



Techniques of Water-Resources Investigations of the United States Geological Survey

Chapter D2

APPLICATION OF SEISMIC-REFRACTION TECHNIQUES TO HYDROLOGIC STUDIES

By F.P. Haeni

Book 2

COLLECTION OF ENVIRONMENTAL DATA

- Do not allow smoking near explosives.
- Do not handle explosives if electrical storms are in the area.
- For additional explosive safety information, see Institute of Makers of Explosives (1978) and the U.S. Geological Survey Safety Handbook (1979) section 3.12, p. 1–10.

6. After the hole is loaded with the explosives or the sound source is prepared, final preparation for the shot is made. The following should be checked:

- Seismograph power is on with proper filter, scale, and gain settings.
- Geophone cable is hooked up to seismograph.
- Sound source is hooked up to shot cable and shot cable is hooked up to seismograph by a safety wire.
- All personnel are clear of shot area and in position to stop any passersby that enter the area.

7. The final step is the firing of the shot or sound source. The party chief checks the background noise monitor on the seismograph and again checks to see that all personnel are in a safe position. The chief then warns everyone by radio that the shot is about to be fired.

8. After the shot is fired, the field personnel reel up the shot line and extension geophone cable and prepare for the next shot. When nonexplosive sound sources are used, the energy input is repeated 5 to 15 times and stacked on the seismograph. When an acceptable signal is obtained, the next shotpoint is prepared by the field crew.

SAFETY NOTE: If a misfire occurs, never leave the explosive in the hole. Try to fire the shot several more times. Check the seismograph firing circuit by exploding a single cap in a shallow hole away from the misfire. Check the cap and shotline in the ground for continuity *ONLY* with a blasting galvanometer. If the cap in the ground has continuity, the seismograph is working, and the explosive still does not fire, the explosive must be dug up or detonated by exploding another charge next to it. Explosive manufacturers should be contacted for the proper procedure to follow.

9. Generally, the same geophone array is used for several shots. The time between shots can be used to determine the elevation and relative location of the geophones and different shotpoints. This information is necessary to interpret the data. Often it is efficient for two crew members to level the geophones and shotpoints while the rest of the crew moves the truck, inspects the seismograph records, enters data in the log book, and prepares for the next shot.

10. After all the shots on a line have been completed, the party chief must again calculate the approximate depth to the refractor of interest, determine the approximate dip of this surface by comparing the crossover distances and intercept times of reversed shots, and establish the plan for the next line. If the refractors are essentially horizontal, the same field geometry can be

used. Unfortunately, this is seldom the case in hydrogeologic investigations.

In most studies, the goal of a seismic-refraction survey is to determine the depth and dip of a particular refractor. In many cases, this involves continuous profiling from some hydrogeologic or geologic boundary such as a valley wall or drainage divide to another boundary of the same type. To accomplish this, the geophone spreads must be moved across the study area. Adjoining spreads can be laid out shotpoint to shotpoint, end geophone to end geophone, or overlapping, as shown in figure 44. Again, the specific objective of the study, and consideration of the quality as opposed to the quantity of data, will determine which technique is used. The overlapping method is the most thorough and provides the best definition of the refracting surface, although it covers less ground in a given time. The shotpoint-to-shotpoint method covers the most ground but does not completely define a continuous refracting surface. The size of the gaps in the refracting surface increases as the distance between the shotpoint and the first geophone increases.

Field records

Precise records must be kept during seismic field operations in order to interpret the data correctly. The following information should be recorded for each geophone spread in a field log book:

Spread number (Which end of geophone cable is attached to seismograph?)

Location

Number of geophones

Distance between geophones

Elevation of each geophone

Remarks—location of outcrops; depth to water in ponds, streams, etc.; location of test holes or domestic wells

In addition, the following should be recorded for each shotpoint:

Shot number

Location

Distance to first geophone

Depth of shothole and explosives

Depth of water in shothole

Elevation of shothole

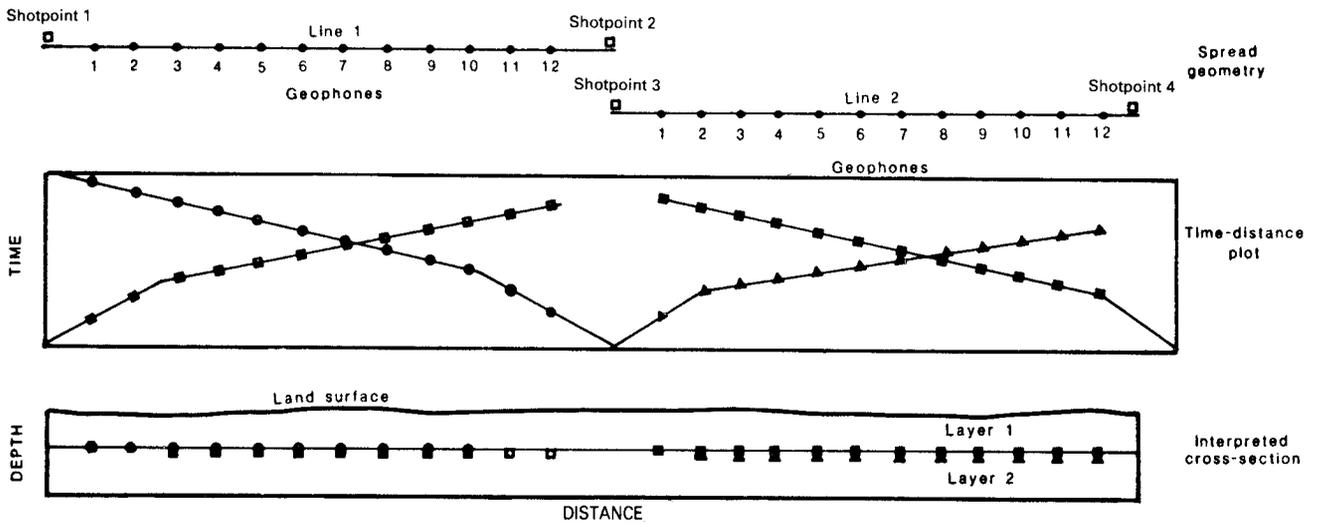
Description of materials in shothole

Spread number

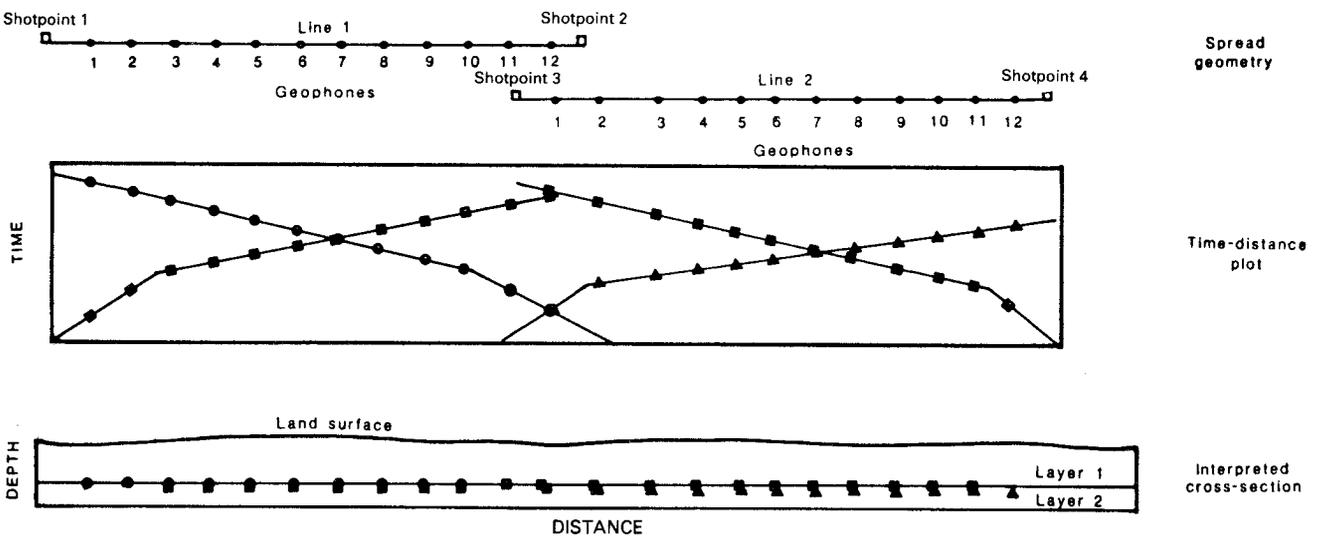
Amount of explosives used (if applicable)

Figure 45 is an example of a data sheet used by some field crews to record field data. Each seismograph record also must be marked. One method that avoids later confusion is to letter or number each array and number each shot consecutively in each geographic area, for example, Area A—Array 1, shot 1, 2, 3, 4, and 5; Array 2, shot 6, 7, 8, 9, and 10, and so forth. A similar system can be used to label tape files when the field data are stored on digital recorders. If explosives are used, the amount of

A. Profiling with spreads laid out shotpoint to shotpoint



B. Profiling with spreads laid out end geophone to end geophone



C. Profiling with spreads overlapping

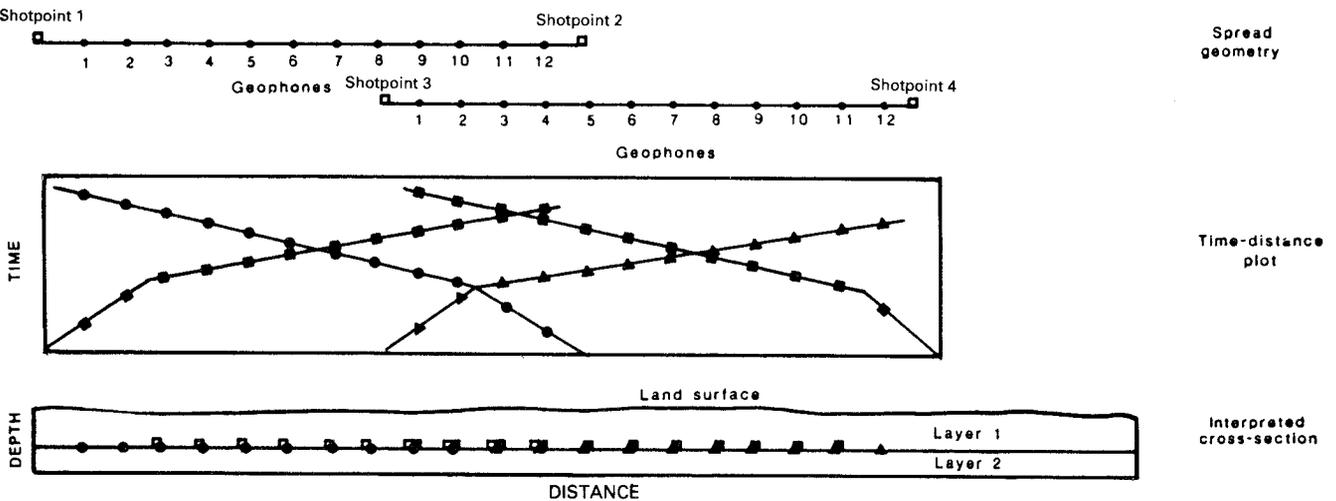


Figure 44.—Various field setups and resulting time-distance and depth plots for each geophone in a two-layer problem.

Town _____ Site _____
 Location _____ Date & Time _____
 Owner _____ Party _____

Obtain approximate X_c to first refractor: $Z =$ _____, $V_1 =$ _____, $V_2 =$ _____

$$X_c = 2(z) / \sqrt{\frac{V_2 - V_1}{V_2 + V_1}} \quad X_c = \text{_____}$$

Spread # _____ Direction of spread _____
 Spread dimensions & variations _____
 Seismograph scale _____ Seismograph delay time _____

SHOT DATA

Shot #	Direction of shot	Distance to first geophone	Depth of shot	No. of sticks (no of stacks)	Remarks

ELEVATION DATA

Level # _____ Performed by _____ (ht. instr) _____

Sta.	F.S.	B.S.	H.I.	ELEV.	X	Y	Remarks	Sta.	F.S.	B.S.	H.I.	ELEV.	X	Y	Remarks

SPREAD DIAGRAM

Figure 45.—Data sheet for recording field data.

explosives and the number of caps used for each shot should be recorded and, at the end of the day, this information transferred to the log book for explosives.

References

- Institute of Makers of Explosives, 1978, Do's and don'ts: Instructions and warnings: Washington, D.C., Institute of Makers of Explosives Publication 4, 13 p.
- U.S. Geological Survey, 1979, Safety handbook: Reston, Va., U.S. Geological Survey, section 3.12, p. 1-10.

Interpretation Techniques

After all the data have been collected in the field, they must be interpreted. Because of the widespread use of seismic-refraction techniques in hydrogeologic and other geologic studies, many seismic-refraction interpretation schemes have been developed and published in the literature (Musgrave, 1967, p. 565-594; Dobrin, 1976, p. 318-331). Formulas, nomographs, and computer programs are available for a wide variety of field problems. Each interpretation scheme has its advantages and, when properly selected and applied, will give satisfactory results. This manual does not attempt to review or summarize the available interpretation schemes but presents one method that has been used successfully in a wide variety of hydrologic studies.

A problem inherent in all geophysical studies is the nonunique correlation between possible geologic models and a single set of field data. This problem arises from the fact that geophysical instruments measure physical properties of the Earth remotely, and different combinations of Earth materials in the subsurface can give the same signal at the surface. This ambiguity can be resolved only through the knowledge and experience of the interpreter. Successful interpretation of seismic-refraction records, therefore, depends on the hydrogeologist's input during the interpretation process. Failure to factor in the expertise of the hydrogeologist leads to poor results. Success of a seismic-refraction study is much more dependent on the ability of the interpreter than on the specific interpretation scheme used.

The interpretation process, although described in a separate section of this manual, cannot be separated from the other phases of a seismic study. Knowledge of the interpretation procedure to be used is required for planning the field layout of geophones and shotpoints.

Seismograph records

The seismograph records obtained in the field contain data about the time it takes for compressional energy generated by the seismic source to travel (by different paths) through the subsurface and back up to the

geophones on the surface. In most hydrogeologic studies, only the first arrival of compressional energy at each geophone is of interest, as this can be used to determine the position of refracting surfaces. Seismic-reflection techniques use subsequent energy arrivals on the seismic record. Figures 46 and 47 show typical seismograph records produced by twelve-channel seismographs.

The first step in the interpretation process is to determine the elapsed time from the activation of the sound source to the first arrival of energy at each geophone. When the first breaks are sharp and there is no ambient noise, this procedure is straightforward.

Complications arise, however, when nonexplosive energy sources are used and (or) high noise levels are present because of nearby vehicular traffic, rain, wind, underground pipelines, airplanes overhead, and so on. Figure 48 is a record from a sledge-hammer energy source stacked 10 times. In the stacking process, random noise tends to cancel out and first breaks are enhanced. The breaks in this figure are rounded and not as sharp as those in figures 46 and 47 (obtained with explosives). Figure 49 is an example of a seismograph record obtained in an area of high noise. Note that the record traces are wiggly even before the first arrival of sound-source energy.

When the first arrival times are picked manually from the seismograph record, the interpreter should use the point where the seismograph trace starts to bend. Care should be taken to ensure that each trace is picked at the same point, that is, at the first point of movement or the point of maximum curvature. This procedure will make the interpretation a more uniform process, as the data will be consistent from one trace to the next.

Automated procedures for picking traveltimes are available. One method is to put the record on a digitizer tablet and use the digitizer stylus to determine the traveltime for each geophone. This technique requires some computer processing so that the data can be put in the proper format for further computer interpretation. A computer-assisted method of picking first arrivals from digitally recorded field data is presented by Hatherly (1981) and Hunter (1981).

The other field data needed prior to interpreting seismic-refraction records are:

1. Location of shotpoints and geophones,
2. Elevations of shotpoints and geophones, and
3. Depths of shotholes, if used.

Time-distance plots

With this information, a plot of arrival times versus shotpoint-to-geophone distance can be constructed. If lines are fitted to these points, the resulting plot is called a time-distance plot. Many such plots have been shown in previous sections. These data can be plotted manually or with a computer and are the foundation of seismic-refraction interpretation. Regardless of the interpretation

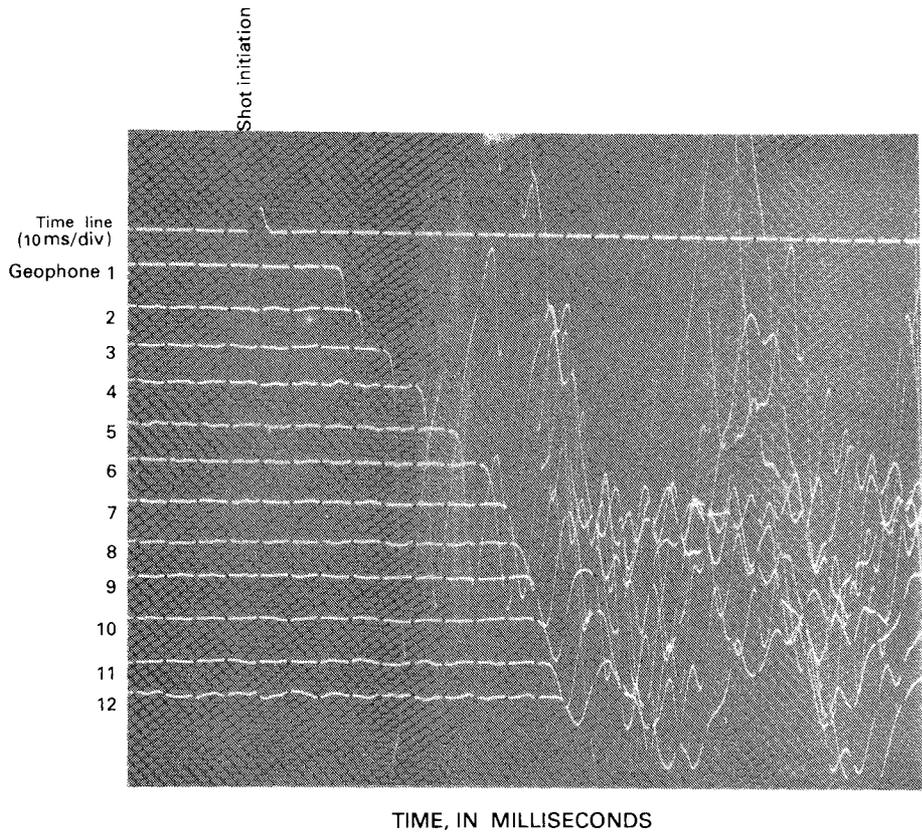


Figure 46.—Twelve-channel analog seismograph record showing good first breaks produced by an explosive sound source.

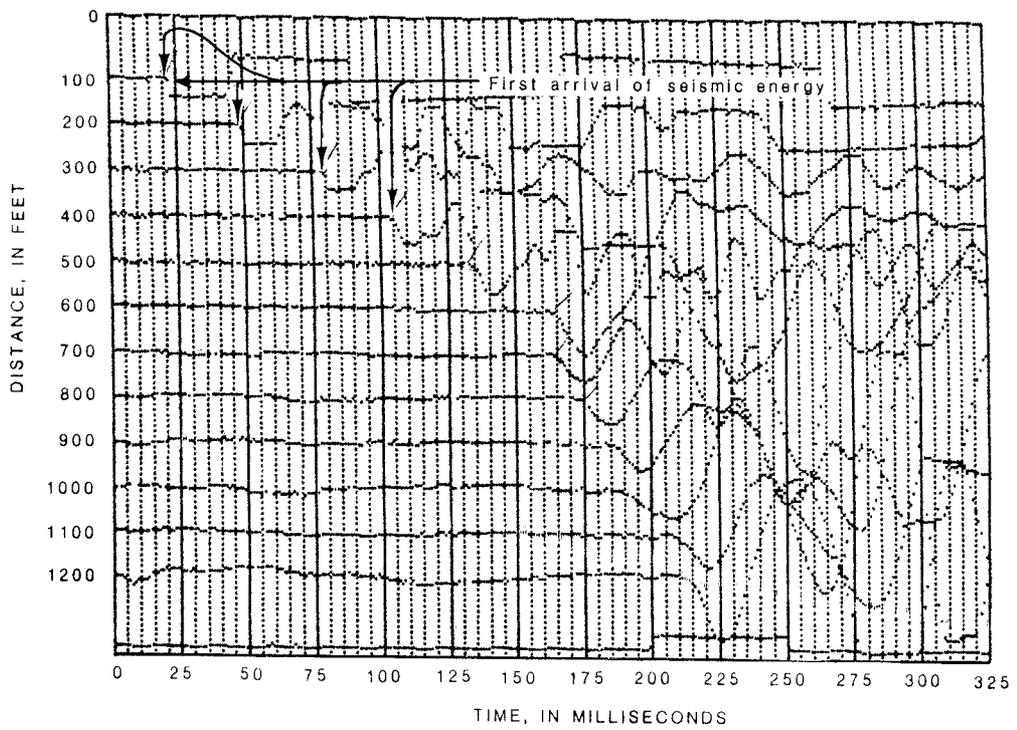


Figure 47.—Twelve-channel digital seismograph record from Little Androscoggin River valley, Maine, showing sharp first breaks produced by an explosive sound source in an area with low background noise.

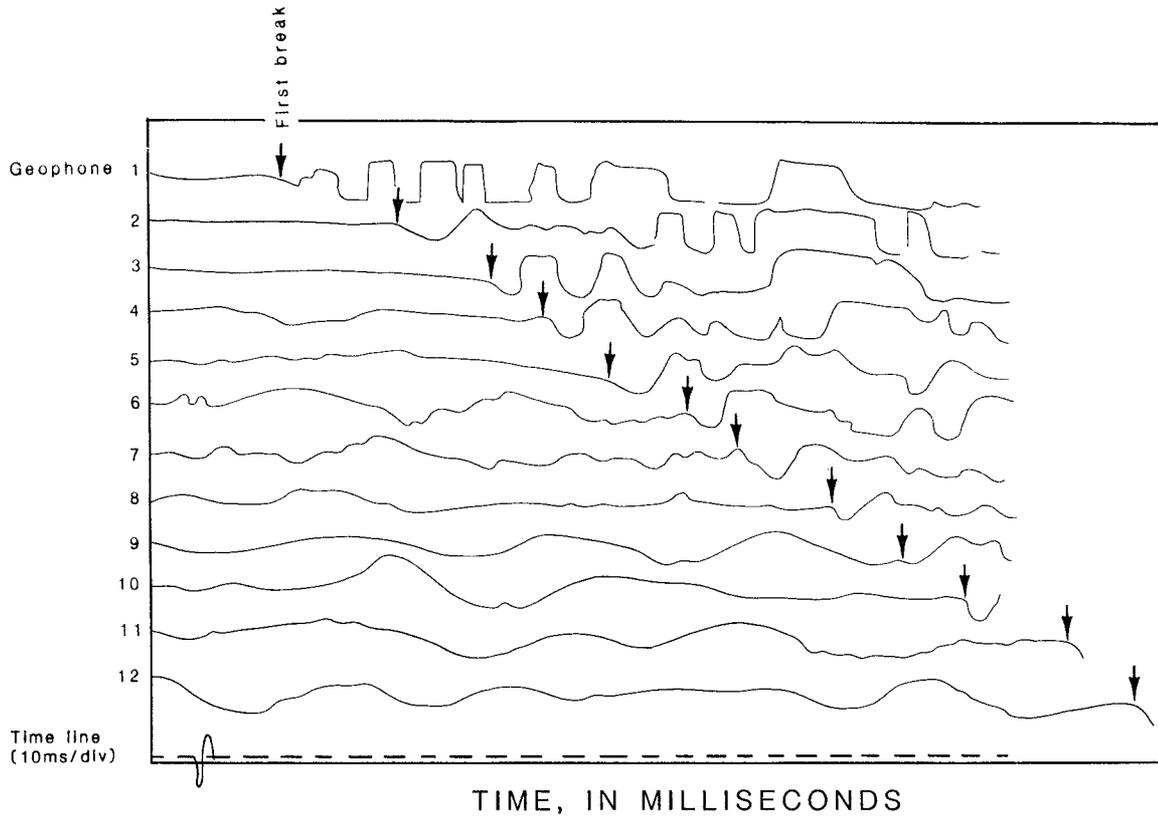


Figure 48.—Seismograph record with rounded first breaks produced by a sledge-hammer sound source in an area with high background noise. Signal stacked 10 times, with geophones spaced 50 ft apart.

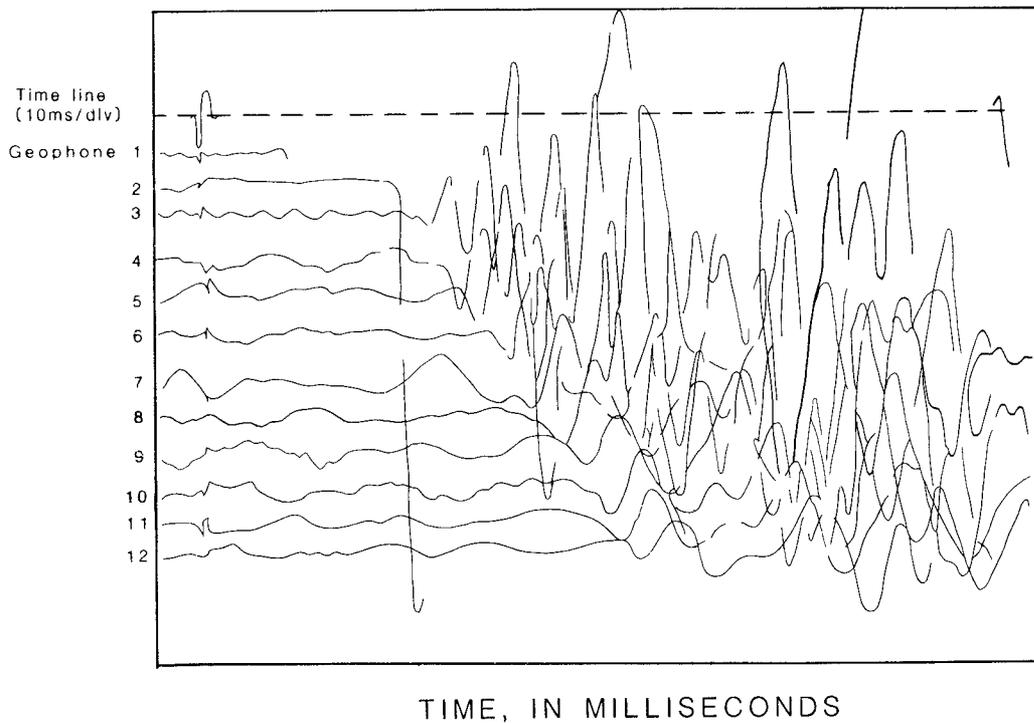


Figure 49.—Seismograph record with sharp first breaks produced by an explosive sound source in an area with high background noise. Geophones were spaced 50 ft apart.

method used, the interpreter must understand the time-distance plot (Ackermann and others, 1983, p. 3-33) and its relationship to the geology in the study area. Excellent examples of time-distance plots and their relationships to possible geologic models are shown by Mooney (1981, chaps. 15, 16) and by Zohdy and others (1974, fig. 57, p. 74). Both of these references show only one-way time-distance plots, and it should be noted that the investigator should always work with reversed profiles as shown in figure 50. Mooney's (1981) chapter 16 clearly shows the nonuniqueness of traveltimes plots and illustrates the need for the investigator to be actively involved in the interpretation process. Only independent geologic knowledge will enable the interpreter to choose the correct interpretation.

Figure 50 shows a time-distance plot with two distinct linear segments. The slope of these segments is inversely proportional to the apparent velocity of sound in that layer of the Earth, and the point where they intersect is termed the "crossover point" (see "Theory" section). The scales chosen to plot the time-distance data are very important. If the ordinate (time) scale is small relative to the abscissa (distance) scale, changes in the slope of the time-distance plot will be hard to distinguish. The opposite case (ordinate scale much greater than the abscissa scale) is also undesirable because each pair of geophones may appear to have a separate slope associated with it. Some experimentation with scales is necessary in order to choose a good working scale.

Manual interpretation techniques

Once the reversed time-distance data are plotted, either manually or by computer, and the proper formulas are selected (see "Theory" section), manual calculations or nomographs can be used to obtain solutions from the seismic field data. There are also many programs for hand-held programmable calculators available for solving the various seismic-refraction formulas (Ballantyne and others, 1981).

Depending on the scope of the hydrogeologic study and the complexity of the hydrogeology at a site, manual calculations in the field or office may provide the desired level of information, in which case no further interpretation is necessary. Normally, however, much more detailed and accurate geologic information can be obtained by interpreting the same field data with a computer program.

Computer-assisted interpretation techniques

Formulas

The same formulas used to interpret seismic-refraction data manually also can be solved by digital computers.

Computer solutions of the formulas are given by Mooney (1981, chap. 11) and Hunter (1981).

Modeling techniques

Another group of computer programs has been designed to handle complex field situations such as high land-surface relief, offset shotpoints, nonlinear geophone spreads, and so on and to develop interpretations for complex geologic settings. These programs can solve multilayer dipping-bed problems for multiple geophone spreads and use a variety of interpretation schemes depending on the particular problem to be solved.

One program that has been used successfully by the U.S. Geological Survey under varying geologic and hydrologic field conditions is a computer-modeling procedure based on a delay-time technique developed by Barthelmes (1946), modified by Pakiser and Black (1957), and further developed by Scott and others (1972), Scott (1973), Scott (1977a), and Scott (1977b).

The original FORTRAN IV source code and its documentation is for a program to do batch processing using a Burroughs mainframe¹ computer system and is given in Scott and others (1972). The documentation for a revised batch-processing version of the program is described in Scott (1977a), and documentation for an interactive version of the same program is described in Scott (1977b). A general description of the modeling program is given in Scott (1973). Other versions of this program have been developed for Multics, Prime, IBM mainframe, IBM-PC, and VAX computer systems. Scott's program first generates a model of the subsurface using the delay-time

¹Use of firm names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

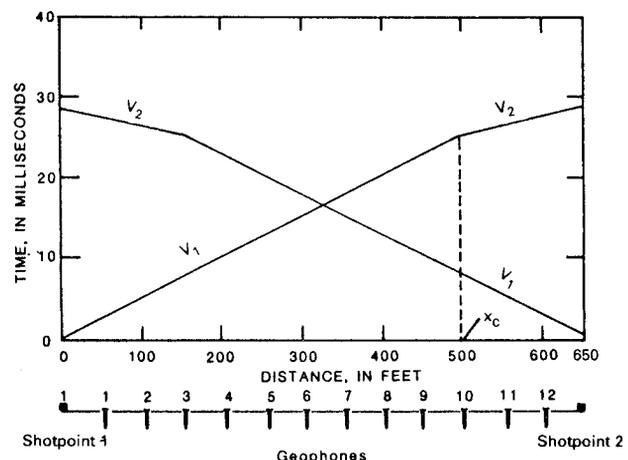


Figure 50.—Reversed seismic-refraction profiles with two velocity layers depicted on the time-distance plot.

technique and then refines the model with a series of iterative ray-tracing procedures. The documentation of this program by Scott is very complete; only a discussion of the use of the program is given here.

The basic theoretical relationships and limitations of seismic-refraction techniques, as discussed in the "Theory" section, must be understood to ensure successful computer-assisted interpretation of refraction data. These limitations are as follows:

1. The seismic velocities of the geologic layers must increase with depth.
2. The thickness of each geologic layer must be great enough so that a refraction event can be observed at the surface.

In addition, use of Scott's program is contingent on the following:

1. The number of layers represented by the data must be predetermined by the interpreter and provided as input data to the program.
2. Each refraction event, as measured by the first break on the seismograph, must be assigned a number that represents the layer carrying the critically refracted ray along its surface.
3. Each layer under each spread is assumed to have a constant horizontal velocity along its upper surface and a constant vertical velocity (which may or may not be the same as the horizontal velocity).
4. Each layer extends from one side of the model to the other and can be represented by straight lines beneath geophone locations connected end to end.
5. The maximum number of layers is five.
6. The maximum number of spreads is five. Each spread may have up to 48 geophones and a maximum of seven shotpoints. These limits can be changed in the program if necessary.
7. Refracted rays are assumed to represent minimum traveltime paths of compressional seismic waves.
8. The final interpreted model layers are defined beneath geophones that receive refracted energy from the surface of that layer and are interpolated or extrapolated to other positions.

With these assumptions and requirements in mind, the investigator is ready to interpret the data. It must be noted, however, that the field data must be collected with the interpretation process in mind in order to define the hydrogeologic layers of interest. In figure 51, shot 1 is positioned to define part of the water table and part of the bedrock surface. Shot 2, on the other hand, does not define the water table at all, but does define the bedrock surface (see "Field Procedures" section). Overlapping velocity segments from multiple shotpoints at both ends of the geophone spread provide the best data for computer interpretation. A single geophone spread with one shot on each end rarely provides enough data to completely define

a multilayer subsurface. Multiple shots and multiple spreads should be used in most field situations.

The input data are entered in the program via cards (batch-processing program) or the computer terminal (interactive program).

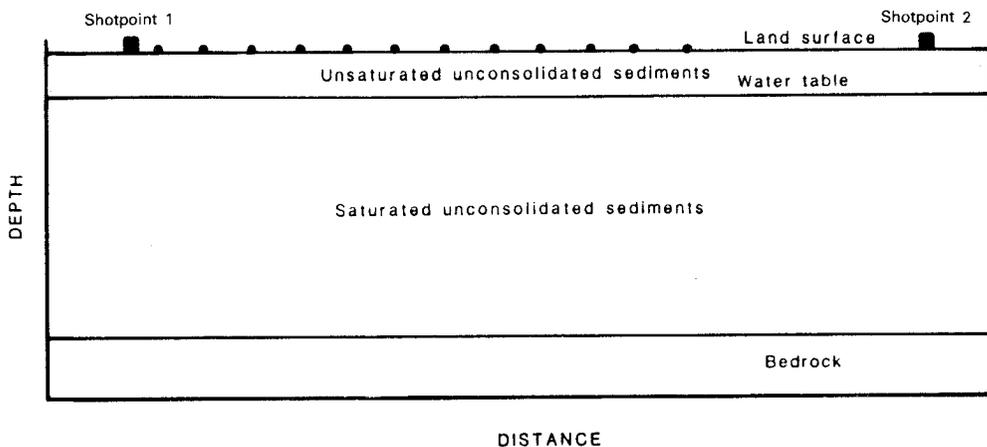
A manual data entry process using the interactive version of the computer program by Scott (1977b) consists of the following steps:

1. Pick arrival times from seismograph records, assign preliminary layer numbers to each refraction event, and record times on data sheet (fig. 52).
2. Plot the position of all shotpoints and geophones using an arbitrary scale on an x, y coordinate system (fig. 53A).
3. Plot the elevation of all shotpoints and geophones (fig. 53B).
4. Choose appropriate scales for the time-distance plot and the interpreted seismic-section plot.
5. Enter information on computer data input form (fig. 54).
6. Enter information in computer. Usually, this is done by entering input data with the text editor and creating an on-line disk file of the data. Table 9 shows an example data set.

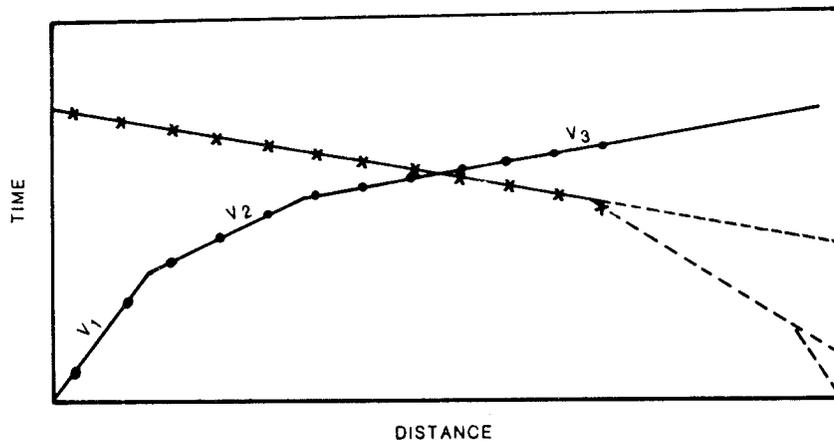
The interactive program is now called from an on-line library on the computer. The program provides a series of prompts that allow the interpreter a number of choices during the interpretation process. A discussion of the prompts and the consequences of the responses follows. Scott and others (1972) present a detailed description of the main program and the subroutines, along with a comprehensive discussion of the various options used in the program. Only the most frequently used options are discussed here.

1. Enter input file name (or <CR> to exit): (prompt)
SIMS 2A (response)
Discussion: SIMS 2A is the file name of the input data file.
2. Enter input FMT type: C=Card, F=Free Field:
(prompt)
F (response)
Discussion: Format type can be card image (fixed fields of data) or free field (data elements are separated by commas).
3. Enter output unit: P=LPT, T=Terminal, B=Both:
(prompt)
T (response)
Discussion: T is for small 72- or 80-column terminals and is the most common choice. B will place a 132-column output file on the machine's disk-storage device for later retrieval by a line printer.
4. Enter new Exit, -6 thru +6 or <CR> for old:
(prompt)
<CR> (response)
Discussion: This statement lets the interpreter exit the program at different places. <CR> returns

(A) Field set-up and geologic section.



(B) Time-distance curve



(C) Final seismic interpretation

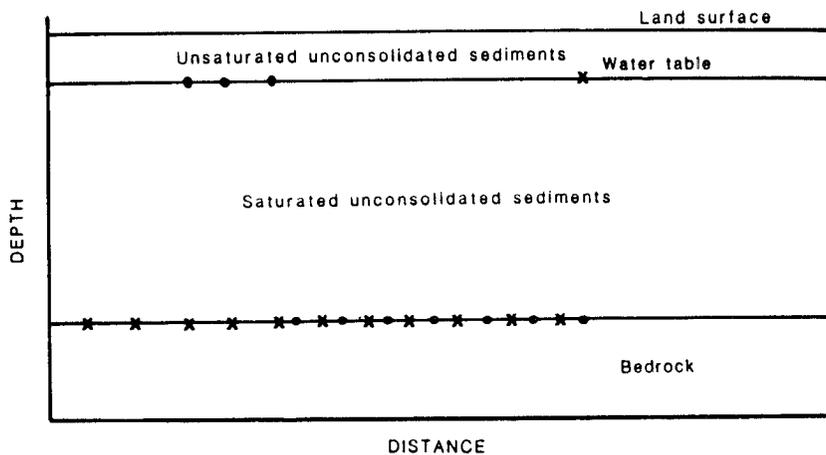


Figure 51.—Relationships between field setup, time-distance plot, and interpreted seismic section.

control to the choice assigned on the problem control line.

5. The program title and the data on the problem-control line are now printed out.
6. Table of SP & Geo data: T to type, <CR> to suppress: (prompt)

T (response)

Discussion: The table of input data should always be printed the first time through the program because the program has editing features that will flag typographic and other obvious data-entry errors. If this happens, the message "error on input cards" will be printed. Execution of the program will be terminated at this point, and the error can be corrected via the computer editor. The input geophone and shotpoint data table is now printed out. These data should be checked for typographic errors not caught by the editor.

7. T-D plot: 1 = raw, 2 = datum, 3 = Pre-D, 4 = L1 remvd: (prompt)

1 (response)

Discussion: The time-distance (T-D) plot will be printed, and the layer 1 velocity computed. If no layer 1 assignments are made on the time-distance plot, the default value of 1,500 ft/s is used by the program.

The most common response is option "1," signifying that the raw time-distance data should be plotted. This option makes use of the raw field data to construct a time-distance plot. If the field site has much topographic relief, the raw time-distance curve may not have straight line segments, and refined layer assignments may be hard to make (fig. 55). Under these conditions, selection of the datum-corrected time-distance plot, option "2" (fig. 55C) may help the interpreter. The raw seismic traveltimes are corrected to a datum plane constructed by a least-square fit through the geophone elevations. Because of this, the local topographic features are smoothed out and the resulting time-distance plot may aid the interpreter in deciding which layer is associated with each arrival time. The "Pre-D" option gives the arrival times just prior to computation of depth of layer 1; these are not normally used.

If layer 1 is very irregular, the time-distance plot still may be hard to interpret. In this case, the interpreter should choose option "4" (L1 rmvd). This option removes layer 1 from the refraction times and plots a new time-distance graph. This option is effective only if raw field information about layer 1 is available. Consequently, it is used only in unusual cases.

Although this discussion is presented here, the work should be done after the computer run is completed and not during program execution. The program has an exit point that allows the interpreter to end the program after

the time-distance plot is printed, or the program can be run to completion.

At this point in the interpretation process, the interpreter should spend some time working with the time-distance plot.

The preliminary layer assignments made in the data-preparation phase are checked for obvious errors on the time-distance plot. The interpreter reconciles the general form of the time-distance plot with prior knowledge of the geology of the area. For example, if the area is known to have dry sand and gravel overlying saturated sand and gravel which in turn overlies crystalline bedrock, the time-distance plot should show three linear segments. If the water table and bedrock are thought to be relatively flat surfaces, the layer velocities derived from the time-distance plot should be within the range of expected values.

Any unexpected results should be analyzed before proceeding with the interpretation process. For example, a large shift in the middle of a time-distance-plot segment might indicate an error in reading, recording, or entering the traveltimes data. Reversed shots that plot in the same direction indicate, for example, an encoding error (fig. 56).

The time-distance plot should be inspected for continuity and uniformity between spreads. For example, if the refracting surface is flat over two or more spreads, the crossover distance or intercept time at all shotpoints should be similar. If the refracting surface is getting deeper, such as in a bedrock valley, the crossover distance or intercept time should be increasing. Two shots in opposite directions but located close to each other should have similarly shaped time-distance plots unless an abrupt change in refractor depth exists. Figure 57 illustrates some of these principles, and the following discussion gives the symbols and generalized relationships.

Crossover distances:

x_{c1} = Crossover distance for interface between layers 1 and 2 (i.e., the water table). These values will all be similar since the water table is a flat surface.

$$x_{c1,1} \cong x_{c1,2} \cong x_{c1,3} \cong x_{c1,4} \cong x_{c1,5} \cong x_{c1,6}$$

x_{c2} = Crossover distance for interface between layers 2 and 3 (i.e., the bedrock surface). These values will increase as the rock gets deeper.

$$x_{c2,1} < x_{c2,2} < x_{c2,3} < x_{c2,4} < x_{c2,5} < x_{c2,6}$$

Layer velocities:

V_1 = Velocity of sound in layer 1 (unsaturated unconsolidated deposits). These values will all be about the same if the deposit is homogeneous.

$$V_{1,1} \cong V_{1,2} \cong V_{1,3} \cong V_{1,4} \cong V_{1,5} \cong V_{1,6}$$

SEISMIC REFRACTION FIRST ARRIVAL TIME RECORD SHEET

Site name _____

Spread # _____

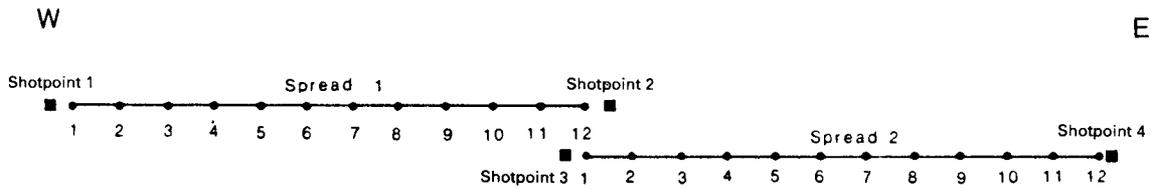
Shot number _____ Shot direction _____

Geophone #	First arrival time (in ms)	Seismograph delay time (in ms)	Total travel time (in ms)	Preliminary layer assignment	Notes
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					

Shot number _____ Shot direction _____

Geophone #	First arrival time (in ms)	Seismograph delay time (in ms)	Total travel time (in ms)	Preliminary layer assignment	Notes
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					

(A) Spread location diagram



(B) Topographic profile

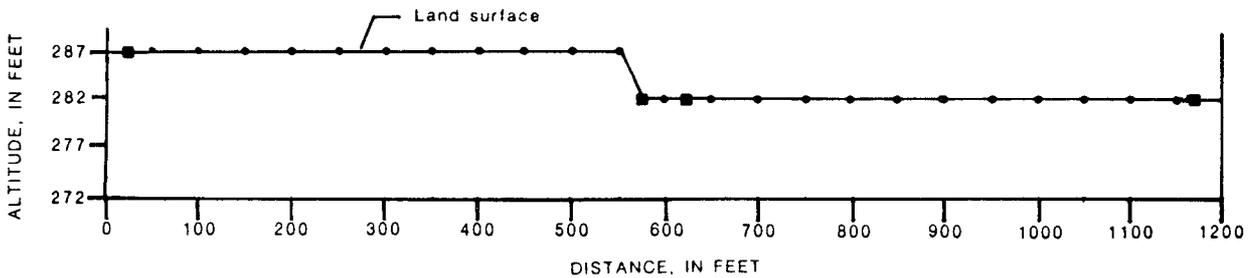


Figure 53.—Shotpoint and geophone locations and altitudes plotted to scale.

V_2 = Apparent velocity of sound in layer 2 (saturated unconsolidated deposits). These values should represent the true velocity and are about equal since the water table is a flat surface.

$$V_{2,1} \cong V_{2,2} \cong V_{2,3} \cong V_{2,4} \cong V_{2,5} \cong V_{2,6}$$

V_3 = Apparent velocity of sound in layer 3 (bedrock). The downdip apparent seismic velocities are less than the updip seismic velocities since the bedrock surface is not horizontal.

$$V_{3,1} \cong V_{3,3} \cong V_{3,5} < V_{3,2} \cong V_{3,4} \cong V_{3,6}$$

After obvious errors are reconciled and corrected, the interpreter should look at the time-distance plot in detail. The individual segments should be drawn in and used to refine the layer assignments further.

The straight line segments on the curve can be drawn using the following guidelines:

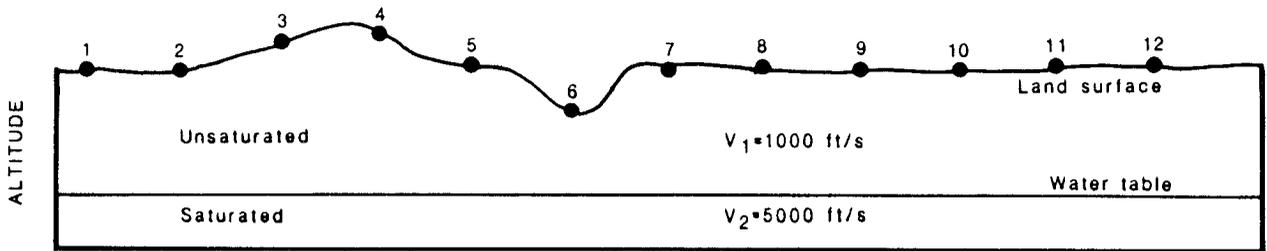
- A. If the land surface is relatively flat, the first refracting surface is the water table. If the saturated zone has a significant thickness, a straight line segment with an inverse slope of about 5,000 ft/s can be aligned with several data points.
- B. The slow surface layer segment can now be constructed through the origin and points below the

5,000-ft/s line. All available geologic data should be used to help the interpreter make the proper layer assignments. If, for example, the shothole was drilled to the water table, the value of the critical distance to layer 2 could be calculated from the formulas in the "Theory" section. All geophones between the shotpoint and this crossover distance must be direct arrivals and assigned to layer 1.

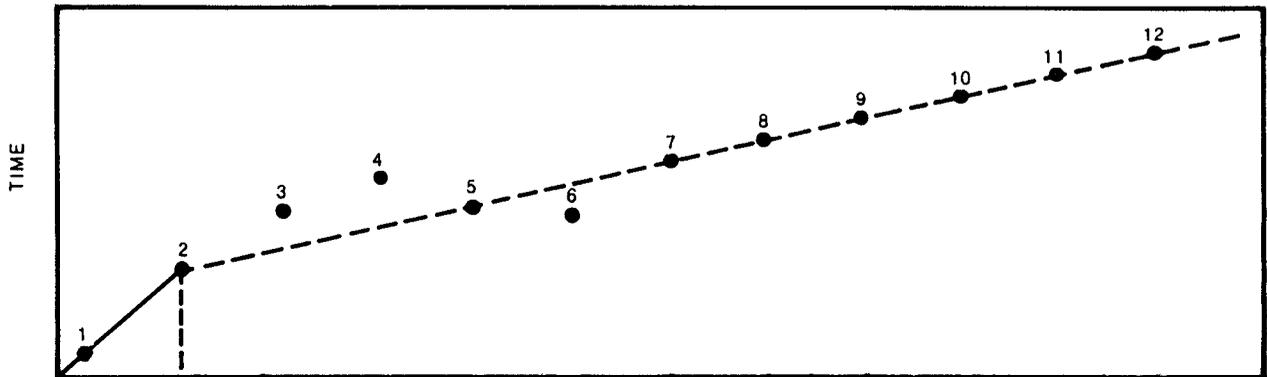
- C. The remaining data points are used to construct line segments that represent refracted sound from deeper layers. It must be noted that if the deep refracting layers have little or no relief, the segments on the time-distance plots should be straight lines. If there is relief on these surfaces, or if the velocity of sound varies significantly in any of the overlying subsurface units, these data points will not form a straight line.
- D. The principle of reciprocity also can be used to help construct time-distance plots. Examining figure 37A, the traveltimes from shotpoint 1 to geophone 12 is the same as from shotpoint 2 to geophone 1. In general, the seismic traveltimes from a source at point A to a geophone at point B is equal to that from a source at point B to a geophone at point A. For the arrangement shown in figure 37A, this criterion is not met but the offsets from shotpoint 1 to geophone 1 and from shotpoint 2 to geophone 12 are small. Hence, the reciprocity principle is applicable and constrains the traveltimes for the end geophones. Good examples of this principle

◀ Figure 52.—Data sheet for recording first-arrival times and other seismic information.

(A) Topographic profile and geologic section.



(B) Raw time-distance curve as plotted by interpretation program.



(C) Datum-corrected time-distance plot as plotted by interpretation program.

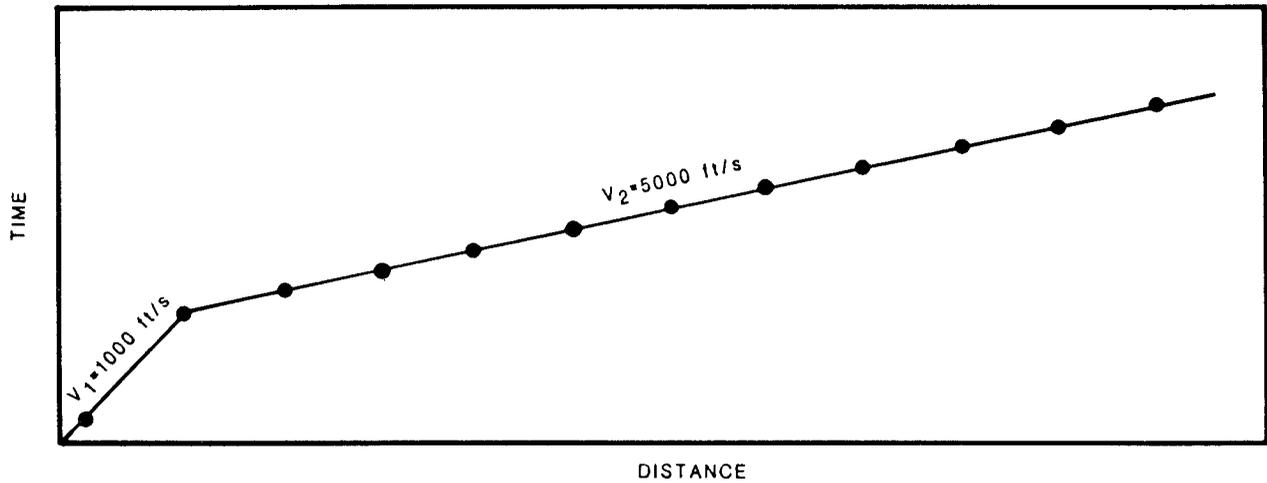
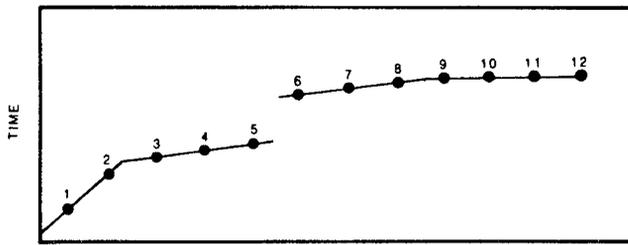


Figure 55.—Effect of topographic relief on raw and datum-corrected time-distance plots.

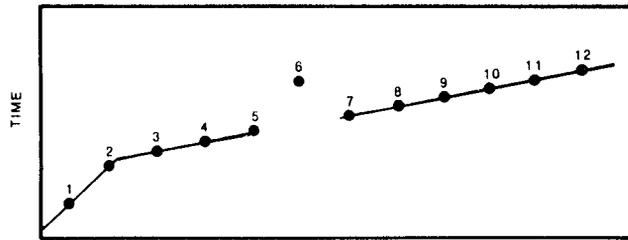
also are shown in figures 37B and, for shotpoints 2 and 4, in figure 39.

◀ Figure 54.—Data input form for entering data in the interactive version of the Seismic Interpretation Program (SIPT) (Scott and others, 1972).

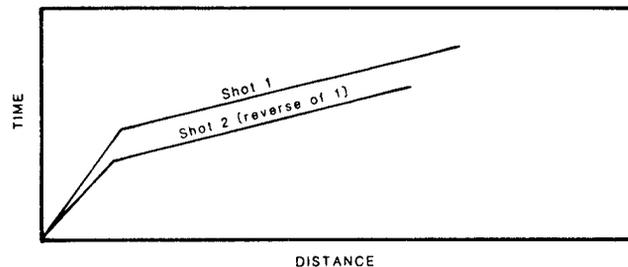
E. Extending the time-distance curves back to the time axis also may help in constructing time-distance plots. The arrival times for the geophone array to the left of shotpoint 2 and for the array to the right of shotpoint 3 are shown in figure 57. Notice that shotpoints 2 and 3 are at the same location and that



Possible error: Travel time at geophone 6 misread on seismograph record and all subsequent geophones referenced to 6



Possible errors: Just geophone 6 misread on seismograph record or typographic error in entering geophone 6 data on computer



Possible error: Shot 2 has been encoded incorrectly since it was the reverse of shot 1

Figure 56.—Common errors indicated by unusual time-distance plots.

the time-distance plots for the first two velocity layers are approximately symmetrical with respect to the time axis.

Rearranging the formula for a two-layer parallel-boundary subsurface (eq. 1), intercept time, t_i , can be calculated as follows:

$$t_i = 2z \frac{\sqrt{(V_2)^2 - (V_1)^2}}{V_2 V_1}$$

Because z , V_1 , and V_2 are equal for both time-distance plots, the intercept times (t_i) also will be equal. Therefore, the line fit to the arrival times for the V_2 layer on each time-distance plot will meet the time axis at t_i for shotpoints 2 and 3. This property constrains the line fit to the arrival times. In general, then, for two geophone arrays laid in opposite directions for which the shotpoint is halfway between the arrays, the intercept times from

common horizons will be equal. This property also is applied appropriately to shotpoints 4 and 5 in figure 57 and shotpoint 3 in figure 37B.

At this point in the interpretation process, some layer assignments near the crossover points may be in question. This should be noted on the time-distance plot so that both options may be tried in subsequent computer runs.

8. Velocity tables: T to type, <CR> to suppress: (prompt)

T (response) The velocity tables will now be printed out.

Discussion: This is an important step in the interpretation process. This table should be thoroughly reviewed. Incorrect layer assignments or errors in entering individual geophone times may cause the velocities of individual layers to appear too low or too high. For example, if layer 1 geophones are given layer 2 assignments, the velocity of sound in layer 2, computed by regression, will be too low. Conversely, if layer 2 geophones are given layer 1 assignments, the velocity in layer 1 will be too high (see fig. 58). The velocity table, therefore, aids the interpreter in assigning the correct layer to refracted geophone travel times.

NOTE: It must be remembered that the velocities computed by regression are affected by dip and are the apparent velocities (see "Theory" section). Velocities computed by the "Hobson-Overtone" method are independent of dip effects (Scott and others, 1972).

9. Table of ray end points: T to type, <CR> to suppress: (prompt)

<CR> (response)

Discussion: Normally, this table is used for troubleshooting the program and is not used in the interpretation process.

10. Depths beneath SPS & Geos: T to type, <CR> to suppress: (prompt)

T (response)

Discussion: This table is usually printed out because it lists depths to the individual refractors. If this is the first run, the interpreter should not be too concerned with the results. The obvious errors mentioned earlier have not been corrected and the solution presented here represents initial layer assignments and incorporates any data-entry error.

11. Depth plot: Enter T to type, <CR> to suppress: (prompt)

T (response)

Discussion: This is usually printed since it is the final plot of the interpreted geologic section. It can be suppressed on the initial run.

12. Enter input file name or <CR> to exit: (prompt)

<CR> (response)

Discussion: Enter file name for next run or <CR> to exit program. The final <CR> must be used to

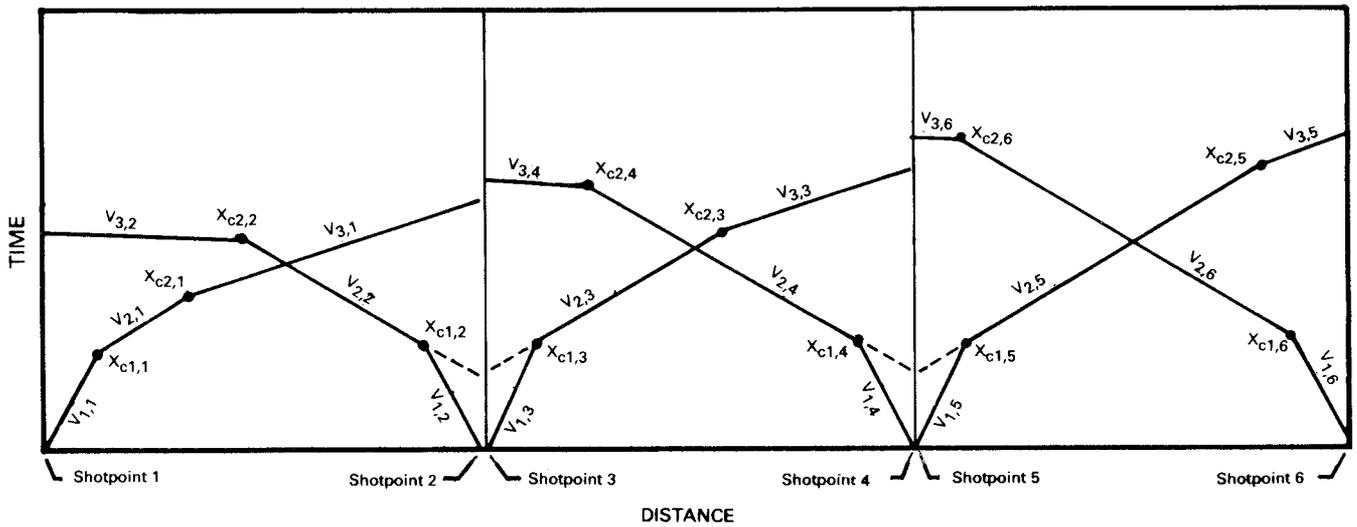
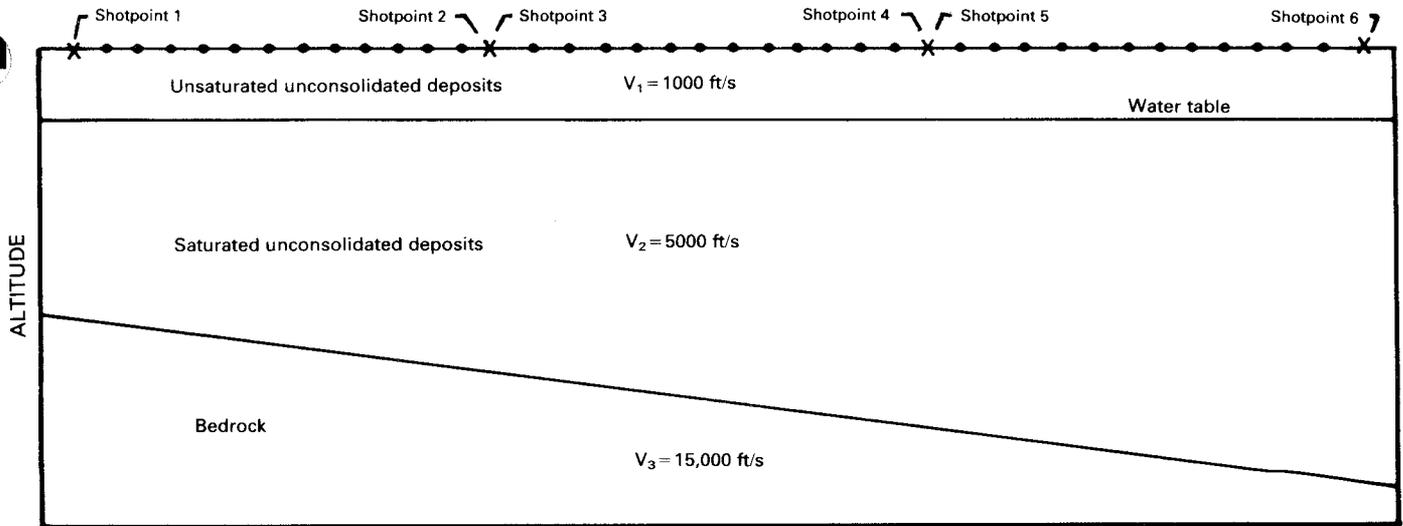


Figure 57.—Seismic section and time-distance plot showing the general relationships of seismic-layer velocities and crossover distances between three seismic-refraction spreads.

exit the program or the program file will remain open. On some computer systems, the interpreter will be prevented from accessing the program again until it is closed.

This completes the first computer run of the seismic-refraction interpretation program. As mentioned previ-

ously, the interpreter now works on the time-distance plot and may have some changes to make in layer assignments or in the input data file.

At this point, the necessary corrections are made to the input data file with the computer editor, and a second run of the SIPT program is begun. This run should produce

Table 9.—Example of input data set for the Seismic Interpretation Program (SIPT)

Format for input data to SIPT program	Explanation of data lines
Simsbury Minister Brook (Htfd. Fire Ins. Co.),	Title
2,6,3,1,5,0, 16.66,2.0,0,0,0,0,0,0,0,0,0,0,0	Problem control line
1,700,0,0,0	Velocity override line
1,2,12,0,0	Spread 1 control data
1,173,0,0,8,0,0,0	Shot 1 data
2,69,1000,0,8,0,0,0	Shot 2 data
1,173,200,0,63,2,133,3	Spread 1, geophone locations, arrival times, and layer selection
2,173,250,0,75,2,130,3	
3,173,300,0,85,3,126,3	
4,173,350,0,90,3,123,3	
5,173,400,0,93,3,120,3	
6,173,450,0,97,2,116,3	
7,173,500,0,103,3,115,3	
8,173,550,0,107,3,112,3	
9,173,600,0,110,3,104,2	
10,173,650,0,115,3,94,2	
11,172,700,0,119,3,85,2	
12,171,750,0,124,3,74,2	
2,2,12,0,0	Spread 2 control data
3,173,400,0,10,0,0,0	Shot 3 data
4.155.1600.00.4.0.0.0	Shot 4 data
1,171,750,0,94,2,152,3	Spread 2 geophone locations, arrival times and layer selection
2,169,800,0,104,3,150,3	
3,169,850,0,109,3,146,3	
4,169,900,0,113,3,142,3	
5,169,950,0,118,3,139,3	
6,169,1000,0,120,3,134,3	
7,169,1050,0,125,3,130,3	
8,169,1100,0,128,3,129,3	
9,169,1150,0,132,3,126,3	
10,168,1200,0,137,3,123,3	
11,165,1250,0,140,3,119,3	
12,164,1300,0,143,3,116,3	

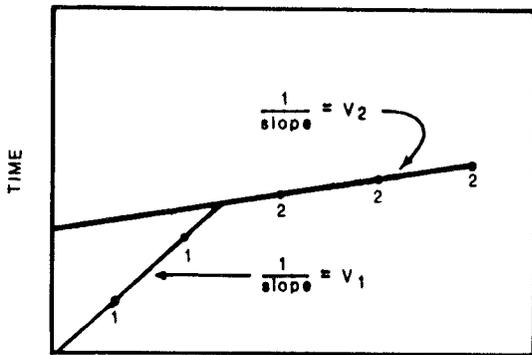
improved results over the first run, and the interpreter can start looking at the depth table and the interpreted seismic section plot to assess the quality of the solution.

During the second run, the following points should be checked again by the interpreter:

1. Input data—Were the intended changes entered properly?
2. Velocity tables—Are there still layer velocities that do not look reasonable?
3. Time-distance plot—Were the changes from the first run made and is the plot now acceptable?
4. Depth table and interpreted seismic section plot—Are any water-well, shothole, or geologic data available to check approximate depths? Are flat interfaces (water table or bedrock surface) basically horizontal, or are there specific problems?

A common interpretation aid can now be used. In some hydrologic studies, few, if any, refraction data points are available for layer 1. This layer is shallow and requires a completely separate field setup to determine the velocity of sound in it. Independent control on layer 2 may be available from nearby observation wells, swamps, or shot-holes. The depth to layer 2, or to the water table, can be adjusted in the interpretation program by using the velocity-override option. The value input to the computer for the seismic velocity of layer 1 is adjusted by trial and error until the solution for the depth to layer 2 generally agrees with field observations. For example, the computer solution often places the water table at depths greater than those observed in the field. This happens when the program uses the default value of 1,500 ft/s for the velocity of sound in layer 1. By decreasing the velocity of

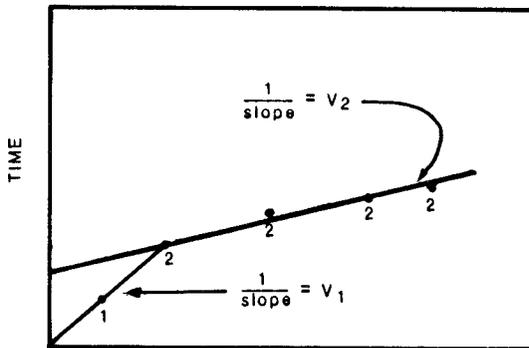
PROPER LAYER ASSIGNMENTS



Computed seismic velocities

$V_1 = 1000 \text{ ft/s}$
 $V_2 = 5000 \text{ ft/s}$

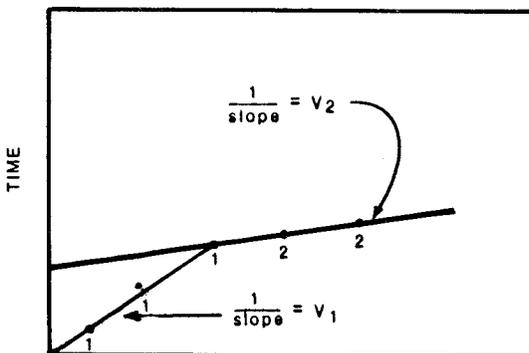
LAYER 1 GEOPHONE GIVEN LAYER 2 ASSIGNMENT



Computed seismic velocities

$V_1 = 1000 \text{ ft/s}$
 $V_2 = 4000 \text{ ft/s}$

LAYER 2 GEOPHONE GIVEN LAYER 1 ASSIGNMENT

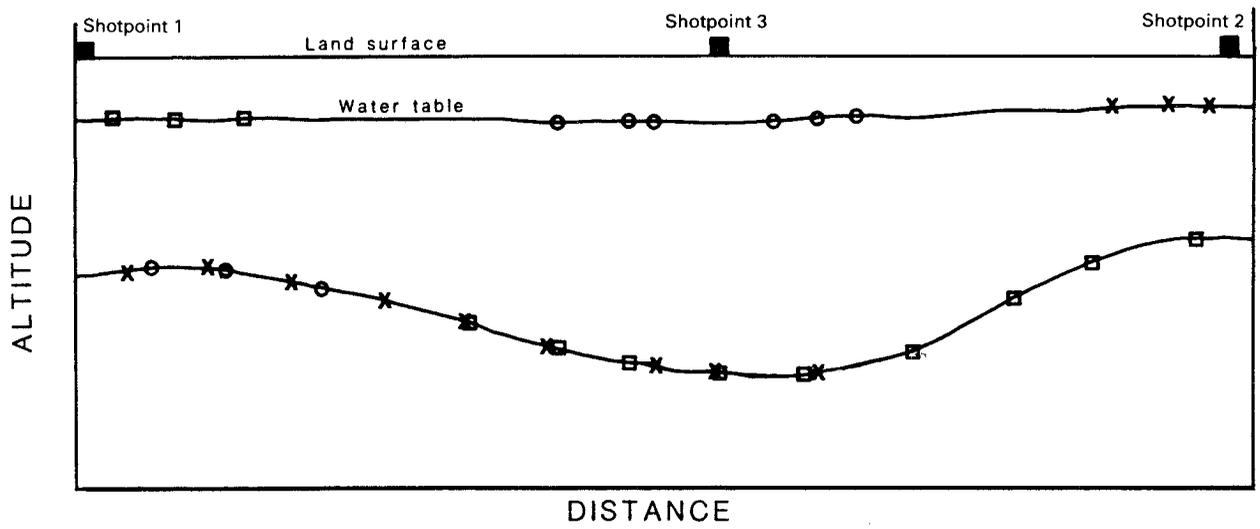


Computed seismic velocities

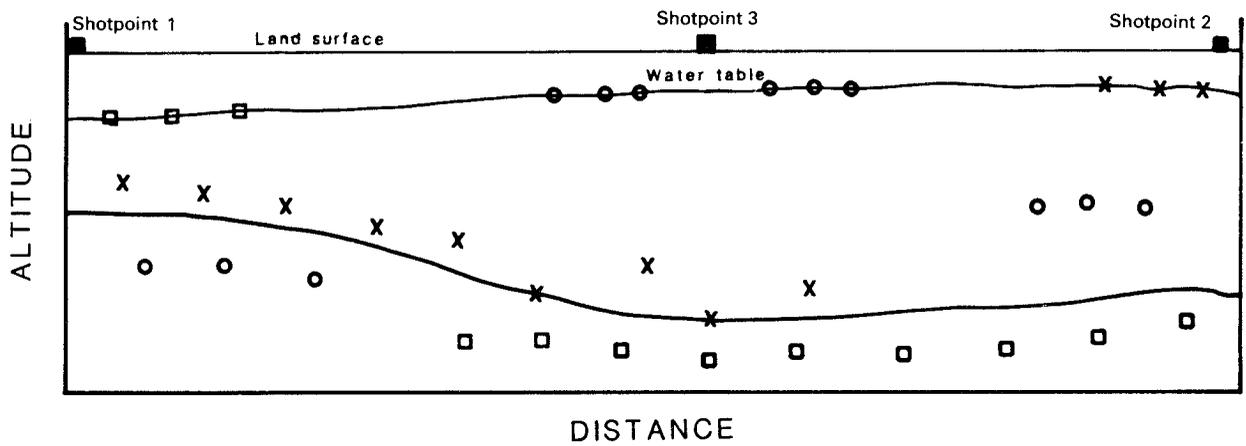
$V_1 = 2500 \text{ ft/s}$
 $V_2 = 5000 \text{ ft/s}$

Figure 58.—Effects of incorrect layer assignments on the velocity of sound as computed by regression in the Seismic Interpretation Program (SIPT).

A. Good computer solution



B. Poor computer solution



EXPLANATION

- Shotpoint
- Interpreted data from shotpoint 1
- × Interpreted data from shotpoint 2
- Interpreted data from shotpoint 3
- Final interpreted interface positions

Figure 59.—Good and poor computer-aided interpretations of seismic-refraction data.

sound in layer 1, the water table can be raised to agree with the independent field data. Similarly, the velocity of sound in layer 1 may change from spread to spread. This situation can again be accounted for by using the velocity override option.

At this point in the interpretation process, two or three computer runs have been made, all the obvious encoding and typing errors have been corrected, and the depth to layer 1 generally agrees with independent field data. The interpreter is now ready to assess the quality of the interpreted seismic section plot, keeping in mind that several layer assignments near the crossover points on the time-distance plot may still be questionable.

The best method for testing the quality of the seismic interpretation is to compare the results with well or test hole data from the study area. Generally these data are not available, so the interpreter must qualitatively judge the results. One way to do this is to examine the final interpreted seismic section plot. Each refractor should be printed as a line on the plot. If the data points from reversed shotpoints that define a refractor overlap and form a continuous line, then a relatively good computer solution has been obtained. If, however, there is scatter in these points, then the solution is not as good. See figure 59 for an example of a good and poor computer solution of the second refracting layer.

Several field and interpretational errors can lead to the poor solution shown in figure 59B. Any departure of the subsurface from the simplifying assumptions listed in the beginning of this subsection can lead to a poor solution. Some common causes of this are inhomogeneous layers such as localized buried swamp or peat deposits, or lateral lithologic facies changes. Layer misassignments and errors in field measurements also can cause poor solutions.

If all of the first arrivals from one shotpoint are consistently late, the possibility that the sound source was located in an atypical setting (recent fill or swamp deposits) should be considered. If this is the case, there is an option in the program that allows the interpreter to add or subtract a constant time delay to each geophone in the spread (see "Fudge Time" in Scott and others, 1972, p. 30).

It is important to realize that the best solution using the delay-time technique is obtained when the refracting surface of interest has many overlapping data points from shots in opposite directions. If only a few isolated data points define a refracting surface, the computer solution should be suspect, even though it may appear unambiguous.

The questionable layer assignments noted earlier on the time-distance plot near the crossover points can now be tested. The interpreter should make several computer runs, systematically varying the questionable layer assign-

ments until a best fit is achieved on the interpreted seismic-section plot that agrees with drill-hole data.

After four to eight computer runs, the interpreter should have a good idea of where the problems are in the solution and whether or not the changes made in the runs have any effect. Under normal circumstances, the interpreter stops the computer-assisted interpretation process when little or no improvement is noted.

It must be emphasized that, because the Earth never exactly meets the simplifying assumptions that have been made, a perfect solution is never possible. In the end, the interpreter must make the final interpretation with the information provided by the computer-assisted seismic-refraction modeling process.

One of the major shortcomings of the seismic-interpretation process just described is that the seismic velocity in each layer is assumed to remain the same for an entire spread. This limitation is not severe for short spread lengths but may impose severe restrictions on the interpretation process for long spreads over deep refractors. The U.S. Geological Survey (Ackermann and others, 1983) has developed a computer interpretation program that overcomes this shortcoming. The details of this interpretation procedure will not be covered here because the procedure is well documented. This procedure is more difficult to use than the one described here, but it is a better interpretational scheme when large spreads and very deep refractors are being studied. Another interpretation method, the generalized reciprocal method (GRM) described by Palmer (1980), also overcomes this problem. The GRM method has been implemented in several computer programs.

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