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19. *Crustal Structure in Northern Kwantô District by Explosion-Seismic Observations.*

Part II. Models of Crustal Structure.

By Tatsuo USAMI,* Takeshi MIKUMO,** Etsuzô SHIMA,***
Ituo TAMAKI,**** Shûzô ASANO,*** Toshi ASADA***
and Takeo MATUZAWA.***

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1. Introduction.

Using the data given in Part I, we can make some plausible models of crustal structure in the vertical section along the line joining Hokota and Nozori shot points. In our observations, the average distance between consecutive stations was about 20 km. Even this density of stations was not large enough for unique determination of the crustal structure. In deriving models for the crustal structure, we first assume a plausible number of layers and the velocity of their P waves. The assumptions were based on the travel time data given in Part I, upon due consideration of the crustal structure obtained in Tôhoku District[1]. As a consequence of lack of sufficient data, different models of crustal structures could explain all the travel times in some degree.

In deriving various models, we used the arrival time of the first tremor, and later phases were referred to only when necessary. Arrival times of first tremors for the first Nozori explosion given in Table 2 were read by T. Asada and S. Komaki and those for the second by T. Usami, T. Asada and T. Matumoto.

At the outset we assumed five tentative models as the first approximation and then each model was subjected to small changes in order to make the residue of calculated travel times as small as possible. In each model, $O-C$'s (O stands for the observed travel time of the first

* Japan Meteorological Agency.
** Geophysical Institute, the University of Kyôtô.
*** Earthquake Research Institute, the University of Tôkyô.
**** Ôsaka Institute of Technology.

1) The Research Group for Explosion Seismology, *Pub. Bureau Central Séism. Int.*, Série A, Trav. Sci., **19** (1956).

wave and C for the calculated one) were calculated graphically, using figures of the vertical section along the line joining Nozori and Hokota shot points, the scale of the figures being 10^{-5} or 5×10^{-6} of the actual.

2. Model I.

This model was assumed in the following process, using the data of Table 2 in Part I and paying no consideration to the crustal structure of the Tôhoku District[2] obtained by our group.

a) Three layers specified by the velocities 5.5, 6.1 and 7.7 km/sec of the P waves are assumed from top to bottom, each boundary between adjacent layers being taken as horizontal. These layers were called the I, II and III layers respectively. From the travel time in Fig. 4, in Part I the true velocity of the P wave in the II layer cannot be determined precisely, however, it is certain, from the data of Nozori explosions, that the velocity lies between 6.0 and 6.1 km/sec. Thus we take 6.1 km/sec as the first approximation.

b) The thickness of the I layer and that of the II layer were obtained as 6 km and 19 km respectively from the assumed velocity of the P wave and the critical distance determined from travel time curves specified by the I and II layers of Nozori explosions and from those specified by the II and III layers of the Hokota explosion.

From these approximations, we got $O-C=0.37$ sec at station Tukuba for Hokota explosion. Near station Tukuba granitic rocks are found on the ground surface. Therefore, to explain the observed travel time of the Tukuba for the Hokota explosion, we assumed that the II layer comes up to the ground surface near Tukuba and that the weathered layer specified by the velocity 1.79 km/sec of the P wave lies on the I layer near the Hokota shot point with thickness corresponding to $O-C=0.37$ sec. Moreover, the existence of the same weathered layer was assumed between Hokota and station Yûki (19), except near Tukuba, with some thickness so as to make $O-C=0$ sec at these stations for the Hokota explosion. Thickness of the weathered layer thus obtained seems not unreasonable from the geological point of view. In order to make the mean value of $O-C$'s, which is taken for stations near and east of Nozori in the Nozori explosions, zero, a weathered layer specified by the velocity 2.7 km/sec of the P wave was assumed on the I layer with thickness 0.1 km near Nozori shot point.

2) The Research Group for Explosion Seismology, *loc. cit.*, 1).

As stations Matusiro (15) and Ômati (25) do not lie on the line joining Hokota and Nozori shot points, we considered the crustal structure in the section along the line joining Nozori, Matusiro and Ômati separately. In this section, the thickness of the I layer was obtained from the later phases recorded at Matusiro and Ômati for the Hokota explosion, and then the position of the boundary between the II and III layers was determined by using the arrival times of the *P* waves at these two stations observed in the Hokota explosion. With some further trials to make $O-C$'s small as a whole, we obtained a crustal structure which is given in Fig. 8a. In this figure model I is given in thin lines. Model II and model III are superimposed.

Though we examined five models, this model is the simplest and as a whole can explain most satisfactorily the observed travel times of the *P* waves. Therefore we adopt model I as the most plausible one.

3. Models II and III.

These models were examined in order to check how far the observed arrival times of the *P* wave can be explained, if the velocity of the *P* wave in the III layer of the model I be 8.1 km/sec, which is often reported as the velocity of the *P* wave under the Mohorovičić surface. The results are shown in Fig. 8a and Table 7. In the figure, model II is given in thick lines and model III is in chain lines. Structural parts common to model I are not specially mentioned.

Though models II and III were constructed for the same purpose, the results differ remarkably from each other. In deriving model II, the depth of the boundary between the II and III layers was assumed as 25 km everywhere, from which the following contradiction turned out. In order to make $O-C$'s small as a whole, the crustal structure must differ on the north and south sides of the line joining Hokota and Nozori shot points. In model III, the depth of the boundary between the II and III layers was taken as 27 km. This model was rejected, because $O-C$'s at stations Hanasiki, Matusiro and Ômati for the Hokota explosion were too large beyond the observational errors.

These trials indicate that, even with such density of observation stations as this, it is difficult to derive a unique solution of the crustal structure.

4. Model IV.

In deriving this model, the following assumptions were made.

a) Layers specified by the velocity 2.7, 6.0 and 7.5 km/sec of the P wave lie from top to bottom in this order, and will be called the I, II and III layers respectively. This model was examined in order to check how far the observed values of travel times can be explained by a model with 7.5 km/sec as the velocity of the P wave under the Mohorovičić discontinuity, because the value is often found from the investigations of natural earthquakes.

b) The I layer lies everywhere near the surface.

c) Thickness of the I layer near Nozori is 0.1 km.

Starting from the above assumptions, a crustal structure was obtained by the method of trial and error so as to make $O-C$'s as small as possible. $O-C$'s were calculated from the delay time. The result is shown in Fig. 8b and Table 7. This model can explain the observed value of travel times fairly well except for the following points.

The I layer was obtained from the data of the Hokota explosion as the hatched part of Fig. 8b. But, the same model does not fit well with the data of the Nozori explosions and $O-C$'s for the Nozori explosions remain 0.77, 0.38, 0.34 and 0.40 sec at stations Ôgo, Ômama, Kiryû and Asikaga respectively, these values being far beyond the error of observations. In order to make $O-C$'s small at these stations for the Nozori explosions, we had to add the cross hatched part of Fig. 8b as the I layer. This is a contradiction, because this additional part would have unfavourable effects on $O-C$'s for the Hokota explosion.

5. Model V.

From the following standpoints, this model was tried.

a) At four stations where seismic waves from both the Hokota and Nozori explosions were observed (Totigi, Asikaga, Ôgo, Tukuba), $O-C$'s for both explosions can be compared.

b) Layers specified by the velocity 5.8 and 6.2 km/sec of the P wave are assumed, because existence of these layers was plausible in Tôhoku District[3].

c) Layers specified by the velocities 1.8, 2.7, 5.8, 6.2 and 8.0 km/sec of the P waves are assumed and they are called the I, II, III, IV and

3) The Research Group for Explosion Seismology, *loc. cit.*, 1).

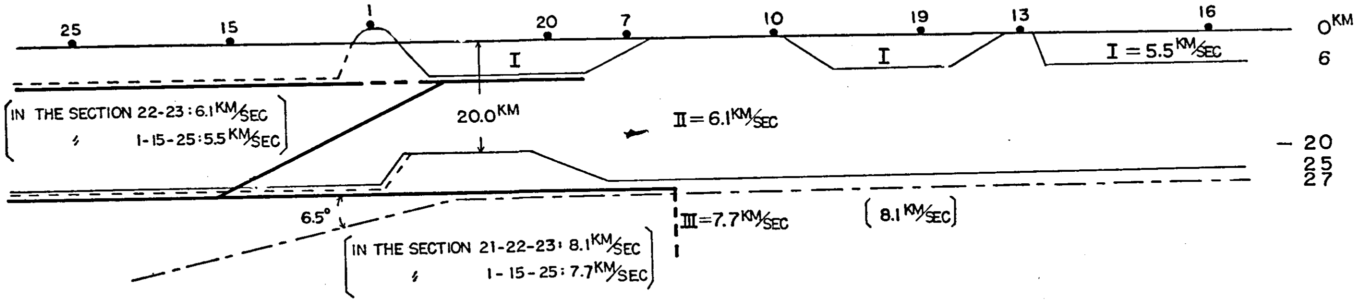

Fig. 8a.

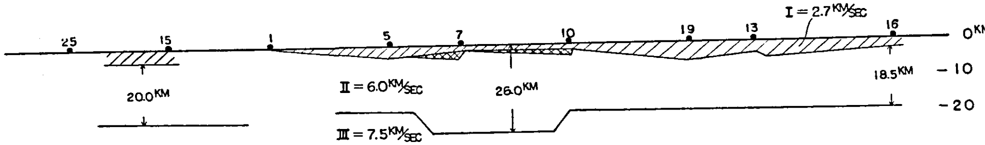

Fig. 8b.

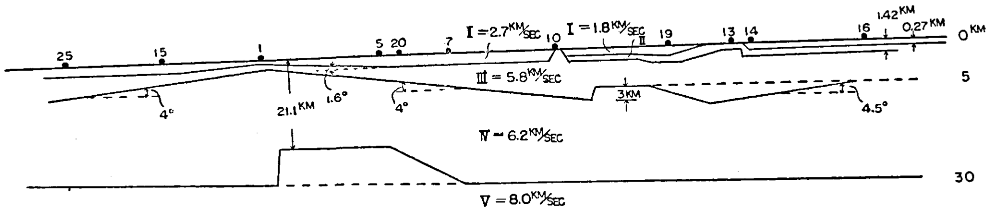

Fig. 8c

Fig. 8. Crustal structure in the section along the line connecting Nozori and Hokota shot points. Observation lines of Nozori and Hokota explosions were superposed so that the positions of Tukuba station in the cases of the three explosions coincide.

a) model I. ——: boundaries of layers in the section 16–1–23.
- - -: boundaries of layers in the section 1–15(15″)–25.
[ ]—: model II } Only boundaries, which differ from model I, are shown. Others are the same as
—·—·: model III } model I.

b) model IV. ▩: layer I, obtained from the first and the second Nozori explosions.

c) model V. Upheaval of layer V between stations Nozori and Takayama do not exist in the sections Hokota-Matusiro and Hokota-Ômati.

Table 7. $T_0 - T_c$ (unit in sec).

Name of Exp.	Ref. No.	Observation point	I	II	III	IV	IV (km)	V
N1, N2	1, 1′	Nozori	sec* 0.1	Same as I	Same as I		*** km	**** $H_{II}=0.15$, $H_{III}=2.8$
N 2	2′	Sima	−0.03 (I, II)			0.01	0.6	−0.10 (II, III)
N 1	3	Sawatariguti	−0.02 (〃)			−0.01	0.7	−0.11 (〃)
N 2	4	Nakanozyō	0.10 (〃)			0.00	1.3	0.02 (〃)
N 1	5	Takayama	0.23 (〃)			−0.01	2.1	0.14 (〃)
N 2	6	Ikaho	0.02 (〃)			0.01	1.6	0.03 (II, III IV) $H_{II}=1.2$
N 1	7	Ōgo	0.07 (〃)			0.77※ 0.01	0.3 2.6	0.41 (〃)
N 2	8	Ōmama	0.03 (II)			0.38 0.02	0.3 1.2	0.02 (〃)
N 2	9	Kiryū	0.05 (〃)			0.34 0.04	0.3 1.1	−0.03 (〃)
N 1	10	Asikaga	0.23 (I, II)			0.40 0.00	0.2 1.4	0.36 (〃)
N 1	11	Totigi	0.00 (〃)			0.07	1.6	−0.08 (〃)
N 2	12	Ōya	0.05 (〃)			0.03	1.7	0.07 (〃)
N 1	13	Tukuba	−0.11 (II, III)		0.01 (II, III)	0.02	1.4	0.97 (II, III, IV, V)
N 2	14	Kakioka	0.17 (I, II, III)		0.20 (I, II, III)	−0.01	2.9	0.99 (I, II, III, IV, V)
N 1	15	Matusiro	−0.02 (I, II)				1.9	0.09 (II, III, IV) $H_{II}=1.2$, $H_{III}=4.3$
H 1	16	Hokota	0.37	Same as	Same as		1.6	$H_I=0.27$, $H_{II}=1.42$, $H_{III}=5.0$
〃	17	Tomoegawa	0.00 (I) 0.61			0.01	1.7	−0.02 (I, II, III)
〃	18	Tamari	0.00 (〃) 0.41			0.01	2.3	0.00 (〃)
〃	13″	Tukuba	0.00 (I, II)			0.01	1.4	0.00 (〃) $H_I=0$, $H_{II}=0.6$, $H_{III}\doteqdot 8.5$
〃	19	Yūki	0.00 (〃) 0.76			0.01	3.8	0.00 (〃) $H_I=0.8$, $H_{II}=2.0$, $H_{III}=6.0$

〃	11″	Totigi	−0.05 (〃)	—	—	0.07	1.6	−0.09 (I, II, III, IV)	
〃	10″	Asikaga	−0.15 (〃)			0.00	0.2	−0.09 (〃)	
〃	7″	Ōgo	−0.09 (〃)			−0.01	0.3	−0.21 (〃)	
〃	20	Sibukawa	0.07 (I, II, III)		−0.01 (I, II, III)	−0.02	1.3	0.09 (I, II, III, IV, V)	
〃	21	Agatuma	0.06 (〃)		−0.04 (〃)	−0.02	1.3	−0.15 (〃)	H_{II}=0.8
〃	22	Hanasiki	−0.08 (〃)	−0.04	−0.78 (〃)	0.01	0.2	−0.04 (〃)	H_{III}=1.9
〃	23	Yamanouti	−0.20 (〃)	−0.01	0.17 (〃)	−0.18	0.0	0.00 (〃)	H_{II}=0.6
〃	15″	Matusiro	0.03 (〃)	−0.12	0.69 (〃)	−0.02	1.9	−0.02 (〃)	
〃	25	Ōmati	0.05 (〃)	0.38	1.02 (〃)	−0.03	1.9	0.02 (〃)	H_{II}=2.2, H_{III}=7.2
〃	15″	Matusiro	−0.83 (I, II) later phase						
〃	25	Ōmati	0.27 (〃) 〃						
〃	23	Yamanouti	0.20 (〃) 〃						
〃	21	Agatuma	−0.40 (〃) 〃						
〃	11″	Totigi	0.16 (〃) 〃	1.08**					
〃	10″	Asikaga		0.18**					
Velocity of P wave (unit in km/sec)			I=5.5 II=6.1 III=7.7	I=5.5 II=6.1 III=8.1	I=5.5 II=6.1 III=8.1	I=2.7 II=6.0 III=7.5		I=1.8 II=2.7 III=5.8 IV=6.2 V=8.0	

(I, II, etc.) denote layers through which the first wave that reached the observation point passed.

*…thickness of the weathering layer with V_p=1.79 km/sec.

**…later phase which passed through the layer with V_p=8.1 km/sec.

***…thickness of the layer having P wave velocity of 2.7 km/sec.

****…depth of the lower boundary of a layer shown by I, II…. (unit in km)

※…upper: $O-C$ calculated from the Hokota explosion.

lower: $O-C$ calculated from the Nozori explosion.

V layers respectively. The II layer is assumed everywhere.

From an inspection of travel times, we adopt at the outset travel time curves with apparent velocities of 5.5 and 6.06 km/sec from the Nozori explosions and 5.5, 6.4 and 8.0 km/sec from the Hokoda explosion.

In the process of deriving a model of the crustal structure, shapes of layers specified by the velocities 2.7 and 5.5 km/sec of the P waves were assumed to be symmetric about the Nozori shot point.

From the critical distance determined from the travel time curves specified by the apparent velocities 2.7 and 5.5 km/sec for the Nozori explosions, the thickness of the II layer was obtained as 0.15 km near Nozori. Using the apparent velocity of 6.06 km/sec obtained from the Nozori explosions, the interface between the III and IV layers is considered to be deeper towards the east with a dip of 4°.

From the critical distance 160 km determined by the travel time curves specified by the apparent velocities of 6.4 and 8.0 km/sec of the Hokota explosion, the depth of the interface between the IV and V layers is obtained as 28.8 km.

Starting from these assumptions, small changes were made so as to make $O-C$'s as small as possible, and finally we get the crustal structure shown in Fig. 8c. This model has two disadvantages. The one is that $O-C$'s of Tukuba and Kakioka for the Nozori explosions are 0.97 and 0.99 sec respectively as shown in Table 7, being far beyond the observational errors. The other is that the upheaval of the V layer between stations Nozori and Takayama continues to exist in the Nozori-Hokota section, on the other hand, however, it must not exist in the Hokota-Matusiro and Hokota-Omati section.

6. Concluding remarks.

It is clear that each model obtained above has some advantages as well as some disadvantages. But, as stated before, we adopt model I as the final one, because it is the simplest and can explain the observed values of travel times most satisfactorily.

It is remarkable that the depth of the Mohorovičić discontinuity is obtained in the range of 20–30 km. This value of the depth is remarkably different from the value of 50 km obtained by one of the writers[4] about 30 years ago, which has been used as the standard of the crustal structure in Japan. From this result and that obtained from the inves-

4) T. MATUZAWA, *Bull. Earthq. Res. Inst.*, **5** (1928), 1; **6** (1929) 177.