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27. *Regional Variation of P Wave Spectrum (1).*

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Abstract

Comparative study of *P*-wave spectrum has been carried out for earthquakes and underground explosions. The epicentral distance of these events from TSK (Tsukuba Seismological Observatory) ranges from 25 to 55 degrees. The USCGS magnitude m_b of most of the earthquakes is between 5.1 and 5.6.

P-wave amplitude in the frequency range from 1.5 to 3.0 cps is compared with that in the range less than 1 cps. The relative amplitude is investigated for earthquakes in various seismic regions. Large local variation of *P*-wave spectrum is also found for closely located earthquakes belonging to the same region.

The regional variation of *P*-wave spectrum can be attributed partly to the difference in the absorption in the vicinity of the source and partly to the difference in the spectral structure of the source.

1. Introduction

Based upon the results of our routine observation, it has been recognized that spectrum of *P* waves from various seismic regions have their own regional characteristics.

The amplitude spectrum $S(\omega)$ of a seismogram recorded at a station can be written as

$$S(\omega) = O(\omega)P(\omega)M(\omega)$$

where $O(\omega)$, $P(\omega)$ and $M(\omega)$ are the source spectrum, the response of the propagating path and the response of the seismograph respectively. The source spectrum is controlled by the source dimension, mechanism and the earth structure in the vicinity of the source. $P(\omega)$ includes the effect of the propagation path and the local structure near the station.

After correcting for the effects of the path $P(\omega)$ and the instrument $M(\omega)$, the records of different events can be compared in terms of their source spectrum. Study of *P*-wave spectrum of world-wide teleseismic events will be useful for understanding the tectonic nature of different seismic regions. It is also useful for the discrimination of underground explosions from natural earthquakes.

This paper describes a comparative analysis of *P*-wave spectrum of explosions and earthquakes in various regions based upon the records obtained at Tsukuba Seismological Observatory (TSK). The location, magnitude *m* and focal depth *h* of all the events used in this paper were obtained from the PDE cards of USCGS.

2. Spectrum analyzer

In order to process a large amount of data on a routine basis, an analogue type spectrum analyzer is used. Detailed description of the analyzer system was given by *Tsujiura* (1966). Therefore the outline of the system will be briefly described in the following.

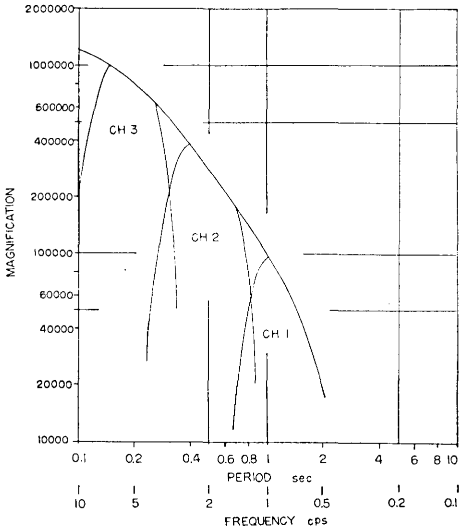

Fig. 1. Magnification curve of the seismograph and frequency characteristics of the filters.

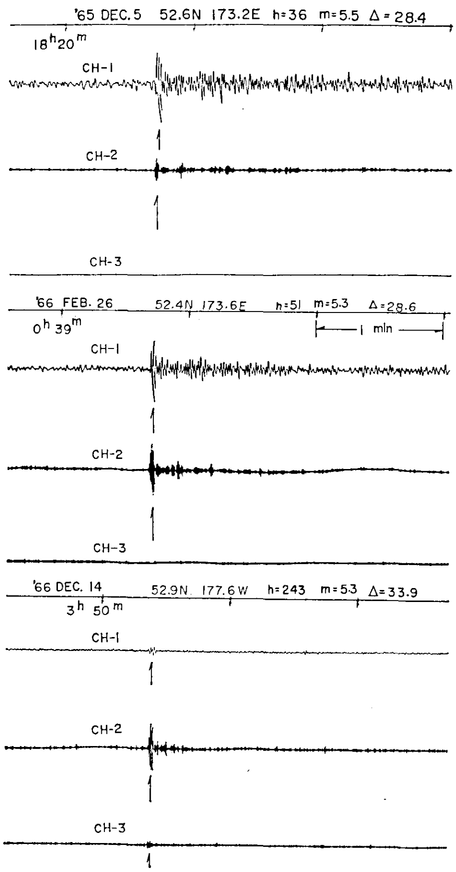

Fig. 2. Examples of the frequency-analyzed data.

The original signal is passed through analogue type band-pass filters which separates it into five channels covering a frequency range from 0.5 to 40 cps. The outputs from each filter are recorded on-line on a multi-channel ink-recording oscillograph together with the original data.

Fig. 1 shows the overall displacement magnification curve and frequency band of each channel used in the analysis. A short-period vertical seismometer with free period of 1 sec is used. CH 1 to CH 3 indicate the channel numbers of the filters. The larger the channel number, the higher the frequency.

Fig. 2 shows the examples of the analyzed data for earthquakes which took place in the Aleutian Is. region. In order to simplify the analysis, the maximum amplitude within 5 sec from the onset of P phase is measured for each channel. The measured amplitudes are indicated by arrows.

3. Effect of magnitude on frequency spectra

It is well known that the predominant period of P waves increases with magnitude. However, how the source spectrum depends on the magnitude is as yet unknown.

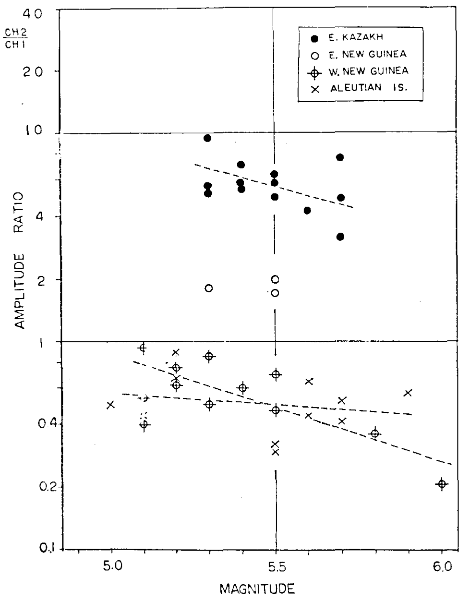

Fig. 3a. Relation between magnitude and amplitude ratio of CH 2/CH 1 for the earthquakes with shallow focal depth.

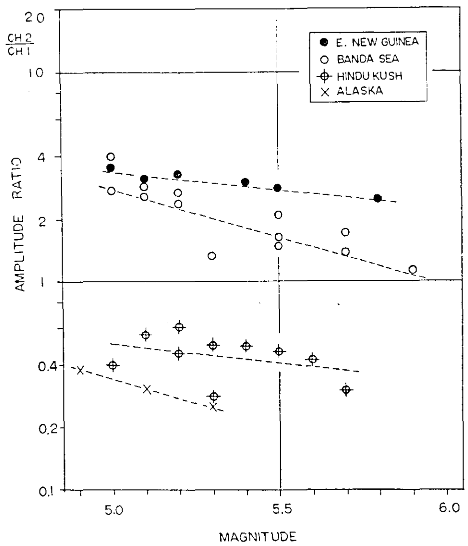

Fig. 3b. Relation between magnitude and amplitude ratio of CH 2/CH 1 for the earthquakes with intermediate focal depth.

In order to see the dependence of the spectrum on magnitude, we took the amplitude ratio CH 2/CH 1 of P-waves for events in some selected regions. The magnitude range from 5.0 to 6.0 is considered.

Fig. 3 shows the preliminary result. The amplitude ratio may also depend on the focal depth. In order to separate the depth effect, we first used the events having nearly the same focal depth for each region and compared the relationship between CH 2/CH 1 amplitude ratio and the magnitude. Fig. 3a is for the shallow events and Fig. 3b is for the intermediate depth earthquakes. Generally speaking, amplitude ratio decreases as the magnitude increases but the trend seems to be different for different regions. In particular, the absolute value of the amplitude ratio itself differs significantly from region to region. As the magnitude ranges from 5.0 to 6.0, we fitted the data by an equation of the form $\log_{10}$ CH 2/CH 1$=a+b(m-5.5)$ and calculated the values of a and b for each region by the least square methods as given in Table 1. The regional difference of a value is especially noteworthy as described above, while that of b is not very definitive and needs further investigation by accumulating more data.

Table 1

Region	Focal depth (km)	Mean distance (degree)	a	b	SD
E. Kazakh	O(R)	46	+0.74	−0.41	±0.04
Aleutian Is.	15-60	39	−0.31	−0.02	±0.14
W. New Guinea	10-50	39	−0.32	−0.53	±0.08
E. New Guinea	130-210	42	+0.44	−0.18	±0.05
Banda Sea	110-160	43	+0.22	−0.46	±0.10
Hindu Kush	150-230	54	−0.39	−0.17	±0.09
Alaska	90-120	47	−0.71	−0.43	±0.01

4. Comparison of frequency spectra of P wave

Before going into the discussion of the spectrum of natural earthquakes, we will show several results for explosions in various regions. Because the source spectrum of explosions will be probably the same, the observed spectrum will provide information concerning the propagation path and the geological settings at the source. The spectra of explosions are also useful, when compared with those of earthquakes in the same region, for studying the source spectrum of earthquakes.

4-1 Underground explosion data

Fig. 4 shows examples of two explosions, one in the E. Kazakh region and the other in the Novaya Zemlya region. The amplitude

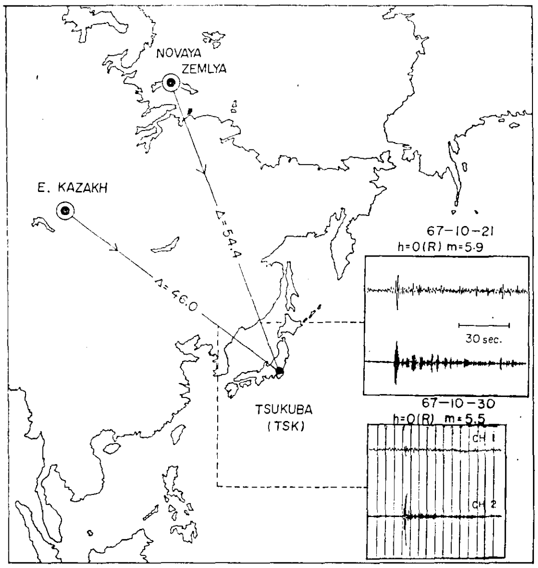

Fig. 4. Examples of the frequency-analyzed data (filtered seismograms) for underground explosions. The arrows show the great circle paths to Tsukuba Observatory (TSK).

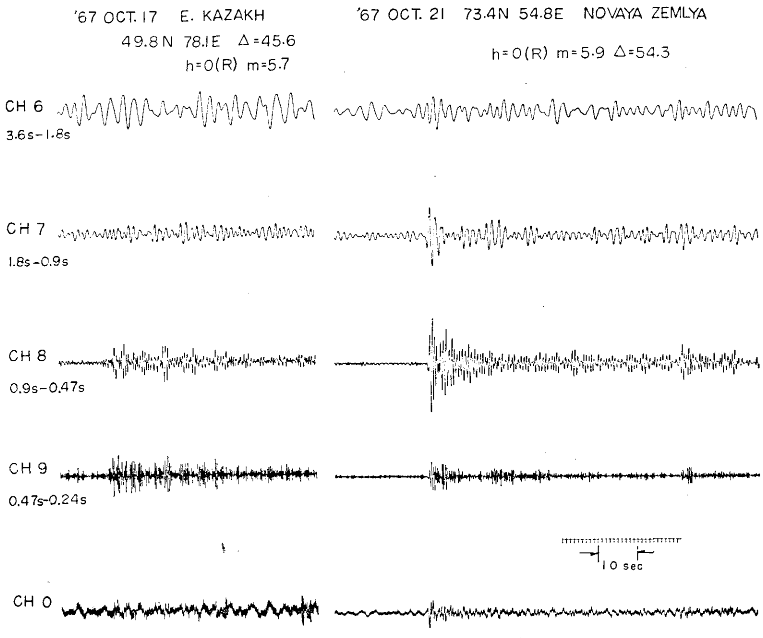

Fig. 5. An example of filtered seismograms (Off-line) for underground explosions recorded at Dodaira Observatory (DDR).

ratio CH 2/CH 1 is 4.8 for the former and 1.3 for the latter. The difference seems to be too large to be explained in terms of the difference in distance and magnitude. An almost similar result was obtained by a wide-band seismograph installed at the Dodaira station (DDR) about 90 km west of TSK.

Fig. 5 shows the analyzed data of two events from the two regions. These data were obtained by the off-line analysis method reported by *Tsujiura* (1967). High-frequency components are more predominant in the Kazakh event than in the Novaya Zemlya event; components with frequencies lower than 1 cps are very small for the Kazakh event. Neither the absorption along the entire propagation path, nor the difference of local structure between the two stations can explain this observation. The geologic settings near the source may have affected the spectrum.

We will treat this problem in considerable detail in the following. The amplitude ratio of the two components with frequencies f_1 and f_2 can be written as

$$r=\frac{a(f_1)}{a(f_2)}=\frac{S(f_1)}{S(f_2)}\exp\left[-\pi\int_C\frac{dt}{Q}(f_1-f_2)\right]$$

where $S(f)$ and Q are the source spectrum and the quality factor respectively. The integration is taken along the path, and dt is the travel time increment along the path. We let r and r' be the ratios for the Kazakh and the Novaya Zemlya events. If we assume that the ratio of the source spectrum is the same for the two events we have

$$\frac{r}{r'}=\exp\left[-\pi(f_1-f_2)\left\{\int_C\frac{dt}{Q}-\int_{C'}\frac{dt'}{Q'}\right\}\right]$$

where primed quantities are for the Novaya Zemlya event. The difference of $A\equiv T/\bar{Q}$ (see *Carpenter and Flinn*, 1965) for two events is then

$$\delta A\equiv\int_C\frac{dt}{Q}-\int_{C'}\frac{dt'}{Q'}=-\ln\left(\frac{r}{r'}\right)\Big/\pi(f_1-f_2)\ .$$

In our case r/r' can be estimated as 3 to 5 when we allowed for the magnitude effect based upon Fig. 3. Putting $f_1=2$ cps and $f_2=0.7$ cps into the above equation we have

$$\delta A\sim-0.27 \quad \text{to} \quad -0.4\ .$$

This means that the waves from the Novaya Zemlya region are subjected to a greater attenuation than those from the Kazakh region.

Carpenter and Flinn (1965) suggested that, for short-period P waves, T/Q is almost constant, about 1 sec, at teleseismic distances. The results by *Kanamori* (1967) show that the difference of T/Q for $\Delta=46°$ and $54°$ is about 0.05 sec. Therefore, we can conclude that the distance effect is very small, and that the observed difference arises from the local effect in the Novaya Zemlya region.

Assuming that the path from the Kazakh region is almost normal, that is,

$$\int_C \frac{dt}{Q}=1$$

we have, for the Novaya Zemlya path,

$$\int_{C'} \frac{dt}{Q'}\sim 1.3 \ .$$

We separate the Novaya Zemlya path into two parts as shown in Fig. 6. Then we have

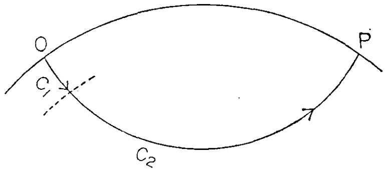

Fig. 6. Schematic illustration of path separated into two rays for P phase.

$$\int_{C_1} \frac{dt}{Q'}+\int_{C_2} \frac{dt}{Q'}\sim 1.3 \tag{1}$$

where C_1 and C_2 are the paths in the first and the second parts. For the normal mantle

$$\int_{C_1} \frac{dt}{Q}+\int_{C_2} \frac{dt}{Q}\sim 1.0 \tag{2}$$

we assume that the anomalous zone is limited only in the neighborhood of the source. Then the second integrals in (1) and (2) are equal, and we have by subtracting (2) from (1)

$$\int_{C_1} \frac{dt}{Q'}-\int_{C_1} \frac{dt}{Q}\sim 0.3 \ .$$

We will denote the average value of Q for the Novaya Zemlya mantle and the normal mantle by $\bar{Q}'$ and $\bar{Q}$ respectively. We let D and V be the path length and the average velocity in the first part of the mantle. Then we have

$$\left[\frac{1}{\bar{Q}'}-\frac{1}{\bar{Q}}\right]\frac{D}{V}\sim 0.3 \ .$$

If we assume $D=300$ km, $V=8$ km/sec, and $\bar{Q}=200$ we have $\bar{Q}'=80$.

This is the average value from the surface down to 300 km in the Novaya Zemlya region. The value of $\bar{Q}$ of the normal mantle used above comes from *Anderson et al.* (1965).

Thus, we may conclude that the mantle beneath the Novaya Zemlya region is significantly more attenuating than the normal mantle.

Santo (1965) pointed out that the velocity of surface waves passing through the Novaya Zemlya region is lower than that through the Kazakh region. This may reflect the low-Q mantle beneath the Novaya Zemlya region.

4-2 Explosion versus earthquake data

Series of underground explosions in the E. Kazakh region were recorded on the same recording system described in the section 2. These are useful for studying the difference of the source function between explosions and earthquakes in this region since the propagation path is the same. Although no earthquake occurred in exactly the same region, we had several earthquakes which occurred in a region fairly close.

Fig. 7 shows an example. The seismogram on the left is for explosion, and that on the right is for earthquake. We see that the explosion seismogram is concentrated on CH 2 (2 cps) while the earthquake seimogram has larger amplitude on CH 1 and smaller motion on CH 2, indicating broader frequency range centered at lower frequency. This may be due to the difference of the time duration of the source.

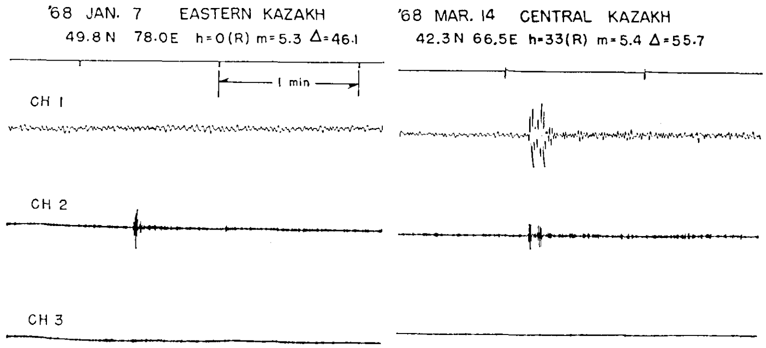

Fig. 7. An example of filtered seismograms for underground explosion and natural earthquake.

4-3 Earthquake data

In the previous section, the regional variation of P-wave spectrum of underground explosions was found. In this section, we will show that earthquake data also show a regional spectral variation.

As pointed out by *Solov'ev et al.* (1964) and *Tsujiura* (1966) P

waves from deep shocks contain, on the average, higher frequency waves than those of shallow shocks. One of the examples is shown in Fig. 2. From this point of view, we will study the relation between the amplitude ratio (CH 2/CH 1) of P waves and focal depth for various seismic regions.

Since the amplitude ratio depends on magnitude as we saw in section 3, it will be necessary to use earthquakes of about the same magnitude in order to study the regional difference of the spectrum. However, if we make the magnitude range very small, the number of earthquakes becomes too small. Based upon Fig. 3, we see that if we take a magnitude range from 5.1 to 5.6, the magnitude effect on CH 2/CH 1 is about $\pm 25\%$ and it may be smaller than the possible regional variation of CH 2/CH 1. Thus, we used earthquakes within the magnitude range from 5.1 to 5.6 and took the average ratios.

Fig. 8 shows P-wave spectra of earthquakes in the Alaska and New Guinea regions. One is the earthquake which occurred in the inland region and the other is that in the coastal region. Although they have almost the same epicentral distance Δ, focal depth h and magnitude m, we find a remarkable difference in the amplitude ratio CH 2/CH 1 between the earthquakes.

The earthquake in the inland district of Alaska contains frequency components higher than that in the coastal district of Alaska.

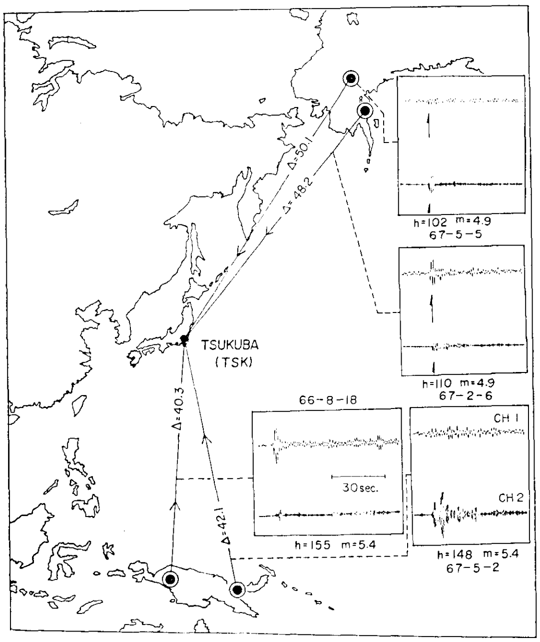

Fig. 8. An example of filtered seismograms indicating the regional variation of P-wave spectrum.

On the other hand, earthquake in the coastal district of East New Guinea contains frequency components higher than that in the inland district of West New Guinea.

We extended this kind of study to various seismic regions. Table 2 shows the investigated regions in relation to seismic activity.

Table 2

No.	Seismic Region and District
1	Aleutian Is. (A, B, C), Alaska (A, B)
2	New Guinea (E., W.), Solomon Is. (A, B), Santa Cruz Is.
3	Philippine, Celebes Is., Banda Sea, Java, Sumatra
4	China, Kazakh, Tadzhik, Hindu Kush

Fig. 9 shows the epicenters of earthquakes in the Aleutian Is. and Alaska regions. The length of the seismic belt along the Aleutian Arc is about 1000 km. Therefore we classified the earthquakes region into three district groups A, B and C in order to make small the attenuation effect due to the difference in path lengths.

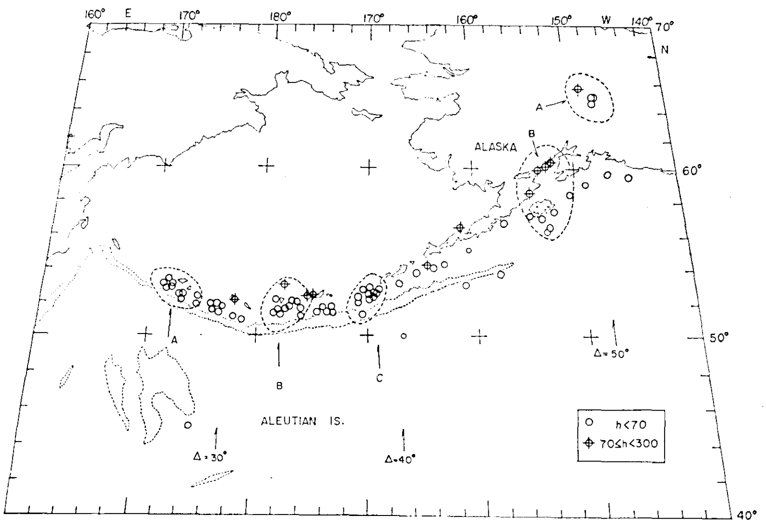

Fig. 9. Epicenter location of earthquakes used.

Fig. 10 shows the relation between the amplitude ratio CH 2/CH 1 and the focal depth for three districts in the Aleutian Is. region. The general trend is the same for the three groups. The amplitude ratio CH 2/CH 1 increases rather rapidly with the focal depth in this region comparing with the other regions described below, i.e., it changes from 0.2 to 1.2 as the focal depth increases from 10 to 60 km. This may be

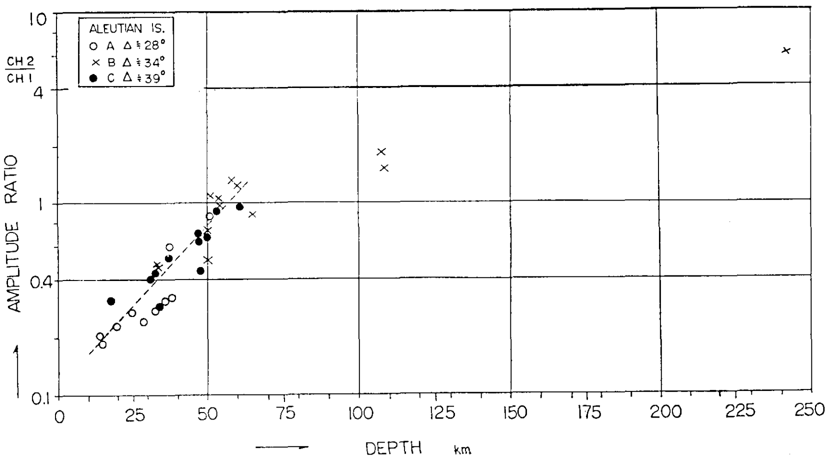

Fig. 10. The amplitude ratio between the two different frequency bands for the P waves of earthquakes in the Aleutian Is. region.

due to two causes; one is the difference of the source spectrum for different depths, the other is the attenuation in the crust and the shallower part of the mantle. The rays from shallow earthquakes are subject to an extra attenuation in the mantle near the source.

If we assume that the source spectrum is about the same for shallow and deep shocks, we can estimate the value of Q of mantle near the source from the slope of CH 2/CH 1 versus focal depth curve.

Let r_1 and r_2 be the ratios as defined in section 4–1 for two earthquakes with depths H_1 and H_2 respectively, we have

$$\frac{r_2}{r_1}=\exp\left[-\frac{\pi(H_1-H_2)}{VQ\cos i}(f_1-f_2)\right]$$

where V is the average velocity and i is the average angle of incidence over the depth range H_1 to H_2. Putting $V=8$ km/sec, $f_1=2$ cps $f_2=0.5$ cps, $i=30°$, $H_1=60$ km $H_2=10$ km and $r_1=1.2$ $r_2=0.2$ into the above expression, and solving it for Q, we have $Q=20$.

This is the average for the depth range from 10 to 60 km. Although the value of Q for P waves for the normal mantle over this period and depth ranges has not been established, a number of works have suggested that the average Q is larger than 80. Our value is significantly smaller than this. This difference may indicate either that the Q value in this region is extremely low or that the assumption that the source spectrum is independent of the depth is incorrect.

Fig. 11 shows the same relation for the earthquakes in the Alaska region shown in Fig. 9. The amplitude ratio also increases with the focal depth but the increase gradient seems less conspicuous than the Aleutian

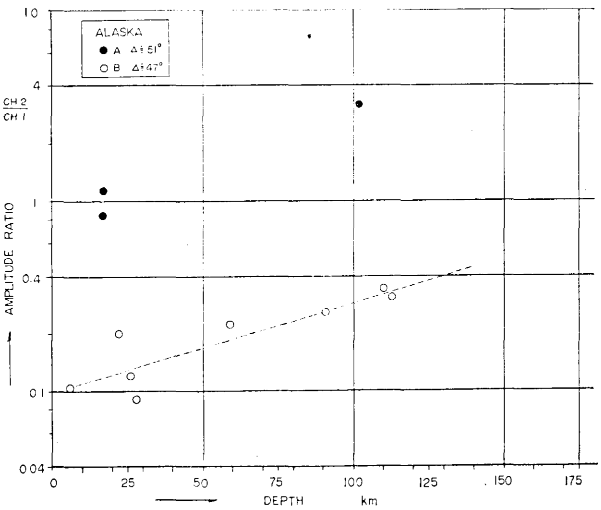

Fig. 11. The amplitude ratio between the two different frequency bands for the P waves of earthquakes in the Alaska region.

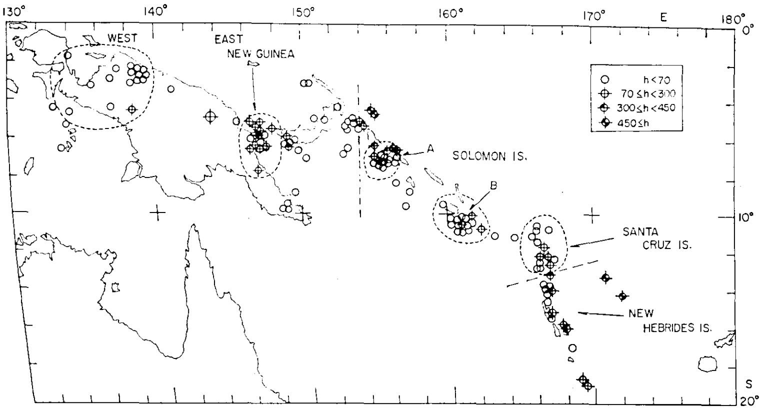

Fig. 12. Epicenter location of earthquakes used.

region given in Fig. 10. Moreover, it is remarkable that the amplitude ratio is larger in the A district than in the B district.

Fig. 12 shows the epicenters of earthquakes in the 2nd group of regions defined in Table 2. Five districts of high seismic activity are encircled by dotted curves.

Fig. 13 shows the relation for the earthquakes in the East and West New Guinea districts (see Fig. 12). The amplitude ratio increases with the focal depth for the earthquakes in the East New Guinea district. However, the slope of the curve is more gentle than that for the Aleutian Is. region and slightly less than that for the Alaska region. We estimated the Q value from the curve by use of the same method for the Aleutian

Is. events, and obtained the Q value of about 90.

The amplitude ratio for the West New Guinea district decreases as the focal depth increases. The amplitude ratio at 150 km depth is very different between the West and East New Guinea districts. This may be explained in terms of the difference of the mantle beneath the two districts. The lateral inhomogeneity of the mantle down to this depth range is now believed to exist. For example, the low-velocity layer certainly exists in some regions but the evidence is not clear elsewhere. The spectral difference between the two districts observed here may be related to the lateral inhomogeneity of the low-velocity layer.

Fig. 14 is for the Solomon Is. region shown in Fig 12. As the data scatter diversely, it is rather difficult to determine the change of ampli-

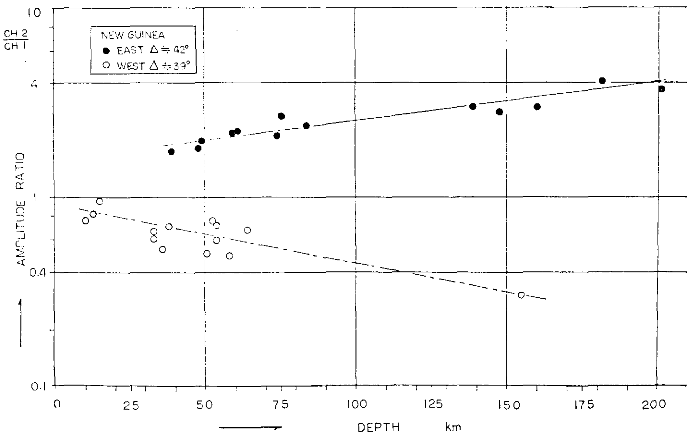

Fig. 13. The amplitude ratio between the two different frequency bands for the P waves of earthquakes in the New Guinea region.

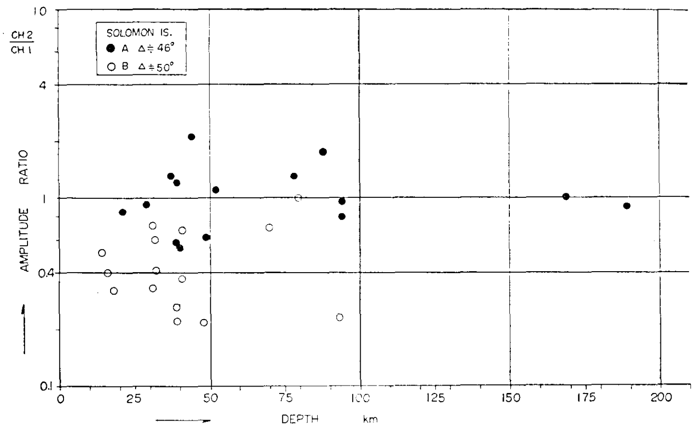

Fig. 14. The amplitude ratio between the two different frequency bands for the P waves of earthquakes in the Solomon Is. region.

tude ratio with focal depth for this region as found for the other regions. However, if we dare to compare it with that of New Guinea region, the relations for the A and B districts of the Solomon Is. resemble those for the E. and W. New Guinea districts respectively.

The results for other seismically active regions within the range 25°–55° are summarized in Fig. 15. In Fig. 15 the average amplitude ratios for the earthquakes with focal depth of 150 km are given for each region. The open circles indicate that the amplitude ratio could not be obtained because of too large data scatter. When earthquakes with about 150 km depth do not occur in the region we use the ratio for the earthquakes at slightly different depths. In those cases both the ratio and the depth are given in the circle. The amplitude ratio differs markedly from one region to another. For example, when we compared the values for the Aleutian, E. New Guinea, W. New Guinea and Celebes which have almost the same distance from TSK, it

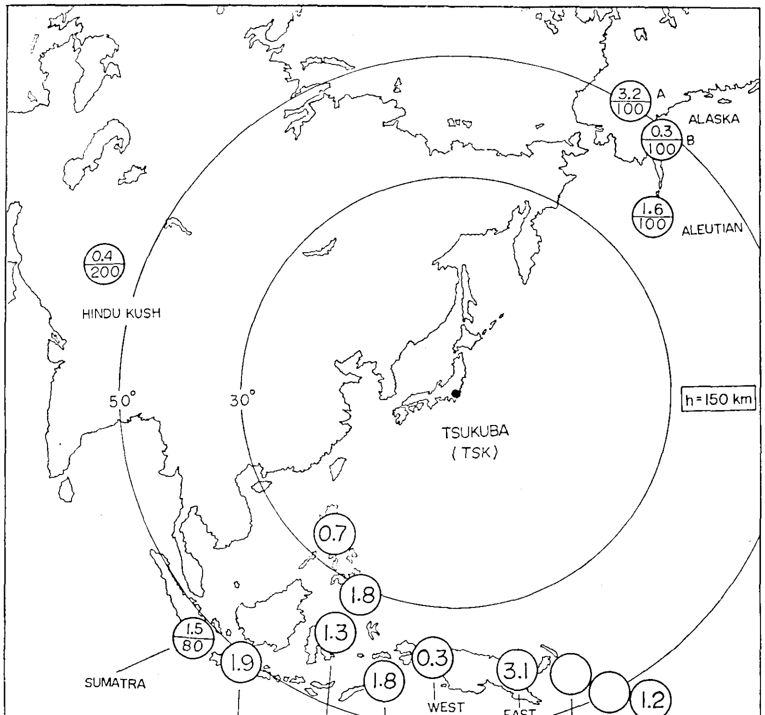

Fig. 15. Average amplitude ratio of CH2/CH1 at focal depth of 150 km. Two values in the circle indicate the amplitude ratio (upper) and focal depth (lower) since there is no earthquake with about 150 km focal depth.

can be found that there is 10 times variation among the regions. Moreover, in the regions among Alaska, Santa Cruz, Java and Hindu Kush there is also about 5 times variation. The value for the Philippine Is. region is low though the distance is the shortest. There is no apparent correlation between the ratio and the distance or azimuth.

5. The effect of propagation path

In order to study the regional variation of *P*-wave spectrum, the effect of propagation path should be considered. *Oliver and Isacks* (1967) found that seismic body waves propagating in a narrow zone associated with deep earthquakes are much less subject to attenuation than are waves of the same type propagating in parts of the mantle at similar depths elsewhere. *Utsu* (1967) also found that seismic body waves travel faster with smaller attenuation in a zone parallel to the seismic zone than in the mantle elsewhere at comparable depths.

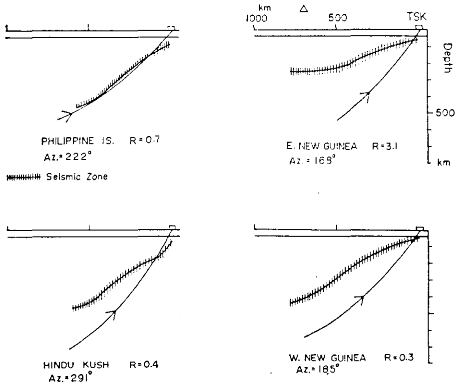

Fig. 16. Cross sections of the structure along the seismic ray.

In order to see the effects as mentioned above, four samples are considered here. Fig. 16 shows the relation between the propagation path and the seismic zone near TSK based on *Wadati* (1935). The symbols R and Az indicate the amplitude ratio CH 2/CH 1 and the azimuth at TSK respectively.

The amplitude ratios of East and West New Guinea are different by a factor of 10, although the relation between the ray and the seismic zone is almost the same for both regions. The value of R for the Northern Philippine Is. region is small although the seismic wave passes through the anomalous zone where the attenuation is presumably small according to the conclusion of *Oliver and Isacks* (1967). Thus, the propagation path near the station apparently has no relation to the value of R. Moreover, in order to see the propagation path effect near the station we studied the data of Shiraki station (SHK) located at about 800 km west of TSK. Fig. 17 shows the propagation paths for the same E. and W. New Guinea earthquakes as used in the previous section. Fig. 17 also shows original record obtained by short-period seismograph ($Tp=1$ sec, $Tg=0.2$ sec) at SHK. The record was digitized

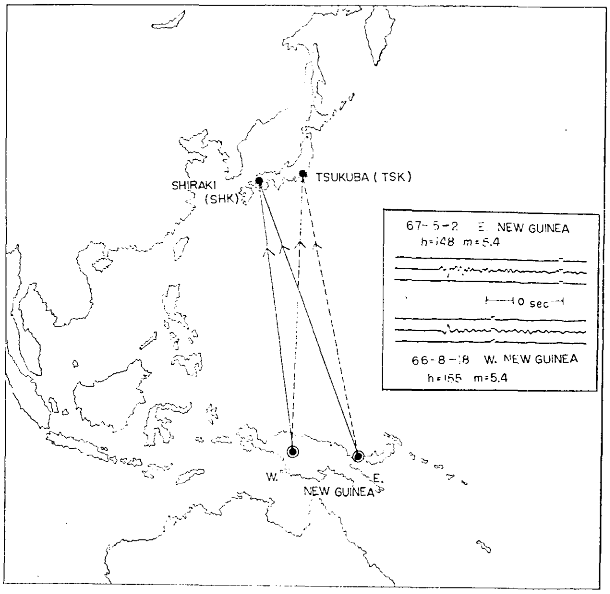

Fig. 17. Map showing the great circle paths from earthquakes in E. and W. New Guinea region.

for 5 sec from onset of P wave at the rate of 17 samples per sec, and analyzed by Fourier's method over the frequency range of 0.2 to 6 cps.

The resulting amplitude spectra is shown in Fig. 18. The spectrum is different for the two events, i.e., the E. New Guinea event contains more high frequency components than the W. New Guinea event. The result is in good agreement with the results of TSK, though the ray path near the station is entirely different. From these results we may conclude that the variation of P-wave spectrum cannot be explained in terms of the effect of the propagation path near the station exclusively. Or, we may rather suggest the regional difference of source spectra which is more fascinating for the earthquake seis-

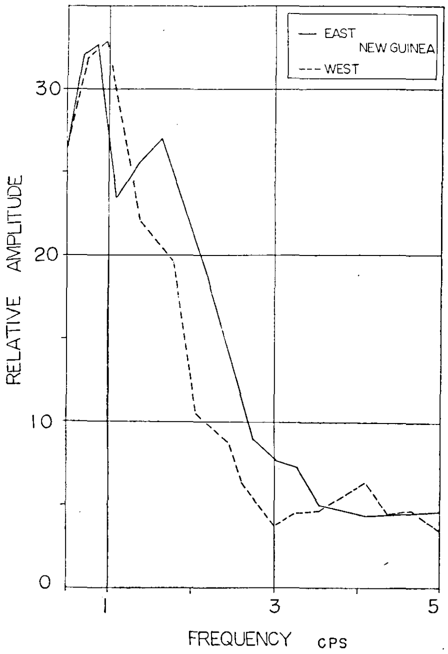

Fig. 18. Comparison of amplitude spectra at SHK station for the earthquakes from E. and W. New Guinea region.

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6. Variation of spectrum with focal depth

The preceding sections are concerned primarily with data for intermediate earthquakes in various seismic regions. In this section, we will show the results for other focal depth ranges together with those for intermediate depth range.

Figs. 19, 20 and 21 show the records for shallow ($h<40$ km), inter-

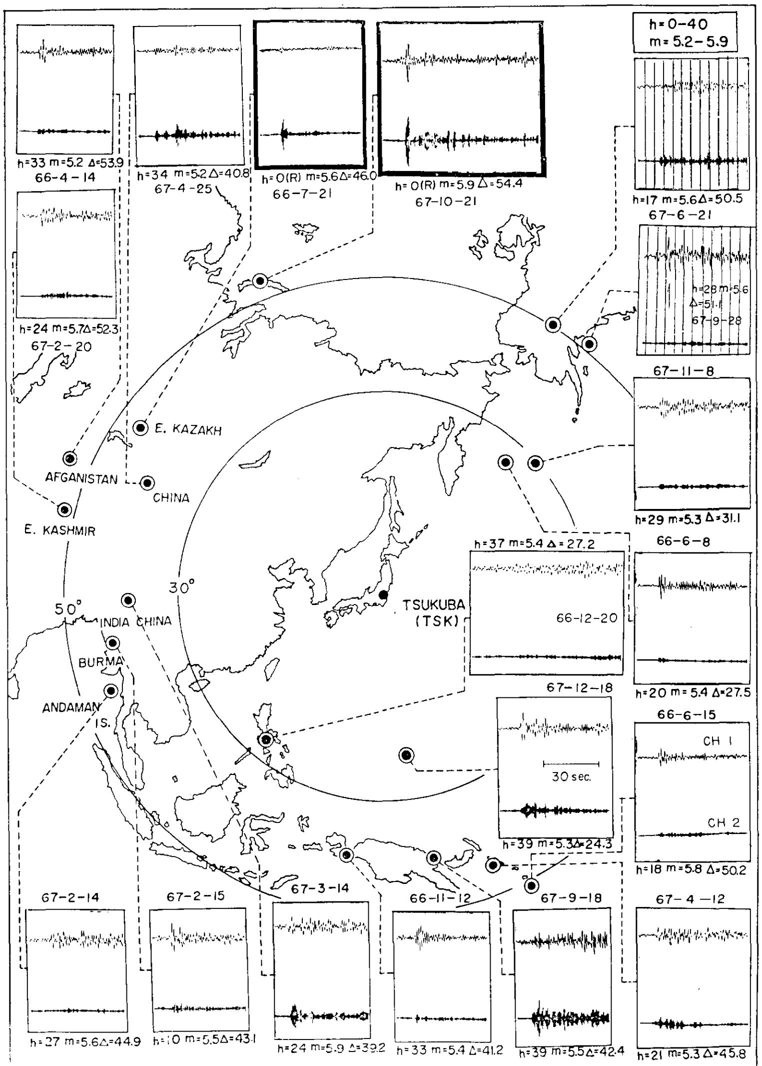

Fig. 19. Filtered seismograms of shallow earthquakes and underground explosions showing the regional characteristics.

mediate ($70<h<300$ km) and deep ($500<h<650$ km) earthquakes respectively. For shallow events (Fig. 19), the events in E. New Guinea and China contain much more high-frequency components than those in the other regions excepting explosions. Although the regional variation is not so remarkable as for the intermediate events given in Fig. 20, it is quite remarkable that the P phase from the Philippine Is. region is very unclear and the amplitude increases gradually.

Deep earthquakes occur only in limited regions as is seen in Fig. 21 and no apparent regional difference of P-wave spectrum is seen in CH 2

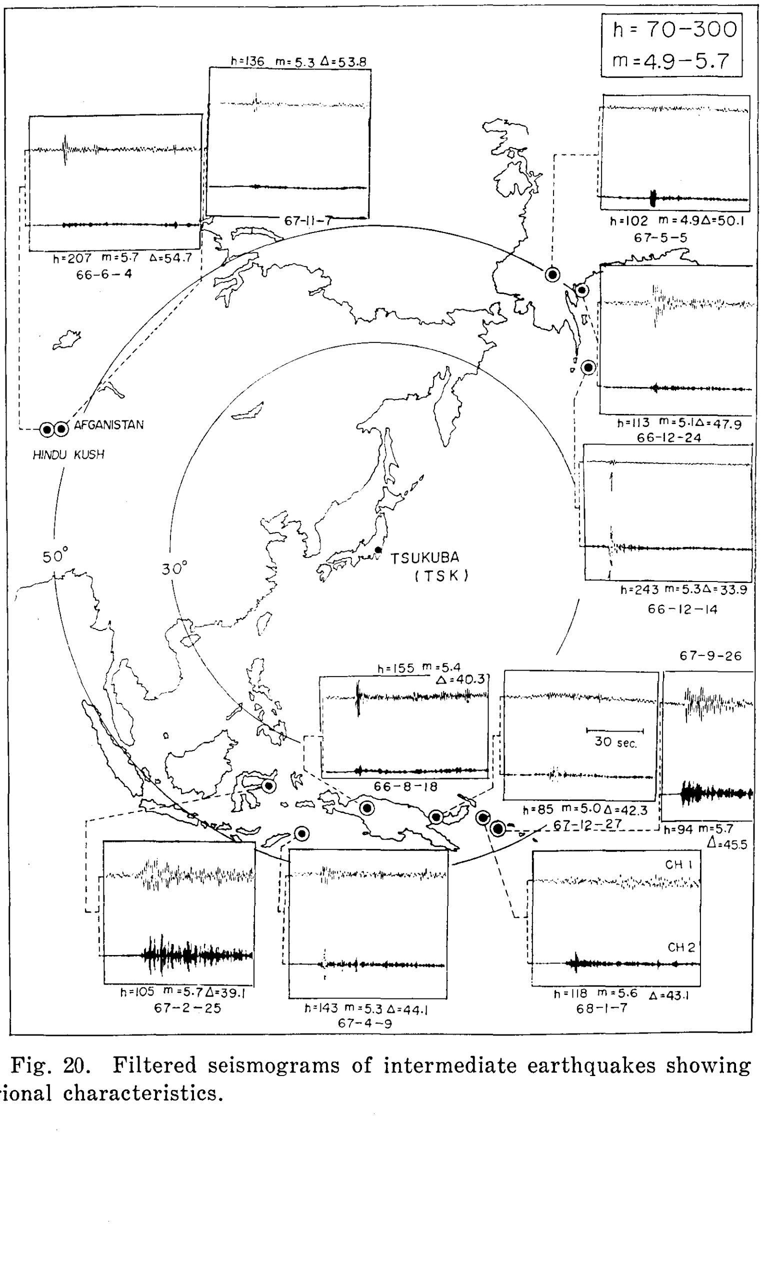

Fig. 20. Filtered seismograms of intermediate earthquakes showing the regional characteristics.

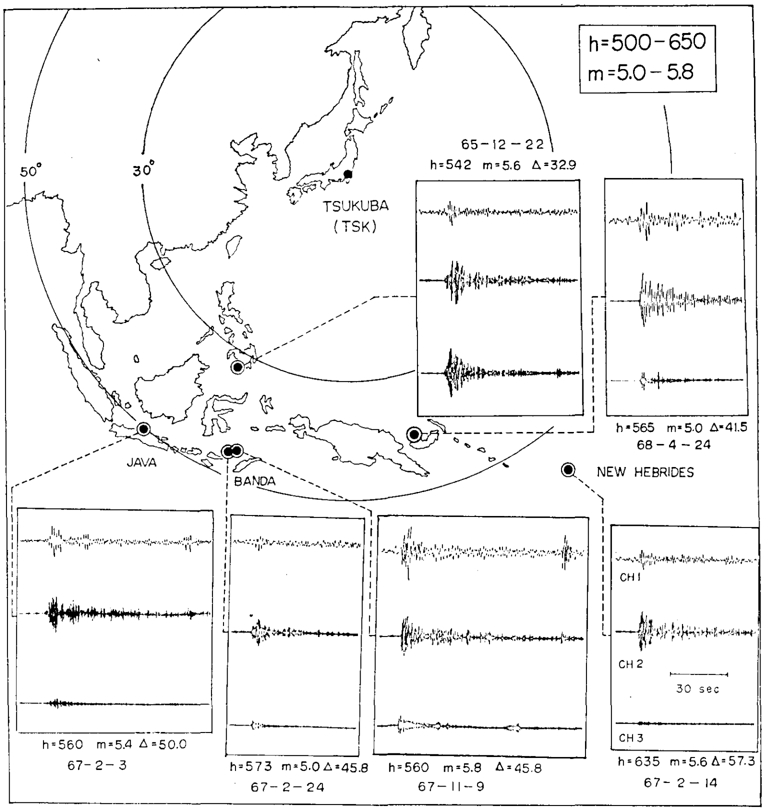

Fig. 21. Filtered seismograms of deep earthquakes. Note there is no regional difference of *P*-wave spectrum as shown in Fig. 19 and Fig. 20.

and CH 1. However, the amplitude of CH 3 (about 6 cps) relative to that of CH 1 is different for different regions. This may be explained in terms of the difference of the attenuation along the path. The difference of the amplitude ratio CH 2/CH 1 between two events in Banda Sea may be due to the magnitude effect as shown in Fig. 3.

7. Conclusion

A large regional variation of *P*-wave spectrum is found from the comparison of the amplitude ratio of two frequency bands for the events in various seismic regions. A tenfold variation of the ratio is found among different regions. In general, the events that occurred in regions with high deep seismic activity contain much high-frequency components. This is most clearly seen for intermediate earthquakes. The spectrum of deep events does not show the regional variation.

It will be interesting to study more detailed relation between focal depth and spectrum, because the relation will provide a clue to the understanding of the tectonic difference of various regions.

The regional Q values for crust and upper mantle are estimated for several regions. The Q value of deep seismic region is larger than that of the region with intermediate earthquakes.

If the effect of the propagating path on the wave spectrum can be correctly removed, the technique described here will be useful to study the regional difference of the source spectrum in relation to the geological setting near the source.

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27. P 波スペクトルの地域性 (1)

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筑波山で観測中の短周期地震計を用い，震源距離 25°~55°，マグニチュード 5.1~5.6 の範囲内にあるすべての地震について P 波のスペクトル構造をしらべた．

用いた解析装置はアナログ型バンドパスフィルターであり，主として 2 サイクルを中心とした成分と 1 サイクル以下の周波数成分の振幅比をもつてスペクトルをあらわすことにした．

以上の方法にしたがつて，まず地震を地域別に分類し，それぞれの地域について震源の深さとスペクトルの関係をしらべた結果，これらの値が地震の発生する地域によつて異なることを見出した．一般に深発地震帯に属する地震は他の地域に比べ大きな振幅比をもち，また同じ地域においてもアラスカあるいはニューギニヤの地震については海岸と内陸で約 10 倍の違いがある．もちろんこれらの違いは地震波の伝播経路による影響を受けるが筑波山から約 800 km 離れた白木観測所のデーターについてもほぼ同じ結果を示す．したがつてこれらの違いは経路による影響よりもむしろ震源における Source spectrum あるいは震源近傍の構造の違いによつて生じたものであろう．なお深発地震 ($h>500$ km) には地域性がみられない．