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# 1992 Lincoln Sea refraction survey: data acquisition and processing report

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# 1992 Lincoln Sea Seismic Refraction Survey: Data Acquisition and Processing Report

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## ABSTRACT

The 1992 Lincoln Sea seismic refraction survey, in Canada's High Arctic, was a cooperative, multi-agency project conducted during the spring of 1992 by the Defence Research Establishment Pacific, with advice, instruments and technical support of the Geological Survey of Canada. The seismic survey, part of 'Iceshelf '92', a multi-disciplinary, international scientific project, acquired the first crustal seismic data from beneath the Lincoln Sea.

The seismic survey consisted of two lines, recorded on the sea ice near the continental slope. Two reversed high resolution deployments along the same three km-long profile, with 50 m recorder spacing and 1.5 km shot spacing, and a parallel reversed deployment along a regional 60 km-long profile, with 1 km recorder spacing and 10 km shot spacing. Both lines cross the area of the shelf-slope break.

This report summarizes the survey parameters, the process of data correction and reduction and includes data logs and final plots of water wave and crustal wave coda.

# 1. INTRODUCTION

The Lincoln Sea continental shelf north of Ellesmere Island is the most northerly contiguous Canadian landmass beneath the Arctic Ocean. From April 1, to April 30, 1992, the Defence Research Establishment Pacific (DREP) conducted a multi-disciplinary, international scientific project, 'Iceshelf '92', on the sea ice of the Lincoln Sea. One component of this project was the first seismic survey conducted in the Lincoln Sea. The seismic refraction experiment (Fig. 1.) was conducted by DREP personnel, utilizing Geological Survey of Canada (GSC) advice, instruments and technical expertise.

The two main objectives of the refraction experiment are to characterize the acoustic properties of the seawater-shallow sediment interface of the seafloor, and to define the velocity structure of the underlying basement rocks in order to place the first seismic constraints on the structure and tectonic history of the Lincoln Sea region between Ellesmere Island and Greenland. The seismic data also augment limited available bathymetry control for the region.

Using insulated tents, a base camp named "Thunder" was set up on the sea ice at 83.90 deg. N and 63.04 deg. W. The camp included facilities for electronics, cooking and living quarters, and storage areas.

Taking advantage of excellent weather conditions, two reversed deployments on the same 3 km-long high resolution line (Line 1a/b), and a parallel, reversed deployment on a 60 km-long regional line (Line 2) were successfully completed (Fig. 2.). Using 64 GSC-developed, Scintrex Ltd. "Lunchbox" single component portable refraction seismographs (PRS-1's), nominal recorder spacings of 50 m and 1 km were achieved on the short, high resolution line and on the longer regional, line respectively. A Shot spacing of 1.5 km, with offset shots at 1.5 and 3.0 km, was used on Line 1a/b, while 10 km shot spacing, with no offset shots, was used on Line 2. A total of 1323 seismic traces were recorded, including 896 seismograms on the higher resolution line and 427 seismograms on the regional line. The maximum shot-receiver offset was 60 km, with twice the density of shots and recorders achieved during the 1990 Ice Island Survey (Forsyth et al., 1990b). The data is presently stored on four-9 track magnetic tapes in SEGY format at DREP in Victoria. Each tape contains data for all deployments within an appropriate time window at a specified reducing velocity. In addition, one tape is available with the complete, unreduced data set.

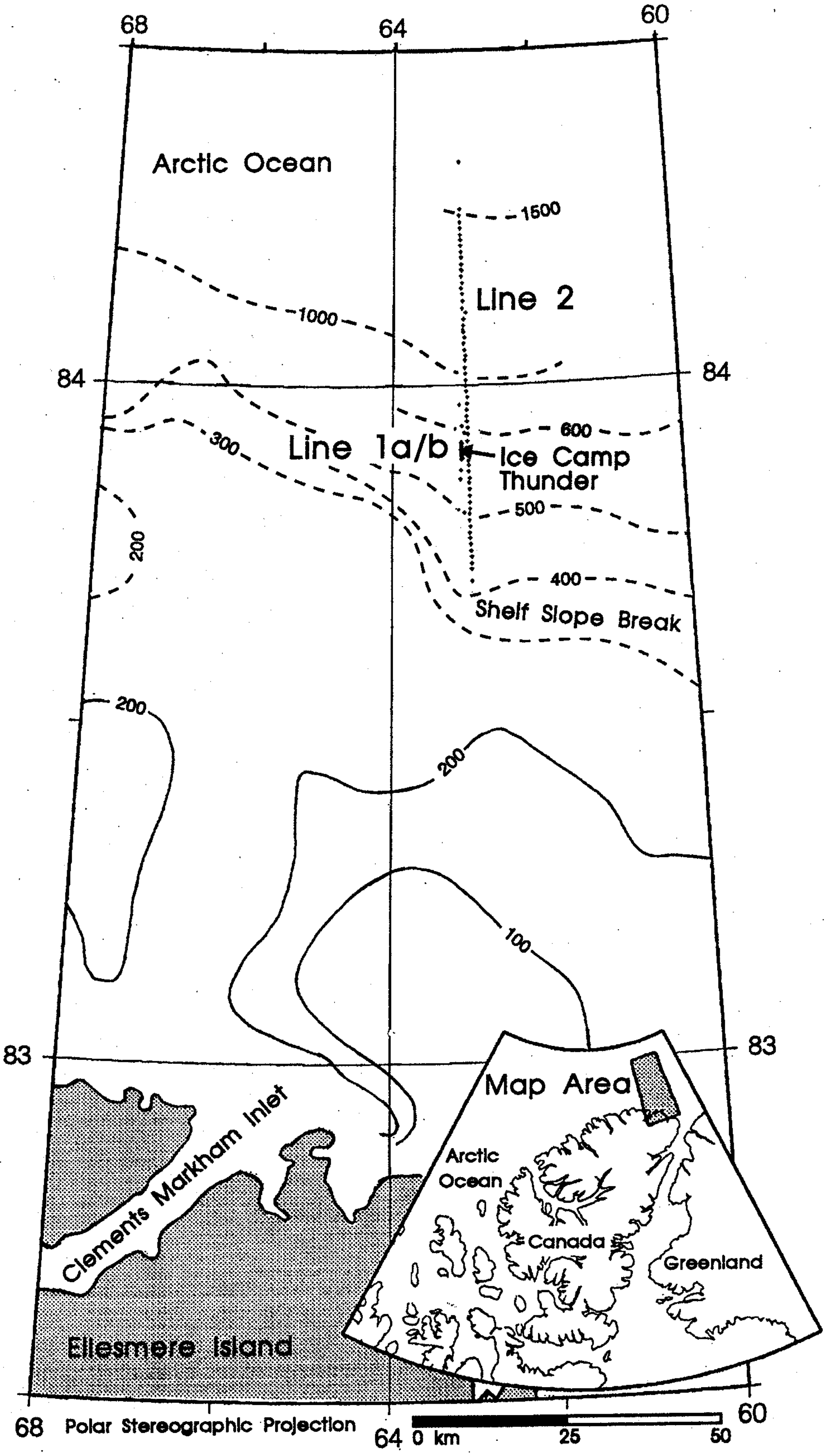


**Figure 1. Location of the Iceshelf 1992 seismic refraction experiment Line 1a/b and Line 2, bathymetry in metres, compiled from various sources as indicated in the text.**

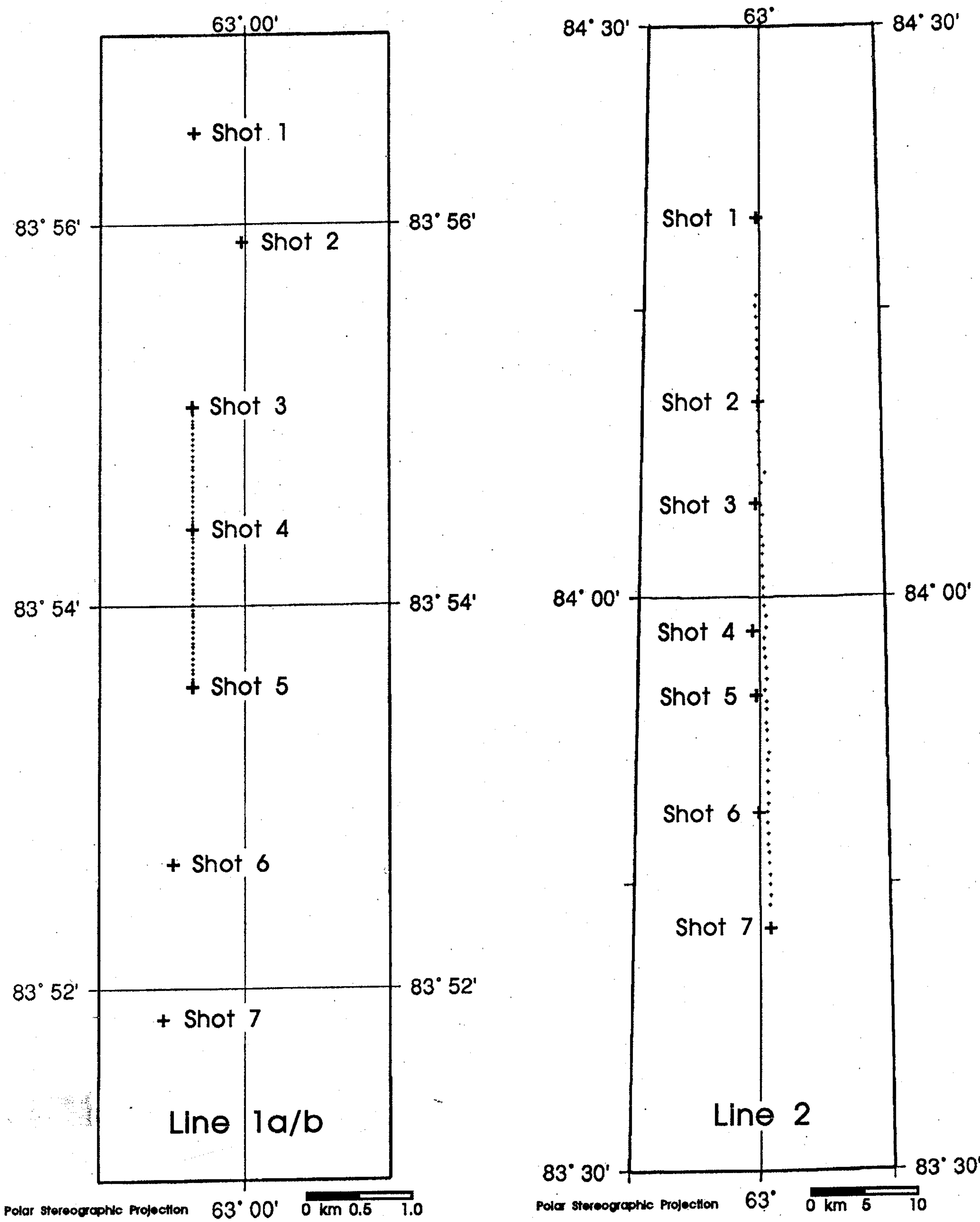


Figure 2. Shot and recorder locations, indicated by large and small crosses respectively, for Line 1a/b (left) and Line 2 (right). Note the different scales used.

## 2. GEOLOGICAL SETTING

Despite significant geological data collected on-land since 1916 (Dawes and Christie, 1982), the tectonic history of the Lincoln Sea area, between the mapped geology and the deep ocean ridges, remains poorly constrained (Dawes 1990). In order to understand the opening of this part of the Arctic Ocean, the effects of a number of different tectonic events will have to be considered. These include: the development of the Alpha Ridge, the Lomonosov Ridge, and the opening of the Fram Basin, as well as the nature of tectonic adjustments between Ellesmere Island and Greenland. In general, the tectonic developments within the Lincoln Sea have been inferred as a result of plate reconstructions not based on constraints provided by data from the Lincoln Sea. The controversy surrounding the possible adjustments along Nares Strait has been the subject of conferences and many papers (eg. Dawes and Christie, 1982). The data described in this report are the first seismic data from the Lincoln Sea and will only begin to place constraints on tectonic developments in a very complex area.

Within the region of interest, the on-shore geology of northeast Ellesmere Island can be divided into four major belts (Fig. 3.). The composite Pearya terrane makes up the majority of the Northern Ellesmere Magmatic Belt (NEMB) (Trettin, 1987). Pearya consists of four major successions which range in age from Middle Proterozoic to Late Silurian. The two successions most relevant to the Lincoln Sea area are: (a) a coastal crystalline basement region of granitoid gneiss with lesser amounts of amphibolite, schist, marble and quartzite (metamorphism and intrusions are dated at 1.0-1.1 Ga) and (b) an Upper Proterozoic to possibly Middle Ordovician succession including sedimentary and volcanic rocks of greenschist to amphibolite metamorphic grade. The terrain is rugged, with a relative relief of from 1000 to 2000 m.

A northeast tapering wedge of Sverdrup Basin rocks of the Clements Markham Fold Belt lies southeast of the NEMB. Structural trends are generally northeast-southwest. In the map area, thick shale and sandstone sequences form the base for mountainous plateaus with elevations of over 2 km. The Sverdrup Basin is bounded on the south by the Hazen Fold Belt. The Hazen Fold Belt is divided into north and south components by the northeast striking Lake Hazen Fault Zone which trends offshore immediately north of Alert. All of these geological belts trend sub-parallel to the northern coast of Greenland.

On Greenland, immediately adjacent to Nares Strait, is a 20-30 km wide fold belt. The folds are not as complex as those to the north, and the thickness of the Devonian sediments decreases to the south. The region is still mountainous with peaks reaching elevations of 1000 m.

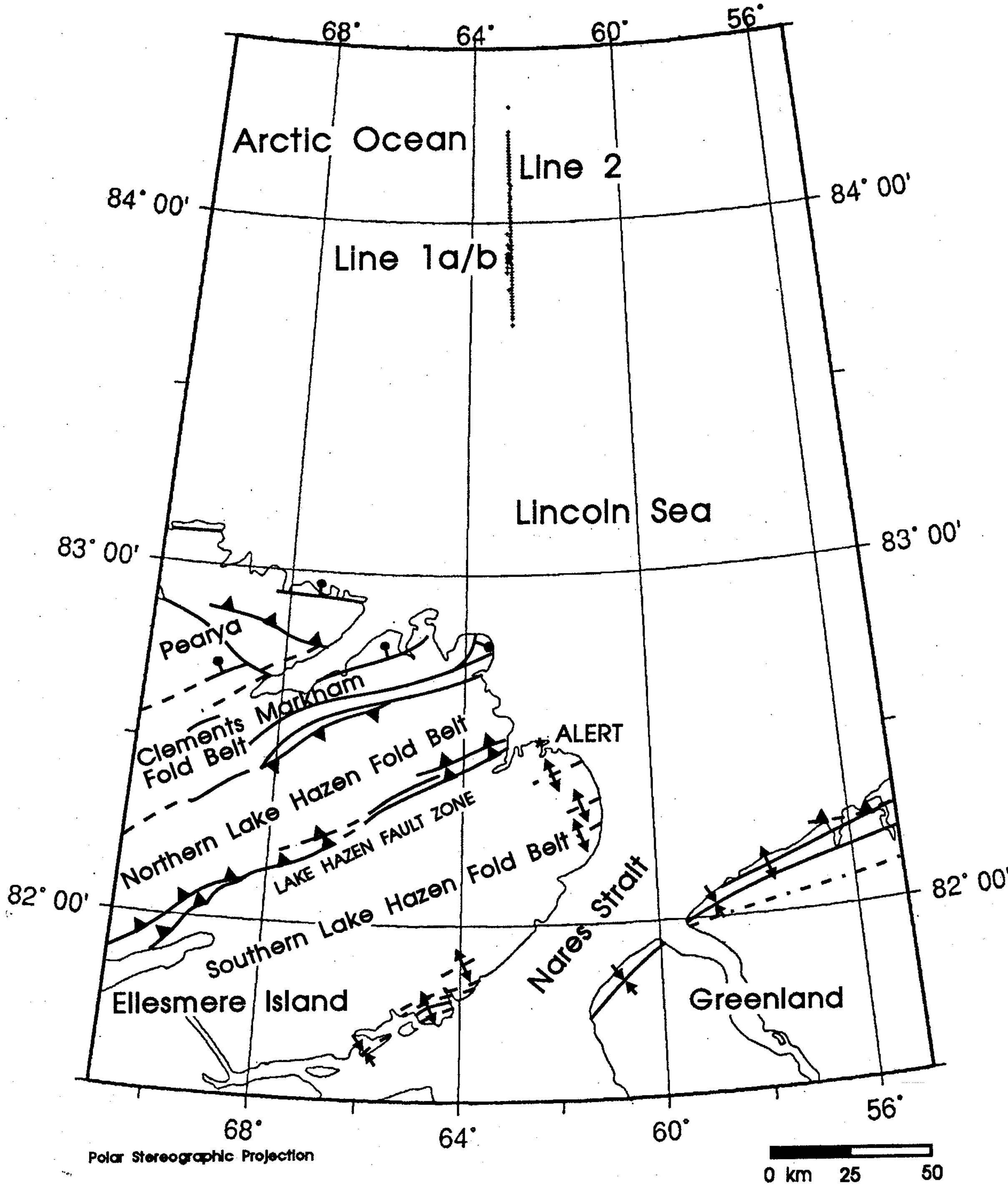


Figure 3. Regional onshore geology in the survey area, after Okulitch (1991).

In addition to these geological belts, late Cretaceous-early Tertiary volcanic rocks (63 ma; Larsen et al., 1978) of the Kap Washington Group occur near $40^0$ W., immediately west of the map area, on the northwest tip of Peary Land. A dyke system related to this event may also extend to the area of the 1992 seismic survey.

# 3. PREVIOUS GEOPHYSICAL STUDIES

Geophysical data of any kind are extremely rare in the eastern half of Canada's High Arctic. Even the available bathymetry database with large unsurveyed areas is incomplete, and often contradictory between charts.

The present gravity data base, although good for Arctic data, is of limited resolution, with average station spacing of 10 km. No data are publicly available for the continental shelf and shelf-slope break in the area immediately to the east of the seismic survey. In the southern portion of the survey area, free-air gravity anomalies follow the trends of onshore geology. There are no available data for the adjacent area north of the survey. The major feature in the survey area is an elongate positive free-air anomaly parallel to, and shoreward of, the shelf-slope break. The lower amplitude of this anomaly, relative to the shelf slope anomalies to the west, may indicate that the thickness of Mezosoic and younger sediments is less in the Lincoln Sea than to the west (Forsyth et al., 1990a).

A conductivity anomaly coinciding with the Lake Hazen Fault Zone and extending offshore to the northeast was reported by Niblett et al. (1974). The anomaly was attributed to an elongated conductor located deep in the crust or upper mantle that extends beneath the continental shelf for 100 km from the coast. The conductor was modelled as an anomalous region about 100 km wide, 10 km thick at depths between 10 and 20 km. The conductivity anomaly is parallel to the aeromagnetic anomaly trends.

The Polar Margin Aeromagnetic Program (PMAP) is an ongoing multi-agency program to collect aeromagnetic data in key areas of tectonic interest in Canada's Arctic. The Lincoln Sea was one of the PMAP target areas from 1989 to 1991, and a preliminary interpretation of this data, with depth to magnetic source calculations, was presented by Nelson et al. (1991). Their interpretation indicates that the seismic refraction lines are in a zone characterized by high amplitude, long wavelength anomalies, and an estimated depth to magnetic basement of approximately 4 km depth below the sea floor. High amplitude-short wavelength, linear anomalies may indicate intrusive dike structures less than 1 km below the sea floor. The aeromagnetic data suggest that the seismic survey is located in an area where three major, probably tectonically controlled, anomalies converge. This data should be used in conjunction with the seismic refraction data to develop models and tectonic constraints for this structurally complex region.

There are no industry data available in the survey area. Several regional seismic refraction programs have been conducted along the Polar Margin. The closest profiles are the 1985, 1986 and 1990 GSC Ice Island surveys, some 400 km to the southwest.

# 4. FIELD PROCEDURES

Using GSC on-ice seismic refraction experience gained from the Ice Island surveys of 1985, 1986 and 1990 (Asudeh et al., 1985; Asudeh et al., 1986; Forsyth et al., 1990b) as well as previous ice camp experience gained by DREP personnel, the first Lincoln Sea seismic survey was successfully carried out in extremely harsh conditions.

## 4.1 LOGISTICS

All equipment was kept in warm storage at Canadian Forces Base Alert, Northwest Territories, until the ice camp was established, in order to minimize thermal shock. Transportation of personnel and equipment from Alert to ice camp Thunder was provided by one military and one commercial Twin Otter fixed wing aircraft. Snowmobiles and a commercial Bell 205 helicopter provided transportation during the experiment, using fuel air-dropped by a military Hercules aircraft.

## 4.2 RECORDING

Seismic systems included Scintrex PRS-1 recorders connected to Mark Products model L4, 2 Hz, seismometers with cold weather cables. Because the recorder locations on Line 1 were to be used twice, and to save time on the day of shooting, the seismometers were placed on the ice the night before deployment, and had frozen to the ice within hours, providing excellent coupling. The following morning, the PRS-1's were connected to the seismometers for Line 1a. After shooting, the PRS-1's were collected and then re-deployed for Line 1b, after which the PRS-1's and seismometers were all retrieved. The seismometers for Line 2 were deployed at the same time as the PRS-1's.

All PRS-1's were enclosed in specially designed thermally insulated bags with pre-heated gelpacks. Their internal clocks were synchronized before deployment using a GPS (Global Positioning Satellite) time signal, and then rated after deployment to allow a clock drift correction to be applied to the recorded data (as discussed in Section 5.2).

The PRS-1's for Line 1 were deployed using snowmobiles with sleds, while deployment of the PRS-1's for Line 2 was accomplished using a Bell 205 helicopter in two runs of 30 instruments, with refuelling between runs.

## 4.3 SHOOTING

All shots for Line 1 were detonated on the sea floor using an electrical connection to CIL MkII Seismocaps, while those for Line 2 were suspended 100 m below the sea ice and detonated with primacord. Each Shot for Line 1a was made up of 5, one-pound boosters strung together, and each shot for Line 1b was a sixty pound string of two-pound boosters. Line 2 employed shots of four 27 kg Geogel charges, with a string of nine charges for the two end shots.

All charges were detonated using GSC-developed high voltage blaster boxes with internal Nanometrics 501 clocks, which were rated relative to a GPS time signal before and after each deployment. This clock drift correction was then applied to the recorded data.

## 4.4 NAVIGATION

Navigation for Line 1 was facilitated by establishing the base camp as the centre of the line and then surveying in sites on either side using a surveyor's geodimeter and a portable Magellan GPS receiver at several reference points along the line. These reference points were re-surveyed before and after each of the two deployments in order to detect any possible ice movement. Although some ice movement was detected, it was less than the estimated +/-10 m accuracy of the positions.

Line 2 was planned using the GPS unit to project sites using the camp as the centre of the line, but the thin ice conditions necessary for shot sites dictated the final positions of the shots. The GPS unit was then used to project recorder sites along a line of best fit to the shot sites. The calculated locations were subsequently input as waypoints to the helicopter onboard GPS system for navigation to the sites. Because the GPS system was not used in differential mode, the positions are estimated to be accurate to +/-100 m. These locations were then refined using water wave analysis to arrive at final locations (as discussed in Section 7.1).

# 5. DATA PROCESSING IN THE FIELD

LithoSEIS software (a GSC-developed seismic data acquisition package) running on two Compaq 386 portable computers, was used to download shot windows to the PRS-1's and to upload the recorded data. The data were stored in LithoSEIS internal format on floppy diskettes and on DC-2000 tape cartridges. Due to hard disk problems with one computer, all data were transferred to the other computer before backup.

## 5.1 POWER SUPPLY

Two DC to AC power inverters, each connected to a 30 amp-hour deep cycle 12 volt battery, provided external power for the PC's. A 5 kW diesel generator was available as a backup power supply. The battery power supply worked well except during high load operations, such as running the PC's tape drive. During tape backup the generator was used to supply power to the PC's. It is recommended that in future a dedicated uninterruptable power supply be available as a power supply for the PC's.

## 5.2 TIMING CORRECTIONS

A Magnavox 4400 GPS clock receiver provided a time base accurate to +/-1 msec. Using a DREP-supplied converter, this time signal was modified to trigger the Nanometrics 500/501 clocks, and provided the time base for the PC's. The PRS-1's and the shooter boxes were all synchronized to GPS time before each deployment and the drift of their internal clocks was rated on return to the icecamp. Clock drift corrections were then applied to the data using LithoSEIS.

## 5.3 INSTRUMENT MALFUNCTIONS

All 64 PRS-1's worked flawlessly throughout the experiment, and no data was lost due to hardware failure. Past experience has shown that clock drift is dependent on total running time and on sudden temperature changes. To reduce thermally induced clock drift, the lag time between bringing the PRS-1's inside and when they were uploaded was minimized. Three of the internal clocks in the blaster boxes failed due to extended exposure to extreme cold during the deployment of line 1. As mentioned previously, one of the PC's experienced hard disk problems, so all resident data were transferred to the other machine.

## 6. DATA PROCESSING IN OTTAWA

After returning from the field, the data were transferred to tape in SEGY format. The data were then transferred to a Sun Sparcstation at the GSC, and converted to IT&A format. At this time, a 15 msec timing correction was applied to the traces of Line 2 to account for the detonation delay introduced by the 100 m of primacord used for these shots. The shots for Line 1 were detonated using a hard wired connection with negligible delay. The data were separated into shot gathers and line gathers, for plotting and analysis.

## 7. DATA ANALYSIS IN OTTAWA

On screen and hard copy plots of the data were used to identify and flag any traces with unacceptable noise levels or no visible seismic signal. In addition, water wave arrival picks were used in Rayinvr, a ray trace seismic refraction modelling program developed by C. Zelt (Zelt and Smith, 1992), in order to detect any shot or recorder location errors and to construct a bathymetry profile for the refraction lines.

### 7.1 WATER WAVE DATA AND BATHYMETRY

Due to the impulsive nature and uniform velocity of the water wave arrival, shotpoint to recording site distance errors of greater than about 20 m are usually detectable in the data, with clear reversed observations. Three types of errors are common with this type of refraction data. The first, and easiest to detect and correct, is a location error for one or more recorders. This error may be due to a poor GPS fix or to a typing error when entering the location into the LithoSEIS database. In closely spaced data, distance errors produce a single trace with an early or late arrival that will stand out among the other traces; large errors may even be noticeable on a map of recorder locations. By applying a suitable position change the trace can be corrected. The second type of error is an incorrect shot location. This will result in all water wave arrivals (primary and multiples) on all traces on one side of the shot being either early or late by an equal amount, while the arrivals on the other side of the shot have the same offset but in the opposite sense. Moving the shot towards the recorders with early arrivals (and thus away from the recorders with late arrivals) by the appropriate amount will correct this problem. The third error is an incorrect shot depth, which will create early or late arrivals for all traces, independent of which side of the shot they are on, and with progressively larger time errors with increasing order of multiple. Since up to 6 multiple events are clearly distinguished, the water wave analysis is very sensitive to both depth and location errors.

Using bathymetry data collected during the experiment as well as published bathymetry data, together with velocity-depth profiles of the arctic ocean compiled from data gathered during the experiment and from deeper historical data (Fig 4a.), 2-D water velocity models along the profiles were created. Due to the constraints of ray theory, the thin surface ice layer was not included in the models, but because of its thickness (averaging less than 4 m) and its relatively high velocity (3.5 km/s), the total time error introduced is less than 1.1 msec and is not significant over the modelled depth range. These models were used as preliminary models for Rayinvr. The first two types of errors, recorder location errors and shot location errors, are usually evident from plots of the water wave data, reduced at the average sound speed in the Arctic Ocean of 1.45 km/s. The third type, shot depth error, becomes very obvious when trying to model high order multiple arrivals. Indeed, preliminary modelling of all water wave arrivals provided excellent quality control of the final navigation data, and suggests that final positions are accurate to better than +/-50 m.

On Line 1 the recorders were positioned using a Geodimeter and are therefore considered to be quite accurately located. The shots, however, were dropped to depths in excess of 500 m, so although the surface location may be accurate, the location at depth could be in error on the order of tens of meters due to local currents and the dive angle of the shot as it dropped through the water. By modelling the data it was determined that the majority of the shots were almost consistently 20 to 30 m north of their measured locations, with one shot 80m north and another 40 m south. Water depth measurements were taken from the shot line and errors up to 100 m were estimated from modelling. Because of the differing frequency content of the recordings from the two lines (due to different shot sizes), and the differing shot locations (after correction), the two sets of data cannot be stacked. Instead, the two lines will be analyzed seperately, but considered complimentary to each other, and the final model will satisfy the arrivals for both deployments.

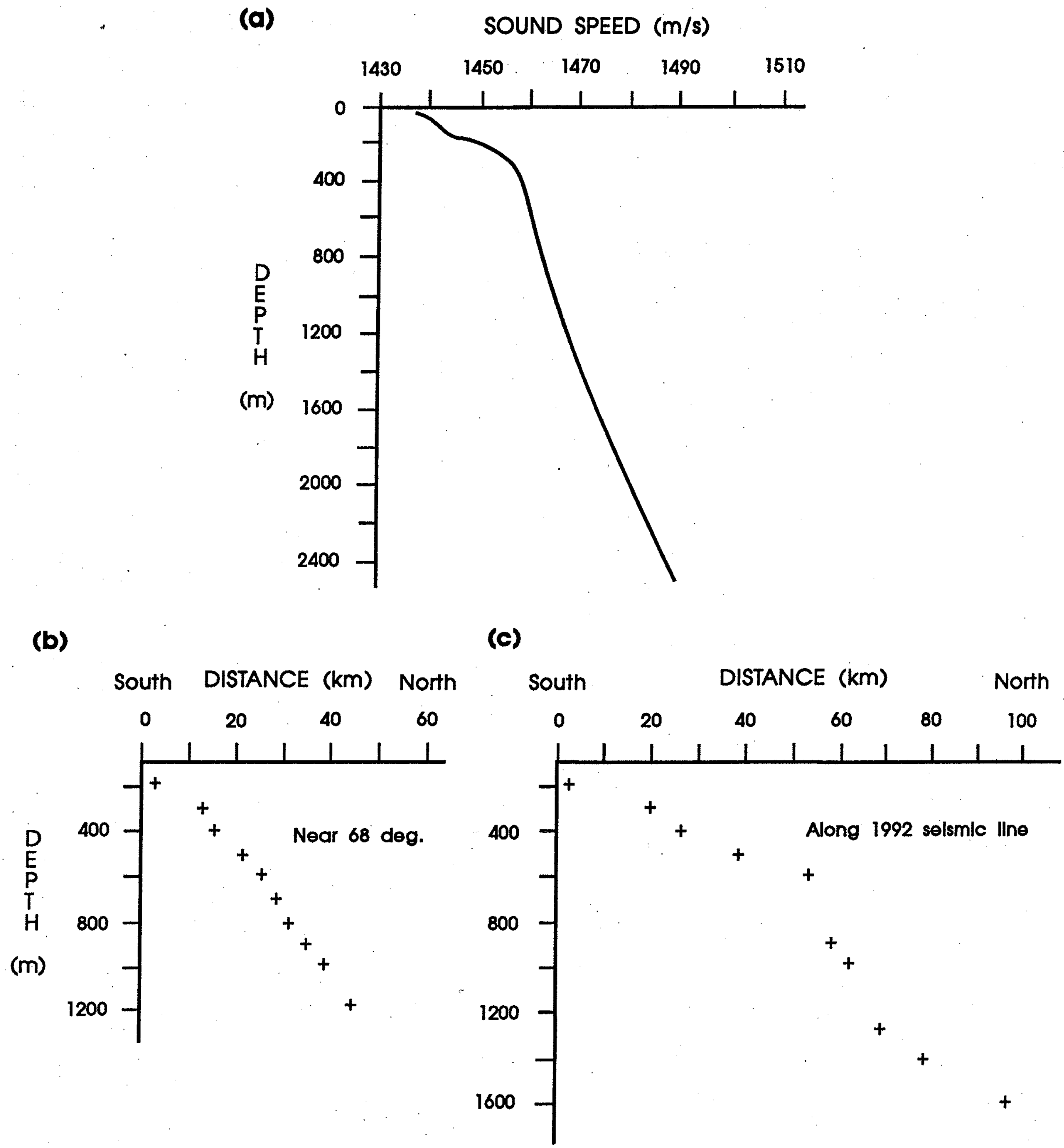


Figure 4. A typical Lincoln Sea sound speed in water v.s. depth profile is shown in (a), after Hughes and Berryman (1989); and two bathymetry profiles are shown from near 68 deg W. (b), and along the 1992 seismic line (c).

On Line 2 the GPS locations for the recorders are considered less accurate, and a few sites were estimated to be in error by up to 80 m (which is within the expected worst-case error of 100 m). The shot depths were well constrained, but the water depth was not, and had to be derived from the initial water bottom reflection and multiples within the seismic record. Using an iterative process, the starting model was used as input into Rayinvr, and the program output calculated travel times for all shots through the model. These times were compared to the recorded data, and the model was perturbed to improve the fit. This new perturbed model was then used as input to Rayinvr, and the process was repeated until a satisfactory fit was obtained for all multiples of all shots. At this point, individual recorder site locations in the database were moved only if it would result in an improved fit for all shots. This resulted in a number of sites being moved by less than 50 m. An interesting trend that emerged was that the majority of relocated sites were moved north relative to their original locations. One possible explanation for this is that when the PRS-1's were placed a distance away from the helicopter (to avoid having the seismometers blown over by rotor-wash) a common direction of travel was used.

For the offshore area, bathymetry data from the Geological Survey of Canada gravity data base, Canadian Hydrographic Service (CHS) field sheets 8182, 3499 and CHS Chart 7304 (used with the permission of CHS), and the 1992 seismic survey have been compiled in Fig.1. The seismic survey crosses the continental slope near a major apparent change in bathymetric gradient along the slope as indicated in Fig. 1. From the available data west of the seismic survey, between approximately $64^{o}$W and $72^{o}$W, the shelf-slope break suggests 2 steps beginning at about 300 m and at about 600 m (Fig. 4b). The inner step appears relatively short and is suspect given the paucity of data. The average apparent slope gradient is approximately 27m/km or about 1.5 degrees. Some 50 km to the east along the seismic survey line, 2 breaks in the continental slope appear more clearly, an inner break at a depth of about 300 m and an outer break at about 600 m (Fig. 4c), similar to the continental slope southwest of Nansen Sound. The shelf-slope break beginning at 300 m has a slope gradient of about .5 degrees to a depth of near 600 m, steepens to over 2.5 degrees to a depth near 1300 m and then decreases to about .6 degrees to the north. Other than suggesting a reasonably significant change, little can be resolved along strike of the shelf-slope break. The available bathymetry data to the east of the seismic survey are insufficient to provide any constraints.

## SUMMARY

During the spring of 1992, a seismic refraction survey was conducted by Defence Research Establishment Pacific, with advice, technical support and equipment of the Geological Survey of Canada. The seismic program was part of a multi-disciplinary, international scientific project, known as Iceshelf '92. The survey acquired the first seismic data from the Lincoln Sea area of Canada's High Arctic, north of Ellesmere Island.

The present seismic refraction data represent the only seismic constraints in this apparently complex region. Through careful analysis and raytrace modelling of the water wave arrivals and numerous multiple phases, a data set of excellent quality has been produced. Through further modelling, the acoustic properties of the water-shallow sediment interface, and underlying basement rocks, will be derived.

By combining the seismic results with available aeromagnetic and gravity data, as well as onshore geology, insight will be gained into the structure and tectonic history of this area.

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TABLE 1

SHOT DATA SUMMARY

| Line ID | Shot No. | Site No. | Dep Code | Shot ID | Shot Site | Shot Depth (m) | Bathymetry below ice surface (m) | Shot Weight (kg) | Shot Time jjj:hh:mm:ss | Shot Corr. (s) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1a | 1 | 1600 | CR02 | SH61 | SH03 | -580 | 580 | 0.9 | 106:22:15:00 | 0.000 |
| 1a | 2 | 1590 | CR02 | SH67 | SH04 | -570 | 570 | 0.9 | 106:23:45:00 | 0.000 |
| 1a | 3 | 1580 | CR01 | SH21 | 1055 | -561 | 561 | 0.9 | 106:00:00:00 | 0.000 |
| 1a | 4 | 1345 | CR01 | SH27 | 1031 | -538 | 538 | 0.9 | 106:01:30:00 | 0.002 |
| 1a | 5 | 1025 | CR01 | SH12 | 1001 | -540 | 540 | 0.9 | 105:21:45:00 | 0.000 |
| 1a | 6 | 1020 | CR02 | SH53 | SH02 | -545 | 545 | 0.9 | 106:20:15:00 | 0.000 |
| 1a | 7 | 1010 | CR02 | SH47 | SH01 | -510 | 510 | 0.9 | 106:18:45:00 | 0.000 |
| 1b | 1 | 1600 | CR02 | SH63 | SH03 | -580 | 580 | 27.7 | 106:22:45:00 | 0.000 |
| 1b | 2 | 1590 | CR02 | SH69 | SH04 | -570 | 570 | 27.7 | 107:00:15:00 | 0.000 |
| 1b | 3 | 1580 | CR01 | SH24 | 1055 | -561 | 561 | 27.7 | 106:00:45:00 | 0.001 |
| 1b | 4 | 1345 | CR01 | SH29 | 1031 | -538 | 538 | 27.7 | 106:02:00:00 | 0.003 |
| 1b | 5 | 1025 | CR01 | SH15 | 1001 | -540 | 540 | 27.7 | 105:22:30:00 | 0.000 |
| 1b | 6 | 1020 | CR02 | SH55 | SH02 | -545 | 545 | 27.7 | 106:20:45:00 | 0.000 |
| 1b | 7 | 1010 | CR02 | SH49 | SH01 | -510 | 510 | 27.7 | 106:19:15:00 | 0.000 |
| 2 | 1 | 1670 | Reg1 | SR07 | SHT0 | -100 | 1600 | 243.0 | 112:19:30:00 | 0.000 |
| 2 | 2 | 1560 | Reg1 | SR08 | SHT1 | -100 | 1450 | 108.0 | 112:19:45:00 | 0.000 |
| 2 | 3 | 1450 | Reg1 | SR09 | SHT2 | -100 | 1300 | 108.0 | 112:20:00:00 | 0.000 |
| 2 | 4 | 1310 | Reg1 | SR13 | SHT3 | -100 | 851 | 108.0 | 112:21:00:00 | 0.000 |
| 2 | 5 | 1240 | Reg1 | SR14 | SHT4 | -100 | 572 | 108.0 | 112:21:15:00 | 0.000 |
| 2 | 6 | 1120 | Reg1 | SR05 | SHT5 | -100 | 510 | 108.0 | 112:19:00:00 | 0.000 |
| 2 | 7 | 1010 | Reg1 | SR03 | SHT6 | -100 | 420 | 243.0 | 112:18:30:00 | 0.000 |

TABLE 2

SHOT AND RECEIVER LOCATIONS

| Site ID | Line ID | Site No. | Lat. (deg:min:sec) | Long. (deg:min:sec) | Site Elev.(m) |
|---|---|---|---|---|---|
| 1001 | 1 | 1030 | 083:53:35.40N | 063:02:31.80W | 0.0 |
| 1002 | 1 | 1040 | 083:53:37.20N | 063:02:31.80W | 0.0 |
| 1003 | 1 | 1050 | 083:53:39.00N | 063:02:31.80W | 0.0 |
| 1004 | 1 | 1060 | 083:53:40.20N | 063:02:31.80W | 0.0 |
| 1005 | 1 | 1070 | 083:53:42.00N | 063:02:31.80W | 0.0 |
| 1006 | 1 | 1080 | 083:53:43.80N | 063:02:31.80W | 0.0 |
| 1007 | 1 | 1090 | 083:53:45.60N | 063:02:31.80W | 0.0 |
| 1008 | 1 | 1100 | 083:53:47.40N | 063:02:31.80W | 0.0 |
| 1009 | 1 | 1110 | 083:53:48.60N | 063:02:31.80W | 0.0 |
| 1010 | 1 | 1120 | 083:53:50.40N | 063:02:31.80W | 0.0 |
| 1011 | 1 | 1130 | 083:53:52.20N | 063:02:31.80W | 0.0 |
| 1012 | 1 | 1140 | 083:53:53.40N | 063:02:31.80W | 0.0 |
| 1013 | 1 | 1150 | 083:53:55.20N | 063:02:31.80W | 0.0 |
| 1014 | 1 | 1160 | 083:53:57.00N | 063:02:31.80W | 0.0 |
| 1015 | 1 | 1170 | 083:53:58.80N | 063:02:31.80W | 0.0 |
| 1016 | 1 | 1180 | 083:54:00.60N | 063:02:31.80W | 0.0 |
| 1017 | 1 | 1190 | 083:54:02.40N | 063:02:31.80W | 0.0 |
| 1018 | 1 | 1200 | 083:54:04.20N | 063:02:31.80W | 0.0 |
| 1019 | 1 | 1210 | 083:54:05.40N | 063:02:31.80W | 0.0 |
| 1020 | 1 | 1220 | 083:54:07.20N | 063:02:31.80W | 0.0 |
| 1021 | 1 | 1230 | 083:54:09.00N | 063:02:31.80W | 0.0 |
| 1022 | 1 | 1240 | 083:54:10.80N | 063:02:31.80W | 0.0 |
| 1023 | 1 | 1250 | 083:54:12.00N | 063:02:31.80W | 0.0 |
| 1024 | 1 | 1260 | 083:54:13.80N | 063:02:31.80W | 0.0 |
| 1025 | 1 | 1270 | 083:54:15.60N | 063:02:31.80W | 0.0 |
| 1026 | 1 | 1280 | 083:54:16.80N | 063:02:31.80W | 0.0 |
| 1027 | 1 | 1290 | 083:54:18.60N | 063:02:31.80W | 0.0 |
| 1028 | 1 | 1300 | 083:54:20.40N | 063:02:31.80W | 0.0 |
| 1029 | 1 | 1310 | 083:54:21.60N | 063:02:31.80W | 0.0 |
| 1030 | 1 | 1320 | 083:54:23.40N | 063:02:31.80W | 0.0 |
| 1031 | 1 | 1330 | 083:54:25.20N | 063:02:31.80W | 0.0 |
| 1032 | 1 | 1340 | 083:54:27.00N | 063:02:31.80W | 0.0 |

TABLE 2 (cont'd)

SHOT AND RECEIVER LOCATIONS

| Site ID | Line ID | Site No. | Lat. (deg:min:sec) | Long. (deg:min:sec) | Site Elev.(m) |
|---|---|---|---|---|---|
| 1033 | 1 | 1350 | 083:54:28.20N | 063:02:31.80W | 0.0 |
| 1034 | 1 | 1360 | 083:54:30.00N | 063:02:31.80W | 0.0 |
| 1035 | 1 | 1370 | 083:54:31.80N | 063:02:31.80W | 0.0 |
| 1036 | 1 | 1380 | 083:54:33.60N | 063:02:31.80W | 0.0 |
| 1037 | 1 | 1390 | 083:54:34.80N | 063:02:31.80W | 0.0 |
| 1038 | 1 | 1400 | 083:54:36.60N | 063:02:31.80W | 0.0 |
| 1039 | 1 | 1410 | 083:54:37.80N | 063:02:31.80W | 0.0 |
| 1040 | 1 | 1420 | 083:54:39.60N | 063:02:31.80W | 0.0 |
| 1041 | 1 | 1430 | 083:54:41.40N | 063:02:31.80W | 0.0 |
| 1042 | 1 | 1440 | 083:54:43.20N | 063:02:31.80W | 0.0 |
| 1043 | 1 | 1450 | 083:54:44.40N | 063:02:31.80W | 0.0 |
| 1044 | 1 | 1460 | 083:54:46.20N | 063:02:31.80W | 0.0 |
| 1045 | 1 | 1470 | 083:54:47.40N | 063:02:31.80W | 0.0 |
| 1046 | 1 | 1480 | 083:54:49.20N | 063:02:31.80W | 0.0 |
| 1047 | 1 | 1490 | 083:54:51.00N | 063:02:31.80W | 0.0 |
| 1048 | 1 | 1500 | 083:54:52.80N | 063:02:31.80W | 0.0 |
| 1049 | 1 | 1510 | 083:54:54.60N | 063:02:31.80W | 0.0 |
| 1050 | 1 | 1520 | 083:54:56.40N | 063:02:31.80W | 0.0 |
| 1051 | 1 | 1530 | 083:54:57.60N | 063:02:31.80W | 0.0 |
| 1052 | 1 | 1540 | 083:54:58.80N | 063:02:31.80W | 0.0 |
| 1053 | 1 | 1550 | 083:55:00.60N | 063:02:31.80W | 0.0 |
| 1054 | 1 | 1560 | 083:55:02.40N | 063:02:31.80W | 0.0 |
| 1055 | 1 | 1570 | 083:55:03.60N | 063:02:31.80W | 0.0 |

TABLE 2 (cont'd)

SHOT AND RECEIVER LOCATIONS

| Site ID | Line ID | Site No. | Lat. (deg:min:sec) | Long. (deg:min:sec) | Site Elev.(m) |
|---|---|---|---|---|---|
| 3001 | 2 | 1660 | 084:15:48.00N | 063:02:18.00W | 0.0 |
| 3002 | 2 | 1650 | 084:15:14.40N | 063:02:54.00W | 0.0 |
| 3003 | 2 | 1640 | 084:14:40.20N | 063:02:21.00W | 0.0 |
| 3004 | 2 | 1630 | 084:14:07.20N | 063:02:01.54W | 0.0 |
| 3005 | 2 | 1620 | 084:13:30.00N | 063:02:00.00W | 0.0 |
| 3006 | 2 | 1610 | 084:13:04.80N | 063:01:48.00W | 0.0 |
| 3007 | 2 | 1600 | 084:12:35.40N | 063:02:00.00W | 0.0 |
| 3008 | 2 | 1590 | 084:11:59.40N | 063:01:38.40W | 0.0 |
| 3009 | 2 | 1580 | 084:11:31.20N | 063:01:23.40W | 0.0 |
| 3010 | 2 | 1570 | 084:10:54.60N | 063:01:12.60W | 0.0 |
| 3011 | 2 | 1550 | 084:10:22.01N | 063:00:56.40W | 0.0 |
| 3012 | 2 | 1540 | 084:09:51.60N | 063:01:19.80W | 0.0 |
| 3013 | 2 | 1530 | 084:09:15.60N | 063:00:34.80W | 0.0 |
| 3014 | 2 | 1520 | 084:08:45.00N | 063:01:26.40W | 0.0 |
| 3015 | 2 | 1510 | 084:08:16.20N | 063:00:51.00W | 0.0 |
| 3016 | 2 | 1500 | 084:07:39.00N | 063:00:37.20W | 0.0 |
| 3017 | 2 | 1490 | 084:07:02.86N | 063:00:54.60W | 0.0 |
| 3018 | 2 | 1480 | 084:06:38.53N | 062:57:58.80W | 0.0 |
| 3019 | 2 | 1470 | 084:06:04.24N | 062:59:46.20W | 0.0 |
| 3020 | 2 | 1460 | 084:05:28.20N | 063:00:26.40W | 0.0 |
| 3021 | 2 | 1440 | 084:04:51.55N | 062:59:52.20W | 0.0 |
| 3022 | 2 | 1430 | 084:04:26.35N | 062:59:05.40W | 0.0 |
| 3023 | 2 | 1420 | 084:03:52.89N | 063:00:08.40W | 0.0 |
| 3024 | 2 | 1410 | 084:03:15.69N | 062:59:36.00W | 0.0 |
| 3025 | 2 | 1400 | 084:02:45.00N | 062:58:44.40W | 0.0 |
| 3026 | 2 | 1390 | 084:02:22.38N | 062:59:13.80W | 0.0 |
| 3027 | 2 | 1380 | 084:01:41.40N | 062:59:13.20W | 0.0 |
| 3028 | 2 | 1370 | 084:01:07.80N | 062:59:01.20W | 0.0 |
| 3029 | 2 | 1360 | 084:00:34.01N | 062:58:48.60W | 0.0 |
| 3030 | 2 | 1350 | 084:00:06.69N | 062:58:46.20W | 0.0 |
| 3031 | 2 | 1340 | 083:59:34.76N | 062:58:20.40W | 0.0 |
| 3032 | 2 | 1330 | 083:59:02.96N | 062:57:36.60W | 0.0 |
| 3033 | 2 | 1320 | 083:58:26.72N | 062:57:34.80W | 0.0 |
| 3034 | 2 | 1300 | 083:57:55.24N | 062:58:19.20W | 0.0 |

TABLE 2 (cont'd)

SHOT AND RECEIVER LOCATIONS

| Site ID | Line ID | Site No. | Lat. (deg:min:sec) | Long. (deg:min:sec) | Site Elev.(m) |
|---|---|---|---|---|---|
| 3035 | 2 | 1290 | 083:57:24.41N | 062:58:17.40W | 0.0 |
| 3036 | 2 | 1280 | 083:56:55.24N | 062:57:56.40W | 0.0 |
| 3037 | 2 | 1270 | 083:56:22.24N | 062:57:15.60W | 0.0 |
| 3038 | 2 | 1260 | 083:55:46.20N | 062:57:12.60W | 0.0 |
| 3039 | 2 | 1250 | 083:55:12.00N | 062:57:57.00W | 0.0 |
| 3040 | 2 | 1230 | 083:54:37.84N | 062:57:06.00W | 0.0 |
| 3041 | 2 | 1220 | 083:54:12.00N | 062:57:10.80W | 0.0 |
| 3042 | 2 | 1210 | 083:53:28.84N | 062:57:24.60W | 0.0 |
| 3043 | 2 | 1200 | 083:53:06.04N | 062:56:56.40W | 0.0 |
| 3044 | 2 | 1190 | 083:52:35.49N | 062:56:55.80W | 0.0 |
| 3045 | 2 | 1180 | 083:51:55.20N | 062:56:08.40W | 0.0 |
| 3046 | 2 | 1170 | 083:51:31.80N | 062:56:37.20W | 0.0 |
| 3047 | 2 | 1160 | 083:50:58.29N | 062:56:26.40W | 0.0 |
| 3048 | 2 | 1150 | 083:50:23.81N | 062:56:38.40W | 0.0 |
| 3049 | 2 | 1140 | 083:49:49.33N | 062:56:15.00W | 0.0 |
| 3050 | 2 | 1130 | 083:49:13.80N | 062:56:19.20W | 0.0 |
| 3051 | 2 | 1110 | 083:48:47.40N | 062:56:39.00W | 0.0 |
| 3052 | 2 | 1100 | 083:48:10.67N | 062:56:49.80W | 0.0 |
| 3053 | 2 | 1090 | 083:47:39.60N | 062:56:18.60W | 0.0 |
| 3054 | 2 | 1080 | 083:47:05.40N | 062:56:36.00W | 0.0 |
| 3055 | 2 | 1070 | 083:46:40.20N | 062:56:06.60W | 0.0 |
| 3056 | 2 | 1060 | 083:46:07.20N | 062:55:52.80W | 0.0 |
| 3057 | 2 | 1050 | 083:45:32.21N | 062:55:28.80W | 0.0 |
| 3058 | 2 | 1040 | 083:45:01.25N | 062:55:29.40W | 0.0 |
| 3059 | 2 | 1030 | 083:44:26.40N | 062:55:20.40W | 0.0 |
| 3060 | 2 | 1020 | 083:43:56.40N | 062:55:39.00W | 0.0 |

TABLE 2 (cont'd)

SHOT AND RECEIVER LOCATIONS

| Site ID | Line ID | Site No. | Lat. (deg:min:sec) | Long. (deg:min:sec) | Site Elev.(m) |
|---|---|---|---|---|---|
| SH01 | 1a | 1010 | 083:51:52.57N | 063:03:54.00W | -510.0 |
| SH02 | 1a | 1020 | 083:52:40.57N | 063:03:25.80W | -545.0 |
| SH03 | 1a | 1600 | 083:56:30.64N | 063:02:28.80W | -580.0 |
| SH04 | 1a | 1590 | 083:55:55.84N | 063:00:09.60W | -570.0 |
| SH05 | 1a | 1025 | 083:53:35.08N | 063:02:31.80W | -540.0 |
| SH06 | 1a | 1345 | 083:54:25.84N | 063:02:31.80W | -538.0 |
| SH07 | 1a | 1580 | 083:55:03.60N | 063:02:31.80W | -561.0 |
| SH01 | 1b | 1010 | 083:51:52.57N | 063:03:54.00W | -510.0 |
| SH02 | 1b | 1020 | 083:52:39.60N | 063:03:25.80W | -545.0 |
| SH03 | 1b | 1600 | 083:56:30.32N | 063:02:28.80W | -580.0 |
| SH04 | 1b | 1590 | 083:55:55.84N | 063:00:09.60W | -570.0 |
| SH05 | 1b | 1025 | 083:53:34.11N | 063:02:31.80W | -540.0 |
| SH06 | 1b | 1345 | 083:54:26.17N | 063:02:31.80W | -538.0 |
| SH07 | 1b | 1580 | 083:55:06.18N | 063:02:31.80W | -561.0 |
| SHT0 | 2 | 1670 | 084:20:03.01N | 063:02:16.80W | -100.0 |
| SHT1 | 2 | 1560 | 084:10:25.80N | 063:01:09.00W | -100.0 |
| SHT2 | 2 | 1450 | 084:05:06.00N | 063:00:44.40W | -100.0 |
| SHT3 | 2 | 1310 | 083:58:24.00N | 063:04:00.60W | -100.0 |
| SHT4 | 2 | 1240 | 083:55:01.80N | 063:01:58.20W | -100.0 |
| SHT5 | 2 | 1120 | 083:48:52.80N | 063:00:49.20W | -100.0 |
| SHT6 | 2 | 1010 | 083:42:52.20N | 062:55:19.20W | -100.0 |

TABLE 3

CORRECTIONS TO SITE BATHYMETRY AND LOCATIONS

| Site No. | Line ID | Distance Moved (m) | Depth Moved (m) | Site No. | Line ID | Distance Moved (m) | Depth Moved (m) |
|---|---|---|---|---|---|---|---|
| 1600 | 1a | 20 N | +100 | 1200 | 2 | 20 N | 0 |
| 1590 | 1a | 20 N | +70 | 1210 | 2 | 20 N | 0 |
| 1345 | 1a | 20 N | 0 | 1230 | 2 | 20 N | 0 |
| 1025 | 1a | 10 S | 0 | 1270 | 2 | 20 N | 0 |
| 1020 | 1a | 30 N | 0 | 1280 | 2 | 20 N | 0 |
| 1010 | 1a | 30 N | +42 | 1290 | 2 | 50 N | 0 |
| | | | | 1300 | 2 | 20 N | 0 |
| 1600 | 1b | 10 N | +100 | 1320 | 2 | 10 N | 0 |
| 1590 | 1b | 20 N | +70 | 1330 | 2 | 20 S | 0 |
| 1580 | 1b | 80 N | 0 | 1340 | 2 | 20 S | 0 |
| 1345 | 1b | 30 N | 0 | 1350 | 2 | 40 N | 0 |
| 1025 | 1b | 40 S | 0 | 1360 | 2 | 50 N | 0 |
| 1010 | 1b | 30 N | +42 | 1390 | 2 | 80 N | 0 |
| | | | | 1410 | 2 | 40 N | 0 |
| 1040 | 2 | 20 N | 0 | 1420 | 2 | 40 N | 0 |
| 1050 | 2 | 50 N | 0 | 1430 | 2 | 110 N | 0 |
| 1100 | 2 | 60 S | 0 | 1440 | 2 | 20 S | 0 |
| 1140 | 2 | 60 N | 0 | 1470 | 2 | 20 N | 0 |
| 1150 | 2 | 50 N | 0 | 1480 | 2 | 60 N | 0 |
| 1160 | 2 | 40 N | 0 | 1490 | 2 | 70 N | 0 |
| 1190 | 2 | 40 N | 0 | 1550 | 2 | 50 N | 0 |

# APPENDIX A - PARTICIPANTS LIST

## Scientific Personnel

| | |
|---|---|
| Gary Brooke | Defence Research Establishment Pacific |
| Stan Dosso | Defence Research Establishment Pacific |
| Del Huston | Defence Research Establishment Pacific |

## Technical Personnel

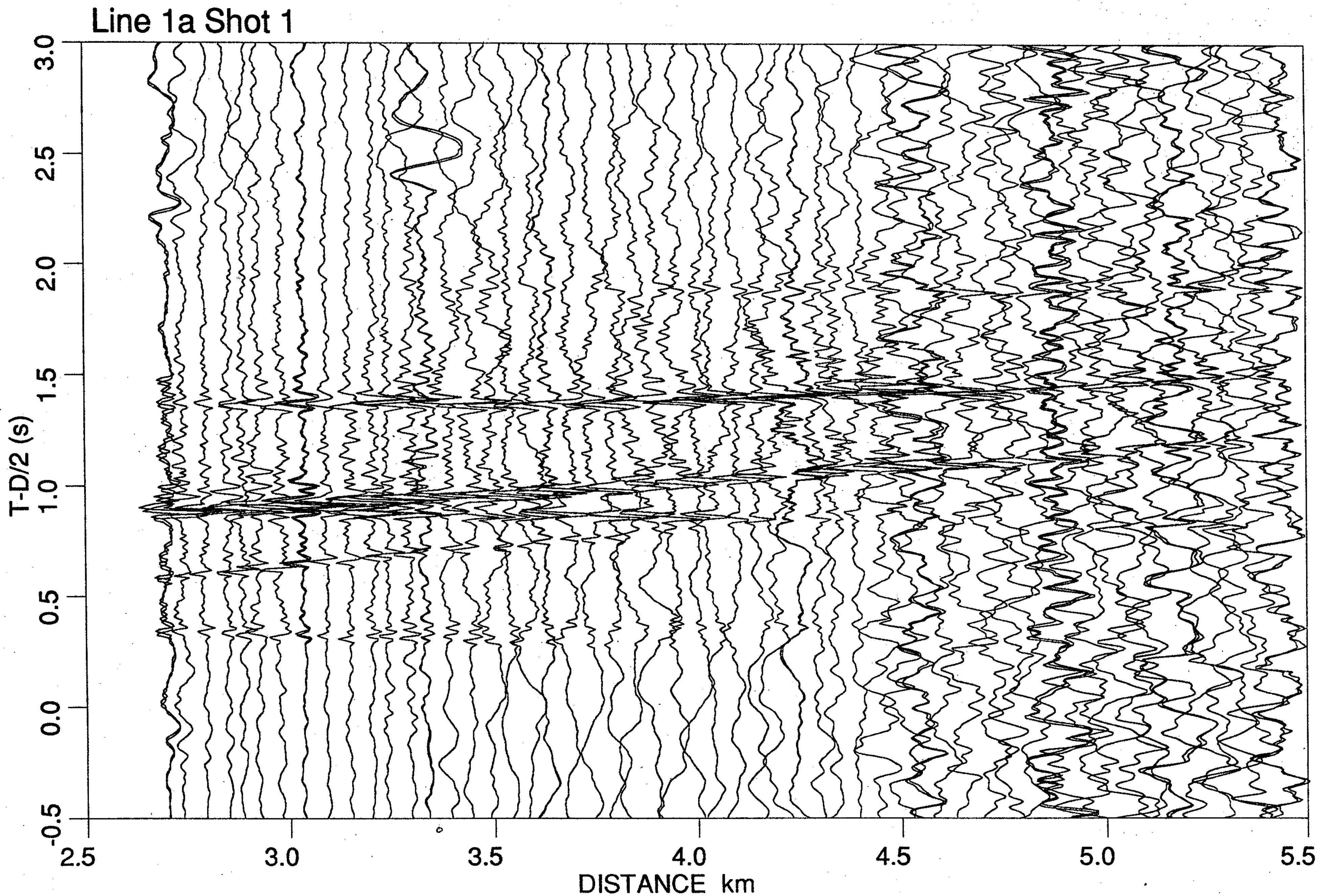
| | |
|---|---|
| Tim Cartwright | 165868 Canada Inc. |
| Brendan Donald | Defence Research Establishment Pacific |
| Dave Holland | Canadian Armed Forces |
| Jack Kristenson | Canadian Armed Forces |
| Jim Perkins | Defence Research Establishnnment Pacific |

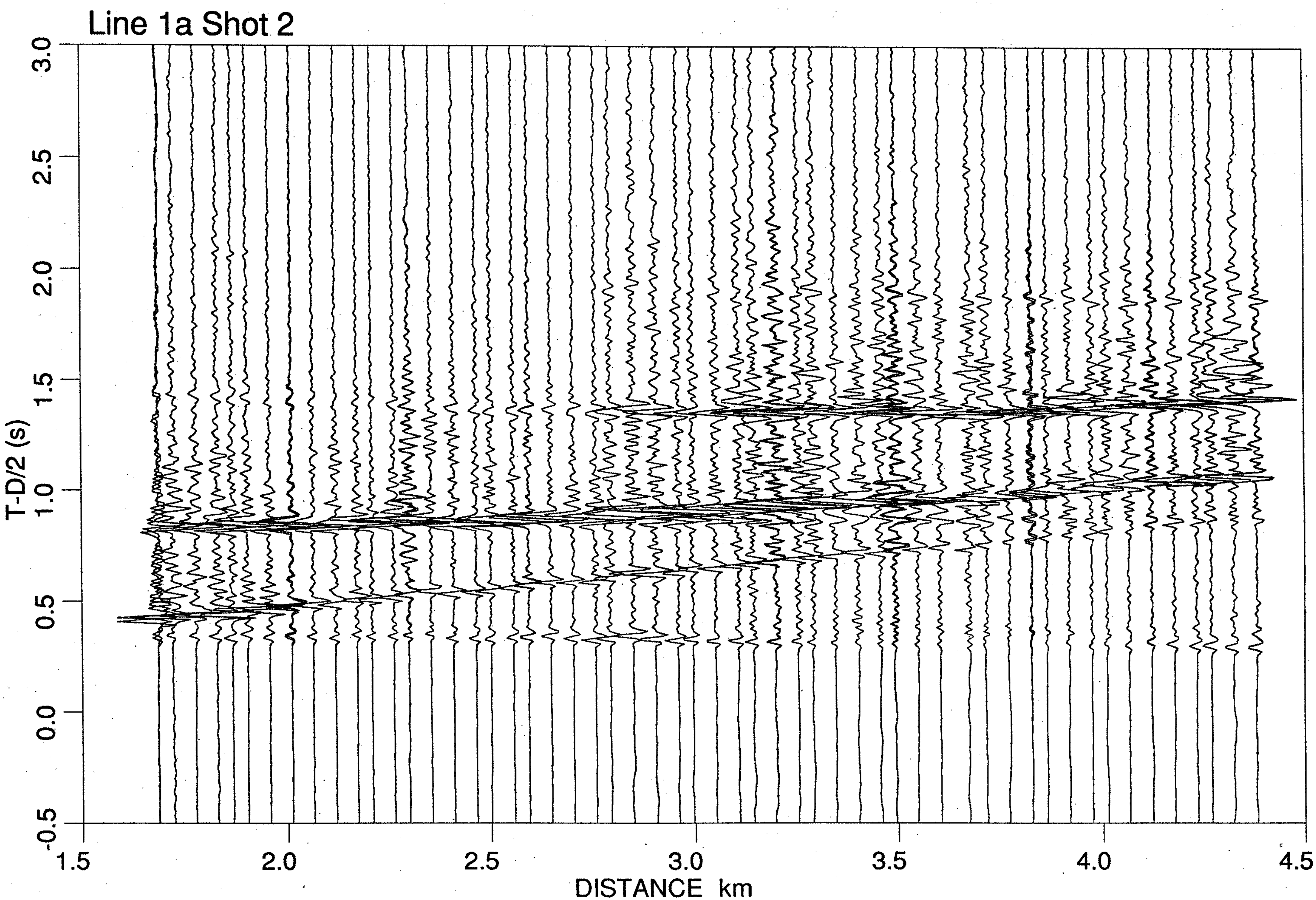
## Scientific and Technical Advice

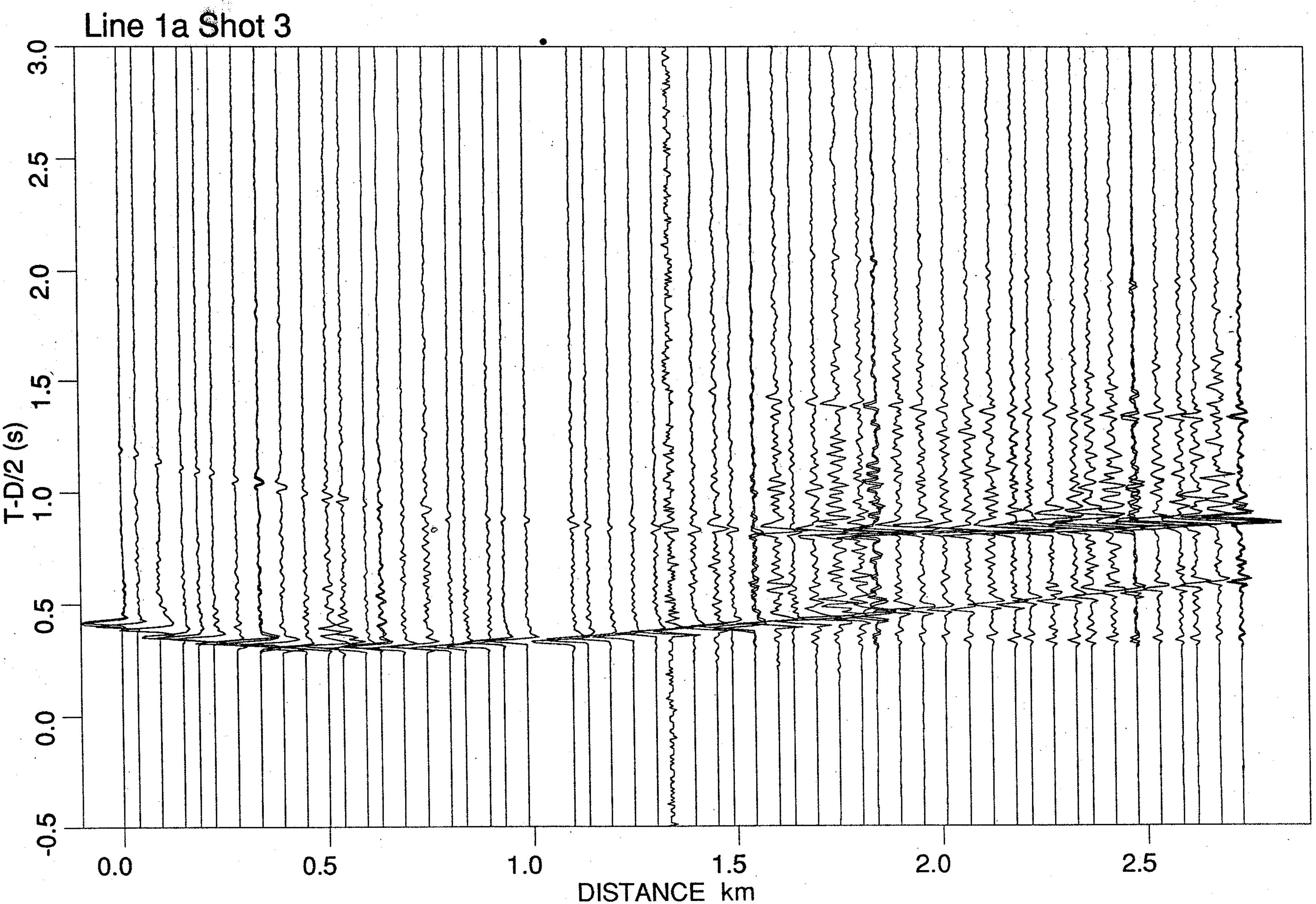
| | |
|---|---|
| Isa Asudeh | Geological Survey of Canada |
| Dave Forsyth | Geological Survey of Canada |

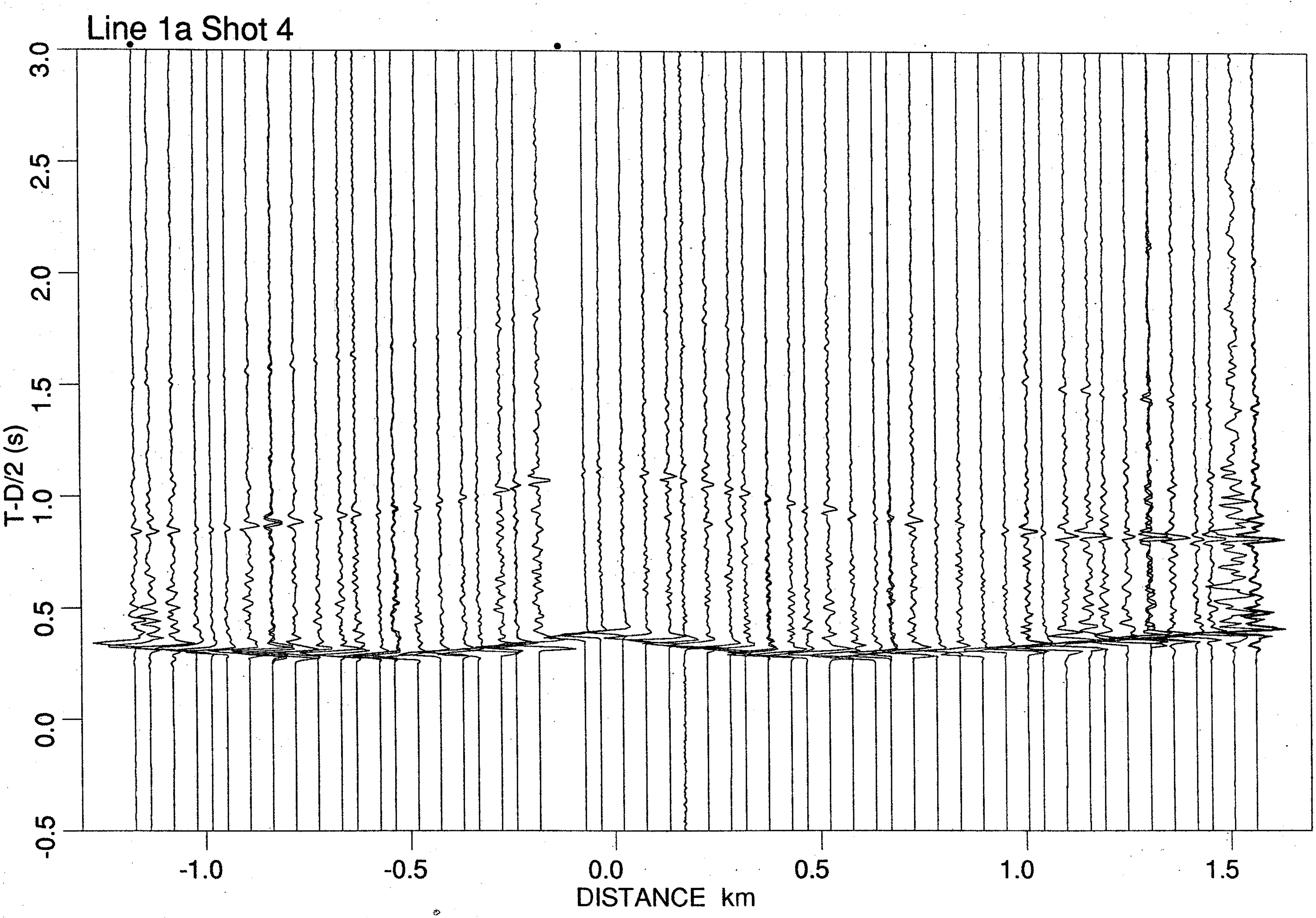
## APPENDIX B - LINE 1A SEISMIC DATA SECTIONS REDUCED AT 2.0 KM/S

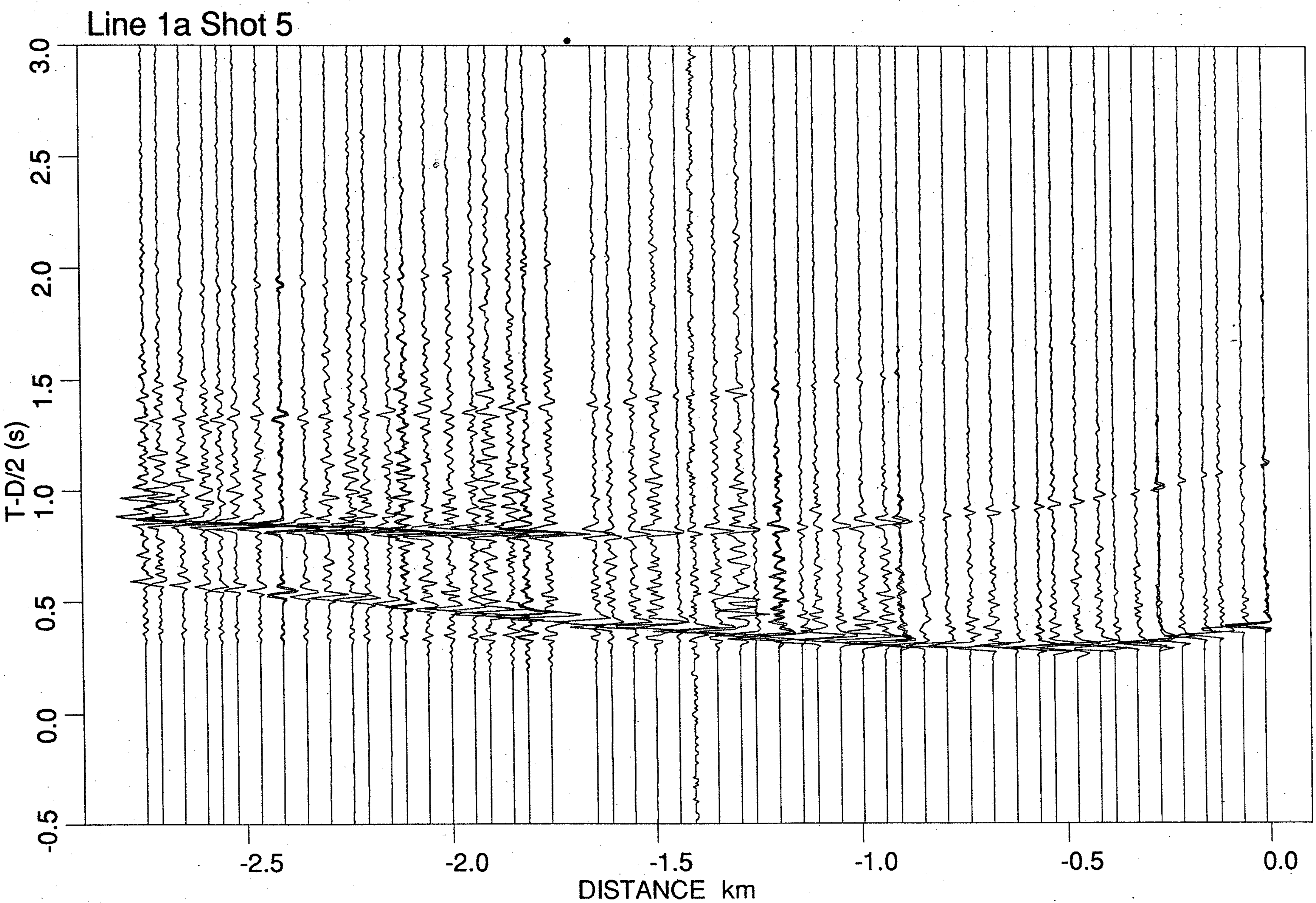
Seismic sections for Line 1a reduced at 2.0 km/s, showing the shallow sediment arrival and high amplitude water wave event, with several later multiples evident. Distance is relative to the shot point and positive towards the south. Amplitudes are trace-normalized.


Line 1a Shot 1
T-D/2 (s)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
2.5
3.0
3.5
4.0
4.5
5.0
5.5
DISTANCE km


Line 1a Shot 2
T-D/2 (s)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
1.5
2.0
2.5
3.0
3.5
4.0
4.5
DISTANCE km

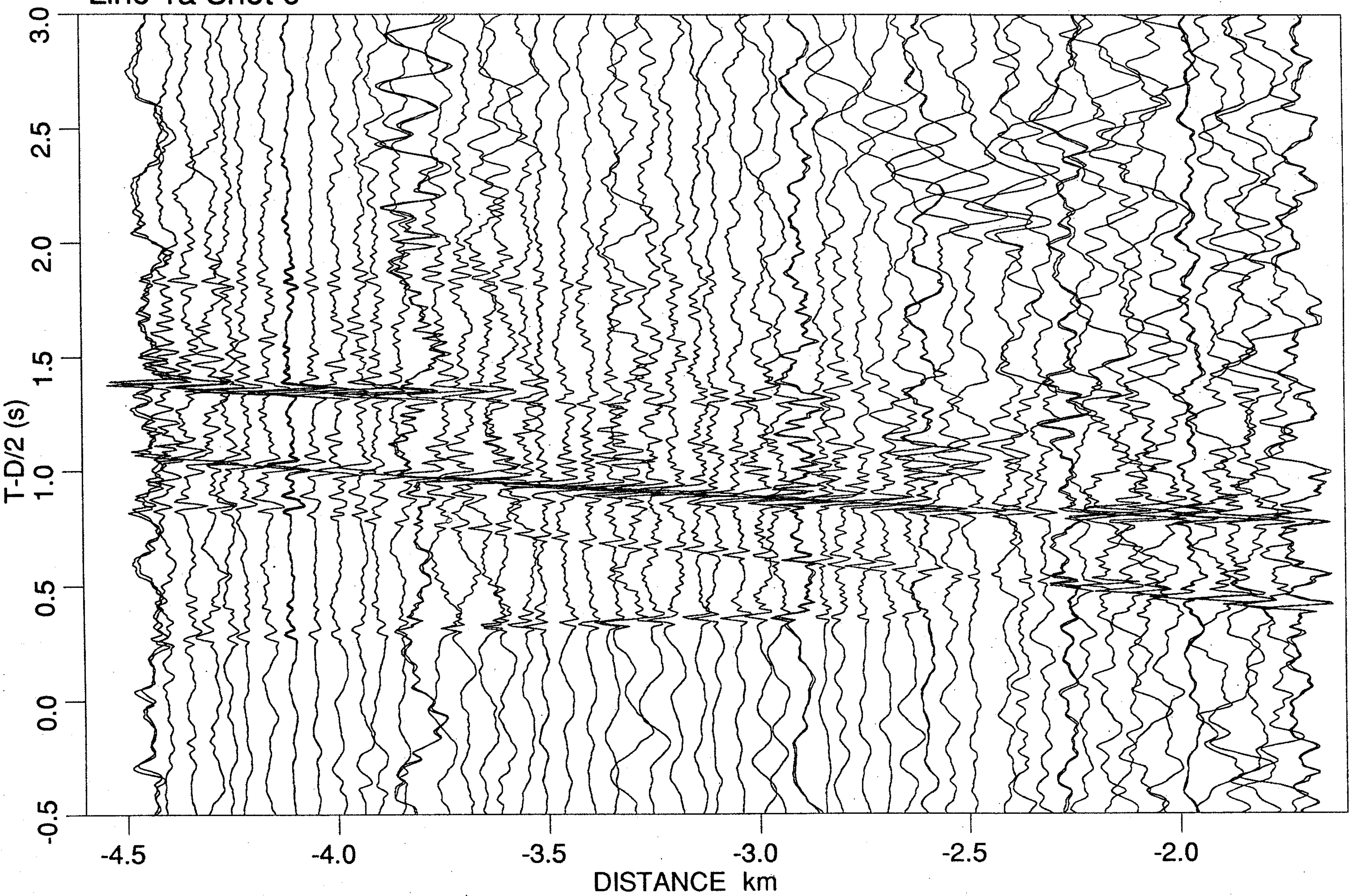

Line 1a Shot 3
T-D/2 (s)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
DISTANCE km


Line 1a Shot 4
T-D/2 (s)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-0.5
0.0
0.5
1.0
1.5
DISTANCE km

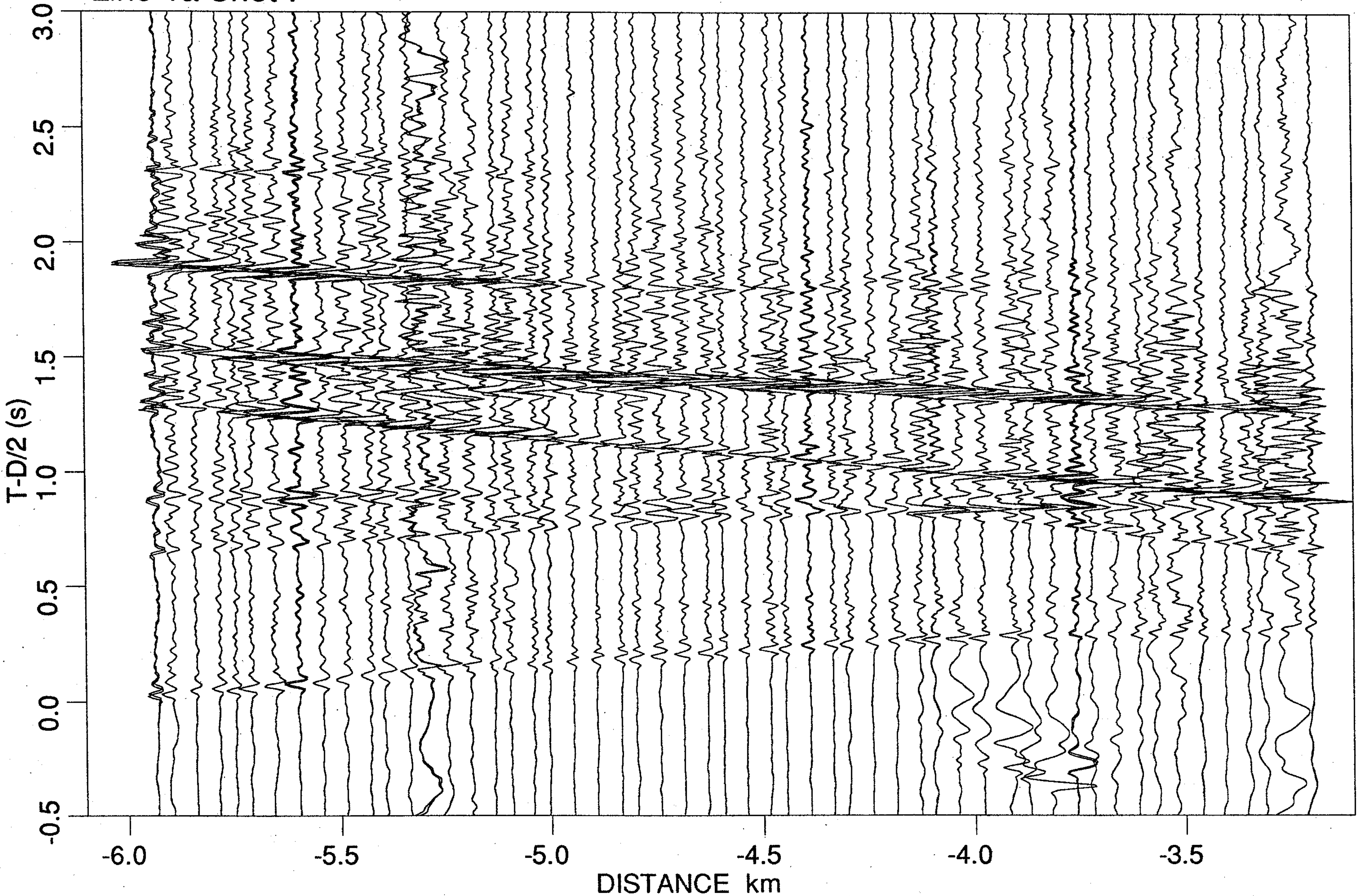


Line 1a Shot 5
T-D/2 (s)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
DISTANCE km

Line 1a Shot 6



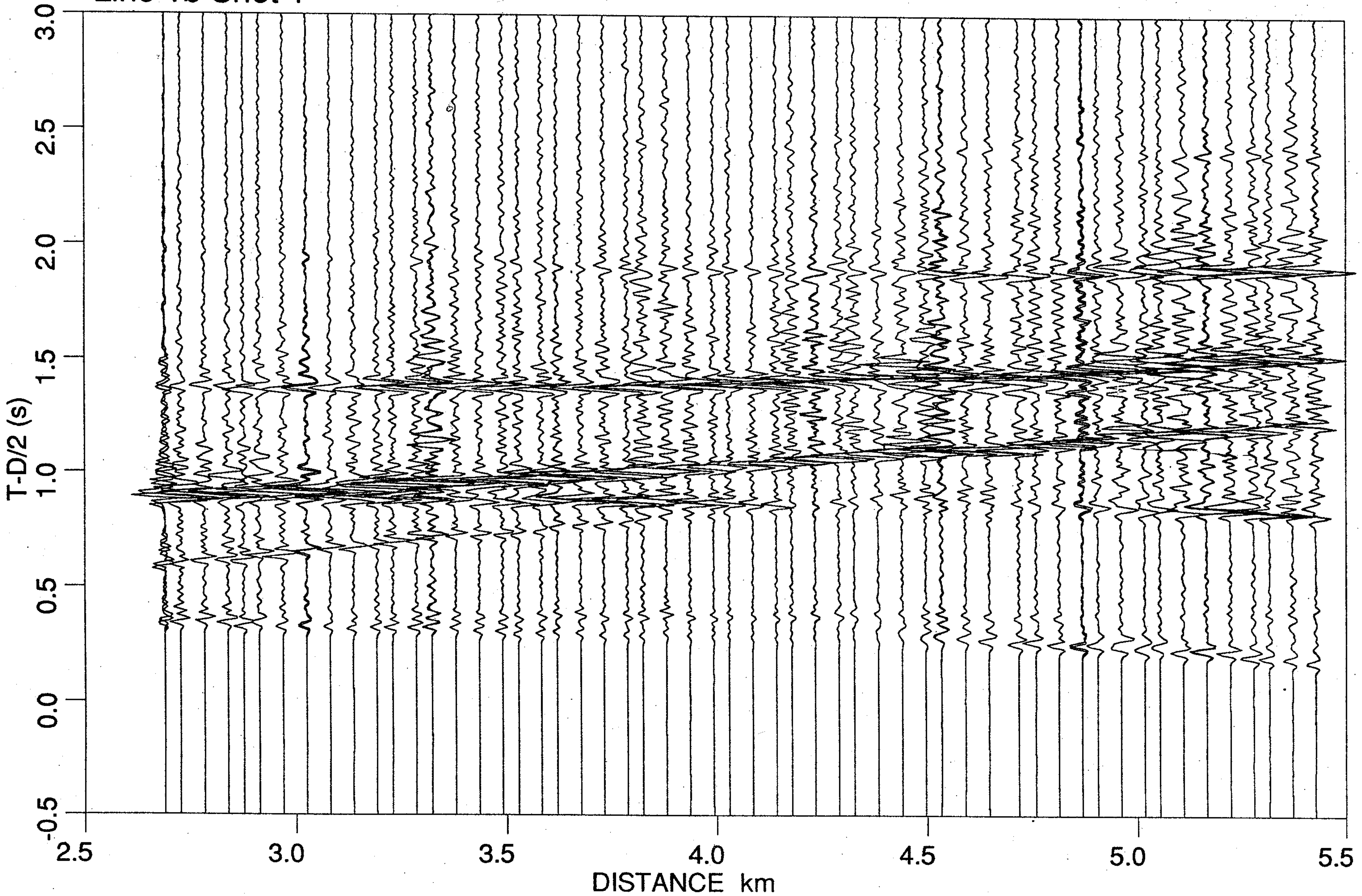
Line 1a Shot 7



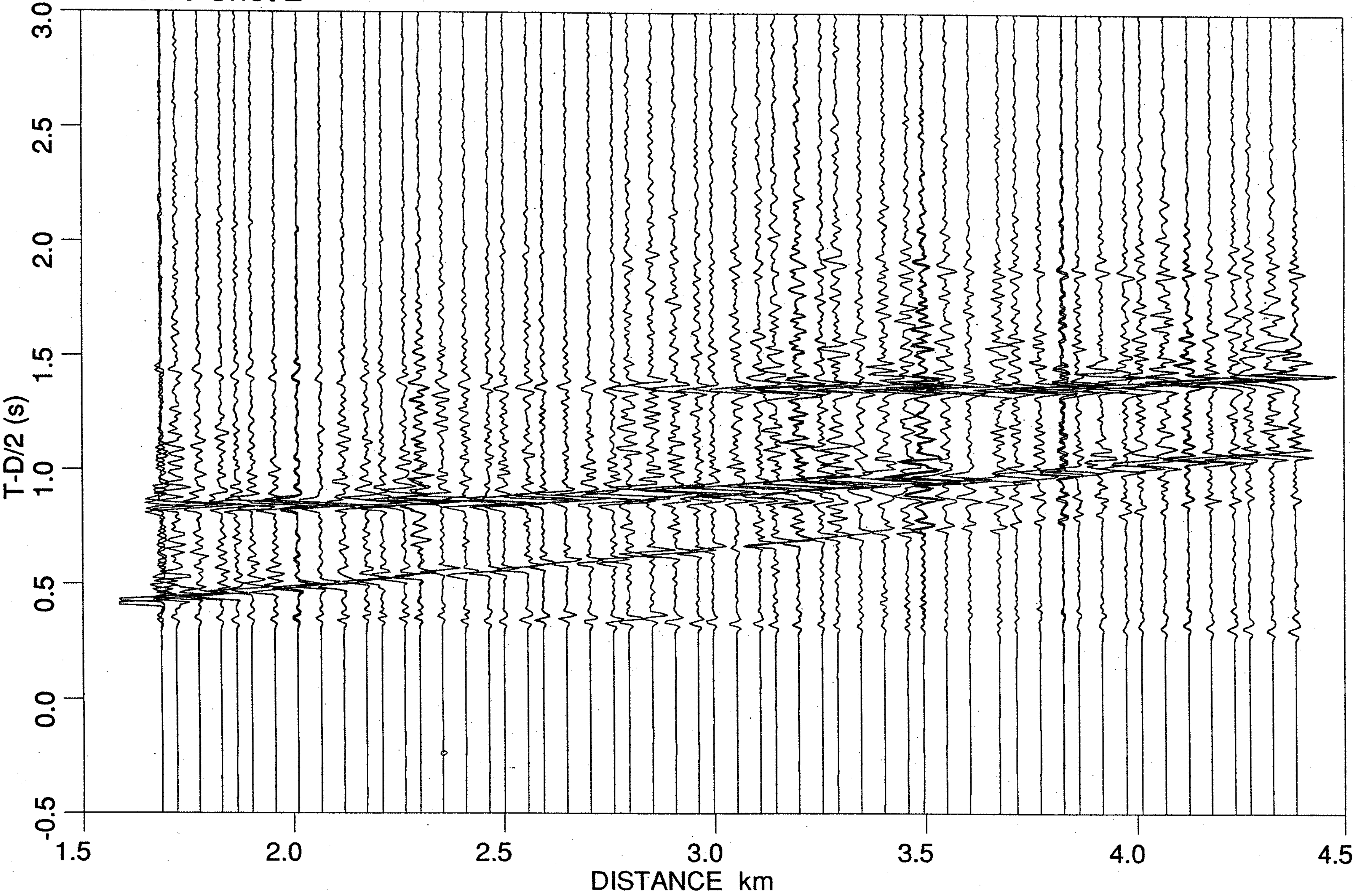
# APPENDIX C - LINE 1B SEISMIC DATA SECTIONS REDUCED AT 2.0 KM/S

Seismic sections for Line 1b reduced at 2.0 km/s, showing the shallow sediment arrival and high amplitude water wave event, with several later multiples evident. Distance is relative to the shot point and positive towards the south. Amplitudes are trace-normalized.

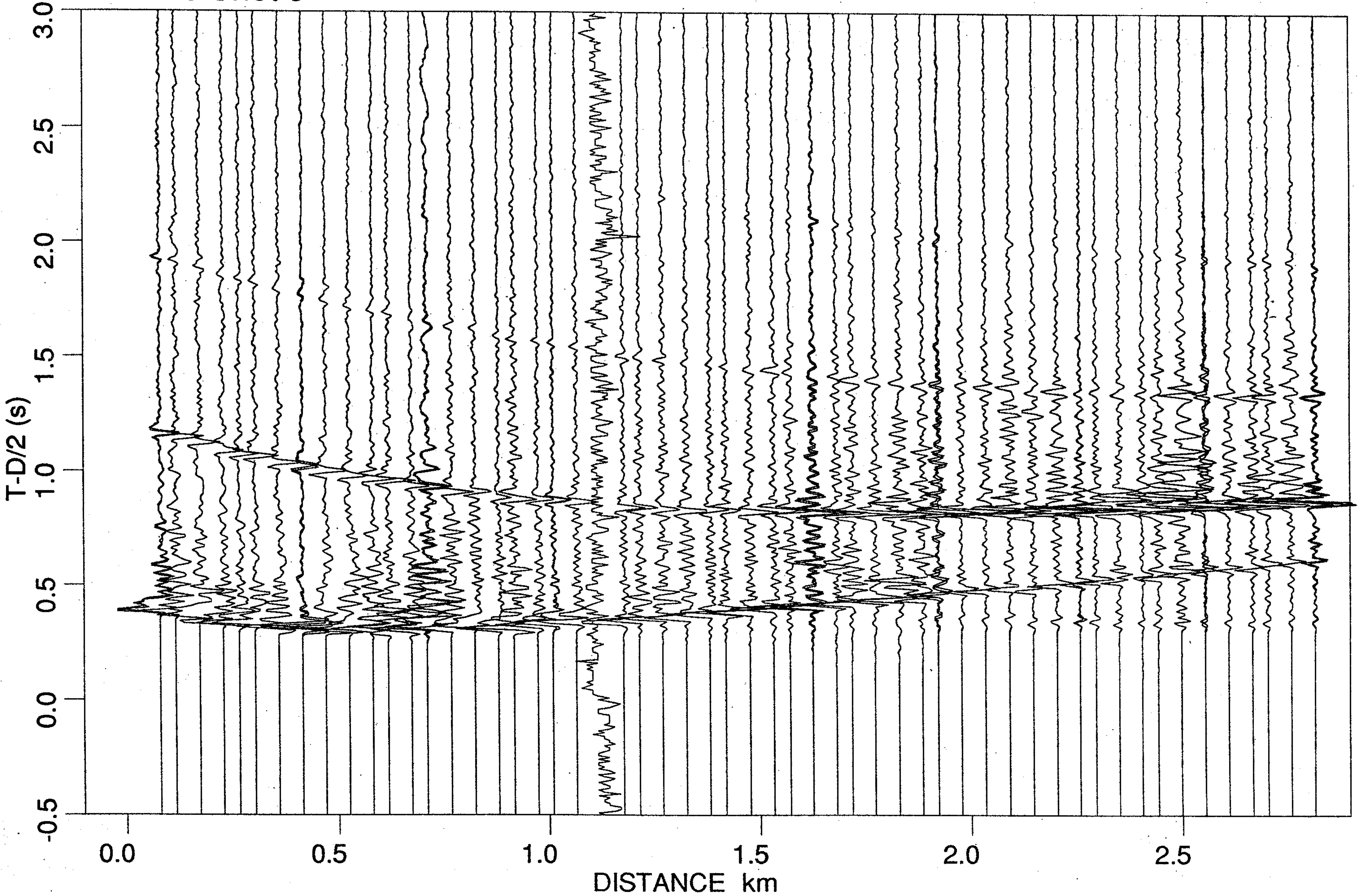
Line 1b Shot 1

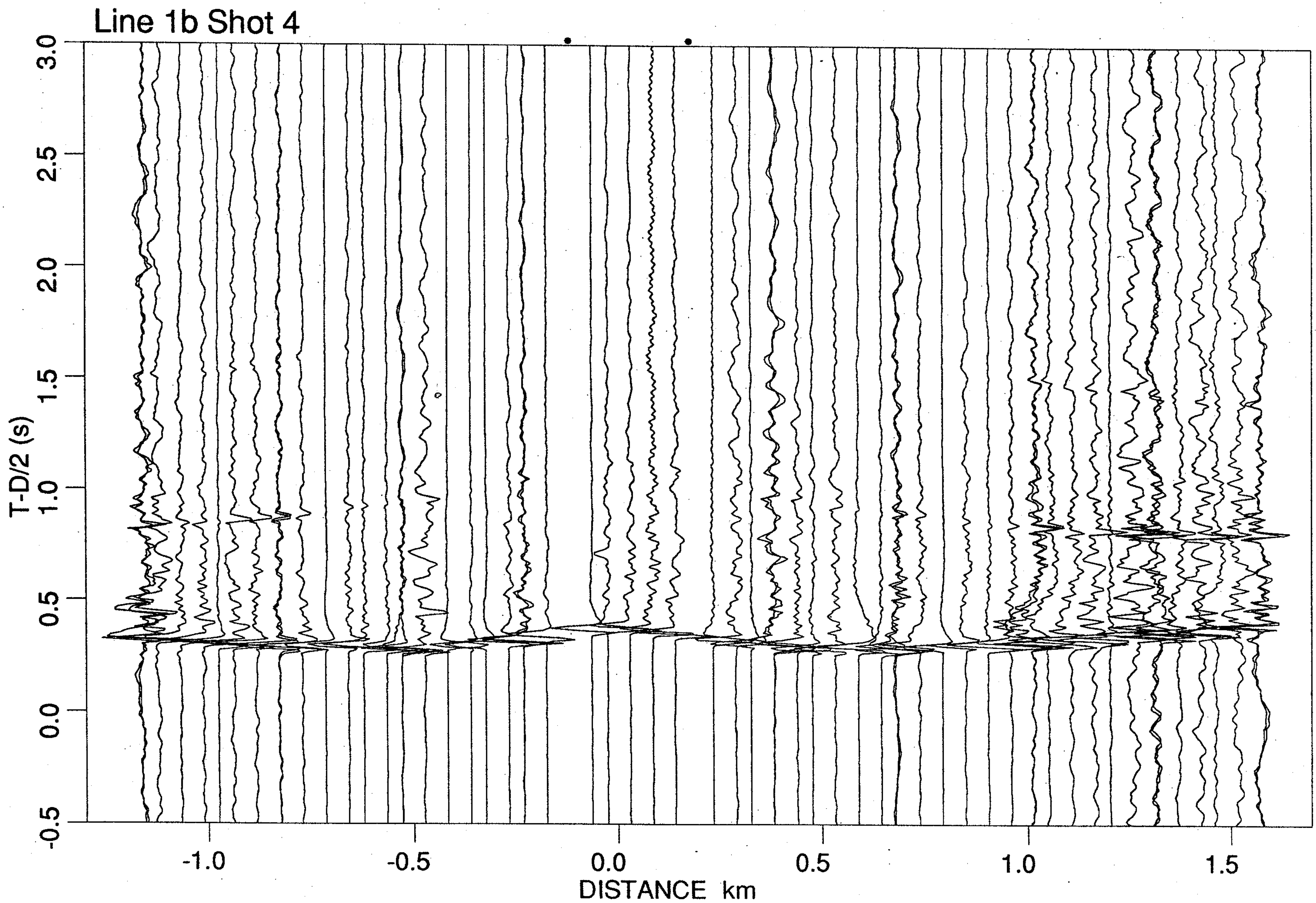


Line 1b Shot 2

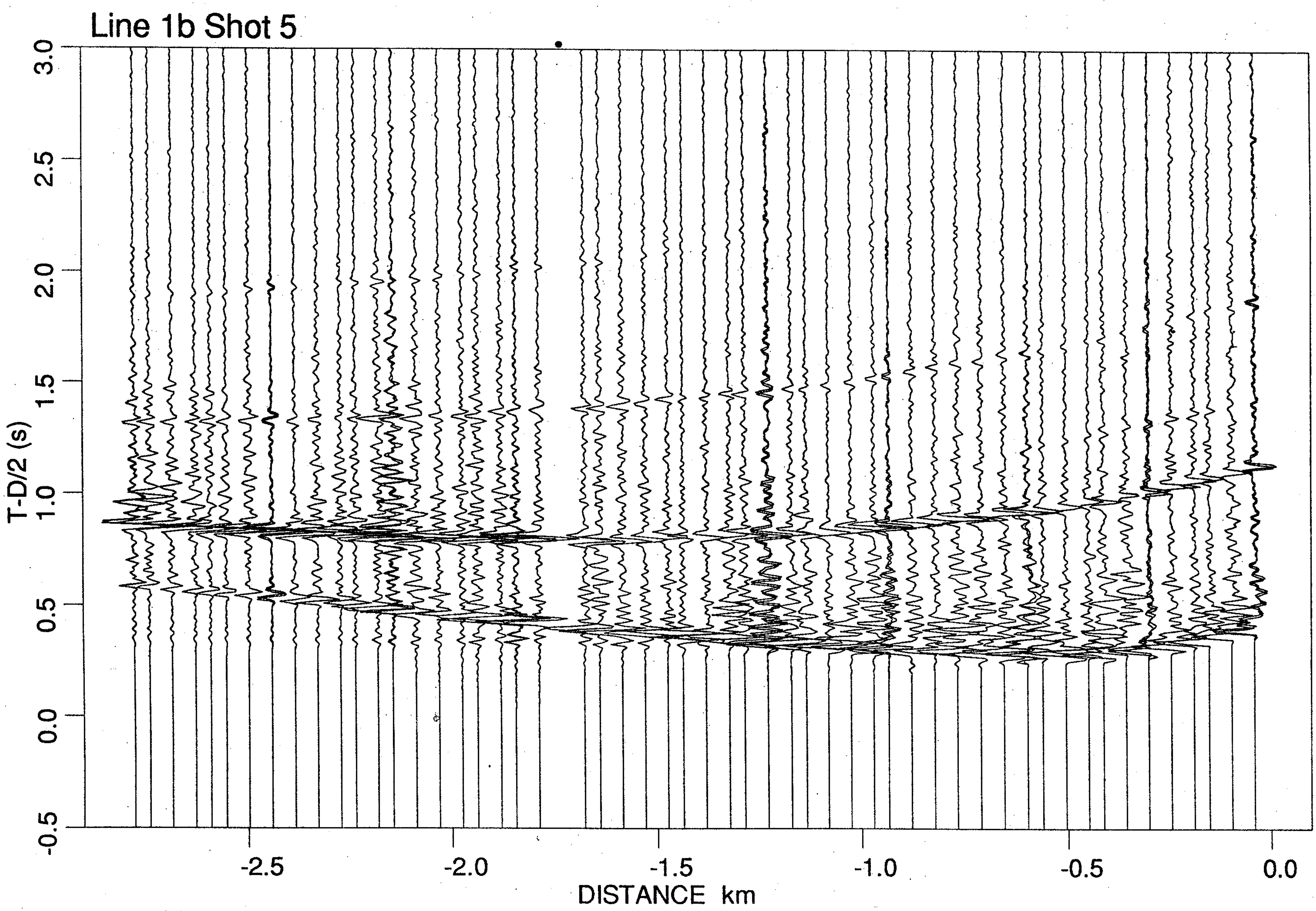


Line 1b Shot 3



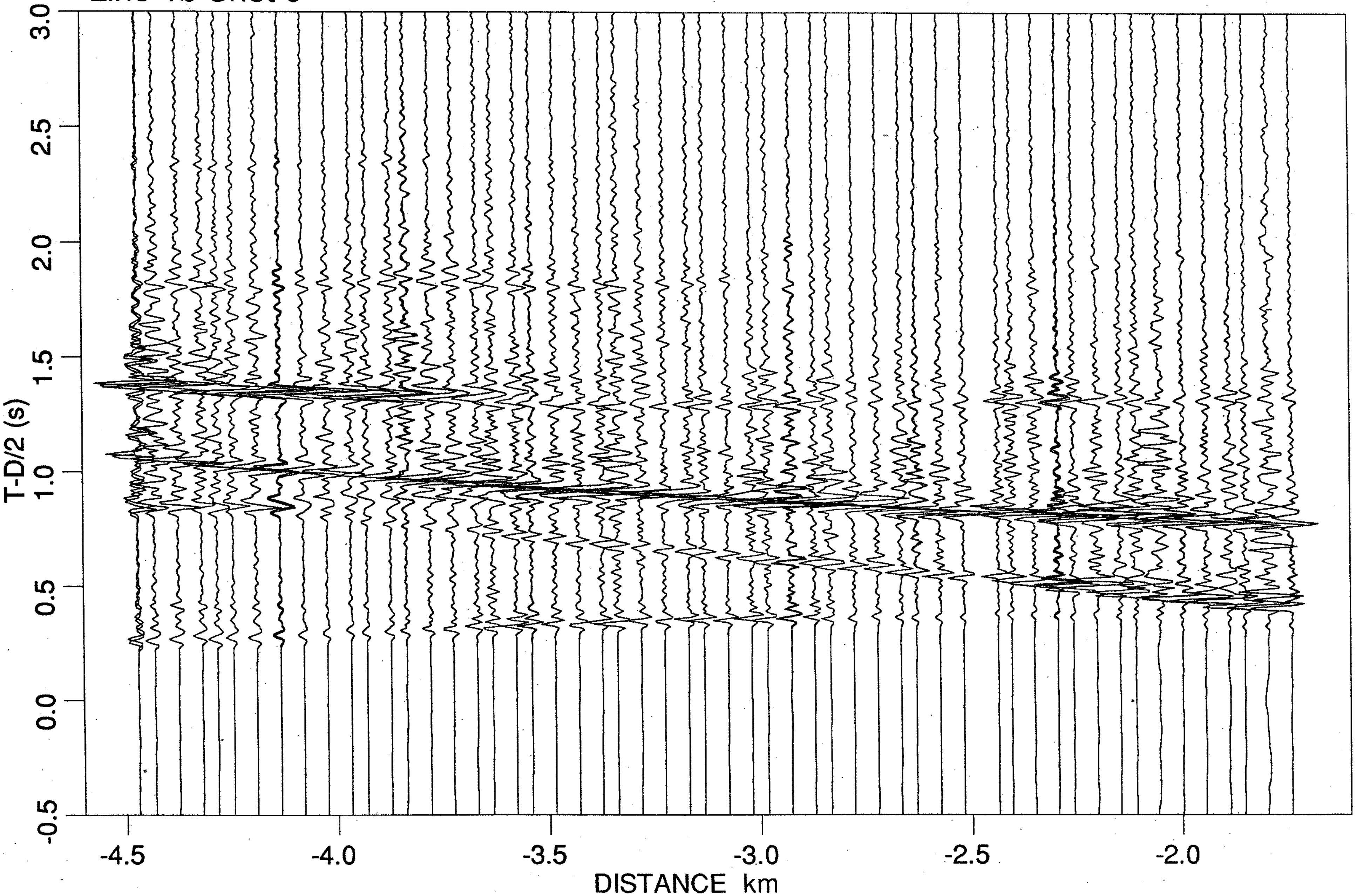


Line 1b Shot 4
T-D/2 (s)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-0.5
0.0
0.5
1.0
1.5
DISTANCE km

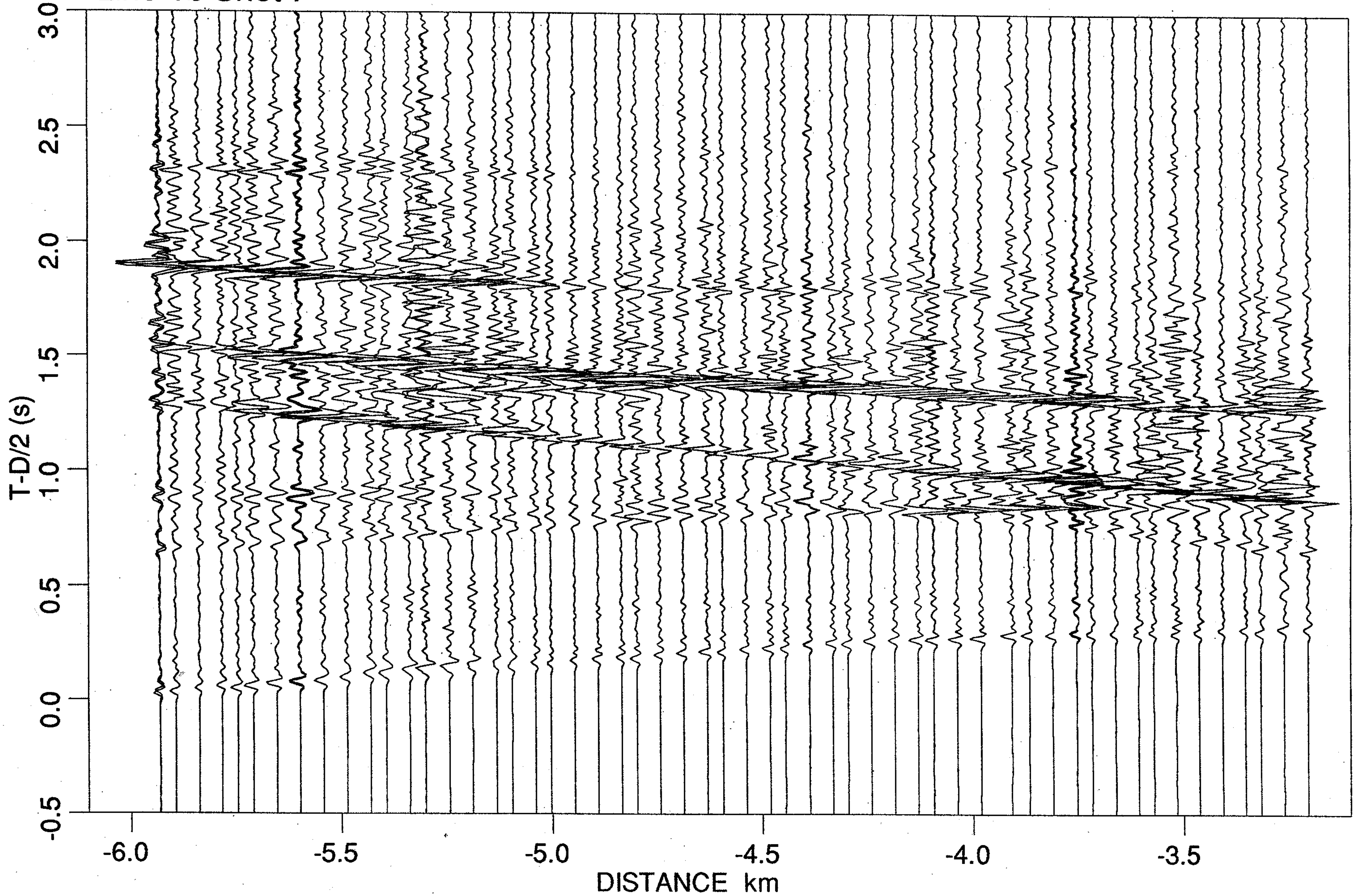


Line 1b Shot 5
T-D/2 (s)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
DISTANCE km

Line 1b Shot 6

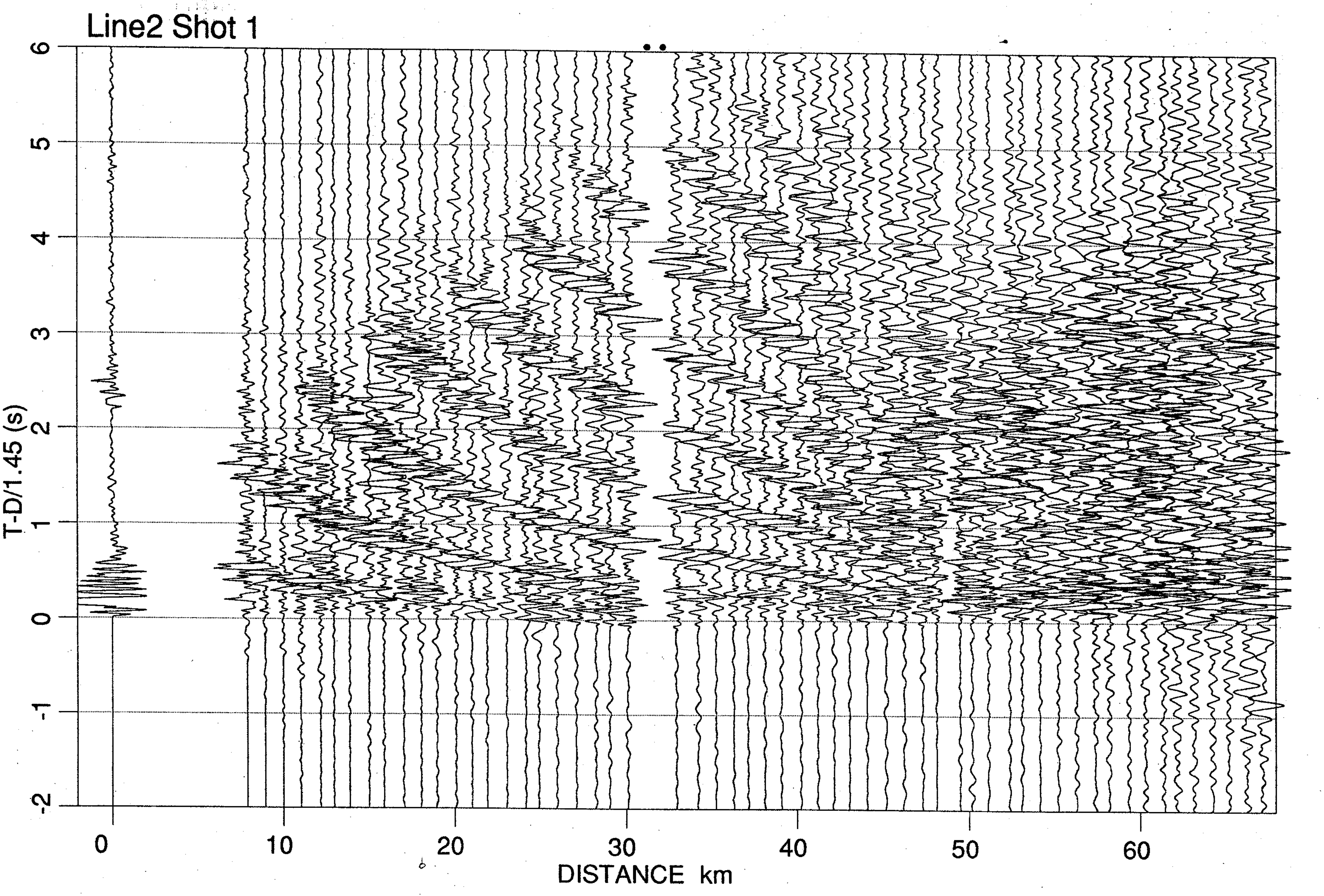


Line 1b Shot 7

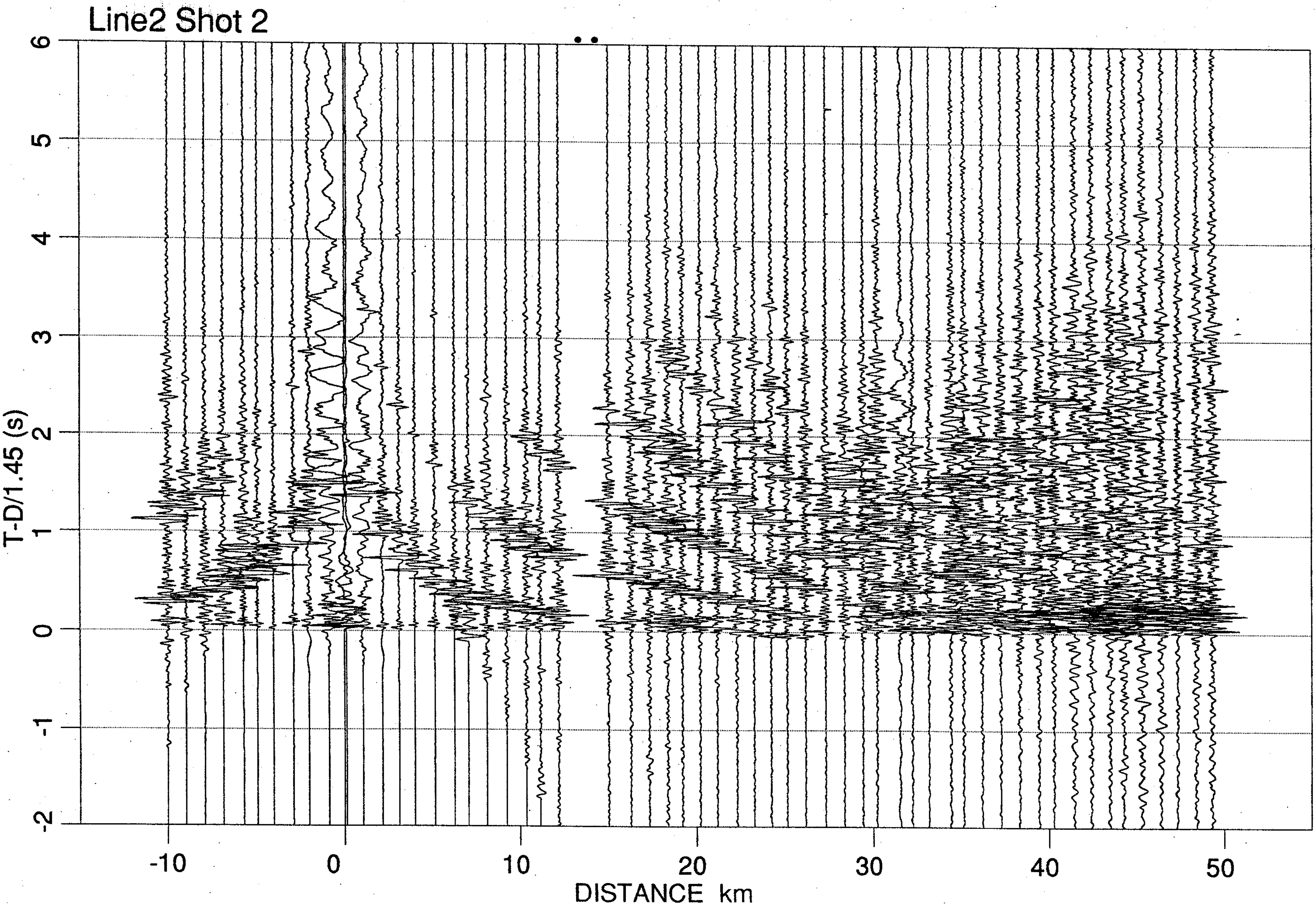


## APPENDIX D - LINE 2 SEISMIC DATA SECTIONS REDUCED AT 1.45 KM/S

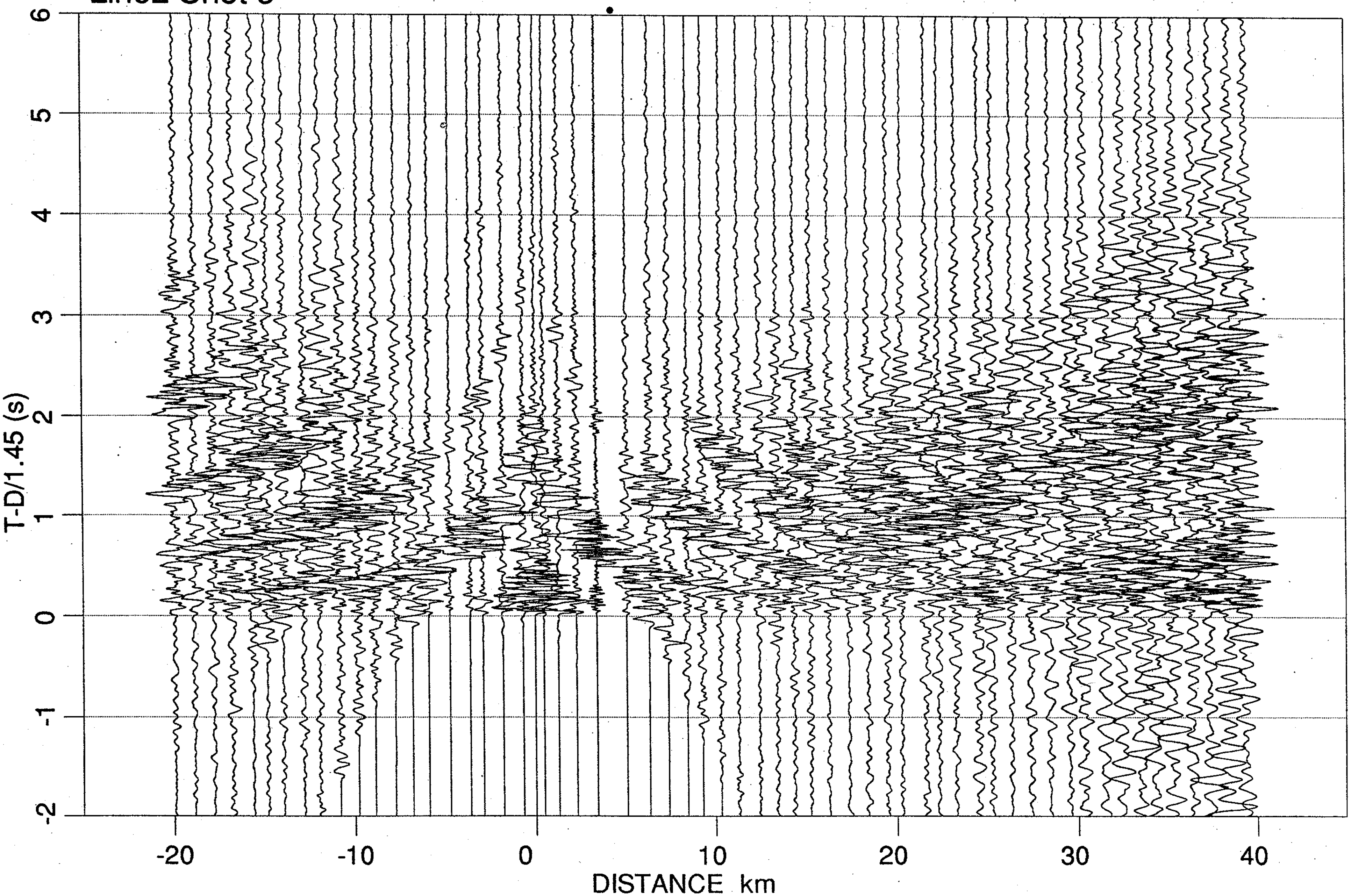
Seismic sections for Line 2 reduced at 1.45 km/s, showing the high amplitude water wave event, with several later multiples evident. Distance is relative to the shot point and positive towards the south. Amplitudes are trace normalized.



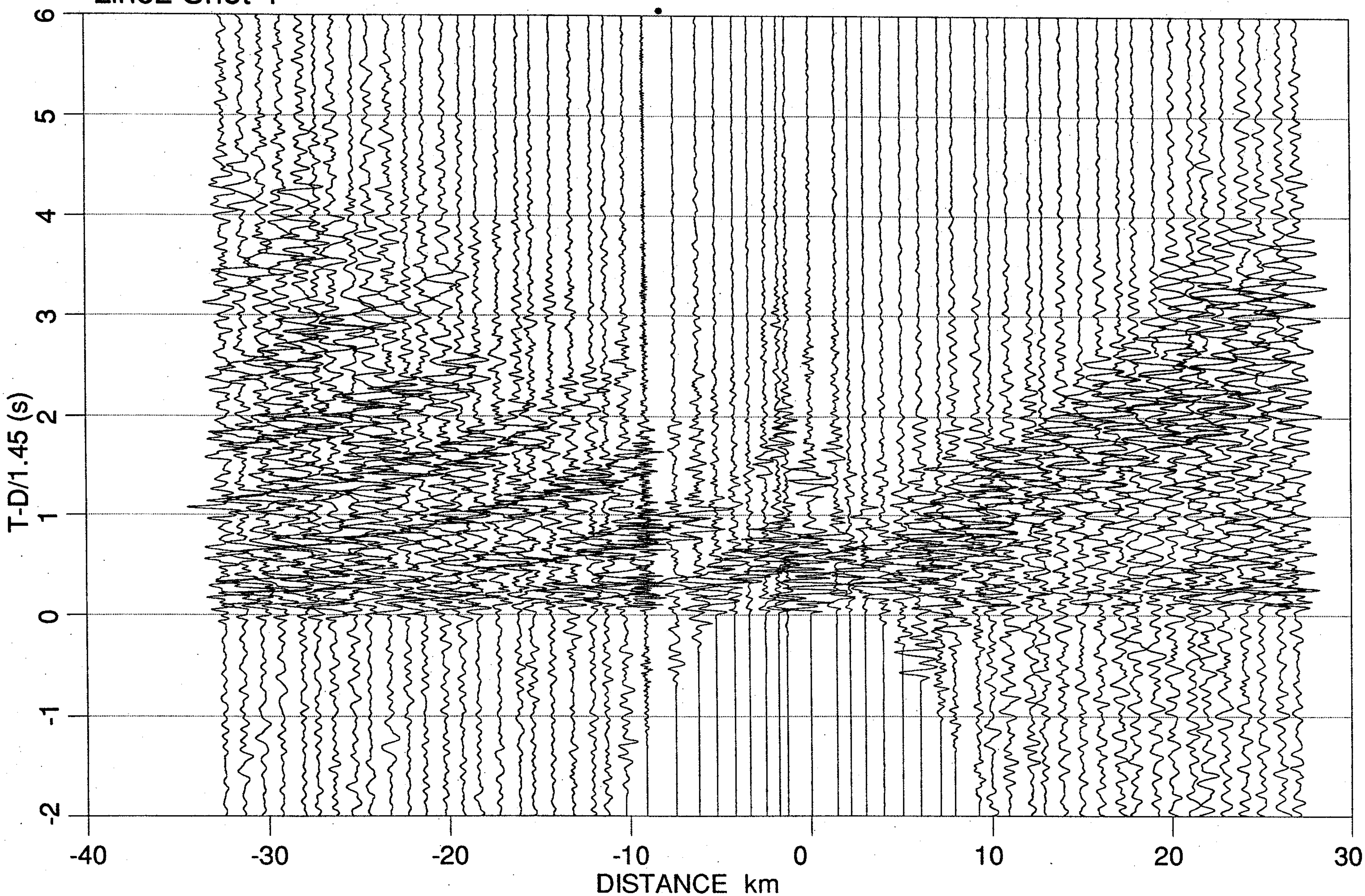
Line2 Shot 1
T-D/1.45 (s)
6
5
4
3
2
1
0
-1
-2
0
10
20
30
40
50
60
DISTANCE km


Line2 Shot 2
T-D/1.45 (s)
6
5
4
3
2
1
0
-1
-2
-10
0
10
20
30
40
50
DISTANCE km

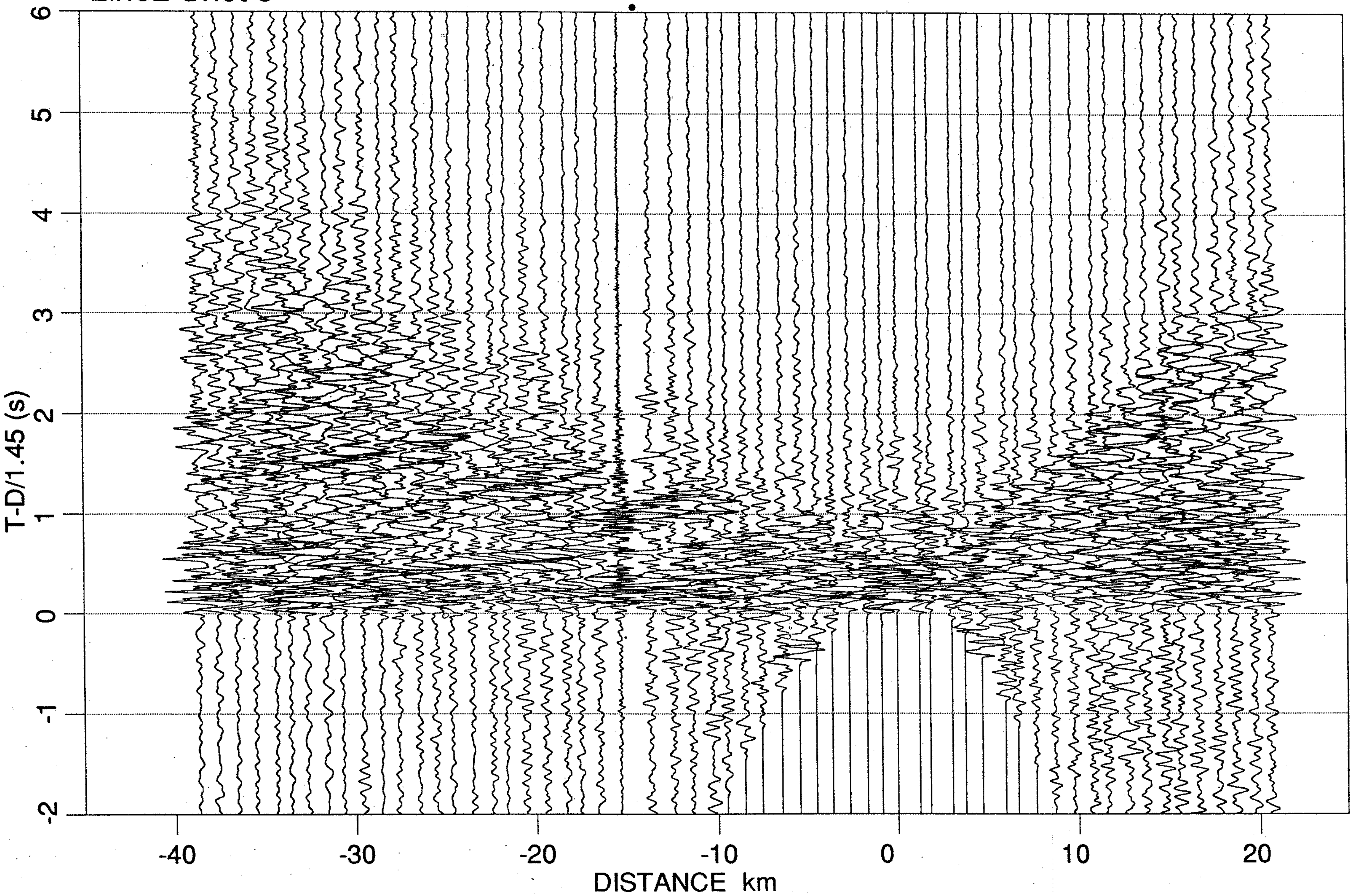
Line2 Shot 3

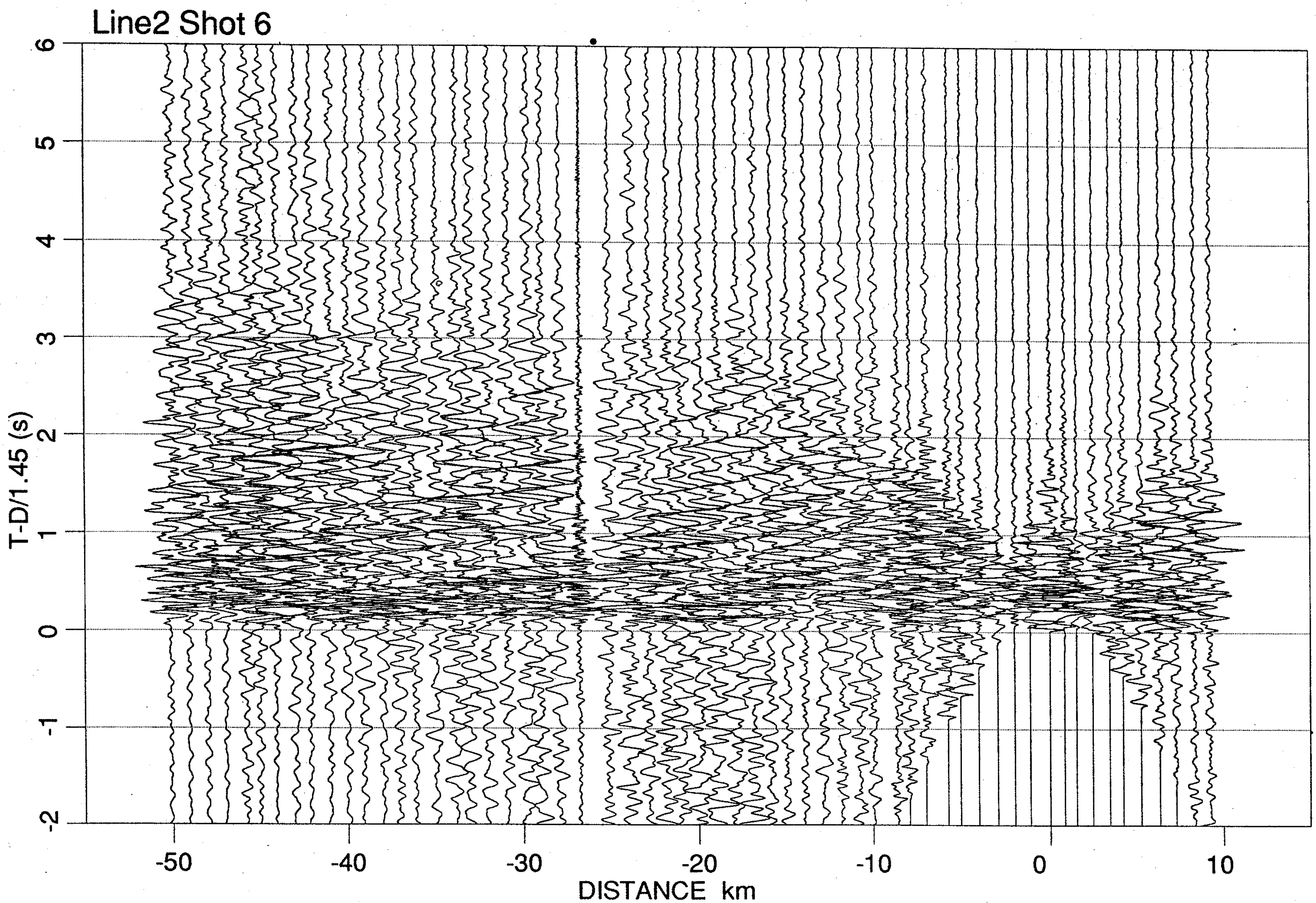


Line2 Shot 4

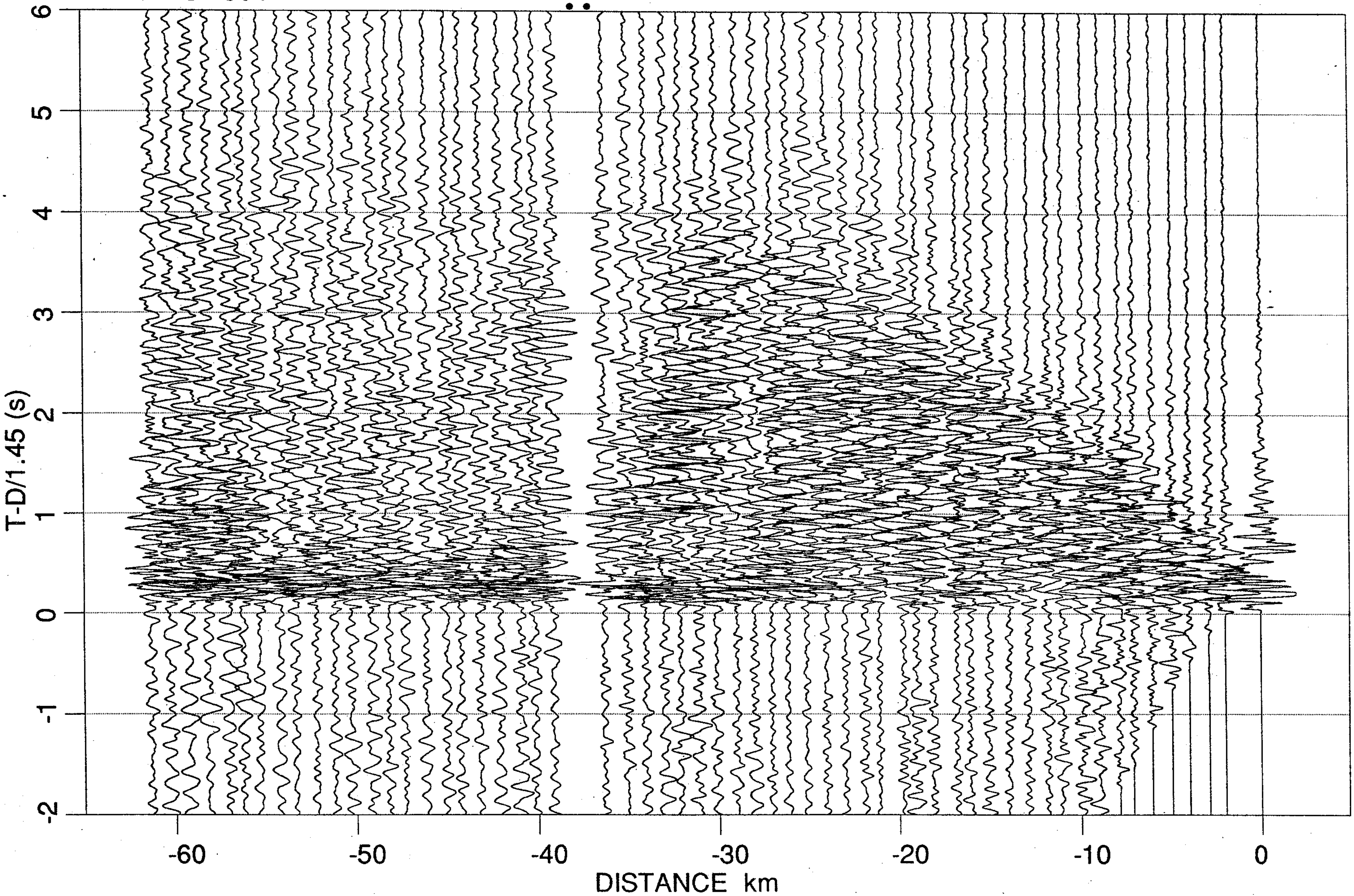


Line2 Shot 5



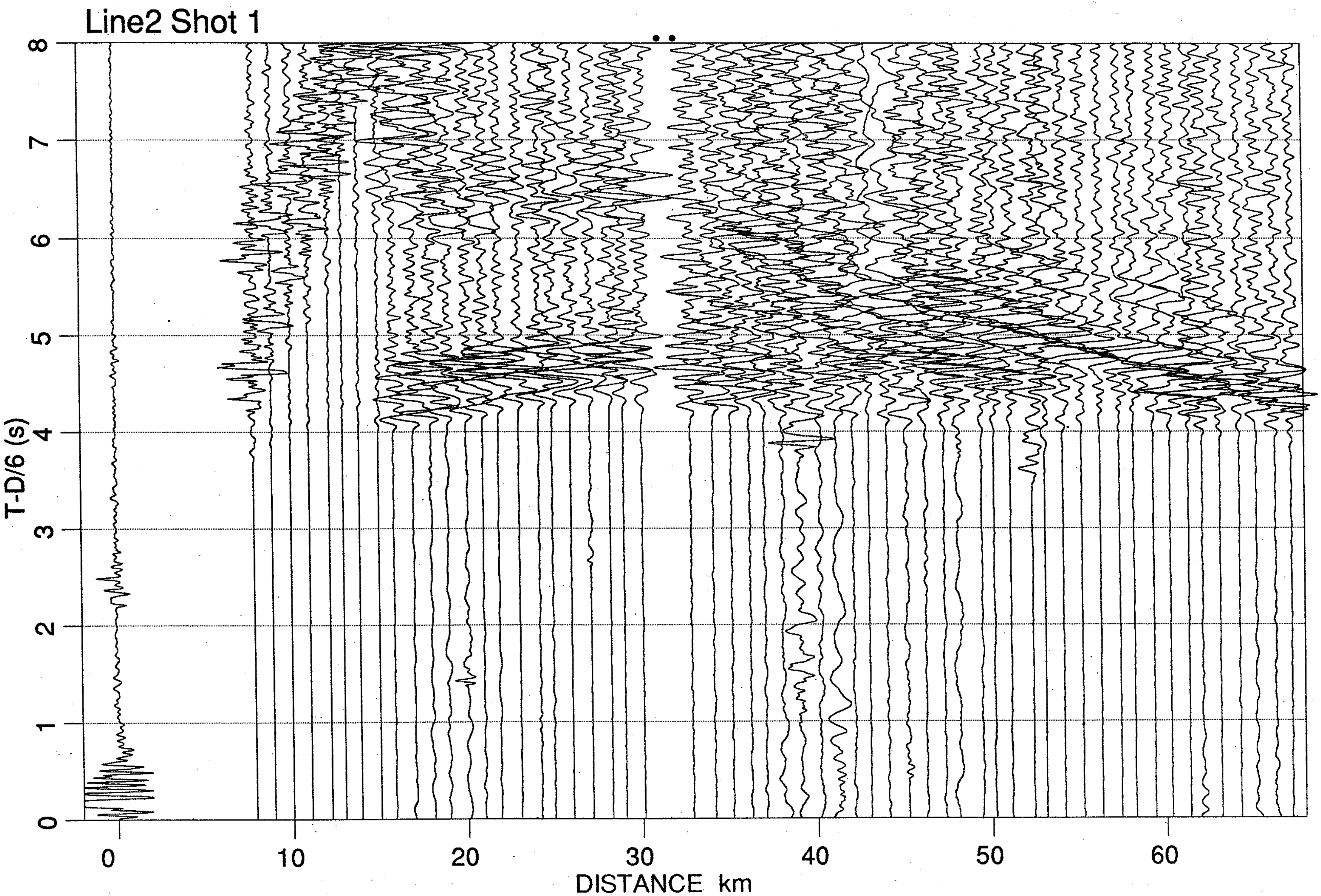

Line2 Shot 6
T-D/1.45 (s)
6
5
4
3
2
1
0
-1
-2
-50
-40
-30
-20
-10
0
10
DISTANCE km

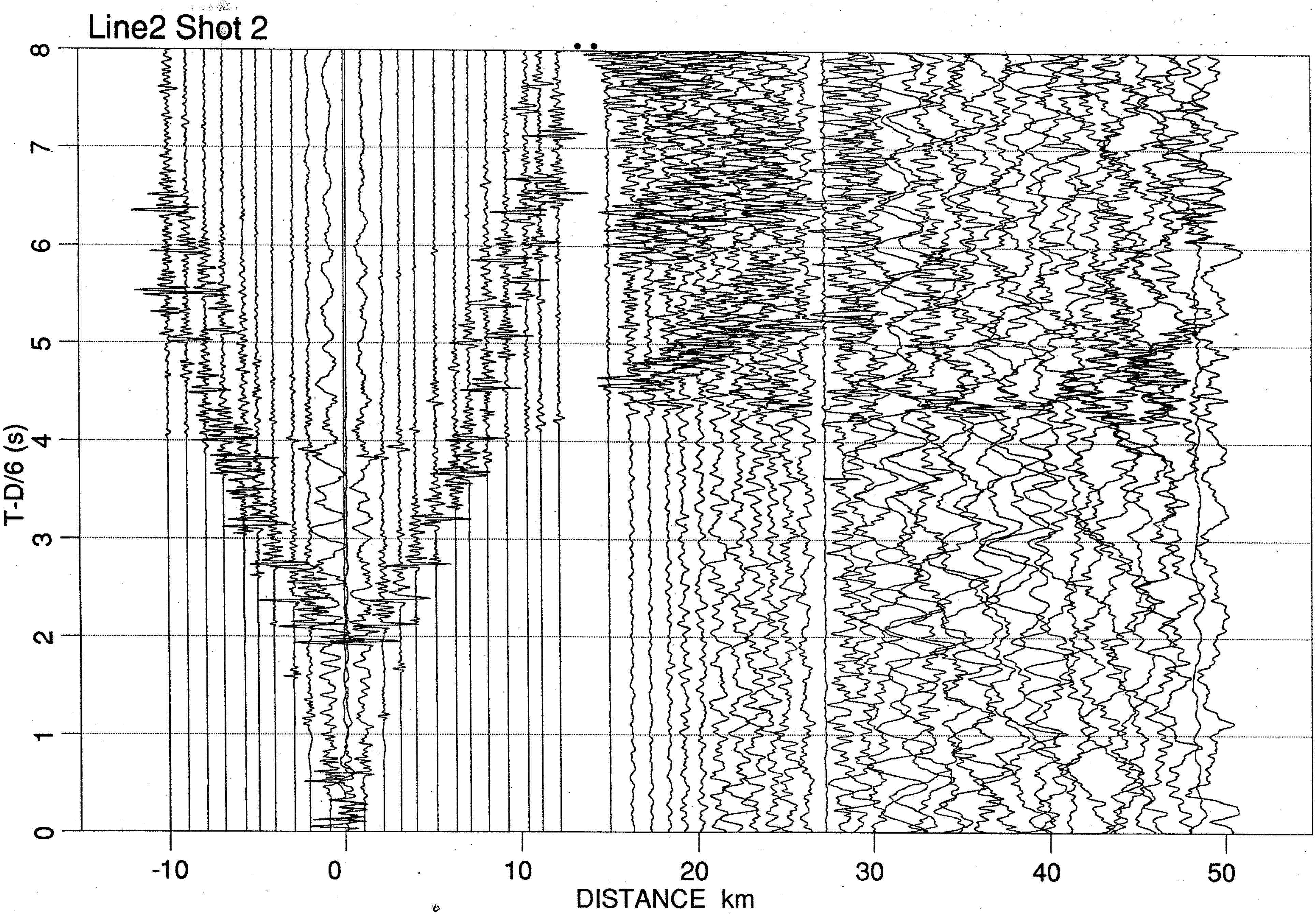
Line2 Shot 7

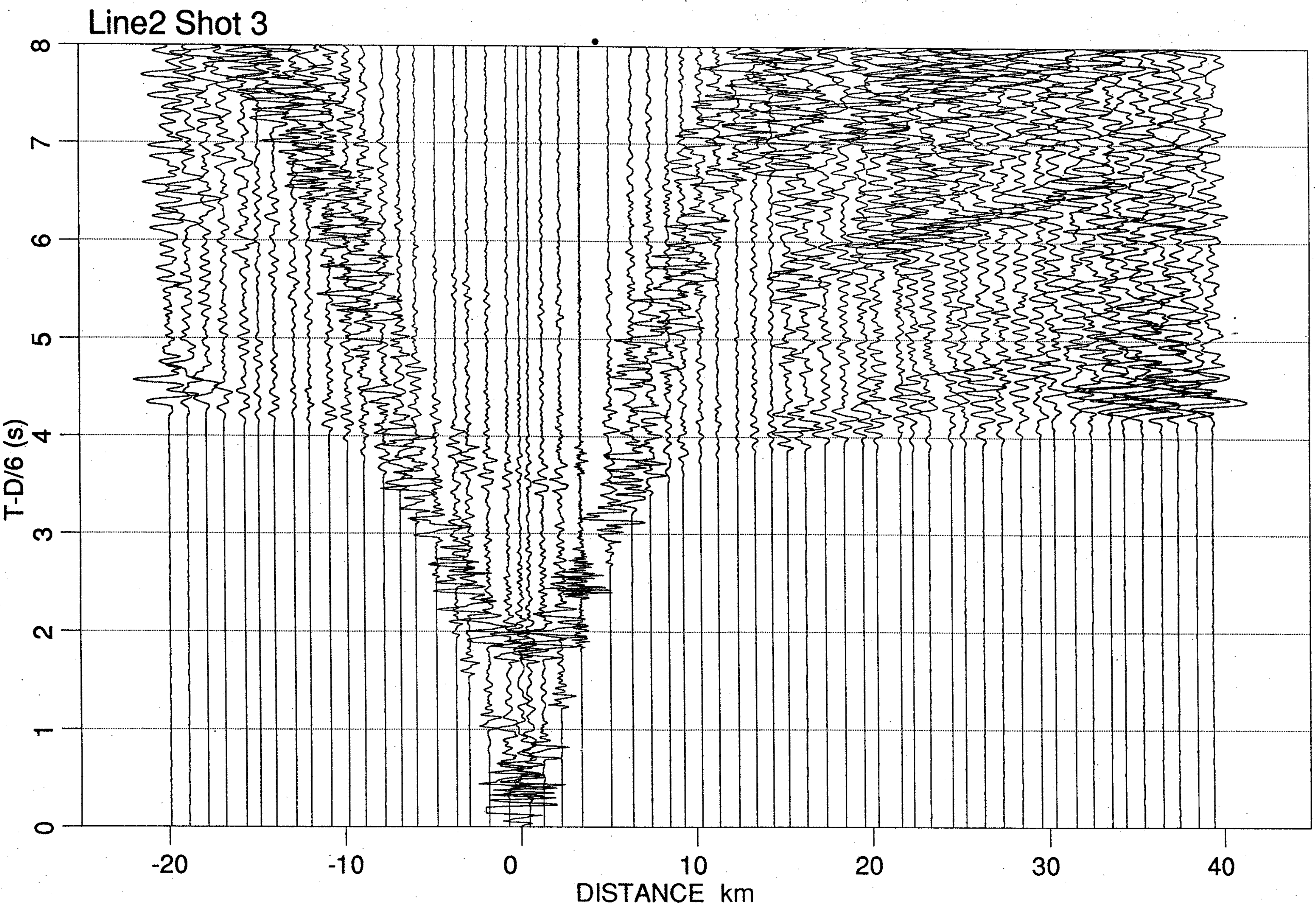


# APPENDIX E - LINE 2 SEISMIC DATA SECTIONS REDUCED AT 6.0 KM/S

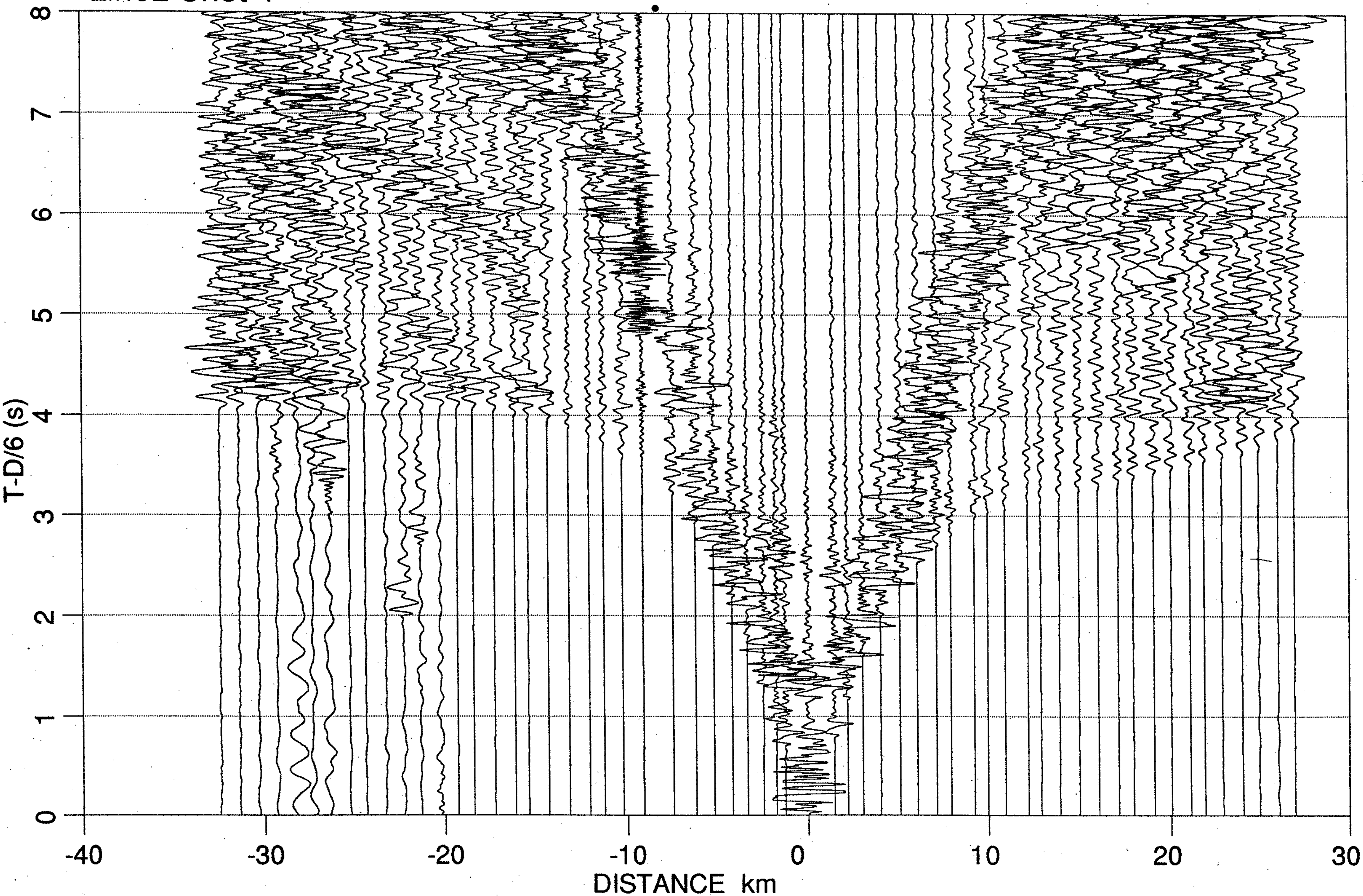
Seismic sections for Line 2 reduced at 6.0 km/s, showing various crustal arrivals. Distance is relative to the shot point and positive towards the south. Amplitudes are trace normalized.

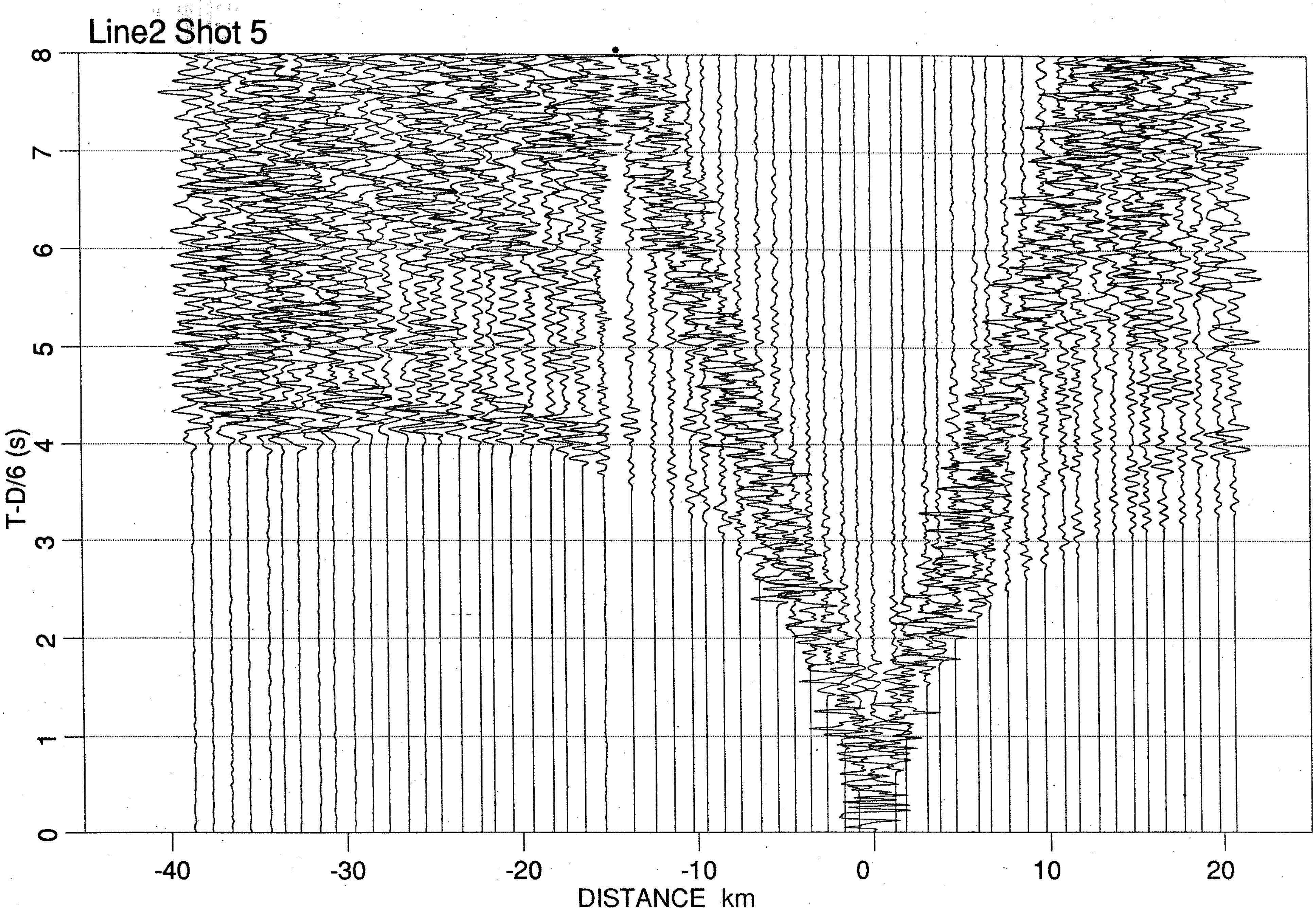

Line2 Shot 1
T-D/6 (s)
0
1
2
3
4
5
6
7
8
0
10
20
30
40
50
60
DISTANCE km


Line2 Shot 2
T-D/6 (s)
0
1
2
3
4
5
6
7
8
-10
0
10
20
30
40
50
DISTANCE km


Line2 Shot 3
T-D/6 (s)
0
1
2
3
4
5
6
7
8
-20
-10
0
10
20
30
40
DISTANCE km

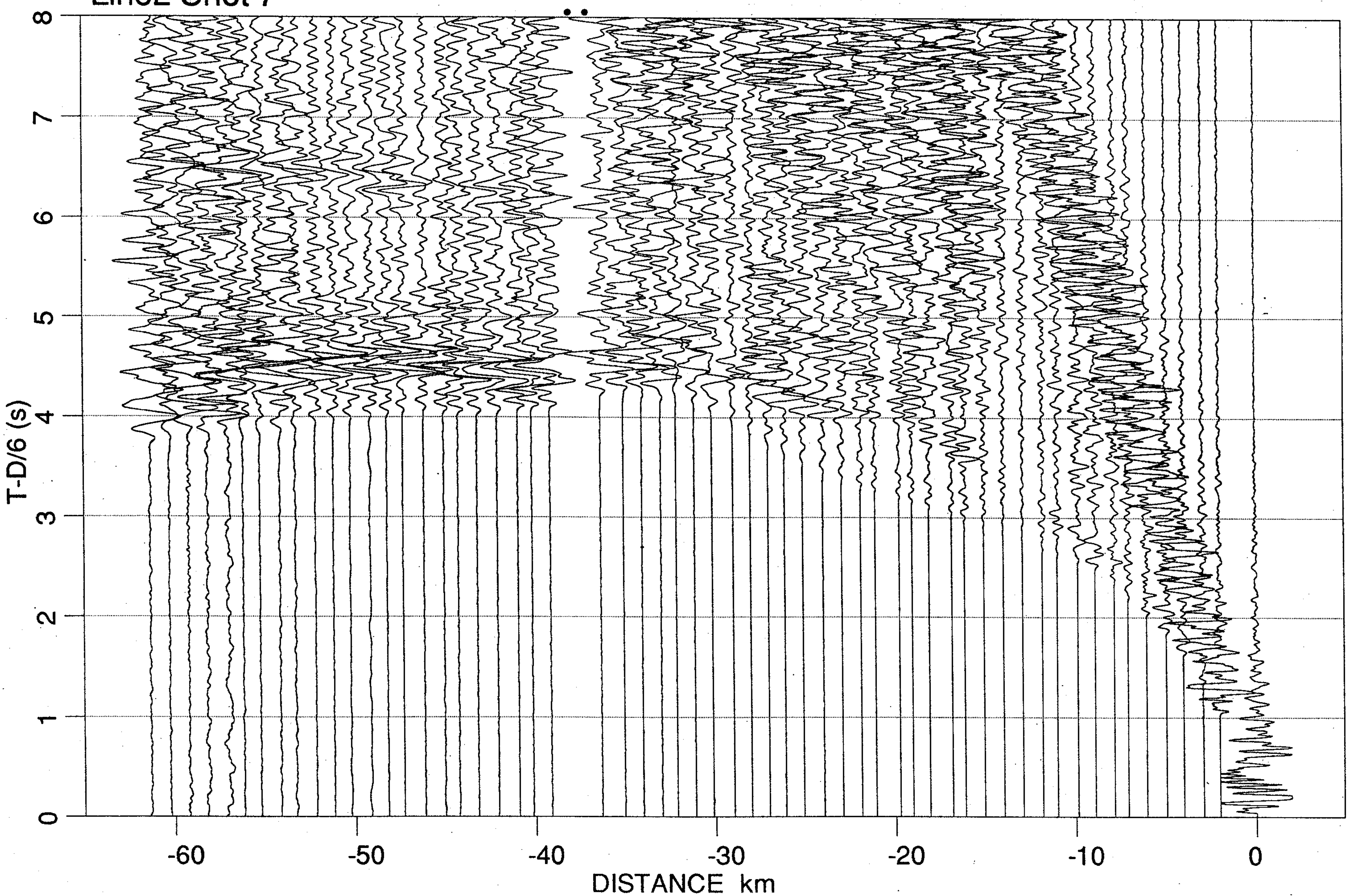
Line2 Shot 4

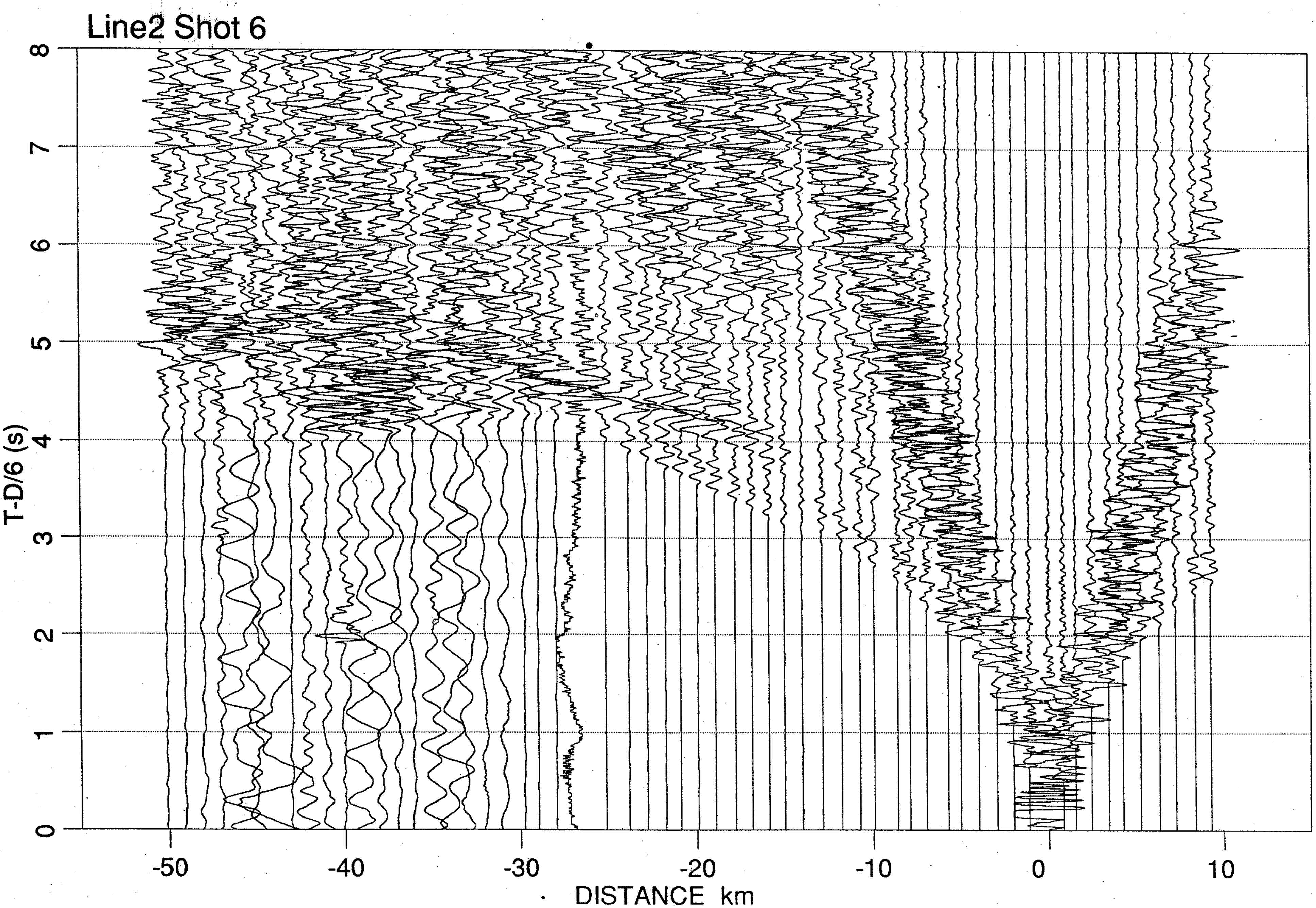




Line2 Shot 5
T-D/6 (s)
DISTANCE km

Line2 Shot 7




Line2 Shot 6
T-D/6 (s)
0
1
2
3
4
5
6
7
8
-50
-40
-30
-20
-10
0
10
DISTANCE km