UNITED STATES DEPARTMENT OF INTERIOR

GEOLOGICAL SURVEY

Detection of Potential Inundation Hazards by Overwater Seismic Methods

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BY OVERWATER SEISMIC METHODS

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ABSTRACT

A reflection and refraction survey was conducted jointly by the Bureau of Mines and the U.S. Geological Survey on Rend Lake, Illinois, in November-December 1980 using a small boat (R/V Neecho), a 12-channel digital recording system, and seismic sources of air and water guns. The purpose was to map mined vs. unmined areas of coal measures underlying the lake and to determine whether known faults in the mines extended to the surface.

A smooth field-testing operation was achieved by coordinating field operation with the processing center using telecopy machines to transmit plots over voice-grade phone lines.

The nature of the bottom of Rend Lake was such that it acted as a wave guide and reverberative mechanism so that water-bottom multiples obscured all reflections from depth. This phenomenon was proved by an extensive model study that developed multiple-removal programs that, when applied to the data, removed all reverberative energy. Unfortunately, no primary reflections remained after this processing. The shallow-water waveguide may be caused by a thin layer of gassy lake sediments (0-3 ft) overlying 10 to 60 ft of weathered Pleistocene glacial deposits which in turn overly the hard Paleozoic sedimentary bedrock. This reverberative mechanism could not have been predicted without additional field recording and data-processing experimentation. Such was impossible due to time and weather constraints. The information learned from this survey provides insight into future methods of solving this problem.

ACKNOWLEDGEMENTS

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F. USGS scientists, Ms. Kaye M. Shedlock and Mr. Samuel T. Harding, for permission to display the stacked cross section from their work on the Mississippi River.

INTRODUCTION

Geologic discontinuities (specifically faults), buried sand channels, and clay zones are potentially hazardous to underlying coal mines as they provide zones of weakness to channel surface water into the workings.

A cooperative research effort to explore the feasibility of developing a high-resolution seismic technique capable of detecting geologic discontinuities from a research vessel on a body of water overlying coal measures was undertaken in 1980 through 1982. The two agencies involved with this work are the U.S. Bureau of Mines (USBM) and the U.S. Geological Survey (USGS), each contributing professional expertise and funds for the project under USGS/USBM Working Fund Agreement No. HO242033.

The research site selected for this study was Rend Lake, a man-made reservoir in south-central Illinois, which overlies working coal mines (fig. 1). A major fault system, the Rend Lake Fault, intersects and passes through the western arm of the reservoir in a N-S direction (fig. 2). Several mining companies are currently extracting coal from developments directly underlying the reservoir. They have mapped the fault system at locations where the workings have intersected the fault, but have no technique to map it remotely and in advance of mining. A recent report by Keys and Nelson (1980) shows the fault system at several underground locations and thus, its trend (fig. 2). Obviously, a technique to more completely delineate this hazardous feature would be of great benefit to the mining companies working in this area and the mining industry in general.

The primary objective of this research effort was directed at developing a high-resolution, overwater seismic technique that could delineate the fault system at Rend Lake from a research surface vessel. Knowledge of the fault location could thus be extended to fill in the gaps between the fault zone areas that have been mapped by the coal companies' personnel. This research is unique because very little work has been conducted over inland bodies of water utilizing high-resolution geophysical techniques for geologic hazard detection that impact on underground mining operations.

The Bureau of Mines (PreMining Hazards Group, Denver Research Center) provided the geologic input, and the Geological Survey (Branch of Atlantic-Gulf of Mexico Marine Geology and Branch of Oil and Gas Resources) provided geophysical expertise. Both parties were involved with the data acquisition which took place in late November and early December 1980. The USGS (Branch of Oil and Gas Resources) has computer processed all of the seismic data for presentation in this report.

The field personnel credited for acquiring the marine seismic data at the Rend Lake site are Messrs. Al Balch, principle investigator and coauthor (USGS); John Grow, chief scientist (USGS); Rusty Tirey, geophysicst (USGS); John Miller, geophysicist and coauthor (USGS); Frank Jennings, electronics technician (USGS); Dave Nichols, physical science technician (USGS); Paul Laud, boat pilot (USGS); Tom O'Brien, electronics specialist (Woods Hole Oceanographic Institute); and Robert A. Speirer, geologist, technical project officer and coauthor (USBM).

BACKGROUND AND JUSTIFICATION

Two previous Bureau of Mines contracts reported on the current industry practice of mining under bodies of water. Both contractors concluded with suggested guidelines which were empirically derived. Each indicated that no complete methodology has been universally accepted. This is partly

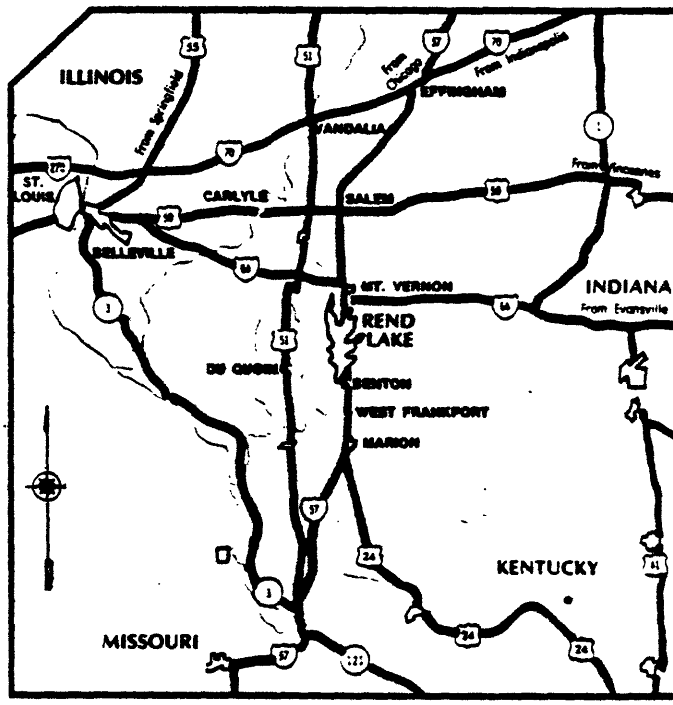


Figure 1. Rend Lake map showing approximate location in the State of Illinois. (From Visitor's Guide Map.)

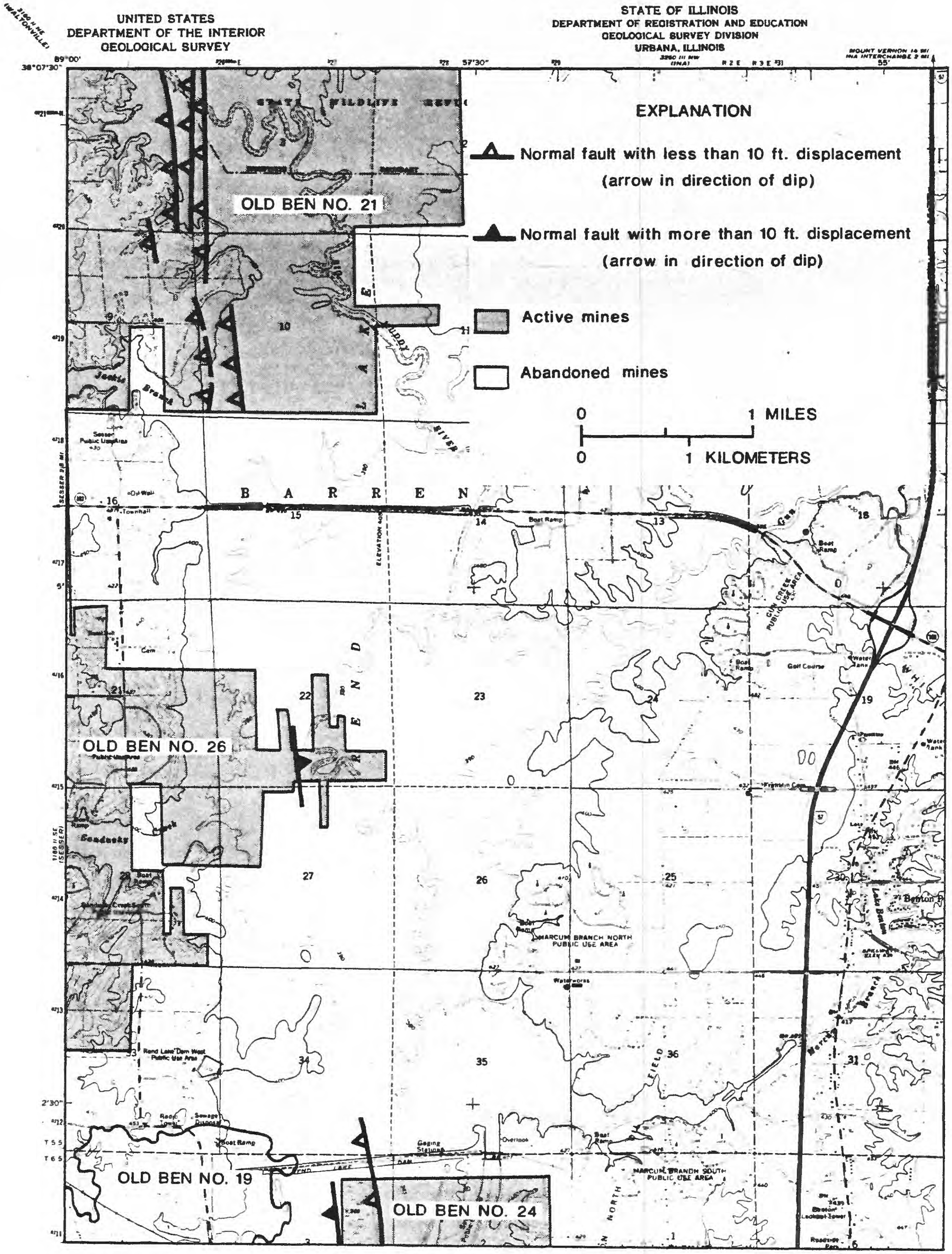


Figure 2. Map showing reservoir, location of mined out zones, Rend Lake faults from underground workings and interpreted trend of fault zone. (Compiled from Nieto and Donath, Keys and Nelson, and USGS topographic map.)

attributable to the few case histories that report measured changes in rock mass parameters where water bodies and underground mining interact.

One study was awarded to K. Wardell and Partners entitled, "Guidelines for Mining under Surface Water" under USBM Contract No. H-252021, completed in June 1976. The second study was done by Skelly and Loy under USBM Contract No. H-282083, "Guidelines for Mining Near Water Bodies," and also was completed in June 1976. A synopsis of these two reports has been compiled by C. O. Babcock and V. E. Hooker of the USBM, Denver Mining Research Center.

Under current Federal Regulations (Sections #75.1726-2 through 76.1716-4 Code of Federal Regulations Title 30 - revised as of July 1, 1976), coal mining operators are required to notify the Coal Mine Safety District Manager, MSHA, of any proposed coal mine development under or adjacent to a surface water body. If, in the judgment of the District Manager, the proposed mining operation would constitute a hazard to miners, he shall notify the operator that a permit is required. One of the requirements of this permit states that the applicant shall provide a profile map showing the type and competency of strata overlying the coal seam and the distance in elevation between the coal seam and overlying body of water.

The investigators believe that a high-resolution surface seismic reflection survey conducted over the zone of interest, supplemented by a few confirmation drill holes, might supply this required information. This survey could supplant a larger number of drill holes normally required to supply the information.

The Rend Lake site was a prime candidate for the investigation. Several mine workings already exist beneath the lake, and a successful investigation would be of immediate value in helping determine to what extent the inundation hazards, if any, currently exist.

GEOLOGIC SETTING

Stratigraphy

The Rend Lake region is blanketed by Pleistocene glacial deposits which vary in thickness from 10 to 50+ ft. Indurated glacial till covers the valley slopes and higher topographic surfaces; till and glacial lacustrine deposits of laminated clay, silt, and very fine sand are found in lowland areas. The valley formed by the Big Muddy River which flows into Rend Lake contains thick sections of clay, silt, and alluvium deposits up to 60 ft in depth. The uppermost portion (about 35 ft) of these surficial deposits consists of clay in the vicinity of the dam (Nieto and Donath, 1976).

The bedrock beneath these tills, glacial lake deposits, and gravels are of Pennsylvanian age and consist predominantly of shales and minor sandstones and a few limestones. The uppermost formation in this section at the dam site is the Bond formation, largely shale, whose lower boundary ranges from 100 to 150 ft below the land surface. This boundary is marked by the Shoal Creek limestone member, a persistent marker bed in the area. About 500 ft below this bed lies the Herrin (No. 6) coal bed, contained in the Carbondale formation, the predominent commercial coal bed in this region. Other less commercially important coal beds occur in this formation, such as the Harrisburg (No. 5) coal and several thinner beds (fig. 3). This figure, from Keys and Nelson (1980), shows the general stratigraphic section of the region with relative thicknesses on the left side of the figure and a blowup of the coal beds on the right. This figure 3 stratigraphic column represents the vertical zone of interest for the study. Horizontal scale is greatly compressed on the blowup diagram on the right portion of this figure.

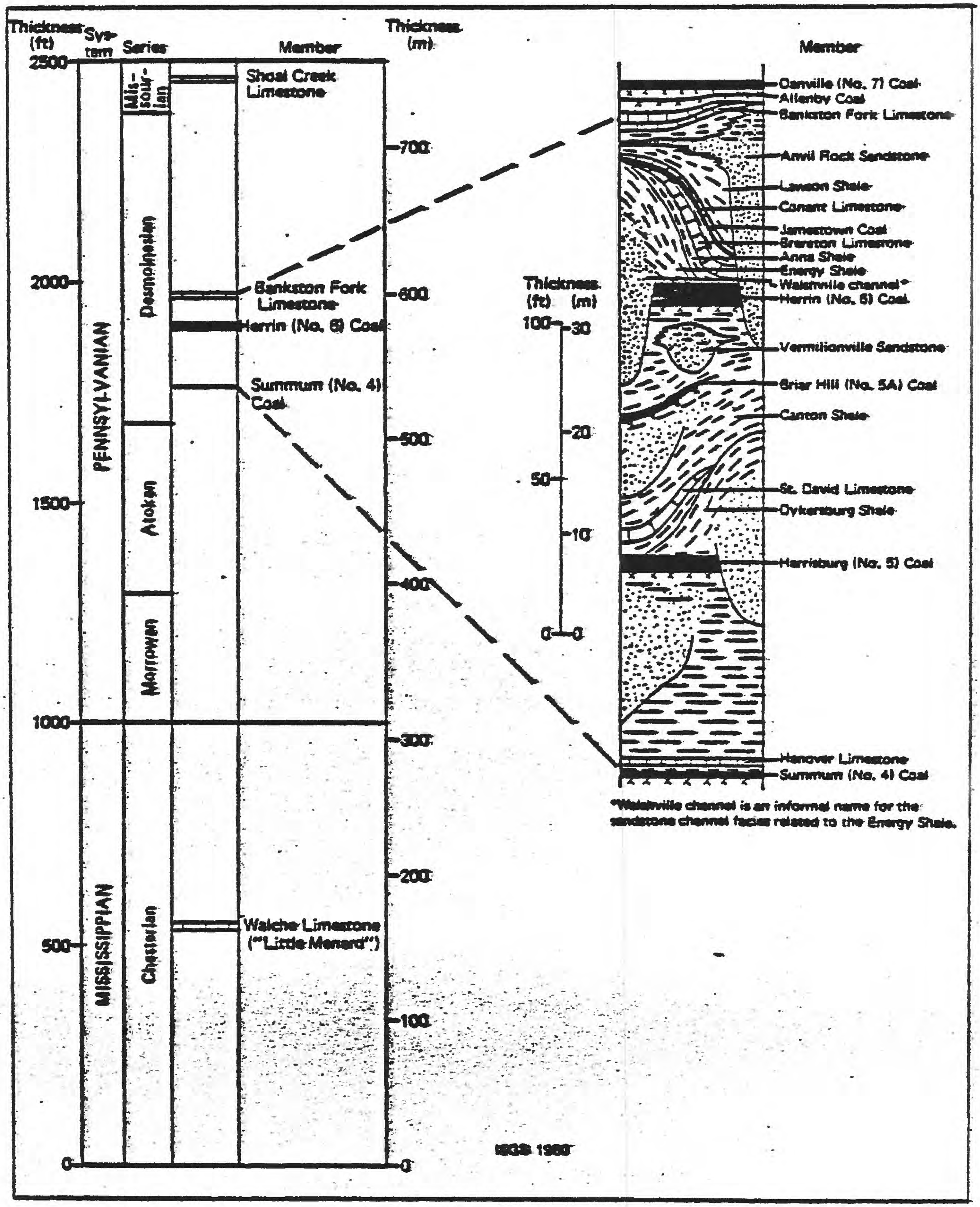


Figure 3. A general stratigraphic section of the study region on the left part and a blowup of the coal beds on the right portion. (From Keys and Nelson.)

Structural Setting

The Rend Lake reservoir area lies in parts of two counties, the northern boundary of Franklin County and the southern boundary of Jefferson County. This reservoir lies along the western margin of the Fairfield Basin, the deep central portion of the Illinois Basin, which is part of a larger cratonic area known as the Central Stable Region. Most of the deformation in this region since Precambrian time has been characterized by broad regional warping and local differential uplift and subsidence (Atherton, 1971). The layers of rock show a very gradual eastward dip toward the center of the Fairfield Basin. The north-trending DuQuoin Monocline, which separates the Fairfield Basin from the western shelf, lies approximately 10 mi west of Rend Lake (fig. 4; from Bristol and Buschback, 1975).

The most prominent structural feature within the study area is a low syncline trending north-south, approximately following the line of the Big Muddy River. The syncline was mapped by Keys and Nelson (1980). Flanking the synclines on the east is a series of low subtle anticlines. These structures have been targets for petroleum exploration.

The Rend Lake Fault System lies along the western margin of the syncline and is described in detail by Keys and Nelson (1980). The faults within this sytem are mostly high-angle normal faults with displacements ranging from a few inches to a maximum of about 55 ft. The major faults are downthrown to the east. It has not yet been established whether or not displacement on these faults was initiated prior to the Pennsylvanian.

Other faults in this system are identified as reverse, dip slip, and strike slip faults. The orientation of these faults is generally N-S which swings to the N.W. in T. 4 S., R. 2 E., following the Old Muddy River channel.

Some of these faults have created examples of horst and graben features. Contemporaneous faulting has developed much of this fault system with a few isolated examples of offsetting faults suggesting one fault predating the cross-cutting fault. Underground observations at fault/mine intersections in coal mines underlying the reservoir have afforded in situ examination of these and other complex features in the coal strata. Those readers desiring to learn more about the geology and fault system in this region will find thorough treatment of these subjects by reading Keys and Nelson (1980), and a graduate thesis by Keys (1968).

Some of the major faults showing their respective vertical throws, orientation, direction of dip, and location to the underground coal mines are shown in figure 5, a cross section compiled from boreholes drilled along the dam.

OUTFITTING THE RESEARCH VESSEL (R/V NEECHO)

Seismic-Recording Equipment Specifications

A Digital Field System V (DFS V) Marine Multichannel Seismic Recording System and associated components were purchased from Mountain Systems Service and installed in the R/V Neecho under USGS contract no. 14-08-0001-18764. This system consisted of the following main components:

A. 12-gain ranging amplifiers, two nongain-ranging auxilliary amplifiers, multiplexer, and analog filters.

B. Analog-to-digital converter capable of digitizing the outputs of the amplifiers at any one of the following sample intervals: .5, 1.0, or 2.0 millisecond (msec).

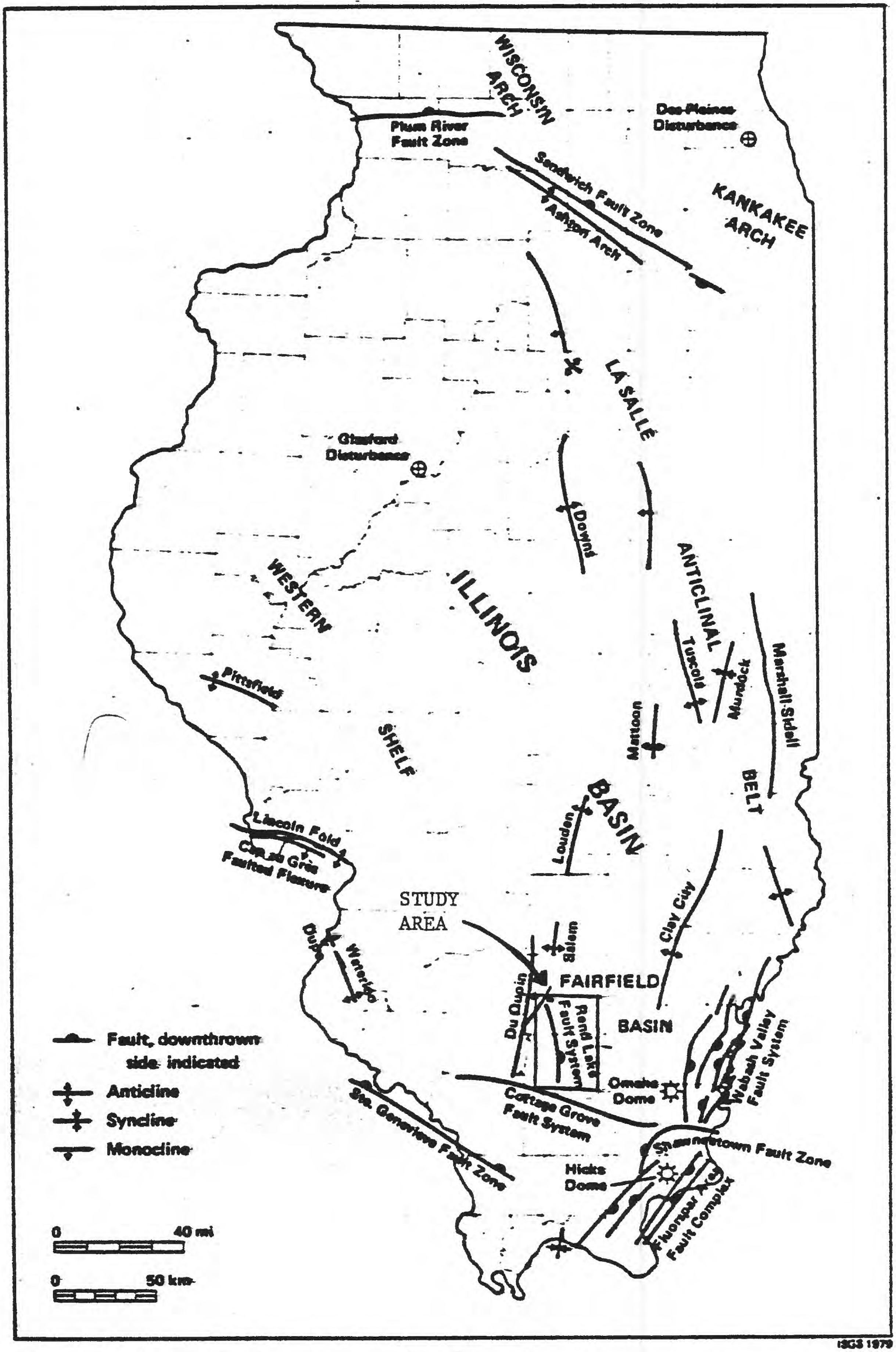
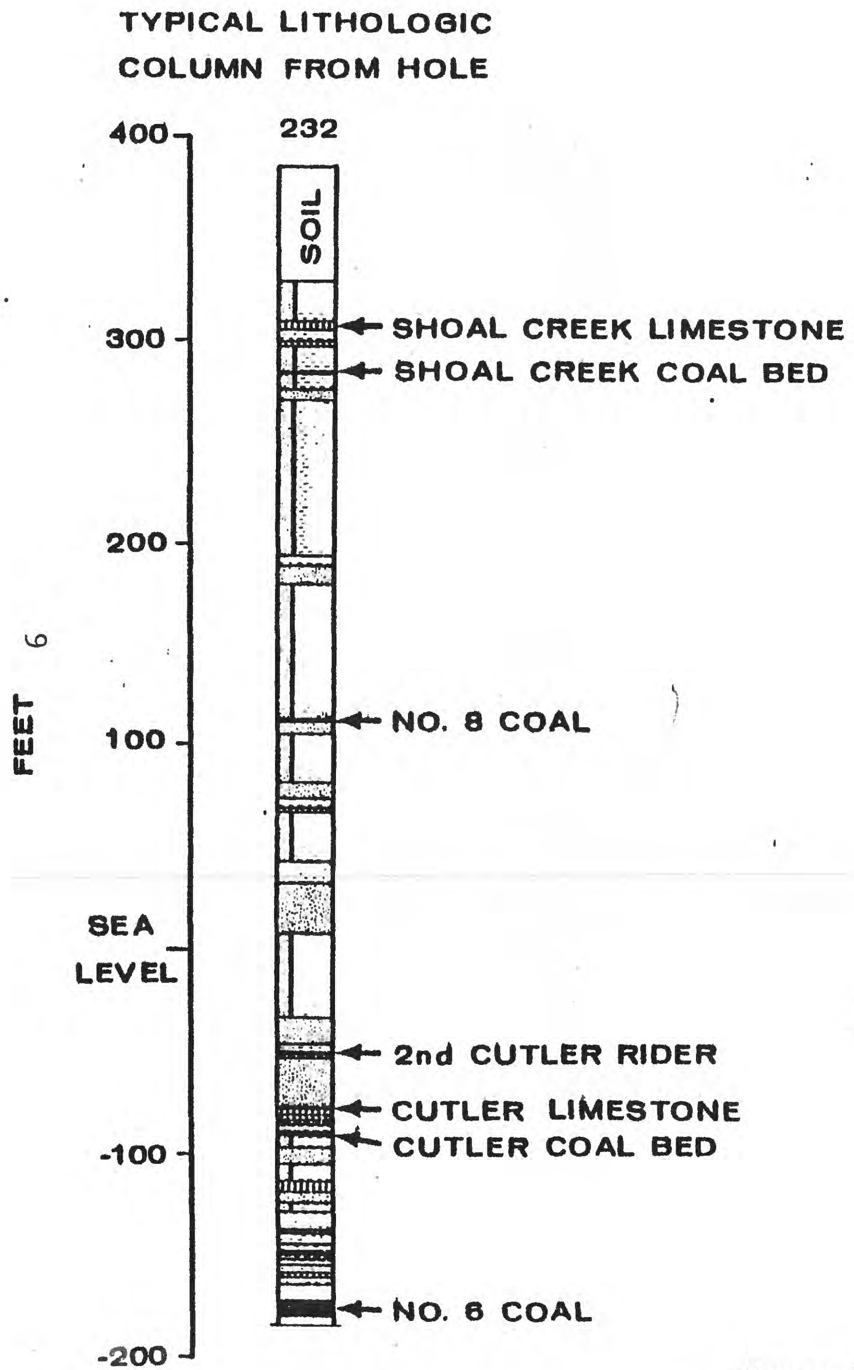
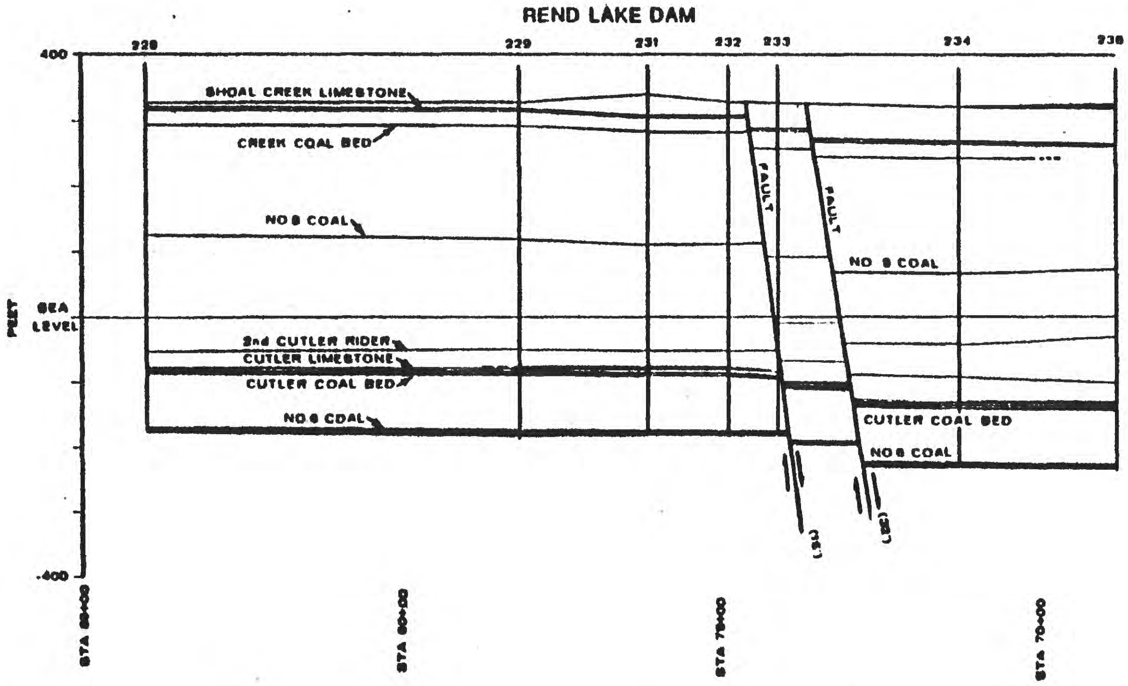


Figure 4. Structural features of the eastern interior region. (From Bristol and Buschback, 1980)





Notes:
1. Section line is 300'± north of the southern boundary of section 34 & 35. This is approximately 1000' north of dam axis.
2. Stationing is dam axis stationing.
3. Boring logs were obtained from Old Ben Coal Co. - Dated in 1966
4. Formation names are from Old Ben drilling logs and I.G.S. Bulletin No. 74.
5. Holes drilled with 3 7/8" roller bit to No. 6 coal. No. 6 coal cored with 2 1/8" ϕ core.

Figure 5. Cross section through Rend Lake dam.

C. Two 9-track magnetic tape transports, each capable of automatically starting when the other gets to the end of the tape without interruption of recording.

D. Multichannel recording oscillograph and camera.

E. Twelve-volt DC power and battery system.

F. Data encoder and extended header electronics system capable of writing date, time, Loran C, and miniranger-navigation data directly into the record header of each shot. This highly desirable option assures that navigation data is permanently saved on tape with the recorded seismic data.

G. Electronic interfaces between all components.

H. Installation of all components including those furnished by the government.

The following items were furnished by the USGS:

A. Seismic energy generating system consisting of one 15 $in.^3$ water gun, one 40 $in.^3$ air gun, and one 80 $in.^3$ water gun.

B. Twelve-channel hydrophone cable, depth controllers, and winch.

C. Real time clock (RTC) whose output was entered into the extended header.

D. System trigger used for initiating a shot.

E. Navigation system, Motorola Miniranger™ and Digital Marine Electronics Northstar™ 6000 Loran C receiver whose outputs were entered into the extended header.

F. Flatbed monitor record recorder.

G. Shot-break detector.

H. Signature monitor hydrophone.

I. AC power supply.

J. Space available on the Neecho for installation.

Training of Personnel in Maintenance and Operation of the System

Two USGS employees attended a training course conducted by Texas Instruments in Houston, Tex. This course covered proper operation and some maintenance trouble-shooting of the DFSV system.

System Operation Verification

Upon installation of the system in the R/V Neecho by the contractor, three test sequences were run. Test one was the standard suite of tests run on all digital recording systems. These tests are cross feed, binary-gain accuracy, digitizer linearity, distortion analyses, dynamic range, and noise.

The above tests were recorded on magnetic tape and processed on the USGS-owned Phoenix I® seismic data processing system in Denver. Some slight problems were discovered at that time. These problems were then corrected and test one was rerun and processed. The results of this test were well within industry standard tolerances. For the second test, the Neecho was taken out into the bay near Woods Hole, Mass., and test shots were made under a simulated production environment. These tapes were also processed at Denver and were satisfactory.

On the third test, the navigation information placed into the record headers was successfully decoded by the processing computer in Denver in order to verify proper operation of the extended header electronics subsystem.

FIELD OPERATIONS

Data-Processing Center Coordination

In order to conduct successful field experimentation, processing the recorded data as soon as possible is highly desirable. Analysis of the processed data will verify the degree of success of recording parameters and they can then be modified accordingly. The best way to accomplish this is to have a seismic data processing system in the field. Because this was not possible in this project, a compromise was made. Two remote copiers (3M VRC Remote Copiers, models 600BB and 603AA) were purchased. These provided the capability of sending seismic plots over a voice-grade telephone line.

One copier was located in the processing center in Denver and the other portable copier was taken to the field. Each night the data tapes recorded that day were taken to St. Louis, Miss., and put on a plane to Denver. They were picked up at the airport in Denver, taken to the processing center, and processed. Late that night or early the next morning, plots of the seismic cross sections were sent via remote copier to the field. Scientists in the field, in cooperation with those at the processing center, analyzed the data and planned the next day's recording operation.

Reflection Recording Parameters Experimentation and Selection

Initially, experimental seismic lines were shot. These were designated Lines 1 through 16 and 3A through J. An attempt was made to try all source-receiver configurations possible with the equipment available: two 12-channel recording streamers, one 110-m long with group intervals of 10 m, and the other, 220-m long with group intervals of 20 m. The two sources available were a 15 $in.^3$ water gun and a 40 $in.^3$ air gun.

The main variables tested were source-vessel separation and source near-receiver separation with the four combinations of sources and streamers. The last variable tested was source interval which determined fold coverage. Table 1a lists all experimental lines and their corresponding recording parameters.

Parameters selected and decisions made from this experimental shooting are as follows.

1. The 220-m streamer was too long to be easily maneuverable in Rend Lake. The average width of the lake available for recording was 1,500 m. This excludes the portions of the lake too shallow for safe operation. Shooting cannot begin until the cable is in line with the vessel's direction and because this process takes up considerable distance, use of the 220-m streamer was eliminated.

2) Some of the data were contaminated by low-frequency noise. It was determined that the streamer was the source of this noise. This was because the source and streamer were too close to the vessel and the streamer was undulating in the vessel's wake. Increasing the separation between the vessel and the streamer reduced the noise almost completely. Figures 6 and 7 show the noise reduction.

3) Optimum source near-receiver separation was determined to be zero. This distance was decided upon because of the high-amplitude, water-bottom reverberations present on the data. It was feared that with a water depth of approximately 8 m and the high reflectivity of the lake bed, the water layer would act as a wave guide with offsets greater than the water depth. Thus, in an attempt to get some penetration vertically through the lake bottom, the source and near-receiver group were arranged to be coincident.

Tables 1a and 1b.--<u>Recording parameters for each line</u>

	Line Number	Source Interval (meters)	Source Type	Source-Near Receiver Offset (meters)	Recording Streamer Length (meters)	Shooting Direction	Comments
1a.	1	10	WG**	50	110	N-S	Experimental lines
	2, 2A,						
E	3-9	10	WG	50	110	E-W	
X	10-16	5	WG	18	110	E-W	Noisy streamer
P	3A	10	AG#	0	110	*	
E	3B	10	AG	0	110	*	
R							
I	3C	10	AG	0	220	*	
M	3D	10	WG	0	220	*	
E	3E	11	WG	0	220	*	
N	3F	9	WG	17	110	*	
T	3G	5	AG	17	110	*	Quiet streamer
A							
L	3H	5	AG	18	110	*	
	3I	5	WG	18	110	*	
	3J	5	WG	7.5	110	*	
1b.	3K	5	WG	0	110	*	Production Lines
	3L	20	LWG	68.5	110	*	
	17-25	5	WG	0	110	E-W	
P	26	5	WG	0	110	N-S	
R	27-35	5	AG	15	110	E-W	
O	27A	5	AG	0	110	E-W	
D	36	5	AG	0	110	dog leg between 27A and 37	
U							
C	37, 38	5	AG	0	110	S-N, N-S	
T	No lines						
I	39, 40						
O	41-44	5	AG	0	110	E-W	
N	45	21	LWG	varying	Sonobuoy	S-N,	Refraction Lines
	46	21	LWG	varying	Sonobuoy	N-S	

*Lines 3, 3A→ 3L were shot along the same track line which was a constant distance of 5,500 m from a miniranger navigation station to the north. This arc was nearly an E-W line.

**WG=15 in.^{3} water gun; #AG=40 in.^{3} air gun; LWG=80 in.^{3} water gun.

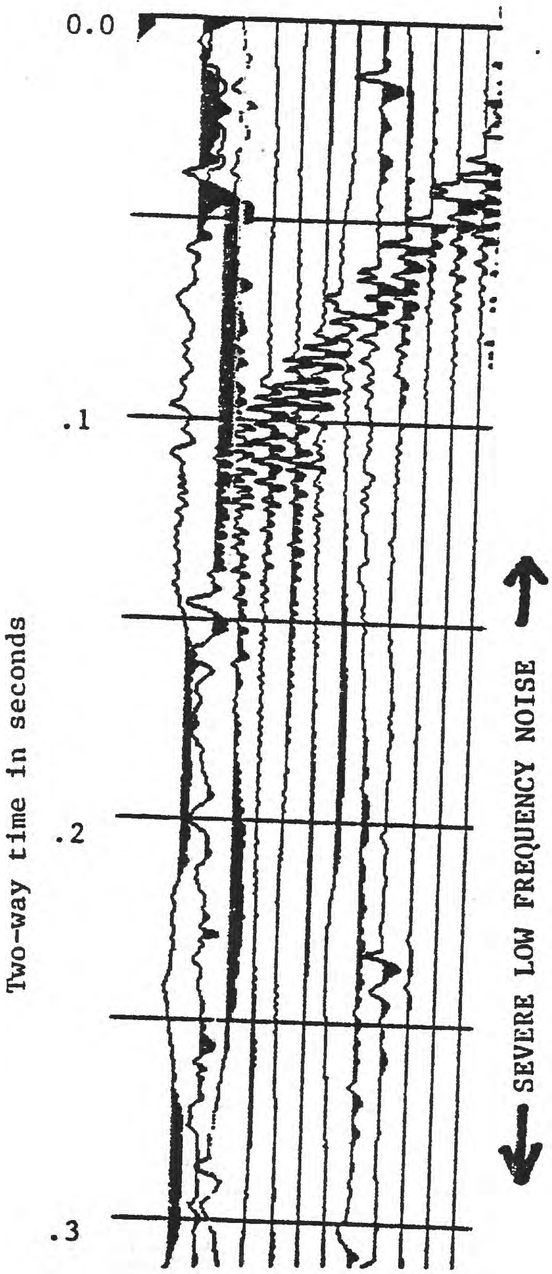


Figure 6. Example of cable noise due to streamer being too close to vessel's wake.

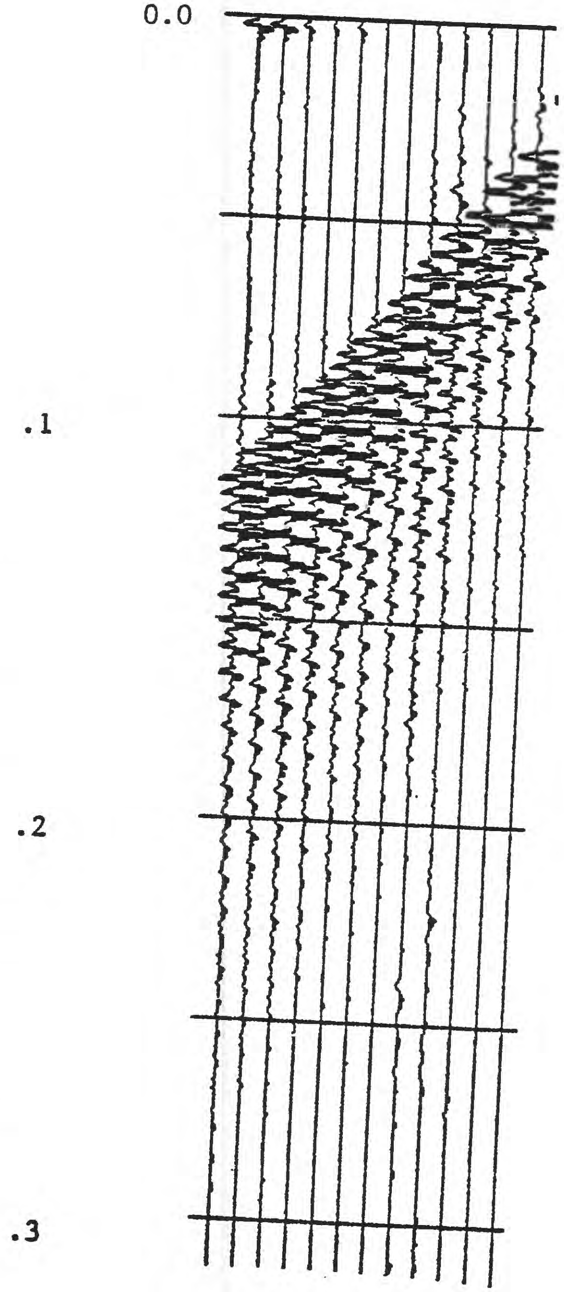


Figure 7. Record after separation of source and cable from vessel by 70 m.

4) Twelve-fold recording showed a marked signal-to-noise ratio (S/N) improvement over six fold and so the source interval of 5 m was chosen. Figure 8 shows this S/N improvement in a 6- vs. 12-fold section.

Production Seismic Reflection Recording

The production-line recording parameters used for lines 3K, 17-26, 27A, 36-44 (fig. 10) are:

1. Source-near receiver offset=0.
2. Source-vessel offset=70 m.
3. 110-m streamer used.
4. 12 fold; 5-m source interval.
5. 1/2 msec sampling interval

Figure 9 graphically shows the source-receiver geometry.

These are the majority of production lines. The method of parameter selection is explained in the previous section. An error caused lines 27-35 to be recorded with a 15-m source near-receiver offset. One line was recorded with an 80 $in.^3$ water gun. It was shot 3-fold and had a 68.5-m source near-receiver offset.

Table 1b lists all production lines and their corresponding recording parameters. Table 2 is a chronological log of both experimental and production lines shot.

Refraction Operation

Two north-south refraction lines were recorded along the length of the lake. The receiver was a fixed sonobuoy which used radio waves to transmit data to the vessel. The source was an 80 $in.^3$ water gun and the source interval was 70 m. One line was shot south to north, with the receiver at the south. The other was shot north to south with the receiver at the north. Recording parameters are listed in table 1b. The refraction line was recorded along the same track as Line 26, figure 10.

REFLECTION DATA PROCESSING

Standard Processing Procedures

Initial data processing consisted of standard state-of-the-art processing techniques performed on the Phoenix I Seismic Data Processing System. Each processing step is summarized below.

Demultiplex.--The data were reformatted from SEGB-sample sequential field format to Phoenix I trace-sequential format. Navigation data recorded in the record headers by the miniranger navigation system were decoded and placed in trace-header words of each trace demultiplexed. This navigation information was then used to plot track lines (shotpoint location maps) of the survey.

Gain recovery.--A trial and error scheme was used to recover amplitude attenuation due to absorption and spherical divergence. Gain functions were calculated and multiplied to each data trace using a T^N scheme where T=two-way travel time in seconds and N=an exponent between 1.2 and 2.0 varying by 0.1 increments each try. A gain curve of $T^{1.5}$ was chosen because it was most successful in balancing amplitude with time (fig. 11).

Table 2.--Lines shot in chronological order

Date	Line(s) Shot	Comments
19 Nov.	1	These are considered experimental lines.
20 Nov.	2, 2A, 3-9	They were shot with varying source-
21 Nov.	3A-3C	receiver (S-R) offsets, different streamer
22 Nov.	3D, 3E	lengths (110 or 220 m) and with source and
23 Nov.	3F	streamer at varying distance behind the boat.
24 Nov.	3G-3J	
25 Nov.	10-16	
26-30 Nov.	None	Holiday
1 Dec.	17	Rain, windy. Reshot as Line 17A.
2 Dec.	None	Rain, windy. Unable to work.
3 Dec.	17A, 18-26, 3K	Zero-offset, water-gun source.
4 Dec.	27-35	15-m S-R offset air-gun source.
5 Dec.	27A, 36-38	Zero-offset, air-gun source.
6 Dec.	3L	80 in.^{3} water-gun source. Failed to shoot refraction.
7 Dec.	41-44	Zero-offset, air-gun source.
8 Dec.	45, 46	Refraction lines using sonobuoy and 80 in.^{3} water gun.

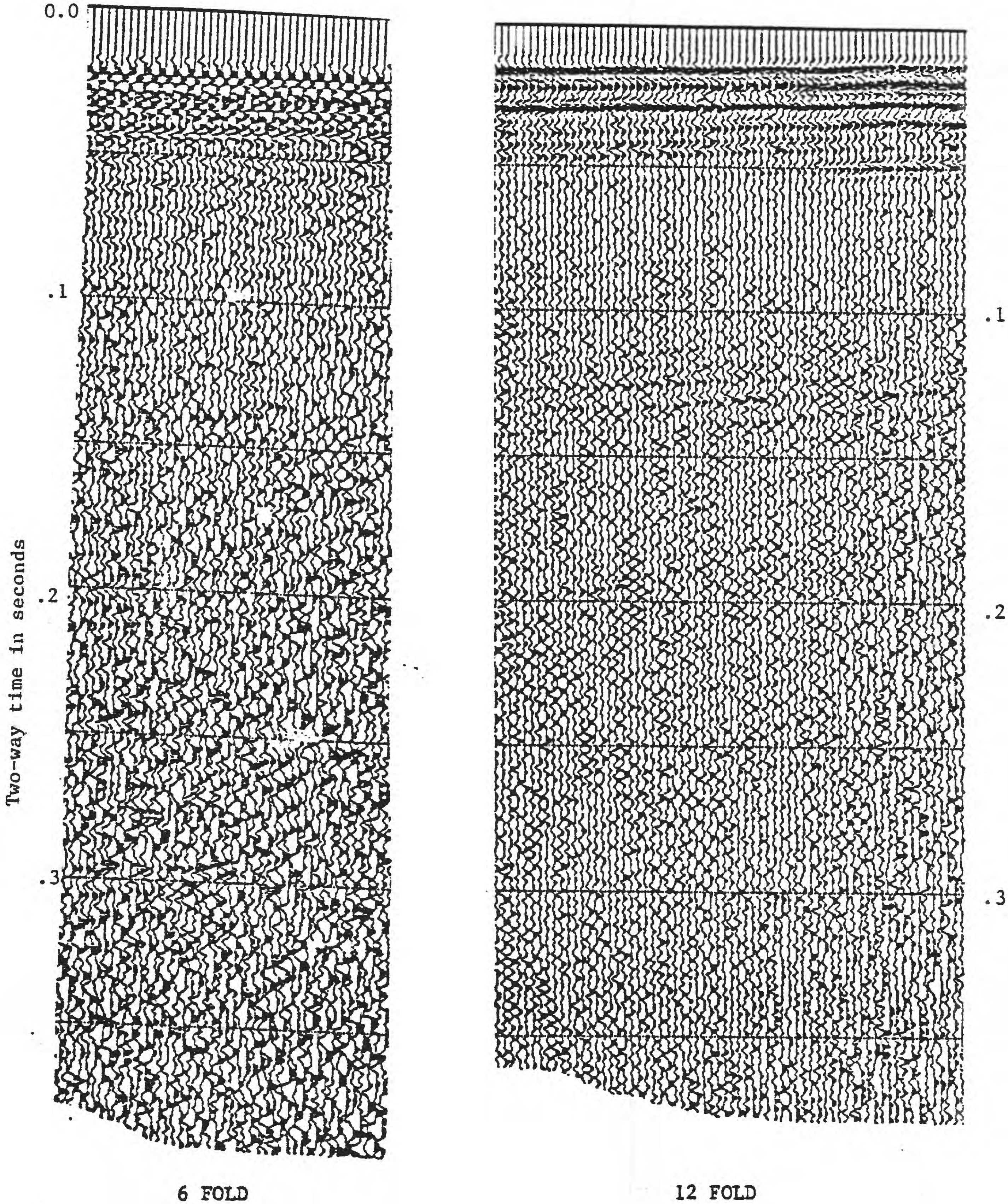


Figure 8. Signal-to-noise ratio improvement by 12 fold vs 6 fold shooting.

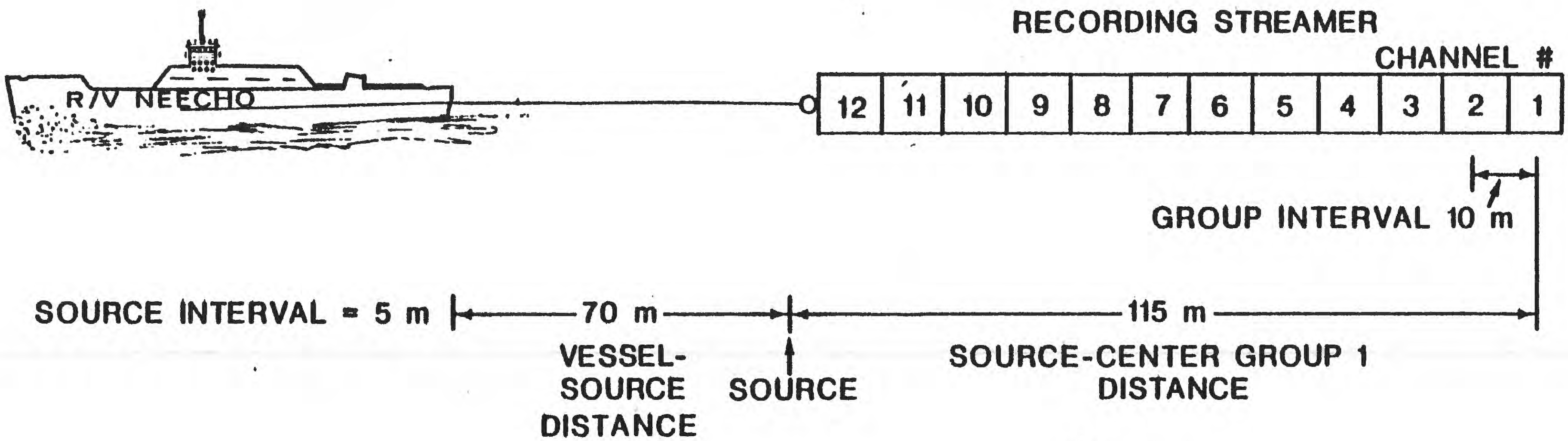
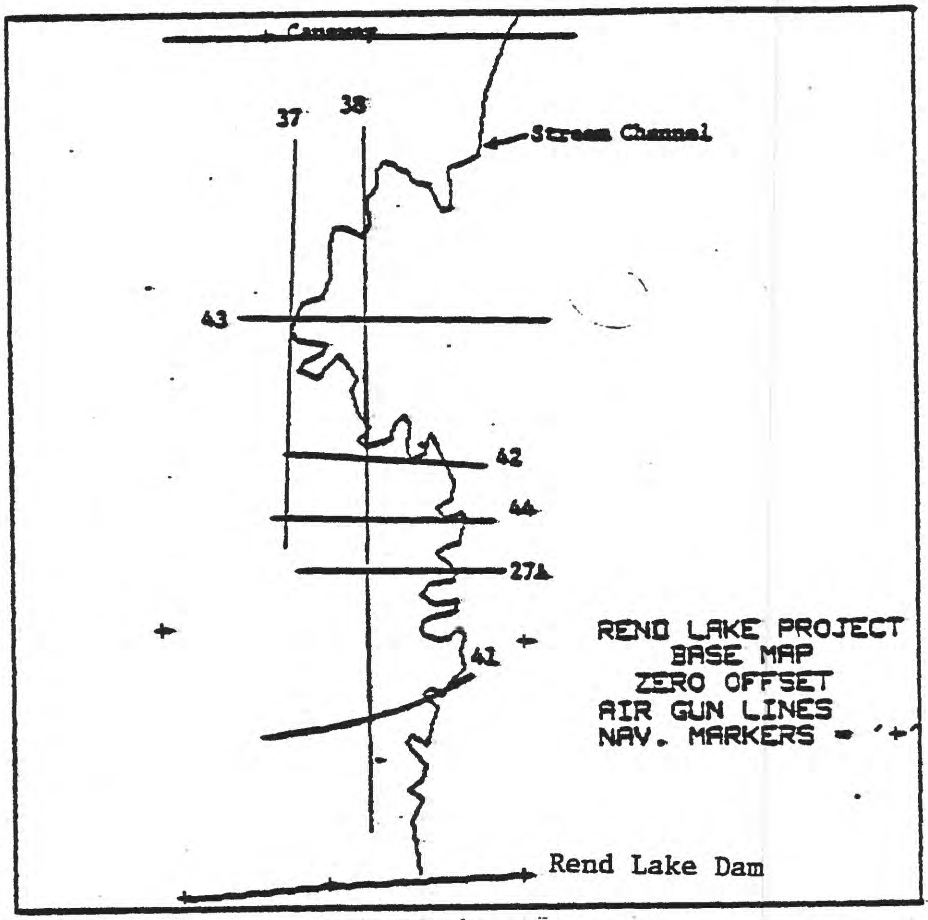


Figure 9. Recording geometry from production lines.



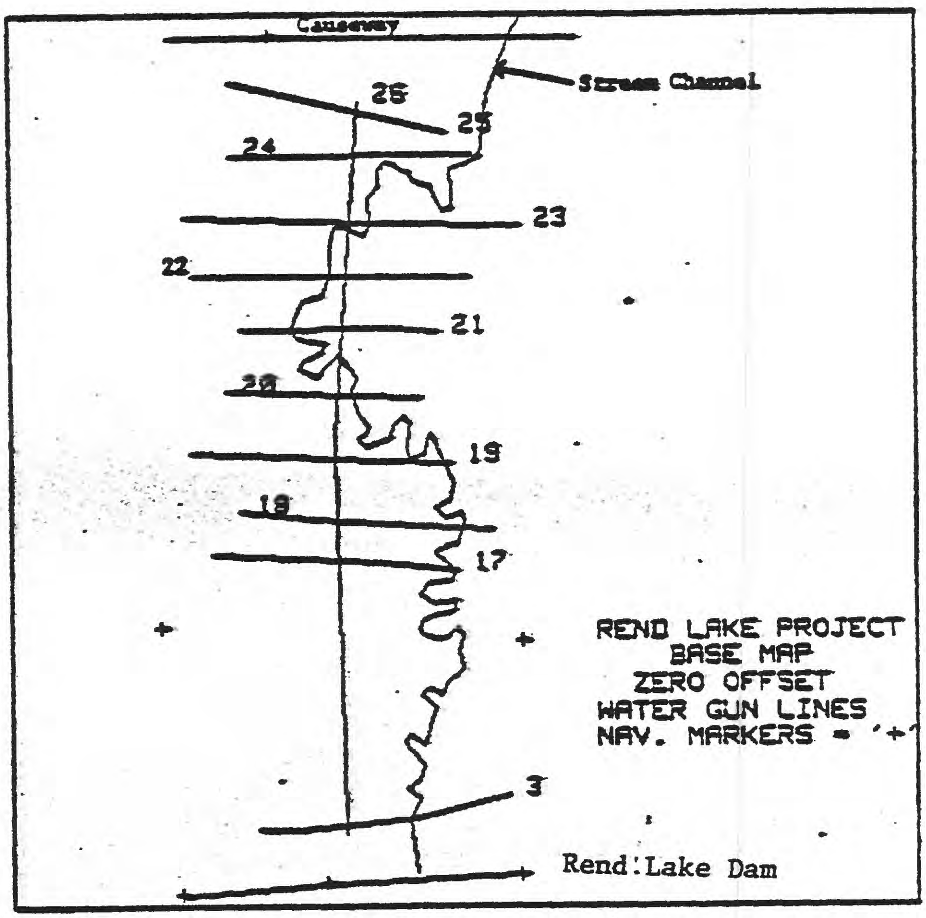


Figure 10. Map of production lines. Top: Lines shot using air-gun source. Bottom: Lines shot using water-gun source.

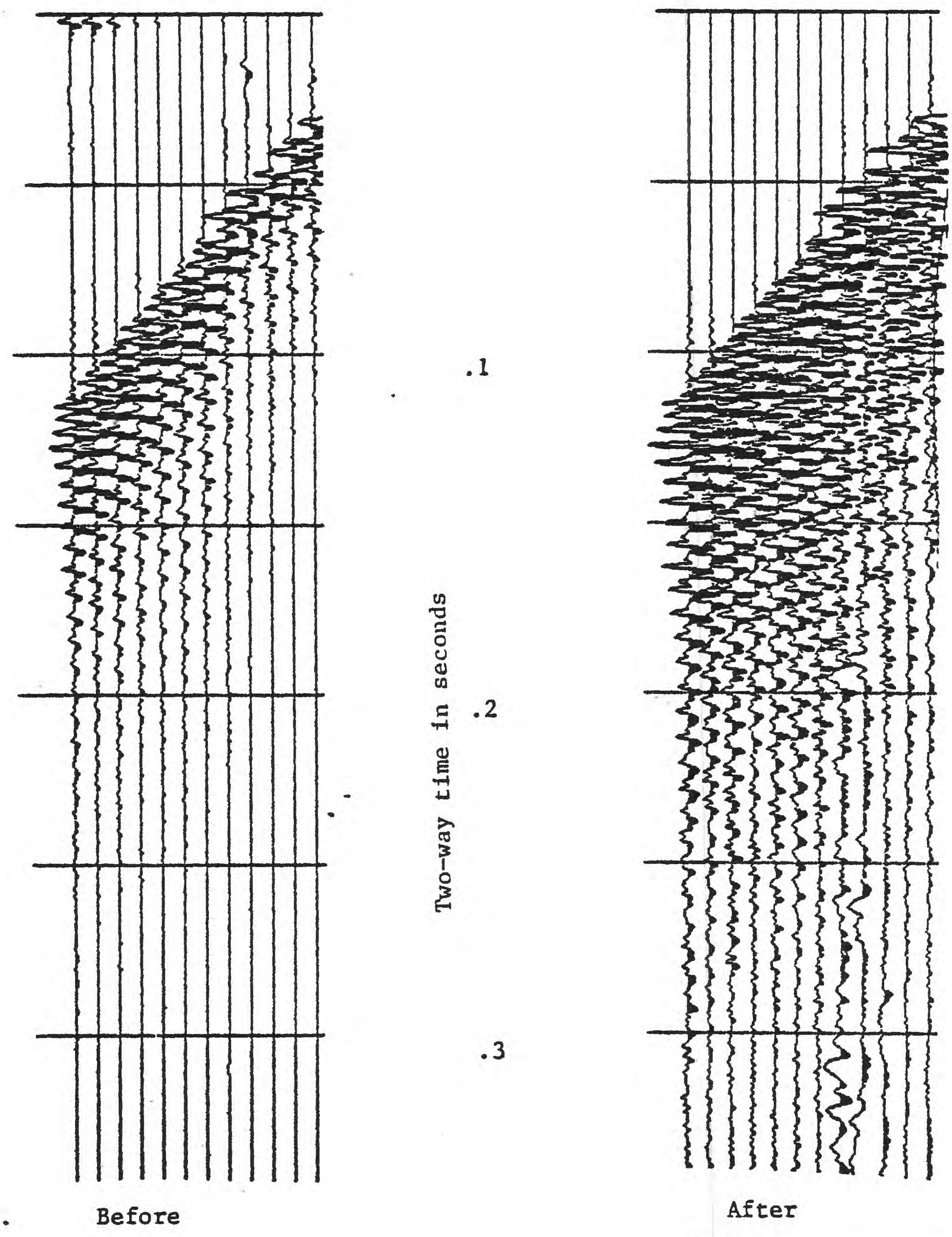


Figure 11. Example of shot records before and after $T^{1.5}$ gain curve application.

Filter analysis.--Various zero-phase, band-pass filters were applied to the gained data in an attempt to suppress spurious frequencies. The band pass chosen is shown in figure 12 and its effect on the data is shown in figure 13. This filter seemed to best eliminate noise while preserving the integrity of the reflected events.

Deconvolution filtering.--Predictive deconvolution was applied in an attempt to remove water-bottom reverberations. A 50-msec filter was designed on autocorrelations calculated between 90 and 300 msec on the far trace and between 25 and 300 msec on the near trace. The second zero crossing of the autocorrelation was used as a predictive distance and 3 percent white noise was added to the data as a stabilizing factor.

Figure 14 shows the deconvolution filter process on an autocorrelogram, a method whereby deconvolution removes reverberations.

RMS Scaling.--Each trace was scaled so that the RMS average amplitude within a window between 0 and 500 msec was equal. Figure 15 is a shot record after $T^{1.5}$ gain, deconvolution, band-pass filter, and RMS scaling.

Geometry.--Source-receiver distances and common-depth-point (CDP) numbers were calculated and placed in the trace headers. The data were sorted into CDP order.

Velocity analysis.--Constant velocity stacks (CVS) were calculated every 50 CDPs. Ten adjacent CDPs were used at each analysis. The velocity range tested was 1,300 to 3,750 m/sec at 50 m/sec increments. A first break mute was applied before analysis with the two traces nearest the source unmuted. Velocity functions were difficult to pick because events stacked at a large range of velocity (fig. 16). A sonic log recorded near the lake showed velocities increasing gradually with depth. This gradual increase was used as a guide when picking stacking velocities from the constant velocity stacks.

NMO, mute and stack.--Using the picked velocity functions, the data were corrected for normal move-out (NMO), muted to remove first breaks and digital stretch, and composite (stacked) into common depth points.

Display.--The stacked cross sections were displayed on the electrostatic plotter at 10 in./sec and 12 traces/in.

Figure 17 is a stacked cross section with all of the previously discussed processes applied.

Special Processing Procedures

The purpose of this special processing was to develop an optimum processing technique to suppress the strong water-bottom reverberation and enhance signal-to-noise ratio. An analysis of the stacked cross sections showed that most apparent reflections mirrored the water bottom. Also, no offset appears where faults were known to be present. We suspected that multiples of the water bottom were being stacked. This phenomenon was further confirmed from the velocity analyses showing that reflections stacked in at a wide variety of velocity functions.

The recorded shot gathers after gain application show the dominance of the water-bottom reverberations over the recorded signal. Figure 18 shows some shot gathers from line 3K. Inspecting figure 18, we can conclude that there are not any reliable reflected signals coming below the water bottom due to the severe water bottom reverberation.

The dereverberation techniques investigated during this project were (1) a 3-term deterministic filter based on a minimum energy criteria, and (2) space-time (two-dimensional) filters based upon velocity decomposition.

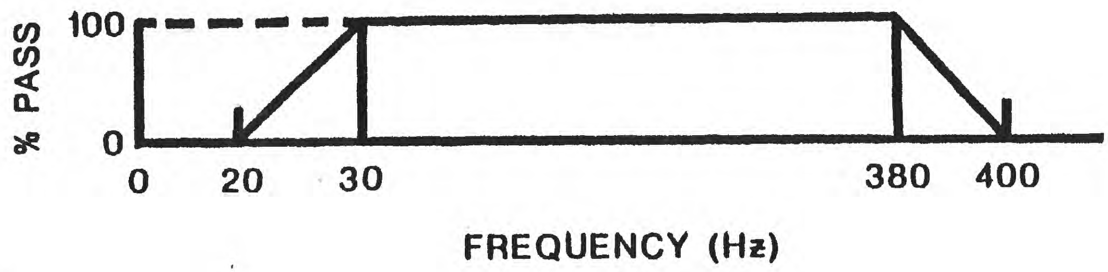


Figure 12. Zero phase band-pass filter amplitude spectrum characteristics.

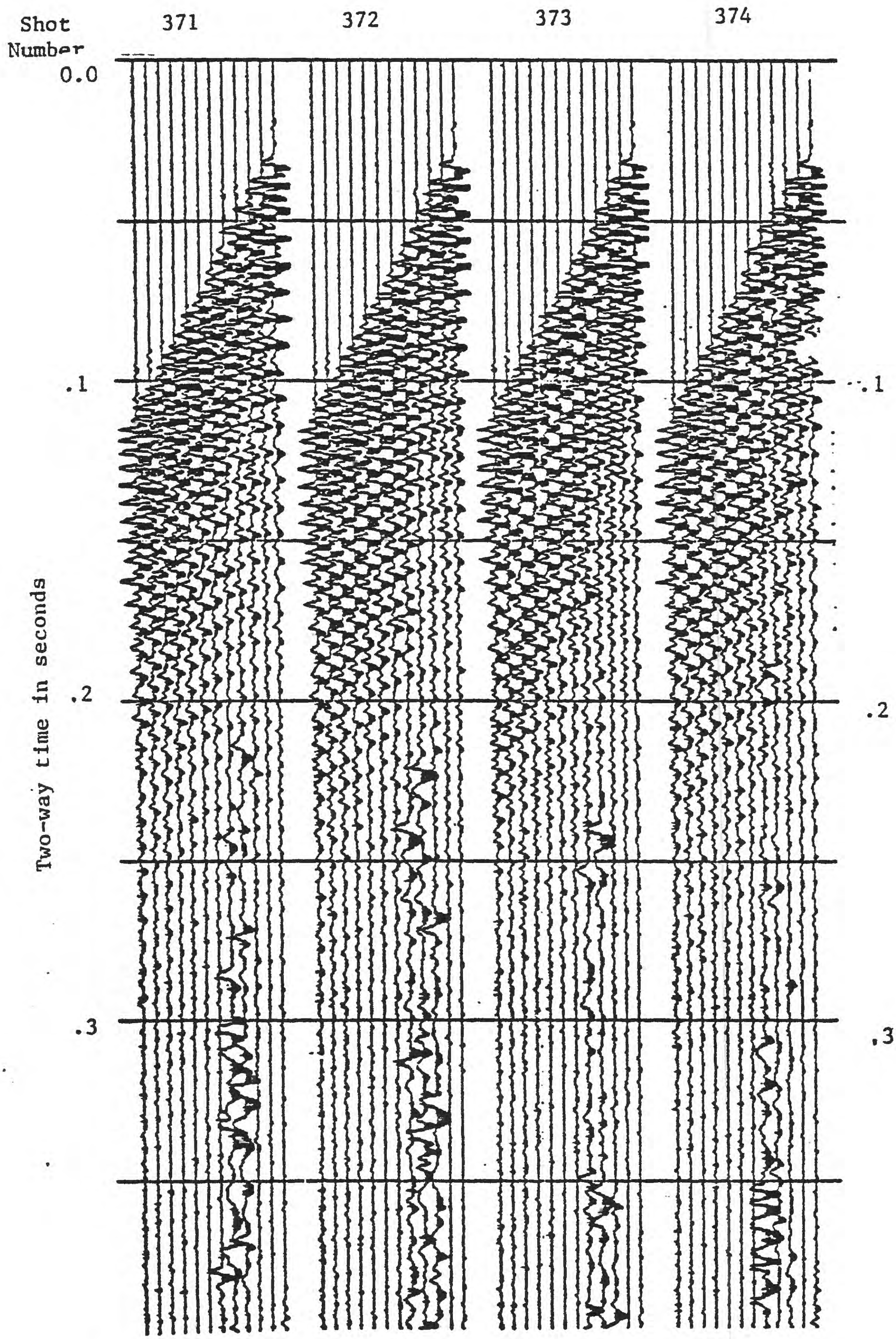


Figure 13. Shot records after $t^{1.5}$ gain, bandpass filter

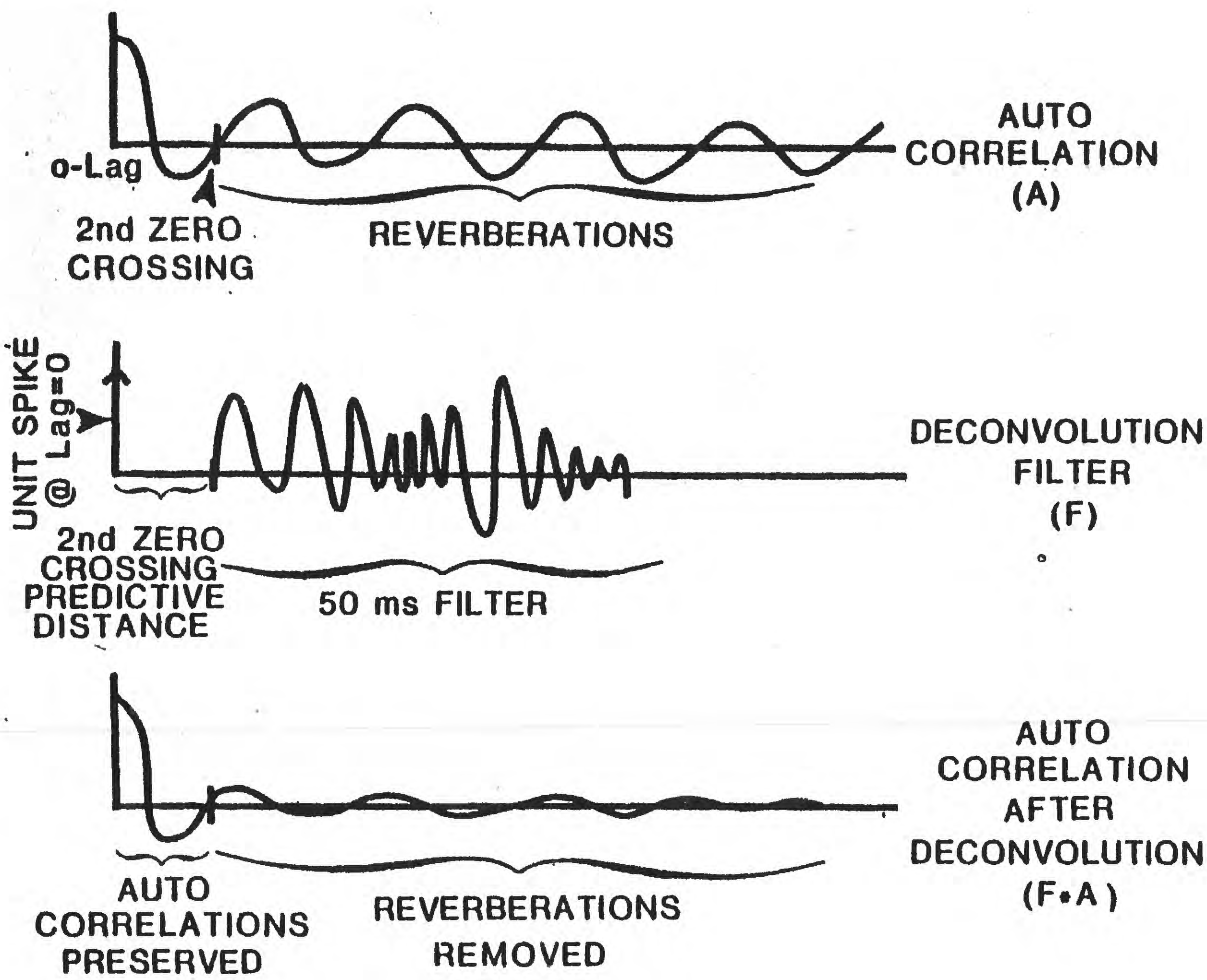


Figure 14. Deconvolution filtering of an autocorrelation.

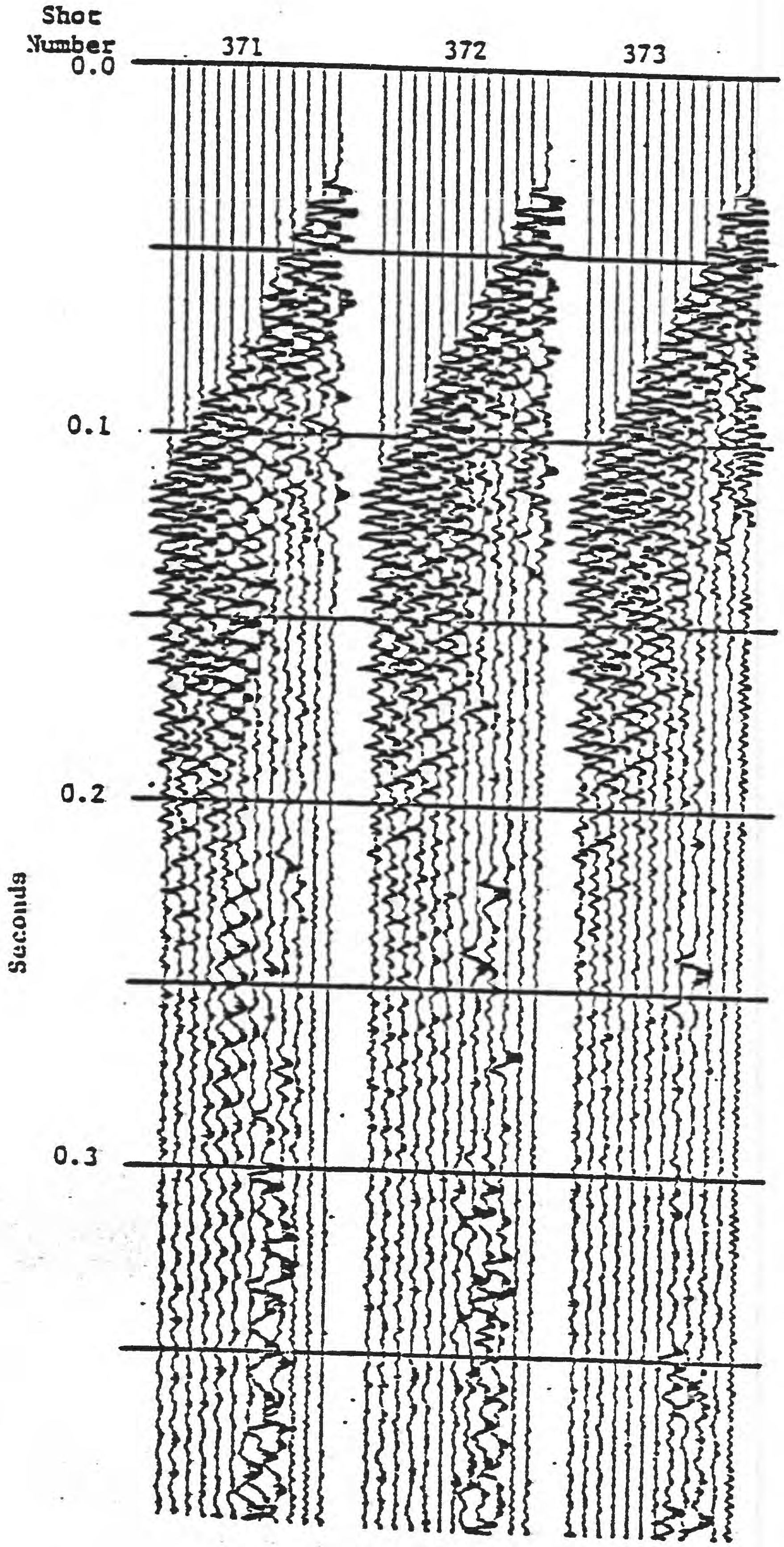


Figure 15. Shot records after $T^{1.5}$ gain curve, bandpass filter, Predictive Deconvolution, and RMS scaling

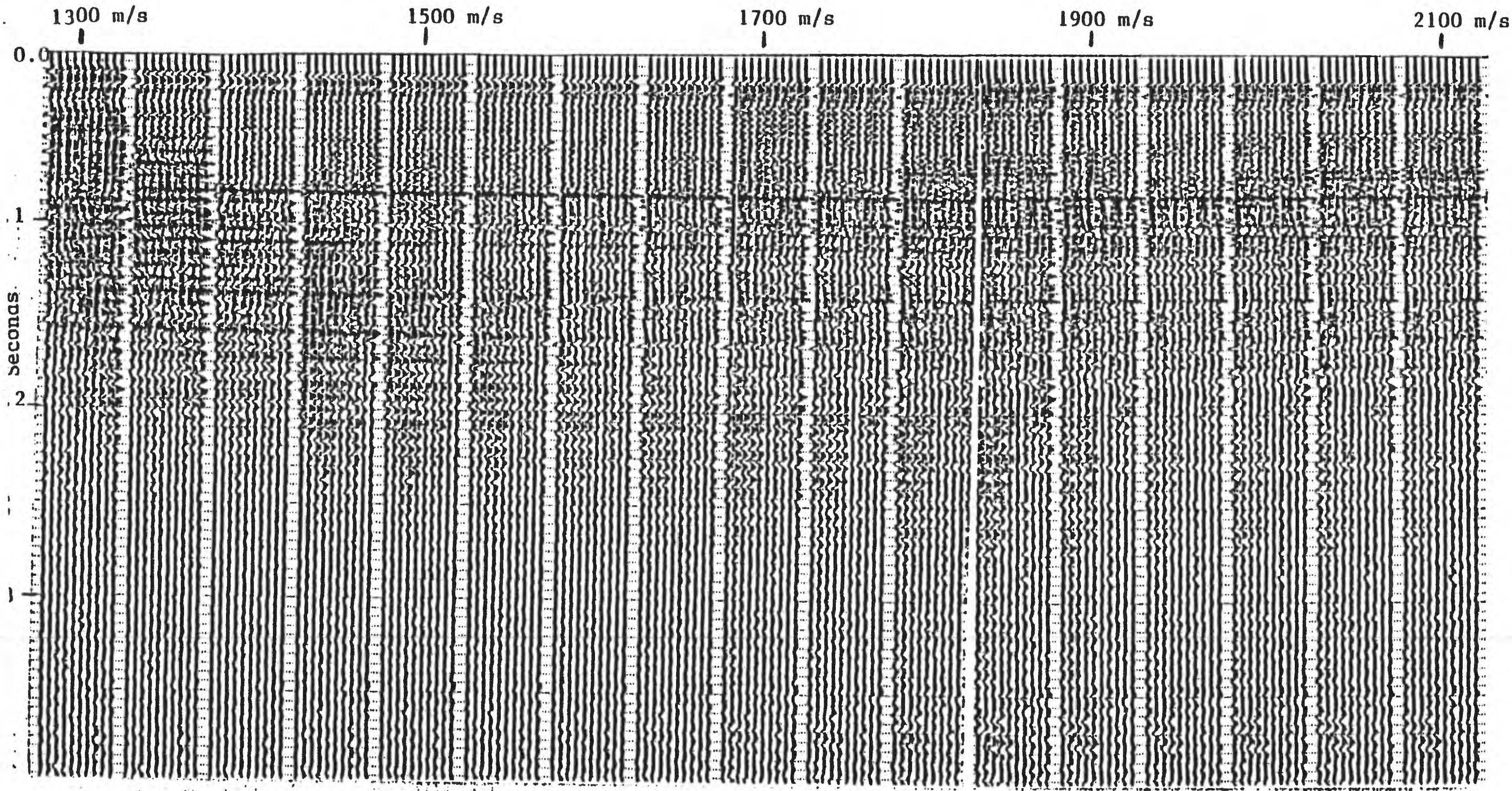


Figure 16. Typical example of constant velocity stack (CVS) velocity analysis.

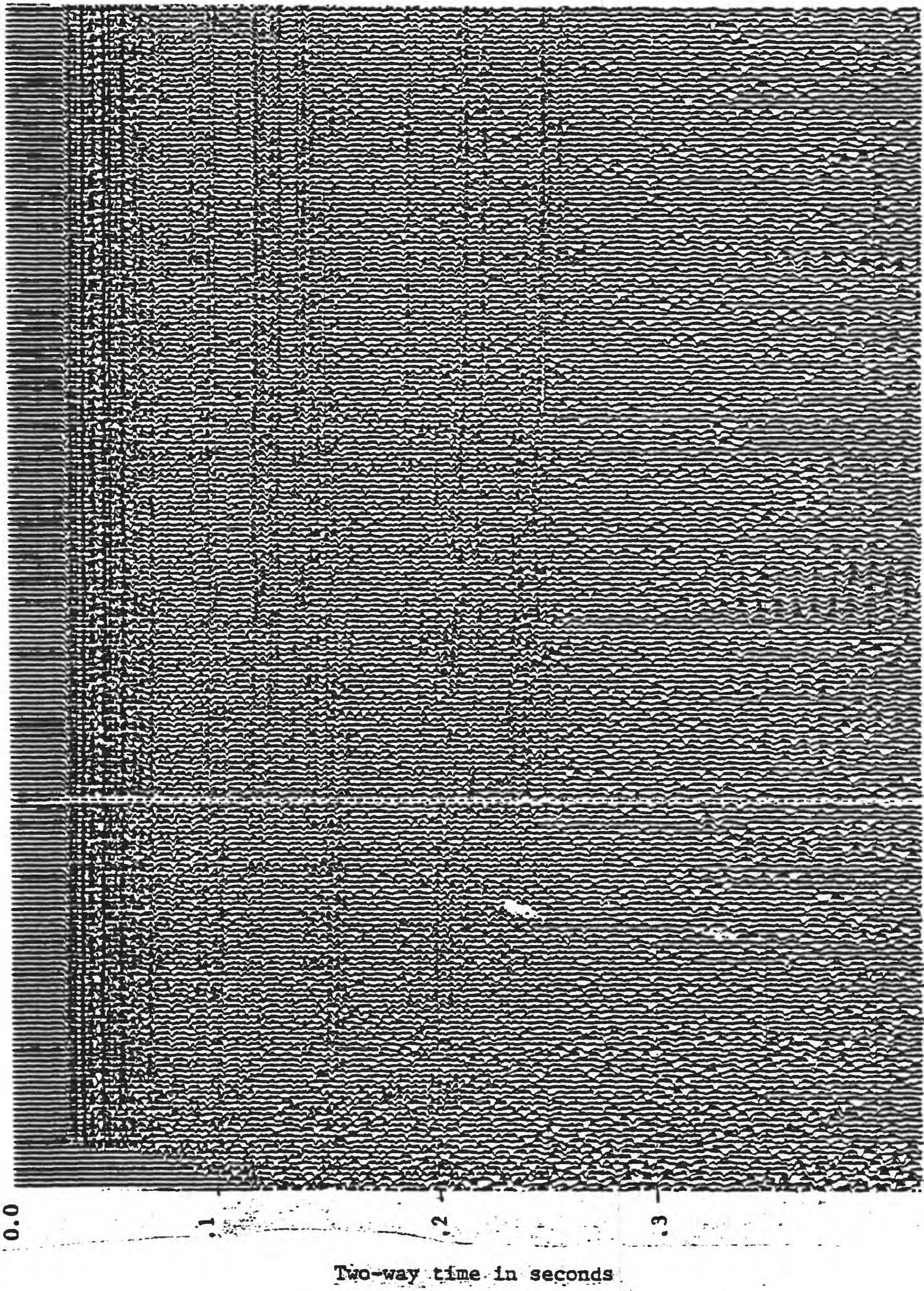


Figure 17. Stacked cross section using standard processing sequence.

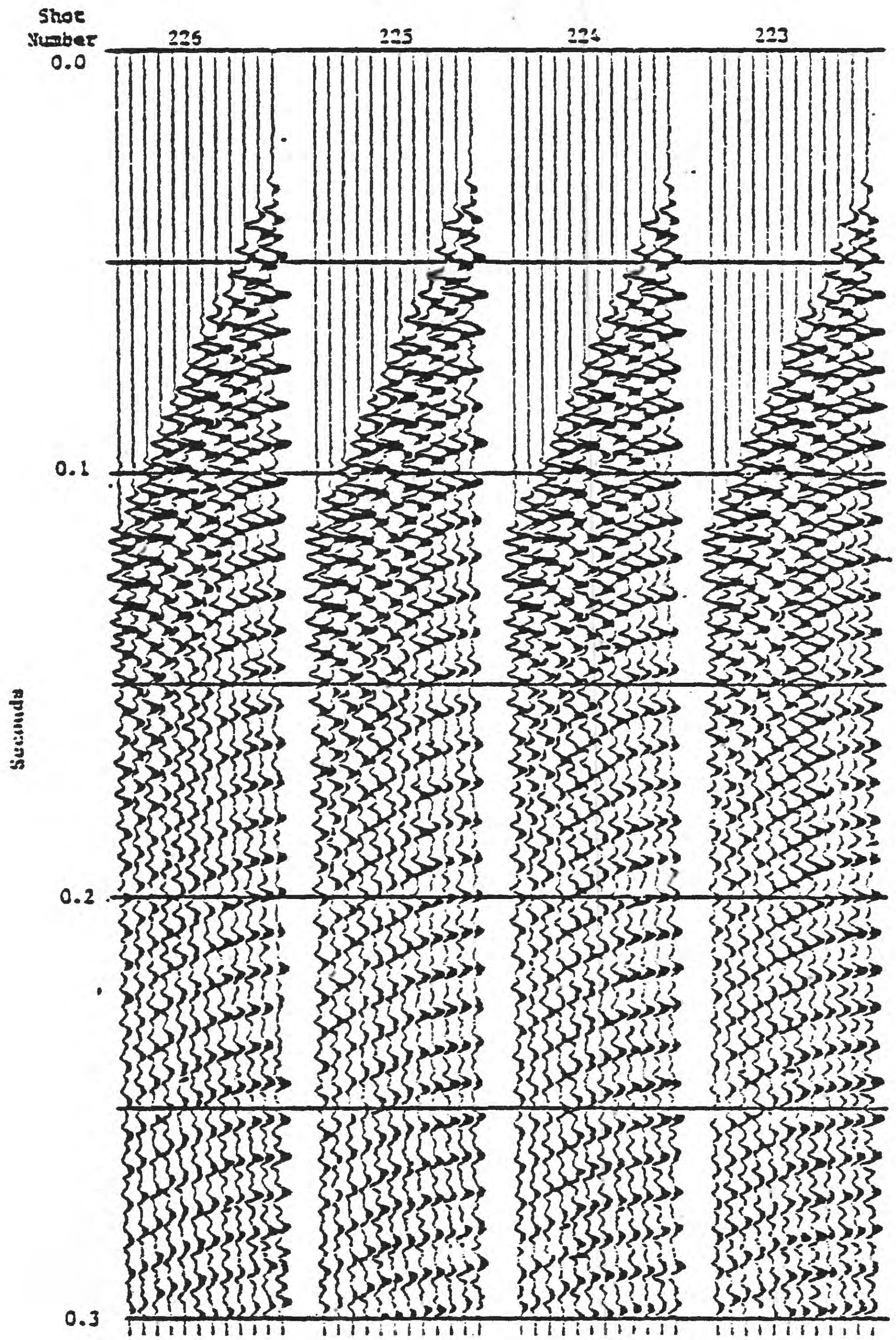


Figure 18. Some examples of original shot gathers after gain application from line 3K showing strong water bottom multiples.

3-Term filter.--This method was developed under the assumption that the total energy of a seismic trace could be minimized after removing the reverberant energy. If the reflection coefficient sequence is nearly white (random), this assumption is reasonably true.

Assume that the seismic trace, using Z-transform S(Z), is given by the following equation:

$$S(Z)=R(Z)/F(Z). \tag{1}$$

where

S(Z): seismic trace,
R(Z): reflection coefficient series, and
F(Z): reverberation operator.

In the above equation (1), R(Z) is the reflection coefficient series that will be estimated from the multiple-corrupted seismic trace S(Z). The reverberating system of the water bottom can be modeled by $F(Z)=(1+rZ\ )$, where r is the reflection coefficient of the water bottom and N is the two-way travel time of seismic energy in the water. Then the reflection coefficient series is given by:

$$R(Z)=S(Z)(1+rZ^{N})^{2}. \tag{2}$$

Therefore, if r and N can be estimated from the original seismic trace, the effect of reverberation can be suppressed by applying equation (2) to the original seismic trace.

In order to estimate r and N from the original seismic trace, an iterative scheme was developed by examining the total energy of equation (2).

To test this algorithm, a synthetic seismogram was generated from a sonic log measured in a borehole a few hundred meters south of Rend Lake dam. Figure 19 shows the reflection coefficient series. The top trace of Figure 19 shows the unfiltered refection coefficient series in equal two-way travel time from the sonic log and the bottom trace shows the primary seismogram by convolving the top trace with a wavelet, which is given by $e^{-.5t}\ \sin(\pi t/5)$.

Figure 20 shows the synthetic seismogram including the water bottom reverberations with r=0.9 and N=20 msec, which was generated by applying equation (1) to the reflection coefficient series given in Figure 19. As in figure 19, the top trace is the unfiltered version and the bottom trace has been convolved with the wavelet.

From figure 20, r and N were estimated, and equation (2) was applied to the data shown in figure 20. The results of this operation are shown in figure 21. Figure 21 is almost identical to figure 19, showing the nearly perfect dereverberation. In this synthetic example, the minimum energy criteria in estimating a dereverberation operator is very effective. In applying 3-term filter to the actual seismic trace, one could expect some deterioration of seismic waveforms due to, primarily, the non-stationary property of the actual seismic data.

Space-time domain filter.--Space-time domain filter method (Ryu, 1982) is based on the difference of apparent velocities betweeen primaries and multiples. In general, the stacking velocities of the primary events are higher than that of the water-bottom multiples.

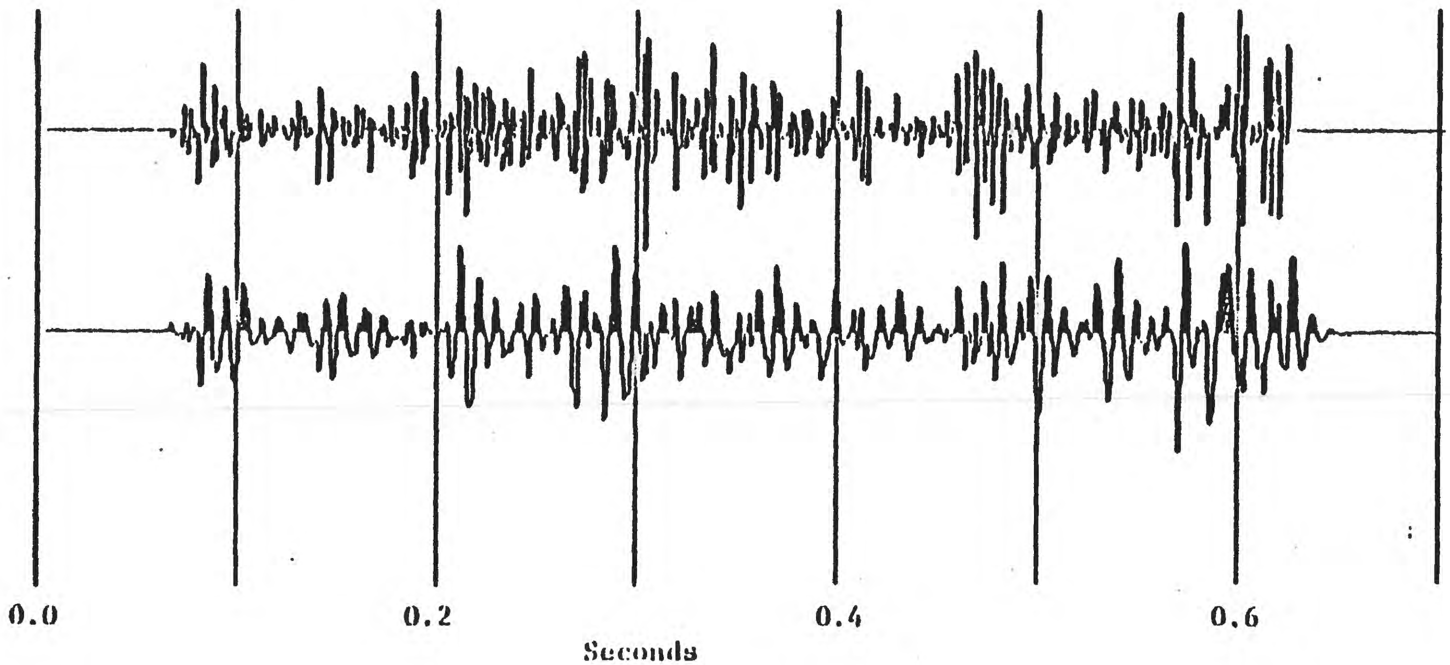


Figure 19. Reflection coefficient series to test 3-term dereverberation filter scheme.
Top: unfiltered reflection coefficient series in equal two-way travel time.
Bottom: convolution product of the top trace with a wavelet, given by $e^{-0.5t}\sin(\pi t/5)$

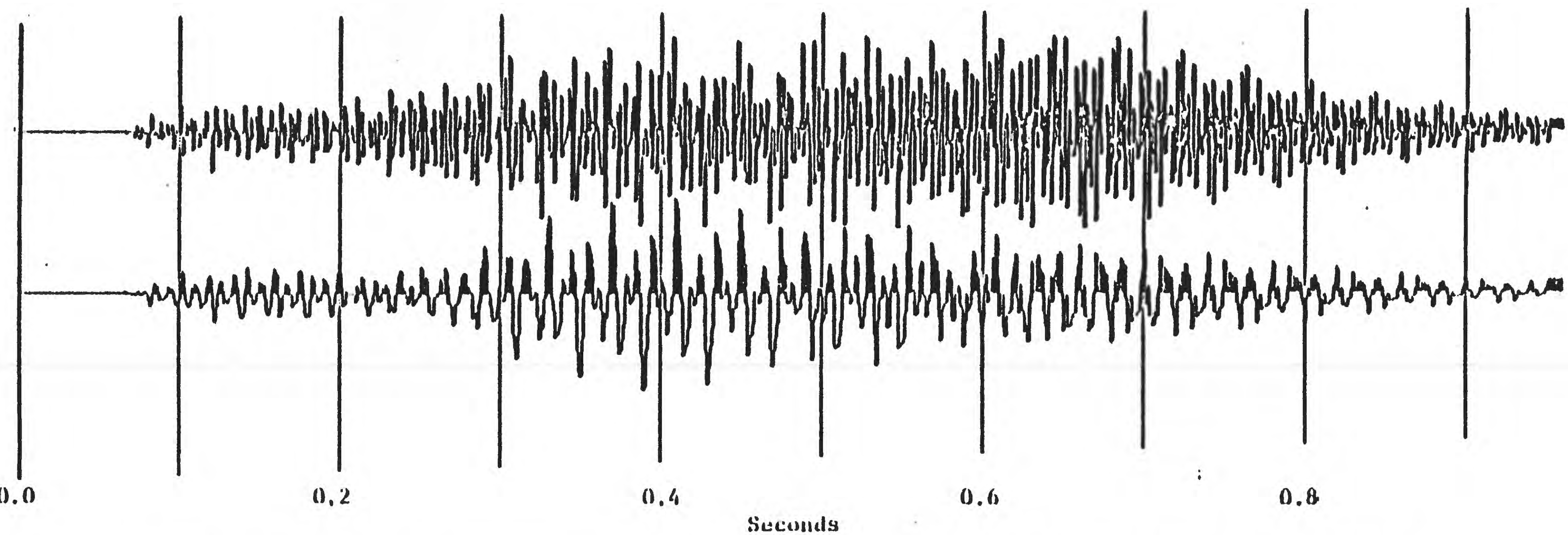


Figure 20. Synthetic seismogram including the water bottom reverberation with r = 0.9 and N = 20 ms.
Top: unfiltered version.
Bottom: wavelet convolved version.

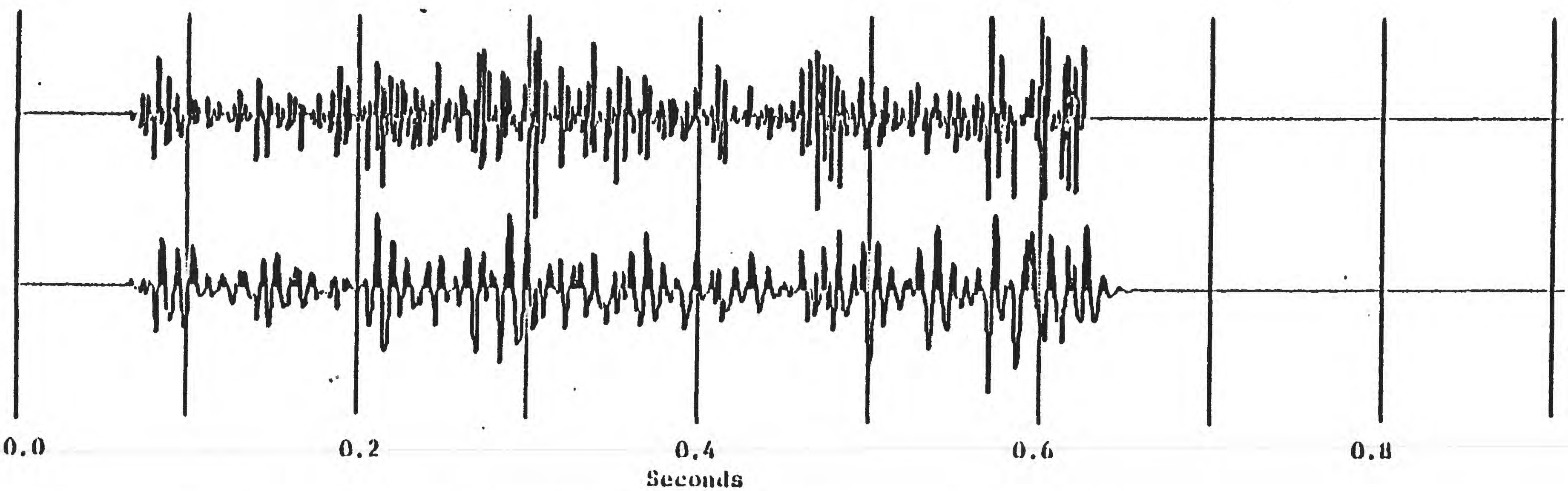


Figure 21. Result of applying 3-term filter to the data shown in Figure 19.
Top: unfiltered version.
Bottom: wavelet convolved version.

Therefore, if the ranges of primary and multiple-stacking velocities could be estimated from the data, the events which fall within the specified moveout range could be effectively suppressed or enhanced. The best advantage of this method is that it distinctively separates the interfering waves without hurting the primaries. This separation is done in velocity-time domain.

The sequence of applying this method are:

1. overcorrect the moveout time of the primary events and undercorrect the multiples using the standard normal move-out (NMO) correction program,
2. apply space-time domain filter, and
3. restore the NMO correction.

Figure 22 shows a model generated to test this technique. In Figure 22 "M" denotes the multiple event to be suppressed. Figure 23 shows the result of applying 12-trace, space-time domain filter to the data shown in Figure 22.

Comparison of the methods.--To compare the dereverberation techniques investigated in this section, predictive deconvolution, 3-term filtering, and space-time domain filters were applied to the data shown in Figure 18.

Figure 24 shows the result of applying the predictive deconvolution technique, described in the previous section. Figure 25 shows the result of applying 3-term filters, and Figure 26 shows the result of applying 12-trace space-time domain filters. These examples show that the 3-term filter and space-time domain filters are superior to the predictive deconvolution technique in suppressing water bottom multiples.

After suppressing the water-bottom multiples using two techniques described in this section, the data were stacked using standard processing sequences described in the previous section.

Unfortunately, no remarkable improvement in the stacked section could be seen. It was concluded that even if the strong water-bottom multiples could be successfully suppressed, the primary reflections are so low in amplitude, compared with residual multiples, that they could not be recovered.

REFRACTION DATA PROCESSING

Computer processing of refraction data is much less complicated than reflection processing. The objective is to remove noise which may obscure the refracted arrivals and to balance their amplitudes.

A band-pass filter of 10 to 50 hertz (Hz) was applied, followed by an amplitude-balancing routine. Amplitudes were muted (set equal to zero) from zero time to just above the refracted arrivals.

Figures 27 and 28 are the processed refraction profiles. Only one refractor is present and this refraction is from a depth much shallower than the coal beds of interest.

CONCLUSIONS

Severe water-bottom multiples obscure any possible reflected arrivals from depth and are due to the nature of the water bottom at Rend Lake. In the model study described in the previous section, the water bottom was assumed to be soft mud, saturated with water and gas, with bedrock a few feet below. This gives rise to a very large reflection coefficient due to the high-impedance contrast between the three materials (water, mud, and rock) at that contact. This reflection coefficient in addition to the shallow water layer (~25 ft) trapped most of the energy within the water.

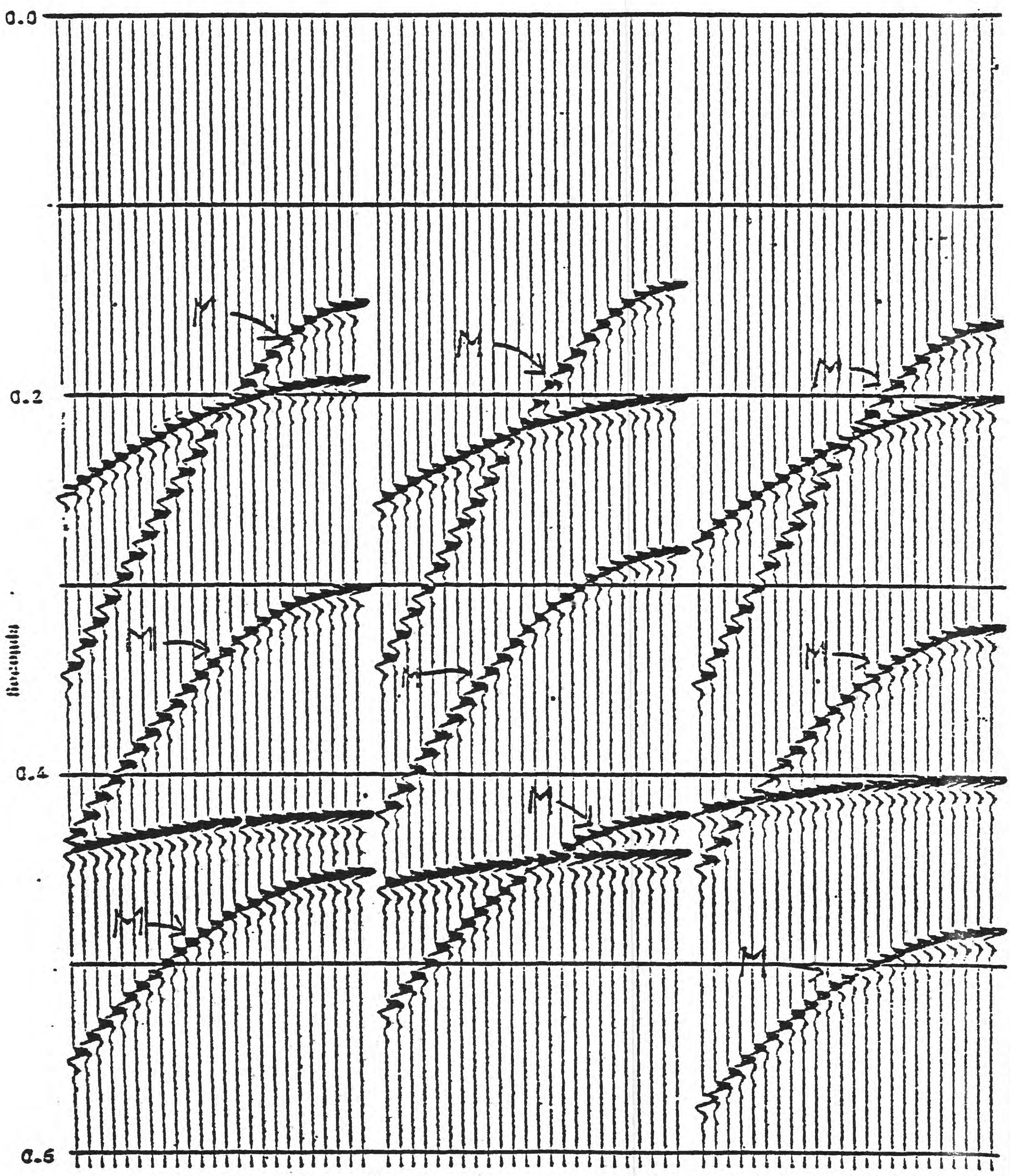


Figure 22. An input model to test space-time domain filter scheme to suppress the multiples. "M" indicates the multiples.

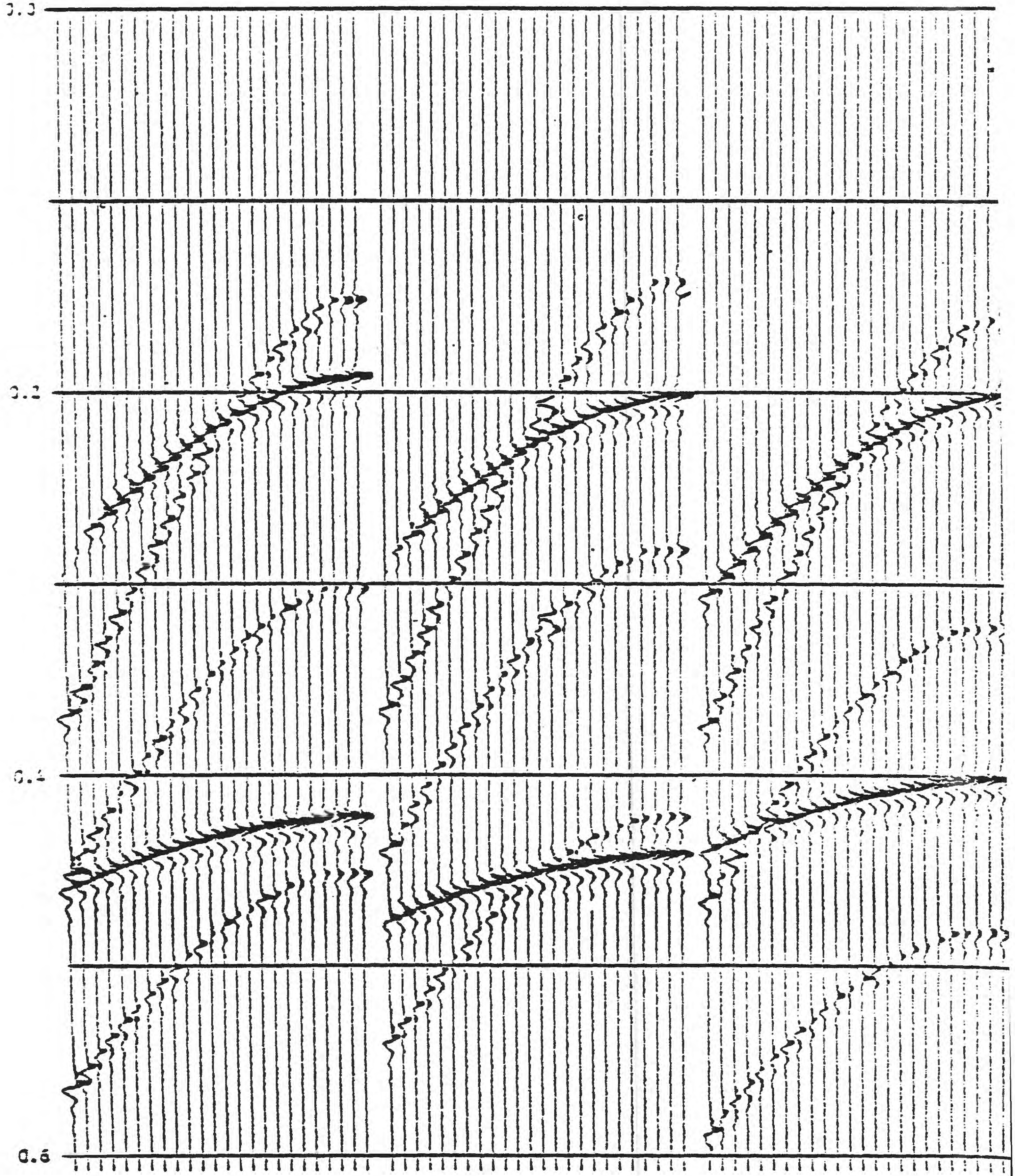


Figure 23. The result of applying 12-trace space-time domain filters to the data shown in Figure 22.

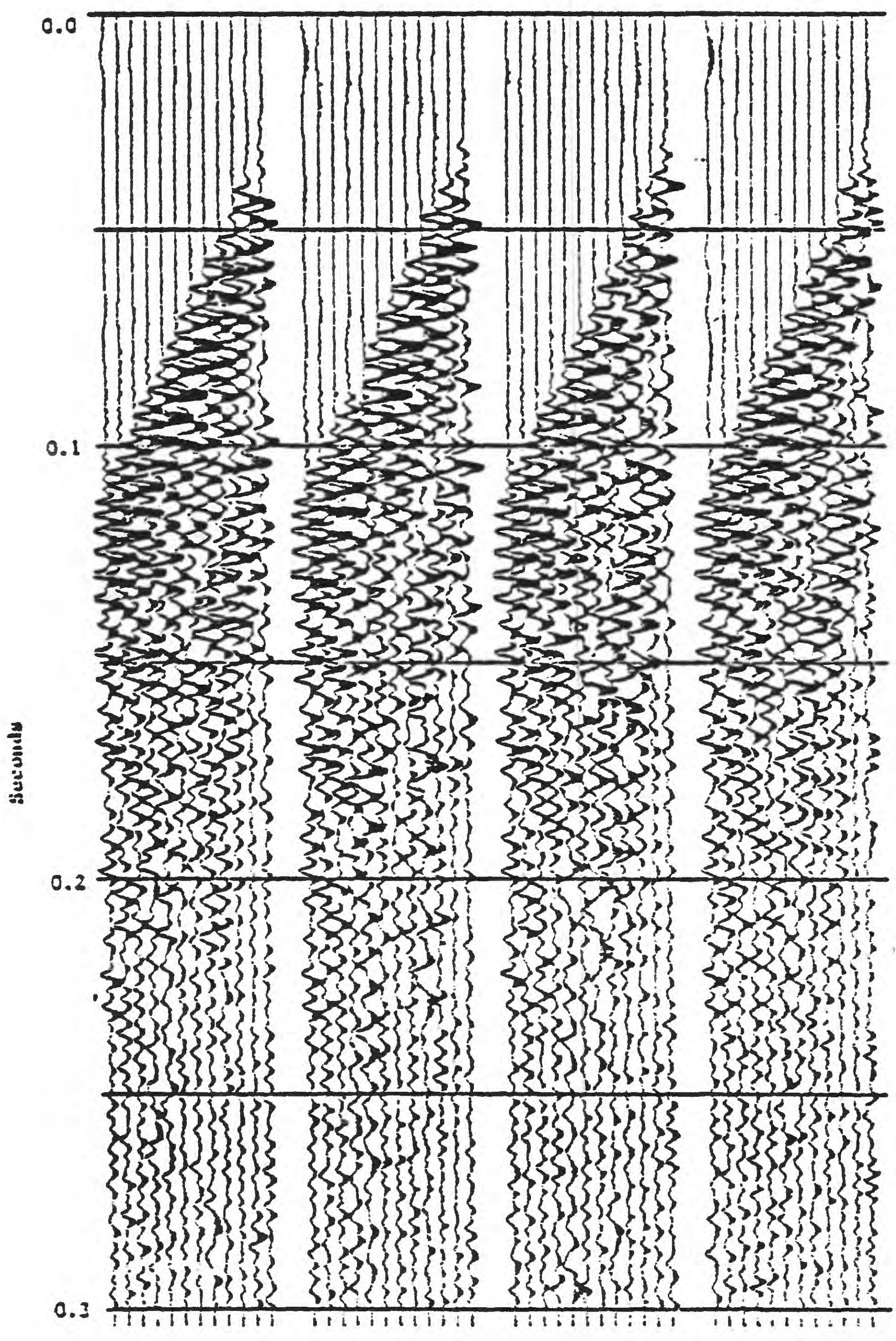


Figure 24. Result of suppressing water bottom multiples on Figure 13 using predictive deconvolution technique.

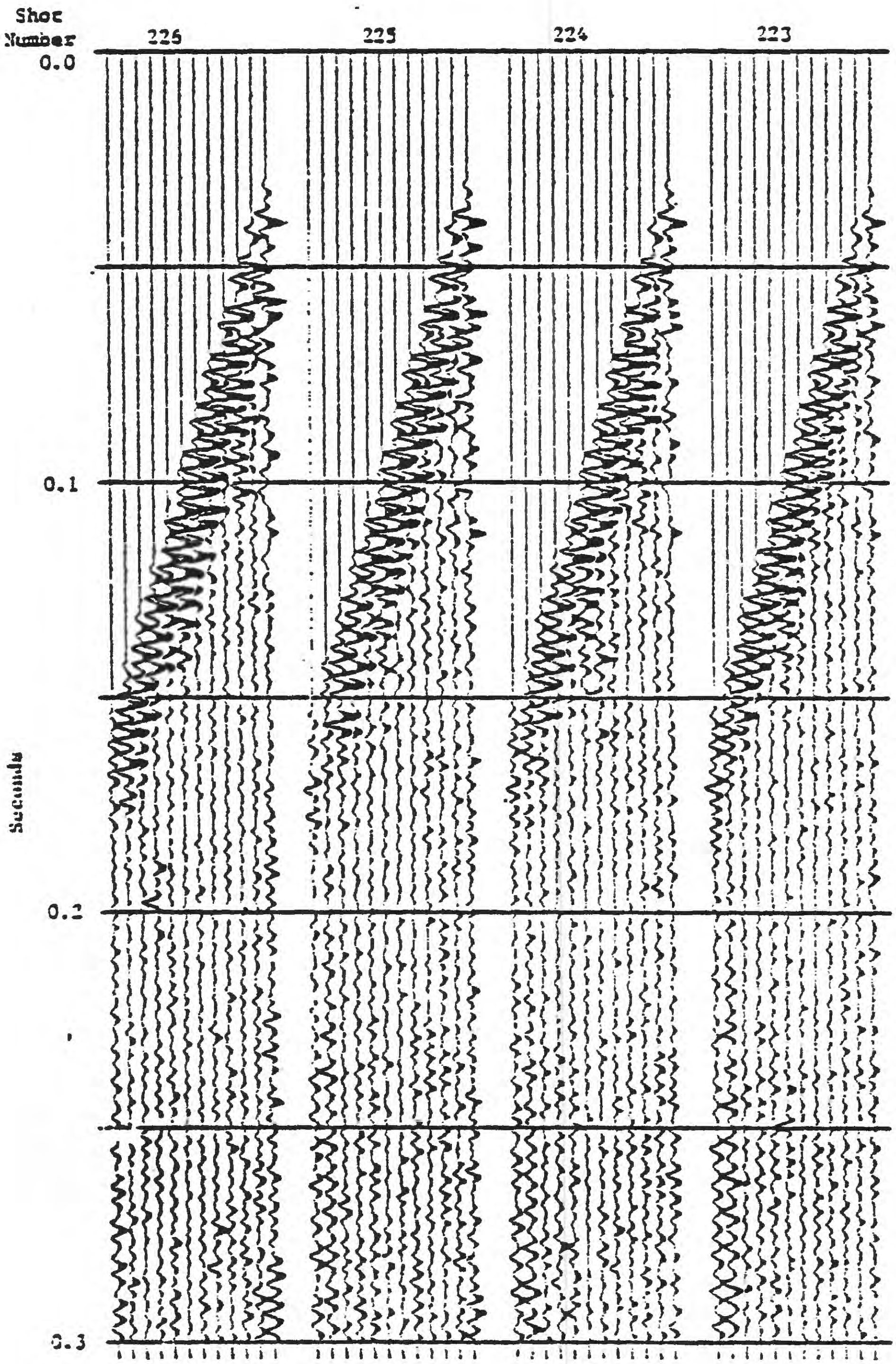


Figure 23. Result of suppressing water bottom multiples from Figure 13 using 3-term filter.

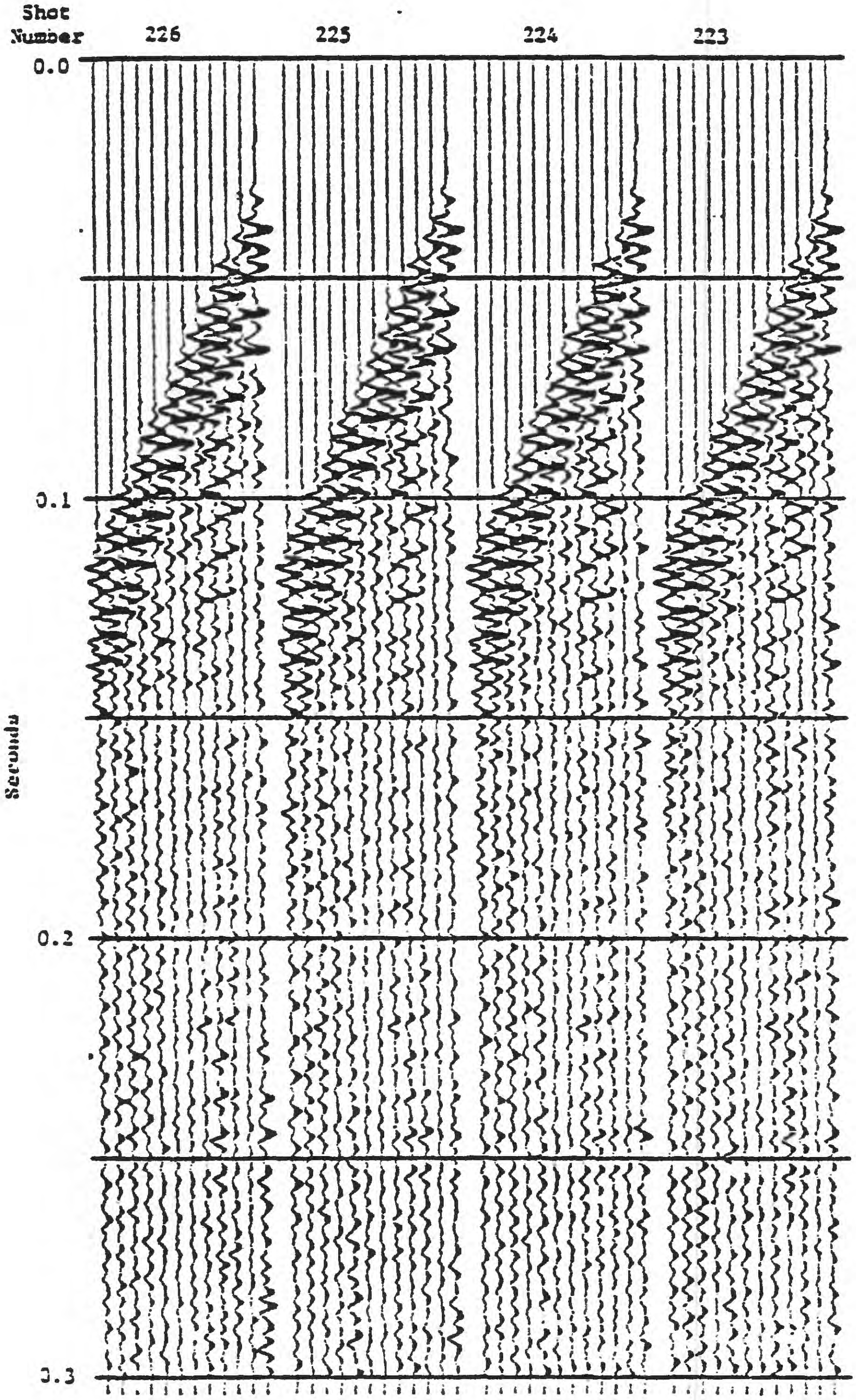


Figure 26. Result of suppressing water bottom multiples from Figure 18 using 12-trace space-time domain filters.

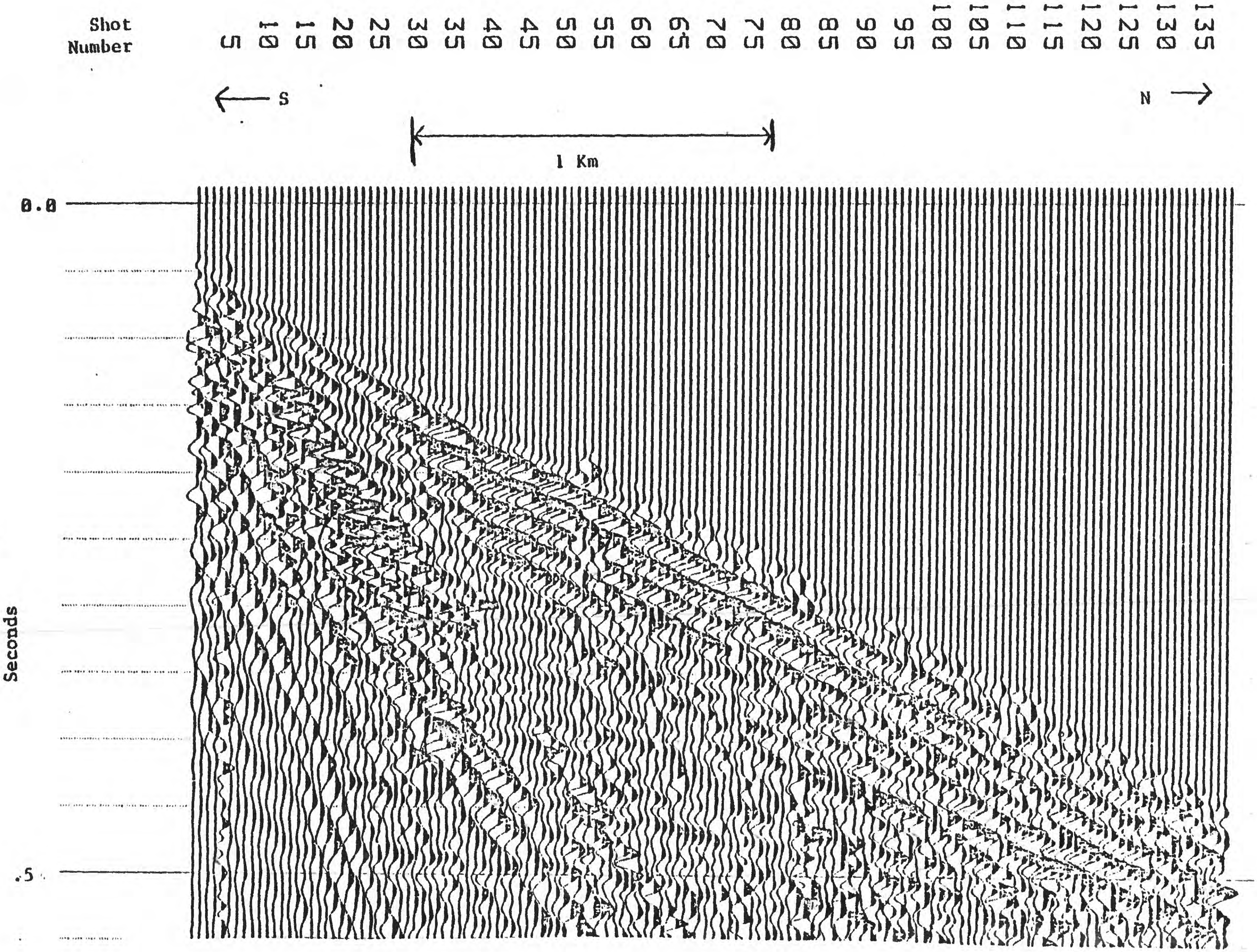


Figure 27. Processed refraction line [illegible]

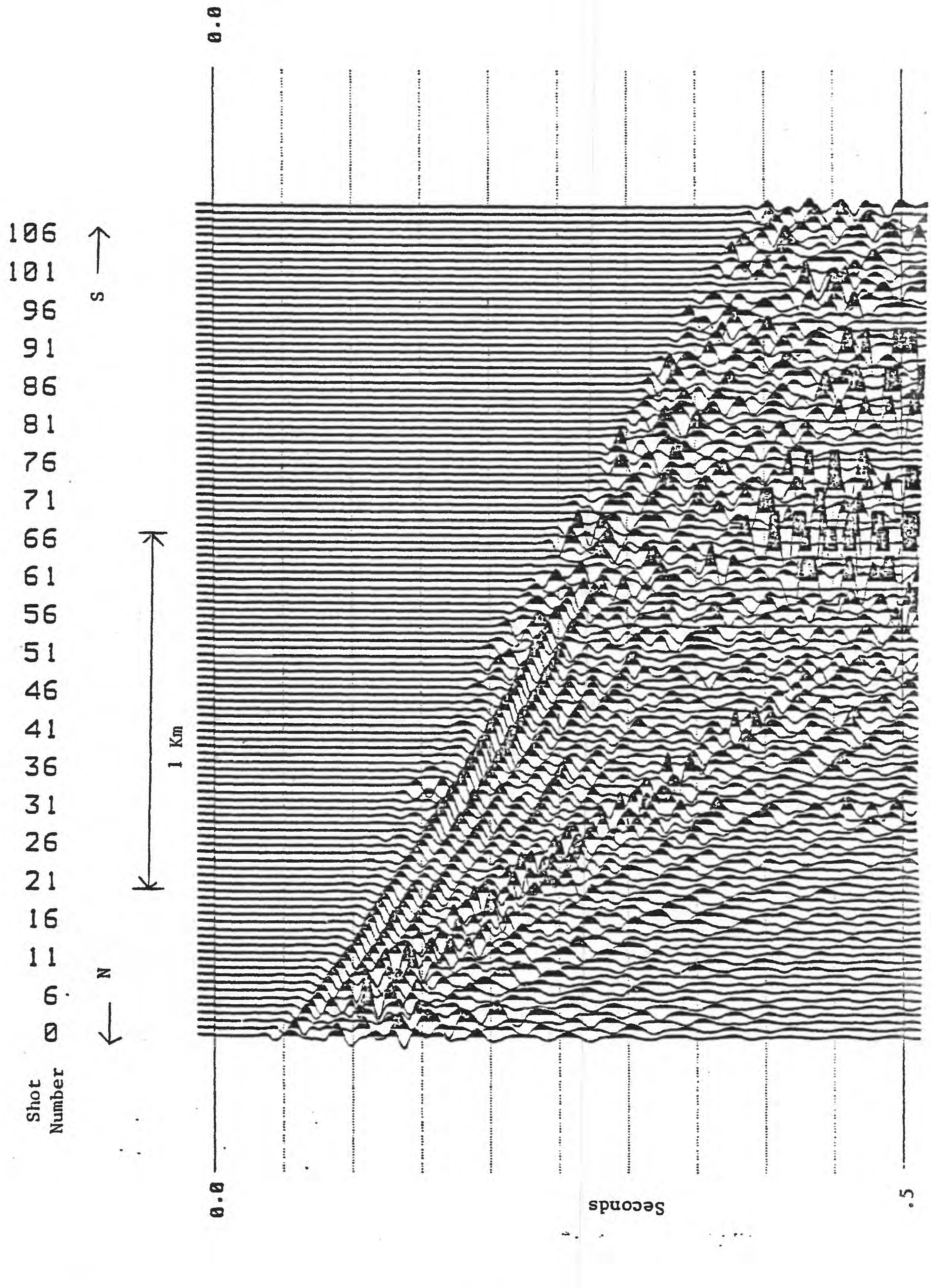


Figure 28. Processed refraction line 46.

Because the multiple-removal programs were so successful, these initial assumptions are probably correct. In any case, the effect of a large reflection coefficient at the water bottom is proved. To solve this problem, special field recording procedures will be required. Some possibly successful approaches are discussed in the recommendations section.

Because of the severity of the water-bottom multiples, no reliable coal-bed reflections were obtained. Consequently, the goal of mapping mined vs. unmined areas and faults offsetting these beds was not achieved. However, fault mapping at this site would have been difficult even if reliable coal-bed reflections were obtained because the fault trend was very near the west shore of the lake. Only a few east-west lines crossed this trend because the water becomes too shallow to safely operate the vessel.

Because this was the maiden voyage of the R/V Neecho and its associated recording system, it might be suspected that the system was not working properly at the time of recording. However in December 1979 and January 1980 (the next months after the Rend Lake experiment), the vessel was moved to the Mississippi River and an extensive data-gathering operation was conducted on the river (Shedlock and Harding, 1982). The recording parameters were the same as those used at Rend Lake and the water depths were approximately equal (about 25 ft). This experiment was successful and figure 29 shows a stacked cross section from a portion of this survey. Reliable continuous reflections are clearly present on this cross section verifying the successful operation of the recording system.

The data acquisition problem at Rend Lake is of such an extremely serious nature that the experiment failed to accomplish its objectives. The physical characteristics of the lake, combined with a short time frame in which to perform the experiment (because of the onset of winter) and unfamiliarity with a new system, contributed to this failure.

However much valuable information was gained by the experiment. It is believed that if enough time and effort is expended, the coal beds (mined vs. unmined areas) and any faults present could be mapped. The following recommendations section details some posssible approaches to a successful solution.

RECOMMENDATIONS

As explained above the most severe problem encountered at Rend Lake was the extremely high-amplitude, water-bottom reverberations (multiples). This problem must be dealt with during field recording of the data.

One possible approach would be to use a high-energy source to force energy through the water-bottom boundary. This would probably mean lower frequency energy being input, and so a study must be conducted to determine lower limits of the frequencies needed to resolve the beds of interest. In order to get high energy input, an array of sources must be used. These arrays can be tuned so as to control the frequencies transmitted. It might take a good deal of time testing arrays before a successful one is found.

To save time and expense in the field, extensive model studies should be performed in the computer center prior to field work. These models could give insight into which types of source arrays might work and, especially, would eliminate arrays which have no chance of success.

One of the problems faced in processing data from a new area is not knowing how the final product should appear. This problem was compounded at Rend Lake because of the low signal-to-noise ratio caused by the reverberations. It would be extremely helpful to have a seismic cross section recorded on land adjacent to the lake before attempting to process

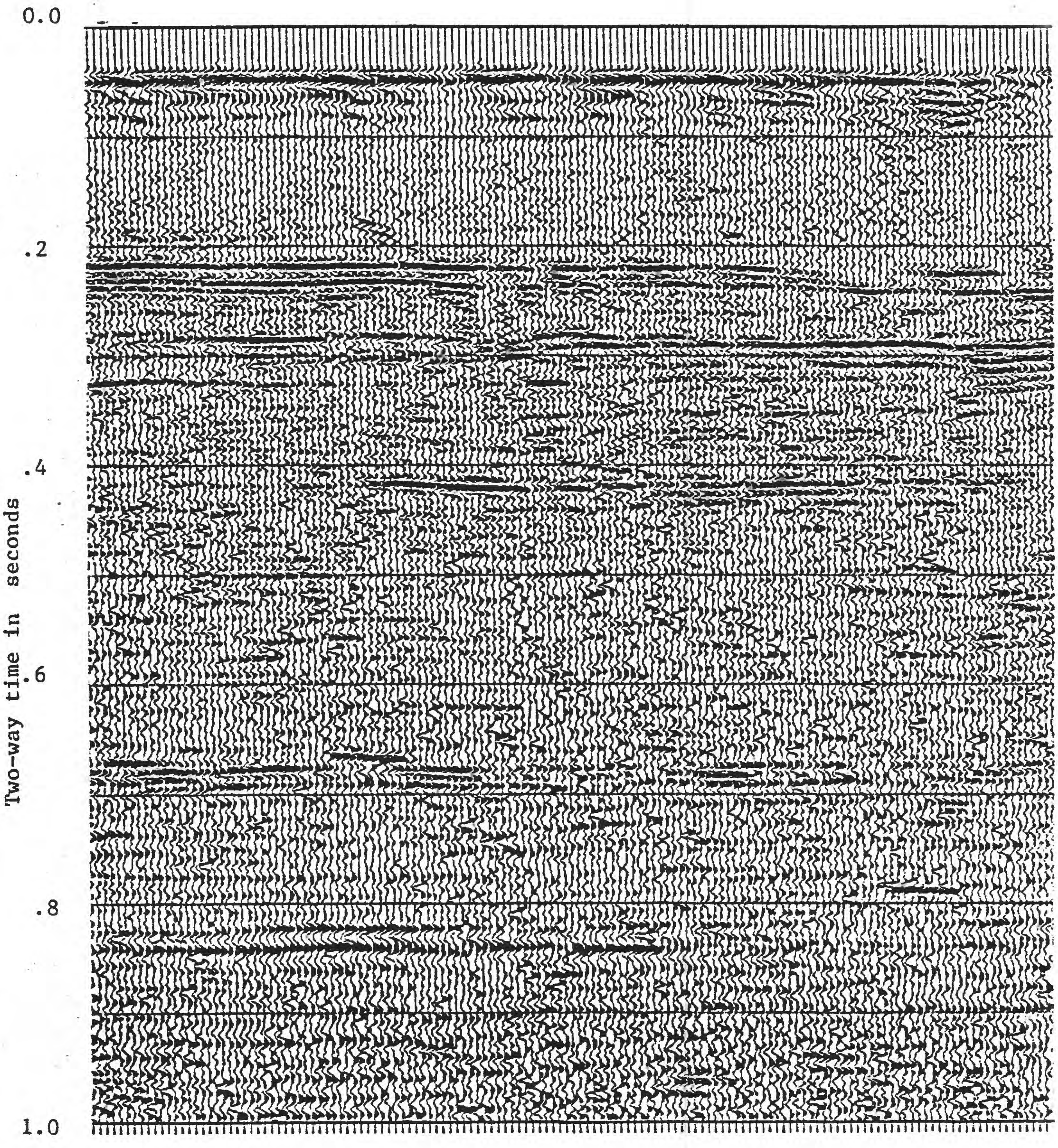


Figure 29. Stacked cross section shot on the Mississippi River one month after Rend Lake experiment with similar recording parameters and water depth

the overwater data. A conventional overland seismic line should not encounter nearly as many problems as overwater. This line should probably be acquired using a high-resolution impulsive source such as explosives, or a high-frequency vibrational source like Mini-Sosie®. Thus, the processors will have insight into time zones of interest and potential processing problems.

One of the other problems at Rend Lake was the inability to cross the fault zone due to water depth. At the time of the experiment, the lake was at a very low level, due to down-drawing, because of the onset of winter. If the work could have been done at another time of year when the lake was at its highest level, the fault zone could have been crossed more often.

Another approach to crossing the fault zone is to use marsh buggies to make the transition from deep to shallow water and then to land. Marsh buggies are all-terrain vehicles used extensively in swampy areas of the southern United States. This method would allow a continuous profile across the fault zone in areas too shallow for safe boat operation and also would tie into a conventional landline as discussed previously.

Finally, if the water-bottom reverberation problem proves to be unsolvable by the above methods, another technique used in the swamplands and marshes might be effective. In this technique, geophones are placed at the end of long poles and are driven into the bottom of the lake from barges so that they are completely covered by mud. Thus the reverberations in the water layer should have very little effect on the recorded signal from depth. Continuous profiling from water to land is also possible using this method. The disadvantage is that this method is more time consuming and expensive than conventional overwater seismic recording.

REFERENCES CITED

Bristol, H. M., and Buschback, T. C., 1971, Structural features of the eastern interior region of the United States, in Background Materials for Symposium on Future Petroleum Potential of NPC Region 9 (Illinois Basin, Cincinnati Arch, and Northern Part of Mississippi Embayment): Illinois State Geological Survey, Illinois Petroleum 96, p. 21-28.

Keys, J. N., 1978, An analysis of the Rend Lake fault system in southern Illinois: Masters thesis for Master of Science in Geology, University of Illinois, 59 p.

Keys, J. N., and Nelson, W. J., 1980, The Rend Lake fault system in southern Illinois: Illinois State Geological Survey Circular 513, 23 p.

Krausse, H. F., Damberger, H. H., Nelson, W. J., Hunt, S. R., Ledvina, C. T., Treworgy, C. G., and White, W. A., 1979, Roof strata of the Herrin (No. 6) coal member in mines of Illinois: their geology and stratigraphy: Summary Report: Illinois State Geological Survey Illinois Minerals Note 72, 54 p.

Nieto, A. S., and Donath, F. A., 1976, Report of a study of structural geology and subsidence of the Rend Lake Dam area, Franklin and Jefferson Counties, Illinois: for U.S. Army Engineer District, St. Louis, Corps of Engineers, 49 p.

Ryu, J. V., 1982, Decomposition (DECOM) approach applied to wave field analysis with seismic reflection records: Geophysics, v. 47, no. 6, p. 869-883.

Shedlock, K. M., and Harding, S. T., 1982, Mississippi River seismic survey: Geophysical Research Letters, 4 p.