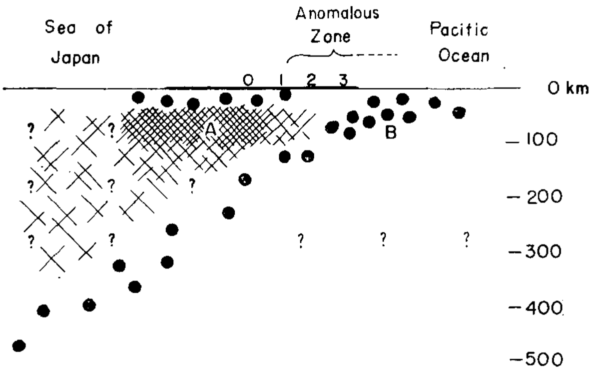


Fig. 18. Vertical cross-section normal to the anomalous zone, showing earthquake foci (solid cricles) and a region of relatively high absorption (A).

It seems difficult to attribute the abnormal intensity distributions to regional changes in absorption within the crust, because this hypothesis cannot explain the fact that the abnormal intensity distributions do not appear in the case of smaller earthquakes occurring in the crust regardless of their epicentral locations. Moreover, unreasonably large differences in Q values must be considered to explain the anomalous seismic intensity in the case of deep-focus earthquakes under this hypothesis.

The idea that the temperature in the highly absorptive region is relatively high and close to the melting point of rock (or partly molten) agrees with the geographical distributions of volcanoes and high heat flow area [23]. Gorshkov[24] found increased absorption of S waves below the volcanic zones in Japan-to-Kamchatka regions.

Katsumata[25] mentioned the high absorption layer in the upper mantle at depths between 100 and 200 km in his study of magnitude determination problems. Vertical distribution of absorption coefficient under Japan was calculated by Wadati and Hirono[26] based on maximum amplitude/period observations. Increased absorption was found near the surface and at depths of around 100 km. These authors do not refer to regional differences. However, since the most part of Japan is free from the anomalous zone (Figure 6) and underlain by the highly absorptive layer, their results probably correspond to this absorptive layer.

Seismic refraction studies and surface wave studies indicate somewhat slower-than-normal upper mantle velocities under Japan[27]. On the other hand, Hisamoto[28] reported a distinctive high velocity region of S waves just below the active seismic zone off the Pacific coast of northeastern Japan. A part marked with B in Figure 18 corresponds to this high velocity region.

6. Anomalous intensities and Q values

The examinations of the isoseismal maps show that the maximum difference in seismic intensity between two points at the same epicentral distance reaches 4. An exmaple is shown in Figure 9 in which the intensity at Obihiro and Urakawa is 4 in contrast to intensity 0 at Asahikawa and Wakkanai where epicentral distances are comparable. Hirono[29] reported, though he based on the idea of amplification factors of the ground, that the factors cause intensity differences as large as 4.5. The following calculations are tried to estimate the difference in Q values between two paths which give rise to the intensity difference of 4.

Spectrum of ground acceleration at a certain point due to P or S waves is expressed by

$$a(f)\,df = a_0(f)\,G\exp(-\pi(\tau/\bar{Q})f)\,df\,, \tag{1}$$

where $a(f)$: acceleration spectrum density for frequencies between f and $f+df$,
$a_0(f)$: acceleration spectrum at the origin,
G: geometrical spreading factor which is independent of frequency,
τ: travel time to the point,
$\bar{Q}$: mean effective Q value along the path defined by $\int\frac{ds}{vQ}=\tau/\bar{Q}$
where v is the seismic wave velocity.

The azimuthal effect about the origin and the local structure near the observing point are neglected.

If the velocity spectrum at the origin is assumed to be flat, it follows that

$$a_0(f) = cf\,, \qquad c\text{: constant}\,. \tag{2}$$

This assumption is only a rough approximation but it is based on the observations near the epicenter[30], and also a fact that the logarithm of velocity spectrum at a distant point is roughly a linear function of frequency. Asada and Takano[31] estimated the Q values in the mantle based on this assumption.

The velocity- and acceleration-spectrum curves calculated from equations (1) and (2) for various values of $\tau/\bar{Q}$ are presented in Figure 19. In this figure logarithms of spectral values in arbitrary unit are plotted against

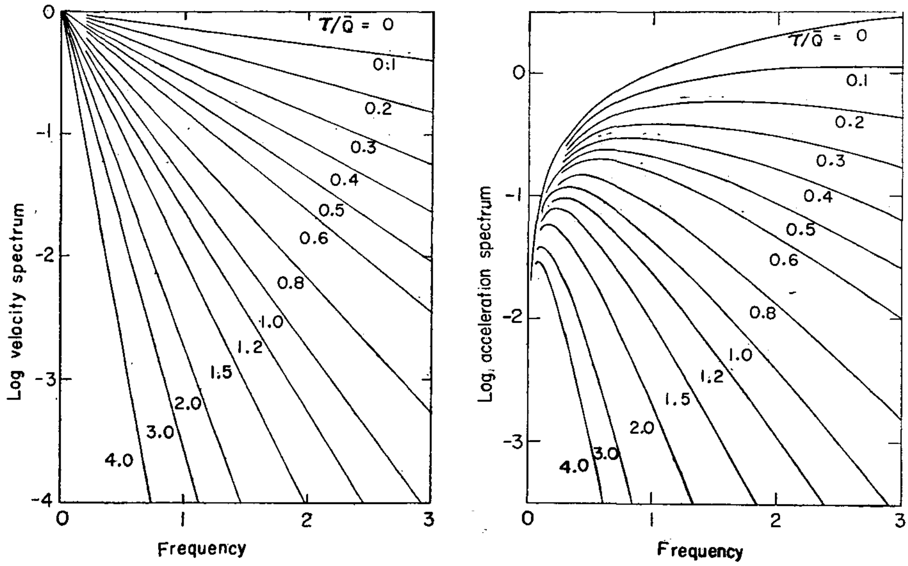


Fig. 19. Logarithms of velocity spectra and acceleration spectra plotted against frequency for various values of $\tau/\bar{Q}$. Frequencies are in the same unit as $1/\tau$.

frequency in the same unit as the reciprocal of travel time τ.

The acceleration-spectrum cruves have a peak at a frequency f_m given by

$$f_m = \frac{1}{\pi(\tau/\bar{Q})} \,. \tag{3}$$

If we use a variable time scale according to f_m and convert frequency f to h by

$$f = h f_m \,, \tag{4}$$

equation (1) takes the form

$$a\,(h)\,dh = \frac{cG}{\pi^2\,(\tau/\bar{Q})^2}\,h \exp\,(-h)\,d\,h \,. \tag{5}$$

It follows from (5) that the acceleration amplitude as a function of time, hence the maximum acceleration, is proportional to $cG/(\tau/\bar{Q})^2$, since a function $h \exp(-h)$ in equation (5) is independent of any quantity other than h and the amplitude in the time domain is independent of the time scale.

The Japanese intensity I is related to ground acceleration by a formufa[32]

$$I = 2 \log a + \text{const} \,. \tag{6}$$

Since $a \propto c\,G/(\tau/\bar{Q})^2$,

$$I = 2\log c\,G - 4\log(\tau/\bar{Q}) + \text{const}. \qquad (7)$$

This equation means that intensities at two points at the same epicentral distance from a certain earthquake differ by 4 if the ratio of mean effective Q values for two paths is 10. Therefore if we adopt a Q value of 300 for a less absorptive part of the upper mantle, the Q value for the most absorptive part falls to 30 or less.

7. Conclusion

In this paper the phenomenon of the abnormal distributions of seismic intensities observed in Japan is explained as an effect produced by regional differences in absorption of seismic waves due to nonelastic properties of the upper mantle. Distributions of absorptive regions estimated from intensity distributions seems to be related to the distributions of some geophysically important quantities such as seismicity, gravity anomalies, heat flow, seismic wave velocity, etc. Distributions of absolute Q values cannot be determined from the present data, but the relative variations in Q values can be estimated to some extent using equation (7).

It is planned to extend this study to obtain a more quantitative description of the upper mantle using seismograms of both near-by and distant earthquakes recorded in Japan.

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