BULLETIN OF THE EARTHQUAKE
RESEARCH INSTITUTE
UNIVERSITY OF TOKYO
Vol. 66 (1991) pp. 37-70

Report on DELP 1988 Cruises in the Okinawa Trough Part 3. Crustal structure of the southern Okinawa Trough

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(Received May 15, 1990)

Abstract

A refraction seismic experiment was conducted in the southern Okinawa Trough to study the crustal structure of a back-arc basin. We deployed 18 ocean bottom seismometers (OBSs) every 11 km along a 195-km profile. We shot three large explosives (600 kg, 500 kg, and 450 kg) and 50 small explosives (50 kg and 25 kg). The explosions were complemented by shots from an array of a 9-liter airgun and a 16-liter airgun. The average shot interval of the explosives was 3.8 km, and that of the airguns was 150 m.

The analysis of the refraction data, using the τ-p method and two-dimensional ray tracing forward modeling of the seismic wave field, showed no evidence of a young oceanic crust even beneath the central axis of the southern Okinawa Trough. A 2-3-km thick sediment was underlain by a layer with a P-wave velocity around 6 km/s. The Moho depth was more than 18 km below the sea surface according to the phase which was propagated in the lower crustal structure, although no clear first arrival of the refraction phase of the uppermost mantle was observed. The distribution of the P-wave velocity and the thickness of the crust indicated that the crust of the southern Okinawa Trough is more similar to that of a continent than to that of an ocean. Our data support the idea that the southern Okinawa Trough is in the stage of incipient rifting of the back-arc basin accompanied by a slight thinning of the continental crust.

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Introduction

The Okinawa Trough is the back-arc basin of the Ryukyu Trench-

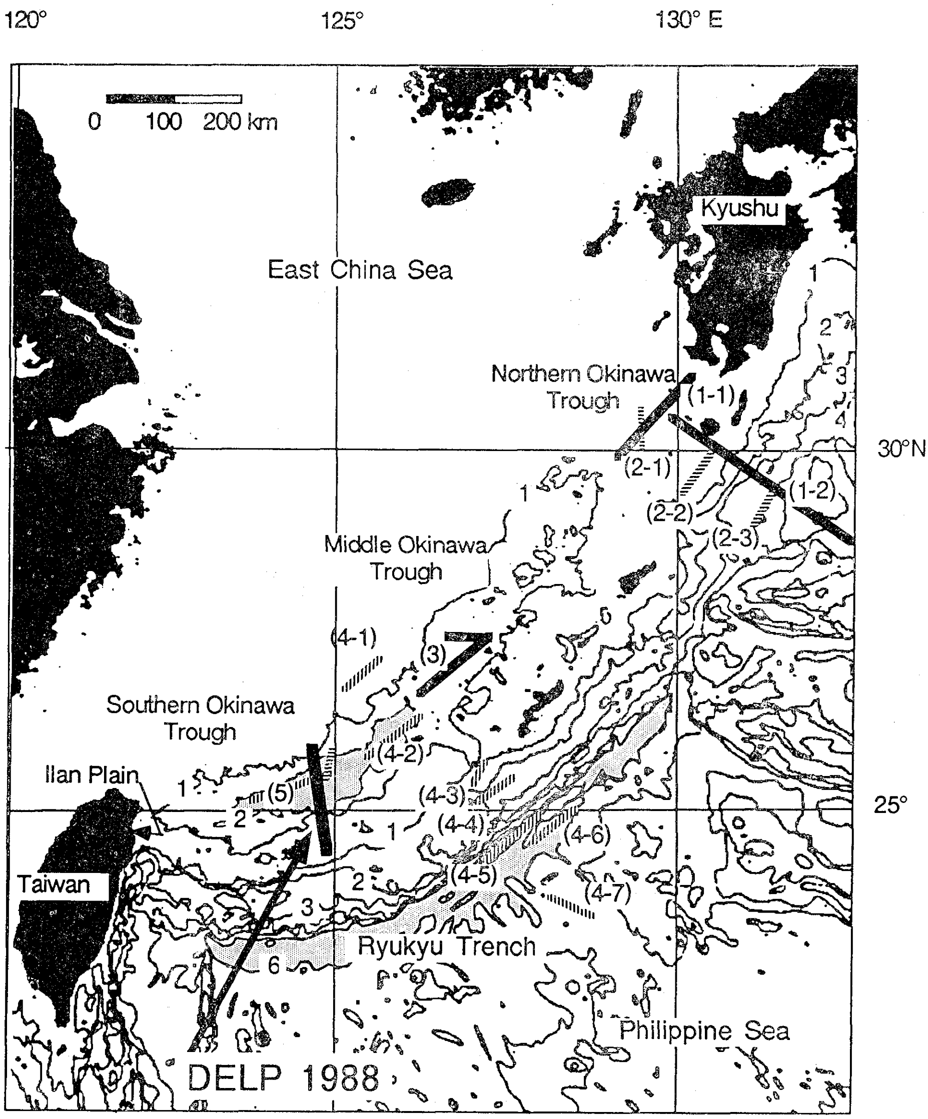

Fig. 1. Map showing the location of the southern Okinawa Trough. Isobaths are in km. Previous seismic refraction profiles are shown by lines with numerals: Profile 1 (1-1) and Profile 2 (1-2) of Iwasaki *et al.* (1990); Profile 14 (2-1), Profile 13 (2-2), Profile 12 (2-3) of Ludwig *et al.* (1973); Nagumo *et al.* (1986) (3); Profiles 13 and 14 (4-1), Profile 15 (4-2), Profile 16 (4-3), Profile 17 (4-4), Profile 19 (4-5), Profile 18 (4-6), and Profile 20 (4-7) of Murauchi *et al.* (1968); Lee *et al.* (1980) (5).

arc-back-arc system. The trough extends over 1000 km, from Ilan plain in north Taiwan to the shallow sea southwest of Kyushu. In terms of morphology and sea bottom geology, the trough consists of three units including the southern Okinawa Trough, the middle Okinawa Trough, and the northern Okinawa Trough (Fig. 1). The water depth reaches a maximum of 2300 m in the southern Okinawa Trough and decreases northward to about 200 m in the northern Okinawa Trough.

The first extensive seismic refraction investigation, conducted by MURAUCHI *et al.* (1968) with the two-ship method, shows a thick crust in the northernmost part of the southern Okinawa Trough, indicating that the crustal velocity is generally similar to that of a continental crust. LEE *et al.* (1980), also using the two-ship refraction method, showed a 15-km thick crust in the western part of the southern Okinawa Trough. They interpreted the structure as a thinned continental crust.

The DELP cruise in 1984 conducted a refraction experiment with ocean bottom seismometers (OBS) in the middle Okinawa Trough. The result shows a continental crustal structure: The upper part of the crust is about 10 km thick and 6.0 km/s in a P-wave velocity. No P_n phase refracted from Moho was detected, indicating very low Q in the uppermost mantle (NAGUMO *et al.*, 1986).

The northern Okinawa Trough was extensively studied by arrays of OBSs, and it was found that the trough has a thick crust with continental properties. The Moho depth increases northeastward from 24 km to 30 km, and the P_n velocity is estimated to be 7.5 km/s or less (IWASAKI *et al.*, 1990). The two-ship refraction experiments also indicate a very thick crust (LUDWIG *et al.*, 1973).

Although many geological and geophysical studies suggest regional differences among the troughs, seismic refraction surveys are not yet adequate to clarify their structural detail. In 1988, the southern Okinawa Trough was covered by an array of OBSs as a part of the 1988 DELP cruise in order to determine whether the trough has a thinned continental crust or a very young oceanic crust due to the back-arc spreading. We present here the main results of the 1988 experiment and some preliminary analysis of data.

Experiment

We deployed 18 ocean bottom seismometers (OBS), spaced every 11 km along a 195-km profile, as receivers to observe refracted seismic waves. We shot explosives and an array of airguns as controlled seismic sources along the profile, as shown in Fig. 2. The ship from which the OBSs were deployed was positioned by LORAN-C (Long Range Naviga-

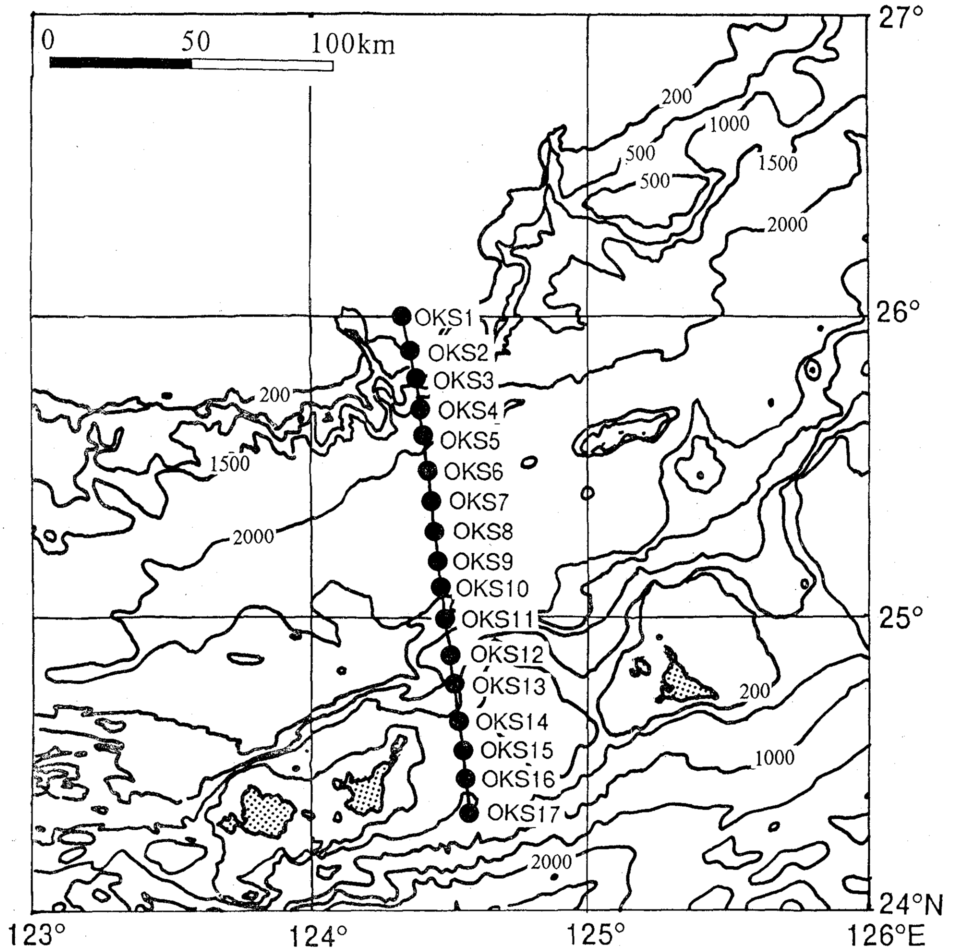

Fig. 2. Positions of the profile along which OBSs were deployed and seismic sources were shot. Locations of OBSs are shown by solid circles with letters and numerals. Isobaths are in meters.

tion C) with the aid of NNSS (the U.S. Navy Navigation Satellite System) and GPS (Global Positioning System). Since the receiving status of LORAN-C in the area of the present study is not very good, we paid special attention to determing relative positions between OBSs and seismic sources. We corrected offset distances between OBSs and shots according to travel times of water waves.

Four types of OBSs were used, which were developed at four institutions of three universities. Details of individual OBSs are given in YAMADA *et al.* (1981), NAGUMO *et al.* (1982), MATSUDA *et al.* (1986), and BABA *et al.* (1988). In general, however, characteristics of the instruments are almost the same: each OBS is equipped with a vertical and one or two horizontal geophones with a natural frequency ranging from 2 to 4.5 Hz. Some OBSs have a hydrophone, which is useful in detecting signals propagating through water. Seismic signals were recorded by the direct analog recording (DAR) method except for one OBS which had a digital recorder (KASAHARA *et al.*, 1985). The signals recorded by the DAR method cover frequencies ranging from a few hertz to 30 Hz. Details of the position and components of observed signals are given in Table 1. All but one OBS were recovered after the experiment. Retrieval of the OBSs was completed by transmitting acoustic signals from the ship that commanded an OBS to release an anchor. Two OBSs had a preprogrammed timer to release the anchor.

We shot three large explosives with a chemical charge size of 600 kg and 50 small explosives with a charge of 50 or 25 kg. The average spacing of the explosions is 3.8 km. The explosives are detonated by an electrical firing system, so that an accuracy of timing of the shot is within the limit of 0.01 s. An array of airguns, including a 9-liter and a 16-liter BOLT type airgun, was shot at intervals between 50 s and 70 s. The ship ran at a speed of about 5 kt (9 km/h) to give shot intervals between 125 and 175 m.

Data

All analog data were converted into a digital form with a sampling rate of approximately 100 samples per second. The digitized data were

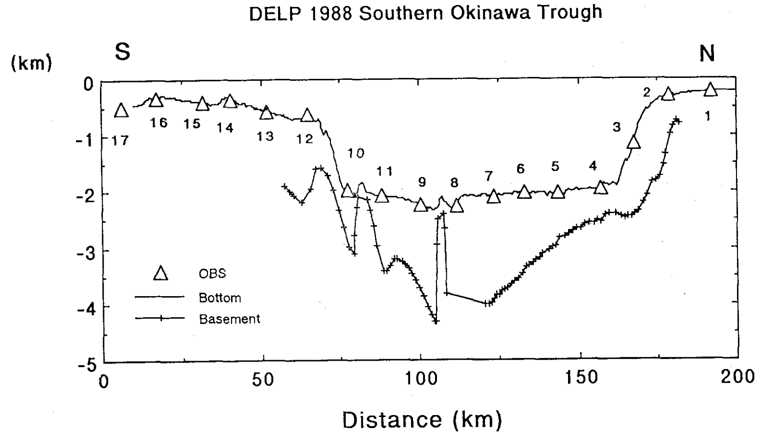

Fig. 3. Cross-section of the profile showing variation in water depth. An acoustic basement interpreted from a multichannel reflection record (FURUKAWA *et al.*, 1991) is shown by a line with crosses.

Table 1. Summary of OBS records in the 1988 DELP Cruise in the southern Okinawa Trough.

OBS	Institution[1]	Recording Period (JST) Deployment	Recording Period (JST) Retrieval	Location Latitude N	Location Longitude E	Depth (m)	Component[2] /Quality of data[3]	Remarks
OKS1	ERI	Jul. 8 08:49	Jul. 13 10:40	26°00.00'	124°18.80'	142	V/NA, H/N, Hy/N	
OKS2	GIT	Jul. 8 07:42	not recovered	25°53.00'	124°21.00'	199	/NA	
OKS3	CHU	Jul. 8 06:56	Jul. 25 10:37	25°48.00'	124°23.20'	553	V/G, H/G, Hy/G	Hy starts at Jul. 11 8:37
OKS4	ERI	Jul. 8 05:48	Jul. 13 19:00	25°41.23'	124°22.77'	1893	V/G, H/G, Hy/G	
OKS5	GIT	Jul. 8 05:06	Jul. 13 20:45	25°35.80'	124°23.68'	2055	V/G, H/G	
OKS6	CHU	Jul. 8 04:27	Jul. 13 22:20	25°29.16'	124°25.34'	2038	V/G, H/G, Hy/G	
OKS7	TKS	Jul. 8 03:42	Jul. 17 05:09	25°23.33'	124°25.35'	2177	V/G, Hy/G	
OKS8	ERI	Jul. 8 02:56	Jul. 14 00:51	25°16.97'	124°26.12'	2275	/NA	trouble in a recorder
OKS8D	ERI	Jul. 8 02:29	Jul. 14 02:14	25°17.00'	124°26.09'	2385	/NA	trouble in a recorder
OKS9	TKS	Jul. 8 01:49	Jul. 17 02:26	25°10.96'	124°27.17'	2153	V/G	
OKS10	GIT	Jul. 8 01:13	Jul. 14 04:43	25°05.73'	124°27.87'	2042	V/G, H/G	
OKS11	CHU	Jul. 7 23:44	Jul. 14 06:32	24°59.01'	124°28.50'	1994	V/G, H/G, Hy/G	
OKS12	ERI	Jul. 7 22:43	Jul. 14 07:51	24°52.00'	124°29.90'	648	V/N, H/N, Hy/N	
OKS13	GIT	Jul. 7 22:02	Jul. 14 09:19	24°46.00'	124°30.60'	821	V/G, H/G	
OKS14	CHU	Jul. 7 21:16	Jul. 14 10:27	24°38.92'	124°32.09'	485	V/N, H/N, Hy/N	
OKS15	ERI	Jul. 7 20:29	Jul. 14 12:19	24°33.09'	124°32.50'	292	V/N, H/N, Hy/N	
OKS16	GIT	Jul. 7 19:37	Jul. 14 13:35	24°27.40'	124°33.10'	438	V/G, H/G	
OKS17	CHU	Jul. 7 18:48	Jul. 14 14:32	24°20.44'	124°34.21'	509	V/N, H/N, Hy/NA	trouble in a recorder for Hy

1) ERI:Earthquake Research Institute, the University of Tokyo, GIT:Geophysical Institute, the University of Tokyo, CHU:Chiba University, TKS:Tokai University

2) V:vertical component of geophone, H:horizontal component of geophone, Hy:hydrophone

3) G:good, N:noisy, NA:not available

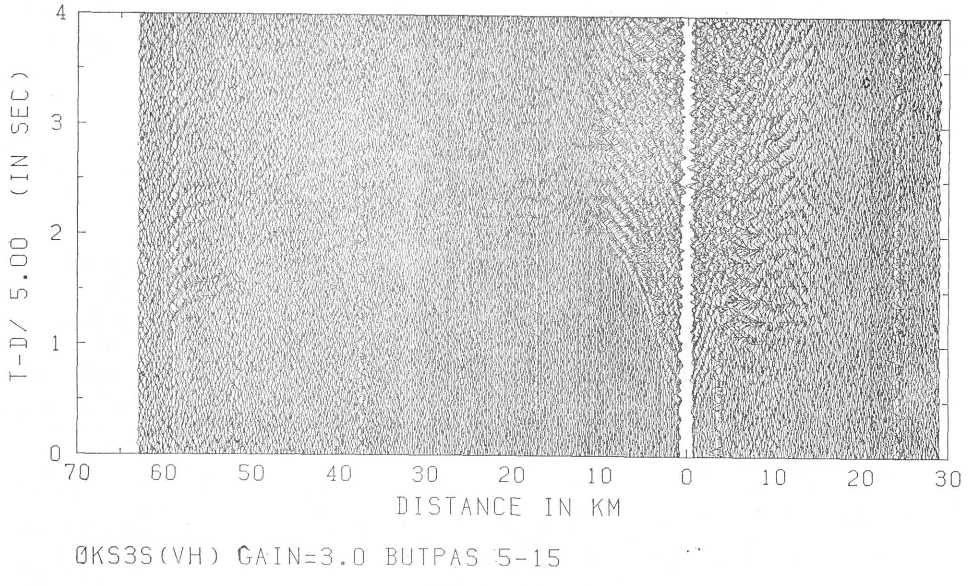

Fig. 4. (a)

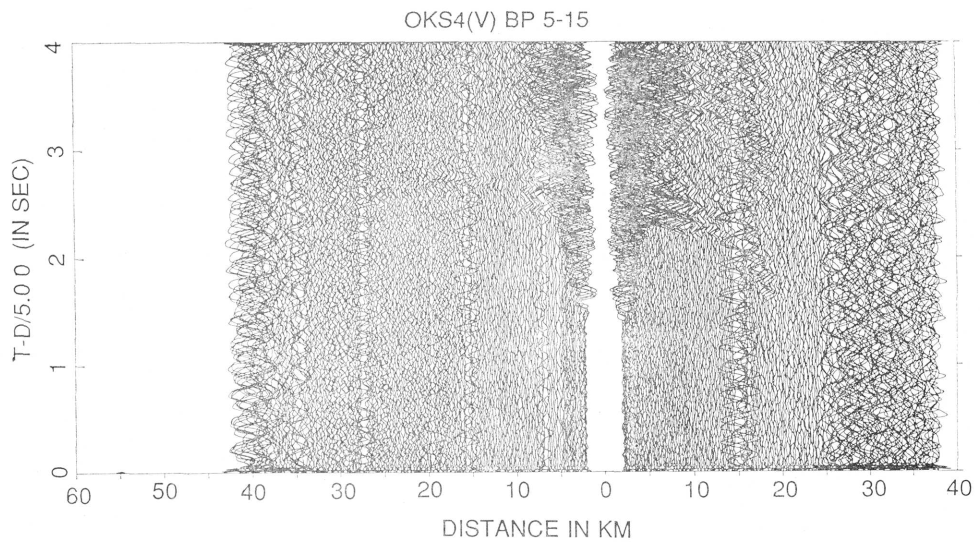

Fig. 4. (b)

edited and processed for analysis, and were shared among different institutions. First and later arrivals of P-waves were picked up manually from seismograms.

Water depth changed along the profile, ranging from 140 m to 2400 m as shown in Fig. 3. OBSs at deep water were generally good for obtaining seismograms with a large signal-to-noise ratio. Some OBSs suffered severe noise, probably due to a water bottom current, especially for

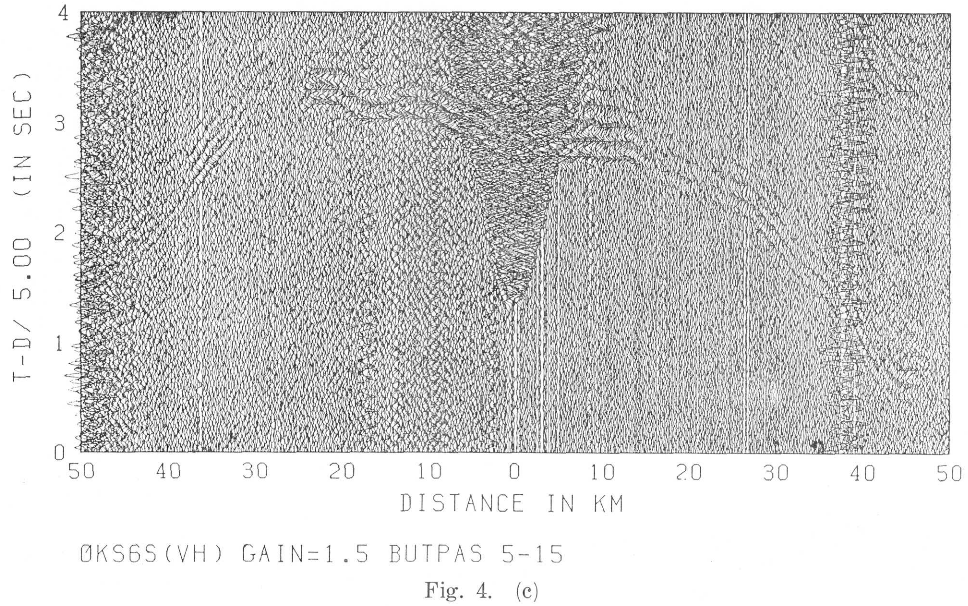

Fig. 4. (c)

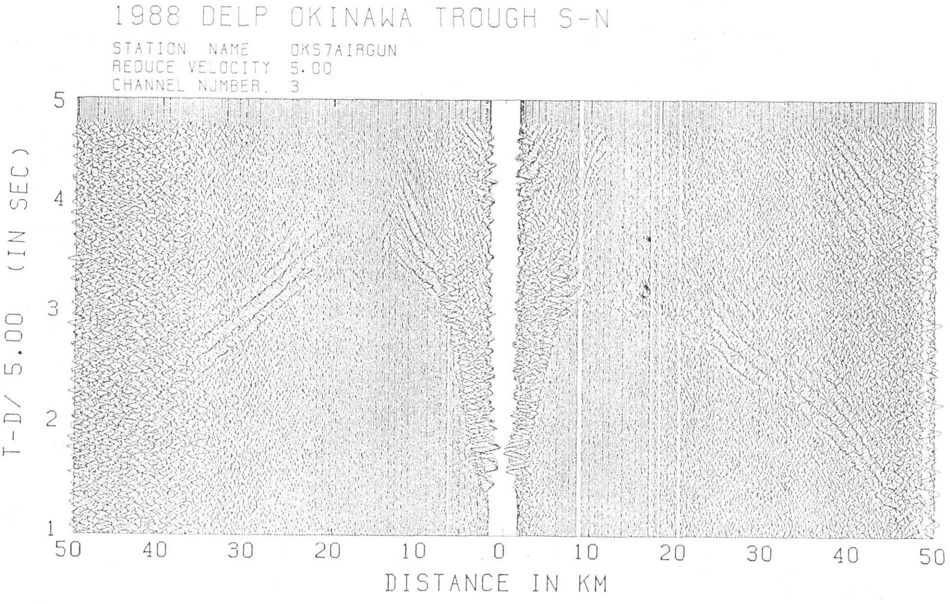

Fig. 4. (d)

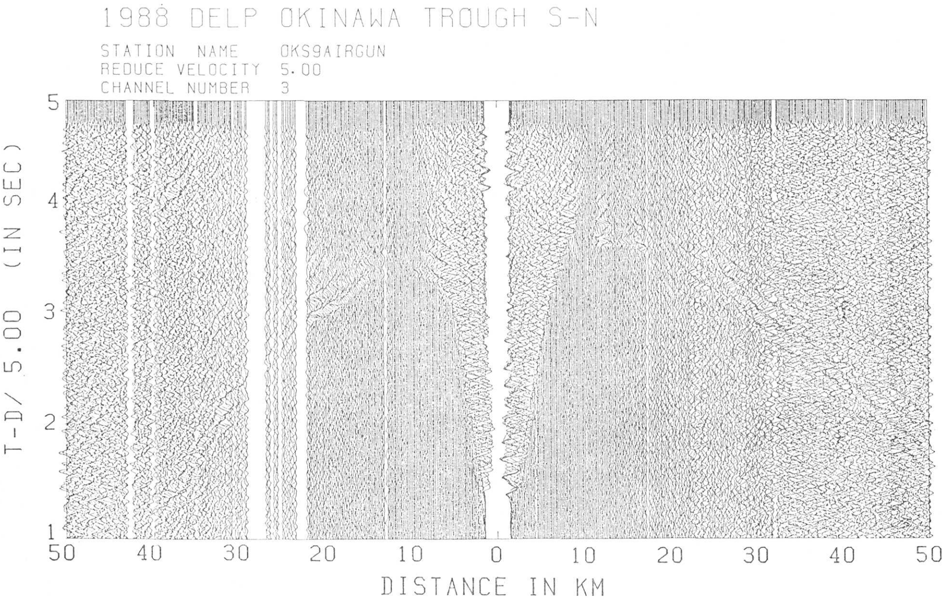

Fig. 4. (e)

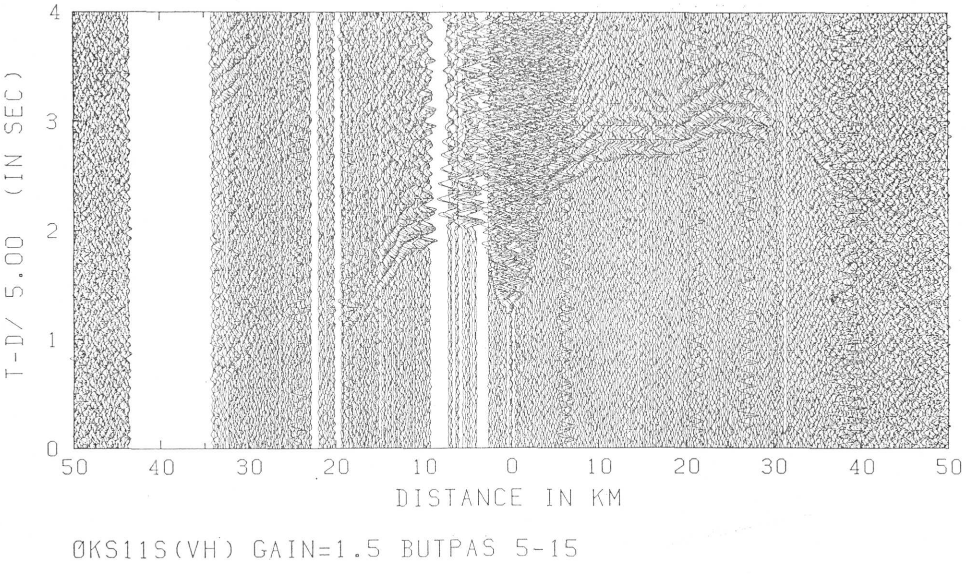

Fig. 4. (f)

Fig. 4. Examples of seismograms generated by the airgun shooting. (a) Vertical component of the geophone of OKS3, (b) OKS4, (c) OKS6, (d) OKS7, (e) OKS9, (f) OKS11. Travel times are reduced by D/(5.0 km/s) where D is the offset distance in km between an OBS and a shot.

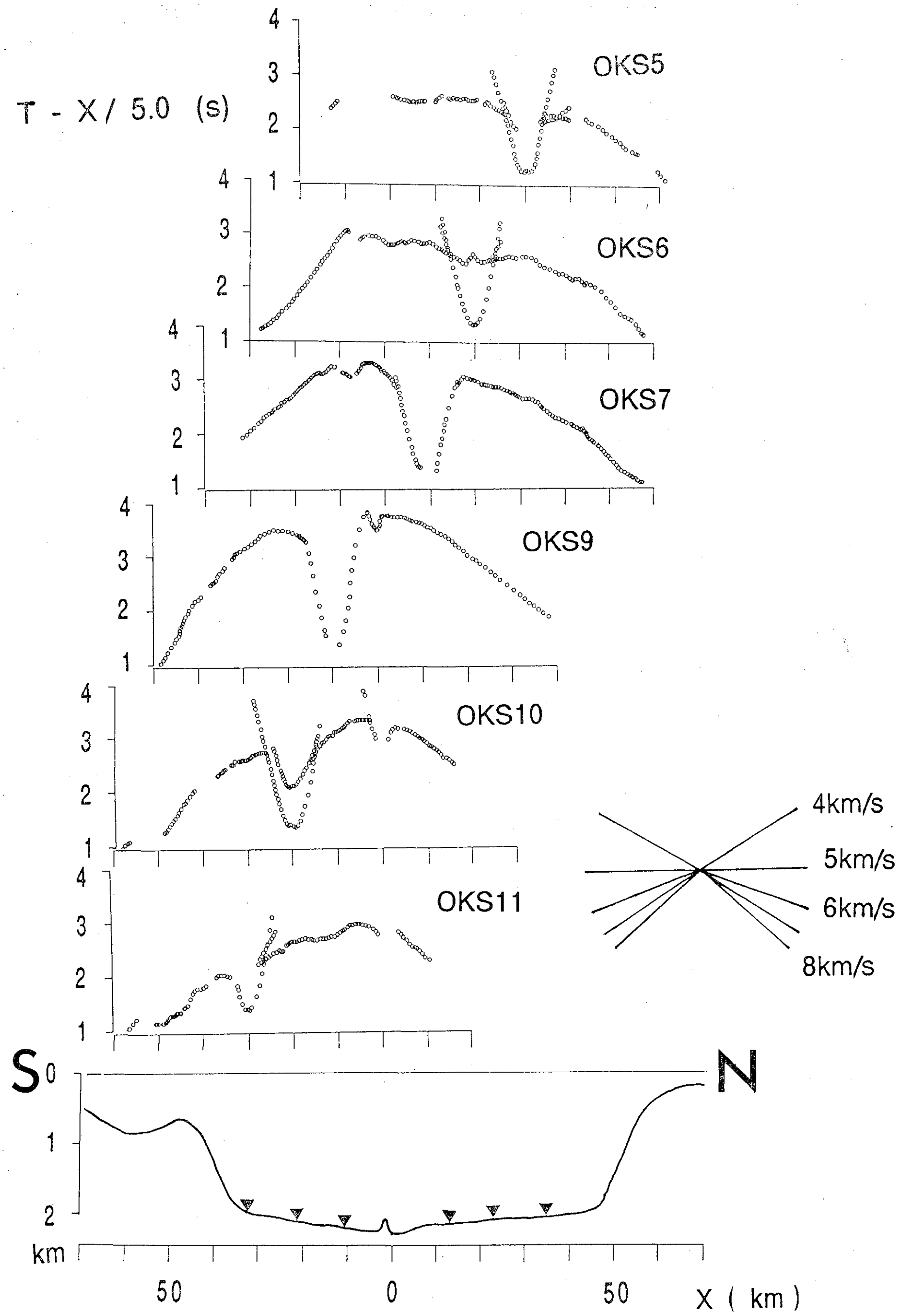

Fig. 5. Observed travel times picked up from seismograms shot by an airgun array. The reduction velocity of the travel time is 5.0 km/s.

those placed in water less than 1000 m deep. The quality of data is summarized in Table 1.

The airgun array generated refracted P-wave signals up to an offset distance of 45 km, which was used to study the crustal structure particularly in an upper crust. The shallowmost part of the sediment of the crust was analyzed by multi-channel reflection data, the results of which appear in another part of the present cruise report (FURUKAWA *et al.*, part 2 of this report). Some examples of seismograms shot by the airgun array and recorded by the OBSs are shown in Fig. 4. Travel times are picked up from seismograms by airgun shooting, as shown in Fig. 5. The data indicate severe lateral heterogeneity in the crustal structure. The refracted waves with an offset distance of less than 10 km have an apparent velocity of approximately 2.0 km/s. The apparent velocity in the offset range between 10 and 30 km gradually increases from 4.5 to 5.5 km/s. In the range of greater than 30 km is a phase with an apparent velocity of about 8.0 km/s for some OBSs. The phases are, however, strongly correlated to the topographical position of the profile: All the OBSs in the trough show a change in apparent velocity from about 5.5 km/s to 7.8 km/s at the very center of the trough, indicating that the velocity of 7.8 km/s is due to syncline of the crust rather than being a true velocity of 7.8 km/s.

P-wave signals generated by explosives were propagated in the crust along the entire distance of the 195-km profile (Fig. 6). Travel times picked up from the seismograms from explosives are shown in Fig. 7. The phase of an apparent velocity of approximately 7.8 km/s or less appears as the first arrival beyond an offset distance of 35 km for OBSs in the central part of the trough. Because the phase corresponds to that observed on the airgun data which we interpret as the crustal phase, we also think that the phase is generated by a crustal wave or wide-angle reflection from Moho: no clear phase from the mantle (P_n) is observed.

Analysis and Results

One-Dimensional Model for the Upper Crust

We transformed the original record in the offset distance(x) - travel time(t) domain into the intercept time(τ) - ray parameter(p) domain and picked up the τ-p trajectory of postcritical arrivals. The τ-p data were then inverted into a velocity-depth profile by the τ-sum inversion method (DIEBOLD and STOFFA, 1981). An example of the procedure is illustrated in Fig. 8, and a velocity-depth profile is shown in Fig. 9. The velocity profile was correlated with multi-channel reflection data and was seen

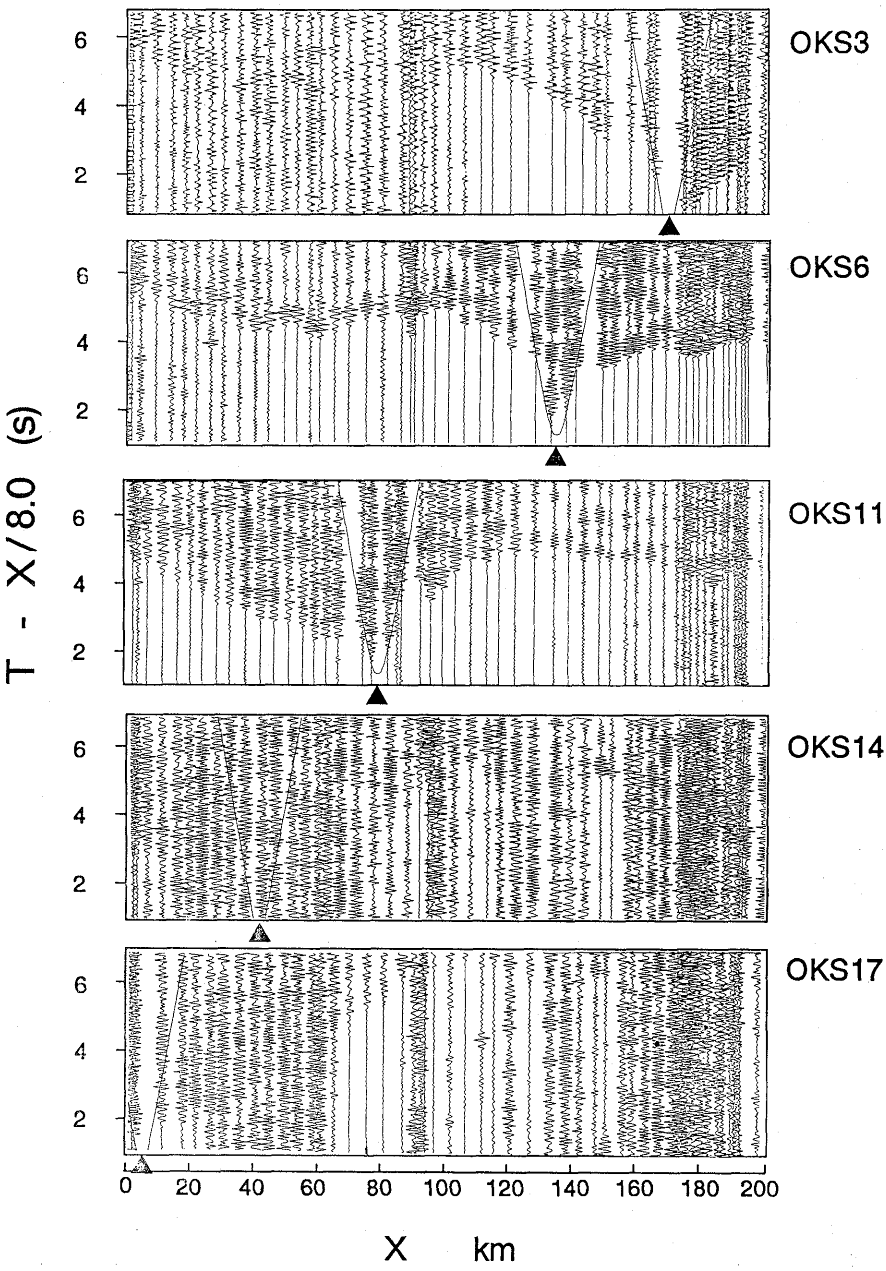
OKS3
OKS6
OKS11
OKS14
OKS17
T - X/8.0 (s)
6
4
2
0
20
40
60
80
100
120
140
160
180
200
X km

Fig. 6. (a)

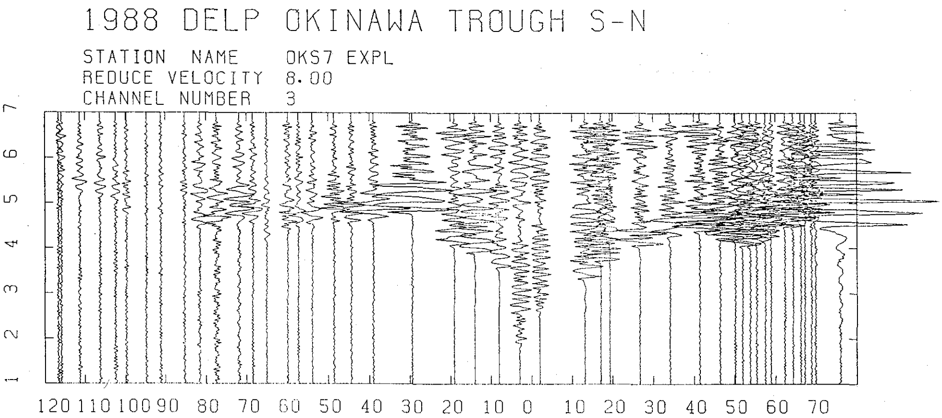

Fig. 6. (b)

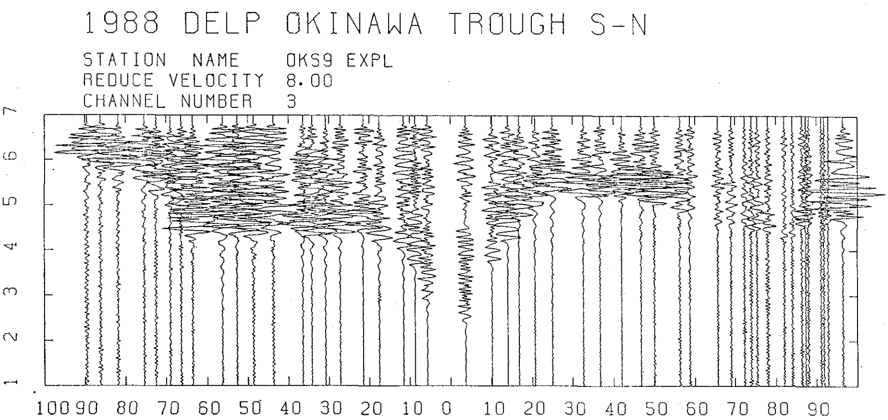

Fig. 6. (c)

Fig. 6. Examples of seismograms due to explosives. The reduction velocity is 8.0 km/s. A vertical component of geophone is displayed. (a) OKS3, OKS6, OKS11, OKS14, and OKS17. (b) OKS7. (c) OKS9.

to be consistent. The model indicates a thick sediment including an upper homogeneous layer with a P-wave velocity of 1.8 km/s and a lower layer where the velocity increases sharply with depth from 2.2 km/s to about 4 km/s.

Two-Dimensional Model for Deep Crustal Structure

Since the inversion method does not account for lateral heterogeneity, we should modify the velocity model. In addition, the lower crust and

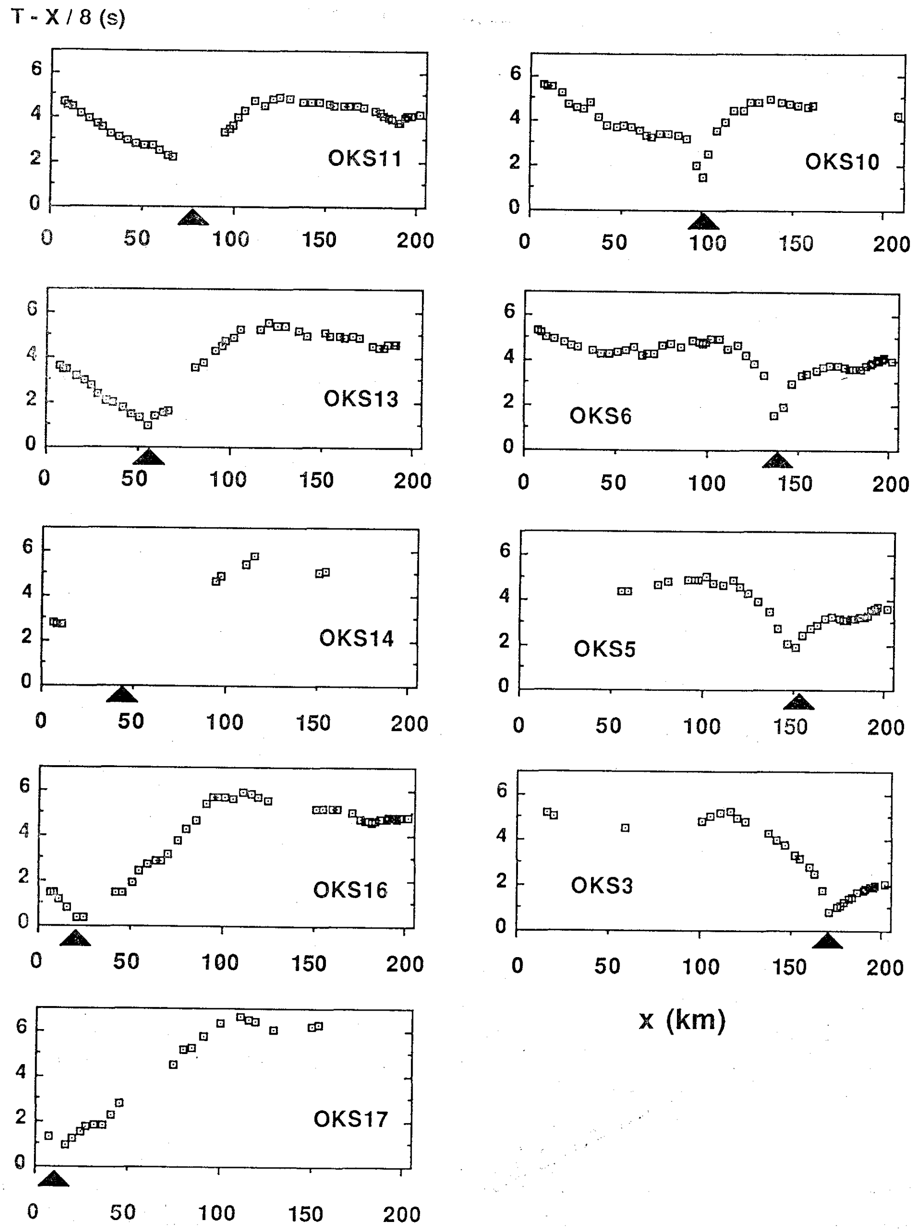

Fig. 7. Observed travel times picked up from seismograms shot by explosives. Data from OKS3, 5, 6, 10, 11, 13, 14, 16, and 17 are shown.

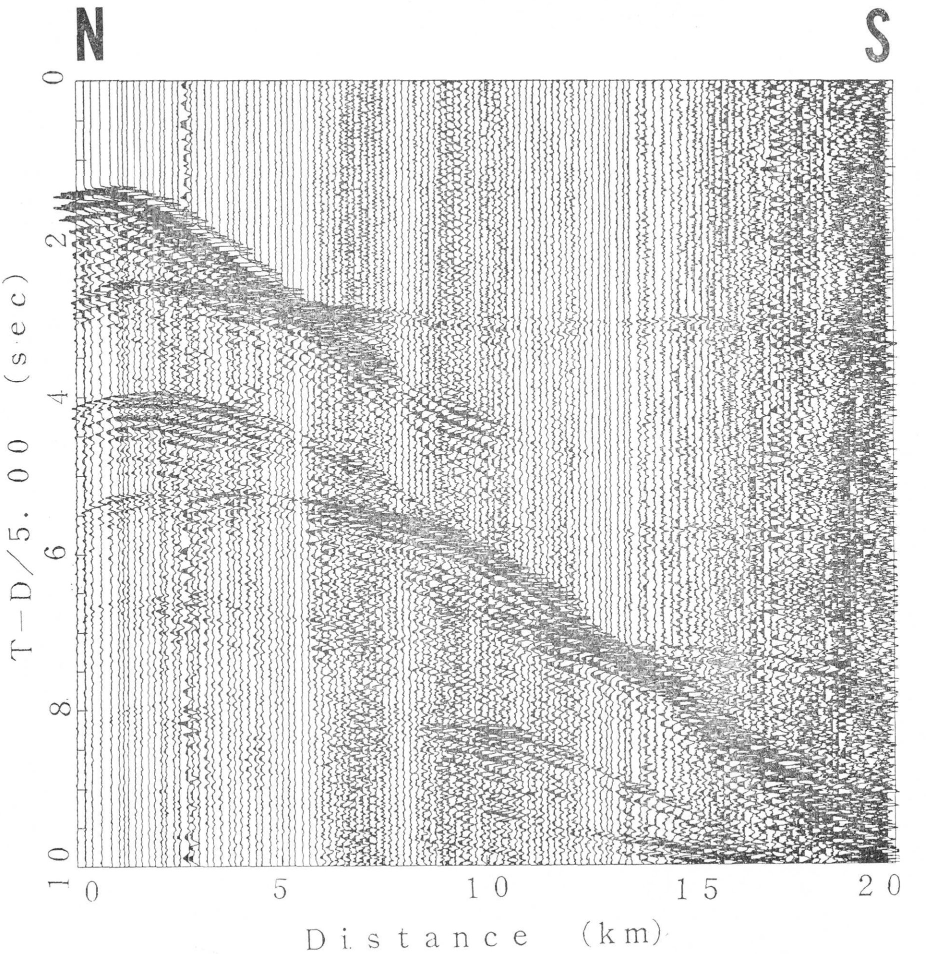

Fig. 8. (a)

the upper mantle are poorly constrained by the airgun data because the energy produced by the guns was not sufficient to penetrate down into Moho. The seismic waves generated by the explosives were used to construct the lower crustal layer structure. We performed a forward modeling of a P-wave field in a two-dimensionally varying velocity structure. One of the preliminary models is shown in Fig. 10. The asymptotic ray method of ČERVENÝ *et al.* (1977) was used to calculate a complex heterogeneous medium. We used a computer code developed by Hirata and Shinjo (1986), which was modified from SEIS83 (ČERVENÝ and PŠENČÍK, 1983) for ocean bottom seismograms. Calculated travel times from the model are compared with observed travel times: Fig. 11 shows observed

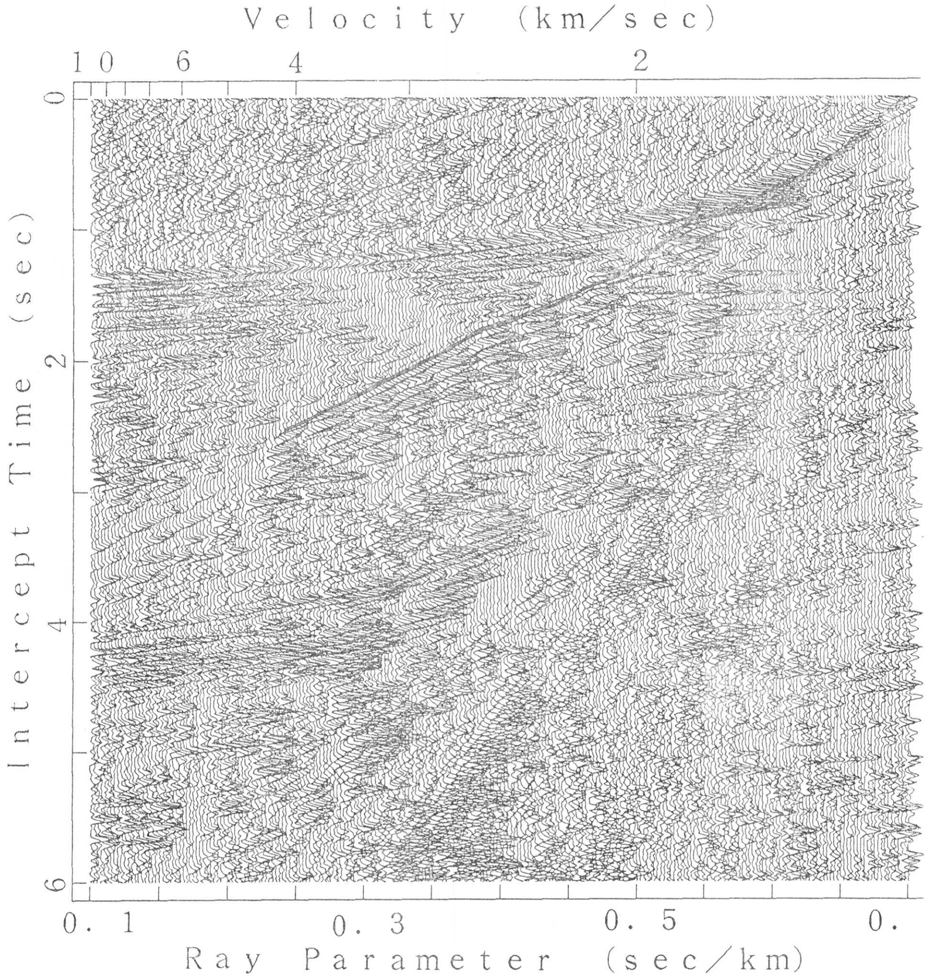

Fig. 8. (b)

Fig. 8. An example of processed data for OKS6. (a) Observed record section in an offset distance(x) - travel time(t) domain. (b) record section transformed into an intercept time(τ)-ray parameter(p) domain. Semblance of the seismogram is calculated for each p.

and calculated travel times from airgun shooting and Fig. 12 shows those from explosives. We can see that the model explains the overall behavior of the travel time curves, especially the change of the apparent velocity at the center of the trough, very well.

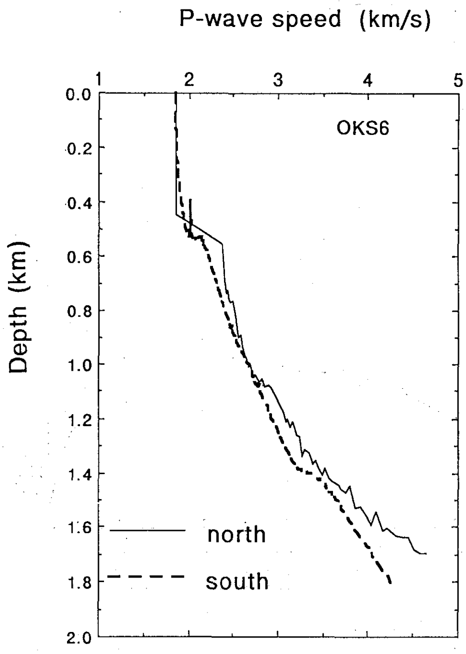

Fig. 9. A velocity-depth profile for OKS6 by the τ-sum inversion. Data from both the northern and the southern sides of the split profile for OKS6 are inverted into the velocity and shown.

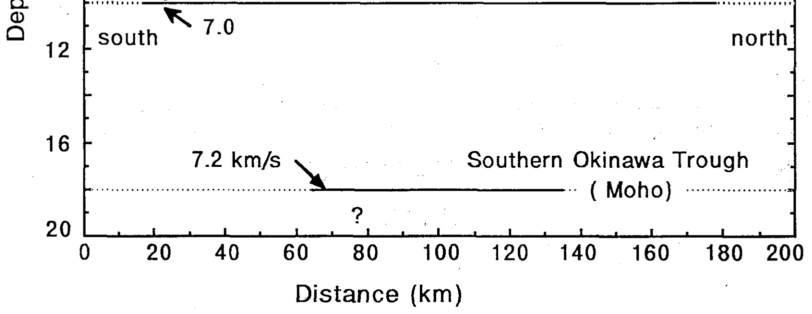

Fig. 10. A 2-dimensional velocity model along the seismic profile of the 1988 DELP cruise in the southern Okinawa Trough. Numerals are P-wave velocities.

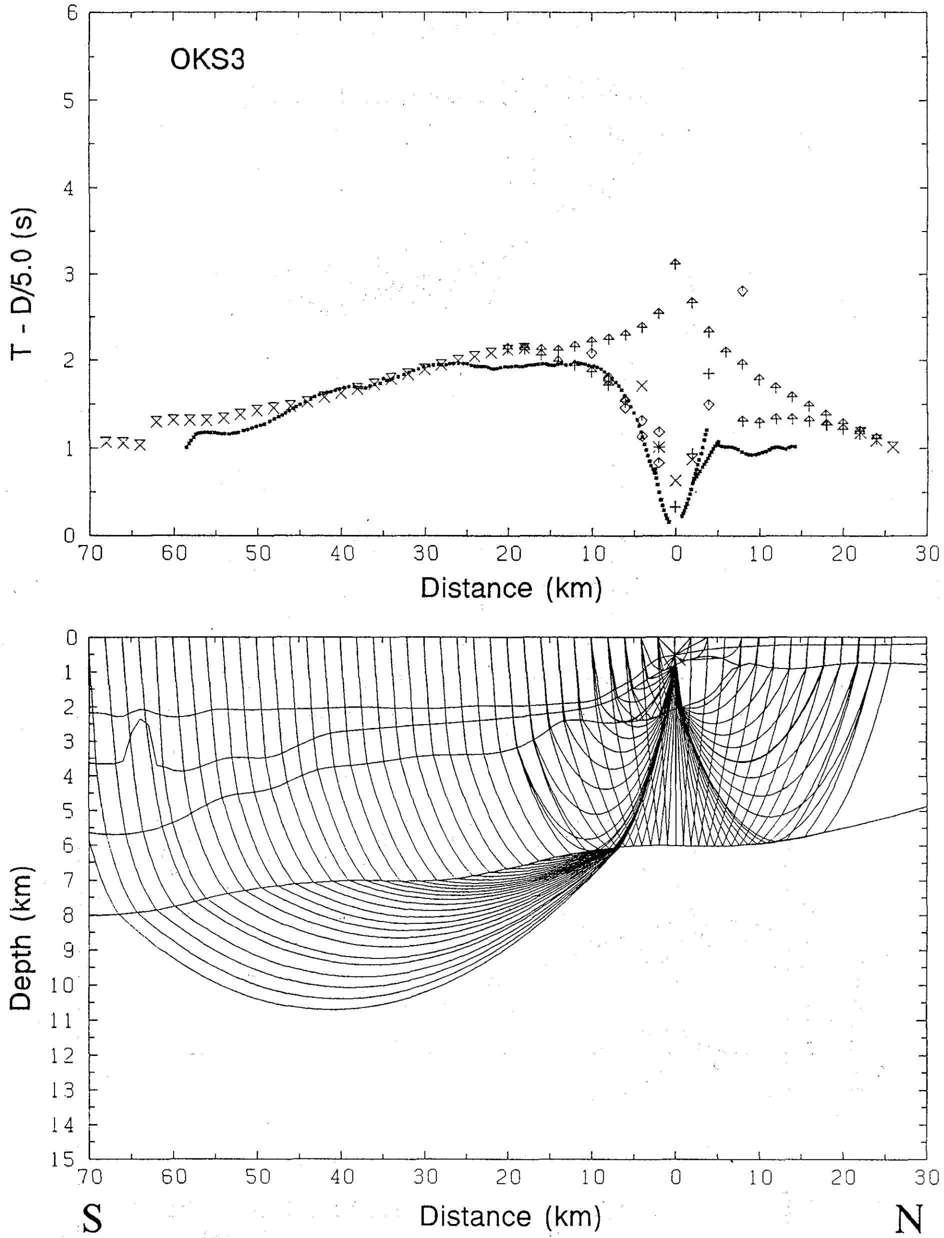

Fig. 11. (a)

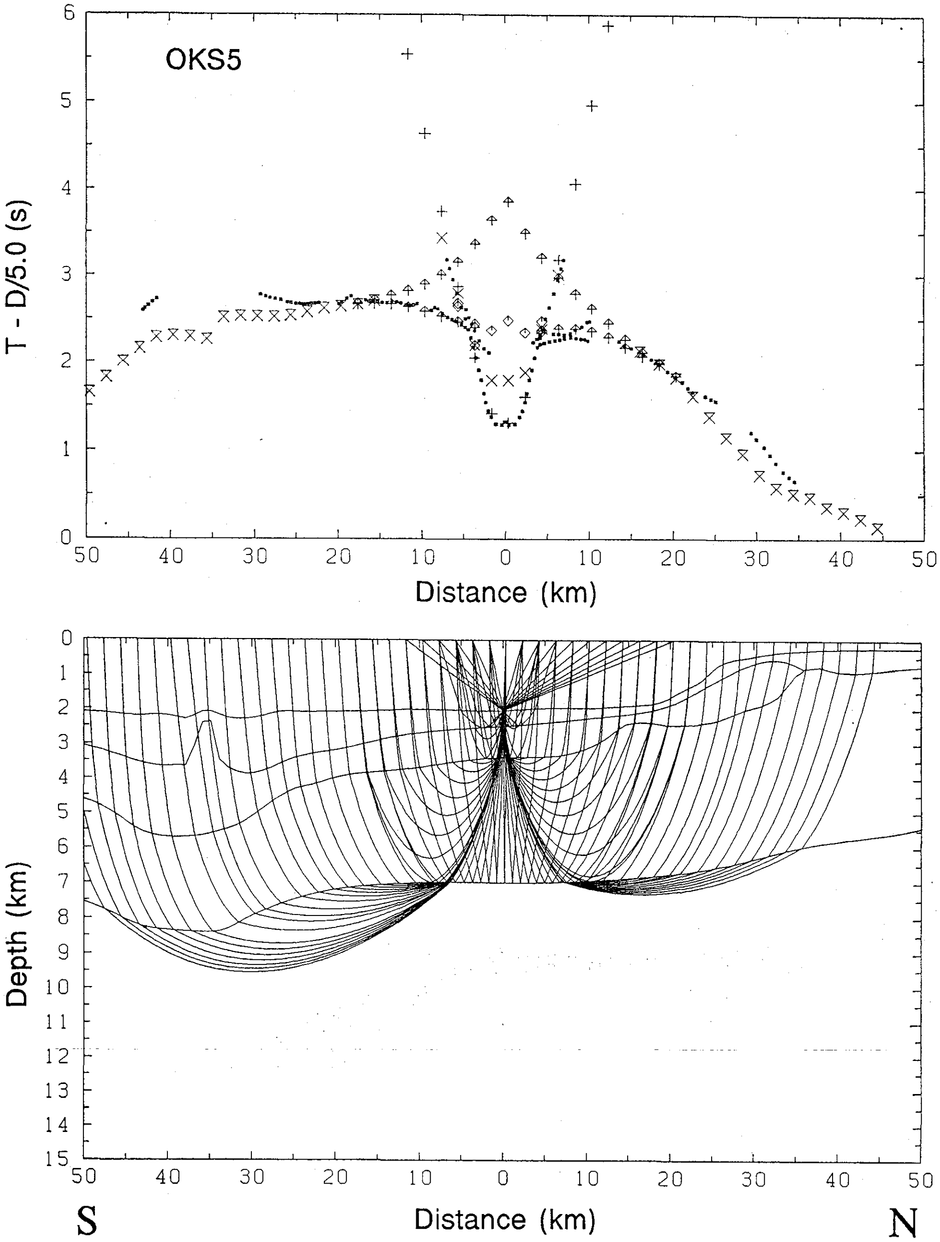

Fig. 11. (b)

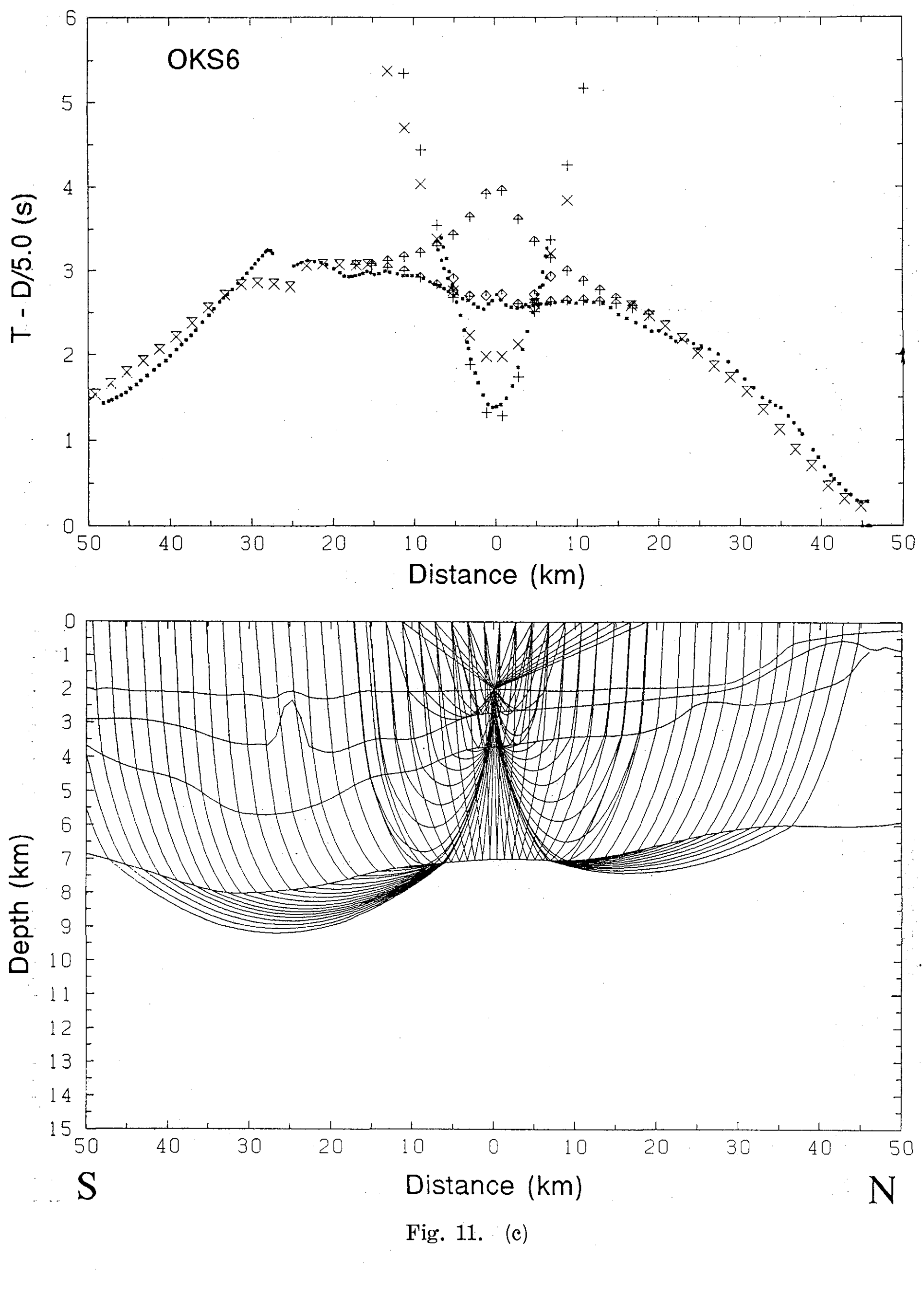

Fig. 11. (c)

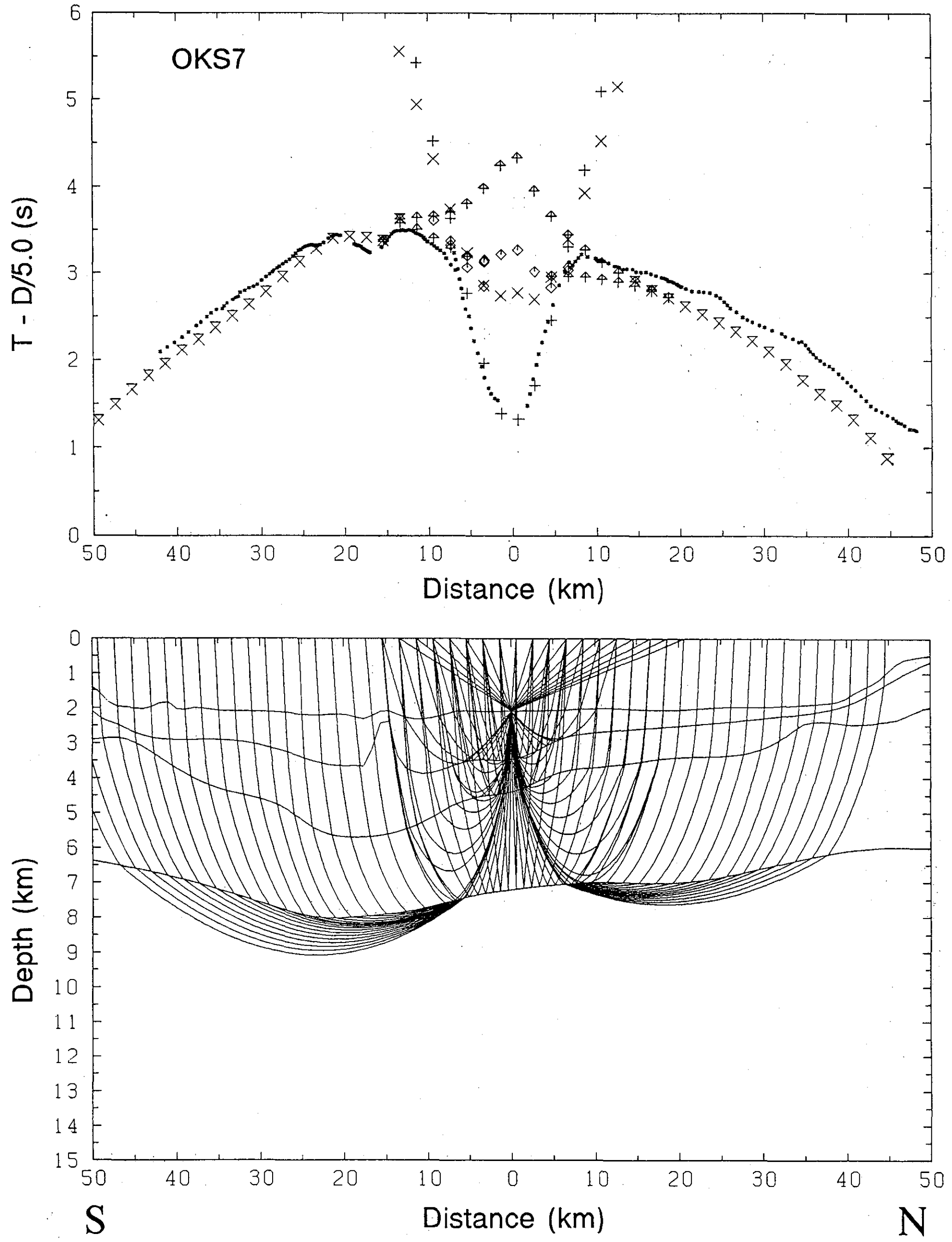

Fig. 11. (d)

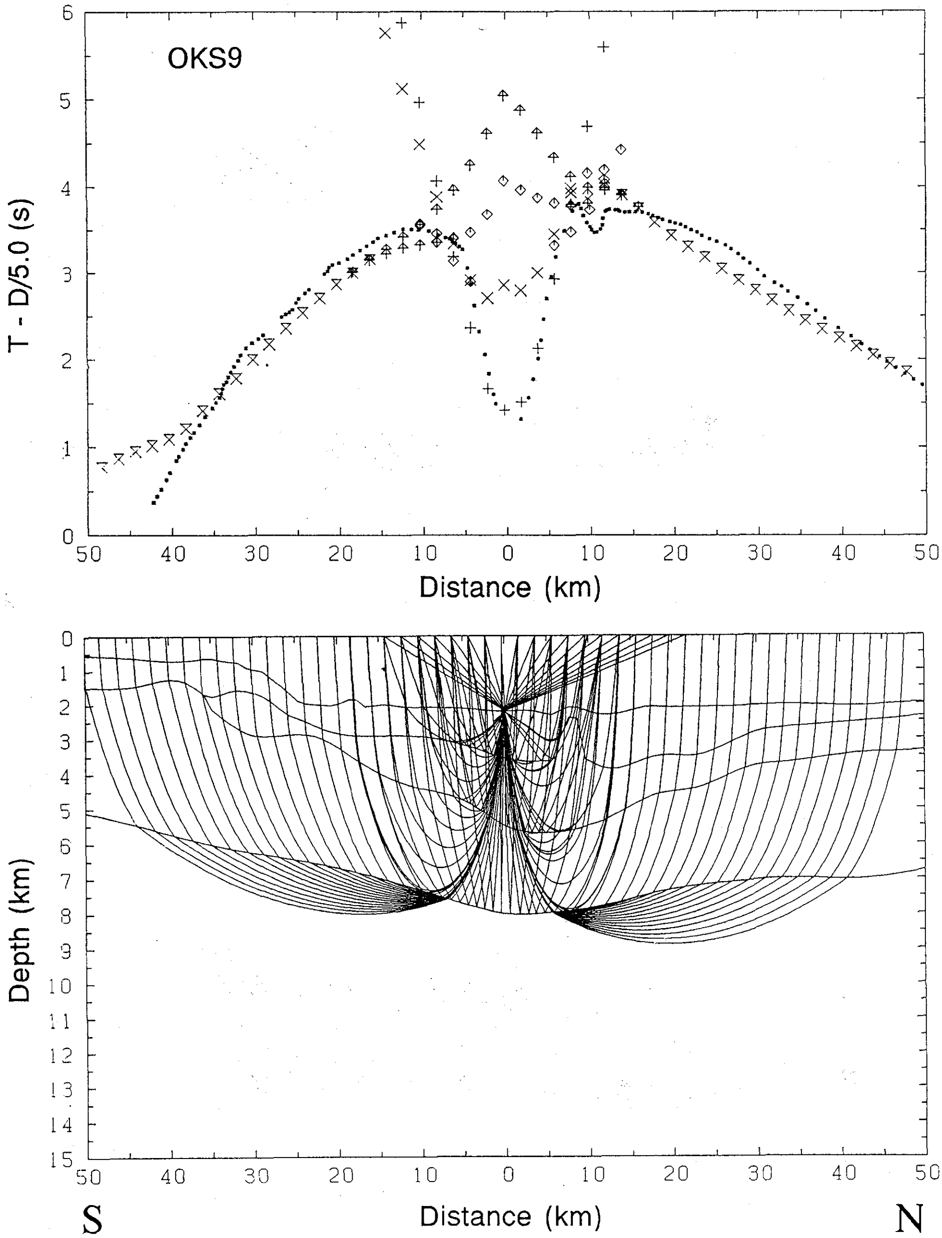

Fig. 11. (e)

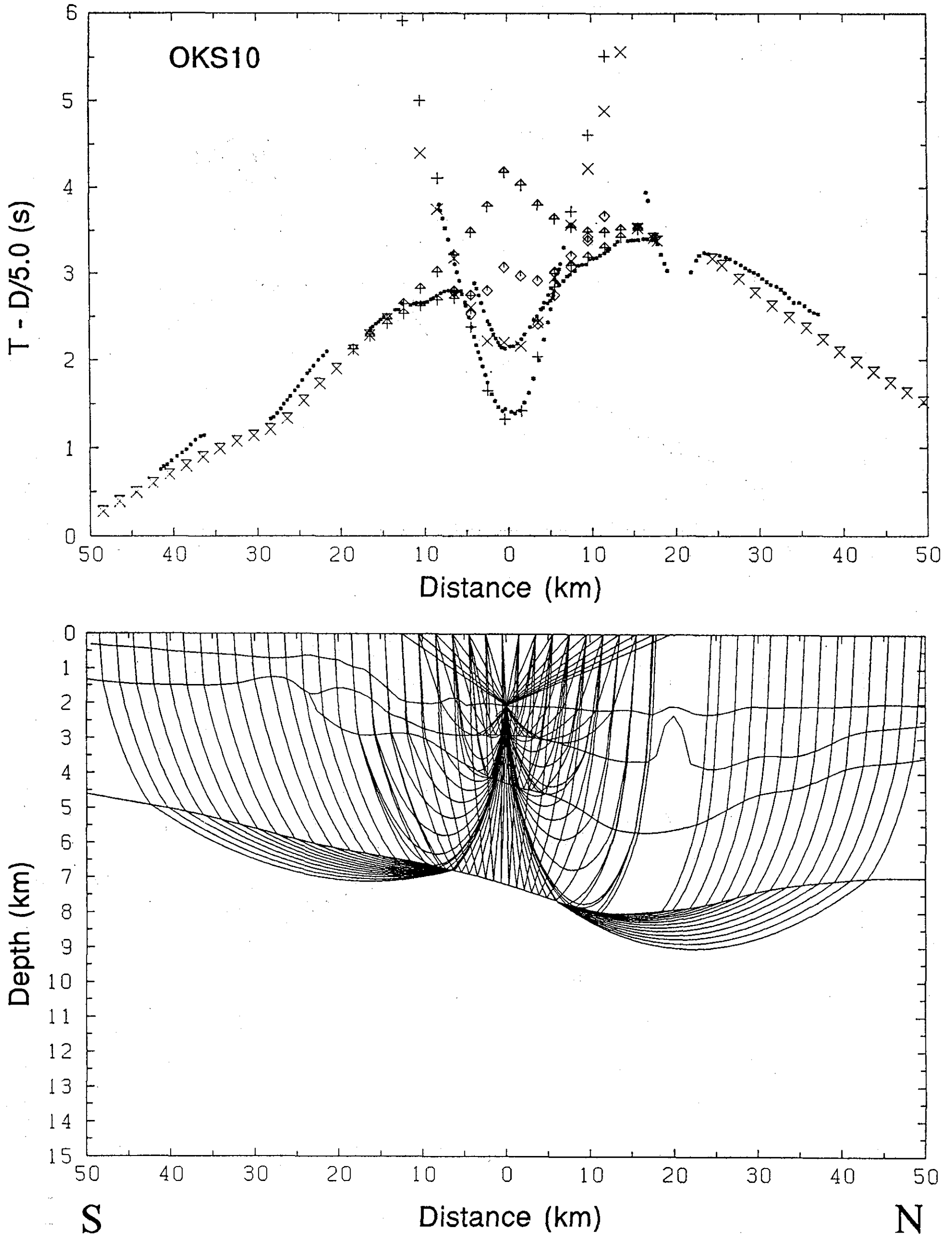

Fig. 11. (f)

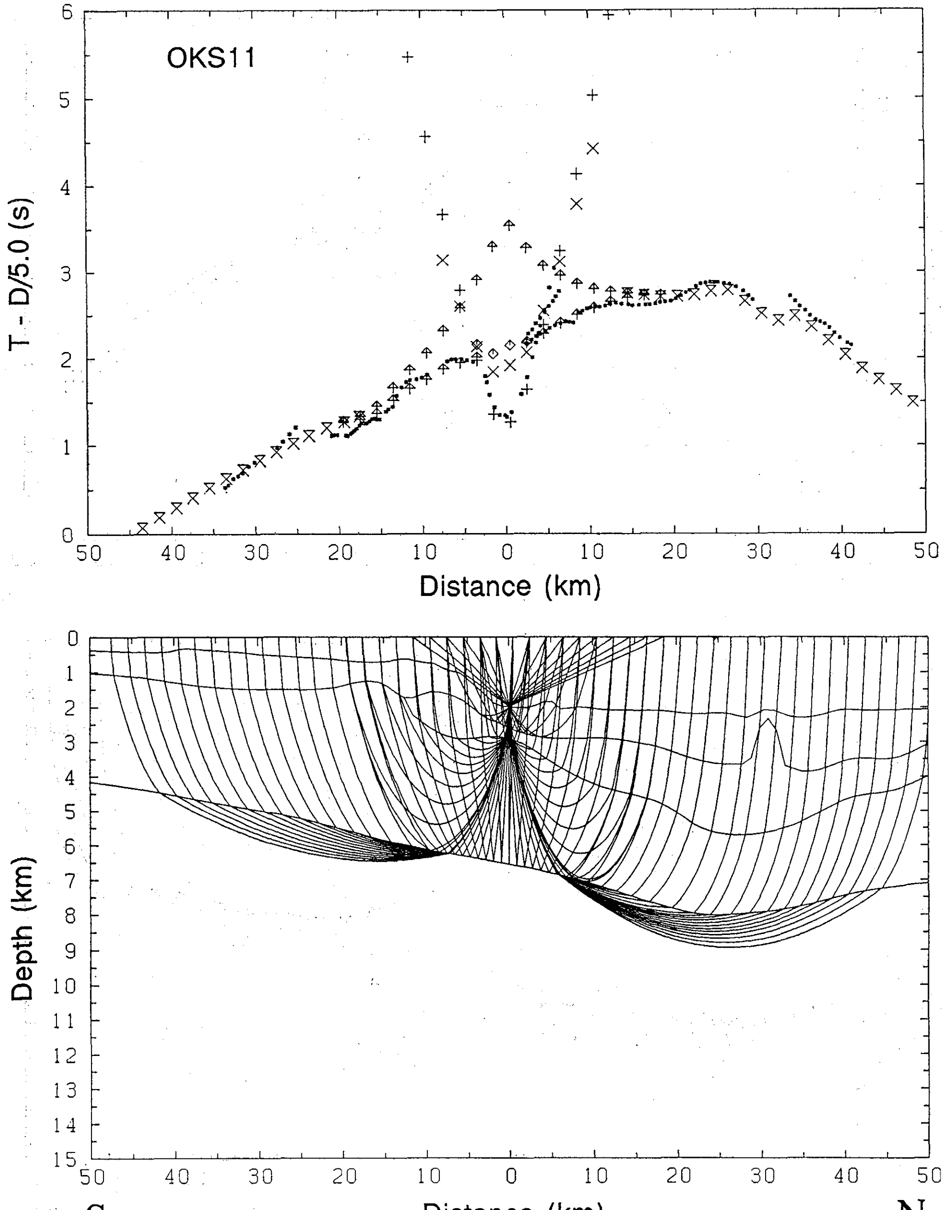

Fig. 11. (g)

Fig. 11. Calculated travel times (large symbols) and observed travel times due to airgun shooting (small symbols). Ray diagrams are shown in the bottom: (a) OKS3, (b) OKS5, (c) OKS6, (d) OKS7, (e) OKS9, (f) OKS10, and (g) OKS11.

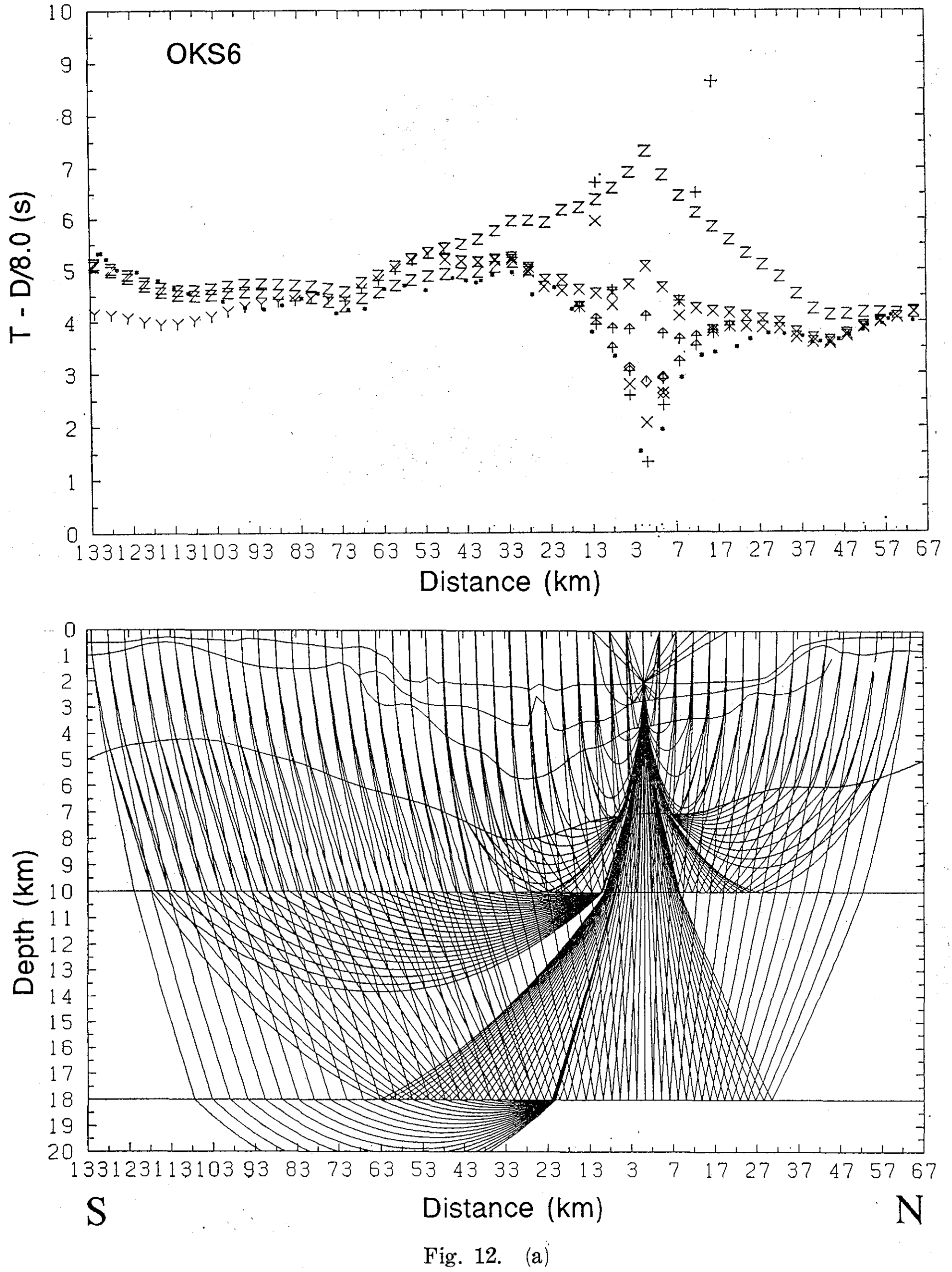

Fig. 12. (a)

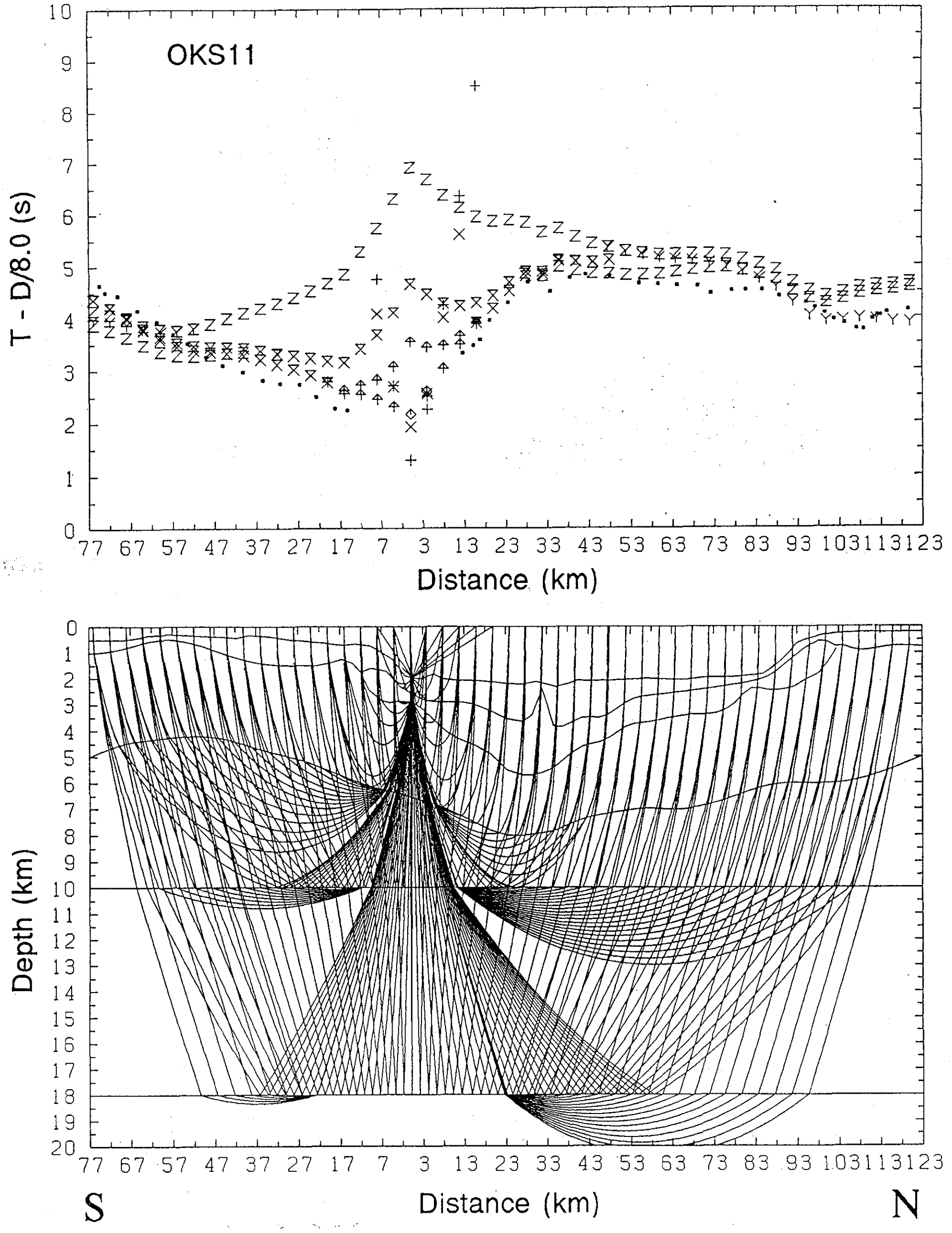

Fig. 12. (b)

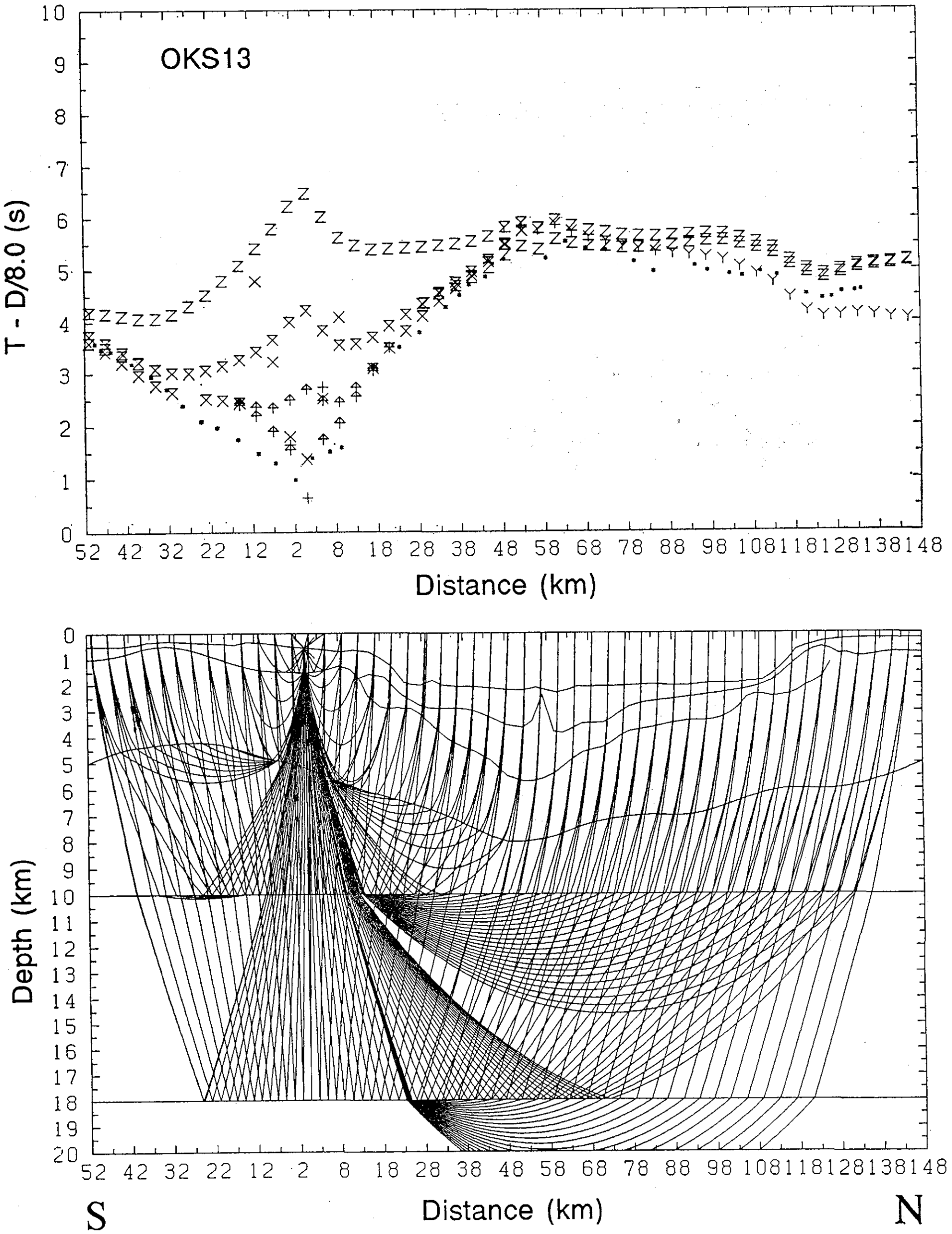

Fig. 12. (c)

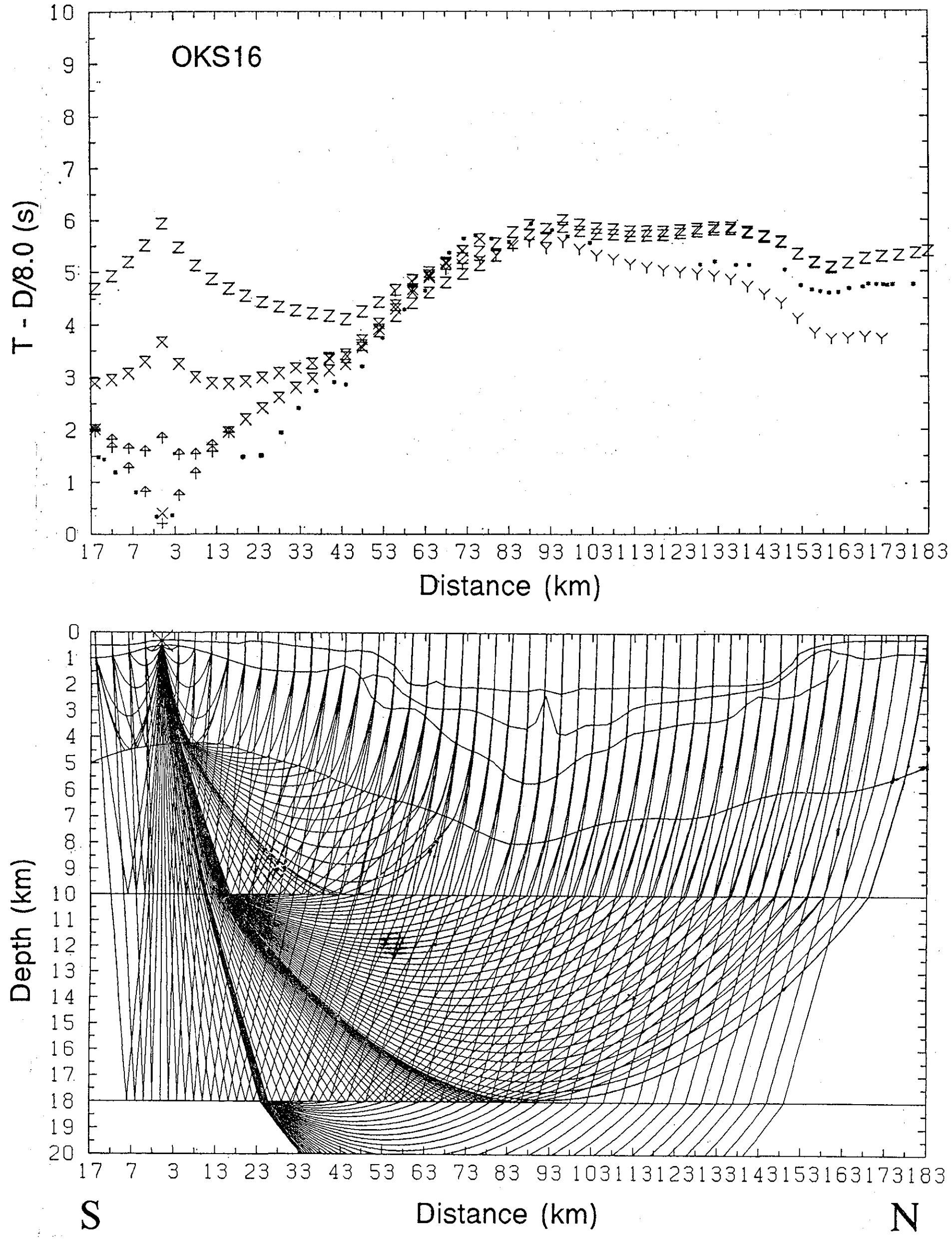

Fig. 12. (d)

Fig. 12. Calculated travel times (large symbols) and observed travel times due to explosives (small symbols). Ray diagrams are shown in the bottom: (a) OKS6, (b) OKS11, (c) OKS13, (d) OKS16.

Discussion

Analysis of the seismic data indicates that the crust is more than 16 km thick. A phase with an apparent velocity of about 7.8 km/s is a crustal phase, which is strongly affected by the change in the thickness of the upper crust. Our data indicate that the sediment is the thickest in the center of the trough and its thickness decreases towards the margins of the trough while the underlying crustal layer, which has velocities between 4.5 and 6.4 km/s, is the thinnest in the center of the trough. The lower crust seems more uniform than the upper crust, having a velocity which increases from 7.0 to 7.2 km/s or more. Consequently, we conclude that the southern Okinawa Trough does not have an oceanic crust but that it is comparable to the continental crust characterized by a thick 6-km/s layer.

The important question to be answered by the present experiment is whether or not the southern Okinawa Trough has started to open due to back-arc spreading. Our data indicate no evidence of the existence of a very thin crust associated with the spreading, even in the center of the trough. Some seismograms (OKS6, OKS7, OKS9, OKS10) show a shadow zone in the *t*-*x* record section, which suggests an abrupt lateral change in the shallow crustal structure located at the very center of the trough, such as a small knoll (Fig. 5). Reflection data indicate evidence consistent with an apparent igneous intrusion into the basement layer. Thus we judge that back-arc spreading in the studied area has not begun yet, or, if it has, it is too narrow to be detected by seismological methods.

Our observation is in agreement with a geological interpretation by SIBUET *et al.* (1987) that the young oceanic crust is limited to a width of a few tens of kilometers or less in the southern and middle Okinawa Trough. Furthermore, our data indicate that the width of the oceanic crust, if any, in the axial portion of the trough is even less than that proposed by SIBUET *et al.* (1987). Our data reinforce the view that, if any, only a limited amount of young oceanic crust exists in the southern Okinawa Trough. Consequently, the trough is essentially composed of a continental crust thinned by a tensional process which is indicated by geological evidence at the sea bottom such as normal faulting (FURUKAWA *et al.*, part 2 of this report). Our data are consistent with the idea that the southern Okinawa Trough is in the rifting stage of the back-arc basin prior to spreading.

LEE *et al.* (1980) reported the crustal structure in the southern Okinawa Trough in approximately the same area as covered by the present study. They claim that Moho exists 15 km below the sea surface

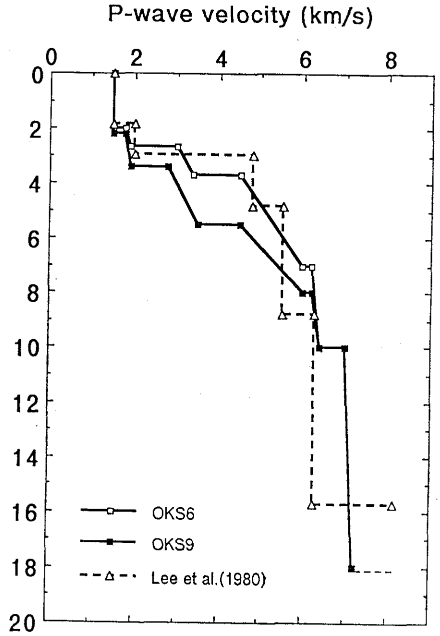

Fig. 13. P-wave velocity distributions in the crust of the southern Okinawa Trough. The crustal structures beneath the center of the trough (OKS6 and OKS9) are compared with the model presented by LEE *et al.* (1980).

beneath the central rift of the trough. Their model is very different from the average structure of the oceanic crust in the northwest Pacific basin. Our data are consistent with their model, although we did not detect a clear refraction phase from the mantle as would be expected from the model (Fig. 13). The discrepancy between our results and theirs is partly due to the ambiguity deduced from the limited amount of data used in their study. It may also be due to the directions of the profiles: the split profile of LEE *et al.* (1980) is parallel to the strike of the trough while ours is perpendicular to it. If the oceanic crust underlain by the 8.0-km/s mantle exists only close to the center of the trough, we did not observe the thin crust: the crust further away from the center, which we observed, could be thicker than that in the center of the trough. So we can safely say that even if the young oceanic crust exists in the southern Okinawa Trough, it will be only in a very limited area near the axis of the trough.

We should mention that all available seismic data on the crustal structure of the Okinawa Trough from north to south show a clear resemblance (Fig. 14): The crust has a thick sediment, which consists of two or three layers with a P-wave velocity of 2.0–4.9 km/s. Below

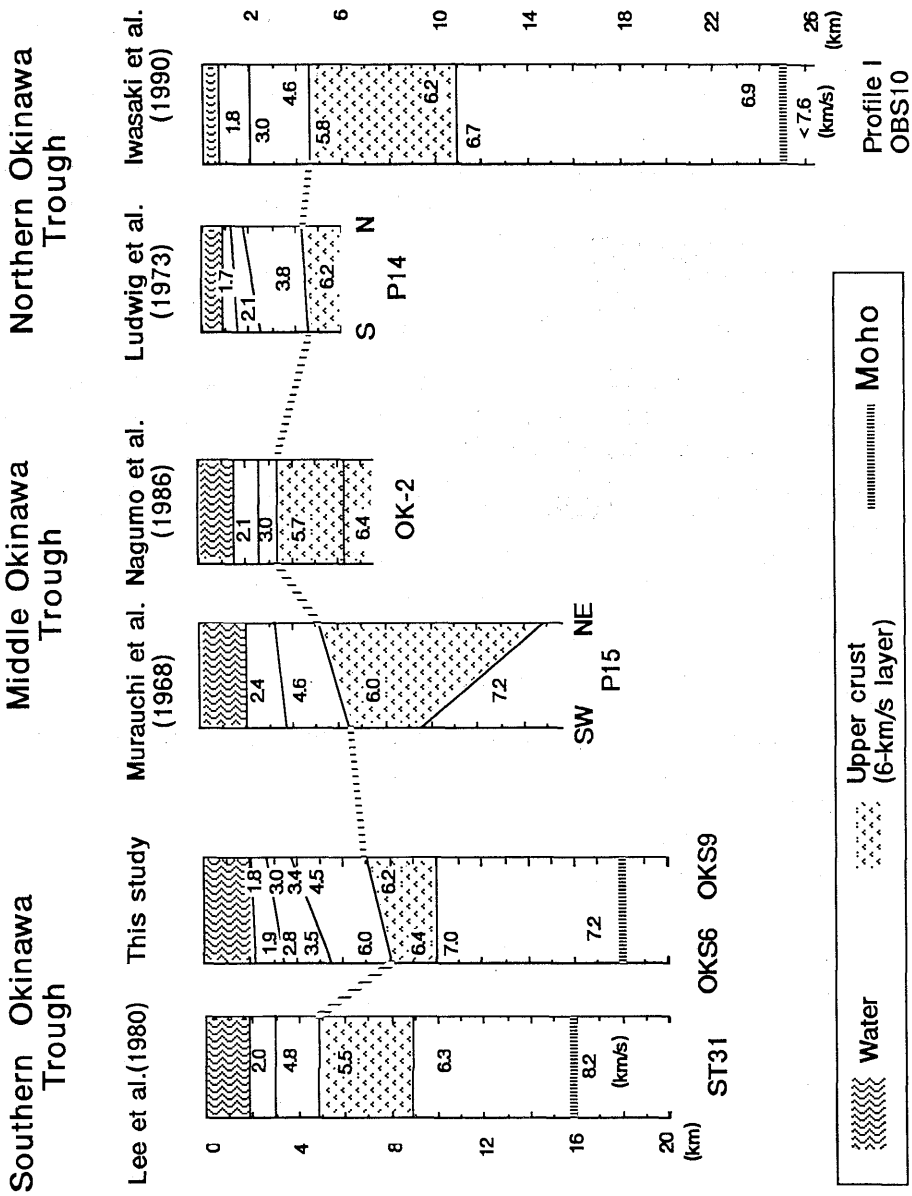

Fig. 14. Comparison of models of the crustal structure in the Okinawa Trough.

the sediment is a layer with a P-wave velocity of around 6 km/s. The distribution of the P-wave velocity in the upper crust is quite different from that in the Shikoku Basin, which basically has the same crustal structure as that in the northwestern Pacific Basin. Thus we can say that all seismic data, including ours, indicate that there is no oceanic crust in the entire Okinawa Trough.

Still, we need further detailed seismic experiments, because no experiment has had a refraction profile long enough to observe the entire crustal structure. We need a profile more than 250 km long and with controlled sources strong enough to generate seismic waves to cover the whole length of the profile.

Conclusion

We conducted a seismic refraction experiment using 18 OBSs and controlled sources of an airgun array and explosives in the southern Okinawa Trough. Results of analysis of the seismic data indicate that the southern Okinawa Trough has a crust 16 km or more thick, suggesting that the trough has not yet started to open due to back-arc spreading, or that any spreading that has occurred is too recent to be detected because no evidence of a very thin young oceanic crust was found.

Acknowledgment

We thank the Captain, officers and crew of R/V Kaikomaru No. 5. We express our thanks to the shipboard scientific party of the 1988 DELP Cruise.

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DELP 1988年度沖縄トラフ海域研究航海報告
3. 南部沖縄トラフの地殻構造

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1988年7月に南部沖縄トラフで，18台の海底地震計を用いた屈折法地震探査が行われた．南北195 km の測線上で3発の大発破 (600, 500, 450 kg) と50発の小発破 (50, 25 kg) を行った．更に，上部地殻を精密に調べるために，91 と 161 のエアガンアレイを 50〜70 秒間隔で発振して，高密度の屈折地震波記録を得た．海底地震計の間隔は平均 11 km，平均火薬発破間隔は 3.8 km，平均エアガン発振間隔は 150 m であった．

海底直下の堆積層及び最上部地殻の構造は，本実験と同時に行われたマルチチャンネル反射法による記録を参考にして，エアガンアレイを震源とした屈折記録の解析に基づいて推定された．堆積層と最上部地殻のP波速度の解析には，時間一空間領域の波形データを τ-p 領域に変換したのちに τ-sum インヴァース法によって速度一深度関数を得る方法を用いた．下部地殻の構造は，2次元の波線追跡法による理論走時と観測走時の比較に基づき試行錯誤的に求めた．

解析の結果，トラフ底には 2-3 km に及ぶ厚い堆積層の下に 4.5-6.0 km/s のP波速度を持つ基盤層が見いだされた．見かけ速度 8 km/s の相が記録上現れたが，これは上部地殻がトラフ中央部で凹んでいることで説明される．明確な P_n 相は検出されなかったが，モホ面は少なくとも海面下 18 km より深いと推定された．下部地殻のP波速度は 7.0-7.2 km/s であった．トラフ中央部にも薄い海洋性地殻の存在を示すデータは得られなかった．これらの観測事実は，現在の南部沖縄トラフは，大陸地殻の伸張を伴う初期リフティング期にあり，未だ海底拡大を始めていないとする考えを支持する．