APPLICATION OF SEISMIC-REFRACTION TECHNIQUES TO HYDROLOGIC STUDIES

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By F. P. Haeni

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ABBREVIATIONS AND CONVERSION FACTORS

Factors for converting inch-pound units to International System of Units (SI) and abbreviation of units:

Multiply inch-pound unit	By	To obtain SI (metric) unit
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
foot per second (ft/s)	0.3048	meter per second (m/s)

GLOSSARY

Angle of incidence: The acute angle between a raypath and the normal to an interface.

Apparent velocity: The velocity at which a fixed point on a seismic wave, usually its front or beginning, passes an observer.

Blind zone: A layer with lower seismic velocity than overlying layers so that it does not carry a head wave.

Conductivity: The property of a material that allows the flow of electrical current.

Critical angle: Angle of incidence at which a refracted ray just grazes the interface between two media with different seismic velocities which is equal to $\sin^{-1} V_1/V_2$.

Critical distance: The offset for which reflection occurs at the critical angle.

Crossover distance: The source-to-receiver distance at which refracted waves following a deep high-speed marker overtake direct waves or refracted waves following shallower markers.

Head wave: A wave characterized by entering and leaving a high-velocity medium at the critical angle.

Isotropic: A substance that has the same physical properties regardless of the direction of measurement.

Reflection: Energy from a seismic source that has been reflected from an acoustic impedence contrast between layers within the earth.

Resistivity: Property of a material which inhibits the flow of electrical current. Resistivity is the reciprocal of conductivity.

Stack: A composite seismic record made by combining traces from different shots.

Unconsolidated: Loose material of the Earth's surface; uncemented particles of solid matter.

Weathered layer: Zone near the Earth's surface characterized by a low seismic wave velocity beneath which the velocity abruptly increases, more properly called the low-velocity layer.

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ABSTRACT

During the past 30 years, seismic-refraction methods have been used extensively in petroleum, mineral, and engineering investigations, and to some extent for hydrologic applications. Recent advances in equipment, sound sources, and computer interpretation techniques make seismic refraction a highly effective and economical means of obtaining subsurface data in hydrologic studies. Aquifers that can be defined by one or more high seismic-velocity surfaces, such as (1) alluvial or glacial deposits in consolidated rock valleys, (2) limestone or sandstone underlain by metamorphic or igneous rock, or (3) saturated unconsolidated deposits overlain by unsaturated unconsolidated deposits, are ideally suited for applying seismic-refraction methods. These methods allow the economical collection of subsurface data, provide the basis for more efficient collection of data by test drilling or aquifer tests, and result in improved hydrologic studies.

This manual briefly reviews the basics of seismic-refraction theory and principles. It emphasizes the use of this technique in hydrologic investigations and describes the planning, equipment, field procedures, and intrepretation techniques needed for this type of study.

Examples of the use of seismic-refraction techniques in a wide variety of hydrologic studies are presented.

INTRODUCTION

Surface geophysical techniques have been used extensively in the petroleum, mineral, and engineering fields. Hydrologic investigations have used surface geophysical techniques in the past, but only to a limited degree. Recent advances in electronic equipment, computer-interpretation programs, and the development of new techniques, make surface geophysics a more effective tool for hydrologists. These techniques should be considered in the project planning process and used where appropriate. Treated as a tool, similar to pump tests, simulation modeling, test drilling, geologic maps, borehole geophysical techniques, and so forth, these techniques are used to help solve hydrologic problems.

Classically, surface geophysical techniques have been used early in the exploration process (Jakosky, 1950). Accordingly, these techniques should be used early in a study, prior to using more expensive data-collection techniques such as drilling. The use of surface geophysics in this manner minimizes expensive data-collection activities and results in more efficient hydrologic studies.

All surface geophysical methods measure some physical property of subsurface materials or fluids. Selection of the appropriate geophysical method is determined by the specific physical property of a hydrologic unit or the differences between adjacent hydrologic units. Typical physical properties measured are electrical resistivity, electrical conductivity, velocity of sound, gravity fields, and magnetic fields. Knowledge of the physical properties of a subsurface unit and the surrounding units is critical for the successful application of surface geophysical methods. Aquifers that can be defined by one or more high seismic velocity surfaces, such as alluvial or glacial deposits in consolidated rock valleys, limestone or sandstone underlain by metamorphic or igneous rock, or saturated unconsolidated deposits overlain by unsaturated, unconsolidated deposits, are ideally suited for seismic-refraction methods. In these hydrogeologic settings, seismic-refraction methods have proven to be the most useful of the surface geophysical techniques (Grant and West, 1965).

Seismic-refraction techniques were among the first geophysical tools used in the exploration for petroleum. In the 1920's, this technique helped find many structures that were associated with petroleum accumulations. With the introduction and refinement of seismic-reflection techniques during the 1930's, use of the refraction method by the petroleum industry declined, and it is now used primarily in special situations and for weathered-layer velocity determinations.

Use of the seismic-refraction technique in engineering and hydrologic applications, and in coal exploration, has increased over the years, as has the wealth of literature on interpretation procedures. A bibliography by Musgrave (1967, p. 565-594) shows the extent of interest in, and the variety of applications of, the seismic-refraction technique.

Although seismic-reflection techniques have dominated the deep exploration work during recent years, shallow exploration work has used seismic-refraction techniques extensively. Advances in the miniaturization of electronic equipment and the use of computers for data interpretation have made seismic-refraction techniques a very effective and economical exploration tool for hydrologists.

Purpose and Scope

A brief review of the literature indicates the diversity of seismic-refraction techniques. The purpose of this manual is to help the hydrologist who wishes to use this technique in a particular project or area of interest. This manual is intended to help the hydrologist determine if seismic-refraction techniques will work in a particular hydrologic setting. In addition, this manual briefly presents the theory of seismic refraction, identifies advantages and limitations of the technique, describes the equipment and general field procedures required, and presents several interpretation procedures. Numerous references are cited to provide the reader with additional sources of information which are beyond the scope of this manual.

The techniques presented here are not standardized or rigid, but they have been used effectively in a wide variety of hydrologic studies conducted by the U.S. Geological Survey and others. References are included with each section so that alternative approaches to field procedures and interpretation methods can be investigated.

Ultimately, success in using the seismic-refraction method will depend more on the ability of the hydrologist to apply the principles of the technique and extract a hydrologically reasonable answer, than on selecting a particular method of interpretation.

Surface Geophysical Techniques In Hydrologic Studies

Surface geophysical techniques are used to obtain information about the subsurface units that control the location and movement of ground water. These techniques are widely used in the mining and petroleum industries to locate and define the extent of ore and petroleum resources.

A standard approach in exploration investigations is first to assess geologic conditions from available surface and subsurface geological data. From this initial study, the regional or local geologic framework can be hypothesized and the magnitude of the exploration problem defined.

At this point in a study, surface geophysical methods can be used to great advantage. The geologic and hydrologic model developed in this first stage of the study from scattered data points can be verified, or if necessary, modified. The importance of the interdependence of geological data, hydrologic data and geophysical data cannot be overemphasized. Geophysical data by itself is susceptible to many interpretations. The input of hydrologic or geologic constraints may eliminate unreasonable interpretations and result in the selection of a unique solution.

Commonly, one or more surface geophysical techniques can be used advantageously in a hydrologic investigation. Papers describing the use of individual and combined surface geophysical techniques in hydrologic studies include Bonini and Hickok (1958), Eaton and Watkins (1967), Lennox and Carlson (1967), Mabey (1967), Ogiluy (1967), Shiftan (1967), Zohdy and others (1974), Worthington (1975), and Collett (1978).

The two surface geophysical techniques that have been used most widely in hydrologic studies are resistivity methods and seismic-refraction methods. The general use of seismic-refraction methods in hydrologic studies has been discussed in the literature, and in cases where velocity discontinuities between hydrologic units are present, these methods have proven to be the most useful geophysical technique. The major use of this technique in hydrologic studies is to assess the hydrogeologic framework and hydrologic boundaries of aquifers. It is generally used early in the investigation, after the preliminary hydrologic assessment, and prior to more site-specific data-gathering activities. Another use of this technique is for specific data-gathering activities later in the study. Specific problems that may arise during the hydrologic analysis section of the study, and that can be investigated with this technique, are the depth to water in unconsolidated aquifers at specific locations, and the location of aquifer boundaries.

After the geophysical work, the study is ready to enter its final stages where more costly and detailed site-specific data are collected. Generally, this phase of the study consists of a drilling program, borehole geophysical studies, detailed hydrologic testing, and data analysis.

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SEISMIC REFRACTION THEORY AND LIMITATIONS

Theory

Numerous textbooks and journal articles present the details of seismic refraction theory (Slotnick, 1959; Grant and West, 1965; Griffiths and King, 1965; Musgrave, 1967; Dobrin, 1976; Telford and others, 1976; Parasnis, 1979; Mooney, 1981). The following discussion will only review the basic principles and limitations of the seismic-refraction method. The annotated bibliography at the end of this section should be used by hydrologists not familiar with seismic theory to select one or more publications that clearly present a rigorous theoretical development.

It must be emphasized that the absence of an extensive section on the theory of seismic refraction does not minimize the importance of the topic. Hydrologists unfamiliar with geophysics must possess a solid understanding of the physics underlying the technique prior to using it.

The seismic-refraction method measures the time it takes for a compressional sound wave generated by a sound source to travel down through the layers of the Earth and back up to detectors placed on the land surface (fig. 1). By measuring the travel-time of the sound wave and applying the laws of physics that govern the propagation of sound, the subsurface geology can be inferred. The field data, therefore, will consist of measured distances and seismic travel times. From this time-distance information, velocity variations and depths to individual layers can be calculated and modeled.

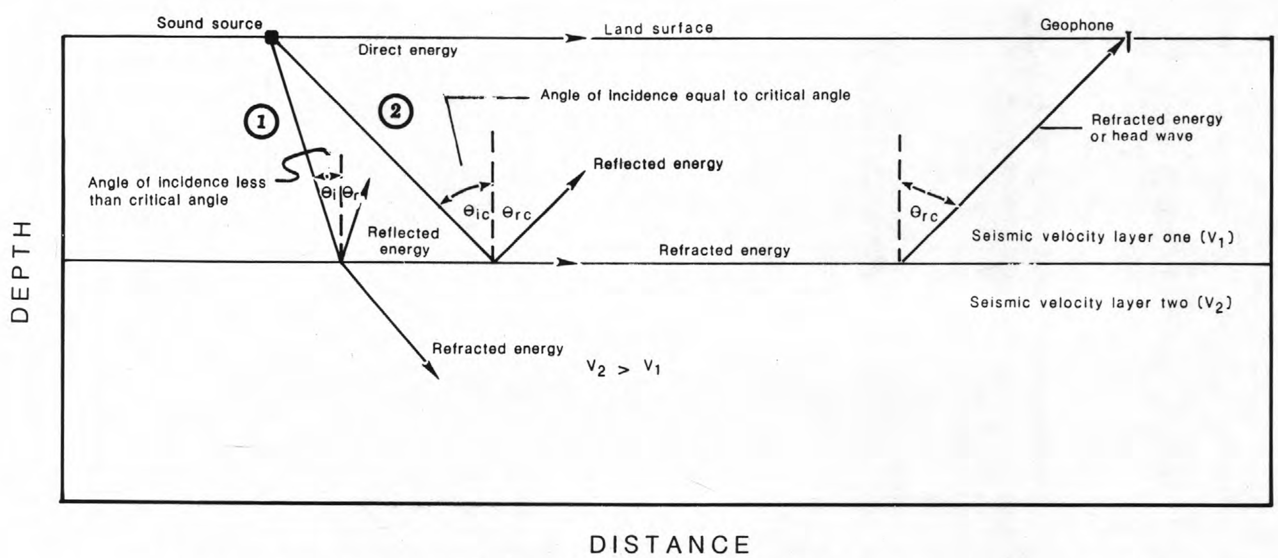


Figure 1.--Raypaths of refracted and reflected sound energy in a two-layer Earth.

The foundation of seismic-refraction theory is Snell's Law, which governs the refraction of sound or light waves across the boundary between layers of different velocities. As sound propagates through one layer and encounters another layer with faster seismic velocities, part of the energy is refracted or bent and part is reflected back into the first layer (see raypath 1 in fig. 1).

As the angle of incidence approaches the critical angle, the compressional energy is transmitted along the surface of the second layer at the velocity of sound in the second layer (see raypath 2 in fig. 1). As this energy propagates along the surface of layer 2, it generates new sound waves in the upper medium according to Huygens' principle, which states that every point on an advancing wave front can be regarded as the source of a sound wave; these new sound waves propagate back to the surface through layer 1 at an angle equal to the critical angle and at the velocity of sound in layer 1. When this refracted wave arrives at the land surface, it activates the geophone and the signal is recorded on a seismograph.

If a series of geophones is spread out on the ground in a geometric array, the arrival times can be plotted versus the shot-to-detector distances (fig. 2), which results in a time-distance plot or time-distance curve. It can be seen

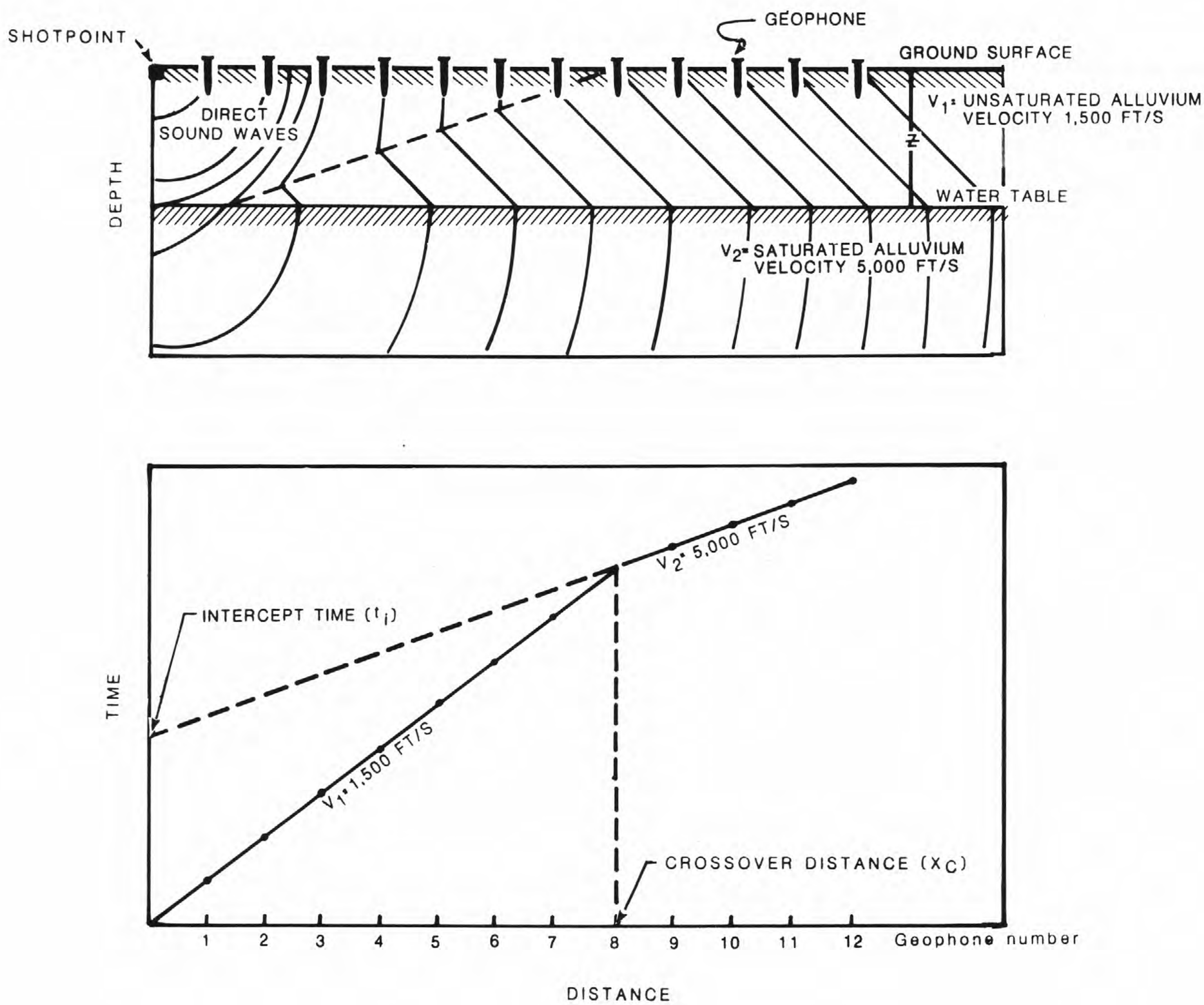


Figure 2.--Seismic wavefronts and raypaths and corresponding time-distance plot.

from figure 2 that at any distance less than the crossover distance (x_c) (sometimes incorrectly called the critical distance), the sound travels directly from the source to the detectors. This compressional wave travels a known distance in a known time and the velocity of layer one can be directly calculated by $V_1 = \frac{x}{t}$, where V_1 is the velocity of sound in layer 1 and x is the distance which a wave travels in layer 1 in time t. Figure 2 is a plot of time as a function of distance; consequently, V_1 is also equal to the inverse slope of the first line segment.

Beyond the crossover distance, the compressional wave that has traveled through layer 1, along the interface of the high-speed layer, and then back up to the surface through layer 1, arrives before the compressional wave that has been in layer 1 (the slow velocity layer). All first compressional wave arrivals at geophones more distant than the crossover distance will be refracted, or head waves, from layer 2 (the high-velocity layer). When these points are plotted on the time-distance plot, the inverse slope of this segment will be equal to the apparent velocity of layer 2. The slope of this line does not intersect the time axis at zero but at some time called the intercept time (t_i). The intercept time and the crossover distance are directly dependent on the velocity of sound in the two materials and the thickness of the first layer, and therefore can be used to determine the thickness of the first layer (z).

Interpretation Formulas

Intercept times and crossover distance-depth formulas have been derived in the literature (Grant and West, 1965; Zohdy, 1974; Dobrin, 1976; Telford and others, 1976; Parasnis, 1979; Mooney, 1981) and only the results will be given here. These derivations are straightforward inasmuch as the total travel time of the sound wave is measured, the velocity in each layer is calculated from the time-distance plot, and the raypath geometry is known. The only unknown is the depth to the high-speed refractor. These interpretation formulas are based on the following assumptions: (1) that the boundaries between layers are planes that are either horizontal or dipping at a constant angle, (2) there is no land surface relief, (3) each layer is homogeneous and isotropic, and (4) the seismic velocity of the layers increases with depth.

Two-Layer Parallel Boundary Formulas (see figure 3)

1. Intercept time formula (Dobrin, 1976, p. 297)

$$z = \frac{t_i}{2} \frac{V_2 V_1}{\sqrt{(V_2)^2 - (V_1)^2}} \qquad (1)$$

where:

z = depth to layer 2 at any point,

t_i = intercept time,

V_2 = velocity of sound in layer 2,

V_1 = velocity of sound in layer 1.

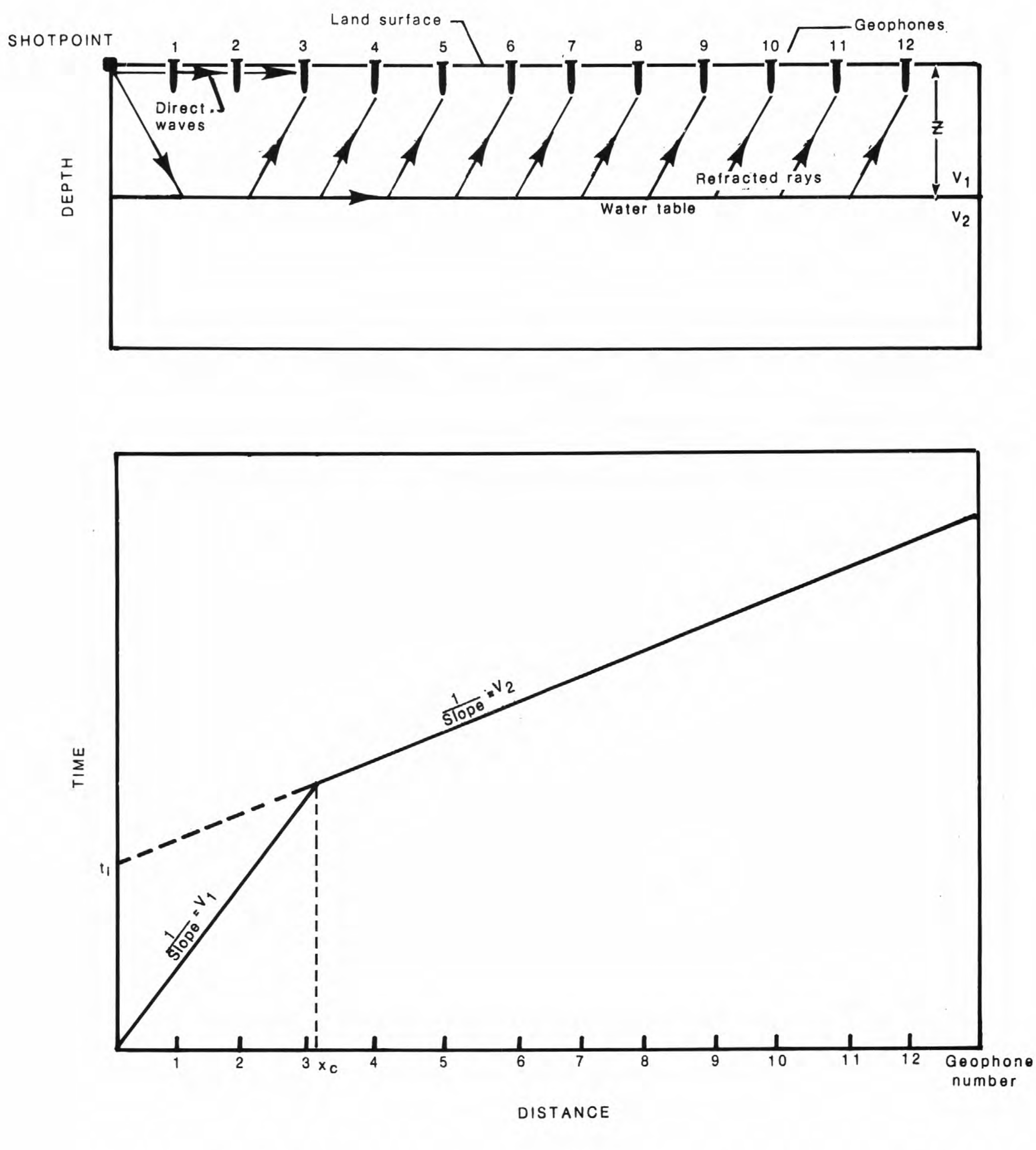


Figure 3.--Seismic raypaths and time-distance plot for a two-layer model with parallel boundaries.

2. Crossover-distance formula (Dobrin, 1976, p. 298)

$$z = \frac{x_c}{2} \sqrt{\frac{V_2 - V_1}{V_2 + V_1}} \qquad (2)$$

where:

z, V_2 and V_1 = are defined above,

x_c = crossover distance.

Three-layer Parallel Boundary Formulas (see figure 4)

1. Intercept-time formulas (Dobrin, 1976, p. 299)

$$z_1 = \frac{t_2}{2} \frac{V_2 \ V_1}{\sqrt{(V_2)^2 - (V_1)^2}} \quad \text{(from two-layer formula 1)} \qquad (3)$$

$$z_2 = \frac{1}{2} \left(t_3 - \frac{2z_1 \sqrt{(V_3)^2 - (V_1)^2}}{V_3 V_1} \right) \frac{V_3 \ V_2}{\sqrt{(V_3)^2 - (V_2)^2}} \qquad (4)$$

$$z_3 = z_1 + z_2 \qquad (5)$$

where:

z_1 = depth to layer 2 or thickness of layer 1,

z_2 = depth from bottom of layer 1 to top of layer 3 or thickness of layer 2,

z_3 = depth from surface to top of layer 3,

t_2 = intercept time for layer 2,

t_3 = intercept time for layer 3,

V_1 = velocity of sound in layer 1,

V_2 = velocity of sound in layer 2,

V_3 = velocity of sound in layer 3.

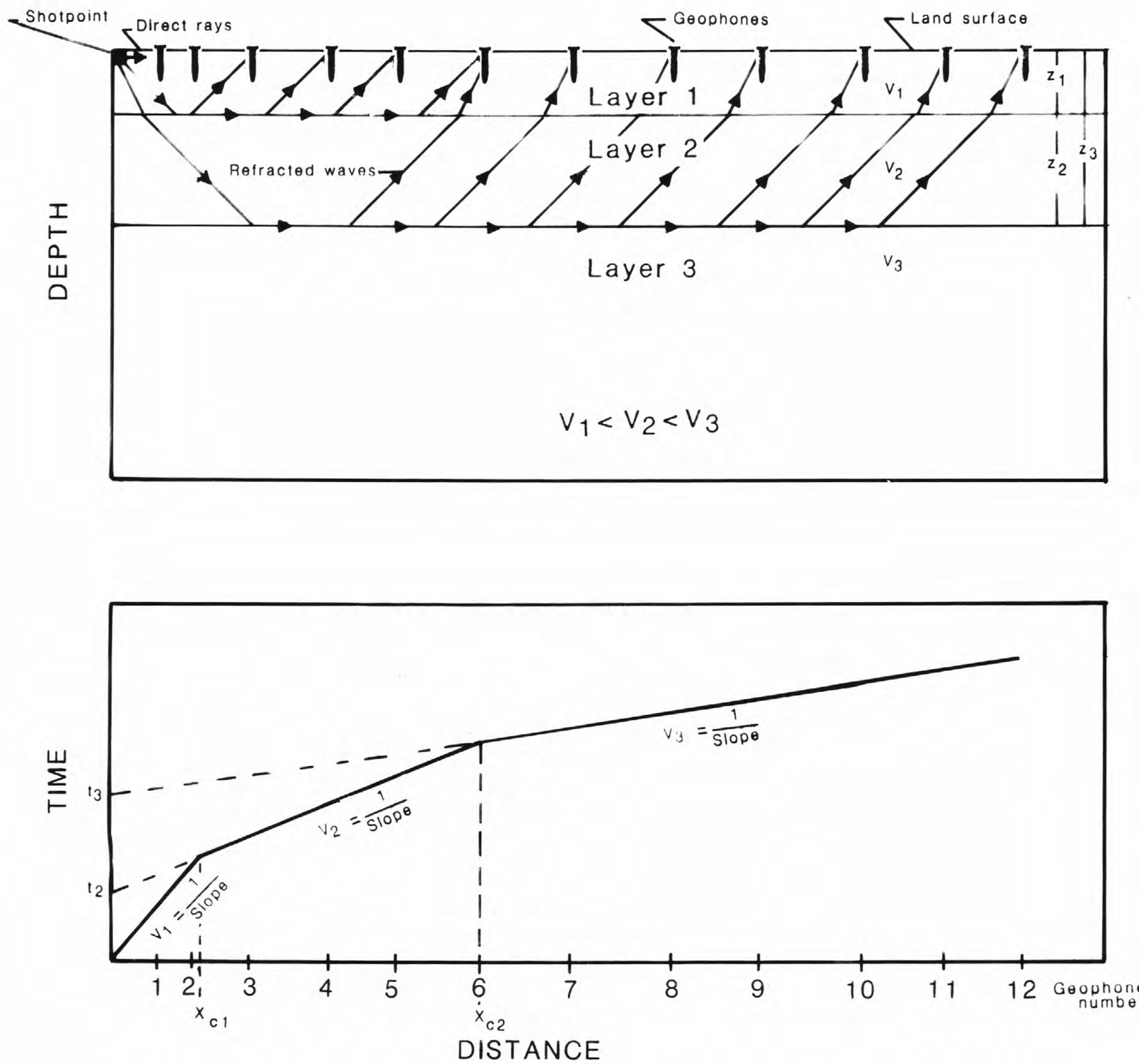


Figure 4.--Seismic raypaths and time-distance plot for a three-layer model with parallel boundaries.

2. Crossover-distance formulas (Parasnis, 1979, p. 197-198) Other forms of this equation are presented by Mooney, 1981, and Alsop, 1982.

$$z_1 = \frac{x_{c1}}{2}\sqrt{\frac{V_2 - V_1}{V_2 + V_1}} \qquad \text{(from two-layer formula 2)}$$

$$z_2 = \frac{x_{c2}}{2}\left(\frac{V_3 - V_2}{\sqrt{(V_3)^2 - (V_2)^2}}\right) - z_1\left(\frac{V_2\sqrt{(V_3)^2 - (V_1)^2} - V_3\sqrt{(V_2)^2 - (V_1)^2}}{V_1\sqrt{(V_3)^2 - (V_2)^2}}\right) \quad (7)$$

$$z_3 = z_2 + z_1 \quad (8)$$

where:

z_1, z_2, z_3, V_1, V_2, V_3 are defined above.

x_{c1} = crossover distance between layers 1 and 2,

x_{c2} = crossover distance between layers 2 and 3.

Two-layer Dipping Boundary Formulas (see figure 5)

The problem of a dipping boundary between layers adds some geometric complexity to the derivation of these formulas. Several important concepts about seismic-refraction theory must be introduced at this point.

To solve the geometry of a dipping boundary, the refraction profile must be reversed. For a one geophone array, a minimum of two shots must be fired, one from each end of the array. This concept is called "reversed-profile shooting" and should be carried out routinely in all seismic-refraction studies. Failure to reverse seismic profiles leads to invalid results in almost all situations. Figure 5 shows a two-layer dipping boundary model and the resultant time-distance plot. A fundamental rule of seismic-refraction theory is shown in figure 5. The total travel time of compressional sound waves from shot point 1 to shot point 2, and in the opposite direction, from shot point 2 to shot point 1, must be equal; that is $T_u = T_d$ because the same wave path is followed in each case. Comparison of the crossover distances or the intercept times on this plot ($x_{cu} > x_{cd}$ and $t_{2u} > t_{2d}$) shows that layer 2 is deeper at shot point 2 than at shot point 1, and a dipping-layer analysis must be used. If these values were equal, and the segments of the time-distance plots were straight lines, then simple two-layer parallel boundary formulas could be used.

In the parallel boundary problems discussed previously, the seismic velocity measured on time-distance plots was in fact the true velocity of the horizontal refracting layer. When the interface is dipping, however, the seismic refraction method measures the apparent seismic velocity and not the true seismic velocity. The true seismic velocity is the harmonic mean of the measured apparent up-dip and down-dip velocities multiplied by the cosine of the dip angle, and can be determined by the following formula.

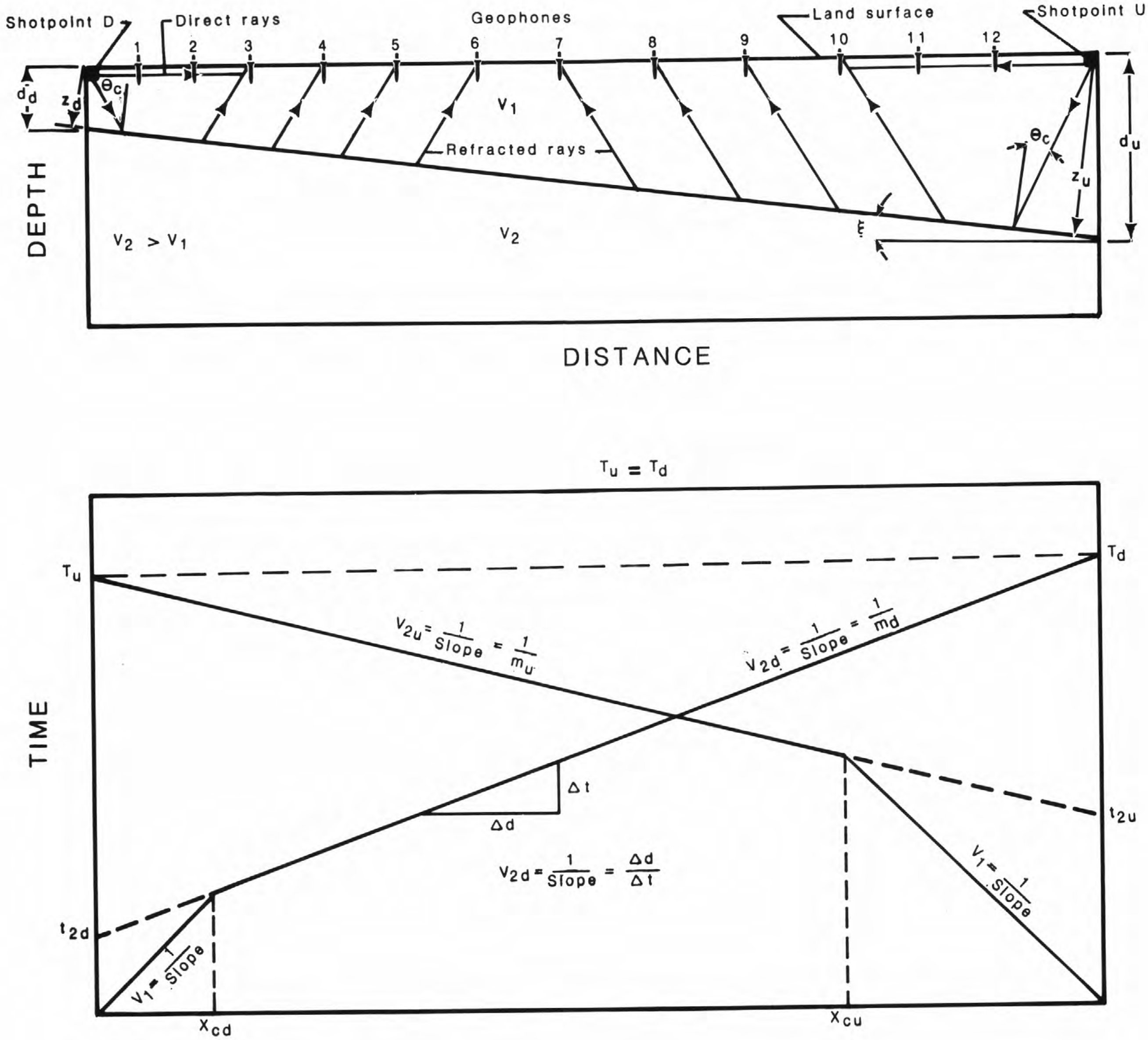


Figure 5.-- Seismic raypaths and time-distance plot for a two-layer model with a dipping boundary.

$$V_2 = \frac{2V_{2u}\, V_{2d}}{V_{2u} + V_{2d}} \cos \xi \quad \text{(Redpath, 1973, p. 9; Mooney, 1981, p. 10-4)} \quad (9)$$

where:

V_2 = true velocity of sound in layer 2,

V_{2u} = apparent up-dip velocity of sound from time-distance plot,

V_{2d} = apparent down-dip velocity of sound from time-distance plot,

ξ = dip angle of layer 2.

A good approximation of the velocity of sound in layer 2 is the harmonic mean since the cosine of small angles is very close to 1.0. Equation 9 reduces to:

$$V_2 = \frac{2V_{2u} V_{2d}}{V_{2u} + V_{2d}} \quad \text{(Redpath, 1973, p. 9)} \qquad (10)$$

The depth to the dipping interface may be calculated by using the following formulas:

1. Intercept-time formulas (Dobrin, 1976, p. 304)

a) $\theta_c = 1/2(\sin^{-1} V_1 m_d + \sin^{-1} V_1 m_u)$ (11)

where:

θ_c = critical angle

V_1 = true velocity of sound in layer 1 (from time-distance plot)

m_d = slope of down-dip V_2 segment on time-distance plot

m_u = slope of up-dip V_2 segment on time-distance plot

b) $\xi = 1/2(\sin^{-1} V_1 m_d - \sin^{-1} V_1 m_u)$ (12)

where:

ξ = dip angle of the refractor

c) $$z_u = \frac{V_1 t_{2u}}{2\cos\ \theta_c} \qquad (13)$$

where:

z_u = perpendicular distance to refractor at the down-dip shot point (shot point #2)

t_{2u} = intercept time of up-dip V_2 segment of time-distance plot

d) $$z_d = \frac{V_1\ t_{2d}}{2\ \cos\ \ \theta_c} \qquad (14)$$

where:

z_d = perpendicular distance to refractor at up-dip shot point (shot point 1)

t_{2d} = intercept time of down-dip V_2 segment of time-distance plot

e) $d_u = \dfrac{z_u}{\cos \xi}$ (15)

where:

d_u = extrapolated vertical depth to the refractor beneath shot point on down dip side (shot point 2)

f) $d_d = \dfrac{z_d}{\cos \xi}$ (16)

where:

d_d = extrapolated vertical depth to the refractor beneath shot point on up-dip side (shot point 1)

2. Crossover-distance formulas (Mooney, 1981, p. 10-8)

a) $du = \dfrac{x_{cu}}{2 \cos \xi} \dfrac{V_2-(V_1 \cos \xi)}{\sqrt{(V_2)^2 - (V_1)^2}} + \dfrac{x_{cu}}{2} \tan \xi$ (17)

b) $dd = \dfrac{x_{cd}}{2 \cos \xi} \dfrac{V_2 - (V_1 \cos \xi)}{\sqrt{(V_2)^2 - (V_1)^2}} - \dfrac{x_{cd}}{2} \tan \xi$ (18)

where:

V_1, ξ, are defined for equations 11 and 12

V_2 = true velocity of sound in layer 2 (calculated)

x_{cd} = crossover-distance of the down-dip time-distance segment

x_{cu} = crossover-distance of the up-dip time-distance segment

which simplifies to the following if the dip angle is small and cosine ξ is almost equal to 1.0:

c) $d_u = \dfrac{x_{cu}}{2} \sqrt{\dfrac{V_2 - V_1}{V_2 + V_1}} + \dfrac{x_{cu}}{2} \sin \xi$ (19)

d) $d_d = \dfrac{x_{cd}}{2} \sqrt{\dfrac{V_2 - V_1}{V_2 + V_1}} - \dfrac{x_{cd}}{2} \sin \xi$ (20)

Example Problem

The following example illustrates the use of these formulas and demonstrates the need for choosing the formula most applicable to the field situation.

A. The time-distance plot in figure 6 is obtained in the field by firing only one shot at one end of a seismic-refraction line.

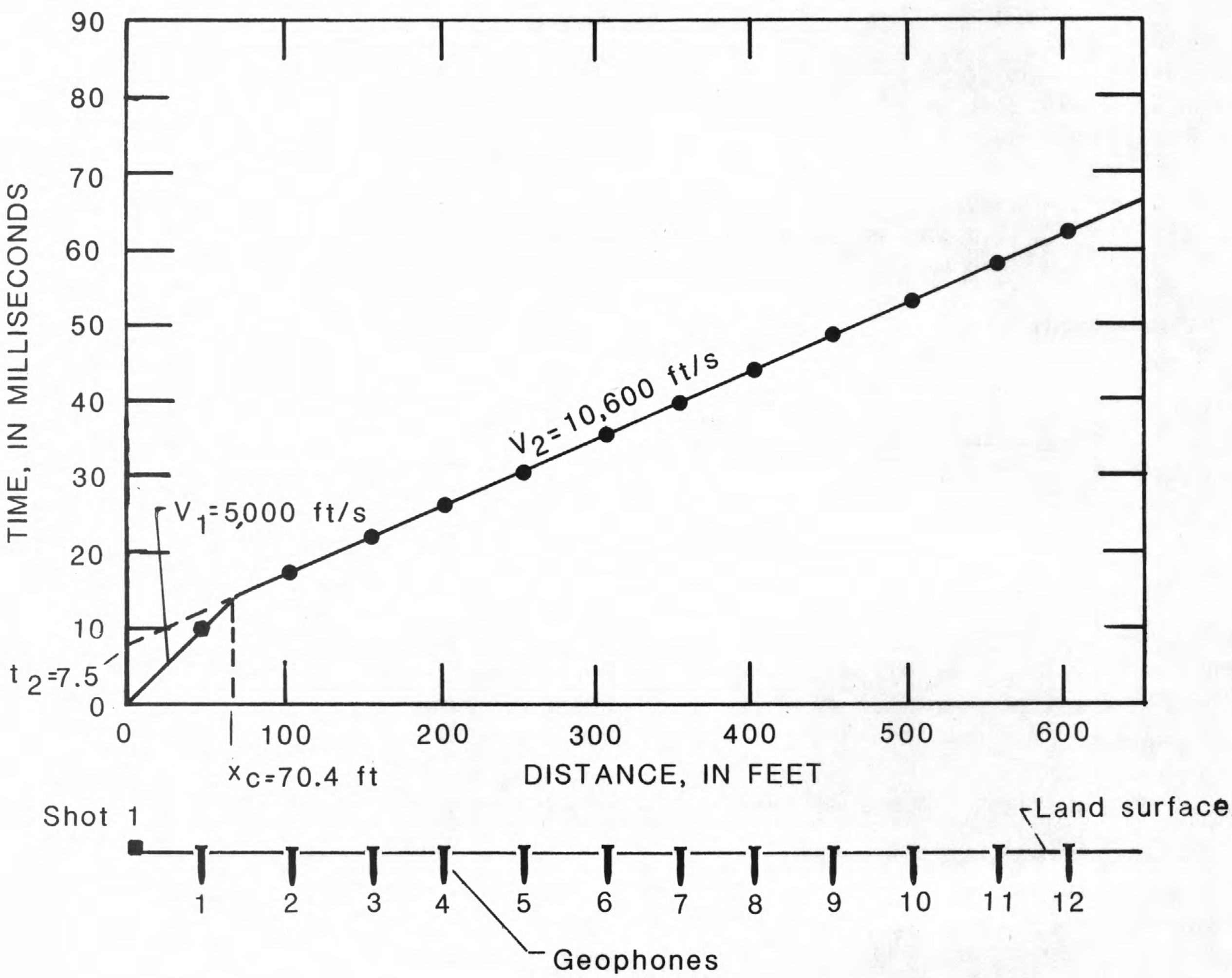


Figure 6.--Time-distance plot resulting from one shotpoint over a two-layer model with a dipping boundary.

If only one shot in one direction is fired in the field, the interpreter would have to use a two-layer horizontal interpretation formula to determine the depth to the refracting layer.

(1) Using the intercept-time formula (eq. 3) to find the depth to the refractor:

$$z = \frac{t_i}{2} \frac{V_2 V_1}{\sqrt{(V_2)^2 - (V_1)^2}} = \frac{0.0075}{2} \frac{10{,}600(5{,}000)}{\sqrt{(10{,}600)^2 - (5{,}000)^2}} = 21 \text{ ft.}$$

The depth to rock is determined to be 21 ft along the entire profile.

(2) Similar results are obtained using the crossover-distance formula (eq. 6):

$$z = \frac{x_c}{2} \sqrt{\frac{V_2 - V_1}{V_2 + V_1}} = \frac{70.4}{2} \sqrt{\frac{10{,}600 - 5{,}000}{10{,}600 + 5{,}000}} = 21 \text{ ft.}$$

B. A shot fired from the opposite end of the geophone spread produces a reversed profile. The time-distance plot shown in figure 7 was plotted from the field data.

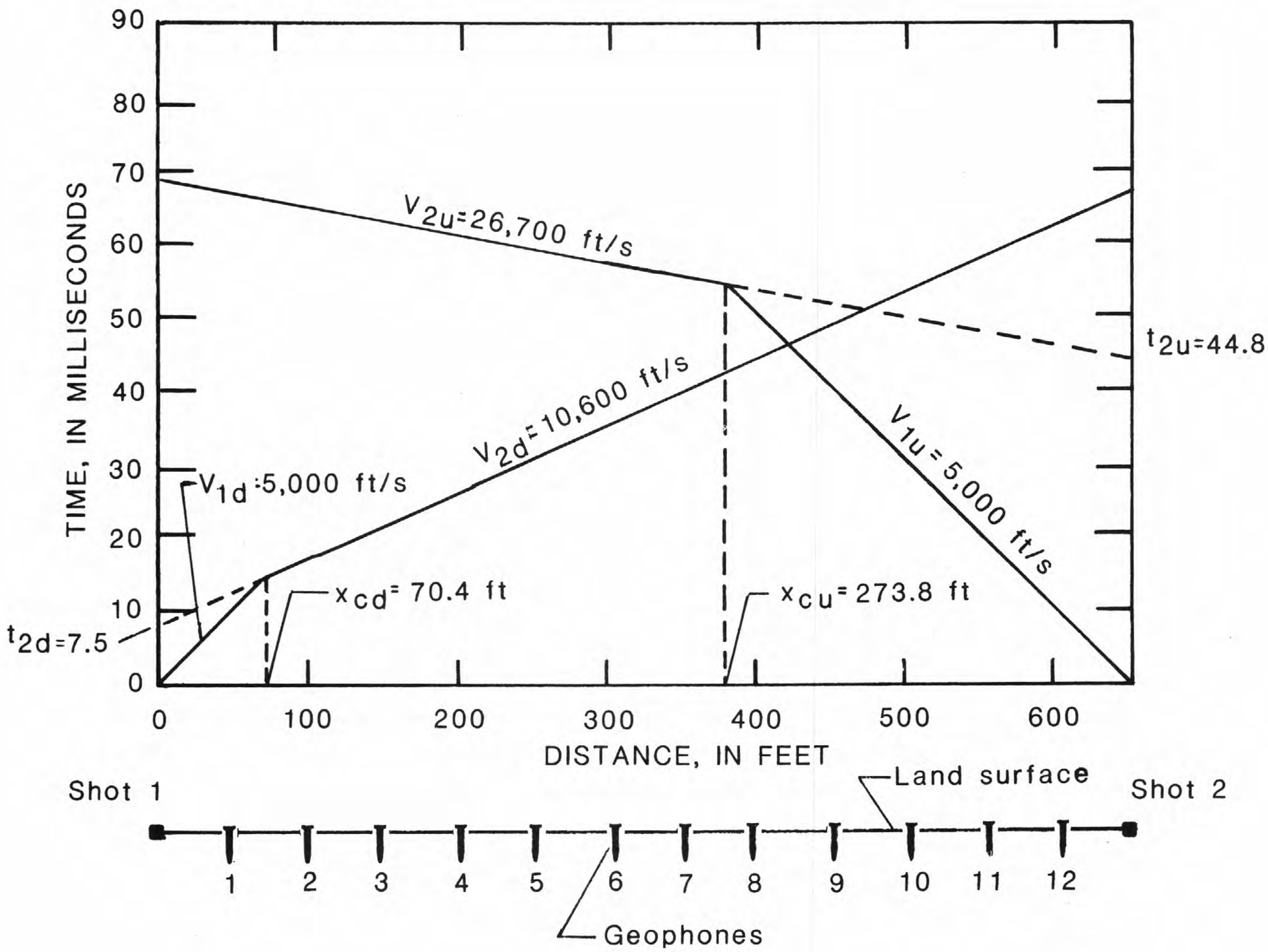


Figure 7.--Time-distance plot resulting from two reversed shots over a two-layer model with a dipping boundary illustrated in figure 5.

(1) Using the two-layer, dipping interface, intercept-time formulas (eqs. 9 and 11-16) and the following data obtained from the time-distance plot, the correct depth to the dipping refractor can be calculated.
From the time-distance plot:

t_{2u} = 0.0448 s

t_{2d} = 0.0075 s

V_1 = 5,000 ft/s

m_u = 0.0000375

m_d = 0.0000945

$$V_{2u} = \frac{1}{m_u} = 26{,}700 \text{ ft/s}$$

$$V_{2d} = \frac{1}{m_d} = 10{,}600 \text{ ft/s}$$

(a) $\xi = 1/2[\sin^{-1}(V_1 m_d) - \sin^{-1}(V_1 m_u)] = 1/2[\sin^{-1}(5{,}000 \cdot 0.0000945) - \sin^{-1}(5{,}000 \cdot 0.0000375)] = 8.75°$

(b) $$V_2 = \frac{2V_{2u}V_{2d}}{V_{2u} + V_{2d}} \cos \xi = \frac{2(26{,}700)(10{,}600)}{26{,}700 + 10{,}600} \cos 8.75 = 15{,}000 \text{ ft/s}$$

(c) $\theta_c = 1/2[\sin^{-1}(V_1 m_d) + \sin^{-1}(V_1 m_u)] = 1/2[\sin^{-1} 5{,}000(0.0000945) + \sin^{-1} 5{,}000(0.0000375)] = 19.5°$

(d) $$z_u = \frac{V_1\ t_{2u}}{2 \cos \theta_c} = \frac{5{,}000(0.0448)}{2 \cos 19.5} = 118.8 \text{ ft}$$

(e) $$z_d = \frac{V_1\ t_{2d}}{2 \cos \theta_c} = \frac{5{,}000(0.0075)}{2 \cos 19.5} = 19.9 \text{ ft}$$

(f) $$d_u = \frac{z_u}{\cos \xi} = \frac{118.8}{\cos 8.7} = 120 \text{ ft}$$

(g) $$d_d = \frac{z_d}{\cos \xi} = \frac{19.9}{\cos 8.7} = 20 \text{ ft}$$

(2) Using the crossover-distance formulas (eqs. 17 and 18) with the same field data, d_u and d_d can again be calculated.

From the time-distance plot:

x_{cd} = 70.4 ft

x_{cu} = 273.8 ft

V_1 = 5,000 ft/s

(a) $\xi = 1/2[\sin^{-1}(V_1 m_d) - \sin^{-1}(V_1 m_u)] = 1/2[\sin^{-1} 5{,}000(0.0000945) - \sin^{-1} 5{,}000(0.0000375)] = 8.75°$

(b) $$V_2 = \frac{2V_{2u}V_{2d}}{V_{2u} + V_{2d}} \cos \xi = \frac{2(26{,}700)(10{,}600)}{26{,}700 + 10{,}600} \cos 8.75 = 15{,}000 \text{ ft/s}$$

(c) $$d_u = \frac{x_{cu}}{2 \cos \xi} \cdot \frac{V_2 - (V_1 \cos \xi)}{\sqrt{(V_2)^2 - (V_1)^2}} + \frac{x_{cu} \tan \xi}{2}$$

$$d_u = \frac{273.8}{2 \cos 8.75} \cdot \frac{15{,}000 - (5{,}000 \cos 8.75)}{\sqrt{(15{,}000)^2 - (5{,}000)^2}} + \frac{273.8 \tan 8.75}{2}$$

$d_u = 120$ ft

(d) $$d_d = \frac{x_{cd}}{2 \cos} \cdot \frac{V_2 - (V_1 \cos \xi)}{\sqrt{(V_2)^2 - (V_1)^2}} - \frac{x_{cd} \tan \xi}{2}$$

$$d_d = \frac{70.4}{2 \cos 8.75} \cdot \frac{15{,}000 - (5{,}000 \cos 8.75)}{\sqrt{(15{,}000)^2 - (5{,}000)^2}} - \frac{70.4 \tan 8.75}{2}$$

$d_d = 20$ ft

Summary of example problem:

1. Using a single shot, non-reversed seismic-refraction profile, and the two-layer parallel boundary formulas, the interpretation gives a subsurface with a velocity of sound in layer 1 of 5,000 ft/s and a second horizontal layer 21 ft deep with a velocity of sound of 10,600 ft/s.

2. Using a reversed seismic-refraction profile and the two-layer dipping-boundary formulas, the correct interpretation gives a subsurface with a velocity of sound in layer 1 of 5,000 ft/s, and a second layer dippi- at 8.7° with a velocity of sound of 15,000 ft/s. The depth to this interface is 20 ft at the up-dip shot point and 120 ft at the down-dip shot point.

Multi-layer Dipping Boundary Formulas

Mota (1954) and Knox (1976) have published formulas that apply to problems with a large number of dipping layers, and nomograms for solving this type of problem have been published by Meridav (1960, 1968) and Habberjam (1966).

In practice, however, it becomes increasingly difficult to distinguish between small discrete changes in the time-distance plots that actually indicate different layers, and small errors due to the field process and nonhomogeneous Earth layers.

Formulas for More Complex Cases

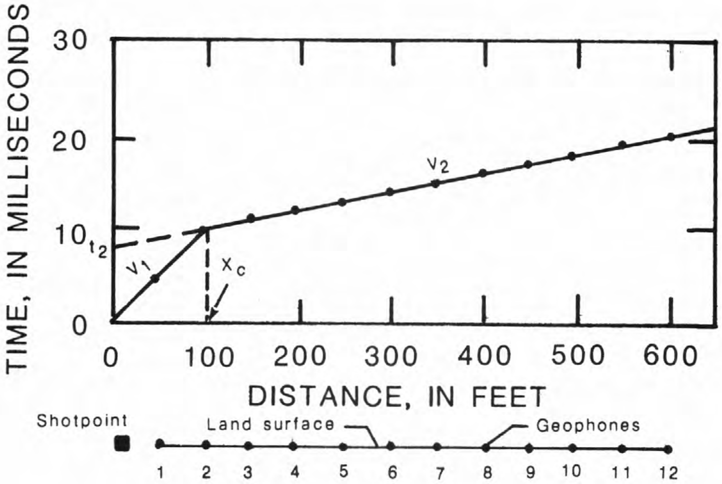
Other solutions for more complex situations are covered in the literature (Dobrin, 1976) but in general, these do not apply to hydrologic problems and consequently will not be covered here.

Field Corrections

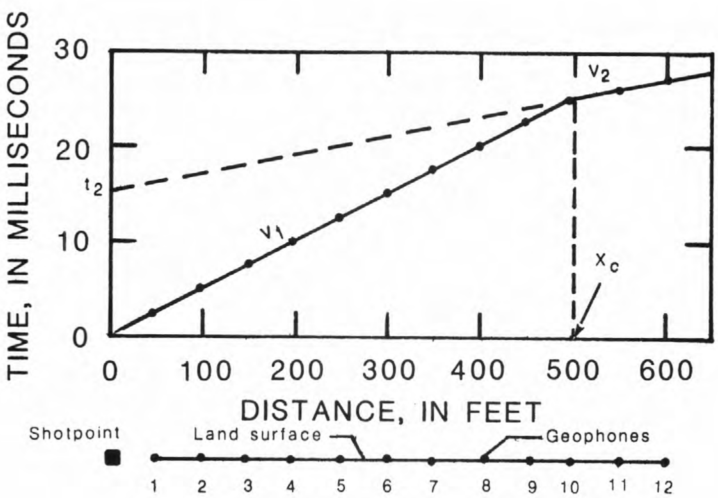
In addition to the theoretical solutions of seismic-refraction problems, corrections for field-related problems have also been developed. The two main field problems are elevation corrections and weathering corrections. Both are used to adjust field-derived travel-times to some selected datum plane, so that straight-line segments on the time-distance plot can be associated with subsurface refractors. These corrections can be applied manually (Dobrin, 1976, p. 335) or by computer (Scott and others, 1972).

Summary

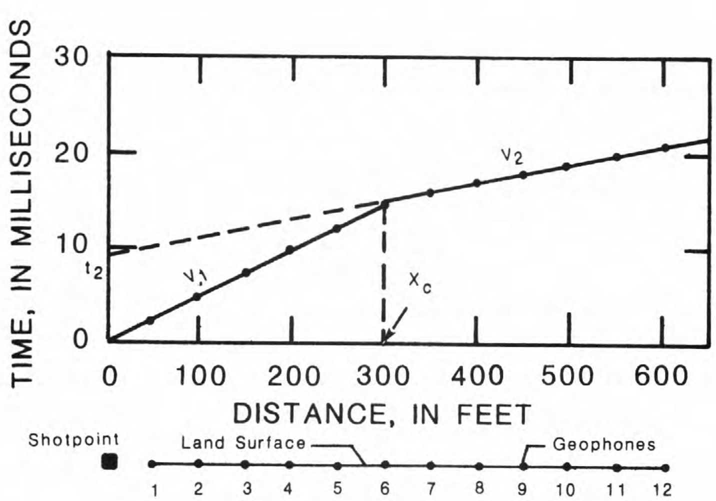
In this section, formulas for both intercept time and crossover distances were presented for determining the depth to a refractor. Several investigators have shown that in general, the crossover distance formulas are less prone to error than the intercept-time formulas (Zirbel, 1954, Meridav, 1960) because of the difficulty in determining the correct slope of the segments of the time-distance plot as compared with determining the crossover distances. Telford and others (1976, p. 279), however, take the opposite view. The final choice of methods, therefore, depends on the quality and quantity of the data on the time-distance plot (Grant and West, 1965, p. 149-150). The time-distance plots shown in figure 8 illustrate the advantages and disadvantages of each method under several different field conditions.



Control for plotting V_2 better than for V_1-- Intercept-time formulas are preferred. V_1 is defined by two points. If the time at geophone 1 was in error, x_c would vary significantly. V_2, however, is defined by many data points and t_2 will not vary with individual arrival time error.



Control for plotting V_1 better than for V_2-- Crossover-distance formulas are preferred. V_2 is defined by three points and an error in the time of geophone 12 would significantly change the intercept time (t_2). The critical distance would not vary significantly.



Control for plotting V_1 and V_2 about the same-- Intercept time and crossover distance formulas are equal. All line segments are defined by about the same amount of data.

Figure 8.--Advantages and disadvantages of intercept-time versus cross-over distance formulas in determining depth to a refractor under different field conditions.

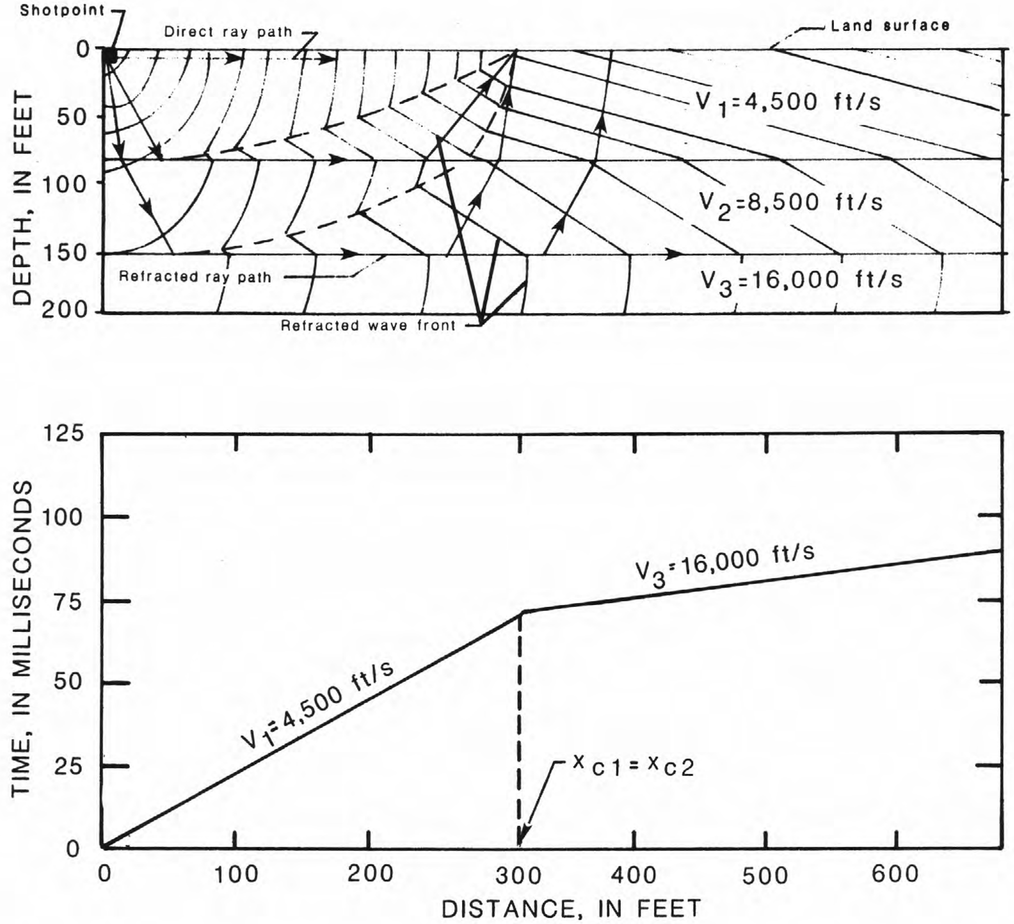
Limitations

Prior to using seismic-refraction techniques, certain problems and limitations need to be considered (Domzalski, 1956; Burke, 1967; Wallace, 1970). Three blind-zone problems that affect the success of seismic-refraction techniques in hydrologic studies will be discussed further. These are (1) thin intermediate seismic-velocity refractors, (2) insufficient seismic-velocity contrasts between hydrologic units, and (3) low seismic-velocity units underlying high seismic-velocity units.

Thin Intermediate Seismic-Velocity Refractor

One of the most serious limitations of the seismic-refraction method is the inability of the method to detect intermediate layers in cases where the layer has insufficient thickness or seismic-velocity contrast to return first-arrival energy. This problem is critical in water-resources investigations, because the intermediate layer may be the zone of interest in the study. For example, saturated unconsolidated aquifer material between unsaturated unconsolidated material and bedrock, or a sandstone aquifer between unconsolidated material and crystalline rock, may not be detected with seismic-refraction methods. These intermediate layers cannot be defined by any alternative location of the geophones or shallow shot points. Deep shot holes may overcome this problem (Soske, 1959) but are usually impractical under normal field conditions. If the presence of such a layer is suspected, however, calculations can be made to determine its minimum and maximum thickness. Figure 9 shows the wave-front and raypath diagram in a situation where a 70-ft thick intermediate velocity layer is not detected by first arrivals on the time-distance plot. If the intermediate layer is a thin, high seismic-velocity layer of till underlying a glacial aquifer, the thickness of the aquifer calculated from the refraction data will be in error (Sander, 1978). Successful interpretation of field data acquired in areas with this problem is dependent upon the correlation of geophysical data with drill holes or knowledge of the local geology.

In the absence of drill hole data, an unexpected velocity change in the time-distance plot should warn the hydrologist that a thin intermediate seismic-velocity layer may be present and a qualified interpretation is in order. An example of this is shown in figure 10 where the time-distance plot indicates that a thin, intermediate seismic-velocity layer may exist, provided the interpreter knows something about the local geology and the speed of sound in the various earth materials near the study area. The case illustrated in figure 10 is a very common one in hydrologic studies. The unsaturated, unconsolidated material has a velocity of 1,000 ft/s, the thin saturated unconsolidated material has a velocity of about 5,000 to 6,000 ft/s (this layer is not detected by the refraction techniques and a segment representing this seismic velocity does not appear in fig. 10), and the crystalline bedrock has a velocity of 15,000 ft/s.



eismic wavefronts with selected raypaths and the corresponding
ime-distance plot for the case of an undetectable intermediate
eismic-velocity layer (modified from Soske, 1959, fig. 4, pp.326).

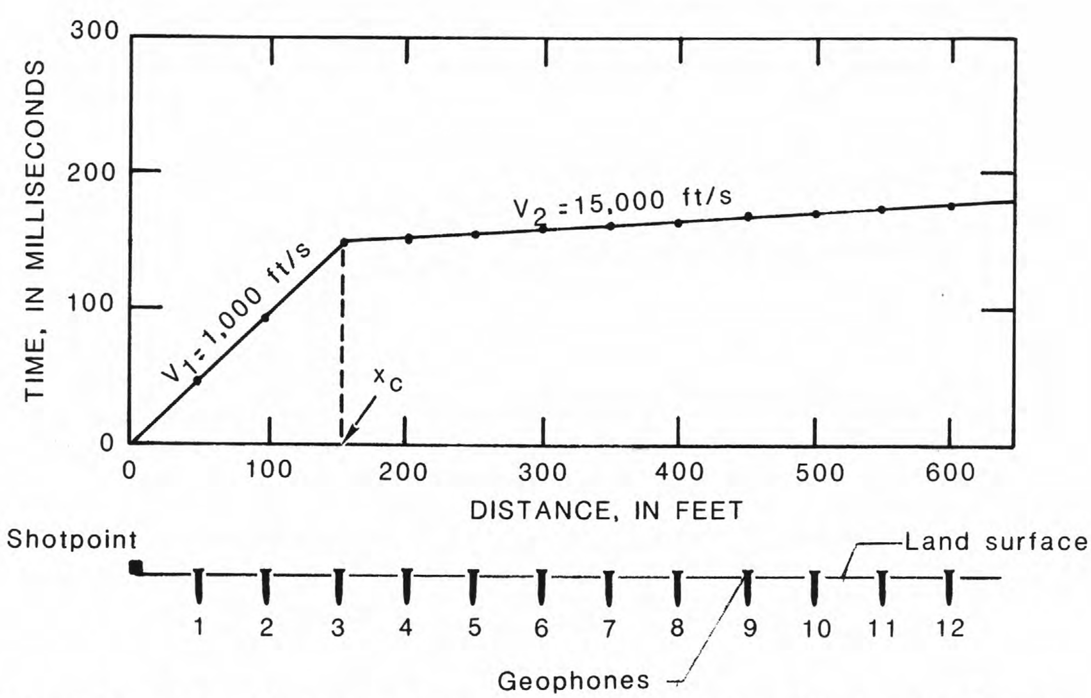


Figure 10.--Time-distance plot showing two layers, in an area known to have three layers.

Table 1.--Maximum thickness of an undetectable layer in various hydrogeologic settings

Hydrogeologic setting and velocity of sound in the geologic units	Thickness of layer 1, (in feet)	Maximum thickness of undetected aquifer material in layer 2, (in feet)	Range in depth to layer 3, (in feet)
Dry sand, v_1 = 1,500 ft/sec	10	8	12-18
Saturated sand aquifer, v_2 = 5,000 ft/sec	20	16	24-36
	40	33	50-74
Bedrock, v_3 = 15,000 ft/sec	50	41	61-91
	100	82	123-182
	200	164	243-364
Till, v_1 = 7,000 ft/sec	10	3	11-13
Sedimentary rock aquifer, v_2 = 13,000 ft/sec	20	7	22-26
	50	17	55-67
Crystalline rock, v_3 = 15,000 ft/sec	100	33	110-133
	200	67	219-267
Saturated sand and gravel, v_1 = 5,000 ft/sec	10	6	12-16
	20	12	24-32
Limestone aquifer, v_2 = 10,000 ft/sec	50	29	61-79
Crystalline rock, v_3 = 15,000 ft/sec	100	58	122-158
	200	115	245-315

If a thin, intermediate seismic-velocity layer is suspected by the investigator, methods are available for determining the maximum thickness of the undetected layer (Soske, 1959; Hawkins and Maggs, 1961; Green, 1962; Redpath, 1973; Mooney, 1981). The following example demonstrates the significance of this problem in water-resources investigations. The calculations in this example and table 1 are based upon a technique described by Mooney (1981, p. 94).

Example Problem

The time-distance plot shown in figure 11 is plotted from field data and the following values are obtained.

x_c = 111 ft from time-distance plot

V_1 = 1,500 ft/s from time-distance plot

V_3 or V_2 = 15,000 ft/s from time-distance plot

V_2 = 5,000 ft/s from previous investigations

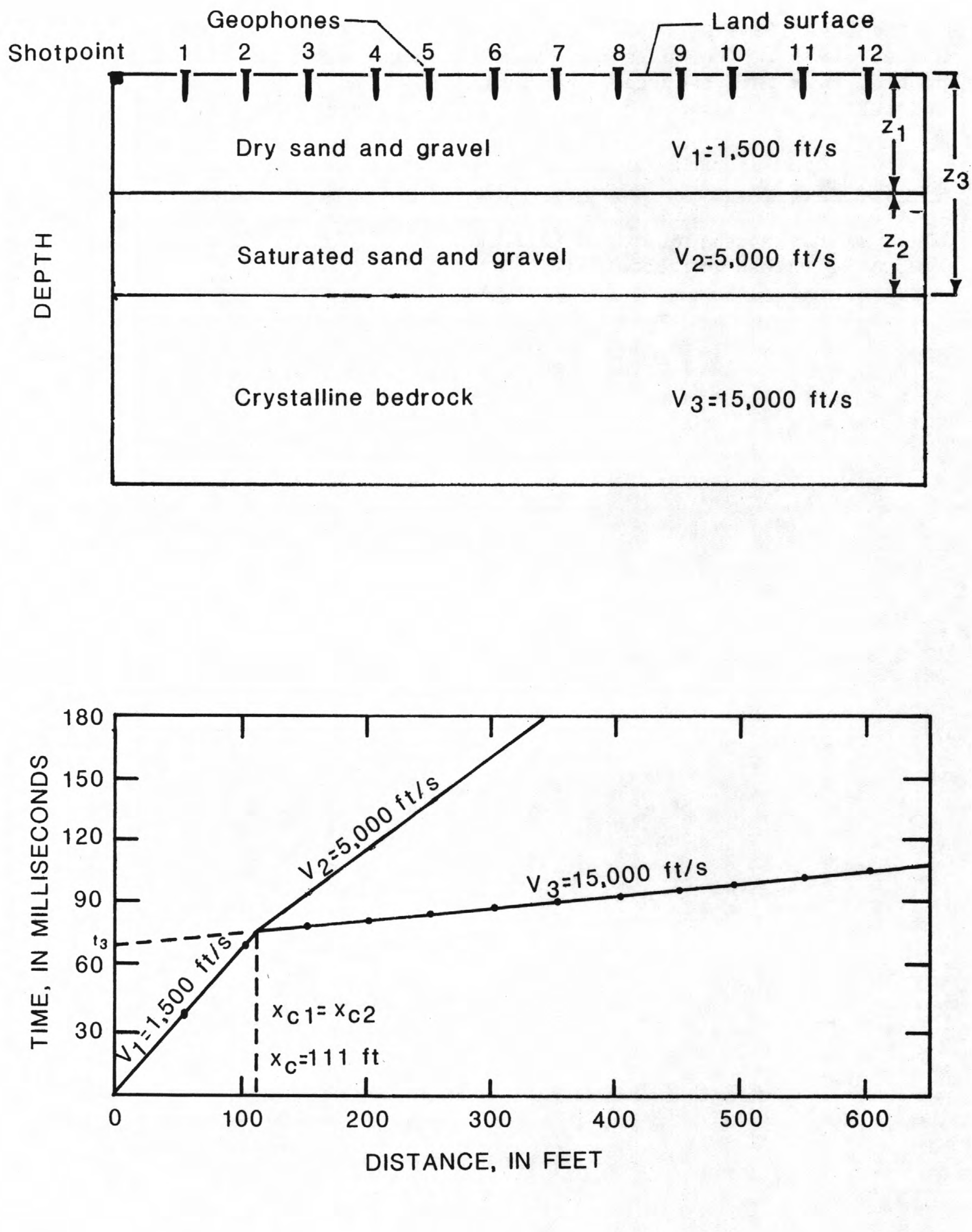


Figure 11.--Seismic section with hidden layer (layer 2), and resulting time-distance plot.

A. Assuming that layer 2 does not exist, we would interpret the time-distance plot as a two-layer subsurface, (eq. 2).

$$\max z_1 = \frac{x_c}{2}\sqrt{\frac{V_2 - V_1}{V_2 + V_1}} = \frac{111}{2}\sqrt{\frac{15{,}000 - 1{,}500}{15{,}000 + 1{,}500}} = 50 \text{ ft}$$

The depth to rock using the two-layer interpretation is therefore 50 ft; tha is, there is no saturated material present in the geologic section. If the presence of a hidden layer of saturated material is suspected, the following calculations can be carried out.

B. The minimum depth to layer 2 (the water table) and the maximum possible thickness of undetectable saturated material will be calculated when layer 2 is not detectable on the time-distance plot and $x_{c1} = x_{c2}$. (See figs. 9 and 11.)

To solve this problem, we assume a three-layer subsurface and proceed with normal three-layer interpretation using either the time intercept formulas (eqs. 3-5) or the crossover-distance formulas (eqs. 6-8). A method described by Mooney (1981) using crossover-distance formulas is used in the following calculations.

1. For the depth to layer 2 or the water table:

$$\min z_1 = \frac{x_{c1}}{2}\sqrt{\frac{V_2 - V_1}{V_2 + V_1}} = \frac{111}{2}\sqrt{\frac{5{,}000 - 1{,}500}{5{,}000 + 1{,}500}} = 41 \text{ ft}$$

That is, the depth to the water table in the three-layer subsurface is 41 f

2. For the depth to layer 3 or the bedrock surface:

$$\max z_3 = P(z_1) + \frac{x_{c2}}{2}\sqrt{\frac{V_3 - V_2}{V_3 + V_2}}$$

where:

$$P = 1 - \left(\frac{\frac{V_2}{V_1}\sqrt{\left|\frac{V_3}{V_1}\right|^2 - 1} - \frac{V_3}{V_1}\sqrt{\left|\frac{V_2}{V_1}\right|^2 - 1}}{\sqrt{\frac{V_3}{V_1}^2 - \frac{V_2}{V_1}^2}} \right)$$

$P = .86$

$$\max z_3 = .86(40.7) + 111 \, \frac{1}{2}\sqrt{\frac{15{,}000 - 5{,}000}{15{,}000 + 5{,}000}} = 74 \text{ ft}$$

The maximum depth to the bedrock surface is 74 ft.

3. For the thickness of layer 2 or the saturated thickness of the unconsolidated material: max $z_2 = z_3 - z_1 = 74 - 41 = 33$ ft

The maximum thickness of layer 2 in the three-layer subsurface is 33 ft.

In summary, a maximum of 33 ft of saturated sand and gravel under 41 ft of unsaturated sand and gravel can not be detected with the seismic-refraction method in the above example. The depth to rock is between 50 and 74 ft depending upon the thickness of the saturated zone. The saturated thickness of the sand and gravel is between 0 and 33 ft. The minimum depth to the water table is 41 ft.

Insufficient Seismic-Velocity Contrasts Between Hydrologic Units

In many studies, significant hydrologic units may not have detectable seismic-velocity contrasts. Many rock surfaces are not fresh and have different degrees of weathering. As the rock surface weathers, the seismic velocity decreases and is no longer indicative of the unweathered bedrock. In these cases, the seismic-refraction technique may not differentiate the weathered surface from the overlying low-velocity material.

Some significant hydrologic boundaries may have no field-measurable velocity contrast across them, and consequently cannot be differentiated with this technique. For example, saturated unconsolidated gravel deposits may have approximately the same seismic velocity as saturated, unconsolidated silt and clay deposits (Burwell, 1940).

Low Seismic-Velocity Units Underlying High Seismic-Velocity Units

In some hydrologic settings, the velocity of sound in each of the Earth's layers does not increase with depth, and low seismic-velocity units underlie high seismic-velocity units. Examples of this are: (1) an unconsolidated sand and gravel aquifer underlying compact glacial tills; (2) semi-consolidated rubble zones beneath dense basalt flows; (3) and dense limestone overlying a poorly cemented sandstone.

In all of these cases, the low-velocity unit will not be detected by the seismic-refraction technique, and the calculated depth to the deep refractor will be in error. The reason for this problem is found in Snell's Law, which says that a sound wave will be refracted toward the low-velocity medium. When a low-velocity layer underlies a high-velocity layer, the seismic raypaths are refracted downward or away from the land surface. The sound wave, therefore, would not be detected at the surface until it encountered a layer with a velocity of sound higher than that of any layer previously encountered (fig. 12).

If a low seismic-velocity unit is known to exist beneath a high seismic-velocity unit from drill-hole or geologic data, and its depth and seismic velocities are approximately known, the depth to a deeper refractor can be estimated (Mooney, 1981; Morgan, 1967). Without this information, the depths calculated from the seismic-refraction data will be greater than the actual depth.

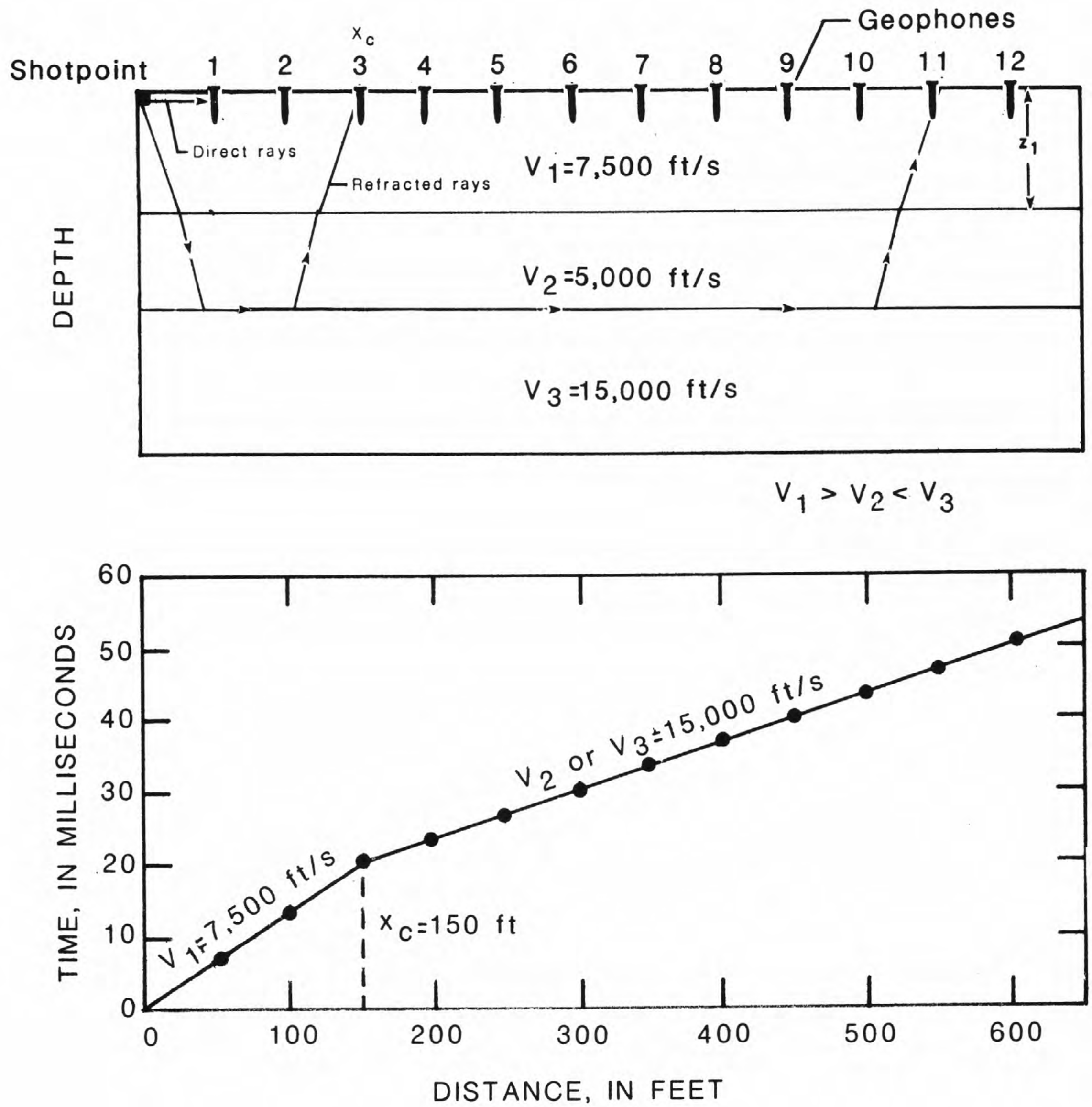


Figure 12.--Seismic section with velocity reversal and resulting time-distance plot.

Example Problem:

A. From the field data plotted in the time-distance plot in figure 12, the existence of layer 2 would not be known and an erroneous depth to layer 3 would be calculated if one used the two-layer parallel-boundary formulas (eqs. 3-5).

V_1 = 7,500 ft/s from the time-distance plot,

V_2 = 15000 ft/s from the time-distance plot,

z_2'= erroneous depth to layer 3.

$$z_2' = \frac{x_c}{2}\sqrt{\frac{V_2-V_1}{V_2+V_1}} = \frac{150}{2}\sqrt{\frac{15{,}000-7{,}500}{15{,}000+7{,}500}} = 43 \text{ ft}$$

The depth to rock using the two-layer interpretation is, therefore, 43 ft. If the thickness and the velocity of sound in layer 2 are known or can be estimated from drill hole or other data, a more accurate depth can be calculated.

B. From a nearby drill hole and a previous seismic-refraction investigation in a nearby area, it is determined that layer 1 is glacial till, approximately 20 ft thick, with a seismic velocity of approximately 7,500 ft/s. It is underlain by saturated sand and gravel having a velocity of about 5,000 ft/s. Now, a more realistic value for the depth to layer 3 (z_2) can be calculated using the following method described by Mooney (1981, p. 9-17).

V_2 = 5,000 ft/s from previous investigation,

V_3 = 15,000 ft/s from time-distance plot,

z_1 = 20 ft from nearby drill hole,

z_2 = true depth to layer 3.

$$z_2 = (Q + 1)\frac{x_c}{2}\sqrt{\frac{V_3 - V_1}{V_3 + V_1}} - z_1 Q \qquad (21)$$

where

$$Q = \sqrt{\frac{\left(\frac{V_3}{V_1}\right)^2 - 1}{\left(\frac{V_3}{V_2}\right)^2 - 1}} - 1 \qquad (22)$$

now substituting

$$Q = \sqrt{\frac{\left(\frac{15,000}{7,500}\right)^2 - 1}{\left(\frac{15,000}{5,000}\right)^2 - 1}} - 1 = -0.39$$

and

$$z_2 = (-0.39+1)\frac{150}{2}\sqrt{\frac{15,000 - 7,500}{15,000 + 7,500}} - 20\,(-0.39) = 34 \text{ ft}$$

In summary, without any external data, a two-layer model with rock at 43 ft was interpreted from the seismic data. Using data from a nearby test hole and the results from a previous seismic-refraction study, a three-layer subsurface with rock at 34 ft was interpreted from the same field data.

One special example of a hidden-layer problem is encountered when seismic-refraction surveys are conducted in areas where the surface of the ground is frozen. The velocity of sound in frozen ground is about 12,000 ft/s (Bush and Schwarz, 1965), and the frozen zone can act as a high-velocity surficial layer. Any layers under the frozen ground cannot be detected unless the velocity of sound in them is greater than 12,000 ft/s. The hydrologist must be careful interpreting data under these field conditions. Figure 13 shows the time-distance plot that would be obtained in a stratified-drift valley with frozen ground at the surface.

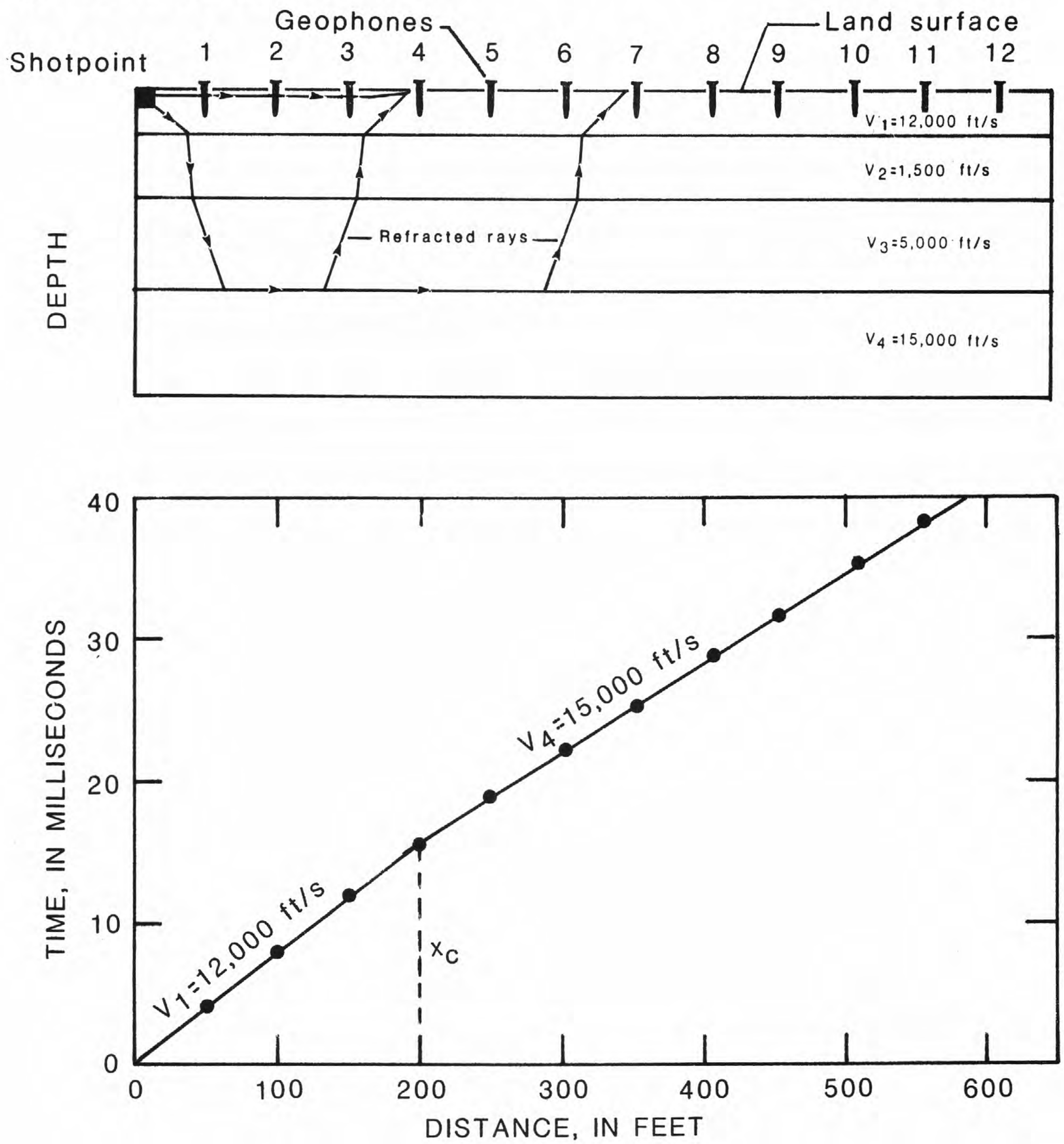


Figure 13.--Interpreted seismic section and time-distance plot for a four-layer model having frozen ground at the surface.

One way to eliminate this problem is to bury both the sound source and the geophones beneath the frozen layer. This usually involves considerable effort and is not economical in most hydrologic programs.

Other Limitations of the Seimic-Refraction Technique

The following limitations are mentioned not to discourage the use of seismic-refraction techniques, but rather to make hydrologists aware of potential pitfalls. These situations, recognized early in the study, can be accounted for in the planning, data-acquisition, and interpretation phases of the study.

Ambient noise

Ambient noise is caused by vehicular traffic, construction equipment, railroads, wind, and so forth, and has a detrimental effect on the quality of seismic-refraction data. Some solutions to this problem are: (1) to decrease the amplifier gains and increase the input signal by using more explo sives or repeated hammer blows; (2) to reschedule operations for a quiet part the day, and, (3) to use selective filters on the seismograph to eliminate unwanted frequencies.

Horizontal variations in the velocity of sound and the thickness of the weathered zone

Horizontal discontinuities in the low-velocity zone near the surface have significant effect on seismic-refraction studies. Usually, this zone is the unsaturated zone and typically has velocities of 400 to 1,600 ft/s. Short spreads are needed to determine the velocity of sound and the thickness of thi layer. A variation of 1 ft in the thickness of a weathered layer consisting of 1,000 ft/s material causes the refracted sound ray to be delayed or sped up by 1 millisecond. This same time interval represents 10 ft of 10,000 ft/s material.

Accuracy of seismic-refraction measurements

The accuracy with which the depth to a refractor can be determined with th seismic-refraction method is dependent upon many factors, some of which are listed below.

1) Type and accuracy of seismic equipment.
2) Number and type of corrections made to field data.
3) Quality of field procedures.
4) Type of interpretation method used.
5) Variation of the earth from simplifying assumptions used in the interpretation procedure.
6) Ability and experience of the interpreter.

Published references (Griffiths and King, 1965; Eaton and Watkins, 1967; Wallace, 1970; Zohdy and others, 1974) and the author's unpublished data indicate that the depth to a refractor can reasonably be determined to within 10 percent of the true depth. Larger errors usually are due to improper interpretation or difficult field situations.

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Parasnis, D. S., 1979, Principles of applied geophysics, 3d ed.: London, England, Chapman and Hall, (distributed in the United States by J. Wiley & Sons, New York), 275 p.

[A very brief descripton of the major surface geophysical methods.]

Redpath, B. B., 1973, Seismic refraction exploration for engineering site investigations, National Technical Information Service AD-768710, 51 p.

[A summary of the theory and practice of using the refraction seismograph for shallow, subsurface investigations.]

Sander, J. E., 1978, The blind zone in seismic ground-water exploration: Ground Water, v. 16, no. 6, p. 394-397.

[Refraction techniques were used to map areas of thick, compacted till beneath an unconfined glacial aquifer in northern Minnesota. Where this unit is thin, a blind-zone layer exists. Treatment of this case is discussed.]

Scott, J. H., Tibbets, B. L., and Burdick, R. G., 1972, Computer analysis of seismic-refraction data: U.S. Bureau of Mines, R.I., 7595, 95 p.

[Presents a computer program which uses seismic refraction data to generate a two-dimensional model representing a layered-geologic section.]

Sheriff, R. E., 1973, Encyclopedic dictionary of exploration geophysics: Tulsa, Society of Exploration Geophysicists, 266 p.

[Exhaustive glossary of exploration geophysics and its related disciplines.]

Slotnick M. M., 1959, Lessons in seismic computing: Tulsa, Society of Exploration Geophysicists, 268 p.

[An in-depth theoretical discussion of the geometrical aspects of refraction prospecting.]

Soske, J. L., 1959, The blind-zone problem in engineering geophysics: Geophysics, v. 24, no. 2, p. 359-365.

[Wave-front diagrams illustrate the cause, results, and solutions for the blind-zone problem in shallow refraction studies.]

Telford, W. M., Geldart, L. P., Sherriff, R. E., and Keys, D. A., 1976, Applied geophysics: New York, Cambridge University Press, 806 p.

[A basic reference text that covers the theoretical and practical aspects of the major geophysical methods. The emphasis is on deep exploration.]

Wallace, D. E., 1970, Some limitations of seismic refraction methods in geohydrological surveys of deep alluvial basins: Ground Water, v. 8, no. 6, p. 8-13.

[A case history illustrating some limitations of seismic-refraction techniques in deep alluvial basins.]

Zirbel, N. N., 1954, Comparison of break-point and time-intercept methods in refraction calculation: Geophysics, v. 19, no. 4, p. 716-721.

[Shows that break-point (cross-over distance) formulas in some instances are more accurate than intercept-time formulas for determining the depth to a refractor.]

Zohdy, A. A. R., Eaton, G. P., and Maby, D. R., 1974, Applications of surface geophysics to ground water investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 2, Chap. D1, 116 p.

[An overview of surface geophysical techniques and their applications to hydrologic studies.]

Seismic-refraction techniques have been used for a variety of studies conducted in many different hydrogeologic settings. This section describes the results of some recent studies involving typical hydrogeologic problems that demonstrate where the technique (1) can be used successfully, (2) may work but with some difficulty either in the field procedures or in the interpretation process, and (3) cannot be used. In addition to the discussion of individual case histories, references to other studies that have applied seismic-refraction techniques to similar hydrogeologic problems are also provided. This section is intended as an initial guide for the hydrologist considering the use of this geophysical technique. Specific applications of the technique should be tested in the field, in areas where adequate geologic and hydrologic controls are available.

Hydrogeologic Problems Where Seismic-Refraction Techniques Can Be Used Successfully

Hydrogeologic settings in which each successively deeper layer has a higher seismic velocity, no thin layers are present, and a significant seismic-velocity change occurs at each hydrogeologic interface are ideally suited for the application of seismic-refraction techniques. Five case histories are presented below that illustrate the successful application of seismic-refraction techniques in hydrogeologic settings that satisfy these conditions.

Unconsolidated Unsaturated Glacial or Alluvial Material Overlying Glacial or Alluvial Aquifers

Determining the depth to a shallow water table within this type of deposit is a common hydrologic problem. Because the velocity of sound in unsaturated, unconsolidated sands and gravel ranges from 400 to 1,600 ft/s, and the velocity of sound in saturated, unconsolidated sands and gravels ranges from 4,000 to 6,000 ft/s, seismic-refraction methods will generally be successful in determining the depth to water. The seismic-velocity contrast between the unsaturated and saturated material, however, will decrease as the grain size of the aquifer decreases and the depth to water increases (White and Sengbush, 1953).

In order to determine the depth to a shallow water table, short geophone spreads must be used so that the velocity of sound in the unsaturated zone is accurately determined. Lateral changes in the seismic velocity of this layer are common and must be measured in the field and accounted for in the interpretation process. However, because the seismic velocity of the unsaturated zone exhibits a gradual increase with depth (Emerson, 1968), it can only be approximated as a constant velocity layer.

Galfi and Palos (1970) demonstrated that in sandy areas, seismic-refraction techniques can accurately determine the depth to water. Their study used a single-channel seismograph, a sledge hammer for the sound source, and a 3.3 ft geophone spacing. The results of one seismic profile and the well control data are shown in figure 14. The seismically-determined depth to the water table of 13.3 ft agreed with the well data of 13.1 ft. The use of the hammer as

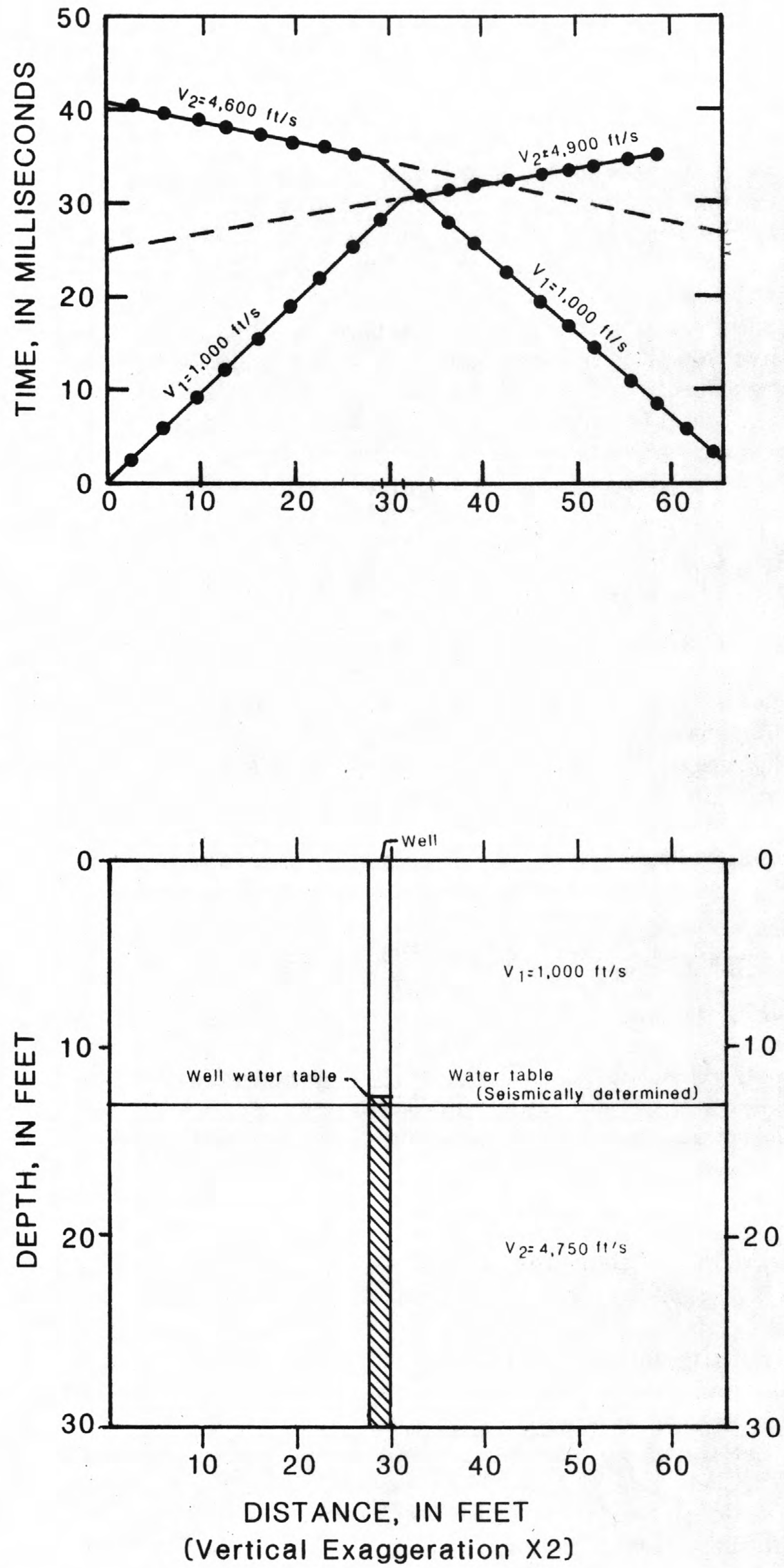


Figure 14.--Time-distance plot and interpreted seismic section from a ground-water study in Vertessomto, Hungary (modified from Galfi and Palos, 1970, p. 45).

a sound source provided sufficient first arrival energy only to a distance of 75 ft from the source, and consequently limited the penetration depth to about 25 ft. To determine deeper depths to water, other more powerful sound sources would be needed. In this study, the unsaturated zone was interpreted using a continuous velocity distribution formula (Dobrin, 1976).

Many seismic-refraction studies have been conducted in Connecticut as part of water-resources investigations. A comparison of the seismically-determined depths to water and the subsequent drill-hole data for four studies is presented in table 2. In these studies, the velocity of the unsaturated zone was considered constant, and the depth to water was calculated by a delay time and ray tracing modeling process described by Scott and others (1972).

Other studies that have used seismic-refraction techniques for determining the depth to water in unconsolidated aquifers include: Burwell (1940); Emerson (1968); Sjogren and Wagner (1969) and Followill (1971).

Table 2.--Comparison of the depth to water determined by seismic-refraction methods and drilling.

Location in Connecticut	Depth to water determined by seismic-refraction methods (feet)	Depth to water determined by drilling (feet)
Plainville	25	26
Newtown	12	9
	5	3
	10	12
	12	7
	25	27
	35	45
	10	5
	9	6
Farmington	10	11
	55	56
	5	3
Stonington	16	12
	6	5
	8	7

Unconsolidated Glacial or Alluvial Material Overlying Consolidated Bedrock

The determination of the saturated thickness of the aquifer material and/or the shape of the bedrock surface in this setting is a common hydrologic problem. The velocity of sound in both the unsaturated and saturated material is the same as in the previous problem (400-1,600 ft/s and 4,000-6,000 ft/s, respectively). The velocity of sound in the consolidated bedrock should be between 10,000 and 20,000 ft/s. The velocity constraints of the refraction technique are met as the velocity of sound in each layer increases with depth. The seismic-refraction technique can define the top of the water table and the top of the bedrock, provided the saturated zone does not get too thin (see section on thin intermediate seismic-velocity layer problems).

In order to map both a shallow refractor like the water table, and a deep refractor like the bedrock surface, careful consideration must be given to the choice of shot points, geophone spacing, and interpretation method used. Multiple shots, variable geophone spacings, and/or test-hole data will be needed, depending upon the geometry of the problem.

A reconnaissance seismic-refraction survey was conducted by the U.S. Geological Survey near the Great Swamp National Wildlife Refuge, Morristown, New Jersey (fig. 15). In order to determine the depth to bedrock several profiles with two or three geophone spreads were run along roads and paths in the area. A typical time-distance plot and the interpreted seismic section are shown in figure 16.

Because the primary purpose of this study was of a reconnaissance nature, and the water table was known to be close to the surface, only one shot point on each end of each geophone spread was used. Each shot was placed in the saturated layer so that small explosive charges could be used and the depth to water measured directly. The measured depths to water were used in the intrepretation procedure to estimate or "back out" the velocity of the thin unsaturated zone. The multiple geophone spreads were overlapped in order to obtain a continuous bedrock profile. The depth to water in the study area averaged about 5 ft and the depth to rock ranged from 75 to 200 ft.

Other studies in similar hydrogeologic settings that have successfully used this technique include: Gill and others (1965); Lennox and Carlson (1967); Duguid (1968); Joiner and others (1968); Peterson and others, (1968); Mercer and Lappala (1970); and Wachs and others (1979).

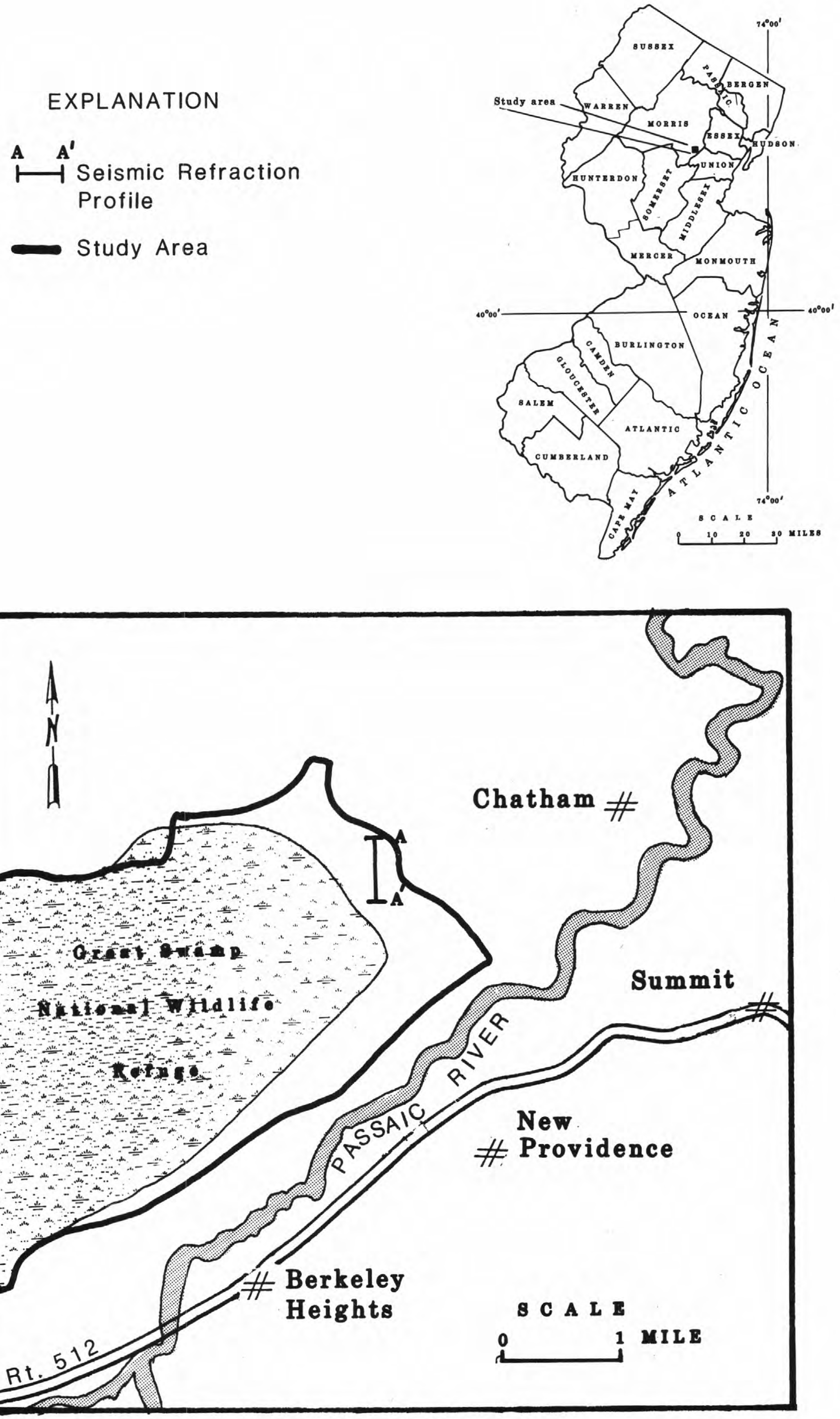


Figure 15.--Generalized location map of Great Swamp National Wildlife Refuge, New Jersey and location of seismic-refraction profile A-A'.

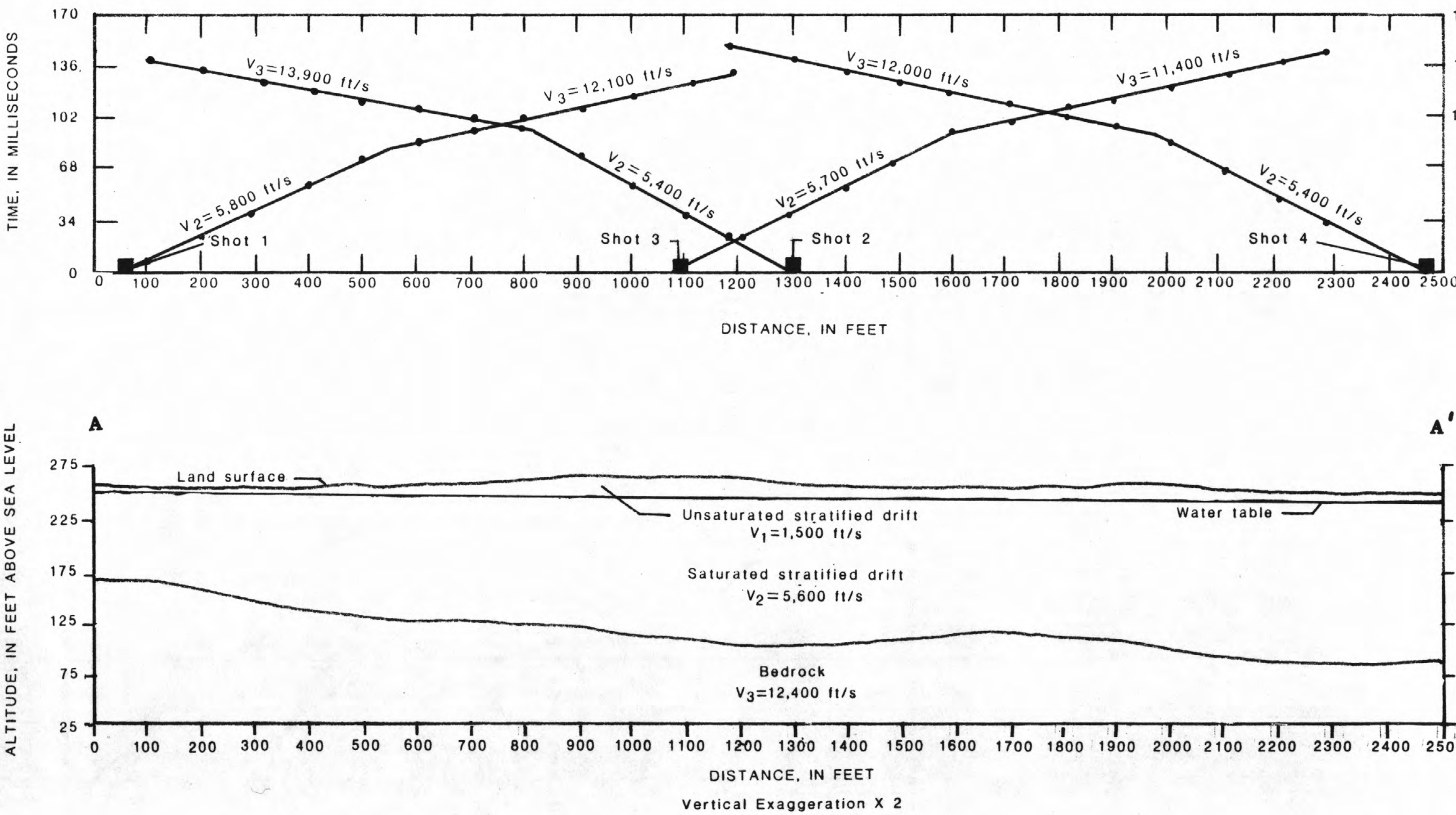


Figure 16.--Time-distance plot and interpreted seismic section near Great Swamp National Wildlife Refuge, Morristown, New Jersey.

Thick Unconsolidated Alluvial or Sedimentary Units Overlying Consolidated Sediments and/or Basement Rock in Large Structural Basins

This problem is similar to the preceding one, except that the geologic section can be more complex and the unsaturated and saturated section is much thicker. As long as the successively deeper units have a higher seismic velocity and are not thin, the seismic-refraction technique will work. As the water-table depth increases, however, the unsaturated-layer seismic-velocity increases, and this may prevent the identification of the saturated zone as a separate refracting layer.

The U.S. Geological Survey conducted a seismic-refraction study near Tucson, Arizona (H. D. Ackermann, U.S. Geological Survey, written communication 1980) in order to determine the saturated thickness of the aquifer near the outlet of ground-water flow from the Avra-Altar basin (fig. 17). Figure 18 shows the results of the interpreted seismic data. The small seismic-velocity contrast between the unsaturated and saturated alluvium made the detection of the water table very difficult. It was finally delineated with the use of available well data in conjunction with a comprehensive seismic-refraction modeling program (Ackermann and others, 1983). The 4 mi profile shown in figure 18 was obtained using two spreads of 24 geophones with each geophone spaced 400 ft apart, and one spread of 24 geophones with each geophone spaced 200 ft apart. Five to seven shots, each consisting of 15 to 80 lbs of explosives buried 30 ft below the surface were used as a sound source.

Other hydrogeologic studies of deep alluvial basins that have used seismic-refraction techniques are described by: Dudley and McGinnis (1962); Arnow and Mattick (1968); Mower (1968); Libby and others (1970); Wallace (1970); Marshall (1971); Robinson and Costain (1971); Mattick and others (1973); Crosby (1976); and Pankratz and others (1978).

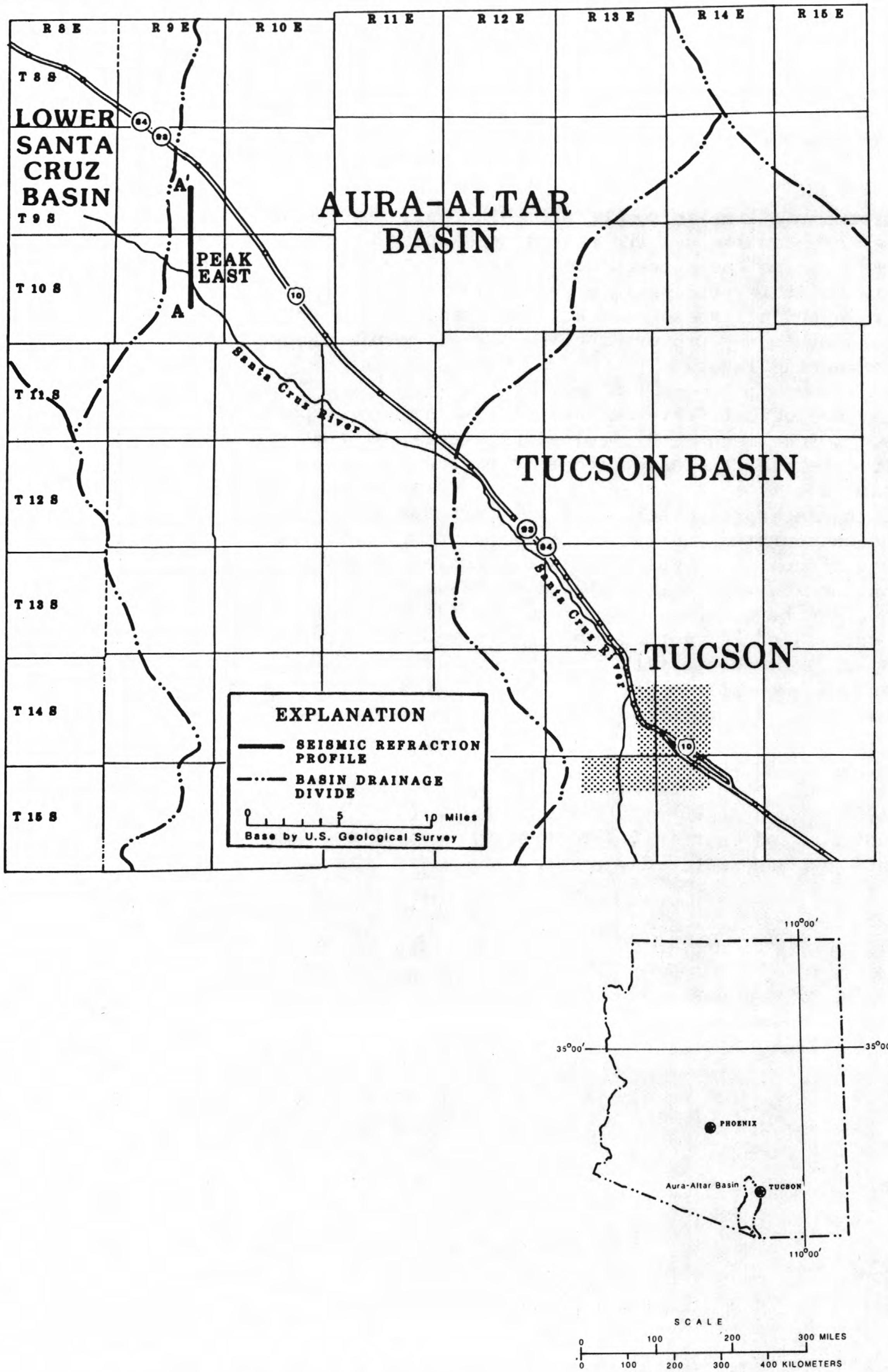


Figure 17.--Generalized location map of Aura-Altar basin, Arizona, and location of seismic-refraction profile A-A°.

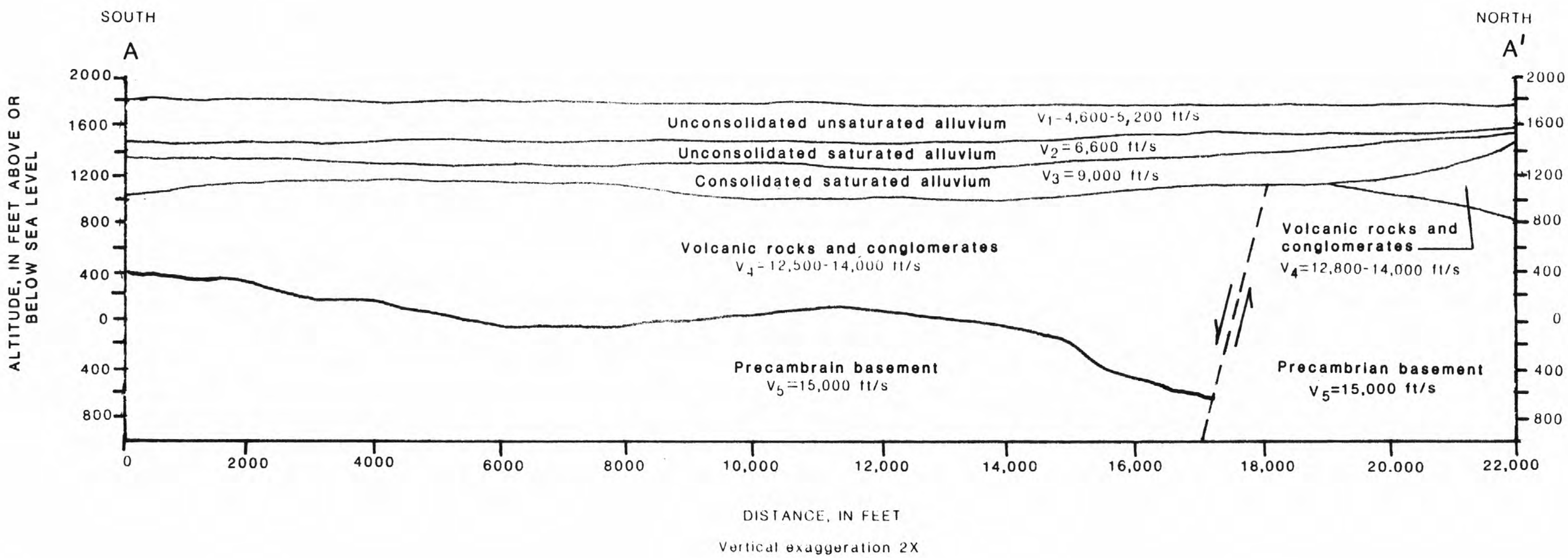


Figure 18.--Interpreted seismic section A-A' in Aura-Altar basin, near Tucson, Arizona.

Unconsolidated Alluvial Material Overlying Sedimentary Rock, Which Overlies Volcanic or Crystalline Bedrock

In this problem, mapping the saturated thickness of the unconsolidated sand aquifer and the thickness of the sedimentary rock aquifer is a common exploration goal. This problem can be solved using the seismic-refraction technique when the velocity of sound in the sedimentary rock aquifer is greater than that in the saturated alluvium and less than that in the underlying volcanic or crystalline rock. Again, the intermediate layer (in this case the sedimentary rock) must not be too thin (see Limitations section). Figure 19 shows the location of a study conducted in the Guanajibo area, Puerto Rico (Colon-Dieppa and Quinones-Marquez, 1985). Figure 20 shows a typical time-distance plot and the interpreted seismic section from one seismic profile. In this study, the alluvial aquifer was underlain by a thick limestone aquifer which in turn is underlain by volcanic basement rock.

In order to map both the shallow and deep refractors, multiple shot points were used for each geophone spread. One shot point was placed on each end of the geophone line while others were offset 1,000 ft from each end. The geophone spread consisted of 12 geophones, spaced 100 ft apart. The seismic velocity of the unsaturated layer was not measured in the field because the water table depth was shallow and could be measured directly in each shot hole. The seismic velocity of this layer was eventually determined in the interpretation program described by Scott and others (1972) by adjusting the seismic velocity of layer 1 until the known depth to water was matched.

Other studies in similar hydrologic settings are described by Visarion and others (1976), and Torres-Gonzalez (1984).

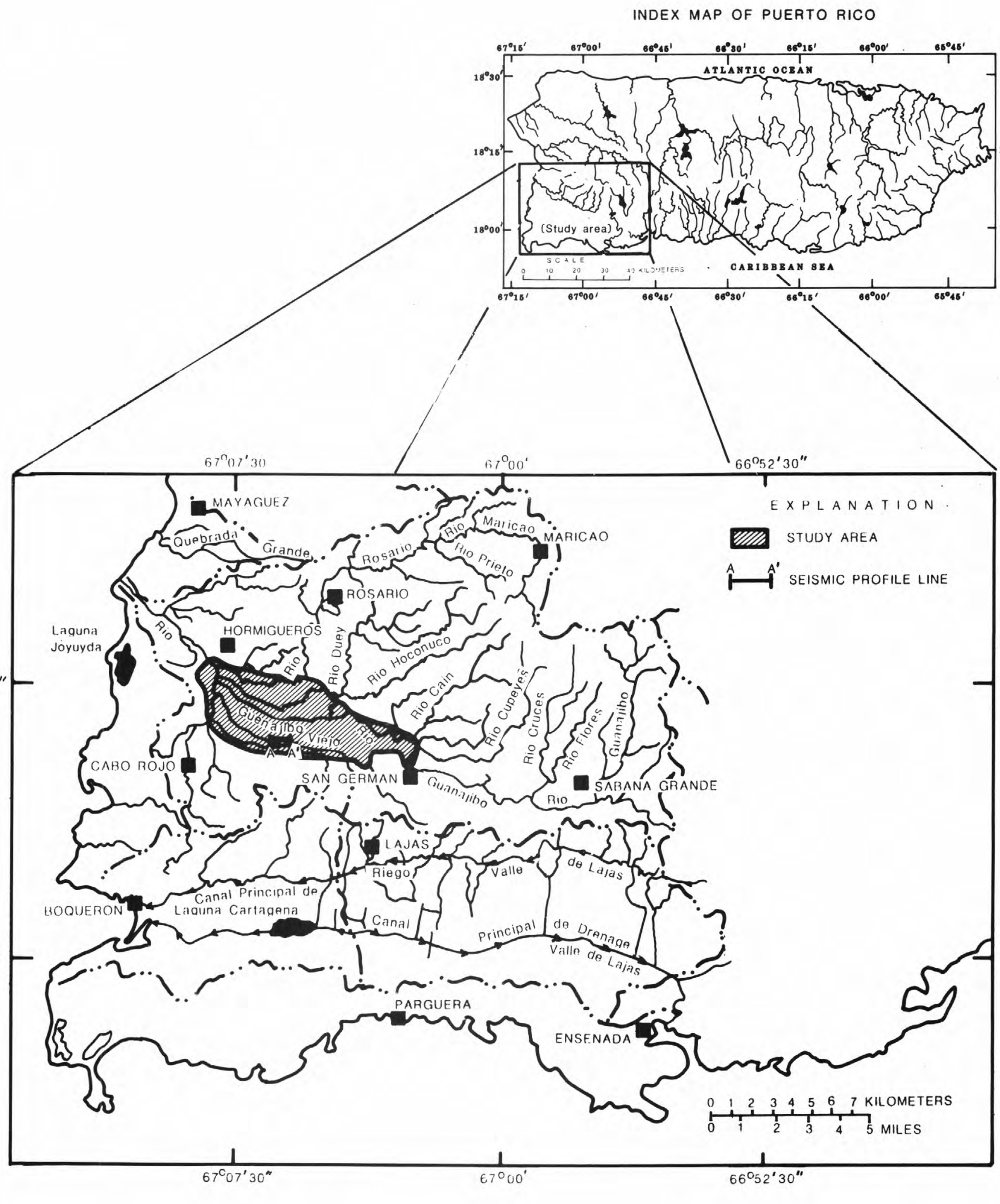
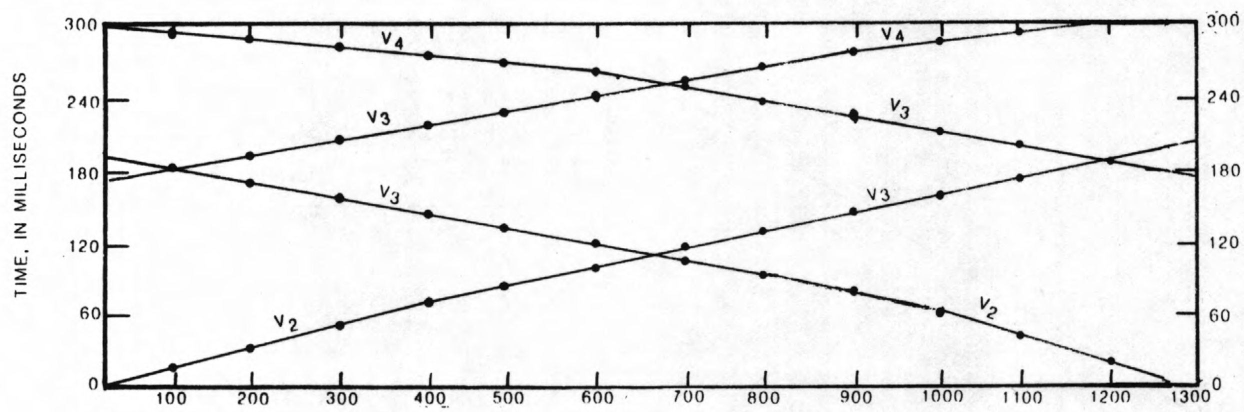


Figure 19.--Generalized location map of Central Guanajibo Valley, Puerto Rico, and location of seismic-refraction profile A-A'.



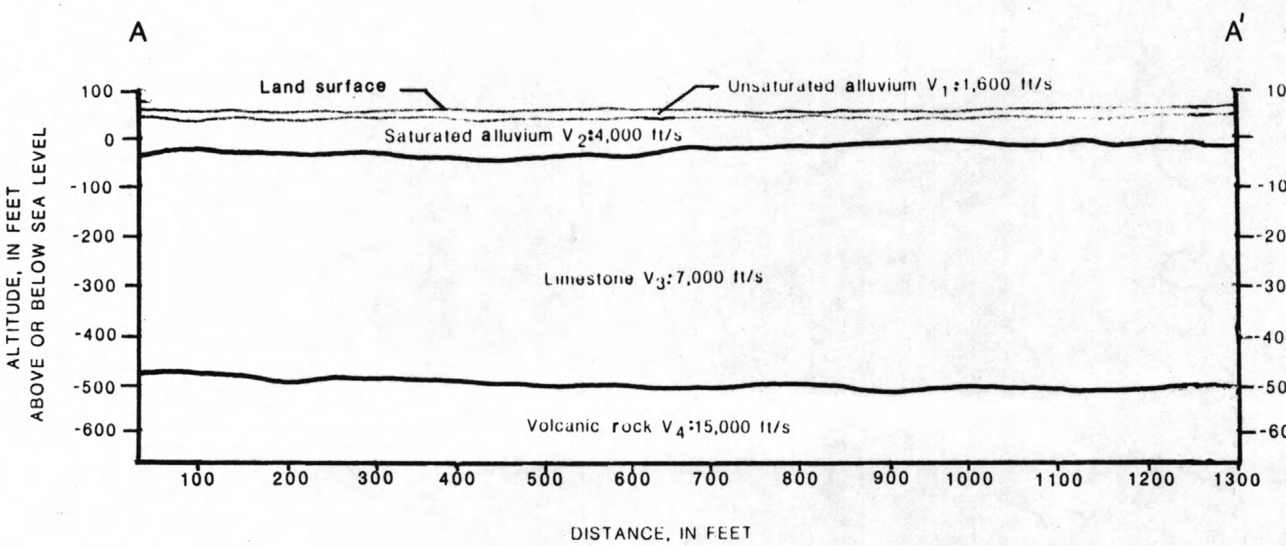


Figure 20.--Time-distance plot and interpreted seismic section at Guanajibo Valley, Puerto Rico.

Unconsolidated Stratified-Drift Material Overlying Significant Deposits of Dense Lodgement Glacial Till, Which Overlies Crystalline Bedrock

The purpose of a refraction study in this geologic setting would be to determine the thickness of the saturated stratified-drift aquifer and the thickness of the till. The velocity constraints of the refraction technique are again satisfied. The estimated seismic velocities are: 1,000 ft/s for the dry stratified drift; 5,000 ft/s for the saturated stratified drift; 7,500 ft/s for the lodgement till; and 15,000 ft/s for the bedrock. The thickness of the till must be substantial in order to be detected by the seismic-refraction technique. Figure 21 shows the location of a seismic line from a study conducted in Farmington, Connecticut (Mazzaferro, 1980). Figure 22 shows one of the time-distance plots and interpreted seismic sections from this study.

Note that the significant thickness of till present at this site (approximately 250 ft) is represented by a short segment on the time-distance plot. The till layer is almost an undetectable intermediate velocity layer.

The field setup for the profile shown in figure 22 was limited by the physiographic setting and proximity to urban development of the study area. Three shots and 12 geophones spaced 100 ft apart were used. The seismic velocity of the unsaturated material was not determined in the field since the depth to the water table could be measured directly in each shot hole. The seismic velocity of the unsaturated zone was subsequently determined using the interpretation program described by Scott and others (1972), and adjusting the seismic velocity of layer 1 until the known depth to water was obtained.

Other studies conducted in similar settings are described by Johnson (1954) and Sander (1978).

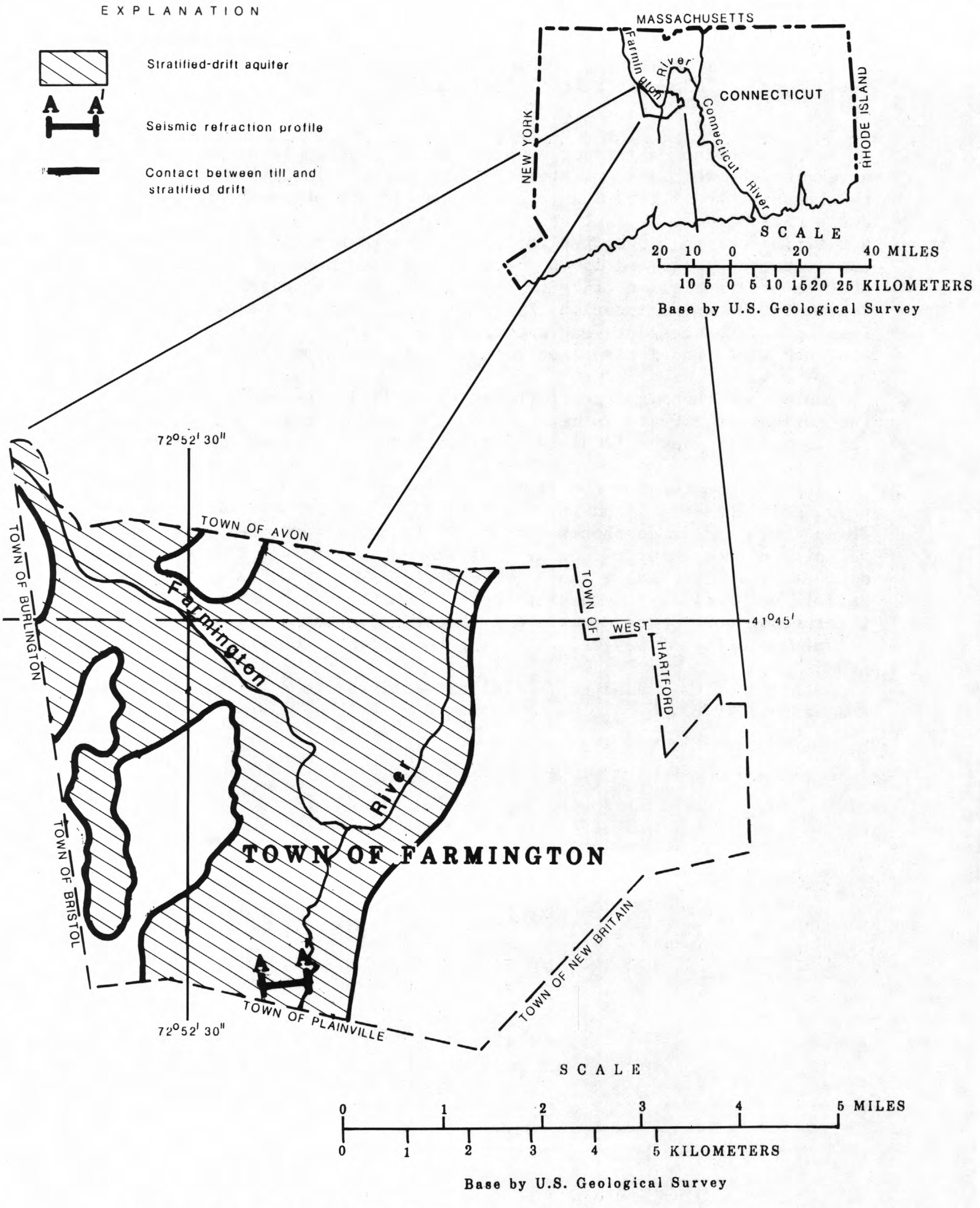


Figure 21.--Generalized location map of Farmington, Connecticut and location of seismic-refraction profile A-A'.

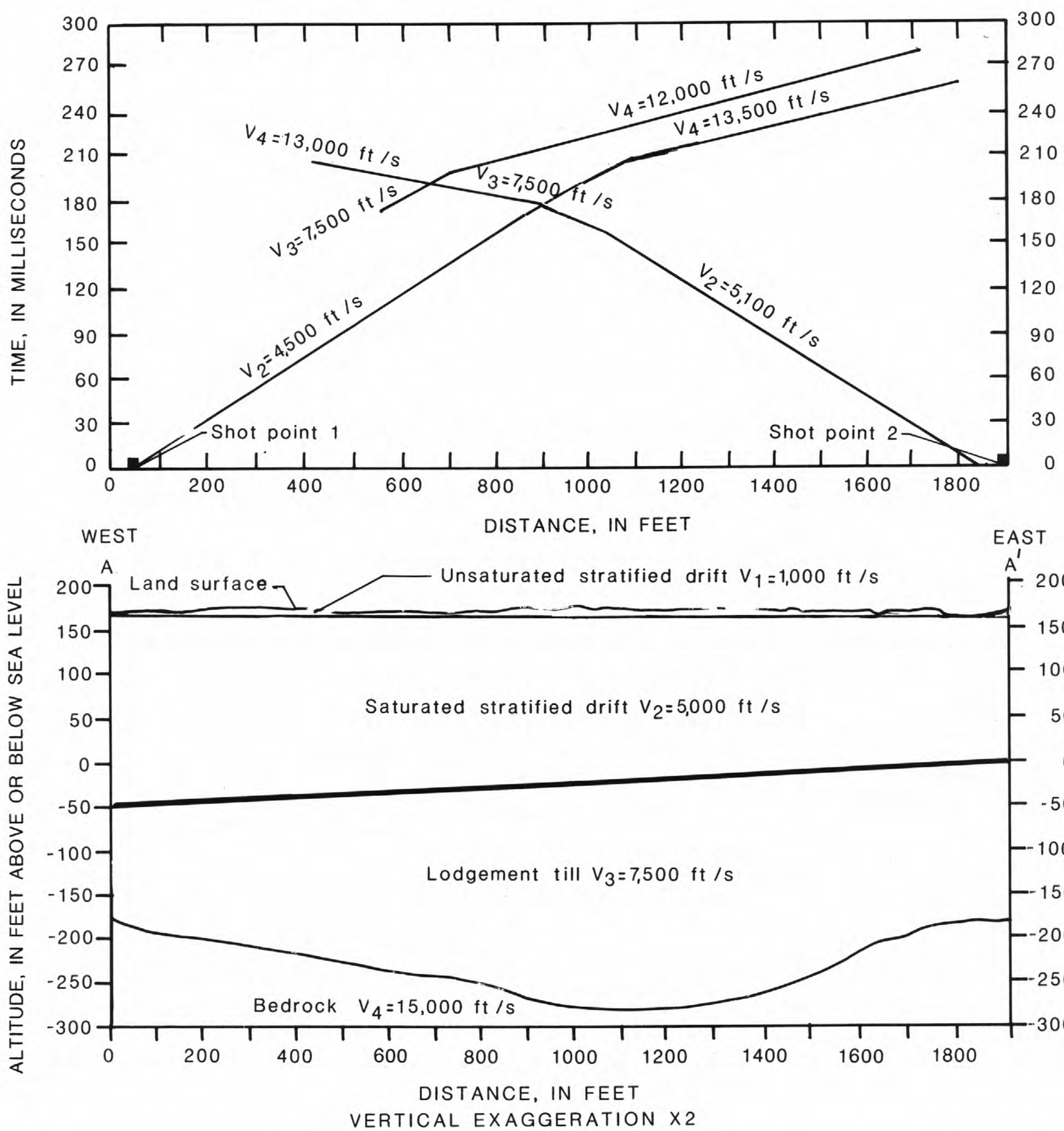


Figure 22.--Time-distance plot and interpreted seismic section near Farmington, Connecticut.

Hydrogeologic Problems Where Seismic-Refraction Techniques May Work But With Difficulty

The main limitations that may prevent the successful completion of a seismic-refraction survey are: (1) the lack of seismic-velocity contrasts between geologic units or hydrologic boundaries; (2) the presence of thin intermediate seismic-velocity layers; and (3) the presence of low seismic-velocity layers beneath high seismic-velocity layers.

All of the examples discussed in the previous section describe geologic materials with distinct seismic velocities. However, some geologic materials or hydrogeologic units display a wide range of seismic velocities. When one unit is at the upper end of its seismic-velocity range and the underlying unit is at the lower end, resulting in a small seismic-velocity contrast across the boundary, it will be difficult to interpret seismic-refraction data. Even if there is a large seismic-velocity contrast between two units, the intermediate unit will not be detected if it is thin, and the bedrock depth will be in error. Seven examples of where it may be difficult to use seismic-refraction techniques are presented below.

Unconsolidated Glacial Sand and Gravel Overlying a Thin Till Layer Overlying Crystalline Bedrock

Determining the aquifer's saturated thickness is a common hydrologic problem in glaciated areas. Because basal till layers are often thin, the top of the till cannot be determined even though it has an intermediate seismic velocity of 7,000 ft/s. The depth to the bedrock surface determined by seismic-refraction techniques under these conditions will be incorrect (Sander, 1978). The correct depth to bedrock, and thickness of the aquifer, can be determined if the thickness of the till can be estimated from drill hole or other data. Thin till layers, however, can often can be considered negligible for the purpose of many hydrologic studies.

In a modeling study of the ground-water availability of a glacial aquifer in Newtown, Connecticut (Haeni, 1978), seismic-refraction profiles (fig. 23) were used to determine the depth to bedrock and help determine the saturated thickness of the aquifer. Existing drill-hole data in this area indicated that the thickness of the saturated aquifer material ranged from 10 to 100 ft and was underlain by 5 to 10 ft of till. Because the till was thin, the seismic velocity of till is close to that of the saturated material, 7,500 ft/s versus 5,000 ft/s, and the accuracy of the seismic-refraction method is ± 10 percent, the seismically-determined depth to rock was considered to be the true depth to rock. The satuated thickness of the aquifer, determined from the refraction results, was arbitrarily decreased by 5 ft to account for the presence of the till.

Figure 24 shows a time-distance plot and the interpreted seismic section of one of the seismic-refraction profiles conducted for this study. In this profile, three overlapping geophone spreads with a geophone spacing of 50 ft, and a total of seven shot points, were used. Small explosive charges, weighing from 1/3 to 2 lbs and placed at the water table, were used as energy sources. The depth to water was recorded in each shot hole and the seismic velocity of the unsaturated zone was determined by the interpretation process described by Scott and others (1972), by adjusting the seismic velocity of layer 1 until the known depth to water was matched. Figure 23 shows a map of the saturated thickness of the aquifer as determined by the refraction survey and drill hole control.

Other hydrologic studies utilizing seismic-refraction techniques, and conducted in similar hydrogeologic settings, are described by: Warrick and Winslow (1960); Watkins and Spieker (1971); Birch (1976); Dickerman and Johnston (1977); Sharp and others (1977); Sander (1978); Frohlick (1979); Haeni and Anderson (1980); Mazzaferro (1980); Grady and Handman (1983); Morrissey (1983); Tolman and others (1983); Haeni and Melvin (1984); Mazzaferro (1984); Winter (1984), and Haeni (1986).

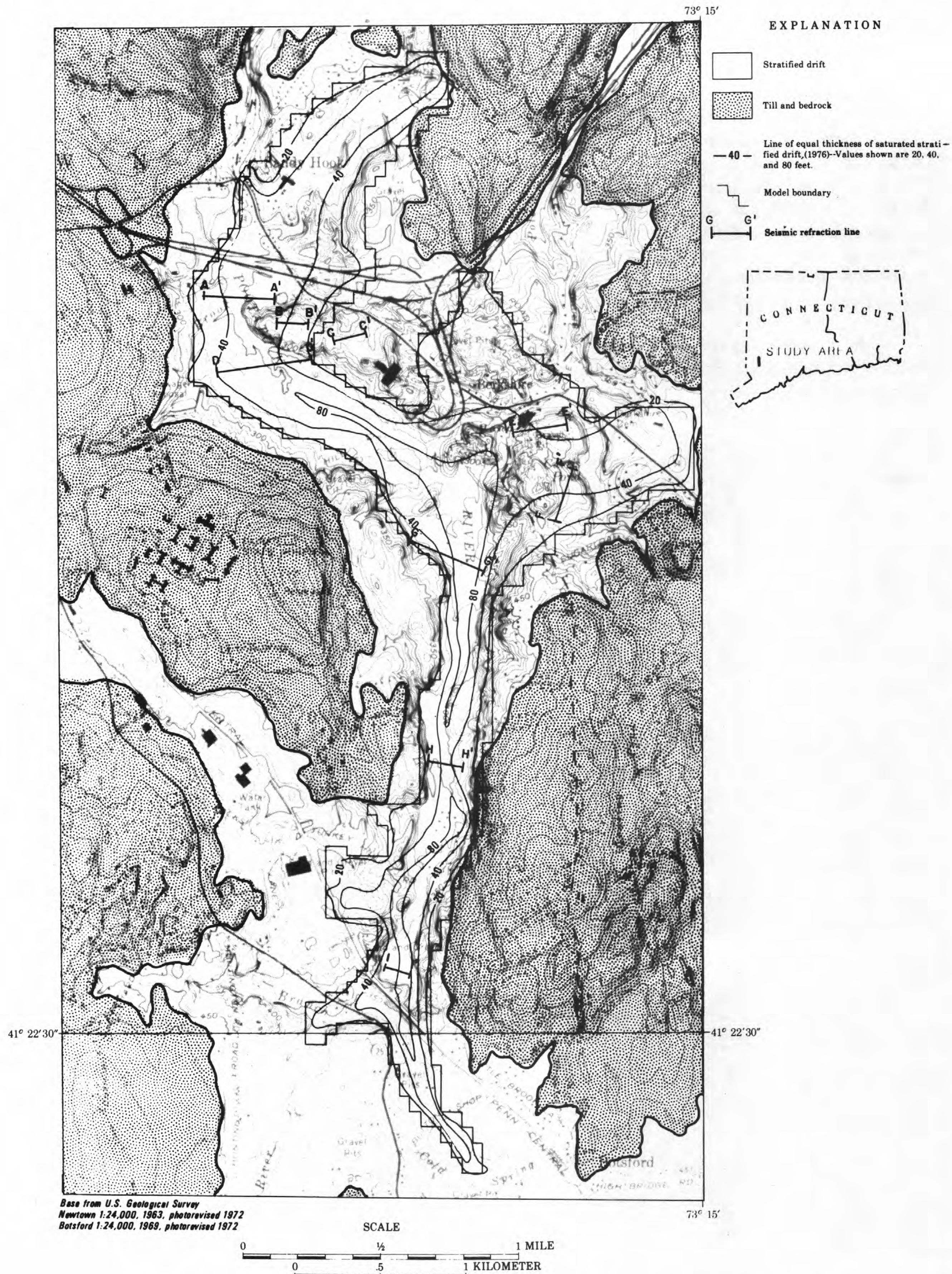


Figure 23.--Saturated thickness of stratified drift and location of seismic refraction lines in the Pootatuck River Valley, Newtown, Connecticut (from Haeni, 1978).

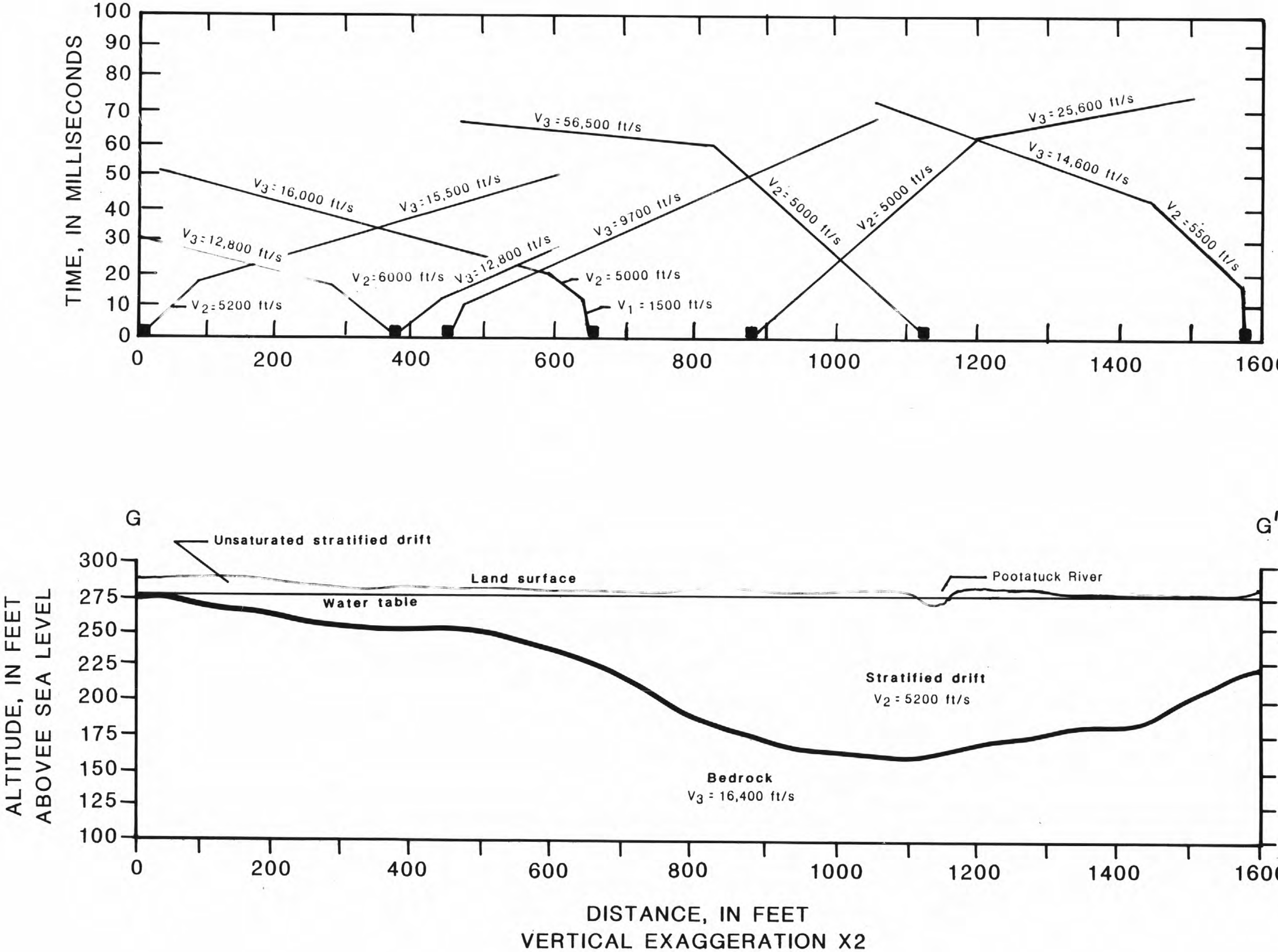


Figure 24.--Time-distance plot and interpreted seismic section of Pootatuck River Valley, Newtown, Connecticut.

An Aquifer Underlain by Bedrock With Similar Seismic Velocity

The hydrologic problem in this geologic setting is to determine the thickness of the upper aquifer. Because the seismic velocities of the two layers overlap, the seismic-refraction method may not yield useful information about the thickness of the upper aquifer. The success of a seismic-refraction survey in this setting will depend upon the actual velocity of sound in the units and the accuracy of seismograph and field data-collection activities. Figure 25 shows a hypothetical time-distance plot where the upper aquifer (for example, sandstone) has a seismic velocity of 10,000 ft/s, and the underlying bedrock (for example, limestone) has a seismic velocity of from 10,000 to 20,000 ft/s. As the seismic velocity of the deeper layer increases, it becomes easier to differentiate between the two layers. If the velocity of sound in the second layer approaches that of the first layer, it may not be possible to differentiate between the two using seismic-refraction techniques.

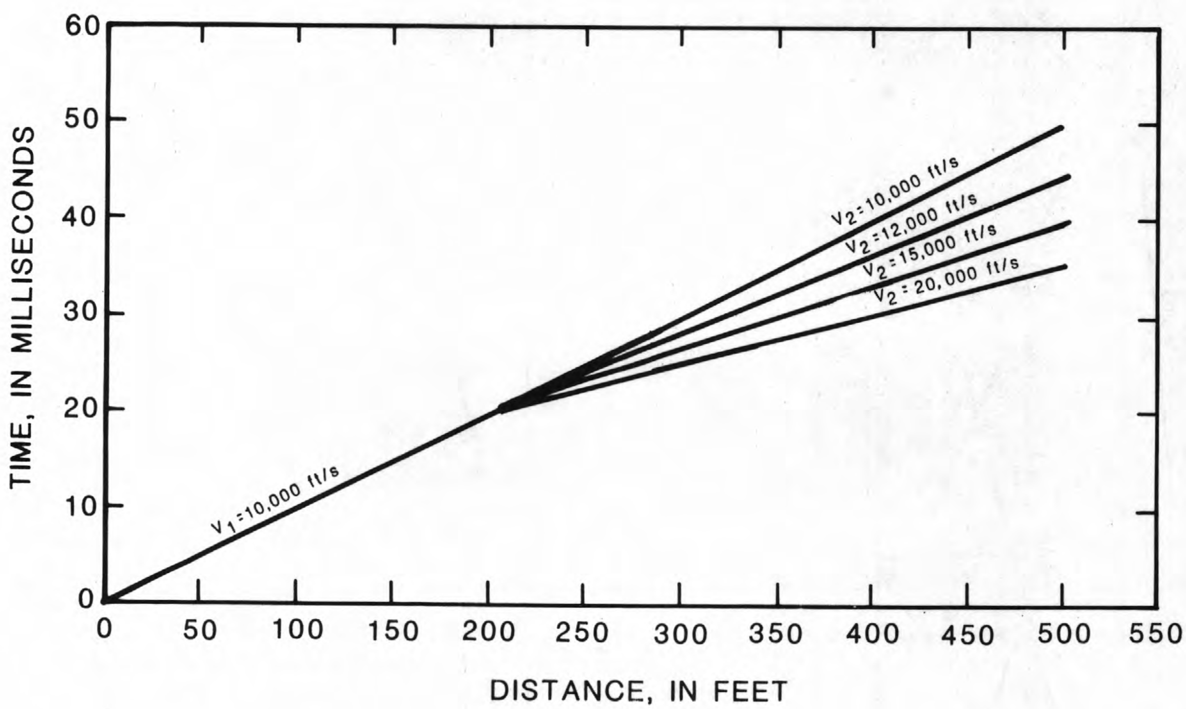


Figure 25.--Hypothetical time-distance plots resulting from different seismic velocities in the second layer.

The problem of similar seismic velocities for adjacent layers has been reported in several hydrogeologic settings. Broadbent (1978) describes a problem where alluvium overlies bedrock having an unusually slow seismic velocity. Topper and Legg (1974) discovered a similar problem when they tried to determine the thickness of a weathered rock aquifer overlying unweathered rock.

A Study Area with a Surface Layer Which Varies Significantly

in Thickness or Material Composition

The hydrologic problem is to map the depth to the undulating surface of a high velocity layer in an area that has discontinuous, shallow, low-seismic-velocity units. Seismic-refraction techniques may work here but with some difficulty. It will be difficult to differentiate between the effects of the discontinuous surficial material and the undulating refractor. Pakiser and Black (1957) describe how to differentiate these two problems in a simple geologic setting.

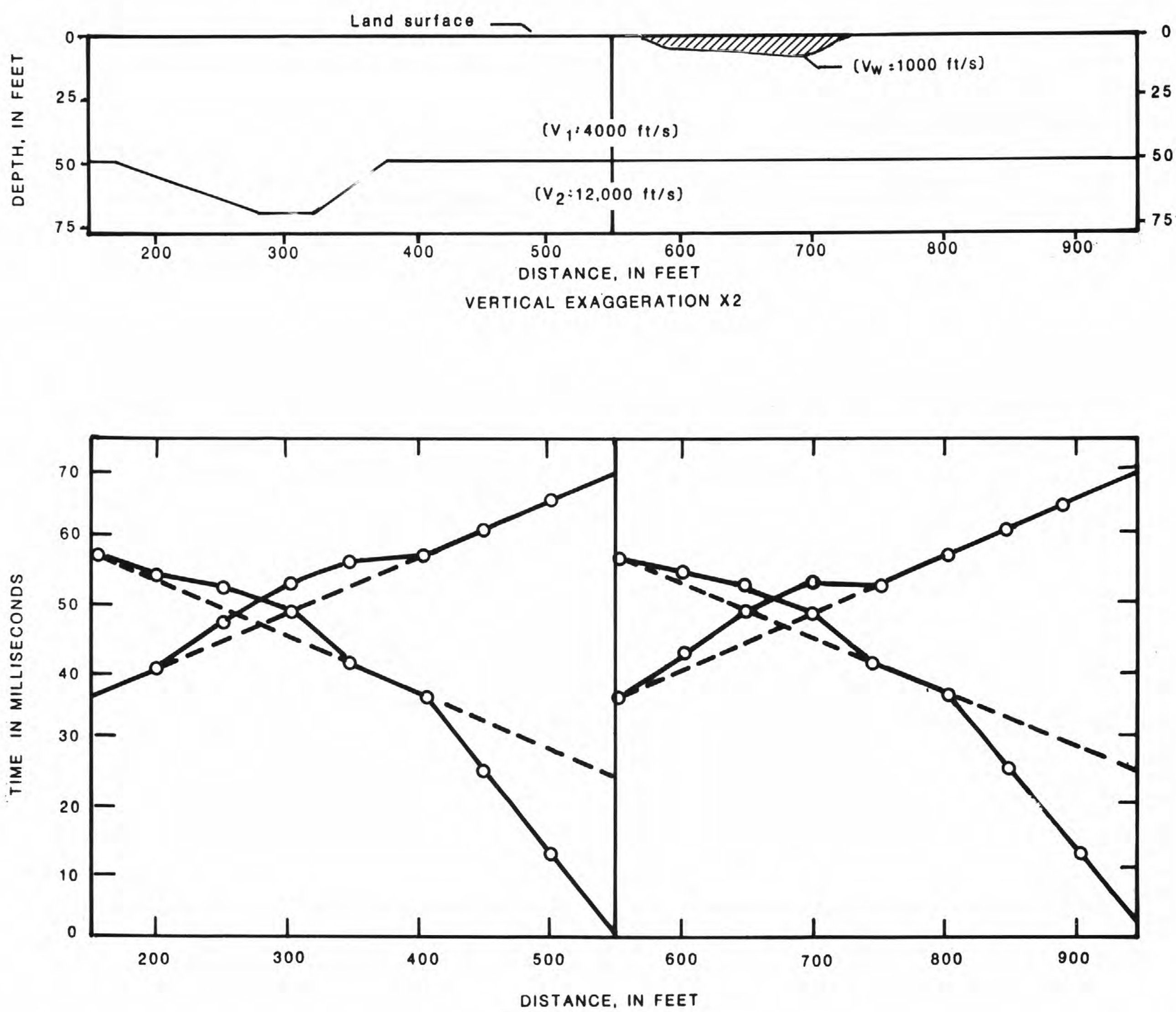


Figure 26.--Seismic section with shallow seismic velocity discontinuities and relief on a refracting surface and the resulting time-distance plot, Monument Valley area of Arizona and Utah (modified from Pakiser and Black, 1957).

Figure 26 shows a seismic section and the resulting time-distance plot in an area that has relief on a refracting surface and seismic-velocity discontinuities in the upper unit. The delay time in first arrival energy, at a particular geophone, caused by a surficial low-velocity unit, will be equal for shots from both ends of the spread. The delay time caused by relief on the refracting surface, at any geophone position, on the other hand, will be different for shots from opposite ends of the spread. This is a very simple example, and as the relief on the refracting surface and the number of shallow discontinuities increases, the problem becomes more difficult to solve.

Quantitative Estimation of Aquifer Hydraulic Properties.

The purpose of some seismic-refraction studies is to obtain estimates of aquifer hydraulic properties. Seismic-refraction methods do not provide a direct measurement of aquifer properties such as permeability or porosity. However, an empirical relationship may be developed and used in areas where the hydrologic setting is known. Although this use of the seismic-refraction method has been demonstrated in some studies (Eaton and Watkins, 1967; Wallace and Spangler, 1970; Watkins and Spieker, 1971; VanZijl and Huyssen, 1971; Barker and Worthington, 1973; Worthington, 1975; Worthington and Griffiths, 1975; and Duffin and Elder, 1979), much remains to be investigated and documented. It must be emphasized that most of the empirical relationships developed in these studies are only valid for a particular study area.

Ground-Water Contamination in Unconsolidated Materials.

The initial phases of ground-water contamination studies involve the characterization of the hydrogeology at the site. Seismic-refraction methods can be used to determine the depth to the water table and the depth to rock, although this method will not provide any direct information about the nature or extent of contamination of the groundwater. This information must be obtained from other surface-geophysical methods such as electrical-resistivity or electromagnetic methods.

In a ground-water contamination study of a municipal landfill site in Farmington, Connecticut, Grady and Haeni (1984) used three seismic-refraction profiles to define the water table and the bedrock surface at the site. Figure 27 shows the landfill, the location of the seismic-refraction lines, and one interpreted seismic section. Multiple overlapping geophone spreads and multiple shot points were used to provide tight control on the depth of the water table and provide a continuous bedrock profile.

Other ground-water contamination studies that used the seismic-refraction methods to characterize the hydrogeology of the site include: Bianchi and Nightingale (1975); Leisch (1976); and Yaffe and others (1981).

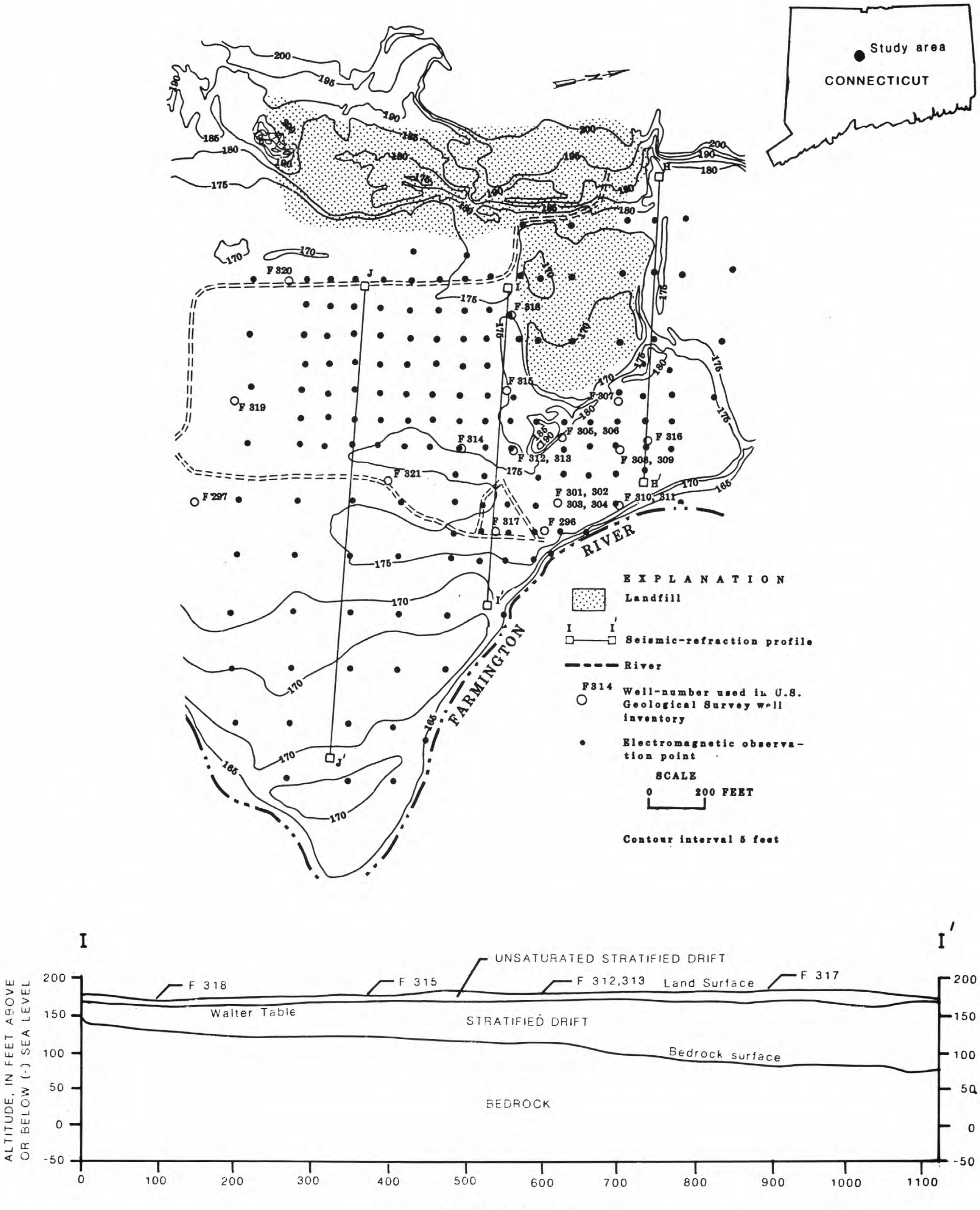


Figure 27.--Site diagram and seismic section of a sanitary landfill in Farmington, Connecticut (from Grady and Haeni, 1984).

A Multi-layered Earth, with a Shallow, Thin Layer, That has a Seismic Velocity Greater Than the Layers Below It

The problem here is to determine the depth to a particular refractor through the high seismic-velocity layer. In most cases, the presence of a shallow high seismic-velocity layer prevents accurate depth determinations of a deep refractor if any low seismic-velocity material underlies it (see section on Limitations). If the high-seismic-velocity layer is very thin, however, seismic-refraction techniques may work.

Bush and Schwarz (1965) found that a thin layer of frozen unconsolidated material did not prevent accurate depth determination of the underlying rock surface. The velocity of the frozen material was 14,000 ft/s and the seismograph records contained some high-frequency early energy arrivals, followed by the low-frequency arrivals from bedrock. In areas of thick frozen ground, however, the calculation of the depth to rock was usually not possible. Ackermann (1976) also used seismic-refraction methods to locate unfrozen materials for water supplies in permafrost areas in Alaska.

Morony (1977) found that a shallow high-seismic-velocity limestone (9,500 ft/s), 33 ft thick, underlain by lower seismic-velocity (6,600 ft/s) aquifer material, prevented the determination of the depth to basement rock (seismic velocity 16,000 ft/s) or the thickness of the limestone unit. Using drill-hole data for the thickness of the limestone, and assuming a velocity of the underlying saturated aquifer material, a reasonable depth to basement rock of 450 ft was calculated from the seismic data.

Miscellaneous Hydrogeologic Problems

There are several other hydrogeologic problems where seismic-refraction techniques have been used. Shields and Sopper (1969) used this technique in a watershed hydrology study. Depth to rock and depth to water, determined from seismic-refraction profiles, were used to help characterize the hydrologic properties of the watershed.

Winter (1984) used seismic-refraction methods in a lake hydrology study of Mirror Lake, New Hampshire. In this study, the interaction of the ground-water system and the water in the lake was studied, and seismic-refraction methods were used to map the saturated thickness of unconsolidated materials around the lake and in the surrounding watershed.

Hydrogeologic Problems Where Seismic-Refraction Techniques Can Not Be Used

The seismic-refraction method cannot be used successfully to detect: 1) low seismic-velocity layers overlain by high seismic-velocity layers; 2) two hydrologically different units with the same seismic velocity; 3) thin beds of intermediate seismic velocity in a sequence of beds that have progressively increasing seismic velocities with depth. Three examples of situations where these limitations apply are cited below.

Basalt Flows with Interflow Zones that are Aquifers

The most important aquifers in layered basalt formations or other layered volcanic rocks generally occur in the zones of rubbly, vesicular, brecciated, or weathered rock that form the top of many of the lava flows, or in the sediments that accumulate on the surface of a flow prior to successive lava flows. These interflow zones are usually separated by dense unfractured basalt.

The problem is to define the depth and thickness of these interflow aquifers. Seismic-refraction techniques will not work, because the seismic velocity of the dense basalt is 15,000 to 20,000 ft/s and the seismic velocity of the interflow zone is 5,000 to 7,000 ft/s. The condition of increasing seismic velocity with depth does not hold and the low seismic-velocity unit cannot be defined with seismic-refraction techniques.

Unconsolidated Sand and Gravel Aquifer Material Underlain by Silt and Clay

The problem is to define the areal extent and thickness of the sand and gravel aquifer. Seismic-refraction techniques usually cannot be used to solve this problem. The velocity of sound in the saturated clay and silt will be almost the same as the velocity of sound in the saturated sand and gravel (Burwell, 1940). In most cases, the seismic velocities of the two units cannot be differentiated on the time-distance plot. Resisitivity techniques may work in this setting.

Saturated Alluvium Underlain by a Thin Confining Shale, Underlain by a Porous Sandstone

The purpose of a hydrologic study in an area like this is to determine the depth and thickness of the confining shale layer. Again, one of the basic assumptions of seismic-refraction technique is not met. A thin refractor at depth cannot be delineated with seismic refraction methods. In some circumstances, the thickness of the shale could be considerable and still remain undetected (Soske, 1959).

Annotated References

Unconsolidated Unsaturated Glacial or Alluvial Sand

Overlying Glacial or Alluvial Aquifers

Burwell, E. B., 1940, Determination of ground-water levels by the seismic method: Transactions American Geophysical Union, v. 21, p. 439-440.

[Changes in velocity at water table shown to be independent of alluvial material present.]

Dobrin, M. B., 1976, Introduction to geophysical prospecting (3d ed.): New York, McGraw-Hill, 630 p.

[A basic reference text that covers theoretical and practical aspects of the major surface geophysical methods. The emphasis is on deep exploration.]

Emerson, D. W., 1968, The determination of ground-water levels in sands by the seismic-refraction method: Civil Engineering Transactions, v. CE 10, no. 1, p. 15-18.

[Dry and partial water-saturated sands can be distinguished from fully saturated sands by compressional-wave velocity. Seismic-refraction determinations of depths to the water table are feasible in theory and in field problems.]

Followill, F. E., 1971, Shallow seismic-refraction mapping of Eocene water tables, northern Mississippi, completion report: Mississippi State University, Water Resources Research Institute, 14 p.

[Seismic-refraction measurements to delineate the areal extent of a perched water table.]

Galfi, J., and Palos, M., 1970, Use of seismic-refraction measurements for ground-water prospecting: Bulletin International Association of Scientific Hydrology, v. 15, no. 3, p. 41-46.

[The water table is mapped in sandy areas by seismic-refraction techniques and compared with well data.]

Scott, J. H., Tibbets, B. L., and Burdick, R. G., 1972, Computer analysis of seismic-refraction data: U.S. Bureau of Mines, R. I., 7595, 95 p.

[Presents a computer program which uses seismic-refraction data to generate a two-dimensional model representing a layered geologic section.]

Sjogren, B., and Wagner, O., 1969, On a soil and ground-water investigation with the shallow refraction method at Moi Rana: Engineering Geology, v. 3., no. 1, p. 61-70.

[Seismic investigations at Rana, Norway, defined the subsurface geology and determined the ground-water levels and direction of flow.]

White, J. E., and Senbush, R. L., 1953, Velocity measurements in near surface formations: Geophysics, v. 18, no. 1, p. 54-69.

[A discussion of theoretical considerations and experimental measurements of shallow formations.]

Duguid, J. O., 1968, Refraction determination of water table depth and alluvium thickness: Geophysics, v. 33, no. 3, p. 481-488.

[Geologic section of the bedrock channel and the water table of the Laramie River area in Wyoming, determined by seismic-refraction methods.]

Gill, H. E., Vecchioli, J., and Bonini, W. E., 1965, Tracing the continuity of Pleistocene aquifers in northern New Jersey by seismic methods: Ground Water, v. 3, no. 4, p. 33-35.

[Seismic-refraction methods were used to map the bedrock surface in parts of Morris County, New Jersey. Bedrock channels were mapped showing the location of potential sand and gravel aquifers.]

Joiner, J. T., Warman, J. C., and Scarbrough, W. L., 1968, An evaluation of some geophysical methods for water exploration in the Piedmont area: Ground Water, v. 6, no. 1, p. 19-25.

[Seismic techniques were used to determine depth to and configuration of bedrock surface in the Heflin area, Cleburne County, Alabama.]

Lennox, D. H., and Carlson, V., 1967, Geophysical exploration for buried valleys in an area north of Two Hills, Alberta: Geophysics, v. 32, no. 2, p. 331-362.

[Seismic-refraction methods were used to determine bedrock depth and locations of buried valleys.]

Mercer, J. W., and Lappala, E. G., 1970, A geophysical study of alluvial valleys in western Mora County, New Mexico: U.S. Geological Survey Open-file Report, 69 p.

[Seismic-refraction methods were used to determine the saturated thickness of alluvial deposits in the valley of the Mora River.]

Peterson, D. W., Yeend, W. E., Oliver, H. W., and Matick, R. E., 1968, Tertiary gold-bearing channel gravel in northern Nevada County, California: U.S. Geological Survey Circular 566, 22 p.

[Seismic-refraction methods were used to determine thickness of sediments overlying consolidated bedrock in northern Nevada County, California.]

Wachs, D., Arad, A., and Olshina, A., 1979, Locating ground water in the Santa Catherina area using geophysical methods: Ground Water, v. 17, no. 3, p. 258-263.

[Seismic-refraction and electric-resistivity methods were used to find the depth to bedrock, depth to water, and depth of jointing in shallow alluvial valleys in a mountainous, arid area in the southern part of the Sinai Peninsula.]

Thick Unconsolidated Alluvial or Sedimentary Units Overlying Consolidated Sediments and/or Basement Rock in Large Structural Basins

Ackermann, H. D., Pankratz, L. W., and Dansereau, D. A., 1983, A comprehensive system for interpreting seismic-refraction arrival-time data using interactive computer methods: U.S. Geological Survey Open-File Report 82-1065, 265 p.

[A seismic-refraction interpretation program that accounts for horizontal variations in seismic velocities.]

Arnow, Ted, and Mattick, R. E., 1968, Thickness of valley fill in the Jordan Valley, east of the Great Salt Lake, Utah: U.S. Geological Survey Professional Paper 600-B, p. B79-B82.

[Seismic-refraction methods were used to determine the thickness of valley fill in areas between Salt Lake City, Utah and Great Salt Lake.]

Crosby, G. W., 1976, Geophysical study of the water-bearing strata in Bitterroot Valley, Montana: Montana University Joint Water-Resources Research Center, Bozeman, Montana, Report no. 80, OWRI A-063-MONT(1), 68 p.

[Refraction studies were used to verify gravity models of the basin and for other ground-water prospecting data.]

Dudley, W. W., Jr., and McGinnis, L. D., 1962, Seismic-refraction and earth resistivity investigation of hydrogeologic problems in the Humboldt River basin, Nevada: University of Nevada, Desert Research Institute, Technical Report 1, 29 p.

[Predicts depth to bedrock and thickness of valley fill using seismic-refraction methods.]

Libby, F., Wallace, D. E., and Spangler, D. P., 1970, Seismic-refraction studies of the subsurface geology of Walnut Gulch Experimental Research Service, ARS 41-164, 14 pp.

[Seismic-refraction methods were used to map bedrock and the depth to the water table in a deep alluvial valley near Tombstone, Arizona.]

Marshall, J. P., 1971, The application of geophysical instruments and procedures to ground-water exploration and research: Montana Water Resources Research Center termination report 5, OWRR A-013-MONT(1).

[Seismic-refraction methods were used to correlate gravity data and determine the structural nature and depth of bedrock in the upper Silver Bow (Butte) Valley of Montana.]

Mattick, R. E., Olmsted, F. H., and Zohdy, A. A. R., 1973, Geophysical studies in the Yuma area, Arizona and California: U.S. Geological Survey Professional Paper 726-D, 36 p.

[The gross distribution and thickness of Cenozoic sediments which contain the major aquifers were determined using a variety of surface geophysical techniques.]

Mower, R. W., 1968, Ground-water discharge toward Great Salt Lake through valley fill in the Jordan Valley, Utah: U.S. Geological Survey Professional Paper 600-D, p. D71-D74.

[Ground-water discharge toward Great Salt Lake based partly on seismic-refraction data collected by Arnow and Mattick, 1968 (above).]

Pankratz, L. W., Ackermann, H. D., and Jachens, R. C., 1978, Results and interpretation of geophysical studies near the Picacho fault, south-central Arizona: U.S. Geological Survey Open-File Report 78-1106, 17 p.

[Six subsurface layers and three basement faults were identified with the seismic-refraction method.]

Robinson, E. S., and Costain, J. K., 1971, Some seismic measurements on the Virginia Coastal Plain: Virginia Water Resources Research Center, completion report, OWRR A-034-VA(1), 37 p.

[Seismic-refraction and reflection measurements were made at two sites on the Virginia coastal plain for determining total thickness and stratigraphic subdivisions of the unconsolidated deposits.]

Wallace, D. E., 1970, Some limitations of seismic-refraction methods in geohydrological surveys of deep alluvial basins: Ground Water, v. 8, no. 6, p. 8-13.

[Seismic-refraction study conducted near Tombstone, Arizona, where the depth to the water table ranged from 0 to 475 ft.]

Unconsolidated Alluvial Sand Overlying Sedimentary Rock, Which in Turn Overlies Volcanic or Crystalline Bedrock

Colon-Dieppa, E., and Quinones-Marquez, 1985, A reconnaissance of the water resources of the central Guanajibo valley, Puerto Rico: U.S. Geological Survey Water Resources Investigations Report 82-4050, 47 p.

[Seismic-refraction techniques were used to map the thickness of saturated unconsolidated deposits and the thickness of the underlying limestone aquifers.]

Scott, J. H., Tibbets, B. L., and Burdick, R. G., 1972, Computer analysis of seismic-refraction data: U.S. Bureau of Mines, R. I., 7595, 95 p.

[Presents a computer program which used seismic-refraction data to generate a two-dimensional model representing a layered geologic section.]

Torres-Gonzalez, Arturo, 1984, Use of surface geophysical techniques for ground-water exploration in the Canovanes-Rio Grande area, Puerto Rico; U.S. Geological Survey Water Resources Investigations Report 84-4113, 34 p.

[Seismic-refraction techniques were used to map the depth and saturated thickness of unconsolidated alluvial aquifers and underlying limestone aquifer.]

Visarion, Marius, Vajdea, Vasile, Stoica, Ion, and Rosca, Vlad, 1976, Features of geophysical exploration for Karst in Romania: Geophysique, v. 20, p. 89-100.

[In Romania, seismic-refraction investigations have indicated a limestone complex (400-500 m thick) overlying a basement of crystalline schists and green schists.]

Unconsolidated Stratified-drift Material Overlying Significant Deposits of Dense Lodgement Glacial Till, Which Overlies Crystalline Bedrock

Johnson, R. B., 1954, Use of the seismic-refraction method for differentiating Pleistocene deposits in the Arcola and Tuscola quadrangles, Illinois: Illinois State Geological Survey Report Investigation 176, 59 p.

[Refraction techniques were used to distinguish drift of Wisconsin age from that of Illinoian age, and to determine the thickness of the stratified drift.]

Mazzaferro, D. L., 1980, Ground-water availability and water quality in Farmington, Connecticut: U.S. Geological Survey Water Resources Investigations 80-751, 57 p.

[A ground-water appraisal study that used seismic-refraction techniques to help to define the depth to rock in the study area.]

Sander, J. E., 1978, The blind zone in seismic ground-water exploration: Ground Water, v. 16, no. 6, p. 394-397.

[Refraction techniques mapped areas of thick, compacted till in northern Minnesota beneath an unconfined glacial aquifer. Where this unit is thin, a blind-zone layer is present and the treatment is discussed.]

Winter, T. C., 1984, Geohydrologic setting of Mirror Lake, West Thornton, New Hampshire: U.S. Geological Survey Water-Resources Investigations Report 84-4266, 60 p.

[Seismic-refraction, continuous seismic-reflection profiling, and borehole techniques were used to define the geometry and texture of glacial material surrounding the lake.]

Unconsolidated Glacial Sand and Gravel Overlying a Thin

Till Layer Overlying Crystalline Bedrock

Birch, F. S., 1976, A seismic ground-water survey in New Hampshire: Ground Water, v. 14, no. 2, p. 94-100.

[Seismic-refraction was used to provide boundary conditions for mathematical model of ground-water flow system.]

Dickerman, D. C., and Johnston, H. E., 1977, Geohydrologic data for the Beaver-Pasquiset ground-water reservoir, Rhode Island: Rhode Island Water Resources Board, Water Information Series Report 3, 128 p.

[A data report that presents results of seismic-refraction profiles, as well as other hydrogeologic data for a glacial basin in Rhode Island.]

Frohlick, R. K., 1979, Geophysical studies of the hydraulic properties of glacial aquifers in the Pawcatuck River basin, Rhode Island: Rhode Island Water Resources Center, University of Rhode Island, project report OWRI A-068-RI(1), 38 p.

[Seismic-refraction, gravity, and resistivity techniques were used to locate glacial aquifers in parts of Rhode Island.]

Grady, S. J., and Handman, E. H., 1983, Hydrogeologic evaluation of selected stratified-drift deposits in Connecticut: U.S. Geological Survey Water-Resources Investigation Report 83-4010, 51 p.

[Seismic-refraction profiles were used to determine the saturated thickness of selected stratified-drift aquifers.]

Haeni, F. P., 1978, Computer modeling of the ground-water availability of the Pootatuck River Valley, Newtown, Connecticut: U.S. Geological Survey Water Resources Investigations 78-77, 64 p.

[Seismic-refraction techniques were used to determine depth to rock and saturated thickness of glacial aquifer.]

______, 1986, Application of seismic refraction methods in ground-water modeling studies in New England: Geophysics, v. 51, no. 2, p. 236-249.

[Describes the use of seismic refraction techniques in ground-water modeling studies.]

Haeni, F. P., and Anderson, H. R., 1980, Hydrogeologic data for south central Connecticut: Connecticut Water Resources Bulletin 32, 43 p.

[Basic data report showing test-hole, well, and seismic-refraction data.]

Haeni, F. P., and Melvin, R. L., 1984, High resolution continuous seismic-reflection study of a stratified-drift deposit in Connecticut, in proceedings of surface and borehole geophysical methods in ground-water investigations, San Antonio, Texas: p. 237-256.

[Seismic-refraction profiles were conducted to determine the thickness of saturated stratified drift and to determine the seismic velocity of this unit for interpretation of continuous seismic-reflection data.]

Mazzaferro, D. L., 1980, Ground-water availability and water quality in Farmington, Connecticut: U.S. Geological Survey Water Resources Investigations Open-file Report 80-751, 57 p.

[Refraction methods were used to obtain topography of bedrock surface for ground-water appraisal study in Farmington, Connecticut.]

______, 1984, Ground-water availability and water quality at Southbury and Woodbury, Connecticut: U.S. Geological Survey Water Resources Investigations Open-file Report 84-4221, 87 p.

[Seismic-refraction techniques were used to determine thickness of saturated stratified drift and profile the bedrock surface for a ground-water simulation study in Southbury and Woodbury, Connecticut.]

Morrissey, D. J., 1983, Hydrology of the Little Androscoggin River Valley aquifer, Oxford County, Maine: U.S. Geological Survey Water Resources Investigations 83-4018, 79 p.

[Seismic-refraction techniques were used to determine the thickness of saturated stratified drift and to profile the bedrock surface for a ground-water modeling study in Oxford County, Maine.]

Sander, J. E., 1978, The blind zone in seismic ground-water exploration: Ground Water, v. 16, no. 6, p. 394-397.

[Study shows that the seismic-refraction method gives incorrectly high values for saturated thickness where a blind-zone layer, such as till beneath a saturated aquifer, occurs.]

Scott, J. H., Tibbets, B. L., and Burdick, R. G., 1972, Computer analysis of seismic-refraction data: U.S. Bureau of Mines Report of Investigation 7595, 95 p.

[Presents a computer program which uses seismic-refraction data to generate a two-dimensional model representing a layered geologic section.]

Sharp, J. M., Jr., Burmester, R. F., and Malvik, O., 1977, Hydrogeology and delineation of buried glacial river valley aquifers in northwestern Missouri: Missouri Water Resources Research Center, Completion report OWRI A-097-MO(1), 65 p.

[Seismic-refraction techniques were used to find the depth to bedrock and confirm that gravity residual lows represented bedrock lows.]

Tolman, A. L., Tepper, D. H., Prescott, J. C. Jr., and Gammon, S. O., 1983, Hydrogeology of significant sand and gravel aquifers in northern York and southern Cumberland Counties, Maine: Maine Geological Survey, Report 83-1, 4 plates.

[Seismic-refraction methods were used to obtain topography of bedrock surface for ground-water appraisal study in northern York and southern Cumberland Counties, Maine.]

Warrick, R. E., and Winslow, J. D., 1960, Application of seismic methods to a ground-water problem in northeastern Ohio: Geophysics, v. 25, no. 2, p. 505-519.

[Seismic-refraction and reflection methods were used to map buried glacial valleys in Ohio.]

Watkins, J. S., and Spieker, A. M., 1971, Seismic-refraction survey of Pleistocene drainage channels in the lower Great Miami River valley, Ohio: U.S. Geological Survey Professional Paper 605-B, p. B1-B17.

[Mapped the bedrock surface and the thickness of sand and gravel deposits in the Miami River valley using seismic-refraction methods.]

Winter, T. C., 1984, Geohydrologic setting of Mirror Lake, West Thornton, New Hampshire: U.S. Geological Survey Water-Resources Investigations Report 84-4266, 60 p.

[Seismic-refraction, continuous seismic-reflection profiling, and borehole techniques were used to define the geometry and texture of glacial material surrounding the lake.]

An Aquifer Unit Underlain by Bedrock With a Similar Seismic Velocity

Broadbent, M., 1978, Seismic-refraction surveys for Canterbury ground-water research: New Zealand Department of Scientific and Industrial Research, Geophysics Division, Report 131, 63 p.

[Alluvium overlying bedrock with small differences in seismic velocities made it difficult to identify in which layer the refracted waves, forming the time-distance curve, originated.]

Topper, K. D., and Legg, C. A., 1974, Geophysical exploration for ground water in the Lusaka District, Republic of Zambia: Journal of Geophysics (Berlin), v. 40, no. 1, p. 97-112.

[Seismic and electrical techniques were used to map the weathered zones of bedrock that are used as water supplies.]

A Study Area with a Surface Layer which varies significantly in Thickness or Material Composition

Pakiser, L. C., and Black, R. A., 1957, Exploring the ancient channels with the refraction seismograph: Geophysics, v. 22, no. 1, p. 32-47.

[Seismic-velocity variations in the upper layer (Shinarump Formation) were differentiated from erosion channels in the deeper refracting surface (Moenkiop Formation).]

Barker, R. D., and Worthington, P. F., 1973, Some hydrogeophysical properties of the Bunter sandstone of northwest England: Geoexploration, v. 11, no. 3, p. 151-170.

[Estimation of sandstone porosity and permeability from seismic velocity in the Fylde area of Lancashire, England.]

Duffin, G. L., and Elder, G. R., 1979, Variations in specific yield in the outcrop of the Carizo sand in south Texas as estimated by seismic refraction: Texas Dept. of Water Resources Report 229, 61 p.

[Compressional-wave velocities in upper unsaturated portion of aquifer were determined by refraction soundings. Empirical relationships were used to estimate total porosity values from the compressional-wave velocities.]

Eaton, G. P., and Watkins, J. S., 1967, The use of seismic-refraction and gravity methods in hydrogeological investigations, in Canadian Centennial Conference, Niagara Falls, 1967, Proceedings: Mining and Ground Water Geophysics, p. 544-568.

[Seismic-refraction methods were used to determine the three-dimensional geometry of the aquifer, the gross stratigraphy and local litho-facies variations of the aquifer, and depth to the water table.]

Van Zijl, J. S. V., and Huyssen, R. M. J., 1971, Some aspects of seismic-refraction investigations for water in arid zones of South Africa: Transactions of the Geological Society of South Africa, no. 74, part II, p. 33-43.

[The porosity of unconsolidated sands was estimated using seismic-refraction techniques and relationships between compressional velocity, porosity, and depth of burial. The result was an estimate of total aquifer storage of a sand aquifer in South Africa.]

Wallace, D. E., and Spangler, D. P., 1970, Estimating storage capacity in deep alluvium by gravity-seismic methods: Bulletin of International Association of Science and Hydrology, v. 15, no. 2, p. 91-104.

[Basin boundaries were determined by gravity methods and density samples were taken from all representative formations. Density values were correlated with seismic velocities to estimate subsurface porosities.]

Watkins, J. S., and Spieker, A. M., 1971, Seismic-refraction survey of Pleistocene drainage channels in the lower Great Miami River valley, Ohio: U.S. Geological Survey Professional Paper 605-B, 17 p.

[A general northeast-southwest decrease in seismic velocity in the saturated outwash deposits is thought to result from sorting of outwash deposits.]

Worthington, P. F., 1975, Quantitative geophysical investigations of granular aquifers: Geophysical Surveys, v. 2, No. 3, p. 313-366.

[A review of seismic-refraction and resistivity techniques in estimating aquifer porosity and permeability using empirical relationships.]

Worthington, P. F., and Griffiths, D. H., 1975, The application of geophysical methods in the exploration and development of sandstone aquifers: Quarterly Journal of Engineering Geology, v. 8, no. 8, p. 73-102.

[The seismic-refraction method with an empirical relationship developed in the laboratory was used to estimate hydrologic conductivity in a Triassic sandstone in England.]

Bianchi, W. C., and Nightingale, H. I., 1975, Hammer seismic timing as a tool for artificial recharge-site location: Soil Science Society of America Proceedings, v. 39, no. 4, p. 747-751.

[Artificial recharge and liquid waste disposal sites were chosen in alluvial areas in the San Joaquin valley using seismic-refraction techniques.]

Grady, S. J., and Haeni, F. P., 1984, Application of electromagnetic techniques in determining distribution and extent of ground-water contamination at a sanitary landfill, Farmington, Connecticut, in Nielsen, D. M., ed.: Proceedings of Surface and Borehole Geophysical Methods in Ground Water Investigations, San Antonio, Texas, Feb. 7-9, 1984: National Water Well Association, Worthington, Ohio, p. 338-367.

[Seismic-refraction techniques used to define the saturated thickness of the aquifer material at a contamination site.]

Leisch, B., 1976, Evaluating pollution-prone strata beneath sewage lagoons: Public Works, v. 107, no. 8, p. 70-71.

[Seismic-refraction techniques were used to determine the physical characteristics and thickness of geologic units under a sewage lagoon site.]

Yaffe, H. J., Cichowicz, N. L., and Pease, R. W., Jr., 1981, Application of remote-sensing techniques to evaluate subsurface contamination and buried drums, in, Environmental Protection Agency Research Symposium, 7th, Philadelphia, 1981, Proceedings: Land Disposal: Hazardous Waste, p. 352-365.

[Seismic-refraction techniques were used to locate the bedrock surface at the Mitre Corp. site in Bedford, Massachusetts.]

Miscellaneous Hydrologic Problems

Shields, R. R., and Sopper, W. E., 1969, An application of surface geophysical techniques to the study of watershed hydrology, Water Resources Bulletin vol. 5, no. 3 p. 37-49.

[Seismic and resistivity techniques used to determine the depth of soils their volumes, depth to bedrock, and the configuration of the bedrock and water table. With this information, the hydrologic properties of the watershed were described in greater detail.]

Winter, T.C., 1984, Geohydrologic setting of Mirror Lake, West Thornton, New Hampshire: U.S. Geological Survey Water-Resources Investigations Report 84-4266, 60 p.

[Seismic-refraction, continuous seismic-reflection profiling, and borehole techniques were used to define the geometry and texture of glacial material surrounding the lake.]

A Multi-layered Earth, With a Shallow, Thin Layer, That has a Seismic Velocity Greater Than the Layers Below It

Ackermann, H., 1976, Geophysical prospecting for ground water in Alaska: U.S. Geological Survey Earthquake Information Bulletin, vol. 8, no. 2, p. 18-20.

[Seismic-refraction and resistivity techniques were used to locate water supplies in frozen areas in Alaska.]

Bush, B. O., and Schwarz, D. S., 1965, Seismic-refraction and electrical-resistivity measurements over frozen ground, in, Brown, R. J. E. (editor), Proceedings of the Canadian Regional Permafrost Conference, 1 and 2 December, 1964: Ottawa, National Research Council of Canada, Associate Committee on Soil and Snow Mechanics, Technical Memorandum No. 86, p. 32-40.

[Seismic-refraction techniques were evaluated for predicting the depth to rock through frozen ground in Manitoba, Canada.]

Morony, G. K., 1977, Seismic-refraction survey Patterson Point limestone, Redcliff area: Geological Survey of South Australia Quarterly Geological Notes, no. 63, p. 18-21.

[Records with first-arrival times characteristic of a near-surface layer with a higher seismic velocity than layers immediately below it were obtained near Redcliff Point on Spencer Gulf, Australia.]

Unconsolidated Sand and Gravel Aquifer Material Underlain by Silt and Clay

Burwell, E. B., 1940, Determination of ground-water levels by the seismic method: Trans. American Geophysical Union, v. 21, p. 439-440.

[Changes in the velocity of sound in saturated alluvium is shown to be independent of the alluvial material.]

Saturated Alluvium Underlain by a Thin Confining Shale, Underlain by a Porous Sandstone

Soske, J. L., 1959, The blind-zone problem in engineering geophysics: Geophysics, v. 24, no. 2, p. 359-365.

[Wave-front diagrams illustrate why a thin intermediate seismic-velocity unit cannot be detected with seismic-refraction techniques.]

PLANNING THE INVESTIGATION

Successful use of surface geophysical techniques in hydrologic studies depends to a great extent on proper planning. The investigator must know the local geology, collect all available data, identify the physical properties to be measured, determine the precise objective of the geophysical survey, and select field sites for the geophysical surveys. Without careful and detailed planning, geophysical surveys will provide disappointing results.

Local Geology

Surface geophysical techniques measure the physical contrasts within sediments and rocks. The investigator must determine the distinctive physical properties of the hydrologic units in the study area and the approximate magnitude of the contrast of these properties before starting the geophysical study. To accomplish this, the local geology and hydrology must be relatively well understood.

Knowledge of an area's depositional or erosional history is helpful in determining the continuity of geologic and hydrologic boundaries, thickness of beds, grain size, compactness of sediments, and other hydrogeologic properties. These properties directly influence the decision whether or not to use the seismic-refraction technique and how to set up the equipment in the field.

The seismic-refraction technique measures the velocity of sound in subsurface materials. Although the velocity of sound in earth materials can be a good indicator of the type of subsurface material, it is not a unique indicator. Table 3 illustrates that each type of rock has a wide range of seismic velocities, and that different rock types have ranges that overlap. The seismic-refraction technique measures the velocity of sound in Earth materials, but it is the investigator who, based on knowledge of the local hydrogeology, must interpret the data and arrive at a reasonable solution.

Available Data

Prior to undertaking any seismic refraction study, the investigator should collect and analyze all available subsurface data from wells or test holes in the study area. In addition, the investigator should review any surface and borehole geophysical studies (particularly seismic studies) completed by oil and gas companies, universities, highway departments, and private consultants. The review of these data usually enables the investigator to determine whether there are significant velocity contrasts between the stratigraphic units of interest. The drill or test-hole data also will serve as control points where the indirect geophysical measurements can be correlated to actual geologic or hydrologic boundaries. Previous studies in similar geologic settings are a good indication of whether the refraction method can be used successfully in the hydrologic study.

Table 3.--Velocity of sound in common Earth materials.

Material	velocities (ft/s)
Unsaturated weathered surface material	400-700[1]
Unsaturated sand and gravel or alluvium	1,200-1,600[1]
Saturated sand and gravel or alluvium	4,000-6,000[1]
Sandstone	5,000-14,000[1]
Shale	9,000-14,000[2]
Limestone	7,000-20,000[2]
Granite	15,000-19,000[2]
Metamorphic rock	10,000-23,000[2]
Basalt	21,000[3]
Ice	12,050[2]
Freshwater at 13°C	4,800[1]
Air	1,000[4]

[1] Clark (1966, p. 204).
[2] Jakosky (1950, p. 660).
[3] Dobrin (1976, p. 50).
[4] Carmichael (1982, p. 134).

Seismic Velocities

One of the most critical elements in planning a seismic-refraction survey is determination of whether or not there is a seismic velocity contrast between two geologic or hydrologic units of interest. Assuming that no previous seismic-refraction surveys have been made in the study area, the investigator is forced to rely on knowledge of the geology, published references containing the seismic velocities of different earth materials (Jakosky, 1950; Clark, 1966; Dobrin, 1976; Carmichael, 1982), and published reports of seismic-refraction studies done in similar hydrogeologic settings (see "Hydrologic Applications" section).

Most rock types have a wide range of seismic velocities inasmuch as the values in published texts summarize the values of individual rock types from locations around the world. Velocities of sound in rocks from a single study area usually exhibit a much narrower range than the published values (Griffiths and King, 1981, p. 28). Table 4 shows the variation of laboratory-determined seismic velocities for a wide range of sedimentary rock types from a single locality; cores from rock underneath saturated stratified drift in a study area in Connecticut. The compressional velocity of sound in these rocks varies from 11,000 to 14,000 ft/s and averages 12,700 ft/s. This is a much narrower range of velocities than might have been expected from table 3.

Table 5 shows some field-determined seismic velocities of saturated unconsolidated materials from studies done by the U.S. Geological Survey. The seismic velocity of saturated unconsolidated materials at shallow depths is relatively independent of the materials location or grain size.

When there is doubt as to whether there is a sufficient seismic velocity contrast, detailed field work (see Field Procedures section) can be done near a control point, such as a test hole or well, to determine the seismic velocities of sediments and rocks in the study area and to assess the feasibility of using seismic-refraction methods.

Objective of the Seismic-Refraction Survey

Another important element in planning a geophysical survey is to clearly define the survey's objectives. Such questions as the following need to be answered: Is this going to be a site-specific study or areal study? Is very detailed information required in a limited area or is a lot of information needed throughout a large area? The answers will affect the money, manpower, and time needed to complete a successful seismic-refraction survey.

In a site-specific or detailed hydrologic study, seismic traverses are short, multiple shots are fired, geophone spacing is close, elevations and locations of geophones and shot points are precisely determined, and test holes and wells are used for geologic control.

In areal hydrologic studies, geophone spacing is large, seismic traverses are long, and only a few shot points are used, topographic maps or hand-level elevations and only a few test holes or wells are used as control points. Under these conditions, the cost per mile of seismic data is relatively low, but the subsurface detail is not as good as in the site-specific studies.

Site Selection

The investigator should complete site selection, field-site checking, and obtain clearance from utility companies prior to starting seismic field activities. Preliminary site selection, usually carried out through the use of topographic maps, should be based on the following criteria: (1) the need for data at that location, (2) the accessibility of the area to field crews, (3) the ease of obtaining the necessary permits to conduct the survey, (4) the proximity of wells or test-holes for control data, and (5) the absence of buried utility lines.

Table 4--Laboratory determined physical properties of sedimentary rock samples in south-central Connecticut. [From Haeni and Anderson, 1980]

Test hole no.	Lithologic description1/	Bulk density (g/cm^3)	Grain density (g/cm^3)	Porosity (percent)	Compressional velocity (ft/s)
Town of Cheshire					
CS 23 th	Sandstone, arkosic, white to buff, medium to very coarse grained, angular to subangular grains, poorly sorted and well cemented.	2.57	2.66	3.3	12,320
CS 27 th	Sandstone, arkosic, red and siltstone, very fine grained, and micaceous.	2.64	2.85	7.4	-
Town of North Branford					
NBR 7 th	Conglomerate, black and dark gray-green, very poorly sorted, with rounded to angular light-green volcanic fragments in a moderate to well-cemented matrix.	2.49	2.80	11.1	11,260
NBR 11 th	Volcanic agglomerate, green-gray; fragments of angular basalt; clasts of quartz in a fine-grained, weathered, green-white calcareous matrix.	2.51	2.77	9.3	13,080
NBR 17 th	Conglomerate, arkosic, gray-green (mostly very coarse sand to very fine gravel and some fine to medium pebble gravel).	2.48	2.74	9.5	13,640
Town of North Haven					
NHV 49 th	Sandstone, arkosic, red, medium to very coarse grained.	2.57	2.74	6.2	-
Town of Plainville					
PV 49 th	Siltstone, red-brown, very fine grained, dirty and mottled with gray-green spots.	2.64	2.72	2.9	13,900
PV 52 th	Sandstone, red, very fine to fine grained.	2.41	2.69	10.4	12,220
Town of Southington					
S 107 th	Sandstone, red, very fine to medium grained, with micaceous silt.	2.55	2.69	5.2	13,710
S 111 th	Sandstone, red, very fine grained, and siltstone, massive, micaceous and well-cemented.	2.63	2.72	3.3	13,790
S 115 th	Sandstone, red, very fine to fine grained.	2.62	2.73	4.0	13,790
S 116 th	Conglomerate, light-red to buff.	2.62	2.73	4.0	11,180
S 120 th	Sandstone, arkosic, tan to buff, and poorly sorted.	2.49	2.69	7.4	12,620
S 147 th	Sandstone, red, very fine to fine grained.	2.36	2.67	11.6	11,050
Town of Wallingford					
WLD 70 th	Sandstone, purple-red and buff-pink, coarse-grained and poorly sorted; with angular to subangular pink feldspars and a white bleached zone.	2.60	2.73	4.8	12,470

1/ Rock samples are from the Triassic-Jurassic New Haven Arkose and Shuttle Meadow Formations of the Newark Supergroup in the Hartford Basin in Connecticut.

Table 5.--Field determined compressional velocity of sound in shallow, saturated unconsolidated deposits.

Location	Lithologic description	Range of compressional velocities[1/] (ft/s)	Number of velocity measurements	Mean compressioal velocity (ft/s)
Connecticut	Glacial outwash, very fine sand, silt, and clay.	4,811-5,711	6	5,075
	Glacial outwash, fine to coarse sand.	4,964-5,572	7	5,178
	Glacial outwash, medium sand.	4,881-6,059	5	5,200
	Glacial outwash, sand and gravel.	5,070-6,074	5	5,584
Maine	Glacial outwash, fine sand silt, and clay.	4,576-5,592	7	5,159
	Glacial outwash, sand and gravel	4,762-5,685	3	5,350
Puerto Rico	Alluvium	5,000-5,983	6	5,546
Minnesota	Glacial drift	4,922-5,239	3	5,079
New Jersey	Glacial outwash	5,505-5,844	4	5,699
New Hampshire	Glacial outwash	4,195-5,249	4	4,524

1/ Compressional velocity determined by regression using seismic arrival times.

In many hydrologic studies, determining the configuration of the rock surface underlying an unconsolidated aquifer is the primary purpose of a seismic-refraction study. Seismic-refraction traverses can be run perpendicular or parallel to the axis of a valley. If the traverses are completed perpendicular to the axis of the valley, a series of cross-sections will be obtained (Haeni, 1978, p. 48-51). These perpendicular surveys are more efficient than surveys run parallel to the axis of the valley, but they may be more difficult to interpret. The spacing between the cross-sections is determined by the requirements of the study and the complexity of the valley area, but typically ranges from one half to one mile in small valleys to several miles in larger valleys.

Seismic-refraction data can be collected in areas that are inaccessible to heavy equipment and drill rigs. Marshes, swamps, river bottoms, and so on, can be profiled using equipment brought in by packpack or small boat. Operation in such terrain is necessarily slow, but the hydrologic information can be obtained. More sites than are needed should be selected, and their priority established, so that field crews can work continuously and efficiently during the allotted field time.

After the initial site selection is made, a field visit is necessary to inspect the site and ensure that the field crew will not encounter unexpected obstacles that would prevent or delay field operations.

The person inspecting the field sites should keep the following items in mind:

(1) Dirt roads and open fields are more desirable than wooded areas for seismic-refraction work.

(2) Buried water pipes, drain pipes, sewers, and telephone and power cables can be damaged by explosives. The extent and location of all buried utilities should be noted.

(3) Heavily developed areas are not good working sites if explosives are used.

(4) Heavily traveled roads or the operation of heavy equipment can cause background noise on the seismograph records and may prevent successful seismic operations. If possible, arrangements should be made to either stop this machinery for the few moments needed to fire the shot, or to schedule field activities for relatively quieter periods of the day.

(5) Newly plowed or cultivated fields have a very slow surface seismic velocity. Geophones should be placed in the undisturbed soil beneath this layer.

(6) If explosives are set in a deep drill hole, very slight damage to the ground will occur. If the explosives are set near the surface, flying rock debris and surface damage will probably result.

(7) When using electric blasting caps, radio frequency sources in the study area should be noted and checked for power output and operating schedules.

(8) Local authorities, including police and fire marshals, should be contacted so that the required permits can be obtained.

Safety Note:

All public or private utilities in the area should be notified if drilling or explosive work is going to take place. Some states have "Dial before you dig" services that help determine the presence and location of utilities in the study area. The utilities check must be as thorough as possible, inasmuch as the safety of the seismic and drilling crew depends upon it.

Summary

A well-planned seismic-refraction study will result in smooth and efficient field data-acquisition, and interpretations that define the hydrology of the study area. The lack of proper planning, on the other hand, will lead to wasted effort in the field, dangerous operating conditions, data that are difficult to interpret, and questionable results.

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A schematic diagram of a typical seismic-refraction system is shown in figure 28. The equipment necessary to carry out a refraction survey includes the following:

- Seismograph
- Geophones
- Geophone cables and geophone extension cables
- Sound source and associated equipment
- Shot cable
- Portable radios
- Field vehicles
- Hand level or transit and surveyor's rod
- Miscellaneous hand tools and shovels

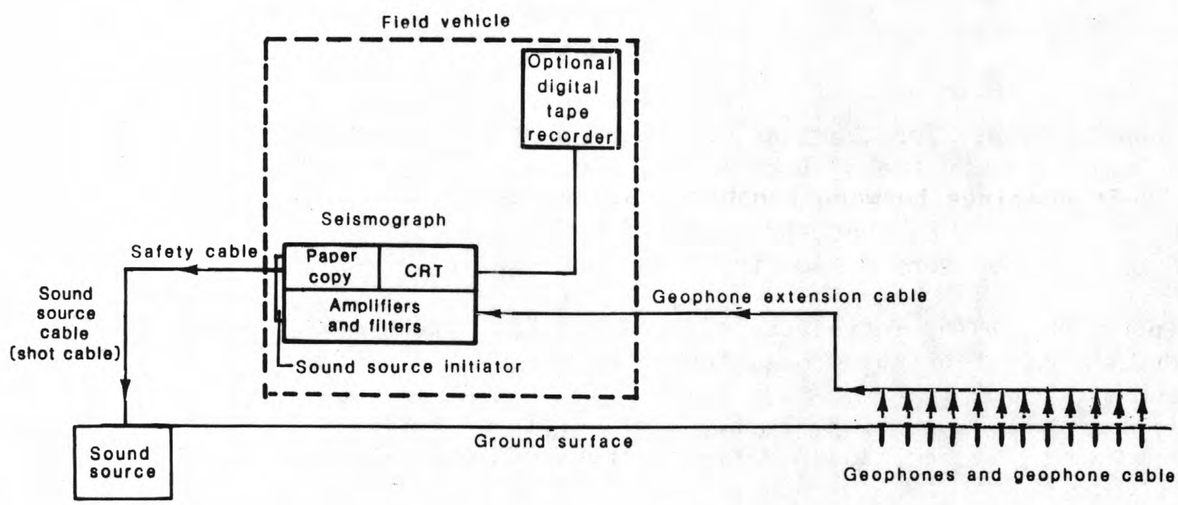


Figure 28.--Schematic diagram of a typical seismic-refraction system.

Seismograph

A large variety of seismographs are available from different manufacturers. They range from relatively simple, inexpensive single-channel units to very sophisticated, expensive, multichannel units like those used by the petroleum industry. Most modern units record the data digitally and are compatible with digital computers. The type of equipment best suited for water-resources studies is typically in the middle of this range, a 12- or 24-channel signal enhancement seismograph (Bullock, 1978). These units are capable of using a nonexplosive sound source because they can add the refracted signals from several successive nonexplosive impacts. The summation of these signals causes the amplitude of the refracted signal to increase and the random noise to cancel out.

Figure 29 shows the result of stacking a signal, first 5 times and then 10 times. The first-arrival energy increases significantly, but some low-frequency noise is also picked up.

The operation of each type of seismograph is explained in the operating manuals provided by each specific manufacturer and, therefore, will not be covered here. In general, these units are rugged, portable, and battery-powered. Figure 30 shows a typical seismograph of this type and some of the main features of these instruments.

Geophones

Geophones are instruments that convert the physical movement of the ground to an electrical signal. In seismic-refraction work, low frequency (8 to 10 Hz) vertical-motion geophones are used. An example is shown in figure 31. Clips are used to attach the geophone to the geophone cable. A spike on the base of each geophone ensures adequate physical contact between the geophone and the ground surface.

Geophone Cables

Geophone cables come in a variety of lengths with predetermined distances between geophone connections. For water-resources studies, cables with 25, 50, or 100-ft spacings between geophones are normally used (fig. 31). The predetermined distances commonly are varied in the field in order to yield more information about the particular subsurface layers of interest. These cables are designed so that either end may be attached to the seismograph and the geophones are sequentially numbered. The cables contain many small, insulated conductors and care must be taken not to damage these conductors when working on heavily traveled roads.

Extension cables are similar in design to the geophone cable except that no provision is made for connecting geophones. These are used in refraction studies to obtain offsets of the shot point from the first geophone. Figure 31 shows the commonly used geophone cables, extension cable, and breast reels.

Energy Sources

Many types of energy sources are available for use with refraction seismographs. Discussions of nonexplosive sources can be found in Mooney (1976), Mooney (1981, p. 21-1 to 21-11), and Beggs and Garriot (1979). Table 6 lists the energy sources most commonly used in hydrologic investigations and their advantages and limitations. Figure 32 shows some of these sound sources in use in the field.

Despite the obvious disadvantages of storage, transportation, and safety, explosives are very good energy sources for refraction work (Institute of makers of explosives, 1980; Institute of makers of explosives, 1981b). Other sources do not provide sufficient energy under most field conditions. A good alternative to the sole use of explosives, however, is the use of a mechanical or electrical source and selective use of explosives in areas where greater energy is needed.

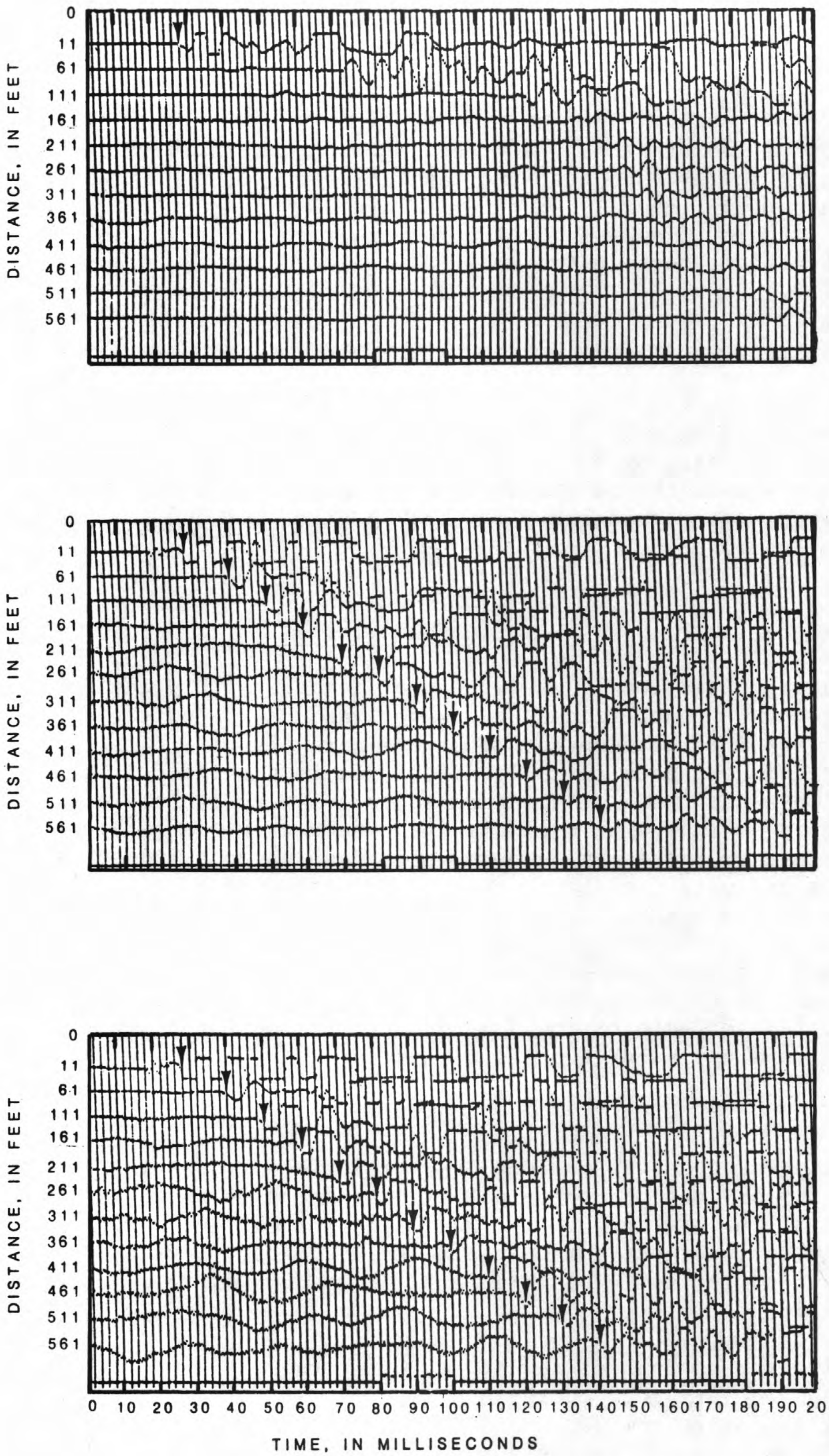


Figure 29.--Seismograms showing improvement in first breaks by stacking successive hammer impacts: A, one impact; B, five impacts; C, ten impacts.

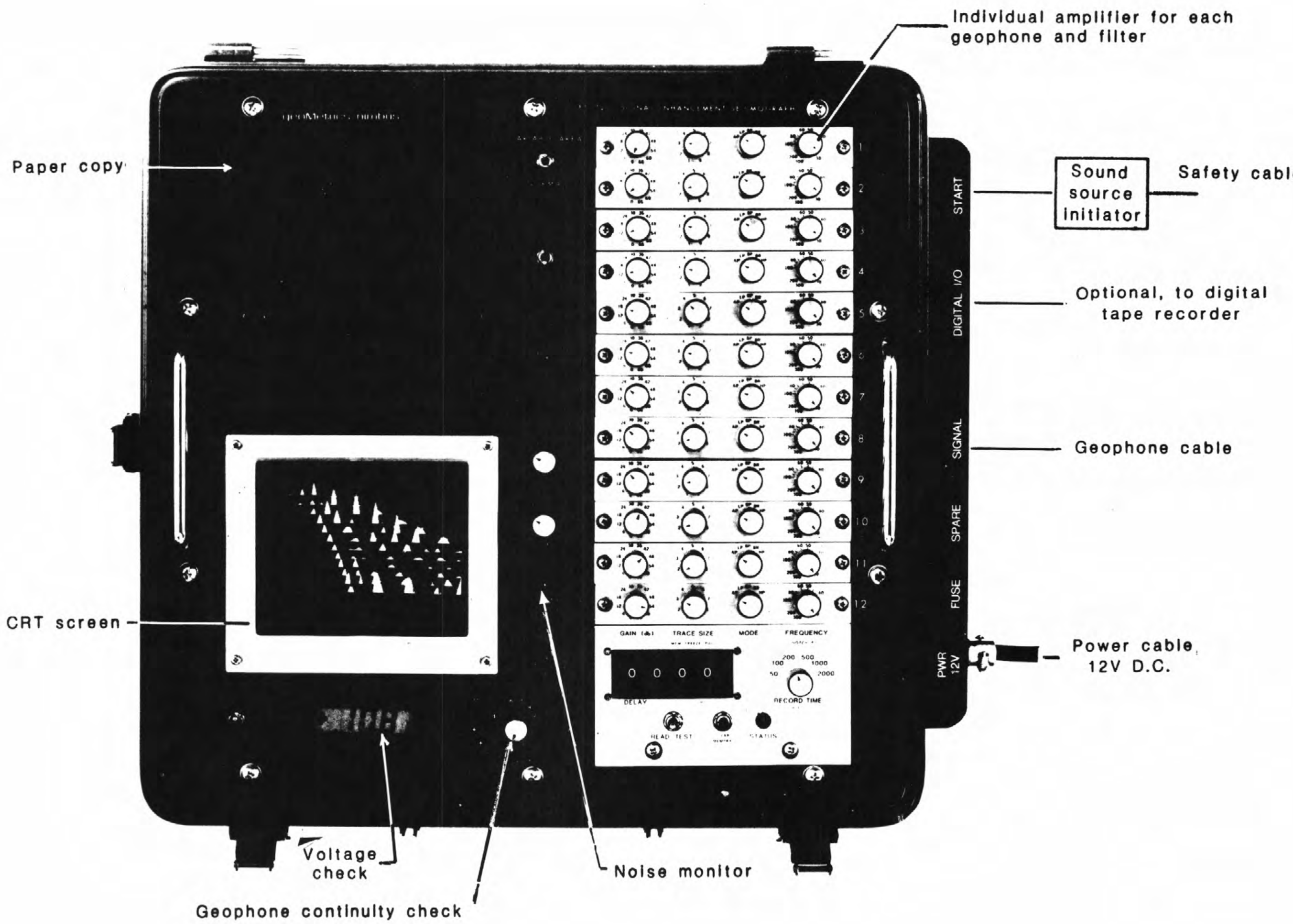
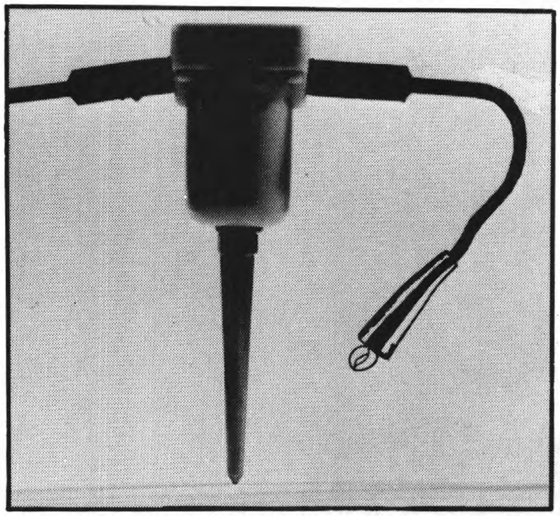
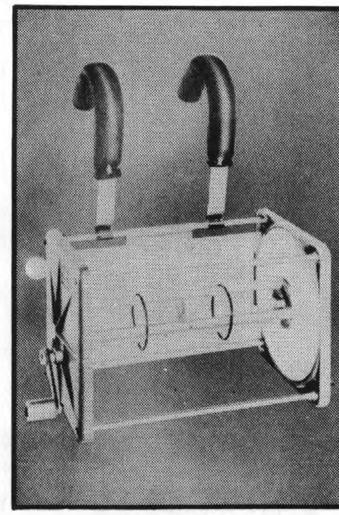


Figure 30.--Typical twelve-channel seismograph.



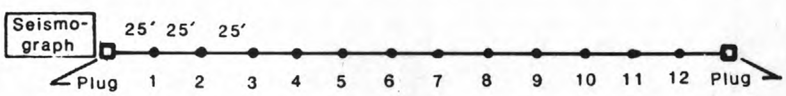
Geophone



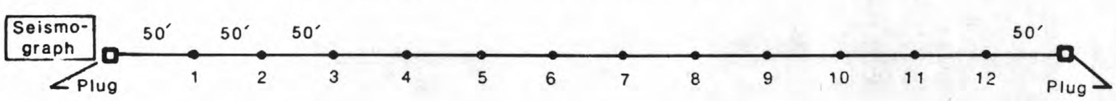
Breast reel

GEOPHONE CABLES

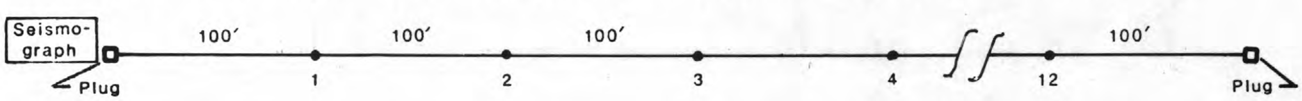
Cable with 25 feet between geophone takeouts. Total length 325 feet



Cable with 50 feet between geophone takeouts. Total length 650 feet.



Cable with 100 feet between geophone takeouts. Total length 1300 feet.



Geophone extension cable-no geophone takeouts. Total length 650 to 1300 feet.

Marked every 50 or 100 feet for ease in determining distance to first geophone from shotpoint.

Figure 31.--Commonly used geophone, breast reel, geophone cables, and geophone extension cable.

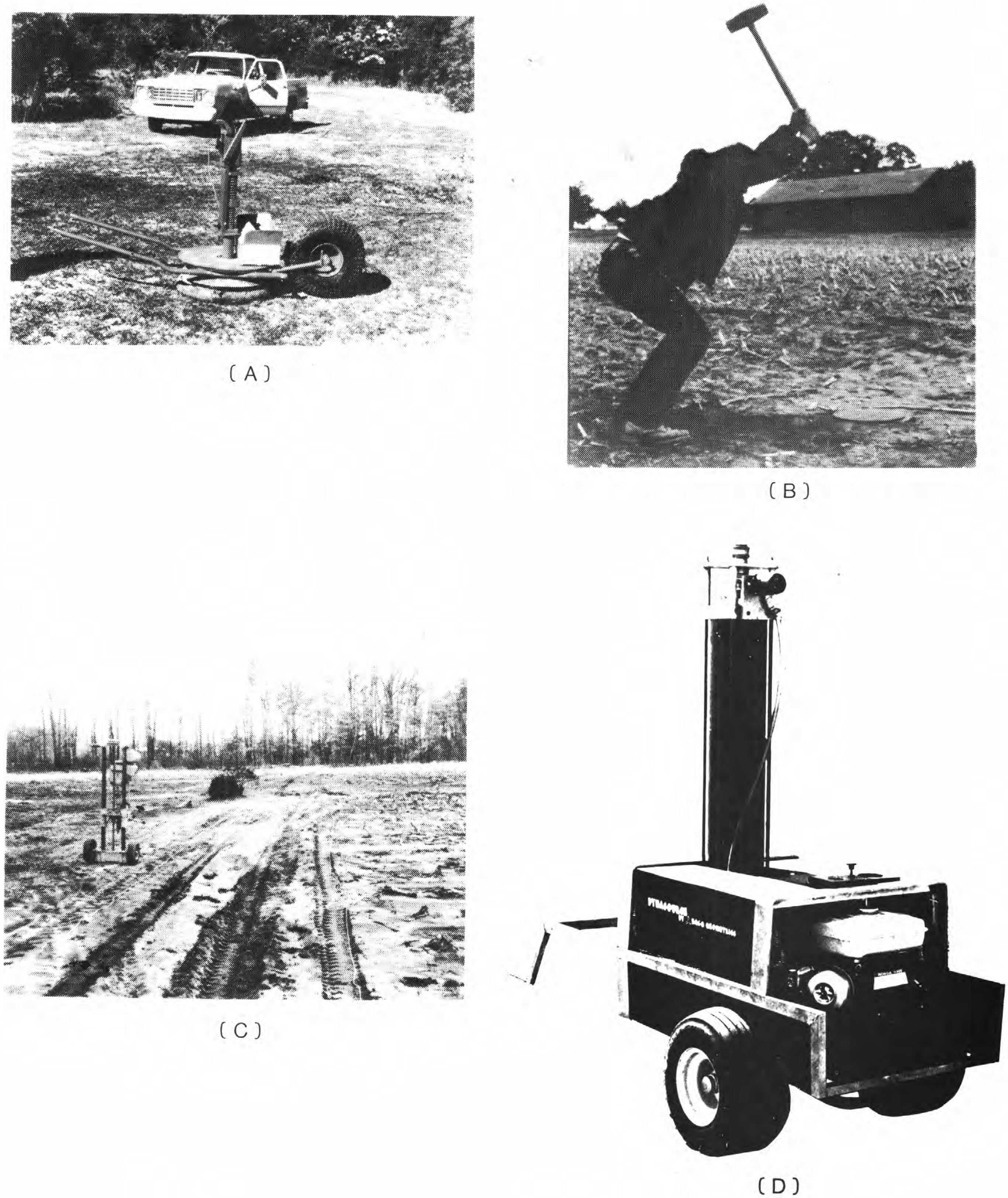


Figure 32.--Commonly used seismic energy sources: A, Shotgun; B, Sledge hammer; C, Explosives; D, Weight drop.

Table 6.--Advantages and limitations of seismic refraction energy sources.

Sound Source	Amount of energy put into ground	Field portability	Cost	Danger	Physical demand on field crew	Workable depth of saturated material	Effectiveness in area of thick unsaturated material (20-60 ft)	Specially trained people
Hammer	Small	Excellent	Low	Low	High	<100 ft	Poor	No
Weight drop	Small-medium	Poor	High	Medium	Low	100-200 ft	Fair	No
Shotgun	Medium	Fair	High	Low	Low	300 ft	Fair	No
Explosives	Small-large	Excellent	Low	High	Low	No limit	Excent	Yes

For hydrologic investigations, explosives generally will be needed under the following conditions:

1. Deep refraction studies requiring very long geophone lines (depth to deepest refractor 100 ft or more.)

2. Thick unsaturated sections, especially in fine-grained or loose materials (unsaturated material thicker than 30 or 40 ft).

Advances in the explosive manufacturing industry have virtually eliminated dynamite as a seismic-energy source. Dynamite has been replaced largely by two-component explosives consisting of a flammable liquid and a dry powder. These chemical components are relatively safe to handle, have minimum storage requirements, and do not form an explosive until mixed. Seismic blasting caps are still needed, however, to detonate the mixed explosive. Exploding bridge-wire detonators can be used instead of electric blasting caps. Bridge-wire detonators are similar to standard electric blasting caps, but can be detonated only with a special blaster. The use of the special detonators prevents accidental detonation of the cap by static charges, radio-frequency energy, or other induced electrical signals. Figure 33 shows two-component explosives being mixed in the field, and figure 32-C shows a detonation.

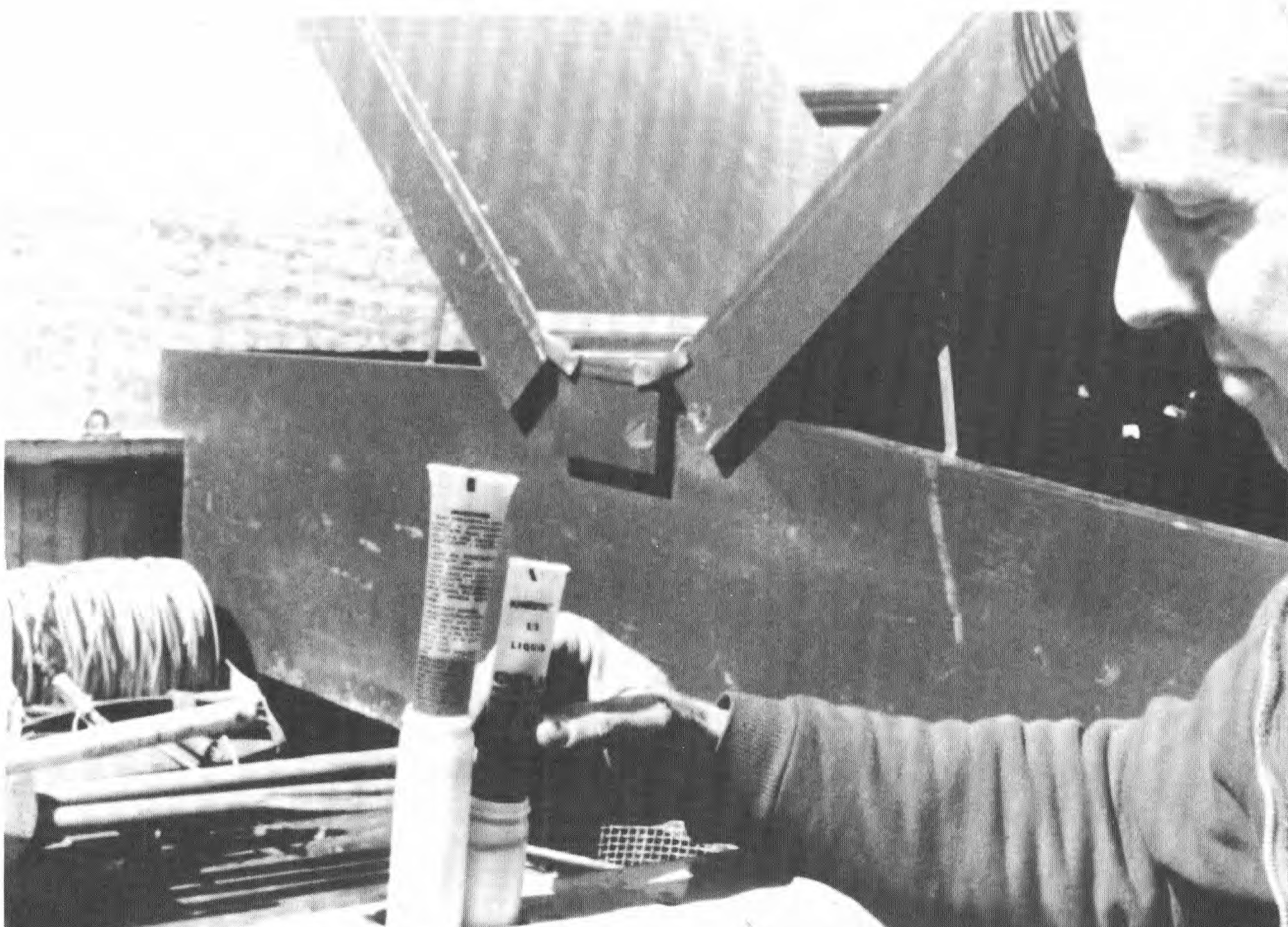


Figure 33.--Mixing two-component explosives in the field.

A hammer and striker plate are commonly used for very shallow investigations. Best results are obtained when the striker plate is placed on firm ground and the signal is stacked in the seismograph 5 to 15 times. The use of a sledge hammer is shown in figure 32-B.

Weight-drop (fig. 32-D) and shotgun (fig. 32-A) systems provide intermediate energy levels. Both these sources have approximately two to five times the energy of a sledge hammer, but significantly less energy than explosives.

Shot Cables

Seismograph manufacturers usually supply a cable that connects the seismograph to the energy source and allows the seismograph operator to activate the energy source. Usually, this is a long cable on a portable breast reel which allows the shot to be placed a long distance from the first geophone. A slight modification of this cable arrangement significantly improves the safety of the operation when using explosives. Figure 34 shows how a small safety cable can be installed that prevents inadvertent firing of the explosive while it is being loaded in the hole. Some blasting units have an integrated safety key that serves the same purpose.

In deep basin studies, very long offsets between the sound source and the first geophone are needed. In these studies, a radio blaster can be used to replace the long shot cables.

Portable Radios

Portable, low-power FM radios are very useful in a seismic-refraction field operation because they allow crew members to communicate with each other over the long distances common in refraction shooting. They also serve as an important safety item when using explosives. Crew members can warn the blaster immediately when people stray into the blasting area, or when other dangerous conditions exist.

SAFETY NOTE: High-powered radio transmitters should not be used near blasting operation nor should a siesmic array be set up near such transmitters (Institute of the Makers of Explosives, 1981a).

Vehicles

Many different types of field vehicles can be used for seismic-refraction work. If the work is performed in off-the-road situations, a four-wheel drive van or truck with a winch greatly improves the efficiency of the operation. Figure 35 shows both a pickup truck and a van set up for seismic field work. Because most seismographs can be powered by 12-volt direct-current power, a means of using the truck system should be installed.

If explosives are to be used during a study, the vehicles should be equipped with a small drill rig to drill the necessary shot holes (fig. 35). The shotgun and sparker sources require water for their use and therefore the truck should be equipped with a water tank.

Levels and Transits

A hand level and a surveyor's rod are usually sufficient to establish the relative elevation of all shotpoints and geophones. For more detailed studies, particularly where geophones cannot be placed along straight lines, a transit is required.

Miscellaneous Tools

Shovels, wooden tamping poles, 100-ft cloth tape, machetes, and a hand tool box are helpful in seismic-refraction field operations. A canvas tarpaulin should also be carried for placing over the explosives to help control flying rock produced by the explosion.

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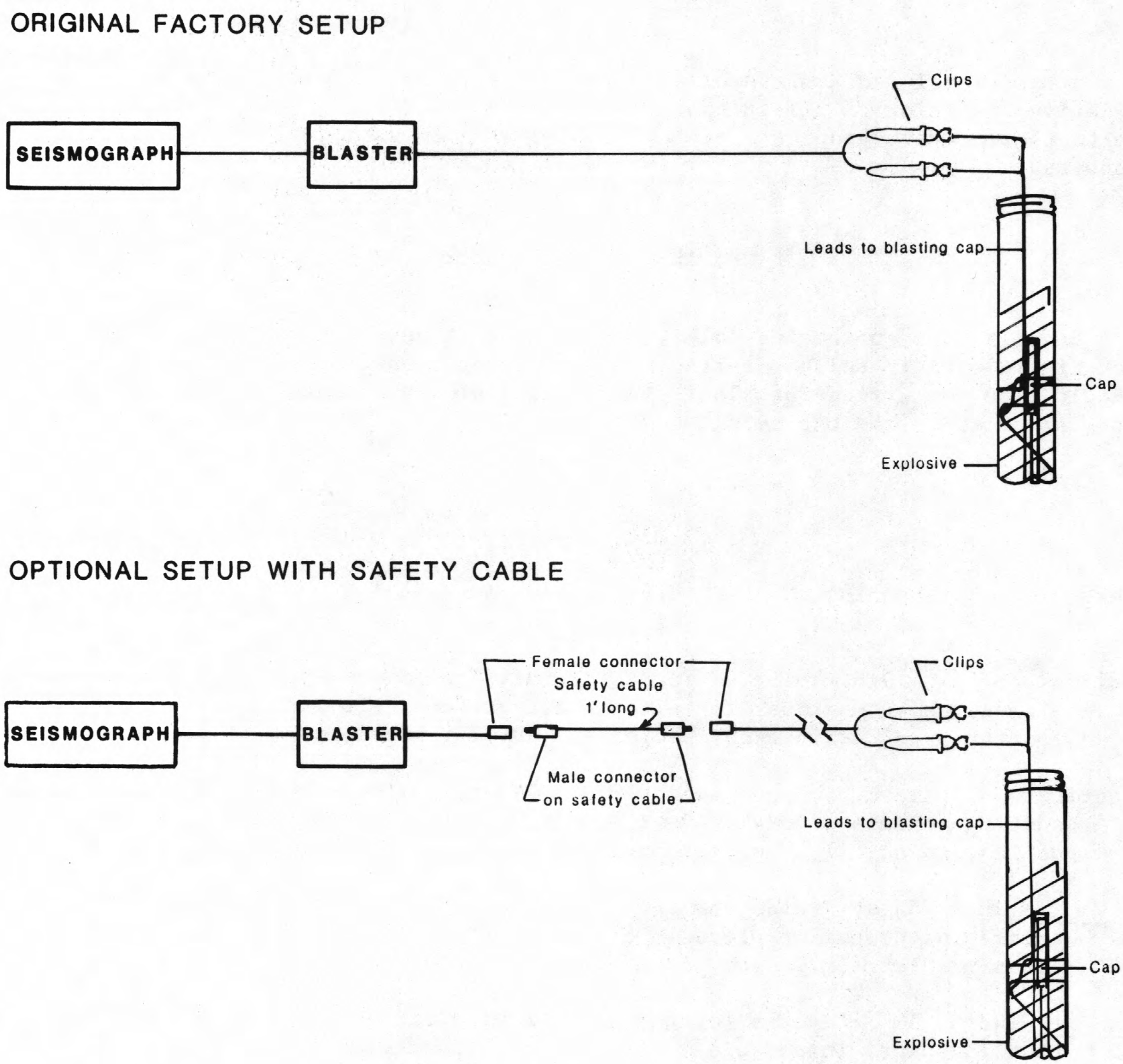


Figure 34.--Safety wire in explosive-firing circuit.

Figure 35.--Van and pickup truck used for seismic-refraction field work.

FIELD PROCEDURES

Reconnaissance Refraction Survey of a Site

If the seismic-refraction survey has been planned properly, the first site visited in the field should be a site about which some subsurface information is known. The main objective of making preliminary seismic measurements at this site is to verify that the assumed seismic-velocity contrasts between the geologic or hydrologic boundaries of interest are present and can be identified with the equipment and techniques available. This is an important phase of the investigation; the decision to continue or terminate the geophysical investigation is often based on the results of this preliminary field work. In this phase of the study, the investigator must be aware of field results that differ from the conceptual hydrologic or geologic earth model; any differences should be reconciled before work continues.

The first field test should be designed to obtain a detailed seismic-velocity profile of the entire geohydrologic section of interest. To accomplish this, spacing between geophones should be selected so that first arrivals are obtained from each individual refracting surface. This may require adjusting the geophone array several times and shooting from each end each time. The geometry of the shotpoints and geophones required for a successful field test may vary considerably, depending upon the depth of the refractors and the velocity of sound in each subsurfaces layer.

In order to design this initial field test, the investigator must do some rough field calculations based on available information and the conceptual model of the subsurface geology.

Field Interpretation and Calculations

It is necessary to make field calculations and rough interpretations prior to the initial phase and during subsequent field operations. This procedure allows the investigator to plan the geometry of each seismic traverse in the field so that the maximum amount of information can be extracted from the resulting field records. It also points out significant departures of the field data from the results expected from the earth model.

One approach to performing these field calculations is to program the dipping two- and three-layer formulas on a hand-held calculator. These programs usually require intercept times that can be obtained from preliminary plots of the field data.

Another approach is to use the critical distance formulas for two- and three-layer horizontally layered cases. These formulas, although not correct for dipping layers, will suffice for rough field calculations and are computationally much simpler. In addition, if layer 1 is thin compared with layer 2, the assumption can be made that layer 1 is not present and the three-layer case can be approximated as a two-layer case. This procedure is only satisfactory for rough field calculations and <u>not</u> for the final interpretation of the data.

If the second approach is chosen, the following formulas (discussed in the Theory Section) can be used for these calculations:

A) Two-layer parallel boundary crossover-distance formula, (eq. 2):

$$z = \frac{x_c}{2}\sqrt{\frac{V_2 - V_1}{V_2 + V_1}}$$

B) Three-layer parallel boundary crossover-distance formulas, (eq. 6-8):

$$z_1 = \frac{x_{c1}}{2}\sqrt{\frac{V_2 - V_1}{V_2 + V_1}}$$

$$z_2 = \frac{x_{c2}}{2}\left(\frac{V_3 - V_2}{\sqrt{(V_3)^2 - (V_2)^2}}\right) - z_1\left(\frac{V_2\sqrt{(V_3)^2 - (V_1)^2} - V_3\sqrt{(V_2)^2 - (V_1)^2}}{V_1\sqrt{(V_3)^2 - (V_2)^2}}\right)$$

$$z_3 = z_1 + z_2$$

If approximate values of V_1, V_2, and V_3 are known or can be estimated, the above equations can be reduced to much simpler forms by treating the velocity terms as a constant throughout the study area. This is a reasonable assumption for a given study area and for the specific purpose of determining spread geometries.

Let:

$$A = \sqrt{\frac{V_2 - V_1}{V_2 + V_1}} \qquad (23)$$

$$B = \frac{V_3 - V_2}{\sqrt{(V3)^2 - (V2)^2}} \qquad (24)$$

$$C = \frac{V_2\sqrt{(V_3)^2 - (V_1)^2} - V_3\sqrt{(V_2)^2 - (V_1)^2}}{V_1\sqrt{(V_3)^2 - (V_2)^2}} \qquad (25)$$

Now for the two-layer case:

$$z = x_c \frac{A}{2} \quad (26)$$

and for the three-layer case:

$$z_1 = x_{c1} \frac{A}{2} \quad (27)$$

$$z_2 = x_{c2} \frac{B}{2} - z_1 C \quad (28)$$

$$z_3 = z_1 + z_2 \quad (29)$$

Rearranging the above:

for the two-layer case:

$$xc = \frac{2z}{A} \quad (30)$$

for the three-layer case:

$$x_{c1} = \frac{2z_1}{A} \quad (31)$$

$$X_{c2} = \frac{2(z_2 + z_1 C)}{B} \quad (32)$$

The investigator can now determine the approximate values of x_{c1} and x_{c2} from assumed values of seismic velocities in layers 1, 2, and 3, and the approximate depths of layers 1 and 2 (from drill hole or other geologic data), prior to going into the field. Using these values, it is possible to make an estimate of the field geometry of the shotpoints and geophone spreads needed to determine the exact values of velocities and layer thicknesses.

The preceding computations are needed to assess the feasibility of using the seismic-refraction technique and to obtain the maximum amount of usable geophysical data from production field surveys. The following example illustrates this process.

Example problem

An alluvial aquifer has a water table about 20 ft below the land surface and crystalline bedrock about 100 ft below the land surface. The saturated thickness of the aquifer is 80 feet. From a nearby study the velocity of sound is known to be 1,000 ft/s in dry alluvium (V_1), 5,000 ft/s, in saturated alluvium, (V_2), and 15,000 ft/s in crystalline bedrock (V_3). In addition, it is assumed that the stratigraphic units are horizontally-layered.

Because this is the beginning of a new project, it is desirable to accurately determine the field velocities for layers 1, 2, and 3. An approximate value for x_{c1} and x_{c2} is needed to design the initial field setup to obtain these data. Figure 36 shows a general geologic section for this area and shows the time-distance plot which would be expected.

First, the constants A, B, and C can be calculated from the assumed velocity values, using equations 23, 24, and 25.

$$A = \sqrt{\frac{V_2 - V_1}{V_2 + V_1}} = \sqrt{\frac{5{,}000 - 1{,}000}{5{,}000 + 1{,}000}} = 0.8$$

$$B = \frac{V_3 - V_2}{\sqrt{(V_3)^2 - (V_2)^2}} = \frac{15{,}000 - 5{,}000}{\sqrt{(15{,}000)^2 - (5{,}000)^2}} = 0.7$$

$$C = \frac{V_2\sqrt{(V_3)^2 - (V_1)^2} - V_3\sqrt{(V_2)^2 - (V_1)^2}}{V_1\sqrt{(V_3)^2 - (V_2)^2}} =$$

$$\frac{5{,}000\sqrt{(15{,}000)^2-(1{,}000)^2} - 15{,}000\sqrt{(5{,}000)^2-(1{,}000)^2}}{1{,}000\sqrt{(15{,}000)^2 - (5{,}000)^2}} = 0.0953$$

Now, using the three-layer equations (31 and 32) and solving for x_{c1} and x_{c2}:

$$x_{c1} = z_1 \frac{(2)}{(A)} = 20 \frac{(2)}{(0.8)} = 50 \text{ ft}$$

$$x_{c2} = [z_2 + z_1(C)] \frac{2}{B} = [80 + 20(0.0953)] \frac{2}{0.7} = 234 \text{ ft}$$

This approximate information and the expected time-distance plot in figure 36 can now be used to design the initial field setup. If the geologic units were dipping instead of horizontal, a rigorous approach would require the use of the dipping layer formulas. The horizontal-layer formulas may be used to obtain a first approximation, however, because only the approximate spread geometries are of interest at this point.

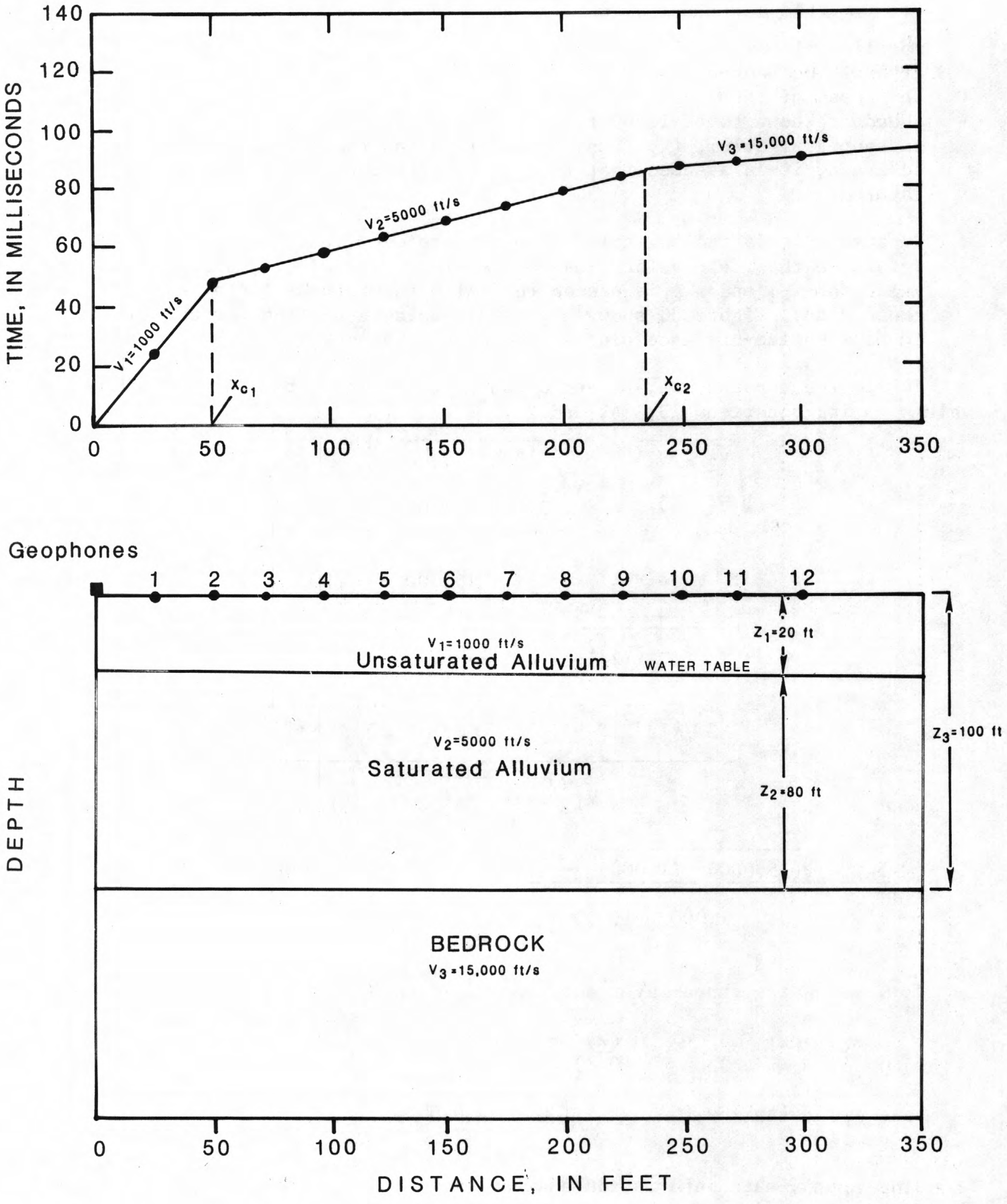


Figure 36.--Time-distance plot and interpreted seismic section for a three-layer problem.

Considerations of spread design for example problem:

a) To determine V_1 in the field and the depth to layer 2, most of the geophones must be located less than 50 ft from the sound source (fig. 37-A).

b) To determine V_2 and the depth to layer 3, most of the geophones must be placed between 50 and 234 ft from the sound source (fig. 37-B).

c) To determine V_3, most of the geophones should be placed more than 234 ft from the sound source (Fig. 37-C).

Because the depths and seismic wave velocities used in the formulas are just estimates, several geophones should be placed on each side of these calculated distances. Note that all velocities will be apparent velocities unless the refracting interface is truly horizontal, in which case the velocity segments on the forward and reversed shots will be equal. If these segments are not equal, the true velocity must be calculated (see Theory Section) and a dipping-layer formula used to eventually interpret the depth and dip of the refracting interface.

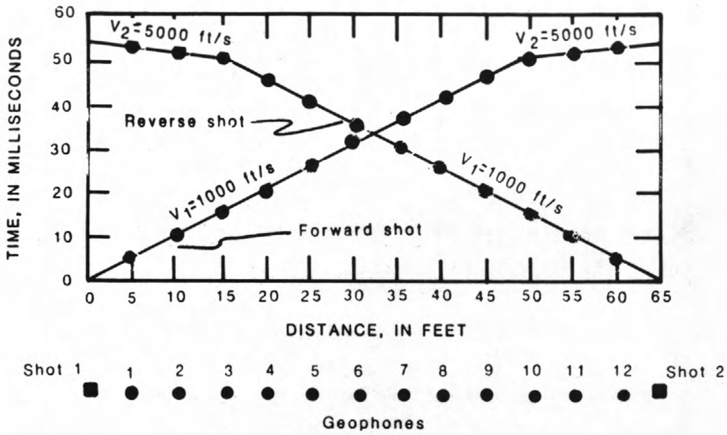
The initial seismic-refraction survey now can be made and the data collected for analysis. The actual travel-time plots will differ from the expected one in figure 36, depending upon how much the study area differs from the conceptual model. As long as the deviation is not extreme, usable data will be collected. If significant variation does occur, the geometry of the spread must be changed in the field so that a complete velocity profile is obtained.

After reviewing the results of the preliminary survey, the investigator should know the velocities of the materials in the hydrologic section and whether or not the seismic-refraction technique will delineate the interface of interest.

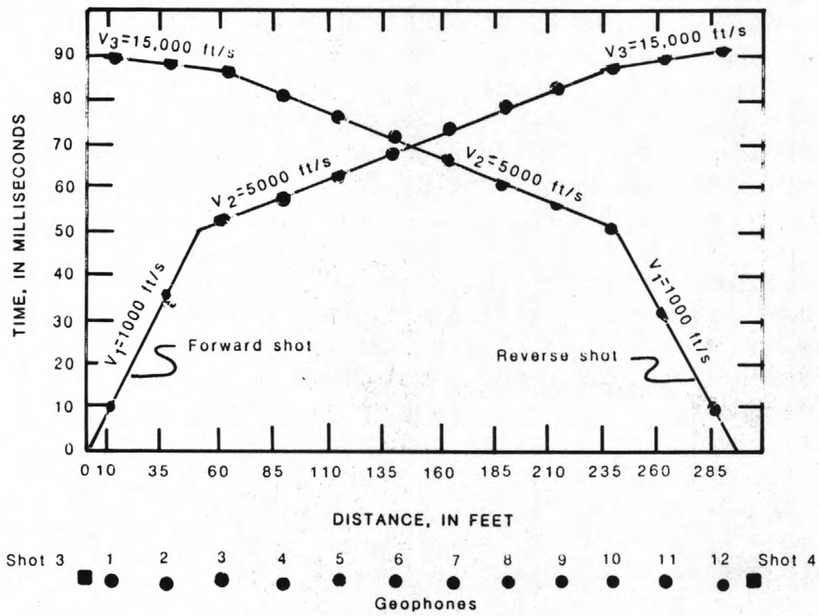
Quality or Quantity of Field Data

By looking at the previous example, it is obvious that some decisions must be made as to what data are to be collected in the operational part of the field activities. Ideally, the shotpoint and the geophone geometry would be set up so that all seismic velocities and layer boundaries in the hydrologic section are defined without changing the geophone geometry. Figure 37 shows that a minimum of six shots and three spread geometries are needed to accurately and fully define all of the subsurface layers. In most hydrologic investigations, data over a wide area is needed, but the data need not be as precise as in an engineering site investigation.

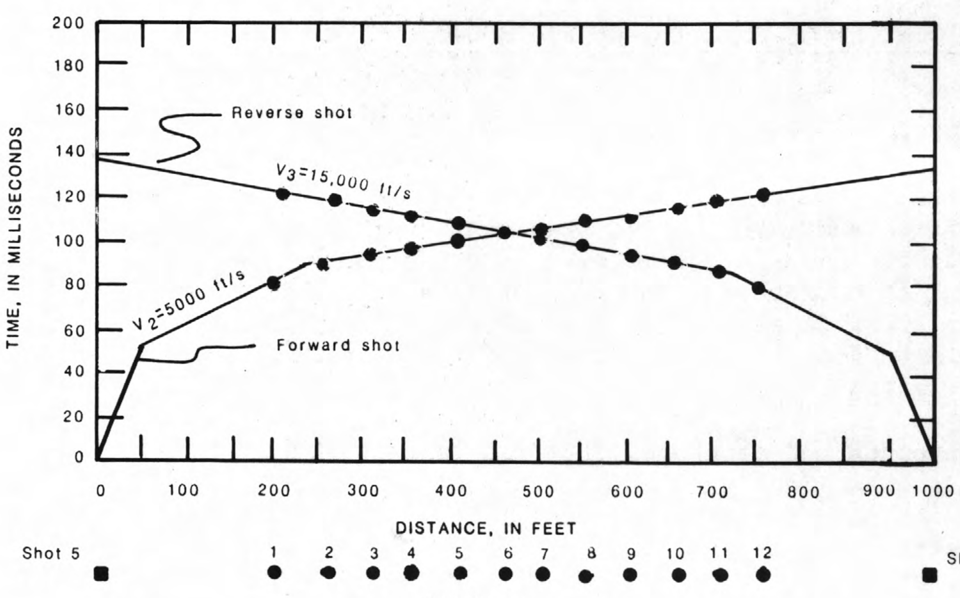
One pattern of shotpoints and geophones that can be used effectively in field production work is shown in figure 38 with the resulting selected ray paths for the first 3 shot points. The resulting time-distance plot and interpreted cross-section are shown in figure 39. This single geophone arrangement allows accurate delineation of a shallow refractor (the water table in unconsolidated alluvium) and a deep refractor (bedrock) with five shot points. Figure 40 shows the time-distance plot and geologic section resulting from only two shotpoints using the same geophone spacing.



A. Field setup: five feet between geophones and 5 feet between shot point and first geophone.



B. Field setup: Twenty five feet between geophones and 10 feet between first geophone and shot point.



C. Field setup: Fifty feet between geophones and 20[illegible] feet between first geophone and shot point.

Figure 37.--Time-distance plots and field setups used to determine the seismic velocities of the three-layer problem shown in figure 36.

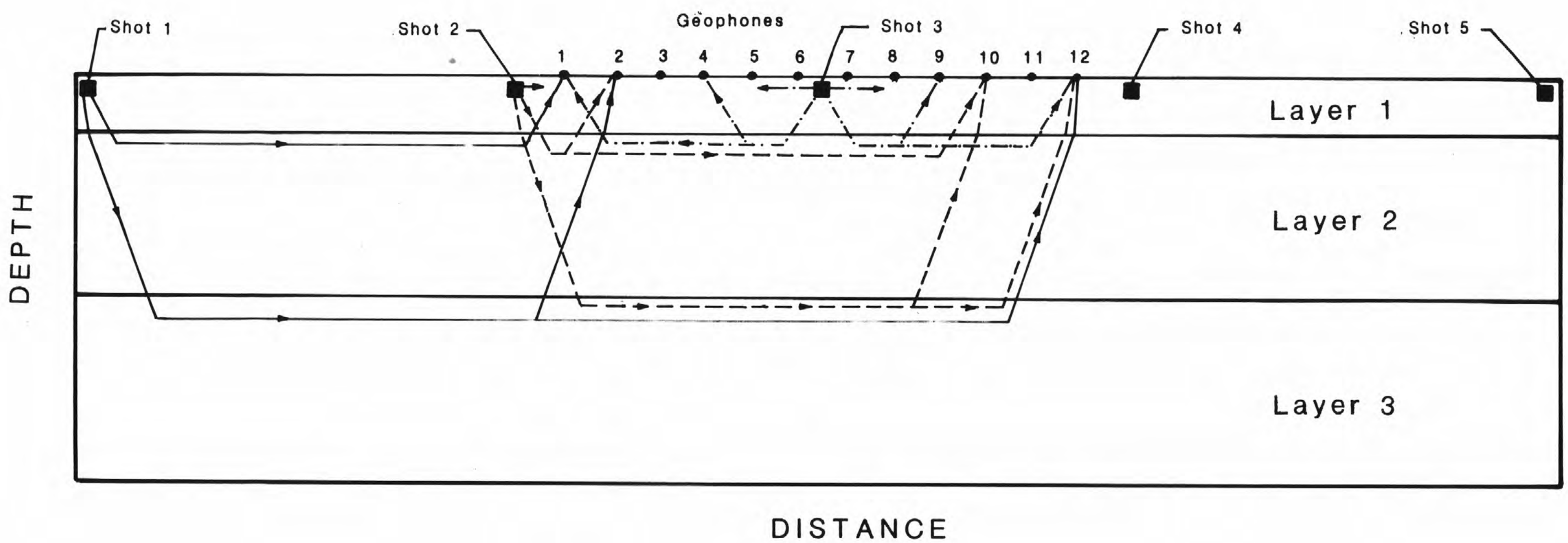


Figure 38.--Field setup of shotpoints and geophones for delineation of multiple-refracting horizons. Only selected raypaths for shotpoints 1, 2, and 3 are shown. The raypaths for shotpoints 4 and 5 are the mirror image (with respect to shotpoint 3) of the raypaths for shotpoints 2 and 1 respectively.

A comparison of figure 39 and 40 shows that individual velocity segments on the time-distance plot in figure 40 are defined by fewer points than in figure 39.

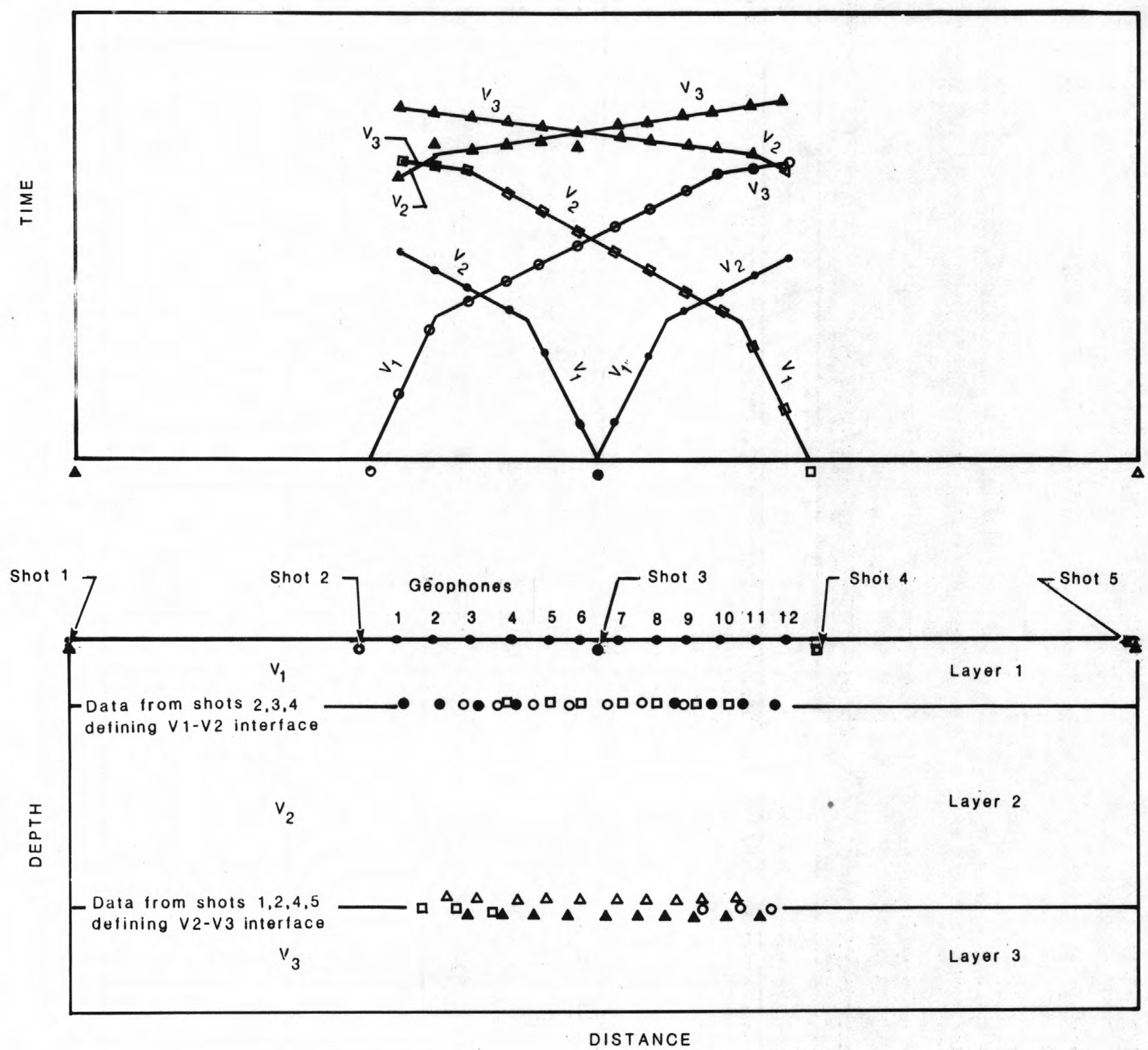


Figure 39.--Time-distance plot and interpreted seismic section resulting from a single geophone spread with five shotpoints.

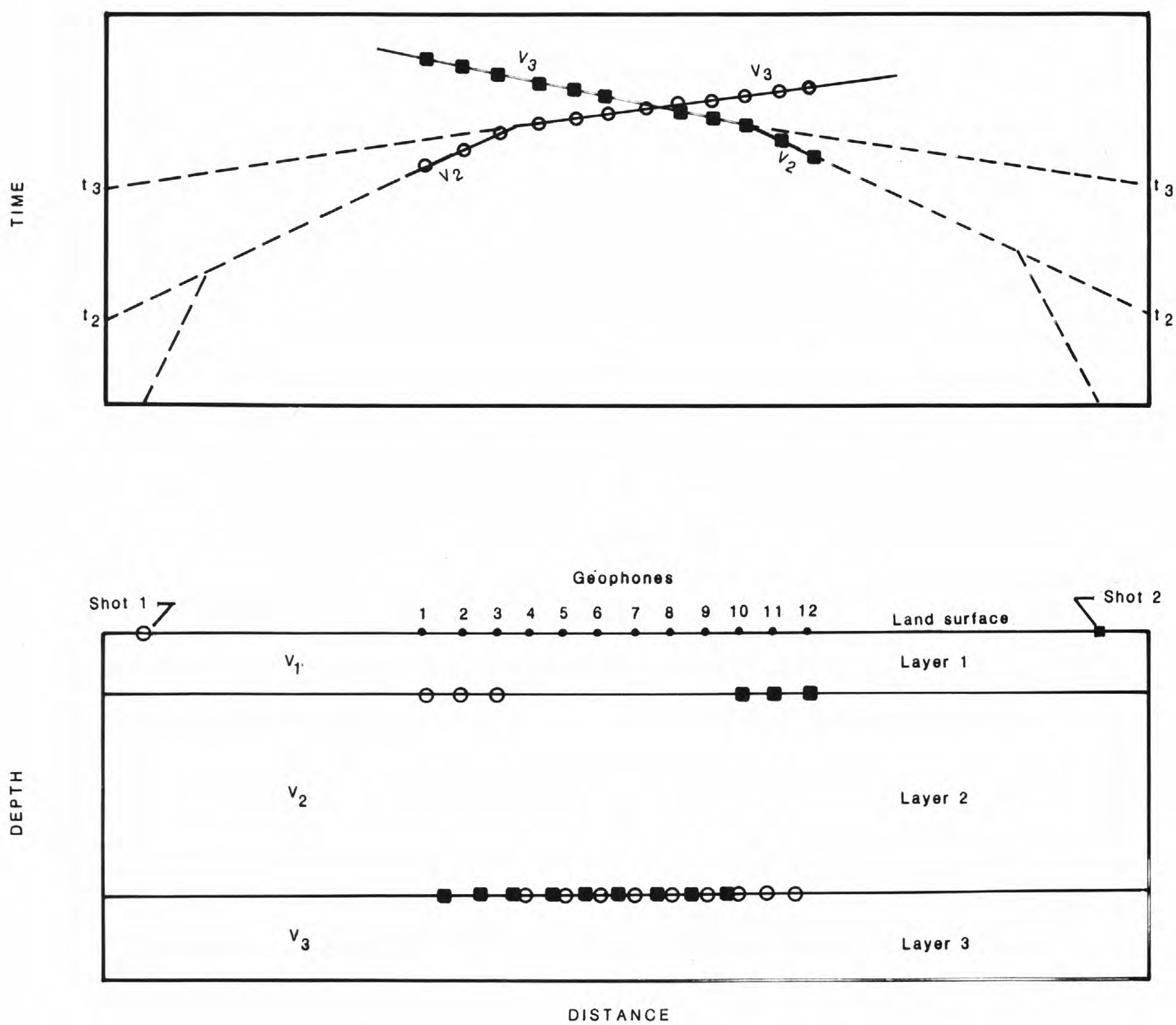


Figure 40.--Time-distance plot and interpreted seismic section resulting from a single geophone spread with two shotpoints.

In figure 39, the velocity of sound in layer 1 is calculated by determining the inverse slope of a line formed by data from two geophones from shotpoints 2, 3, and 4. Likewise, the velocity of sound in layer 2 is calculated by using seven points from shots 2 and 4, and eight points from shot 3. The velocity of sound in layer 3 is calculated by using three points from shots 2 and 4, and 11 points from shots 1 and 5.

In figure 40, the velocity of sound in layer 2 is defined by only two points from each shotpoint, and the velocity of sound in layer 3 is defined by 10 points from each shot. Again, the quality of the data has decreased, but the number of shots has been decreased from five to two, increasing field production. In this case, no velocity data were obtained from layer 1, so this information would have to be determined by other means. Obviously, this arrangement represents a compromise between quantity and quality of field data, and can be used only in areas where the geology is well known.

The following section describes various techniques of interpretation of seismic-refraction data. If the delay-time technique is used, the field set up should be designed so that a large number of geophones receive energy from shots in opposite directions whose head wave is refracted off the subsurface interface of interest. For example, if the main purpose of the refraction study is to map the bedrock surface, most of the geophones should have first arrival energy refracted from the bedrock surface.

Figure 41 shows the different time-distance plots that would result from different shotpoint/geophone array field geometries over a three-layer subsurface. This figure assumes horizontal layers and seismic velocities of 1,000 ft/s, 5,000 ft/s, and 15,000 ft/s. These velocities are common in hydrologic studies and could represent a geologic section consisting of dry alluvium or stratified drift, overlying saturated alluvium or stratified drift, overlying crystalline bedrock.

Example Problem:

The water table in an alluvial aquifer is assumed to be 20 ft deep and the bedrock is approximately 120 ft deep. Seismic velocities are estimated to be 1,000, 5,000, and 15,000 ft/sec for V_1, V_2, and V_3, respectively.

Entering figure 41 with the assumed values for the depth to water (20 ft) on the vertical axis and the thickness of saturated material (100 ft) on the horizontal axis, a hypothetical time-distance plot is found. This is the plot that would be obtained in the field, if the assumptions about the subsurface were correct, and the spread was designed as indicated by the diagram below the plot (using the distances listed above the plot). For this example, a spread cable with 50 ft between geophones and two offset shotpoints (25 and 200 ft from the first geophone) would be used.

Reversed shots should always be taken to determine if the assumption of a horizontally-layered Earth is valid. If this is a valid assumption, the forward and reverse plots will be mirror images of one another. The diagrams in figure 41 are only a guide to aide in the design of field setups.

The problem of quantity as opposed to quality affects every seismic-refraction field survey and should be clearly understood by anyone applying this technique. Specifically, the decision whether to conduct detailed surveys over little ground or to cover much ground with a general survey must be made early in the study and depends on the objective and purpose of the study.

Field Crew

After the initial tests have been completed and the seismic-refraction technique has been shown to work in the study area, production work is ready to begin. The organization and operation of a small field crew varies, depending upon the number of people available, the type of equipment to be used, the terrain, and the objectives of the investigation.

Hydrologic seismic-refraction studies generally are directed toward shallow targets (less than 500 ft), in areas of relatively flat terrain with some open space. Some studies, however, are done in heavily wooded, swampy, or suburban areas where special field procedures and more people may be needed. An experienced crew of three people in open areas can complete three to four reversed seismic-refraction profiles in an 8-hour day. The same crew in swampy and wooded areas may be able to complete only one or two profiles per day.

A field crew should consist of a minimum of three people for small-scale hydrologic refraction studies (target depths from 0 to 500 ft), and four or more people for larger operations (target depths 500 ft or more). Upon arrival at a site, the party chief should design the field layout of the geophones and shot points, set up the seismograph, check the continuity of each geophone, and prepare to record the first shot. The other members of the crew should lay out the geophone cable, connect the geophones, prepare the sound source at the first shot point, run the shot cable to the truck, and survey the location and elevation of each geophone and shotpoint. The sequence of these tasks will vary, and each party should establish its own routine. In general, however, each member should be proficient in most of the jobs and be able to fill in when someone is delayed on one particular job. This approach will add greatly to the overall efficiency of a small seismic operation. An example of the work assignments for a three-person crew setting up a seismic line with one shot on each end of a line is given in table 7.

Figure 42 shows a small truck outfitted with the seismic-refraction equipmient needed in a hydrologic study. The vehicle is used to carry the seismograph, drilling equipment, and all other gear. Figure 42 also shows a typical field setup for a seismic-refraction survey.

The following is a list of the steps that need to be completed in order to conduct a seismic-refraction survey.

(1) The truck is set up for field work and the geophones and appropriate spread cable are unpacked.

SAFETY NOTE: Although the site should have been checked previously for electric wires, underground utilities, and so forth, it should be checked again. Telephone poles that have no overhead wires to a building but have attached electrical cables may indicate buried electrical lines. Cleared areas through woods may indicate buried pipelines. Blasting operations should not be performed if lightning storms are occurring in the area or if unchecked radio-transmission towers are visible. Smoking must not be allowed near explosives, and hard hats should be worn.

(2) The site is set up for the sound source. If explosives are to be used, a hole should be drilled. If possible, the sound source should be placed at the water table to improve acoustic coupling and reduce the amount of energy required from the source. A drilled hole also reduces the possibility of flying rock if explosives are used. Table 8 is a guide to the possibility of encountering fly rock with various amounts of explosives under different field conditions.

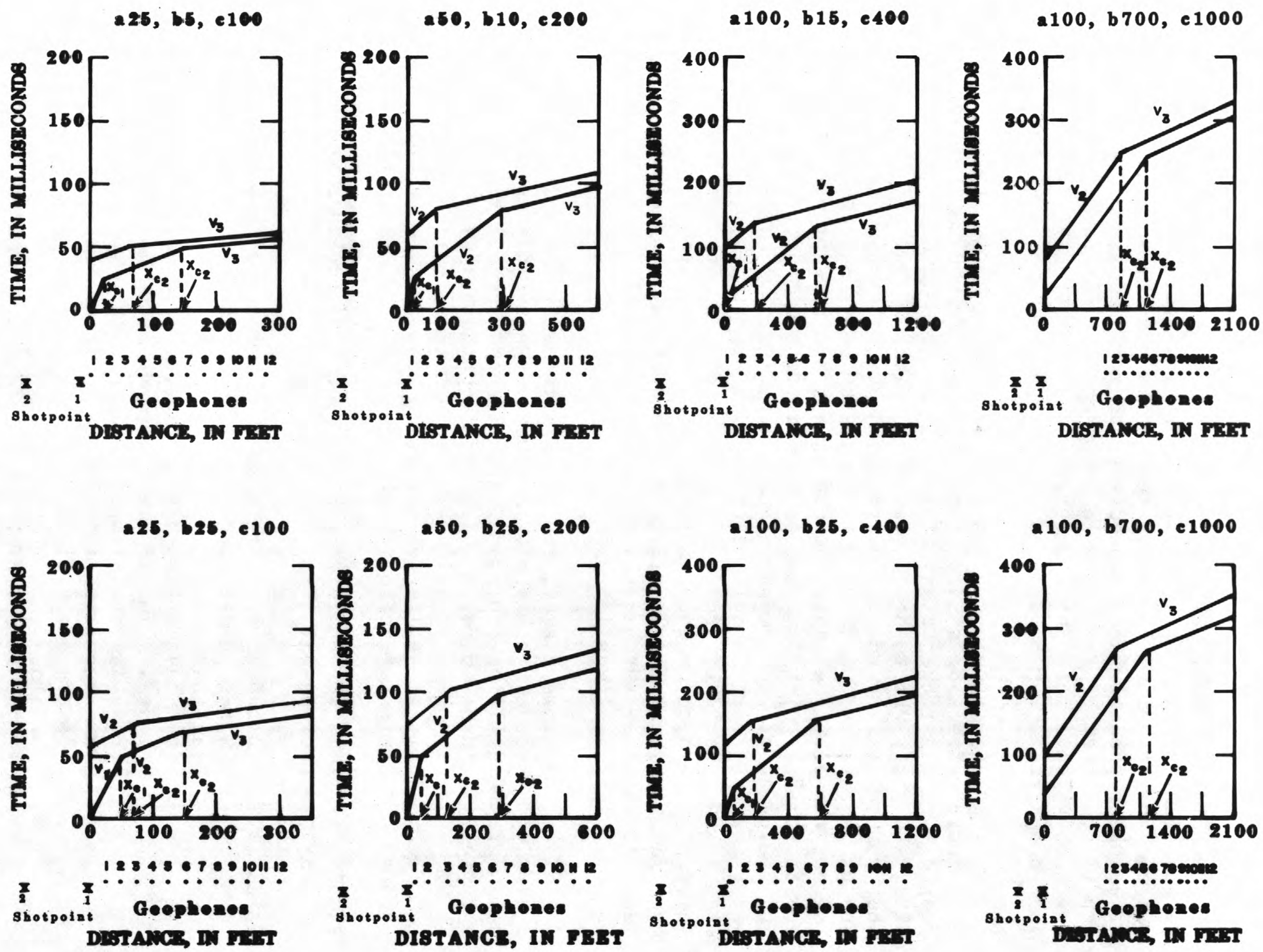
DEPTH TO LAYER 2

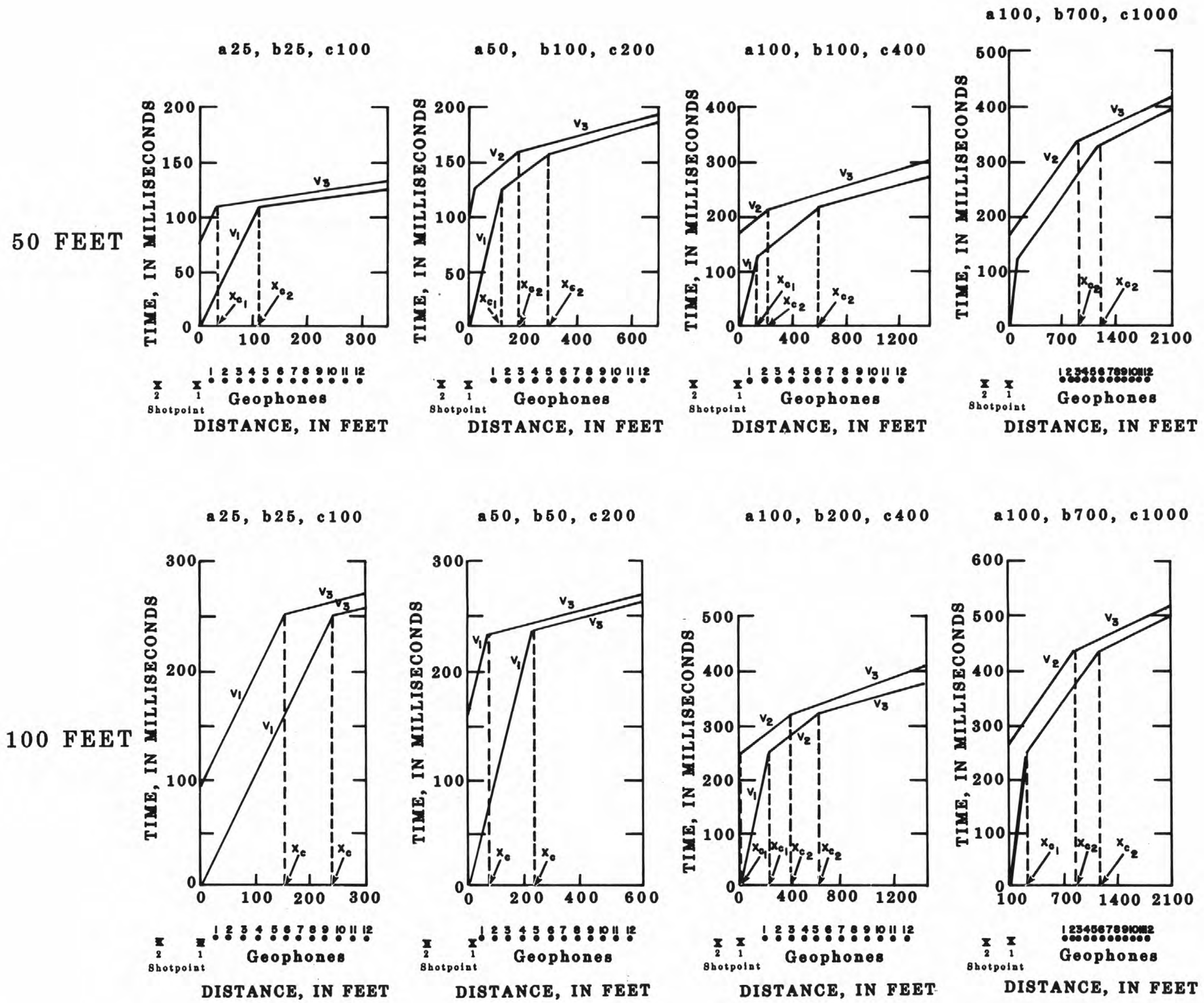
THICKNESS OF LAYER 2

50 FEET | **100 FEET** | **200 FEET** | **400 FEET**

10 FEET

20 FEET





a) Distance between geophones b) Distance between shotpoint 1 and the first geophone c) Distance between shotpoint 2 and first geophone

Note: When V_2 does not appear or T-D plot, blind zone conditions may exist.

Figure 41.--Shotpoint and geophone geometries for various thicknesses and depths of layer two and the resulting time-distance plots.

Table 7.--Typical seismic field-crew work assignments.

Hydrologist (party chief)	Helper 1	Helper 2
1. Tells helpers geometry of line.	1. Lays out geophone line and attaches geophones.	1. Drills hole 1 for explosive.
2. Checks continuity of geophones on seismograph.	2. Lays out shot cable.	2. Helps load hole with explosive and tamps backfill or stemming.
3. Mixes two-compound explosive, installs cap, and immediately loads hole.	3. Surveys in the line.	3. Surveys in the line.
4. Fires shot 1 and checks record.	4. Helps drill hole 2 and set explosive.	4. Drills hole 2 for explosive.
5. Records field data.		
6. Moves truck for shot 2.		
7. Repeats steps 2-6 for the remaining shots.		

Table 8.--Probability of hazardous flying rock debris resulting from use of different quantities of explosives under different field conditions.

Depth to water (ft)	Amount of explosives (lb)	Depth of hole (ft)	Probability of hazardous flying rock debris
1	1/3 - 1/2	1	High.
5	1/3 - 1/2	5	Medium.
10	1/3 - 1/2	10	Low.
20	1 - 2	15	Low.
50	4 - 10	15	Medium.

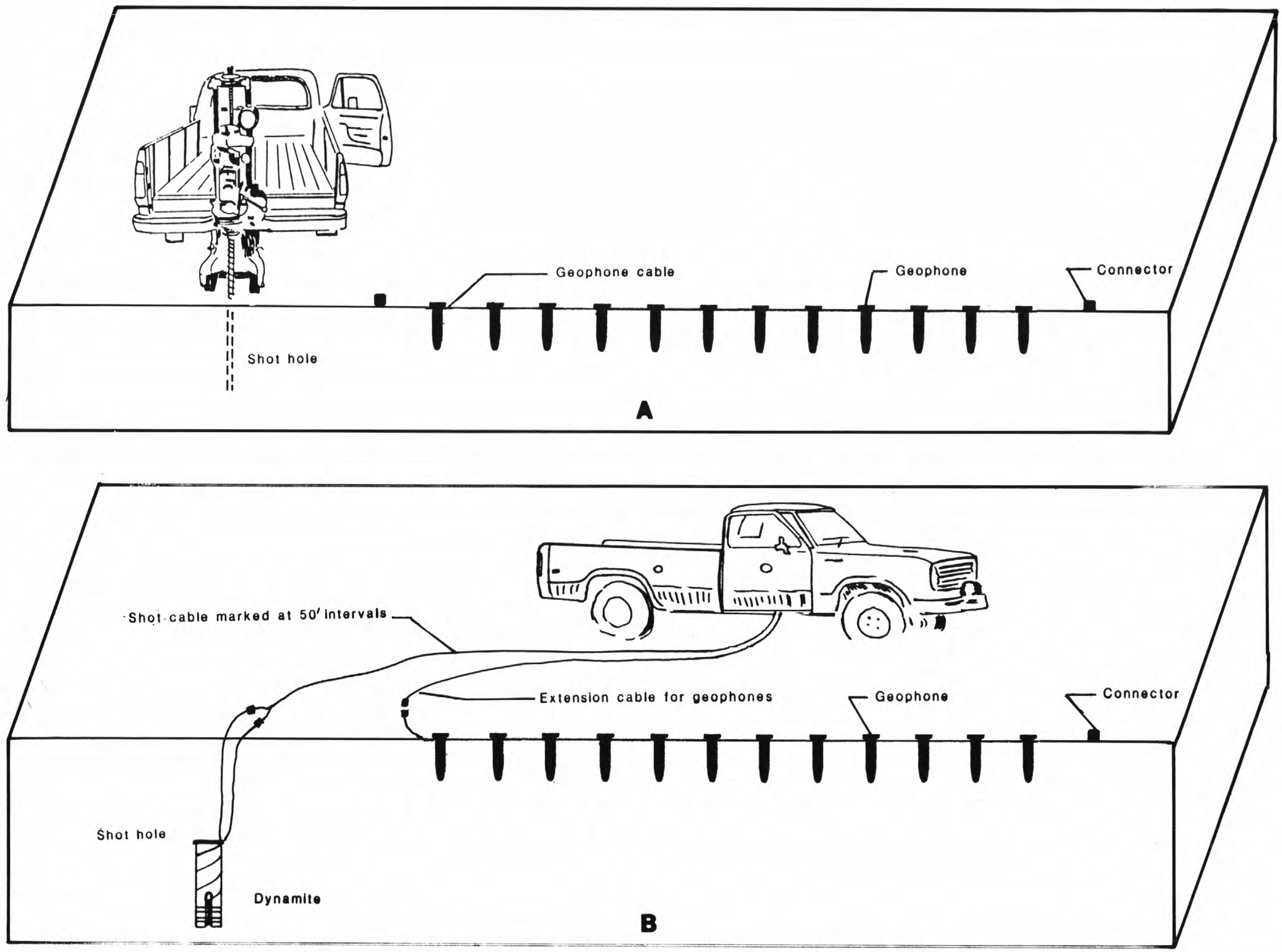


Figure 42.--Field setup of seismic truck, geophones and shot hole.

SAFETY NOTE: When in doubt as to the possibility of producing flying rock, use an extension cable or a long shot cable and clear the area near the shot. A heavy canvas tarpaulin placed over the shot point will reduce the risk of flying rock debris.

(3) The geophone cable is laid out and the geophones attached. The person laying out the cable takes the geophones and a radio, and connects the geophones to the cable on the way back to the seismic truck. The party chief should inform the helper by radio when the cable is extended to the predetermined length.

The geophones should be planted in firm ground, if possible. Old stumps, previously used shot holes, and soft or loose surface material should be avoided. A shovel is needed to remove the upper layer of soil and reach firm subsoil. Once firm ground has been reached, the geophone should be pushed into the ground. If loose material is unavoidable, each geophone placed in such material should be noted by the field helper and logged in the record book for subsequent use by the interpreter. The geophone connection should be kept out of standing water.

For most hydrologic studies, the location of the geophone line does not need to be determined by surveying, but the line should be laid out as straight as possible and marked on a topographic map. In heavily wooded areas, and for very long lines, the person laying out the cable should carry a compass.

(4) The seismograph is set up in the truck. If the unit is to remain in the truck, it is probably most convenient to use the truck's 12-volt direct current system to power the seismograph. Adapters are available to connect the seismograph to this power supply through the truck's cigarette lighter receptacle.

Once the seismograph is hooked up, it should be checked for proper voltage (usually a meter on the seismograph), and smooth paper record feed. In addition, the continuity of the geophones should be checked as they are being implanted. If continuity problems are discovered, the connection and geophone should be checked by the crew member laying out the line.

(5) The sound source is set up. If explosives are being used, they should be placed in the borehole and tamped with with dirt or sand.

The person loading the hole and wiring the explosive should ensure that the shot cannot be fired during this process. To accomplish this, a short safety cable or a safety key should be used to connect the shot cable to the firing device. This cable or key should be in the possession of the person loading and wiring the explosive. After the explosive is wired, the shot cable should be attached to the firing device using the safety cable or safety key (see Shot Cables Section for details on this procedure).

If explosives are used, the blasting cap should be tested with a blasting galvanometer before it is attached to the explosive. If the circuit is good, the cap should be inserted in the bottom of the explosive, secured with two half-hitches of the cap wire, and then taped. Figure 43 shows the proper way to assemble explosive cartridges and blasting caps. When using explosives, a book accounting for the receipt and discharge of all explosives is required by most explosive regulatory agencies.

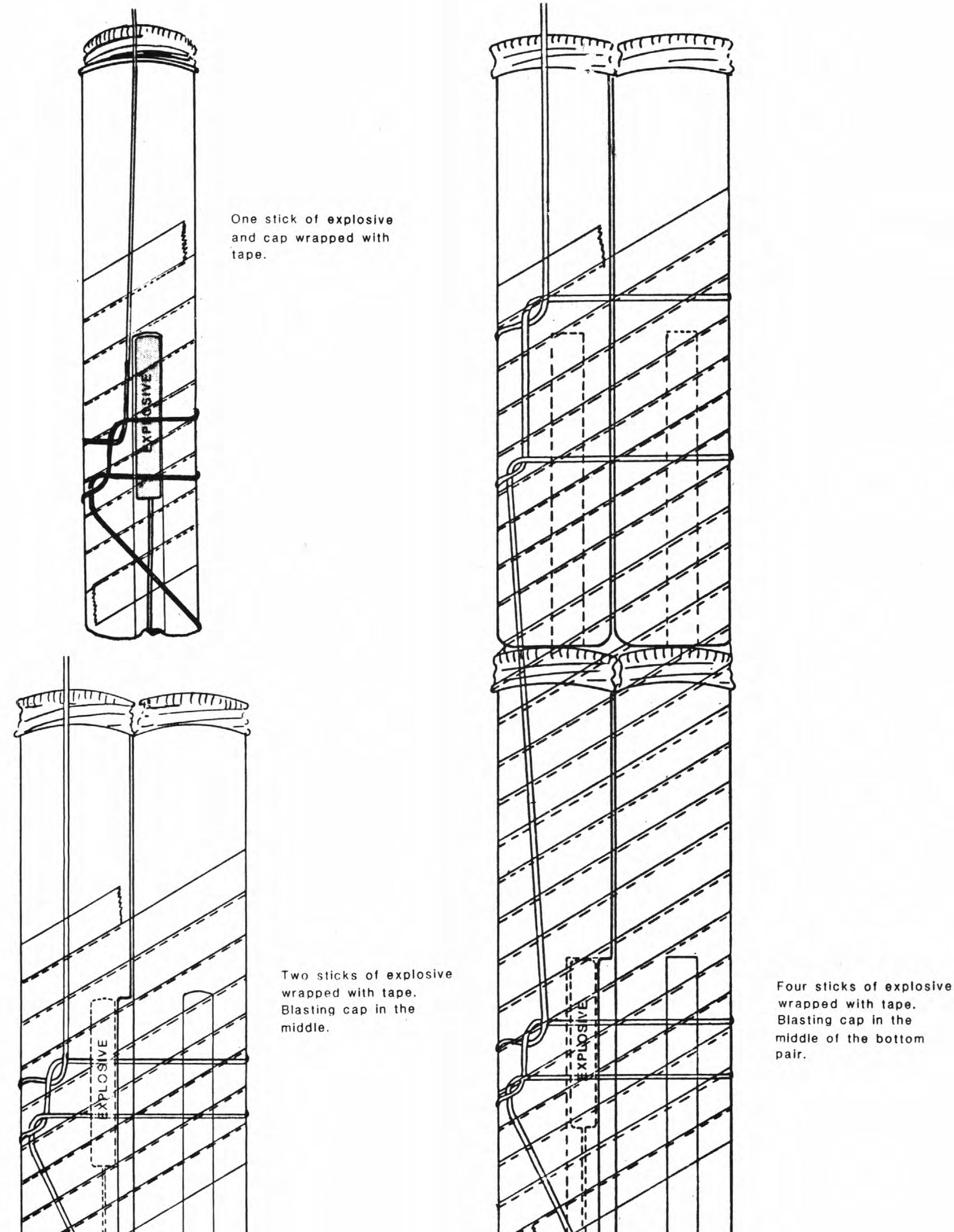


Figure 43.--Assembly of explosive cartridges and electric blasting caps.

SAFETY NOTES:

1. Do not place explosives in a hot hole.

2. Use only a wooden tamping pole.

3. Mix explosive and install cap just prior to loading hole. Manufacturer instructions for mixing the explosives must be followed to prevent misfires.

4. Check the cap with a blasting galvanometer, not a standard voltmeter.

5. The cap should be on the bottom of the explosive.

6. Record the depth of the top of the explosive and the depth of the hole in case of misfires (the explosive not firing).

7. Fill and tamp the hole with dirt or sand. Do not use grass, weeds, or cobbles.

8. Always tape the cap wires to the explosive cartridges; the main reasons for misfires are separation of the cap from the explosives and electrical malfunction in the firing circuit.

9. Personnel handling explosives should have special training and may need to be licensed.

10. Local police and regulatory authorities should be notified if explosives are to be used.

11. After detonation, do not inhale fumes, as they are often toxic.

12. Do not allow smoking near explosives.

13. Do not handle explosives if electrical storms are in the area.

14. For additional explosive safety information, see Institute of Manufacturers of Explosives, (1978) and the U.S. Geological Survey Safety Handbook, 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:

1. Seismograph power is on with proper filter, scale, and gain settings.

2. Geophone cable is hooked up to seismograph.

3. Sound source is hooked up to shot cable, and shot cable is hooked up to seismograph by a safety wire.

4. 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 shot line 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 inbetween shots can be used to determine the elevations and relative location of the geophones and different shot points. 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 into 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 hydrologic 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 hydrologic 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 these gaps in the refracting surface increases as the distance between the shot point and first geophone increases.

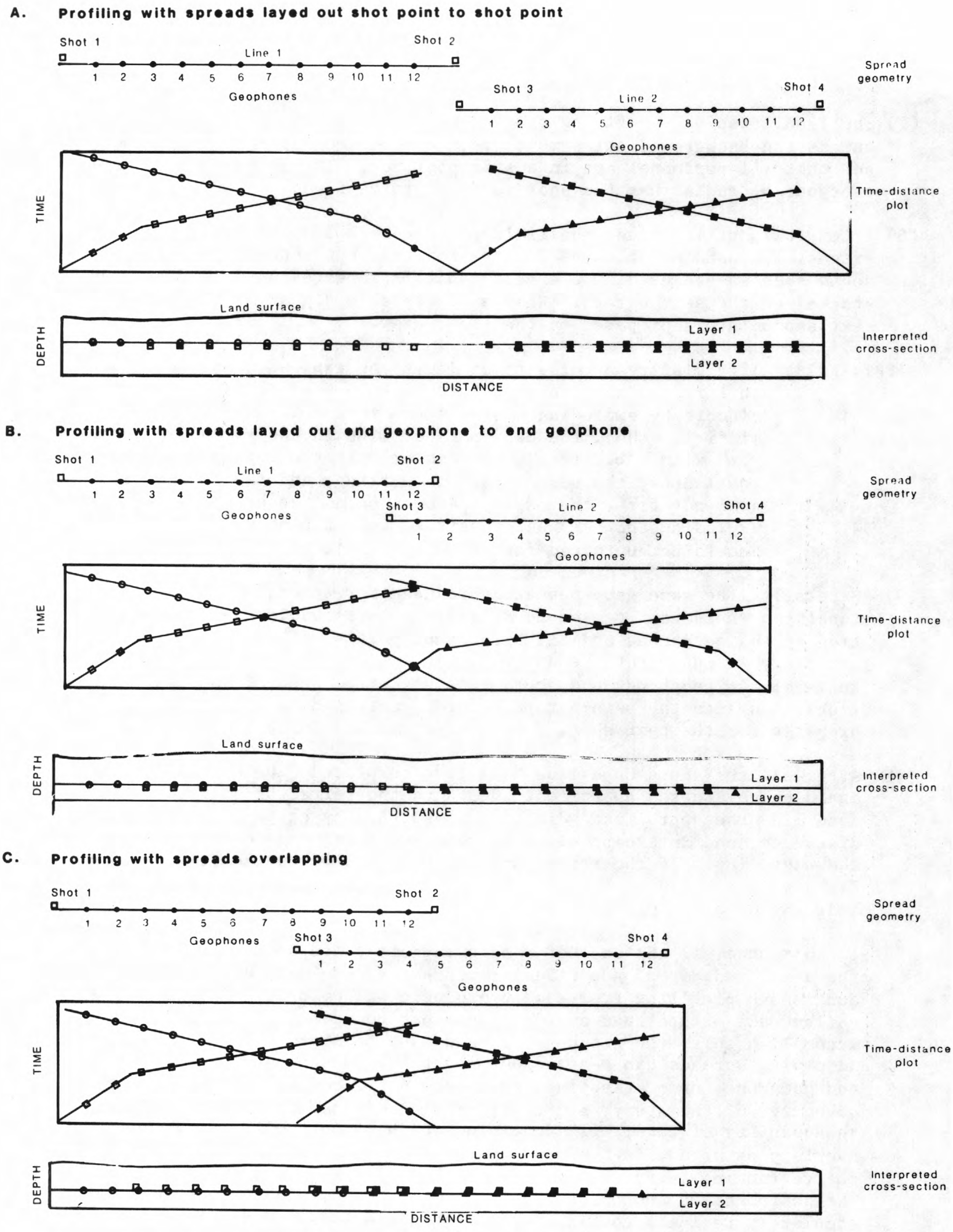


Figure 44.--Various field setups and resulting time-distance and depth plots for each geophone in a two-layer problem.

Field Records

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

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

Location

Number of geophones

Distance between all geophones

Elevation of all geophones

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 shot point:

Shot number

Location

Distance to first geophone

Depth of shot hole and explosives

Depth of water in shot hole

Elevation of shot hole

Description of materials in shot hole

Spread number

Amount of explosives used (if applicable)

Figure 45 is an example of a data sheet used by some field crews to record this 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, & 5; Array 2, shot 6, 7, 8, 9, & 10, etc. A similar system can be used to label tape files when the field data is stored on digital recorders. If explosives are used, the amount of 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 explosive log book.

Town ______________________ Site ______________________

Location ______________________ Date & Time ______________________

Owner ______________________ Party ______________________

Obtain approximate X_c to first refractor: Z = ________, V_1 = ______, V_2 = ______

$$X_c = 2(z)\sqrt{\frac{V_2 - V_1}{V_2 + V_1}} \qquad X_c = \_\_\_\_\_\_$$

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.--Field data sheet.

INTERPRETATION TECHNIQUES

After all the data has been collected in the field, it must be interpreted. Because of the widespread use of seismic-refraction techniques in hydrologic and other geologic studies, many seismic-refraction interpretation schemes have been developed and published in the literature (Dobrin, 1976, p. 318-331; Musgrave 1967, p. 565-594). 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 will present one method that has been used successfully in a wide variety of hydrologic studies.

A problem inherent in all geophysical studies is the non-unique 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 upon the hydrologist's input in the interpretation process. Failure to factor in the expertise of the hydrogeologist will inevitably lead 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 its own 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 the planning of the field layout of geophones and shot points.

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 hydrologic 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 arrival of sound source energy.

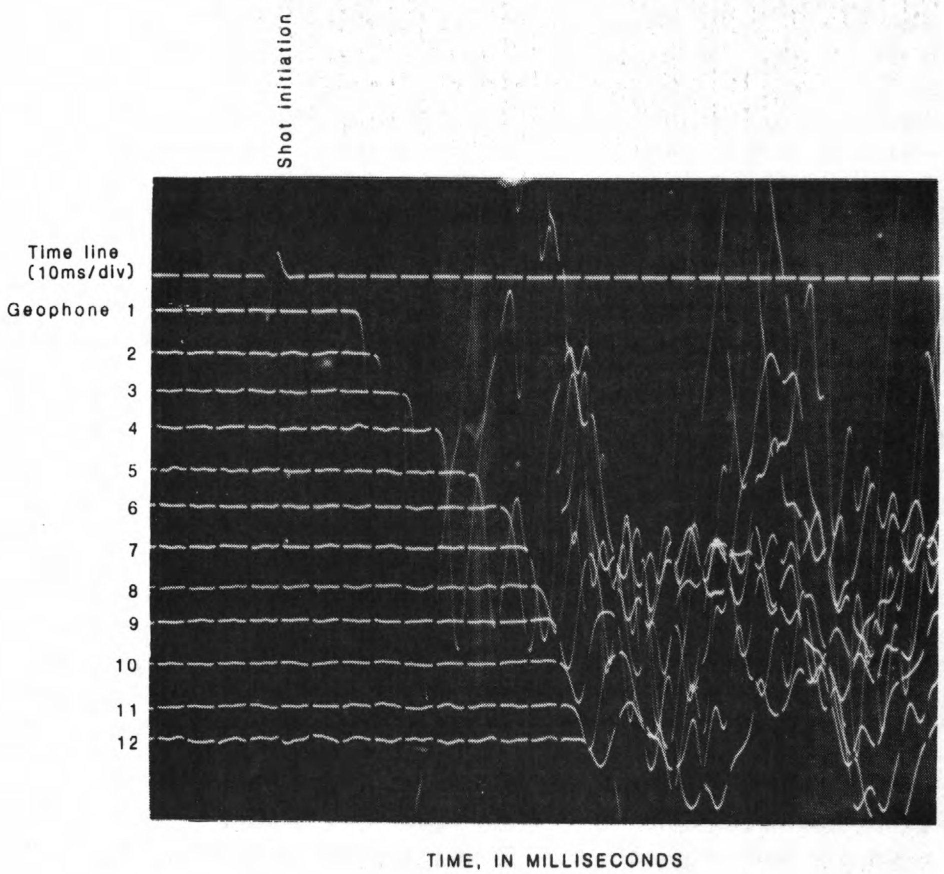


Figure 46.--Twelve-channel analog seismograph record showing good first breaks produced by an explosive sound source.

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.

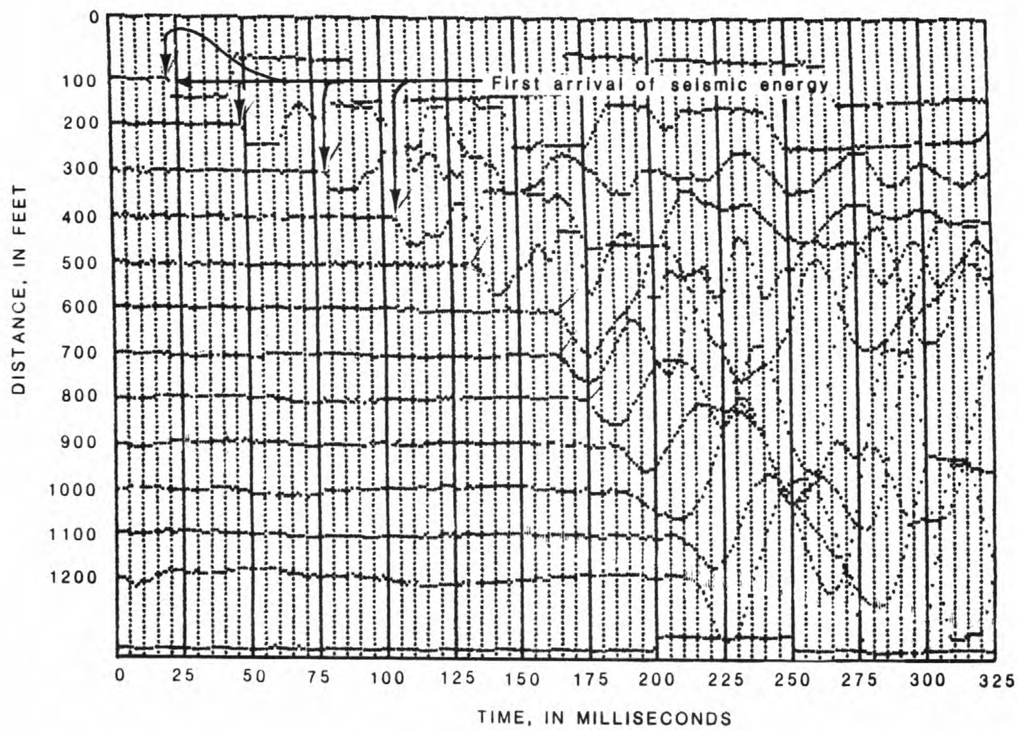


Figure 47.--Twelve-channel digital seismograph record from Little Androscoggin River valley, Maine, showing sharp first breaks produced by an explosive sound source in an area with low background noise.

Automated procedures for picking travel times are available. One method is to put the record on a digitizer tablet and use the digitizer stylus to determine the travel time 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.

(3) Depths of shot holes if used.

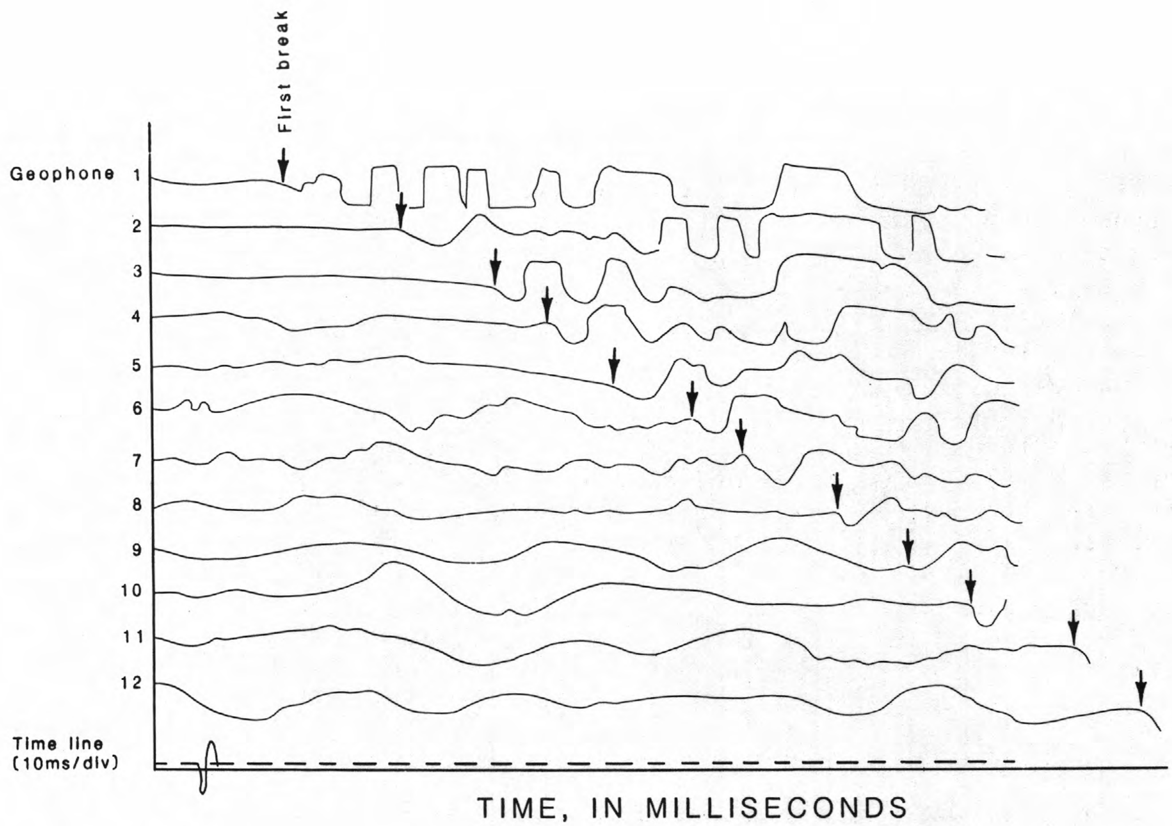


Figure 48.--Seismograph record with rounded first breaks produced by a sledge-hammer sound source, in an area with high background noise. Signal stacked 10 times, with geophones spaced 50 ft apart.

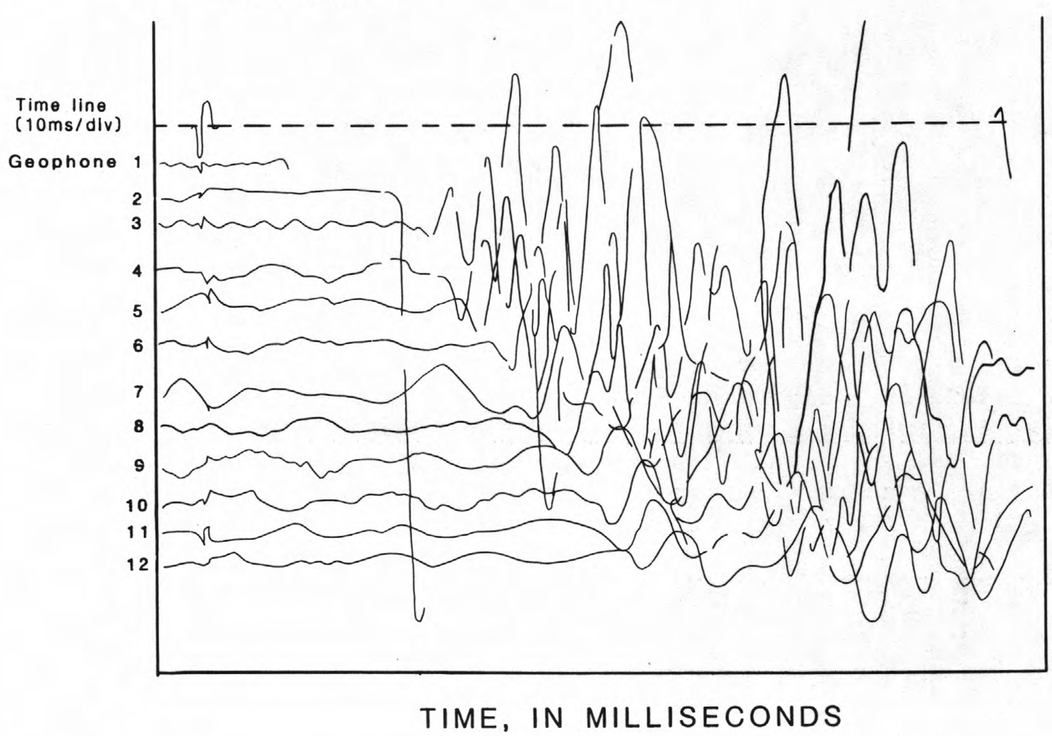


Figure 49.--Seismograph record with sharp first breaks produced by an an explosive sound source, in an area with high background noise. Geophones were spaced 50 ft apart.

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 method used, the interpreter must understand the time-distance plot (Ackerman, 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, Chap. 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 non-uniqueness of travel-time plots, and illustrates the need for the Hydrologist to be actively involved in the interpretation process. Only independent geologic knowledge will enable the seismic interpreter choose the correct interpretation.

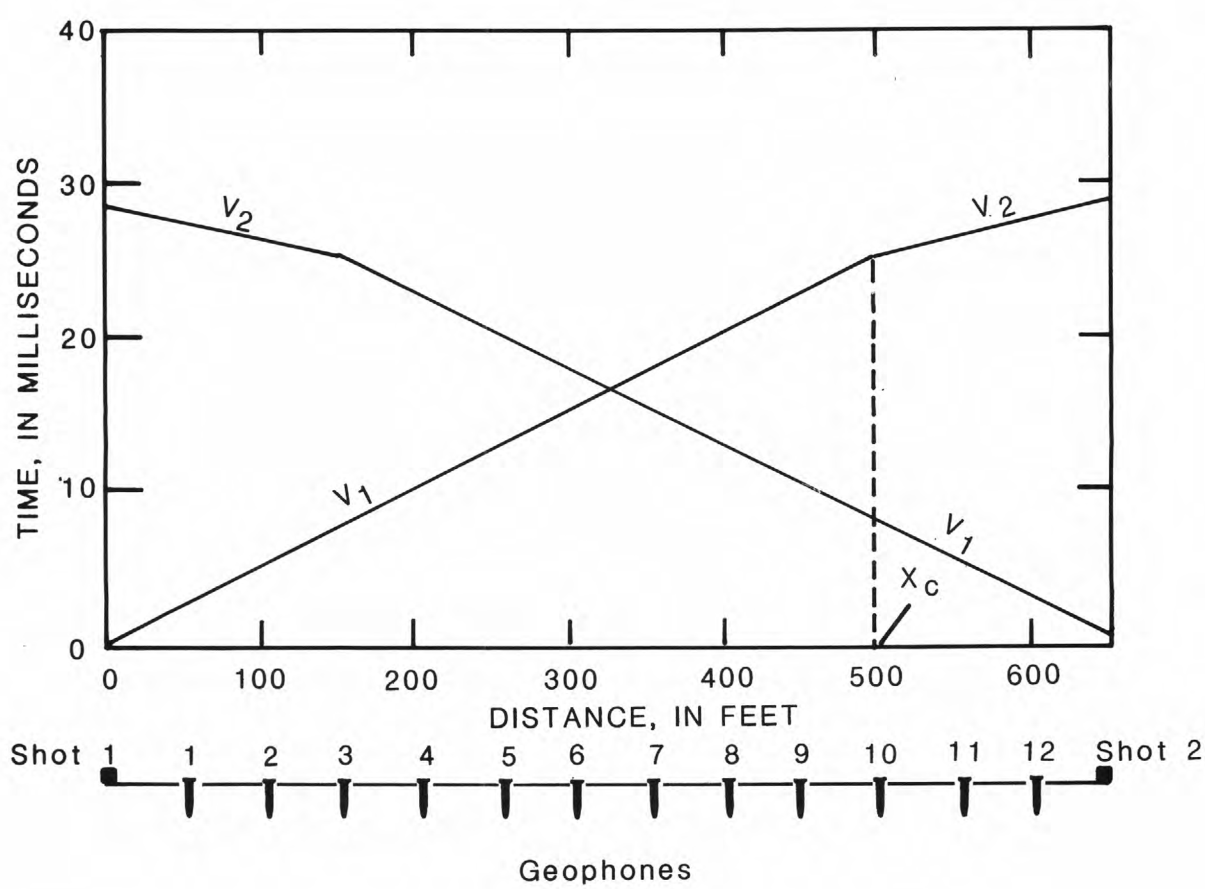


Figure 50.--Reversed seismic-refraction profiles with two velocity layers depicted on the time-distance plot.

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 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 abcissa (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 abcissa scale) is also undesirable because each pair of geophones may appear to have a separate slope associated with them. 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 hand-held programmable calculator programs available for solving the various seismic refraction formulas (Ballantyne and others, 1981).

Depending upon the scope of the hydrologic 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, chapter 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, non-linear geophone spreads, and so on, and to develop interpretations for complex geologic settings. These programs can solve multi-layer dipping-bed problems for multiple geophone spreads, and use a variety of interpretation schemes depending upon 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 Mainframe (1/) 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 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 the seismic refraction technique, as discussed in the Theory Section, must be understood to ensure successful computer-assisted interpretation of refraction data. These limitations are:

(1) All geologic layers must have seismic velocities that increases with depth.

(2) Each layer must have a large enough thickness 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 needed.

(7) Refracted rays are assumed to represent minimum travel-time 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.

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

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 geologic 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 shot points 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 multi-layer subsurface. Multiple shots and multiple spreads should be used in most field situations.

The input data is entered into the program via cards (batch-processing program) or 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 X-Y coordinate system (fig. 53-A).

(3) Plot the elevation of all shotpoints and geophones (fig. 53-B).

(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 into computer. Usually, this is done by entering input data with the computer editor and creating an online 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).

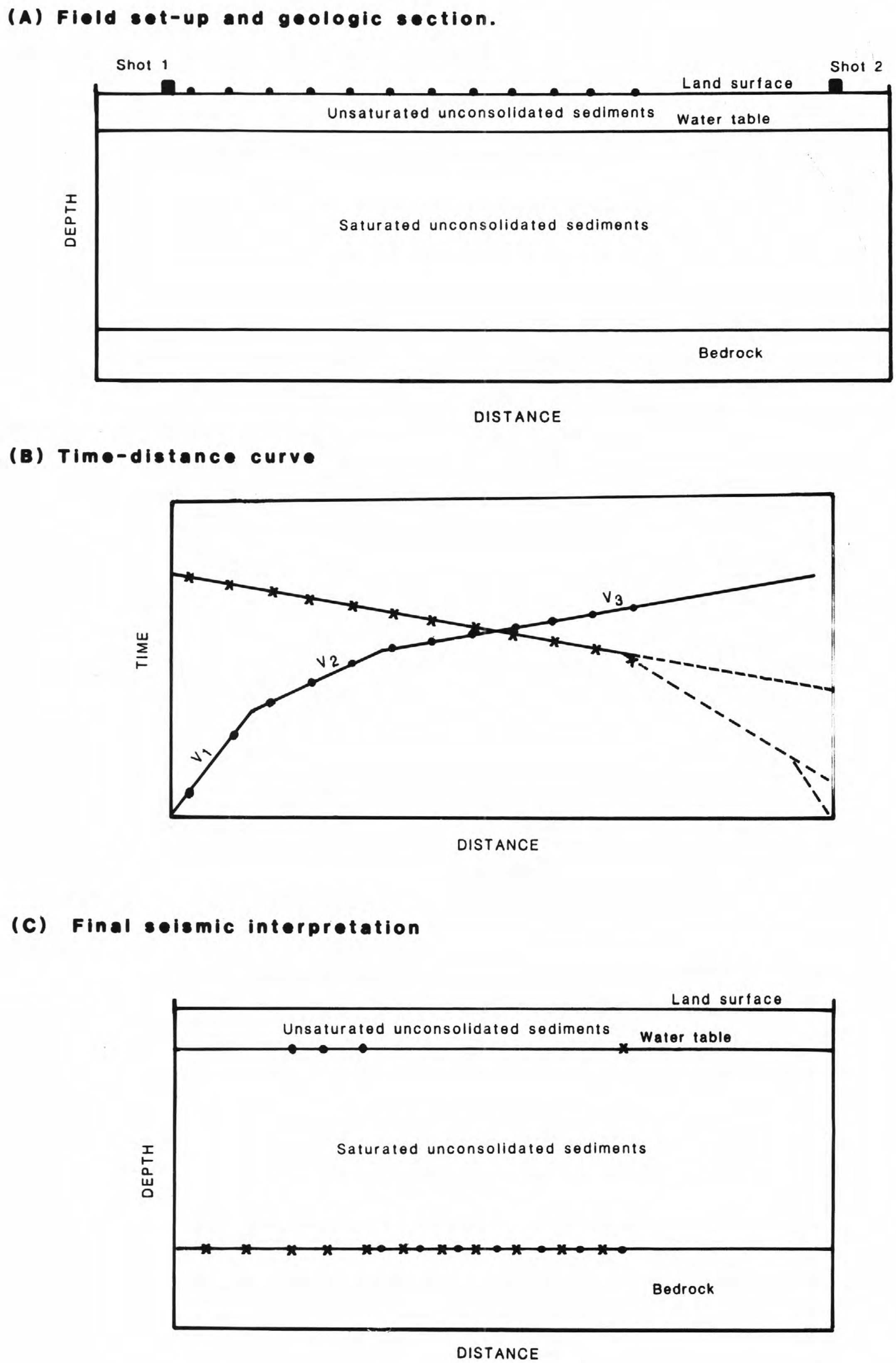


Figure 51.--Relationships between field setup, time-distance plot, and interpreted seismic section.

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					

Figure 52.--Seismic refraction first-arrival record sheet.

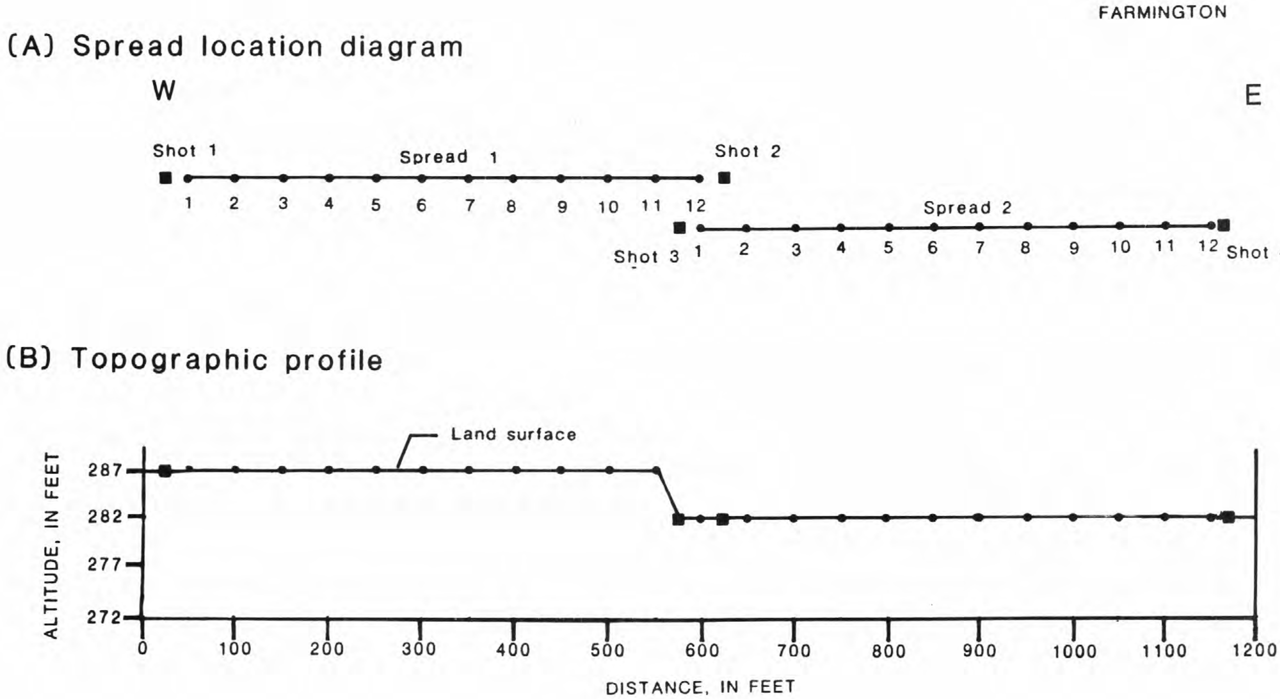


Figure 53.--Shotpoint and geophone locations and altitudes plotted to scale.

(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 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

Note: each number is followed by a comma when entering data into the computer.

One set per problem (1 to 5 spreads)

PROBLEM IDENTIFICATION LINE (UP TO 78 COLUMNS OF TEXTOR NUMBERS)

PROBLEM CONTROL LINE

Number of spreads	Program exit point	Number of Layers	Number of velocity cards	Elevation plot scale	Horizontal distance plot scale	Time plot scale	
							0,0,0,0,0,0,0,0,0,0,0

VELOCITY LINE (ONE PER LAYER)

Layer Number	Vertical velocity spread #1	Horizontal velocity spread #1	(Number of 0,0 pairs depends on the number of spreads. ie two spreads would have 0,0,0,0)
		0,	0,0

One set per each spread

SPREAD CONTROL LINE

Spread number	Number of shot Points	Number of geophones	
			0,0

SHOT POINT LINES

Shot point number	Elevation of Shot point	In line coordinate	Transverse coordinate	Depth of shot point	
			0,		0,0,0
					Multiple shotpoints must be listed in increasing in-line coordinate order.

GEOPHONE LINES (Travel times from shot points must be in the same order as on shot point line)

Geophone number	Elevation of geophones	In line coordinate	Transverse coordinate	Travel time Shot point #	Layer	Travel time Shot point #	Layer	Travel time Shot point #	Layer	Travel time Shot point #	Layer	Travel time Shot point #	Layer	Travel time Shot point #	Layer	
1																
2																
3																
4																
5																
6																
7																
8																
9																
10																
11																
12																

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

Table 9.--Example of input data set for 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
4,155,1600,0,4,0,0,0	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	

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 plot is now printed, and the layer 1 velocity is 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 "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 "2" may help the interpreter. The raw seismic travel times 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. Pre-D shows the arrival times just prior to depth computation 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 remvd). This option removes layer 1 from the refraction times and plots a new time-distance graph. This option is only effective if raw field information about layer 1 is available. Consequently, it is used only in unusual cases.

Although the discussion is presented here, the actual work should be done after the computer run is completed. The program has an exit point that allows the interpreter to end the program after the T-D 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, overlying 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 travel-time data. Reversed shots that plot in the same direction indicate, for example, an encoding error (fig. 56).

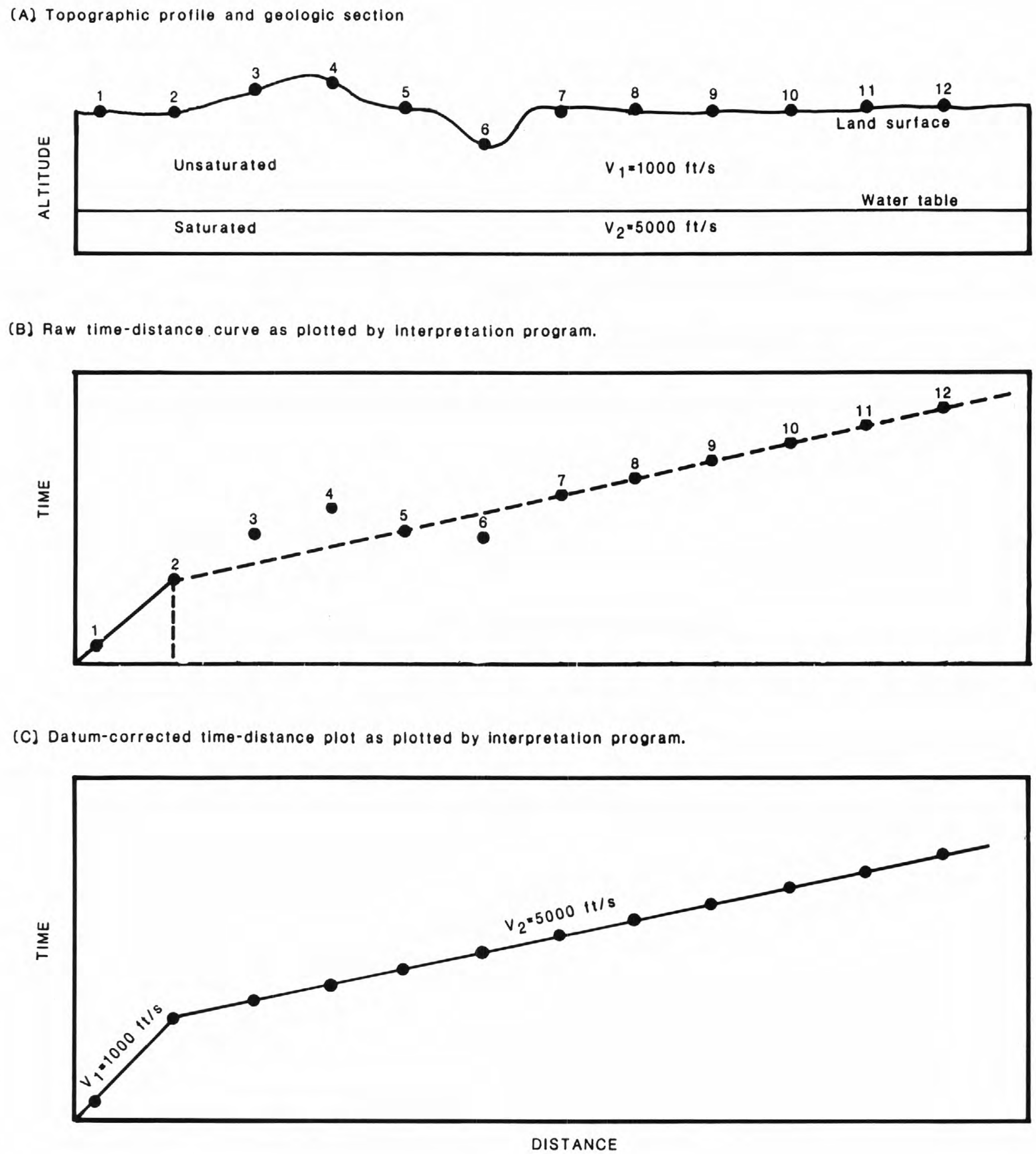
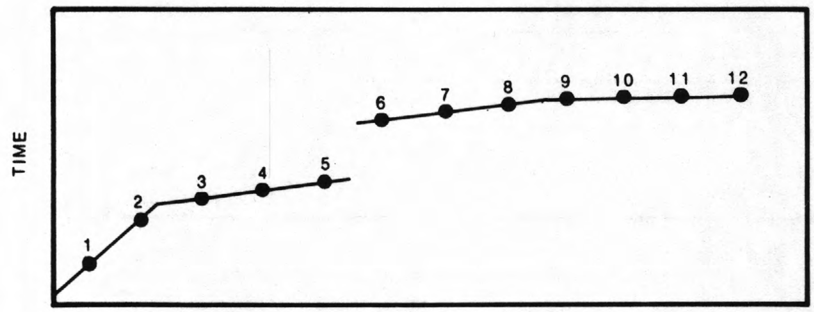
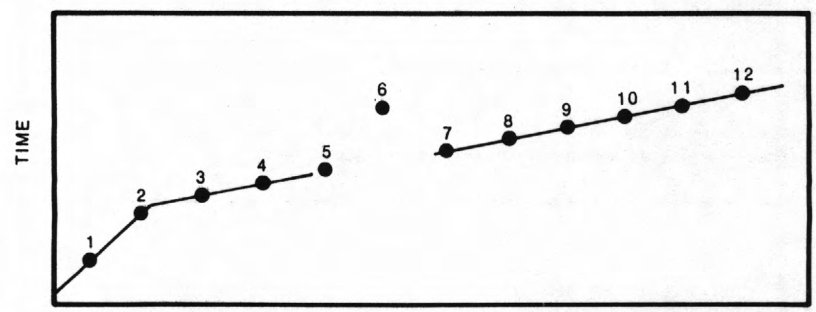


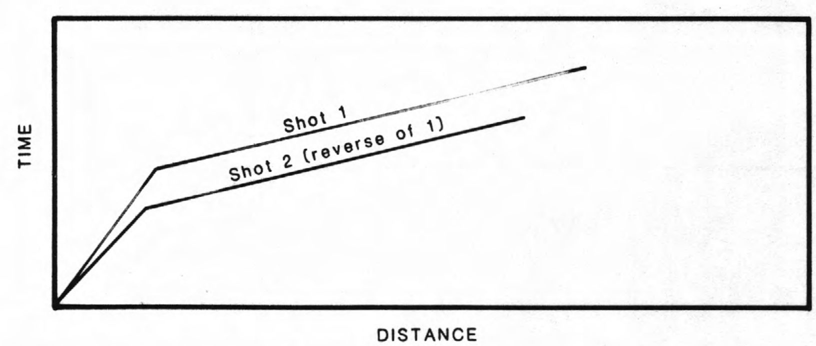
Figure 55.--Effect of topographic relief on raw and datum corrected time-distance plots.



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 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 the refractor depth exists. Figure 57 illustrates some of these principles, and the following discussion gives the symbols and generalized relationships.

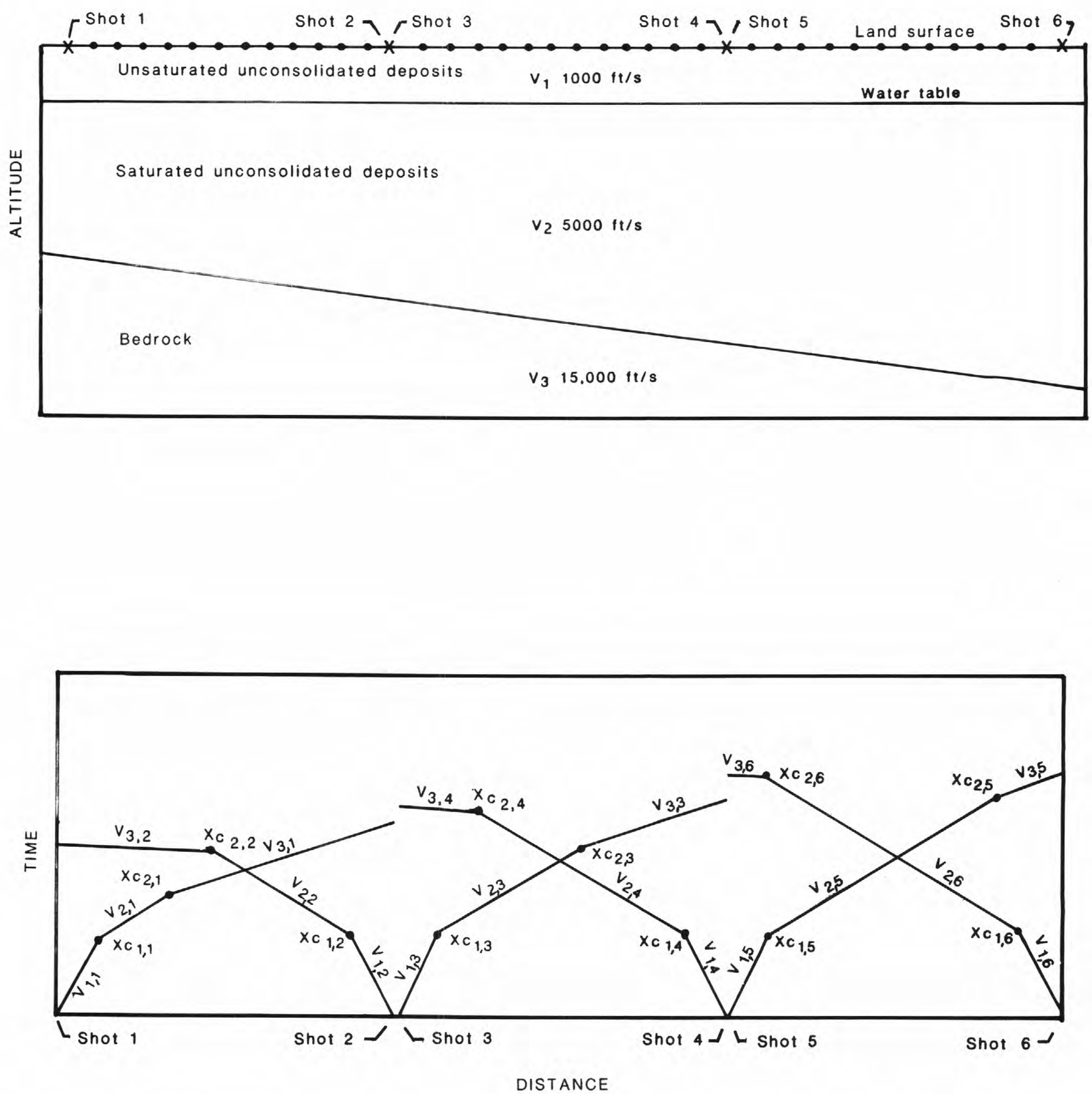


Figure 57.--Seismic section and time-distance plot showing the general relationships of seismic velocities and cross-over distances between three seismic-refraction spreads.

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.

$$xc_{1,1} \cong xc_{12} \cong xc_{1,3} \cong xc_{1,4} \cong xc_{1,5} \cong xc_{1,6}$$

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.

$$xc_{2,1} < xc_{2,2} < xc_{2,3} < xc_{2,4} < xc_{2,5} < xc_{2,6}$$

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.

$$V_{1,1} = V_{1,2} = V_{1,3} = V_{1,4} = V_{1,5} = V_{1,6}$$

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 down-dip apparent seismic velocities are less than the up-dip 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 5000 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 shot hole 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 principal of reciprocity also can be used to help construct time-distance plots. Examining figure 37-A, the travel-time from shotpoint 1 to geophone 12 is the same as from shotpoint 2 to geophone 1. In general, the seismic travel-time 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 37-A, 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 travel-times for the end geophones. Good examples of this principle also are shown in figures 37-B and 39 for shot points 2 and 4, respectively.

E. Extending the time-distance curves back to the time axis also may help to construct time-distance plots. The arrival times for the geophone array to the left of shot point 2 and for the array to the right of shot point 3 (fig. 54a) are shown in figure 54b. Notice that shot points 2 and 3 are at the same location and that the time-distance plots for the first two velocity layers are symmetrical with respect to the time axis.

Rearranging the formula for a two-layer parallel boundary subsurface (eq. 1) yields the intercept time:

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

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 37-B.

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 sub-sequent computer runs.

(8) Velocity Tables: T to type, ⟨CR⟩ to suppress: (prompt)
T (response)

Discussion: The velocity tables will now be printed out. This is an important step in the interpretation process. This table should be thoroughly reviewed. Incorrect layer assignments or data input errors of 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-Overton" 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 trouble-shooting 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 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 previously, 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 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 which do not look reasonable?
3. Time-distance plot - Were the changes from run one made and is the plot now acceptable?
4. Depth table and interpreted seismic section plot - Are any water well, shot hole, or geologic data available to check approximate depths? Are flat interfaces (water table, or bedrock) 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 for 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 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 this data is 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 which 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 59-B. Any departure of the subsurface from the simplifying assumptions listed in the beginning of this section 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.

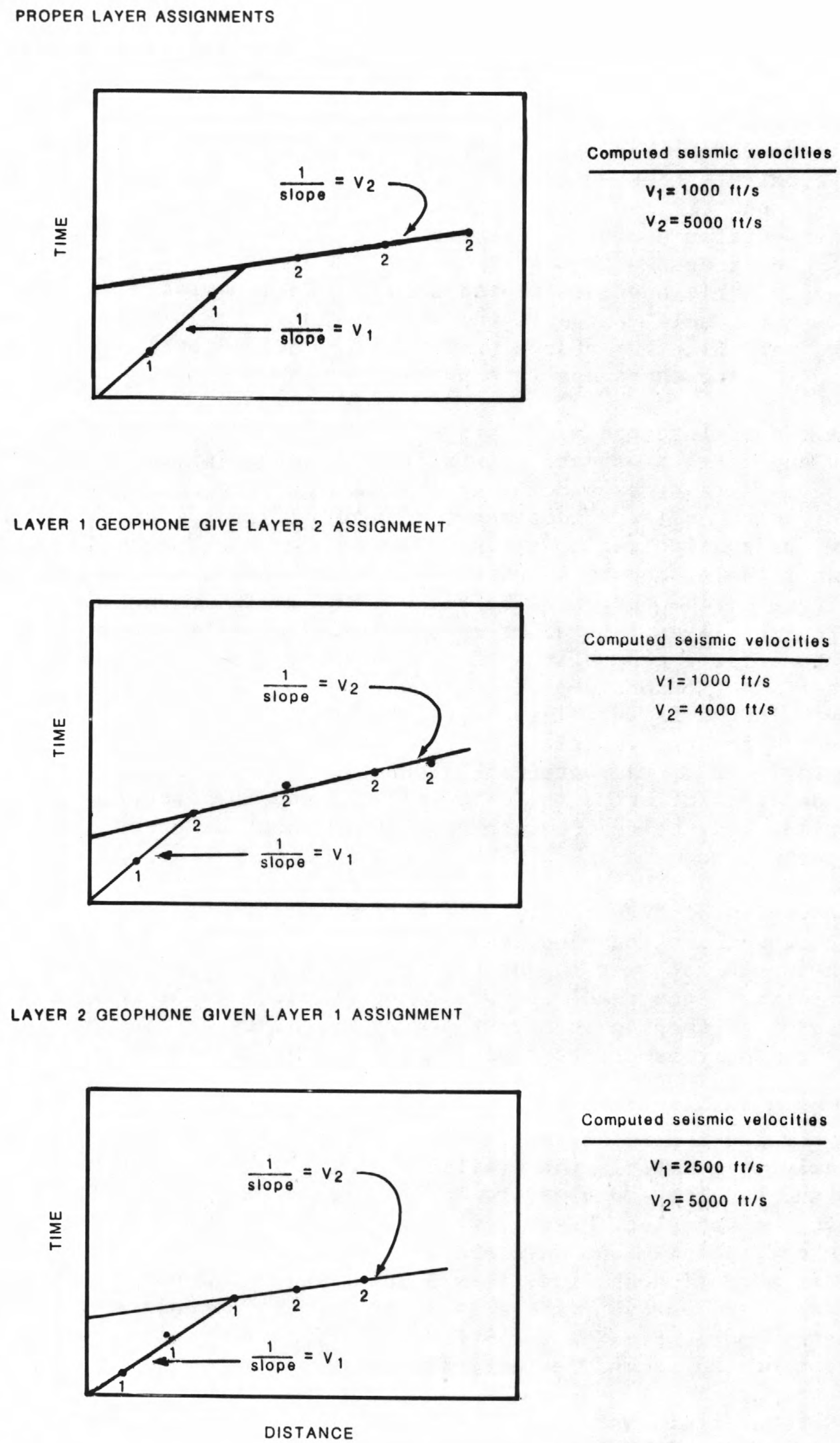


Figure 58.--Effects of incorrect layer assignments on the velocity of sound as computed by regression in the Seismic Interpretation Program (SIPT).

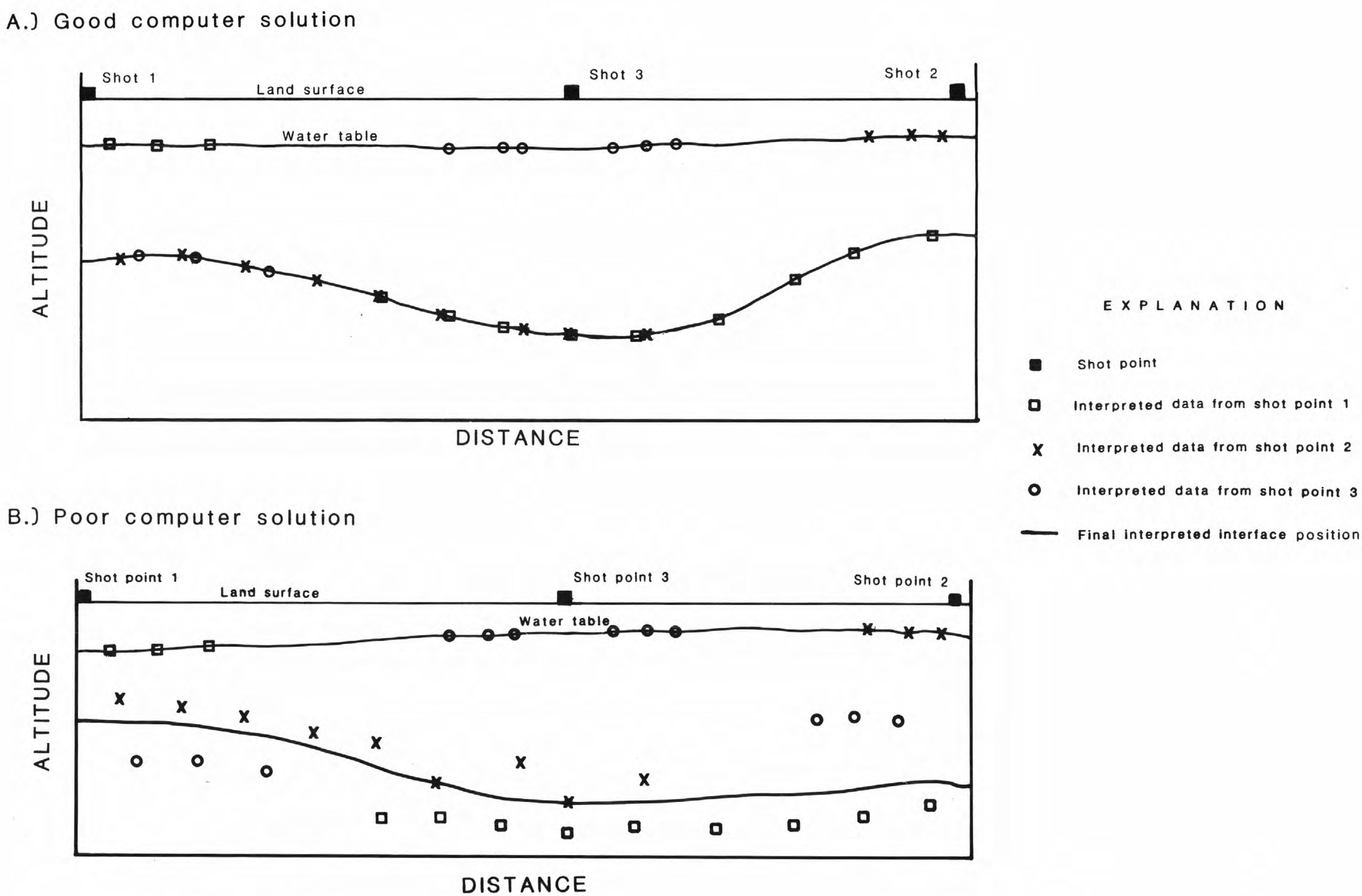


Figure 59.--Good and poor computer solutions.

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 which 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).

It is important to realize that the best solution of the delay-time technique occurs 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 assignments 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 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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