BULLETIN OF THE EARTHQUAKE
RESEARCH INSTITUTE
Vol. 44 (1966), pp. 109-120

6. Crustal Structure in the Western Part of Japan Derived from the Observation of the First and Second Kurayosi and the Hanabusa Explosions. Part 2. Crustal Structure in the Western Part of Japan.

By Michio HASHIZUME,* Osamu KAWAMOTO,**
Shuzo ASANO,*** Ikuei MURAMATU,+
Toshi ASADA,++ Itsuo TAMAKI**
and Sadanori MURAUCHI.+++

(Read May 25, 1965.—Received Dec. 28, 1965.)

Abstract

By using data of the first and second Kurayosi and the Hanabusa explosions presented in Part 1, the crustal structure in the western part of Japan was derived. The velocity structure of the second layer with velocity 6.1 km/s was considered and the existence of the layer with velocity 6.4-6.6 km/s was ascertained. On the travel time graph of the Kurayosi explosions, the phase with velocity 6.4-6.6 km/s gives clear first arrivals. Neglecting fluctuation of travel times due to inhomogeneity of the surface or within the crust, the trial was made to obtain the range of depth of boundaries as well as that of velocity whenever possible. From the interpretation of travel time graphs, two possibilities for the deeper part of crust, Model I and Model II, are given in Figs. 3 and 4. In Model I there is a gap of the Mohorovičić discontinuity west of Biwa Lake by about 4 km and in Model II there is another layer with pretty high velocity 7.4-7.5 km/s above the layer with velocity 8.0-8.2 km/s. The thickness of crust is quite different between the two models. The apparent velocity of 8.1 km/s was obtained pretty clearly.

§ 1. Introduction

In this paper the crustal structure derived from the data obtained from three explosions—the first and second Kurayosi and Hanabusa ex-

* Disaster Prevention Research Institute, Kyoto University; ** Osaka Institute of Technology; *** Earthquake Research Institute, University of Tokyo; + Gifu University; ++ Geophysical Institute, University of Tokyo; +++ National Science Museum.

plosions[1]—is discussed. As mentioned in Part 1,[2] the quality of the data is good because of the improvement of the instruments and the method of explosions. The recording with magnetic tape recorders (data recorders) enabled a more detailed analysis to be made of later phases and wave forms than in the past.

§ 2. Fundamental assumptions and procedures

The analysis of travel time was carried out on the basis of the following assumptions or procedures:

1) The first arrivals and all later phases are picked up and classified into four grades by considering clearness of phases and time accuracy of identification.[3]

2) Layered structure model is adopted.

3) Probable lines are drawn on the travel time graph with considerations of the quality of each point and efforts are made to obtain the possible ranges of depth of boundaries and velocities.

4) The fluctuation of travel times within ± 0.1 sec is assumed to be due to the inhomogeneity near the earth's surface or within the crust, or the change of thickness of surface layers. Therefore, no effort has been made to explain fluctuation of travel times as long as 0.1 sec only by the change of thickness of surface layers. Thus the ambiguity as large as 0.1 km/s was left for apparent velocity.

5) In order to take amplitude into account and to find correlation between phases of records obtained at different sites by naked eyes, seismograms with the same paper speed were reproduced and arranged on the same sheet as shown in Figs. 5, 6 and 7, so that we could compare these figures with travel time graphs (Figs. 1 and 2).

§ 3. Travel time graphs

Reduced travel time graphs for the two Kurayosi explosions and the Hanabusa explosion are given in Figs. 1 and 2. In these figures two sets of probable travel time lines are given.

i) The first layer

The travel time line near shot points has the velocity of 5.5 km/s. It

---

1) THE RESEARCH GROUP FOR EXPLOSION SEISMOLOGY, *Bull. Earthq. Res. Inst.*, **44** (1966), 89-107.

2) THE RESEARCH GROUP FOR EXPLOSION SEISMOLOGY, *loc. cit.*, 1).

3) THE RESEARCH GROUP FOR EXPLOSION SEISMOLOGY, *loc. cit.*, 1).

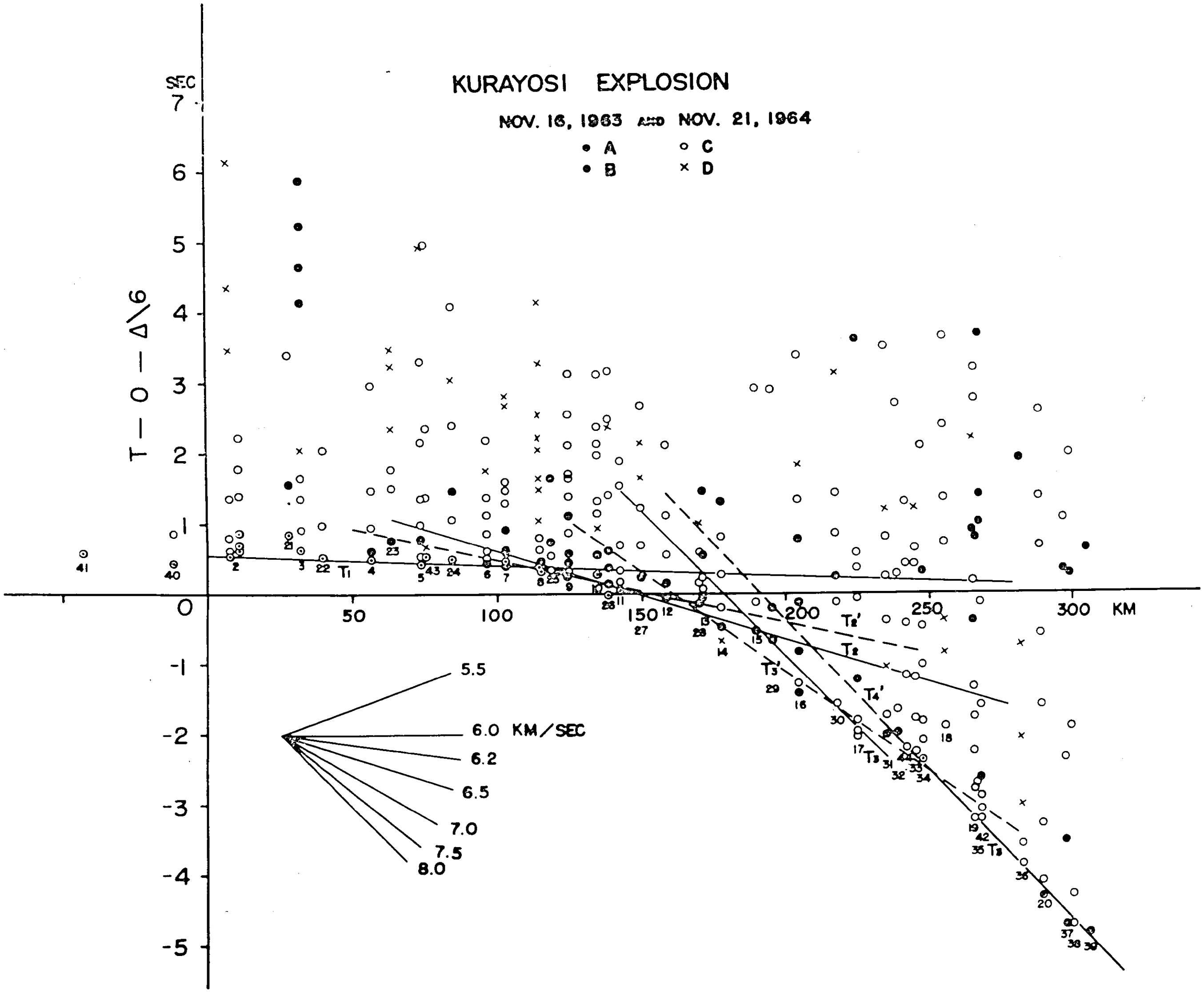

Fig. 1. Travel time graph for the Kurayosi explosions.
A: very clear first arrivals; B: good phases; C: fairly good phases; D: doubtful phases.
T_1, T_2, T_3: travel time lines for Model I.
T_1, T'_2, T'_3, T'_4: travel time lines for Model II.
Numbers refer to Station No. in Table 4 a, b of Part 1.

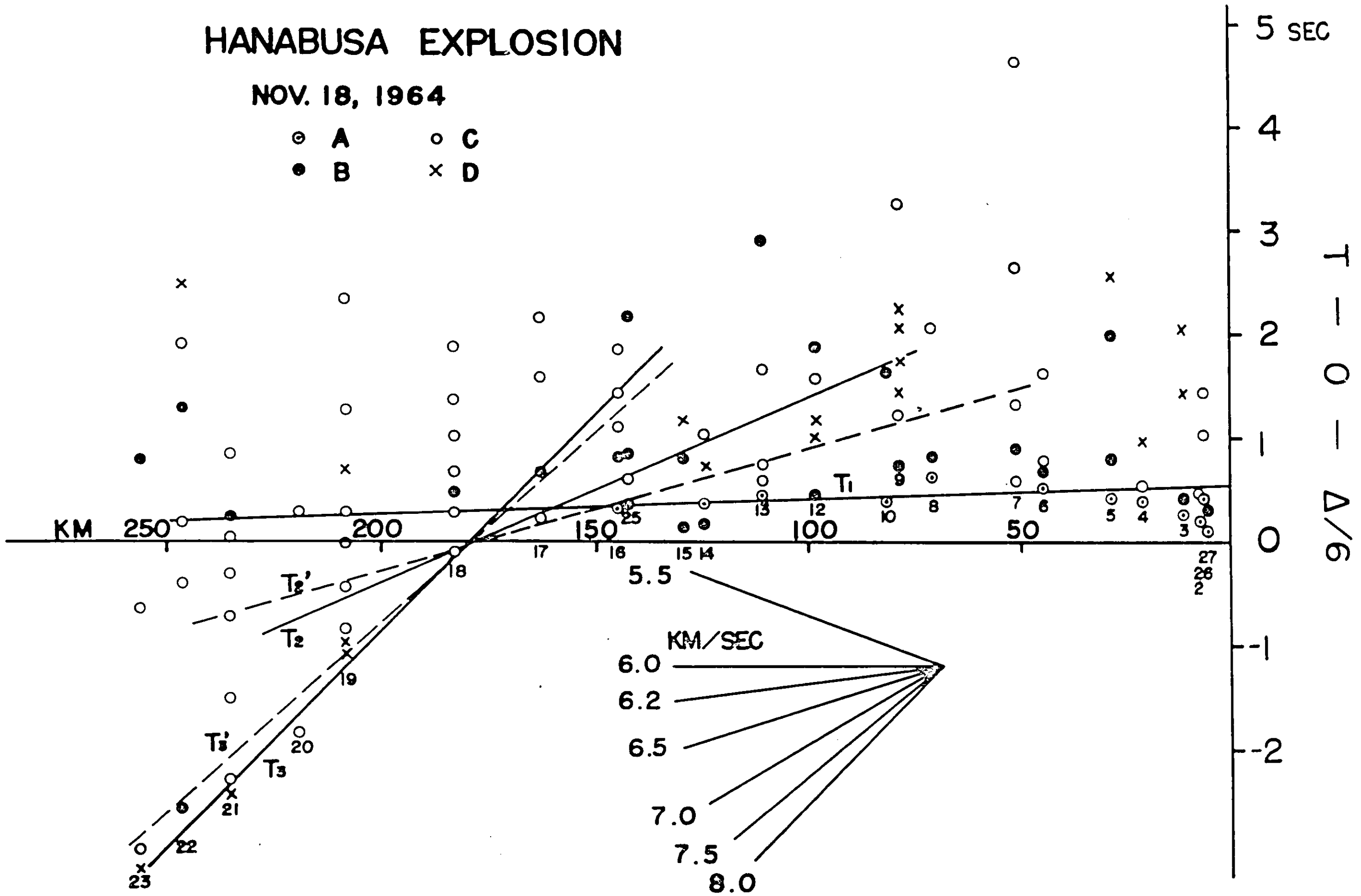

Fig. 2. Travel time graph for the Hanabusa explosion.
A: very clear first arrivals; B: good phases; C: fairly good phases; D: doubtful phases.
T_1, T_2, T_3: travel time lines for Model I.
T_1, T_2', T_3': travel time lines for Model II.
Numbers refer to Station No. in Table 5 of Part 1.

is assumed that the whole profile is covered by this layer.

ii) The second layer

The travel time line corresponding to this layer is designated as T_1 in Figs. 1 and 2. The travel time for T_1 from the three explosions is given by the formula

$$T_1 = \Delta/6.05 + 0.56 \ .$$

Most of the first arrivals show quite clear onsets and many observed points fit to this travel time line. The value of true velocity is 6.1 km/s which is the value frequently found by previous observations of seismic waves from explosions. The existence of this layer seems to be certain so far as a layered model is adopted.

iii) The third layer

Travel times are given by the following formulas:

Kurayosi explosions:

$$T_2 = \Delta/6.49 + 1.90 \quad \text{or} \quad T_2' = \Delta/6.35 + 1.40 \ ;$$

Hanabusa explosion:

$$T_2 = \Delta/6.72 + 3.18 \quad \text{or} \quad T_2' = \Delta/6.45 + 2.00 \ ;$$

where T_2 is for Model I and T_2' for Model II as mentioned later. Clear first arrivals were obtained between 110 and 170 km of epicentral distance for Kurayosi explosions. Seismograms from the Hanabusa explosion are not sufficient in quality and quantity of data to determine the velocity definitely. The true velocity of the third layer is estimated to be between 6.4 and 6.6 km/s.

For deeper layers, two models are proposed tentatively because of the freedom in the interpretation of travel time graphs for the epicentral distance larger than 170 km. This situation comes mostly from the scantiness of data for the Hanabusa explosion, although more data for the Kurayosi shots are also necessary.

Model I

iv) The fourth layer

The line on the travel time graphs in Figs. 1 and 2 for this layer is designated as T_3. The travel time for observation stations of the Kurayosi explosions farther than Sakauti (No. K31 in Table 3 of Part 1,[4] $\Delta = 234.84$ km) can be regarded as delayed systematically and the gap of

4) The Research Group For Explosion Seismology, *loc. cit.*, 1).

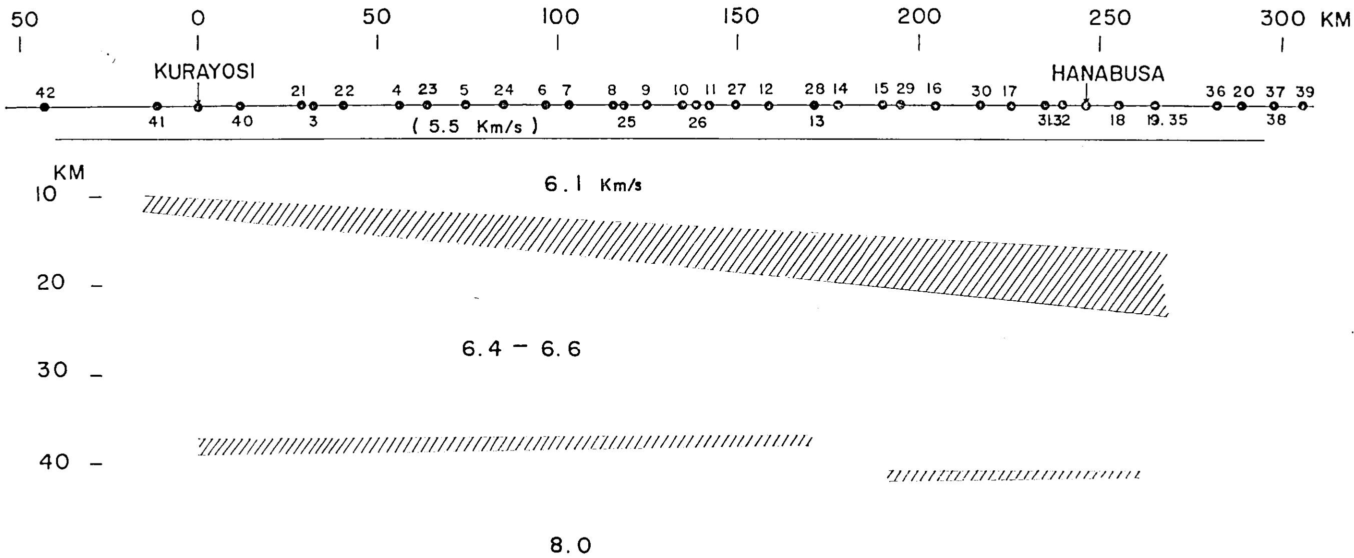

Fig. 3. Model I. Closed circles show observation points. Station numbers are those for the Kurayosi explosions, that is, No. 30 means K30 in Table 3 of Part 1. The possible range for boundaries is shown by hatched area.

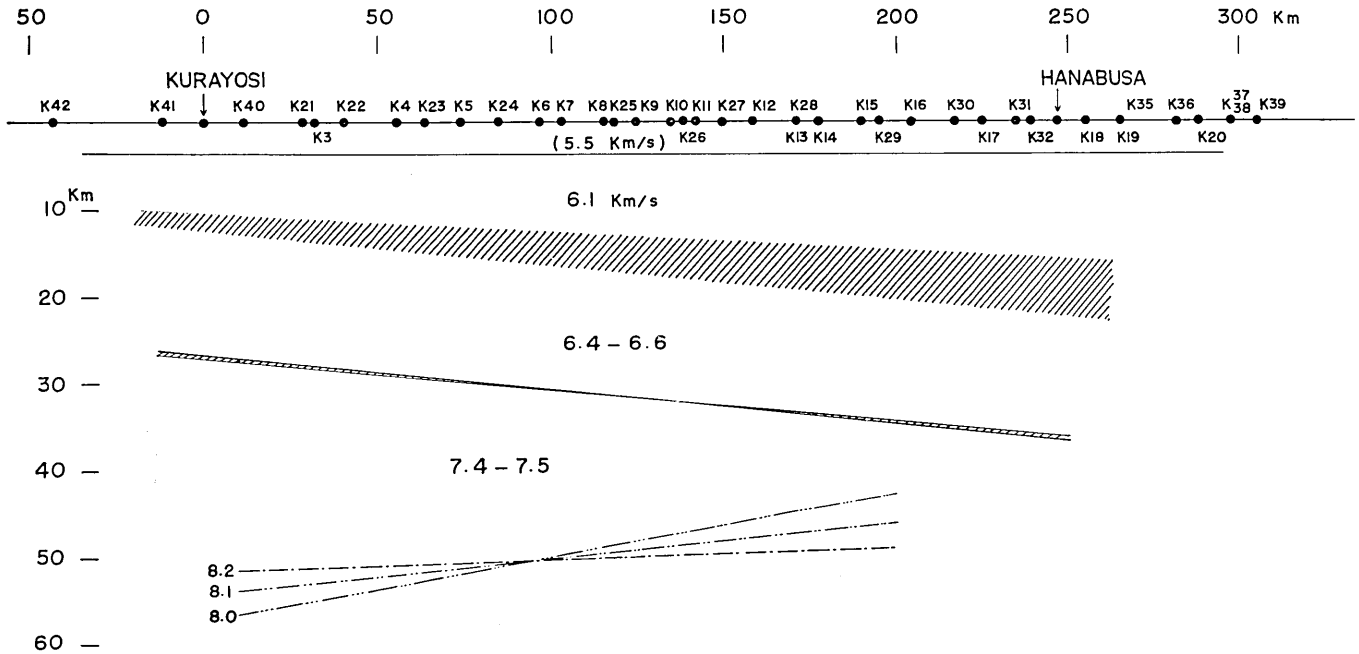

Fig. 4. Model II. Closed circles show observation sites. For example, K30 corresponds to K30 in Table 3 of Part 1. The possible range for boundaries is shown by hatched area.

two travel time lines around Sakauti amounts to 0.4 sec.

Travel time of the Kurayosi explosions up to Tutikura ($\Delta=224.82$ km) is given by

$$T_3=\Delta/7.98+7.45 .$$

The first arrivals fit well to this line except station No. K16 as shown in Fig. 1. Observed travel times at sites farther than Sakauti fit well to the line with velocity of 8.1 km/s (Fig. 1). This line is quite close to T_4' of Model II and good first arrivals belong to this line as mentioned later. For the Hanabusa explosion, the following travel time line is adopted.

$$T_3=\Delta/8.02+7.46 .$$

This line does not fit to observed data so well as the corresponding line for the Kurayosi explosions.

One of possible explanation of the gap of travel time lines around Sakauti is the existence of a gap of the Mohorovičić discontinuity of about 4 km. That is, the Mohorovičić discontinuity suddenly becomes deeper by about 4 km a little west of Biwa Lake. For the Hanabusa explosion, no systematic anomally on the travel time could be found probably because all P_n waves would be affected by this proposed gap of the Mohorovičić discontinuity.

Model II

iv) The fourth layer

On the travel time graph for the Kurayosi explosions, the line T_3' with apparent velocity of 7.26 km/s given by the formula

$$T_3'=\Delta/7.26+4.67$$

fits the observed data. This has fairly clear later phases as seen from Figs. 1, 5 and 6. However, on the travel time graph for the Hanabusa explosion, it is difficult to find the line with apparent velocity of about 7 km/s. Only T_3' given below is obtained.

$$T_3'=\Delta/7.67+6.48$$

These two lines are regarded as a pair. The fittings of observed data to the above two travel time lines are not so good as those of the other lines.

v) The fifth layer

The travel time line for this layer is designated as T_4' in Fig. 1 and given by the following formula:

$$T_4' = \Delta/8.13 + 8.40\ .$$

On the travel time graph for the Kurayosi explosions the first arrivals at observation sites more distant than about 250 km fit the above formula. Most of these first arrivals give clear onsets in comparison with those for T_3'. While in this model it is assumed that the corresponding first arrivals for the Hanabusa explosion are not observed so sufficiently as the travel time line with apparent velocity of about 8 km/s can be determined. Consequently assuming the true velocity for this layer to be 8.0–8.2 km/s, the Mohorovičić discontinuity is as given by the broken lines in Fig. 4. In order to avoid the crossing of this discontinuity with the above boundary, fairly high velocity (at least higher than 7.9 km/s) has to be assumed.

The final crustal structure Model I is given in Fig. 3 and that for Model II, in Fig. 4.

§ 4. Remarks on later phases, reflected waves, gravity and the Mohorovičić discontinuity

a) On later phases

First by examining seismograms in Figs. 5, 6 and 7, clear later phases with apparent velocity 6.1 km/s can be recognized even for the distant observation stations. It seems that in the distance longer than about 150 km these phases carry most of the wave energy.

To explain the manner in which a wave can propagate with large amplitude to the distant stations, the following three possible waves were considered:

i) direct *P* wave traveling through the second layer with velocity gradient,

ii) wave which travels through the first layer and the second layer with velocity gradient and reflects at the surface more than once (like *PP* or *PPP*),

iii) waves reflected totally at the upper boundary of the third layer.

If we assume velocity gradient within the second layer from the standpoint of i), the deepest point of seismic ray must not be in the third layer to be observed as direct wave through the second layer at observation sites farther than 300 km. From this condition, the velocity gradient within the second layer should be less than 0.005 km/s/km. This velocity gradient is reasonable from Birch's high pressure experiment on granite.[5] Since the second layer is about 15 km thick and the increase in velocity with this gradient is pretty small, the boundary with the lower layer is expected to be sharp.

From the second standpoint, it is possible to explain the phases with waves like *PP* if we assume the velocity gradient within the second layer with which the velocity of the second layer is able to reach the velocity of the third layer at the interface between these layers. From the travel times of wave with apparent velocity 6.1 km/s, the travel time of phases *PP* is estimated to be delayed by about 0.5 sec from that of *P*.

If we take the third interpretation, we have to assume that there exists a very sharp plane boundary with uniform dip. At present we do not have enough data to determine which of three possibilities would be adopted.

In addition to the phases mentioned above, it is interesting to note that in the Kurayosi explosions first arrivals could be observed at the observation sites even around 300 km better than was expected.

b) Reflected waves

Waves reflected critically from the boundary concerned are expected to arrive around the above end of each travel time line in Figs. 5, 6 and 7. As seen from these figures, there are not specially clear phases around these points.

At Misasa in the first Kurayosi explosion, an *E.T.L. M*3 type seismic prospecting instrument was used to observe reflected waves. Arrival times and travel times of reflected waves and the depth of reflecting boundaries are as follows:

P	*P–O*	*D*
5.30 sec	4.80 sec	14 km
5.90	5.40	16
7.92	7.42	23

where *D* values were computed from the structure given in Figs. 3 and 4. These results support neither Model I nor Model II.

c) Bouguer anomaly

Around Biwa Lake there are large negative Bouguer anomalies, the amounts of which are −50 to −30 mgal. These anomalies can be explained qualitatively by the gap of the Mohorovičić discontinuity in Model I.

d) On the Mohorovičić discontinuity

5) F. BIRCH, *Contributions in Geophysics*, 1 (Pergamon, 1958), pp. 158-170.

In Model I, the Mohorovičić discontinuity is the interface between the third and the fourth layers and about 38 km deep under Kurayosi shot point. The velocity of P_n wave is estimated to be about 8.0 km/s. While in Model II it is now impossible to tell which boundary the Mohorovičić discontinuity is, the boundary between the third and the fourth layers or that between the fourth and the fifth. Therefore, we can only say that the velocity of P_n is 7.4–7.5 km/s and the Mohorovičić discontinuity is about 25 km deep under Kurayosi shot point, or the velocity of P_n, 8.0–8.2 km/s and the Mohorovičić discontinuity, about 50 km deep under Kurayosi shot point. However, 7.4–7.5 km/s may be too small for the velocity in the upper mantle even in Japan and also the true velocity larger than 8.0 km/s may be too large for the upper mantle in Japan. As mentioned previously, the big difference of two models in the deeper part of crust is due to coarse observations not only for the Hanabusa explosion at a distance larger than 150 km but also for the Kurayosi explosions in the range from 170 to 260 km. These are left for future studies.

§ 5. Conclusions

The crustal structure in the western part of Japan was derived from data of the Kurayosi and Hanabusa explosions as given in Figs. 3 and 4. The existence of the layer of 6.1 km/s becomes convincing because of good first and later arrivals. Also the existence of the layer with velocity 6.4–6.6 km/s was ascertained.

The apparent velocity larger than 8.0 km/s was obtained pretty clearly. However, for the structure of the deeper part of the crust two possibilities, Model I and Model II, were tentatively proposed. Both are different from models obtained previously in the other parts of Japan. That is, in Model I there is a gap in the Mohorovičić discontinuity and in Model II above the layer of 8.0–8.2 km/s there is another layer with velocity 7.4–7.5 km/s. By observing at stations more distant than 300 km, adding more and better data on the same profiles, especially on the profile from Hanabusa and improving techniques of observation as well as analysis, the results obtained here are expected to be checked.

Acknowledgement

We wish to express our sincere thanks to the members of the Research Group for Explosion Seismology for their fruitful discussions and advice. Our thanks are also due to Misses K. Fuzii and E. Iwata for their help in preparing tables and figures.

A part of computation of the crustal structure was carried out by an OKITAC 5090 at the Computation Centre of the University of Tokyo and also by an IBM 7090 through the project UNICON, IBM, Japan, to which our sincere thanks are due.

---

6. 第1回，第2回倉吉爆破および花房爆破観測より得られた西部日本の地殼構造

第2部　西部日本の地殼構造

京都大学防災研究所　橋爪　道郎
大阪工業大学　川本　整
東京大学地震研究所　浅野　周三
岐阜大学　村松　郁栄
東京大学　浅田　敏
大阪工業大学　玉城　逸夫
国立科学博物館　村内　必典

第1部に与えられた第1回，第2回倉吉爆破および花房爆破の資料を用いて西部日本の地殼構造を求めた．良好な資料によつて 6.1 km/s の層の速度構造について考察する事が出来，6.4～6.6 km/s の層の存在が確かめられた．倉吉爆破では，6.4～6.6 km/s の位相が初動として明瞭に現れている．地表層や地殼内部の不均一性に起因する走時の変動を表層の厚さを変える事によつて説明する事はやめて，0.1 秒程度の変動は考慮しなかつた．すべての記録の送り速度を揃えて震央距離順に並べ，位相の追跡の際に，肉眼による相関を行なつた．可能な場合には，境界面の深さおよび速度の範囲を求める様にし，6.5 km/s の層までは成功したが，深部の構造については，走時曲線の解釈によつて Model I, Model II の 2 つになつた．従来の Moho と異り，Model I では，琵琶湖のやや西で Moho 面に約 4 km の食違いがあり，Model II では 8.0～8.2 km/s の層の上に 7.4～7.5 km/s の層があり，いづれが Moho か現在では断定出来ない．Moho 面の深さも Model I では倉吉の下で約 38 km, Model II では 7.4～7.5 km/s の層の上の境界が Moho 面とすれば倉吉の下で約 25 km, 8.0～8.2 km/s の上の境界が Moho 面ならば，50 km となる．また，8.1 km/s のみかけ速度が割合明瞭に得られた事は注意すべき事である．

[Bull. Earthq. Res. Inst., Vol. 44, Pl. 4]

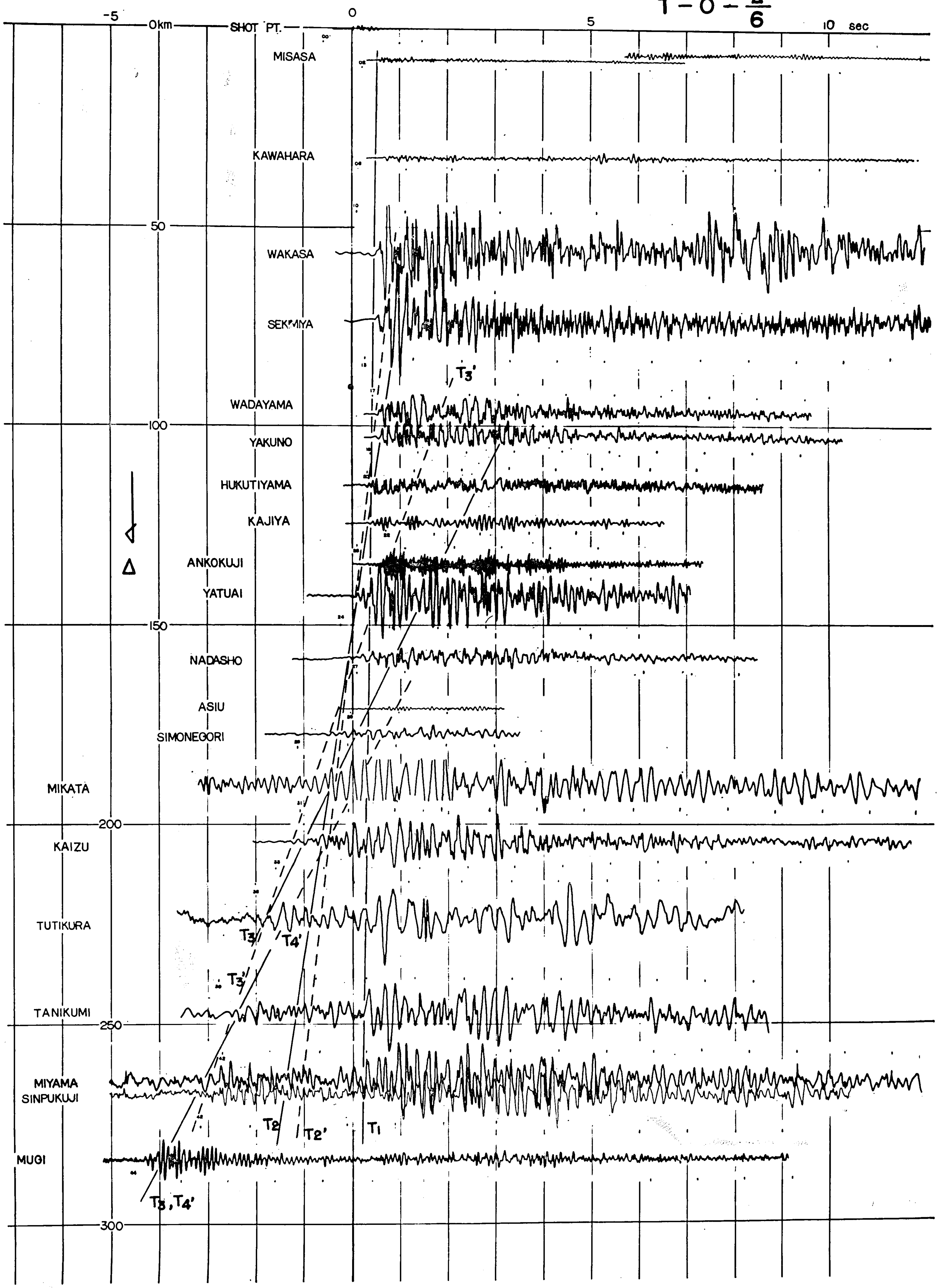

Fig. 5. Seismograms for the first Kurayosi explosion. T_1, T_2, T_2', etc. are given in the text. Small number near each seismogram is time in sec for respective seismogram. Seismogram at Mugi should be shifted to right by about 0.3 sec.

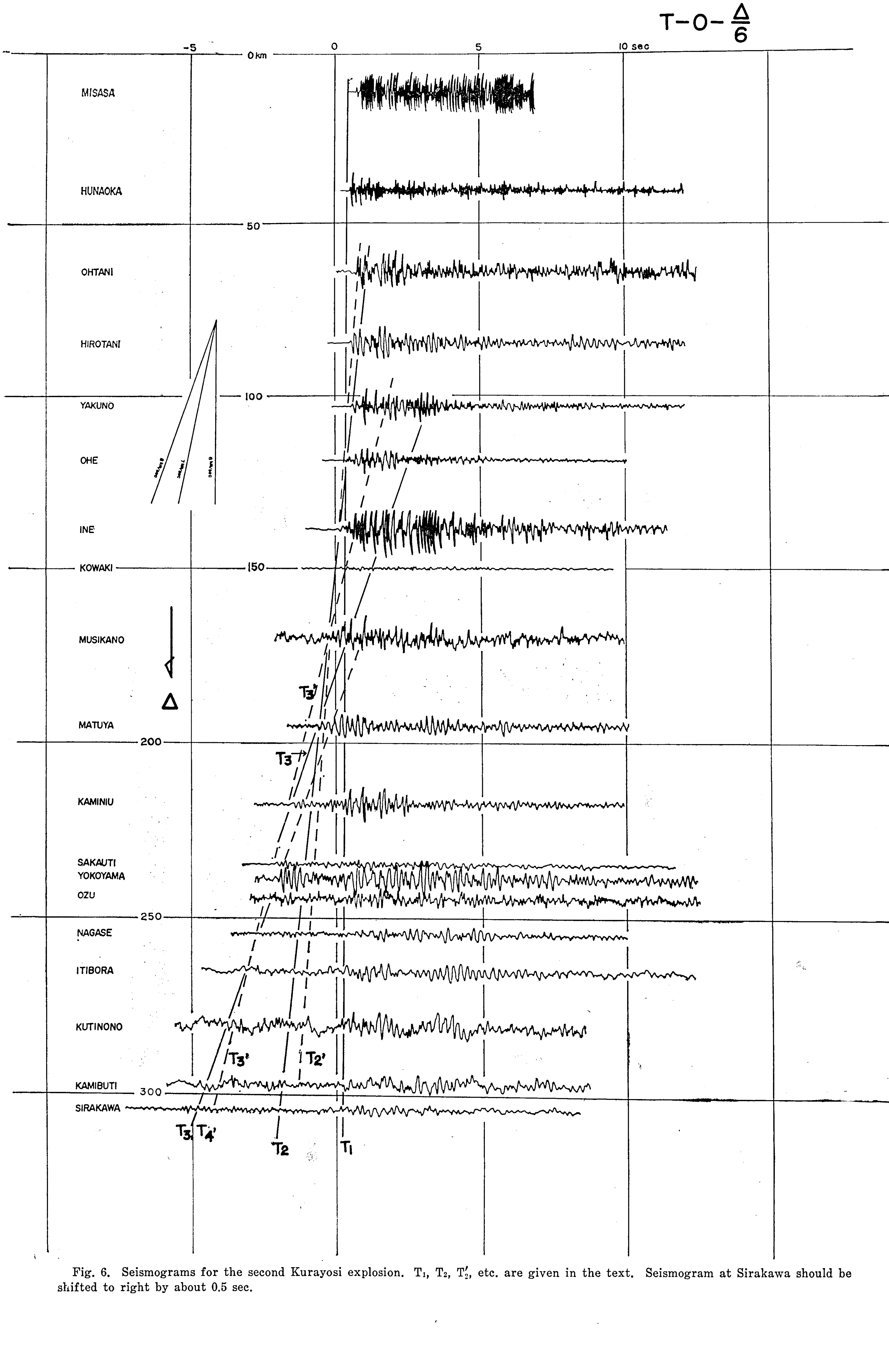

Fig. 6. Seismograms for the second Kurayosi explosion. T_1, T_2, T_2', etc. are given in the text. Seismogram at Sirakawa should be shifted to right by about 0.5 sec.

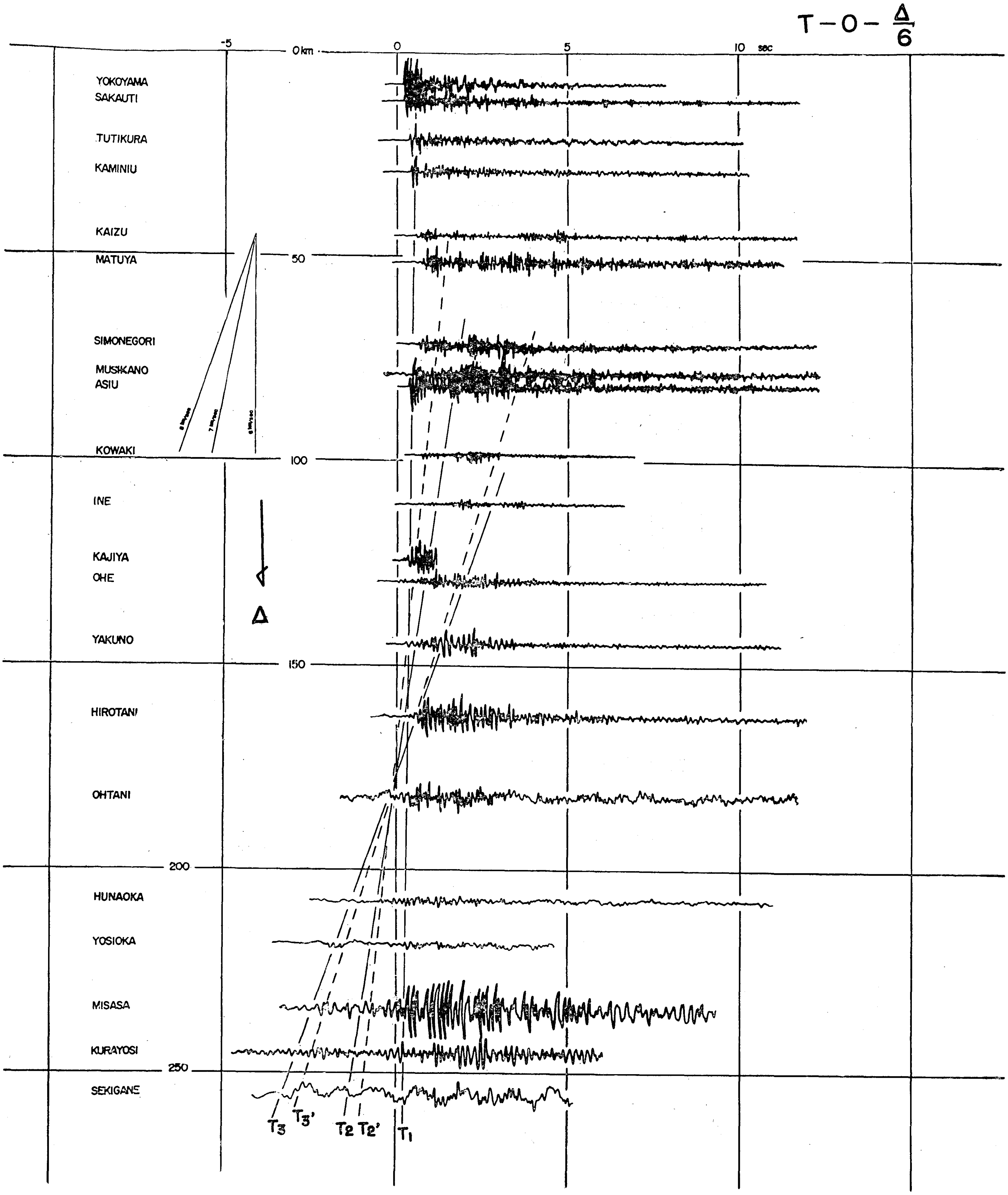

Fig. 7. Seismograms for the Hanabusa explosion. T_1, T_2, T_2', etc. are given in the text.

(震研彙報 第四十四号 図版 橋爪 他)