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

Chapter D2

APPLICATION OF SEISMIC-REFRACTION TECHNIQUES TO HYDROLOGIC STUDIES

By F.P. Haeni

Book 2

COLLECTION OF ENVIRONMENTAL DATA

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, *Secretary*

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PREFACE

The series of manuals on techniques describes procedures for planning and executing specialized work in water-resources investigations. The material is grouped under major subject headings called Books and is further subdivided into Sections and Chapters. Section D of Book 2 is on surface geophysical methods.

The unit of publication, the Chapter, is limited to a narrow field of subject matter. This format permits flexibility in revision and publication as the need arises. "Application of Seismic-Refraction Techniques to Hydrologic Studies" is Chapter D2 of Book 2.

Reference to trade names, commercial products, manufacturers, or distributors in this manual does not constitute endorsement by the U.S. Geological Survey or recommendation for use.

This manual is intended to supplement the more general "Application of Surface Geophysics to Ground-Water Investigations," by A.A.R. Zohdy, G.P. Eaton, and D.R. Mabey (U.S. Geological Survey Techniques of Water-Resources Investigations, Book 2, Chapter D1, 1974).

TECHNIQUES OF WATER-RESOURCES INVESTIGATIONS OF THE UNITED STATES GEOLOGICAL SURVEY

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TWI 3-A10. Discharge ratings at gaging stations, by E.J. Kennedy. 1984. 59 pages.
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TWI 3-B6. The principle of superposition and its application in ground-water hydraulics, by Thomas E. Reilly, O. Lehn Franke, and Gordon D. Bennett. 1987. 28 pages.
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TWI 4-D1. Computation of rate and volume of stream depletion by wells, by C.T. Jenkins. 1970. 17 pages.

[1]Spanish translation also available.

TWI 5-A1. Methods for determination of inorganic substances in water and fluvial sediments, by M.W. Skougstad and others, editors. 1979. 626 pages.

TWI 5-A2. Determination of minor elements in water by emission spectroscopy, by P.R. Barnett and E.C. Mallory, Jr. 1971. 31 pages.

TWI 5-A3. Methods for the determination of organic substances in water and fluvial sediments, edited by R.L. Wershaw, M.J. Fishman, R.R. Grabbe, and L.E. Lowe. 1987. 80 pages. This manual is a revision of "Methods for Analysis of Organic Substances in Water" by Donald F. Goerlitz and Eugene Brown, Book 5, Chapter A3, published in 1972.

TWI 5-A4. Methods for collection and analysis of aquatic biological and microbiological samples, edited by P.E. Greeson, T.A. Ehlke, G.A. Irwin, B.W. Lium, and K.V. Slack. 1977. 332 pages.

TWI 5-A5. Methods for determination of radioactive substances in water and fluvial sediments, by L.L. Thatcher, V.J. Janzer, and K.W. Edwards. 1977. 95 pages.

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TWI 5-C1. Laboratory theory and methods for sediment analysis, by H.P. Guy. 1969. 58 pages.

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TWI 7-C1. Finite difference model for aquifer simulation in two dimensions with results of numerical experiments, by P.C. Trescott, G.F. Pinder, and S.P. Larson. 1976. 116 pages.

TWI 7-C2. Computer model of two-dimensional solute transport and dispersion in ground water, by L.F. Konikow and J.D. Bredehoeft. 1978. 90 pages.

TWI 7-C3. A model for simulation of flow in singular and interconnected channels, by R.W. Schaffranek, R.A. Baltzer, and D.E. Goldberg. 1981. 110 pages.

TWI 8-A1. Methods of measuring water levels in deep wells, by M.S. Garber and F.C. Koopman. 1968. 23 pages.

TWI 8-A2. Installation and service manual for U.S. Geological Survey monometers, by J.D. Craig. 1983. 57 pages.

TWI 8-B2. Calibration and maintenance of vertical-axis type current meters, by G.F. Smoot and C.E. Novak. 1968. 15 pages.

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FIGURES

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*
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Velocity	
foot per second (ft/s)	0.3048	meter per second (m/s)
	Density	
ounce per cubic inch (oz/in^3)	1.7297	gram per cubic centimeter (g/cm^3)

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

Critical distance. The offset at 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.

Geophone spacing. The distance between adjacent geophones within a spread.

Geophone spread. The arrangement of geophones in relation to the position of the energy source.

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. The property of a material that 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.

TABLES

APPLICATION OF SEISMIC-REFRACTION TECHNIQUES TO HYDROLOGIC STUDIES

By F.P. Haeni

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 surface, 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 seismic-refraction methods. These methods allow 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 these techniques in hydrologic investigations and describes the planning, equipment, field procedures, and intrepretation techniques needed for this type of study. Furthermore, 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 to only a limited degree. Recent advances in electronic equipment and 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 can be used to help solve hydrologic problems.

Classically, surface geophysical techniques have been used early in the exploration process, prior to use of more expensive data-collection techniques such as drilling (Jakosky, 1950). 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 by 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 material is critical for 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 proved 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, these techniques 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 refraction methods by the petroleum industry declined, and they are now used primarily in special situations and for weathered-layer velocity determinations.

Use of seismic-refraction techniques 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, seismic-refraction techniques.

Although seismic-reflection techniques have dominated deep-exploration work in 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 apply seismic refraction to a particular project or area of interest. It is intended to help the hydrologist determine if seismic-refraction techniques will work in a particular hydrologic setting. In addition, the manual briefly presents the theory of seismic refraction, identifies advantages and limitations of the techniques, 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 seismic-refraction methods will depend more on the ability of the hydrologist to apply the principles of the techniques and to extract a hydrologically reasonable answer than on the use of 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.

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 those of Bonini and Hickok (1958), Eaton and Watkins (1967), Lennox and Carlson (1967), Mabey (1967), Ogiluy (1967), Shiftan (1967), Kent and Sendlein (1972), Zohdy and others (1974), Worthington (1975), and Collett (1978).

The two types of 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 in which velocity discontinuities between hydrologic units are present, these methods have proved to be the most useful geophysical technique. The major use of seismic-refraction techniques in hydrologic studies is to assess the hydrogeologic framework and hydrologic boundaries of aquifers. They are generally used early in the investigation, after the preliminary hydrologic assessment and prior to more site-specific data-gathering activities. Another use is for specific data-gathering activities later in the study. Specific information that may be sought during the hydrologic analysis stage of the study, and that can be investigated by seismic-refraction methods, 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 when more costly, detailed site-specific data are collected. Generally, these stages of the study involve a drilling program, borehole geophysical studies, detailed hydrologic testing, and data analysis.

References

Bonini, W.E., and Hickok, E.A., 1958, Seismic refraction method in ground-water exploration: Transactions of the American Institute of Mining, Metallurgical, and Petroleum Engineers, v. 211, p. 485–488.

Collett, L.S., 1978, Introduction to hydrogeophysics: Conference of the International Association of Hydrogeologists, Canadian chapter, Edmonton, September 30-October 4, 1978, Proceedings, p. 16–35.

Eaton, G.P., and Watkins, J.S., 1967, The use of seismic refraction and gravity methods in hydrologic investigations, *in* Morey, L.W., ed., Mining and ground-water geophysics: Geological Survey of Canada Economic Geology Report 26, p. 554–568.

Grant, F.S., and West, G.F., 1965, Interpretation theory in applied geophysics: New York, McGraw Hill, 583 p.

Jakosky, J.J., 1950, Exploration geophysics (2d ed.): Los Angeles, Calif., Times-Mirror Press, 1,195 p.

Kent, D.C., and Sendlein, L.V.A., 1972, A basin study of ground-water discharge from bedrock into glacial drift: Part 1, Definition of ground-water systems: Ground Water, v. 10, no. 4, p. 24–34.

Lennox, D.H., and Carlson, V., 1967, Integration of geophysical methods for ground-water exploration in the prairie provinces, Canada, *in* Morey, L.W., ed., Mining and ground-water geophysics: Geological Survey of Canada Economic Geology Report 26, p. 517–535.

Mabey, D.R., 1967, The role of geophysics in the development of the World's ground-water resources, *in* Morey, L.W., ed., Mining and ground-water geophysics: Geological Survey of Canada Economic Geology Report 26, p. 267–271.

Musgrave, A.W., ed., 1967, Seismic refraction prospecting: Tulsa, Okla., Society of Exploration Geophysicists, 604 p.

Ogiluy, A.A., 1967, Geophysical prospecting for ground water in the Soviet Union, *in* Morey, L.W., ed., Mining and ground-water geophysics: Geological Survey of Canada Economic Geology Report 26, p. 536–543.

Shiftan, Z.L., 1967, Integration of geophysics and hydrogeology in the solution of regional ground-water problems, *in* Morey, L.W., ed., Mining and ground-water geophysics: Geological Survey of Canada Economic Geology Report 26, p. 507–516.

Worthington, P.A., 1975, Procedures for the optimum use of geophysical methods in ground-water development programs: Association of Engineering Geologists Bulletin, v. 12, no. 1, p. 23–38.

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

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 reviews only the basic principles and limitations of seismic-refraction methods. 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. An encyclopedic dictionary of terms used in exploration geophysics is published by the Society of Exploration Geophysicists (Sheriff, 1973).

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 have a solid understanding of the physics underlying the technique prior to using it.

Seismic-refraction methods measure 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 traveltime 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 traveltimes. From this time-distance information, velocity variations and depths to individual layers can be calculated and modeled.

The foundation of seismic-refraction theory is Snell's Law, which governs the refraction of sound or light waves across the boundary between layers having different velocities. As sound propagates through one layer and encounters another layer having 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). When the angle of incidence equals the critical angle, the compressional energy is transmitted along the upper 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 a geophone and arrival energy is recorded on a seismograph.

If a series of geophones is spread out on the ground in a geometric array, arrival times can be plotted against source-to-geophone distances (fig. 2), which results in a time-distance plot, or time-distance curve. It can be seen 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 1 can be directly calculated by $V_1 = x/t$, where V_1 is the velocity of sound in layer 1 and x is the distance 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 with the high-velocity layer, and then back up to the surface through layer 1 arrives before the compressional wave that has been in layer 1 (the low-velocity layer). All first compressional waves arriving at geophones more distant than the crossover distance will be refracted waves, 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 and others, 1974; Dobrin, 1976; Telford and

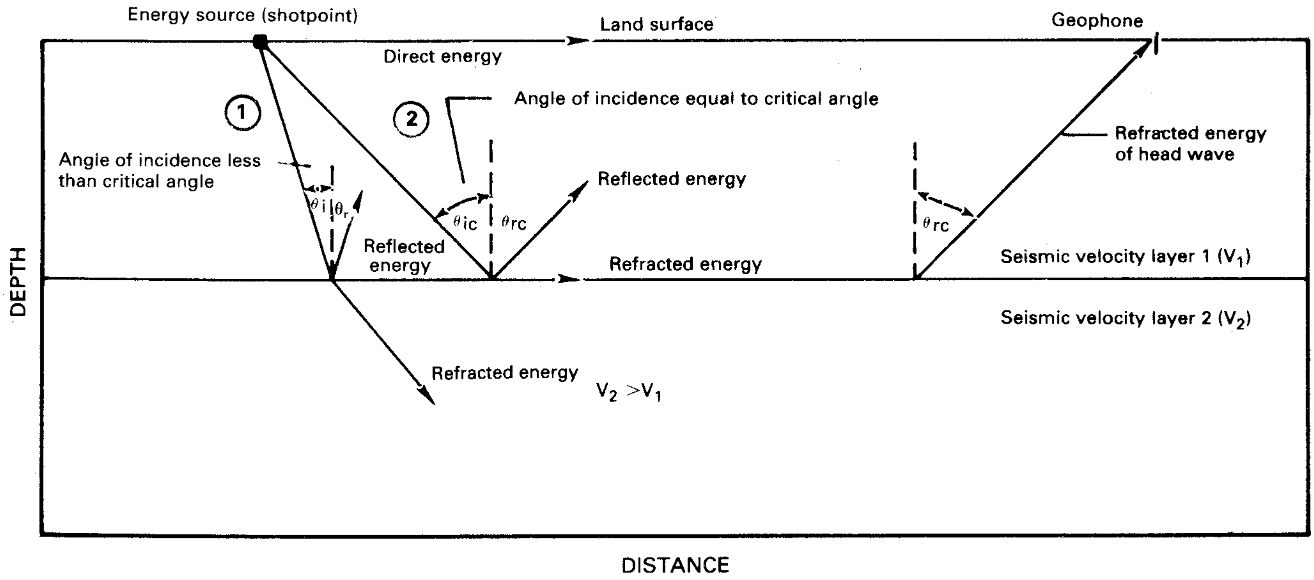


Figure 1.—Raypaths of refracted (1) and reflected (2) sound energy in a two-layer Earth.

others, 1976; Parasnis, 1979; Mooney, 1981), and only the results are given here. These derivations are straightforward inasmuch as the total traveltime 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-velocity refractor. These interpretation formulas are based on the following assumptions: (1) 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 point,
- t_i =intercept time,
- V_2 =velocity of sound in layer 2, and
- V_1 =velocity of sound in layer 1.

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 as defined earlier and
- x_c =crossover distance.

Three-layer parallel-boundary formulas (See figure 4)

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

$$z_1=\frac{t_2}{2}\frac{V_2V_1}{\sqrt{(V_2)^2-(V_1)^2}} \text{ (from two-layer formula 1)}, \qquad (3)$$

$$z_2=\frac{1}{2}\left(t_3-\frac{2z_1\sqrt{(V_3)^2-(V_1)^2}}{V_3V_1}\right)\frac{V_3V_2}{\sqrt{(V_3)^2-(V_2)^2}}, \qquad (4)$$

and

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

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, and
- V_3 =velocity of sound in layer 3.

2. Crossover-distance formulas (Parasnis, 1979, p. 197–198):

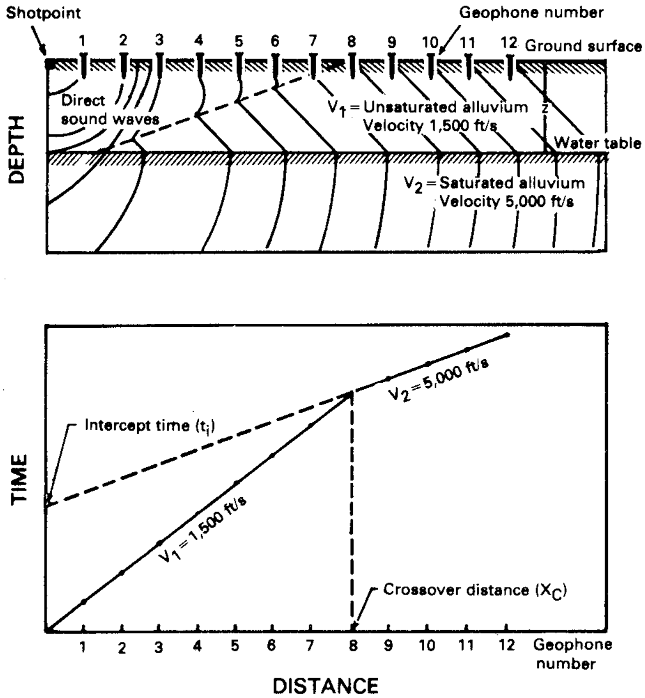


Figure 2.—Seismic wave fronts and raypaths and corresponding time-distance plot.

$$z_1=\frac{x_{c1}}{2}\sqrt{\frac{V_2-V_1}{V_2+V_1}}\ \text{(from two-layer formula 2)}, \tag{6}$$

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

$$-z_1\left(\frac{V_2\sqrt{(V_3)^2-(V_1)^2}-V_3\sqrt{(V_2)^2-(V_1)^2}}{V_1\sqrt{(V_3)^2-(V_2)^2}}\right), \tag{7}$$

and

$$z_3=z_1+z_2\ , \tag{8}$$

where

z_1, z_2, z_3, V_1, V_2, and V_3 are as defined earlier,
x_{c1} = crossover distance between layers 1 and 2, and
x_{c2} = crossover distance between layers 2 and 3.

Other forms of this equation are presented by Mooney (1981) and Alsop (1982).

Two-layer dipping-boundary formulas (See figure 5)

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

To learn about the geometry of a dipping boundary, the refraction profile must be reversed. For a single array, a minimum of two shots must be fired, one from each end of the array. This concept is termed "reversed-profile shooting," and the practice should be followed 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 illustrated in figure 5. The total traveltime of compressional sound waves from shotpoint D to shotpoint U, and in the opposite direction, from shotpoint U to shotpoint D, must be equal; that is, T_u must equal 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 shotpoint 2 than at shotpoint 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, seismic-refraction methods measure the apparent seismic velocity and not the true seismic velocity. The true seismic velocity is the harmonic mean of the measured apparent updip and downdip velocities multiplied by the cosine of the dip angle. It can be determined by the following formula:

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

where

V_2 = true velocity of sound in layer 2,
V_{2u} = apparent updip velocity of sound (from time-distance plot),
V_{2d} = apparent downdip velocity of sound (from time-distance plot), and
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

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

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

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

$$\text{(a)}\quad \theta_c=\tfrac{1}{2}\left(\sin^{-1} V_1m_d+\sin^{-1} V_1m_u\right), \tag{11}$$

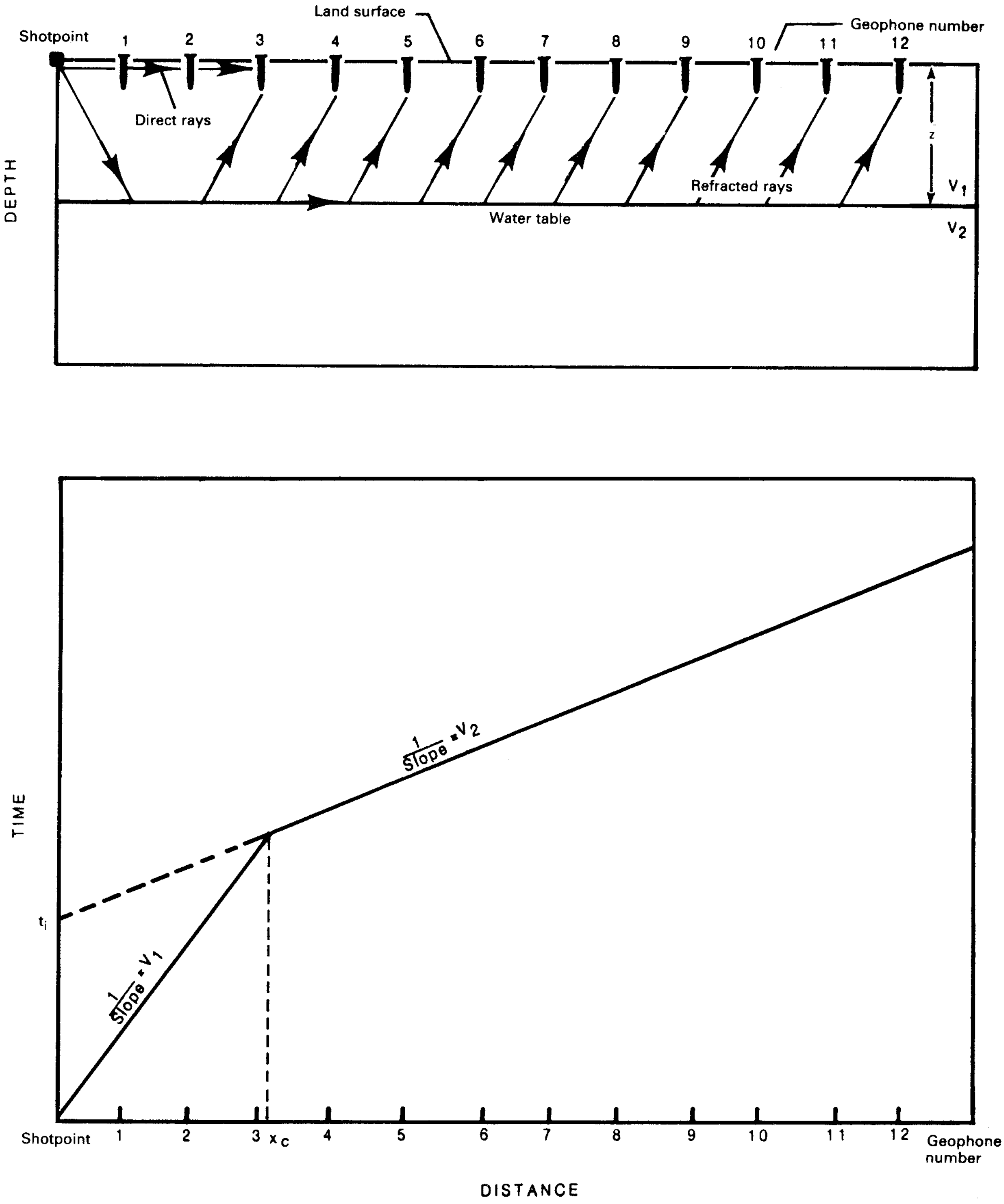


Figure 3.—Seismic raypaths and time-distance plot for a two-layer model with parallel boundaries.

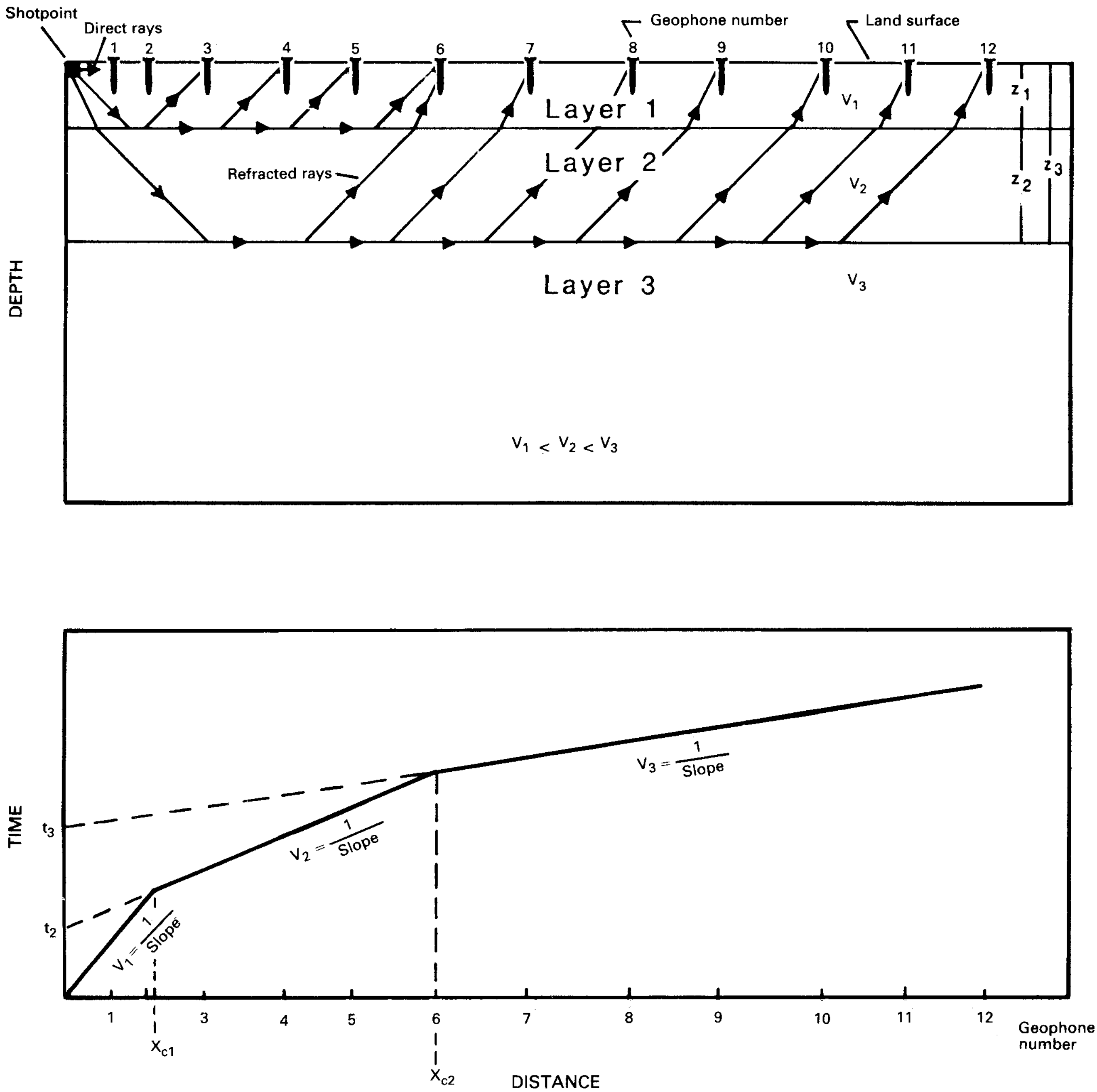


Figure 4.—Seismic raypaths and time-distance plot for a three-layer model with parallel boundaries.

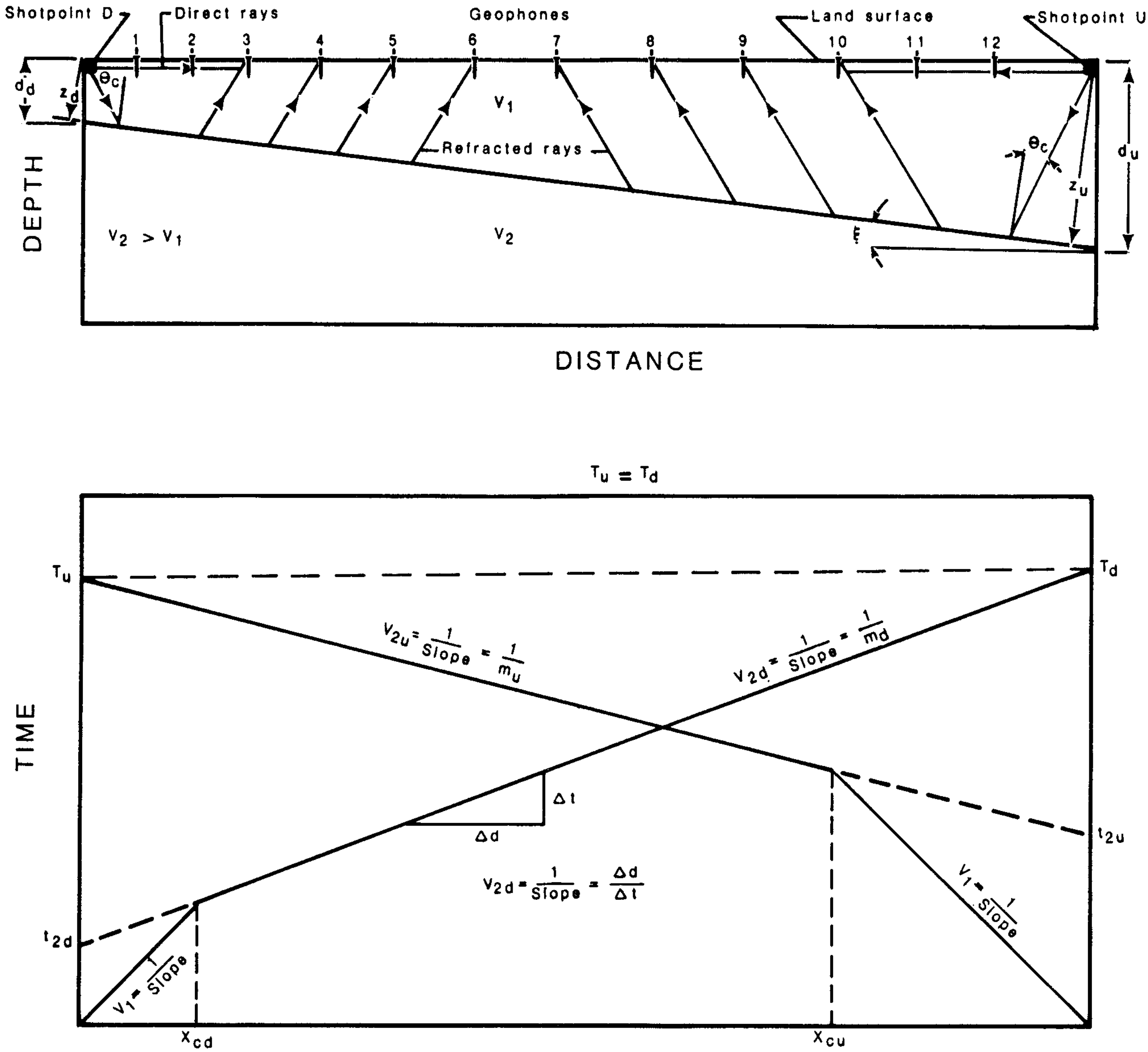


Figure 5.—Seismic raypaths and time-distance plot for a two-layer model with a dipping boundary.

where

θ_c = critical angle,

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

m_d = slope of downdip V_2 segment on time-distance plot, and

m_u = slope of updip V_2 segment on time-distance plot.

(b) $$\xi = \tfrac{1}{2}\left(\sin^{-1} V_1 m_d - \sin^{-1} V_1 m_u\right), \qquad (12)$$

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 updip shotpoint (shotpoint 2) and

t_{2u} = intercept time of updip 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 downdip shotpoint (shotpoint 1) and

t_{2d} = intercept time of downdip V_2 segment of time-distance plot.

(e)
$$d_u = \frac{z_u}{\cos \xi}, \tag{15}$$

where

d_u = extrapolated vertical depth to the refractor beneath shotpoint on updip side (shotpoint 2).

(f)
$$d_d = \frac{z_d}{\cos \xi}, \tag{16}$$

where

d_d = extrapolated vertical depth to the refractor beneath shotpoint on downdip side (shotpoint 1).

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

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

and

(b)
$$d_d = \frac{x_{cd}}{2 \cos \xi} \frac{V_2-(V_1 \cos \xi)}{\sqrt{(V_2)^2-(V_1)^2}} - \frac{x_{cd}}{2} \tan \xi, \tag{18}$$

where

V_1 and ξ are as defined for equations 11 and 12,

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

x_{cu} = crossover distance of the updip time-distance segment, and

x_{cd} = crossover distance of the downdip time-distance segment.

Equations 17 and 18 simplify to the following if the dip angle is small and cosine ξ is almost equal to 1.0:

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

and

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

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. If only one shot in one direction is fired, 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,

$$z = \frac{t_1}{2} \frac{V_2 V_1}{\sqrt{(V_2)^2-(V_1)^2}}$$

$$= \frac{0.0075}{2} \frac{10{,}600(5{,}000)}{\sqrt{(10{,}600)^2-(5{,}000)^2}}$$

$$= 21 \text{ ft.}$$

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.

(1) Using the two-layer, dipping-interface, intercept-time formulas (eqs. 9, 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 ft/s

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

(a)
$$\xi = ½[\sin^{-1}(V_1 m_d) - \sin^{-1}(V_1 m_u)]$$

$$= ½[\sin^{-1} 5{,}000(0.0000945) - \sin^{-1} 5{,}000(0.0000375)]$$

$$= 8.75°$$

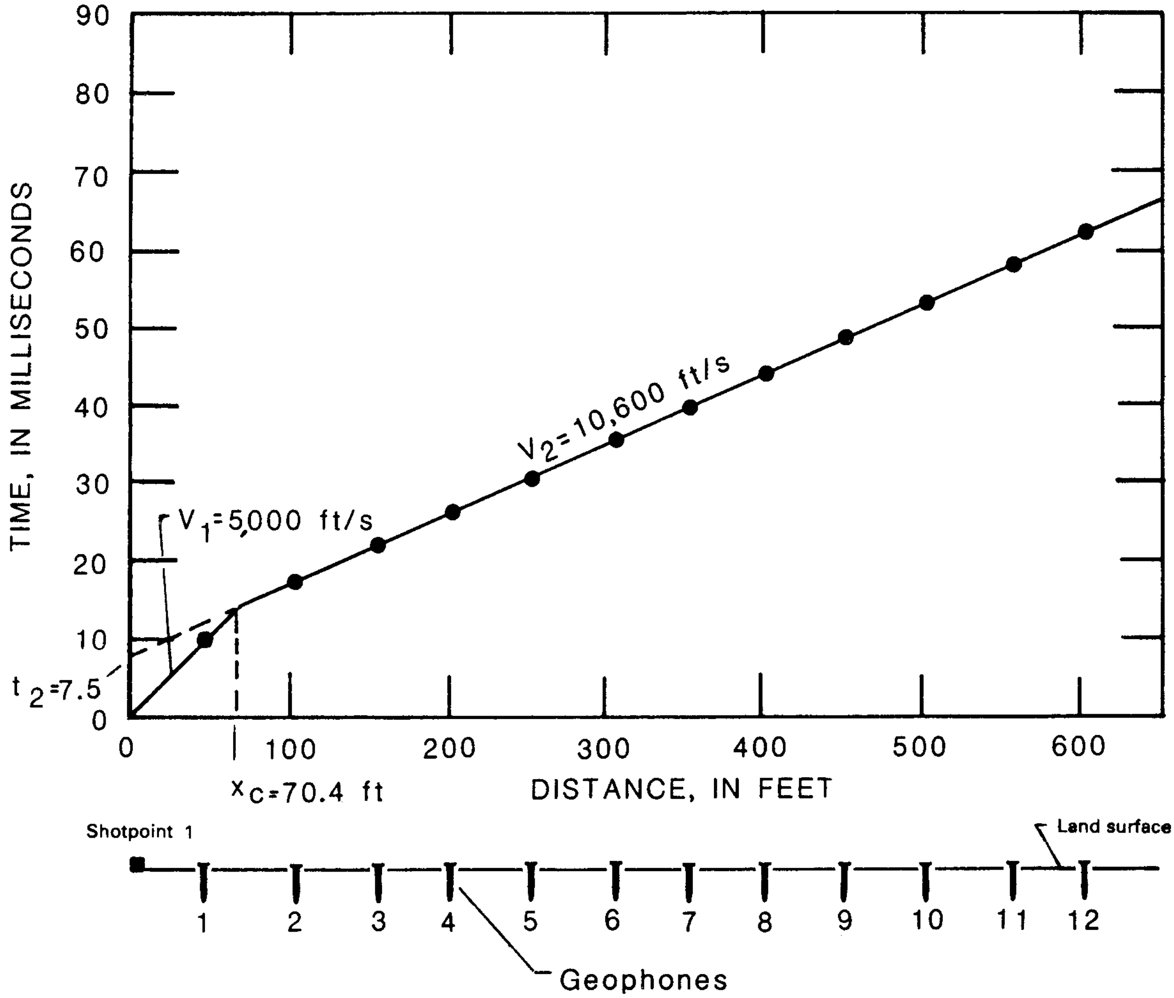


Figure 6.—Time-distance plot resulting from one shotpoint over a two-layer model with a dipping boundary.

(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) $$\theta=\tfrac{1}{2}[\sin^{-1}(V_1m_d)+\sin^{-1}(V_1m_u)]$$
$$=\tfrac{1}{2}[\sin^{-1}5{,}000(0.0000945)$$
$$+\sin^{-1}5{,}000(0.0000375)]$$
$$=19.5°$$

(d) $$z_u=\frac{V_1t_{2u}}{2\cos\theta}=\frac{5{,}000(0.0448)}{2\cos 19.5}=118.8\ \text{ft}$$

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

(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, 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

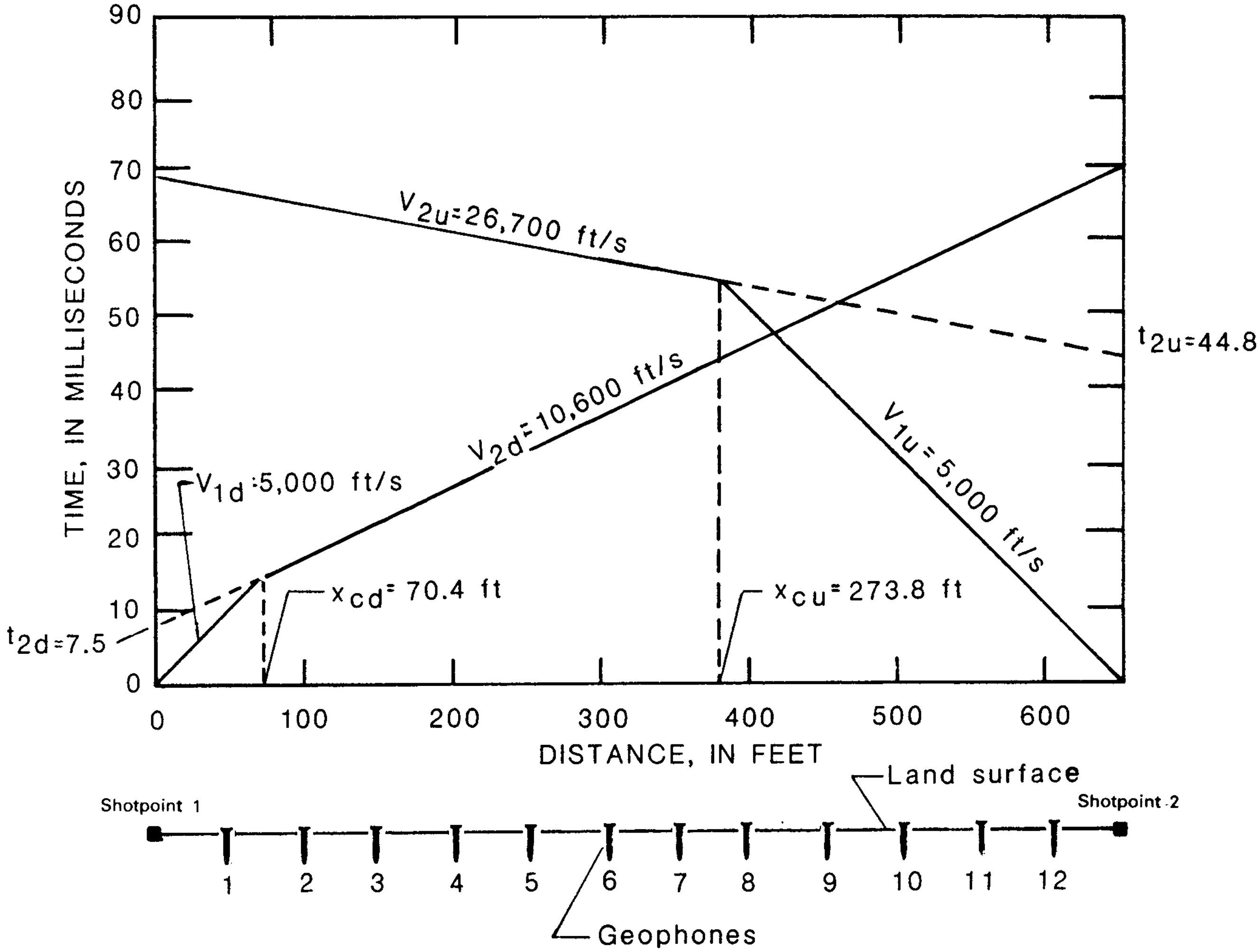


Figure 7.—Time-distance plot resulting from two reversed shots over the two-layer model with a dipping boundary illustrated in figure 5.

(a) $\xi = \tfrac{1}{2}[\sin^{-1}(V_1 m_d) - \sin^{-1}(V_1 m_u)]$

$= \tfrac{1}{2}[\sin^{-1} 5{,}000(0.0000945)$

$- \sin^{-1} 5{,}000(0.0000375)]$

$= 8.75°$

(b) $V_2 = \dfrac{2V_{2u}V_{2d}}{V_{2u}+V_{2d}} \cos \xi$

$= \dfrac{2(26{,}700)(10{,}600)}{26{,}700+10{,}600} \cos 8.75$

$= 15{,}000$ ft/s

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

$= \dfrac{273.8}{2 \cos 8.75} \cdot \dfrac{15{,}000 - (5{,}000 \cos 8.75)}{\sqrt{(15{,}000)^2 - (5{,}000)^2}}$

$+ \dfrac{273.8 \tan 8.75}{2}$

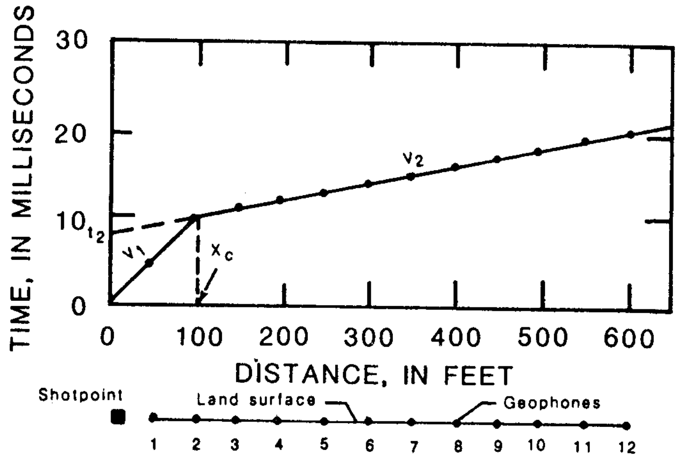
$= 120$ ft

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

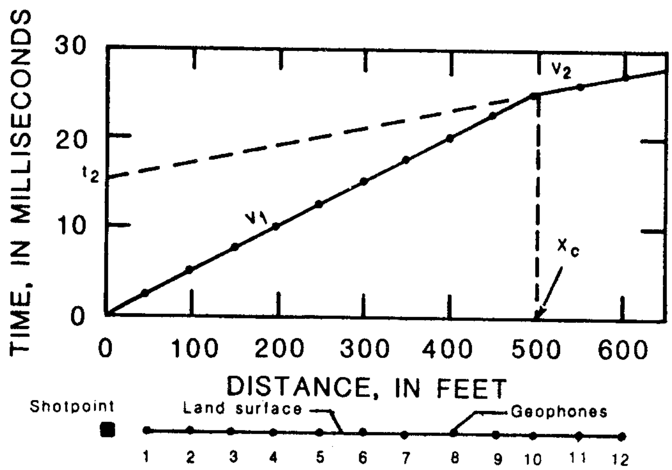
$= \dfrac{70.4}{2 \cos 8.75} \cdot \dfrac{15{,}000 - (5{,}000 \cos 8.75)}{(15{,}000)^2 - (5{,}000)^2}$

$- \dfrac{70.4 \tan 8.75}{2}$

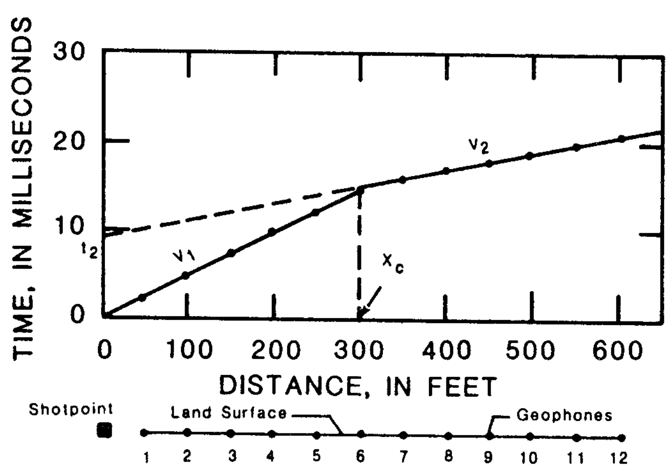
$= 20$ ft



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 errors.



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 crossover-distance formulas in determining depth to a refractor under different field conditions.

Summary of example problem:

1. Using a single-shot, nonreversed seismic-refraction profile and the two-layer parallel-boundary formulas, the interpretation gives a subsurface having a velocity of sound in layer 1 of 5,000 ft/s and a second horizontal layer 21 ft deep having 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 having a velocity of sound in layer 1 of 5,000 ft/s and a second layer dipping at 8.7° and having a velocity of sound of 15,000 ft/s. The depth to this interface is 20 ft at the updip shotpoint and 120 ft at the downdip shotpoint.

Multilayer dipping-boundary formulas

Mota (1954), Johnson (1976), and Knox (1976) have published formulas that apply to problems involving 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 attributable to the field process and to 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 are not covered here.

Field corrections

In addition to the theoretical solutions to seismic-refraction problems, corrections for field-related problems have also been developed. The two main types of corrections are elevation corrections and weathering corrections. Both are used to adjust field-derived traveltimes to some selected datum planes, 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 distance 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 greater difficulty in determining the correct slope of the segments of the time-distance plot 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.

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 using 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) slow-seismic-velocity units underlying high-seismic-velocity units.

Thin, intermediate-seismic-velocity refractor

One of the most serious limitations of seismic-refraction methods is their inability to detect intermediate layers in cases in which 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. 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 by shallow shotpoints. Deep shotholes may overcome this problem (Soske, 1959), but they 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 illustrating a situation in which a 70-ft-thick intermediate-seismic-velocity layer is not detected by first arrivals on the time-distance plot. If the intermediate layer is a thin, intermediate-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 exhibiting this problem is dependent on 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 that a qualified interpretation is in order. An example of this is shown in figure 10, in which 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.

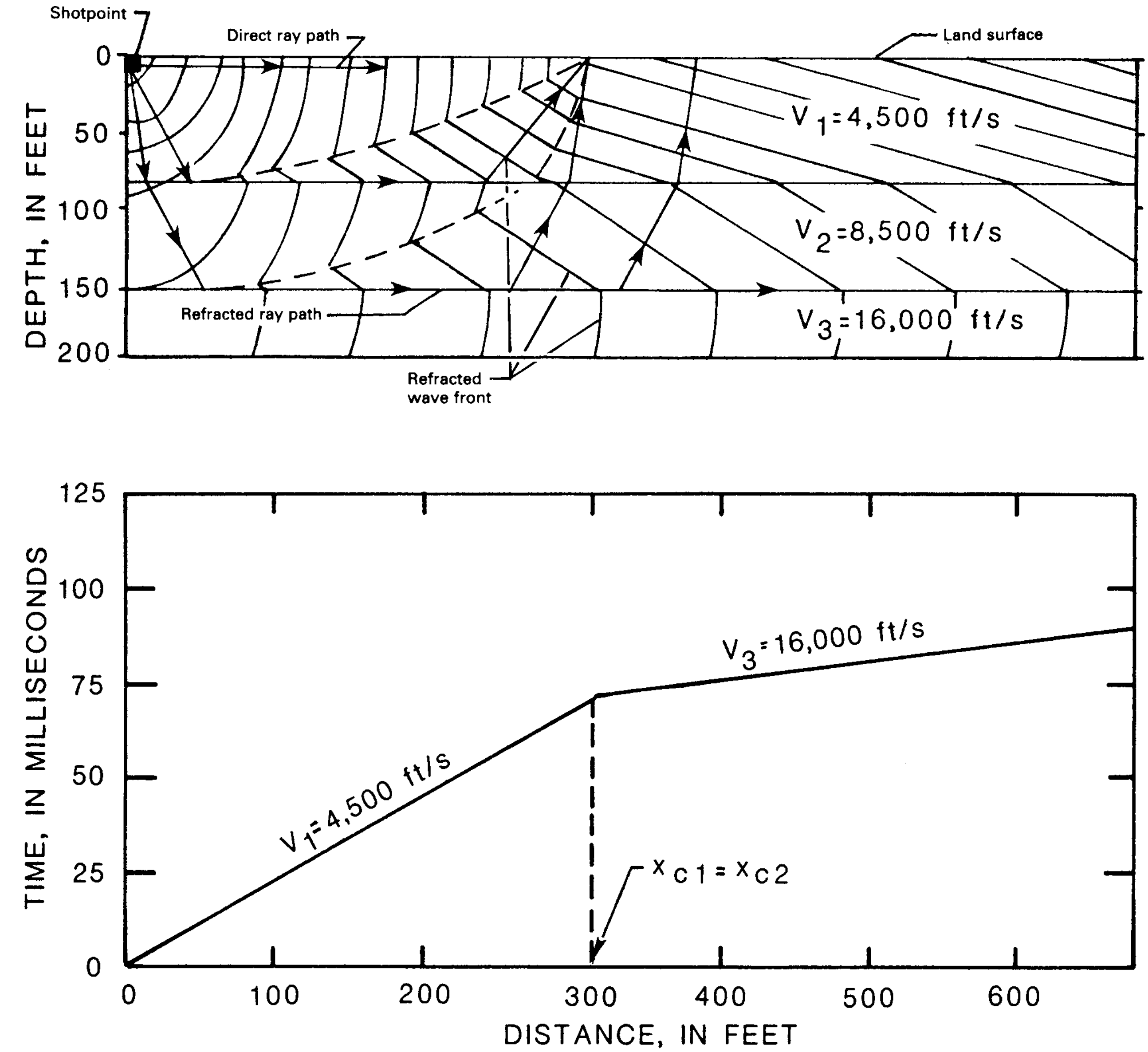


Figure 9.—Seismic wave fronts with selected raypaths and the corresponding time-distance plot for the case of an undetectable intermediate-seismic-velocity layer (modified from Soske, 1959, fig. 4, p. 362).

The case illustrated in figure 10 is very common 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 refraction techniques and is not shown in fig. 10), and the crystalline bedrock has a velocity of 15,000 ft/s.

If a thin, intermediate-seismic-velocity layer is suspected, 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 in table 1 are based on 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), and
V_2 = 5,000 ft/s (from previous investigations).

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

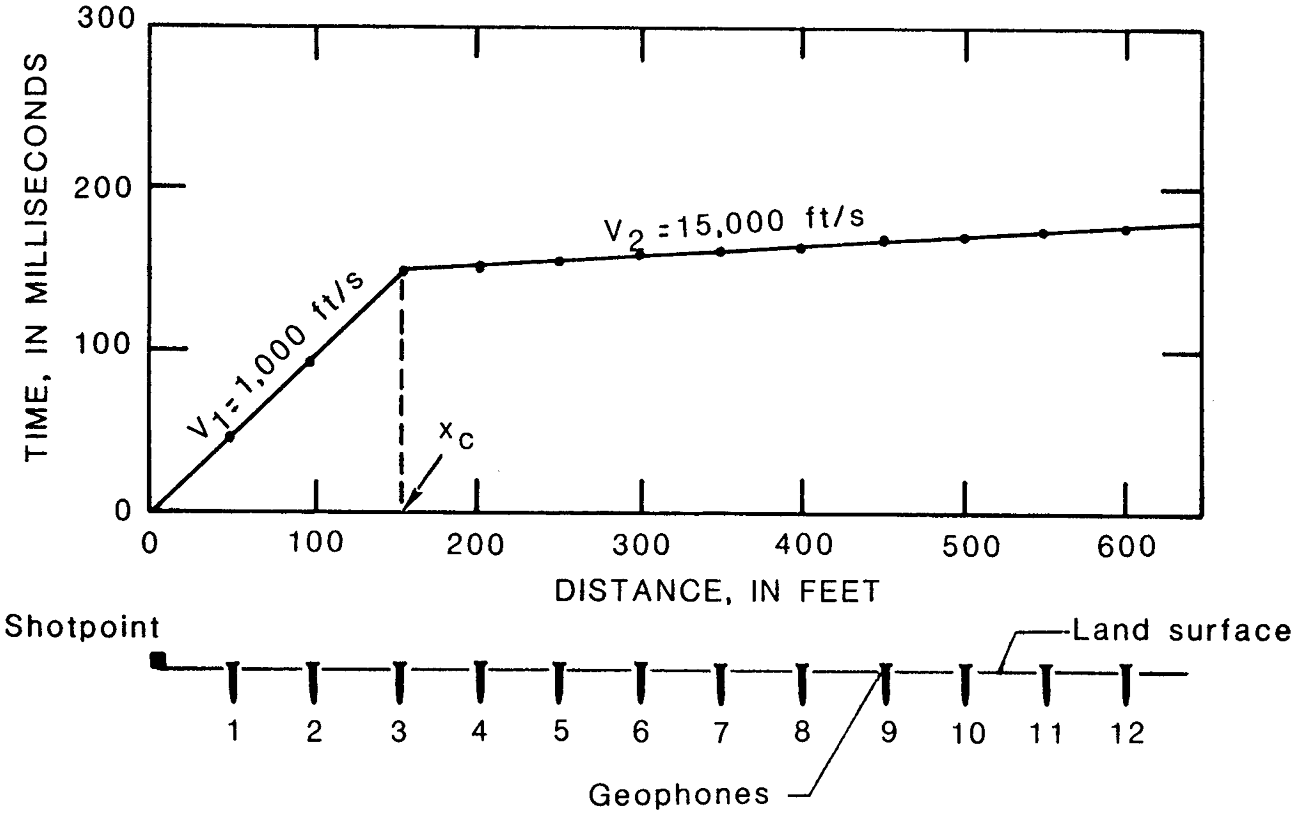


Figure 10.—Time-distance plot showing two layers in an area known to have three layers.

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

The depth to rock using the two-layer interpretation (that is, assuming that there is no saturated material in the geologic section) is, therefore, 50 ft.

B. If the presence of a hidden layer of saturated material is suspected from wells or test holes in the area, the following calculations can be carried out. The minimum depth to layer 2 (the water table) and the maximum possible thickness of undetectable saturated material can be calculated when $x_{c1}=x_{c2}$. (See figs. 9, 11.) In order to calculate these values we assume that a three-layer subsurface exists and proceed with a 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 (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 minimum depth to the water table in the three-layer subsurface is 41 ft.

2. For the depth to layer 3 (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 is defined as

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

$$P=.86$$

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

The maximum depth to the bedrock surface is 74 ft.

3. For the maximum undetected thickness of layer 2 (that is, the saturated thickness of the unconsolidated material),

$$\max z_2=z_3-z_1=74-41=33 \text{ ft.}$$

The maximum thickness of an undetected layer 2 in a three-layer subsurface is 33 ft.

In summary, a maximum of 33 ft of saturated sand and gravel under a minimum of 41 ft of unsaturated sand and

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/s	10	8	12-18
Saturated sand aquifer, V_2 = 5,000 ft/s	20	16	24-36
	40	33	50-74
Bedrock, V_3 = 15,000 ft/s	50	41	61-91
	100	82	123-182
	200	164	243-364
Till, V_1 = 7,000 ft/s	10	3	11-13
Sedimentary rock aquifer, V_2 = 13,000 ft/s	20	7	22-26
	50	17	55-67
Crystalline rock, V_3 = 15,000 ft/s	100	33	110-133
	200	67	219-267
Saturated sand and gravel, V_1 = 5,000 ft/s	10	6	12-16
	20	12	24-32
Limestone aquifer, V_2 = 10,000 ft/s	50	29	61-79
Crystalline rock, V_3 = 15,000 ft/s	100	58	122-158
	200	115	245-315

gravel could not be detected with the seismic-refraction method in the above example. The depth to rock is between 50 and 74 ft depending on the thickness of the saturated zone. The saturated thickness of undetected sand and gravel is between 0 and 33 ft. The minimum depth to the water table is 41 ft.

Insufficient seismic-velocity contrasts between hydrogeologic units

In many studies, significant hydrogeologic materials may not have detectable seismic-velocity contrasts. Many rock surfaces are not fresh and exhibit 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, seismic-refraction techniques 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 these techniques. 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 hydrogeologic 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) semiconsolidated rubble zones beneath dense basalt flows, and (3) dense limestone overlying a poorly cemented sandstone.

In all of these cases, the low-velocity unit will not be detected by seismic-refraction techniques 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

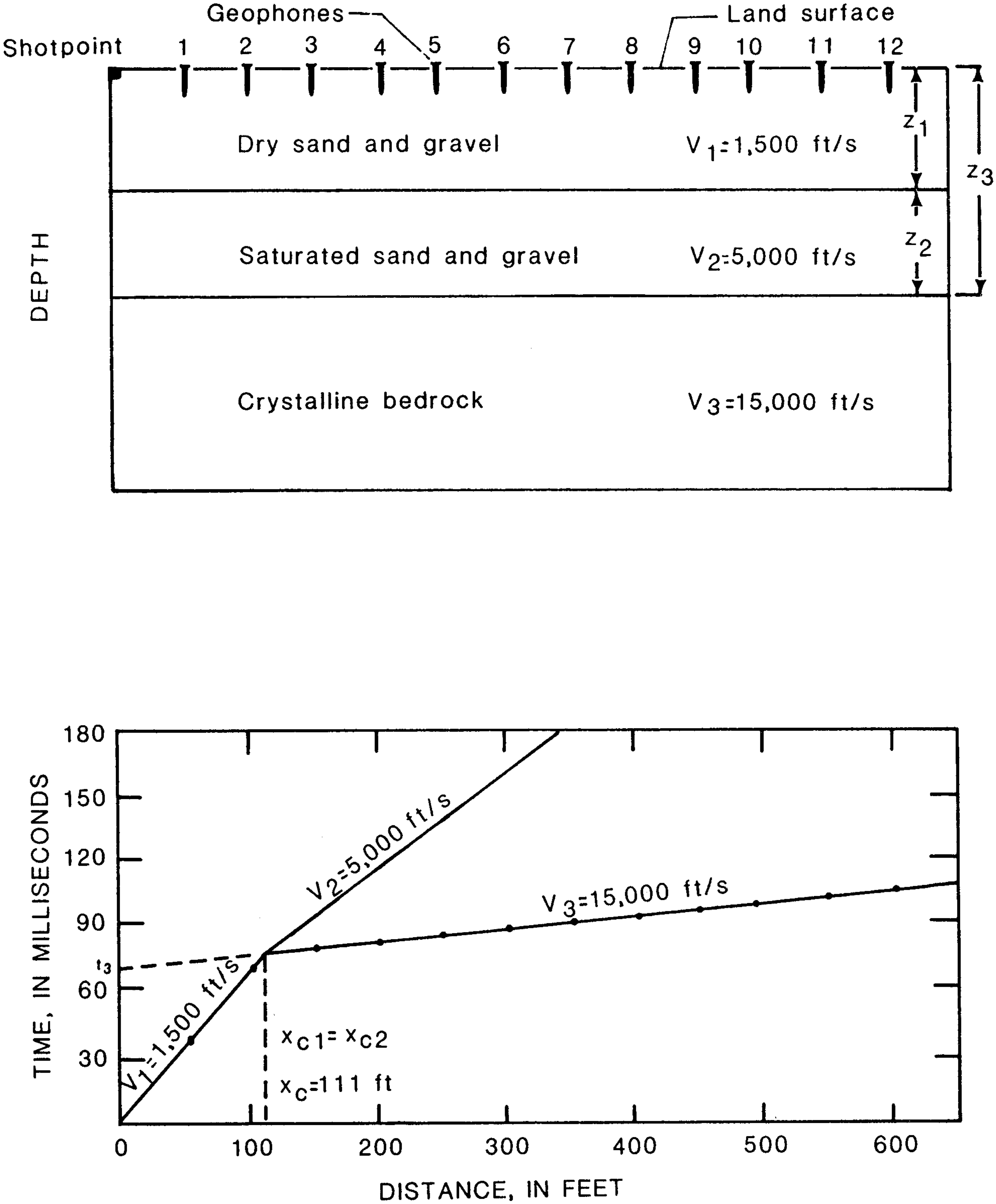


Figure 11.—Seismic section with hidden layer (layer 2) and resulting time-distance plot.

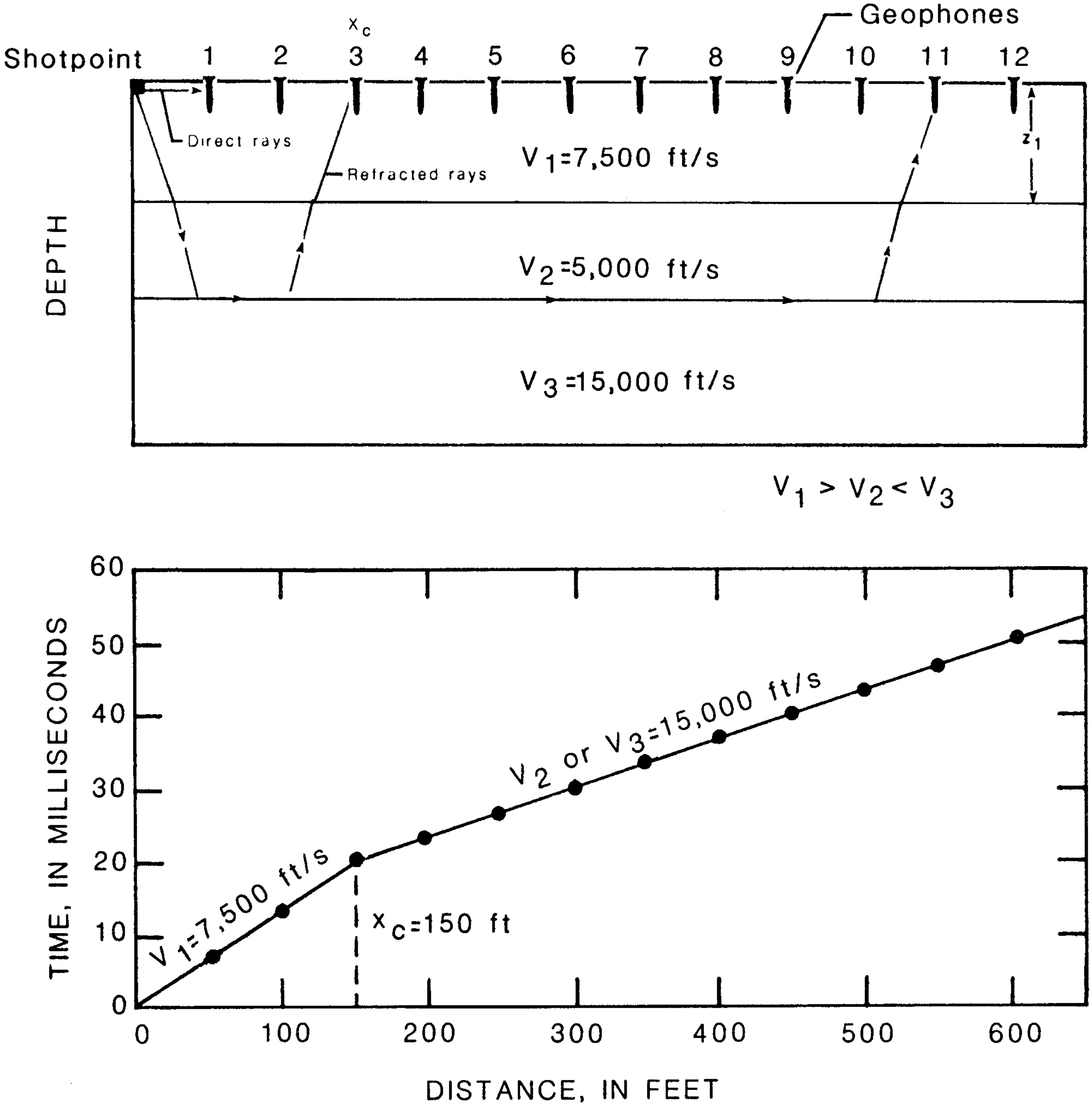


Figure 12.—Seismic section with velocity reversal and resulting time-distance plot.

encountered a layer having 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 if its depth and seismic velocity are approximately known, the depth to a deeper refractor can be estimated (Mooney, 1981; Morgan, 1967). Without this information, the depth calculated from the seismic-refraction data will be greater than the actual depth.

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 time-distance plot),
V_2 = 15,000 ft/s (from time-distance plot),
z_2' = erroneous depth to layer 3, and
x_c = 150 ft (from time-distance plot).

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

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 and having 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_1 =7,500 ft/s,
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), and
z_2 =true depth to layer 3.

$$z_2=(Q+1)\frac{x_c}{2}\sqrt{\frac{V_3-V_1}{V_3+V_1}}-z_1Q, \tag{21}$$

where Q is defined as

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

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 subsurface 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 in interpreting data gathered 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.

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 seismic-refraction techniques

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, that is, the noise produced by vehicular traffic, construction equipment, railroads, wind, and so forth, has a detrimental effect on the quality of seismic-refraction data. Some solutions to this problem are as follows: (1) decrease the amplifier gains and increase the input signal by using more explosives or repeated hammer blows, (2) reschedule operations for a quiet part of the day, and (3) 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 a significant effect on seismic-refraction studies. This zone usually is the unsaturated zone and typically has velocities of 400 to 1,600 ft/s. Short geographic spreads are needed to determine the velocity of sound and the thickness of this layer. A variation of 1 ft in the thickness of a weathered layer consisting of material having a velocity of sound of 1,000 ft/s causes the refracted sound ray to be delayed or sped up by 1 ms. This same time interval represents 10 ft of material having a velocity of sound of 10,000 ft/s.

Accuracy of seismic-refraction measurements

The accuracy with which the depth to a refractor can be determined by seismic-refraction methods depends on many factors. Some of these factors are

- Type and accuracy of seismic equipment,
- Number and type of corrections made to field data,
- Quality of field procedures,

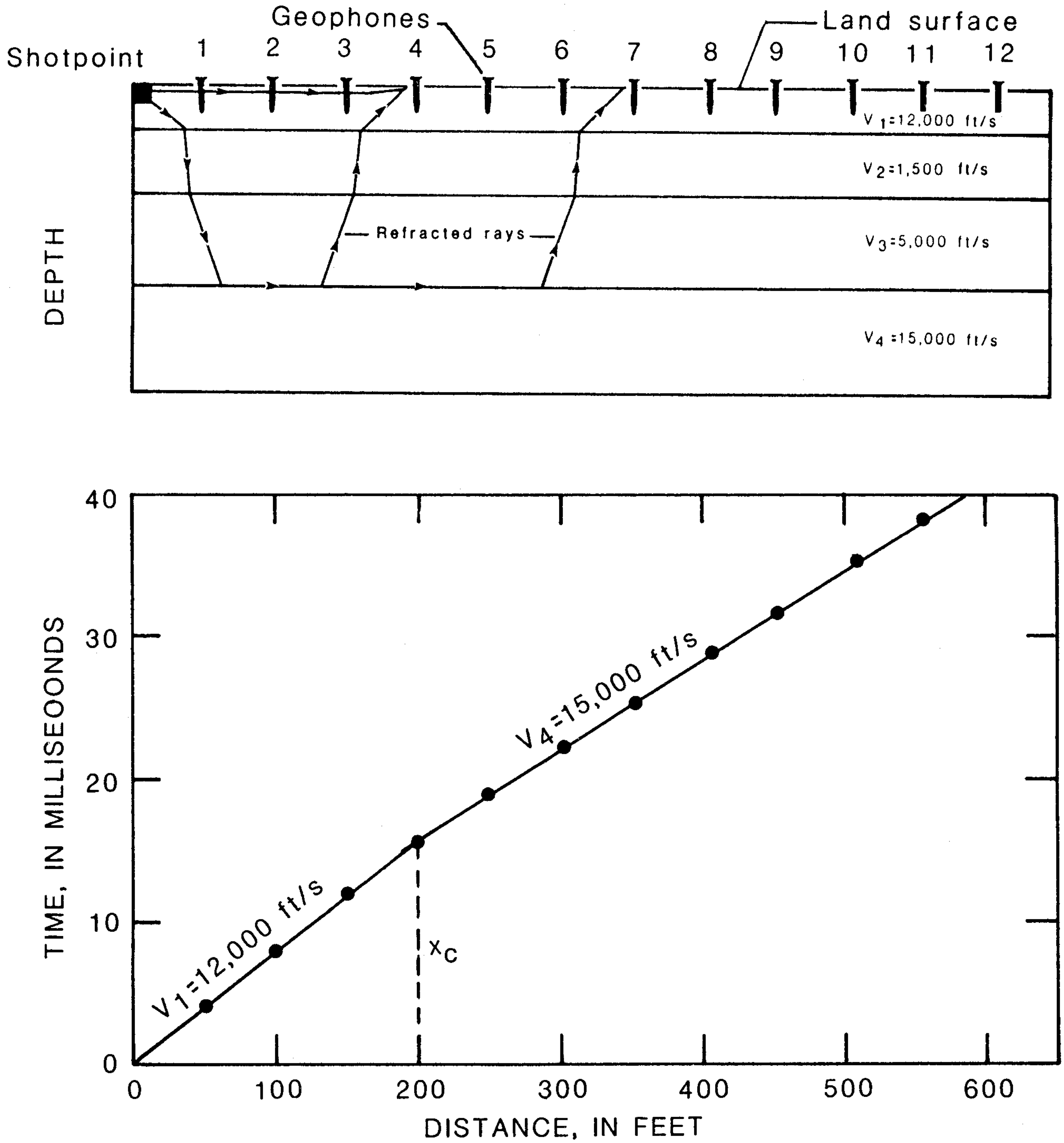


Figure 13.—Interpreted seismic section and time-distance plot for a four-layer model having frozen ground at the surface.

- Type of interpretation method used,
- Variation of the Earth from simplifying assumptions used in the interpretation procedure, and
- 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 of difficult field situations.

Annotated references

Alsop, S.A., 1982, Engineering geophysics: Association of Engineering Geologists Bulletin, v. 19, no. 2, p. 181–186.
[Brief review of the engineering application of seismic-refraction techniques.]

Burke, K.B.S., 1967, A review of some problems of seismic prospecting for ground water in surficial deposits, *in* Morey, L.W., ed., Mining and ground-water geophysics: Canada Geological Survey Economic Geology Report 26, p. 569–579.
[Review and evaluation of three problems encountered while using seismic prospecting for ground water: (1) the difficulty in generating simple seismic waves in unconsolidated materials, (2) the lack of a definitive relationship between seismic velocity and a particular deposit, and (3) the much greater significance of error in small-scale seismic investigations.]

Burwell, E.B., 1940, Determination of ground-water levels by the seismic method: Transactions of the American Geophysical Union, v. 21, p. 439–440.
[Changes in velocity of sound in saturated material shown to be independent of alluvial material present.]

Bush, B.O., and Schwarz, S.D., 1965, Seismic refraction and electrical resistivity measurements over frozen ground, *in* Brown, R.J.E., ed., 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 86, p. 32–40.
[Seismic-refraction techniques were evaluated for predicting the depth to rock with frozen ground at the surface.]

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, with emphasis on deep exploration.]

Domzalski, W., 1956, Some problems of shallow refraction investigations: Geophysical Prospecting, v. 4, no. 2, p. 140–166.
[Detailed discussion and examples of problems encountered in shallow seismic-refraction studies.]

Eaton, G.P., and Watkins, J.S., 1967, The use of seismic-refraction and gravity methods in hydrologic investigations, *in* Morey, L.W., ed., Mining and ground-water geophysics: Geological Survey of Canada Economic Geology Report 26, p. 554–568.
[A review of seismic-refraction methods with case histories pertaining to ground-water studies. Includes a comprehensive bibliography of work prior to 1967.]

Grant, F.S., and West, G.F., 1965, Interpretation theory in applied geophysics: New York, McGraw-Hill, 583 p.
[Detailed discussions of the basic theory behind surface geophysical techniques.]

Green, R., 1962, The hidden layer problem: Geophysical Prospecting, v. 10, no. 2, p. 166–170.
[Discusses how to determine the range in thickness of a hidden layer given a refraction time-distance curve.]

Griffiths, D.H., and King, R.F., 1965, Applied geophsyics for engineers and geologists (2d ed.): Oxford, England, Pergamon Press, 223 p.
[Clear, short text explaining various geophysical techniques.]

Habberjam, G.M., 1966, A nomogram for investigation of the three-layer refraction problem: Geoexploration, v. 4, no. 4, p. 219–225.
[Describes construction of a single-sheet nomogram for investigating the three-horizontal-layer refraction problem when the deepest layer has the highest seismic velocity.]

Hawkins, L.V., and Maggs, D., 1961, Nomographs for determining maximum error problem: Geophysical Prospecting, v. 9, no. 4, p. 526–532.
[Has nomograms for solution of the thin, intermediate-seismic-velocity-layer problem for critical-distance and time-intercept formulas.]

Johnson, S.H., 1976, Interpretation of split-spread refraction data in terms of plane dipping layers: Geophysics, v. 41, no. 3, p. 418–424.
[Develops a computing procedure to interpret split-spread refraction data assuming that the geologic formation may be approximated by planar, dipping velocity layers.]

Knox, W.A., 1976, Multi-layer near surface refraction computations, *in* Musgrave, A.W., ed., Seismic-refraction prospecting: Tulsa, Okla., Society of Exploration Geophysicists, p. 197–216.
[Discussion of near-surface geologic conditions and the effects of varying shot depths on the interpretation of shallow refraction formulas.]

Meridav, Tsvi, 1960, Nomograms to speed up seismic refraction computations: Geophysics, v. 25, no. 5, p. 1035–1053.
[Includes nomograms for the solution of two-layer crossover-distance formulas, critical-angle and offset-distance formulas, and two-layer intercept-time formulas, and calculation of true velocity from apparent updip and downdip velocity.]

———1968, A multi-layer seismic refraction nomogram: Geophysics, v. 33, no. 3, p. 524–526.
[A nomogram for solving multilayer refraction problems using crossover distances and layer velocities.]

Mooney, H.M., 1981, Handbook of engineering geophysics, v. 1: Seismic: Minneapolis, Bison Instruments, Inc., 220 p.
[A thorough handbook covering the theory and practical aspects of shallow refraction and reflection techniques.]

Morgan, N.A., 1967, The use of continuous seismic profiles to solve hidden-layer problems: Geophysical Prospecting, v. 15, no. 1, p. 35–43.
[Shows that use of a continuous seismic-reflection profiler may overcome the hidden-layer problem in refraction surveys. This technique allows calculation of the velocity and thickness of the hidden layer.]

Mota, L., 1954, Determination of dips and depths of geological layers by the seismic refraction method: Geophysics, v. 19, p. 242–254.
[Equations developed for computing depths and dips of inclined interfaces from seismic-refraction data.]

Musgrave, A.W., ed., 1967, Seismic-refraction prospecting: Tulsa, Okla., Society of Exploration Geophysicists, 604 p.
[A volume of papers on the refraction method with an extensive bibliography of seismic-refraction techniques.]

Parasnis, D.S., 1979, Principles of applied geophysics (3d ed.): London, Chapman and Hall (distributed in the United States by John Wiley and Sons, New York), 275 p.
[A very brief description 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 Report of Investigation 7595, 95 p.
[Presents a computer program that 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, Okla., Society of Exploration Geophysicists, 266 p.
[Exhaustive glossary of exploration geophysics and its related disciplines.]

Slotnick M.M., 1959, Lessons in seismic computing: Tulsa, Okla., 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 and results of, 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, with emphasis 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 (crossover-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 Mabey, D.R., 1974, Application of surface geophysics to ground-water investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 2, Chapter D1, 116 p.
[An overview of surface geophysical techniques and their applications to hydrologic studies.]

Applications of Seismic-Refraction Techniques to Hydrology

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 techniques (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 provided. This section is intended as an initial guide for the hydrologist considering the use of geophysical techniques. Specific applications of the techniques should be tested in the field, in areas where adequate geologic and hydrologic controls are available.

Hydrogeologic settings in which 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. The five case histories presented below illustrate 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 setting is a common hydrologic goal. Because the velocity of sound in unconsolidated, unsaturated sands and gravels ranges from 400 to 1,600 ft/s, and because the velocity of sound in unconsolidated, saturated 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).

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, 13.1 ft. The use of the sledge hammer as a sound source provided sufficient first-arrival energy to a distance of only 75 ft from the source and, consequently, limited the penetration depth to about 25 ft. To determine greater 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 those of Burwell (1940), Emerson (1968), Sjogren and Wagner (1969), and Followill (1971).

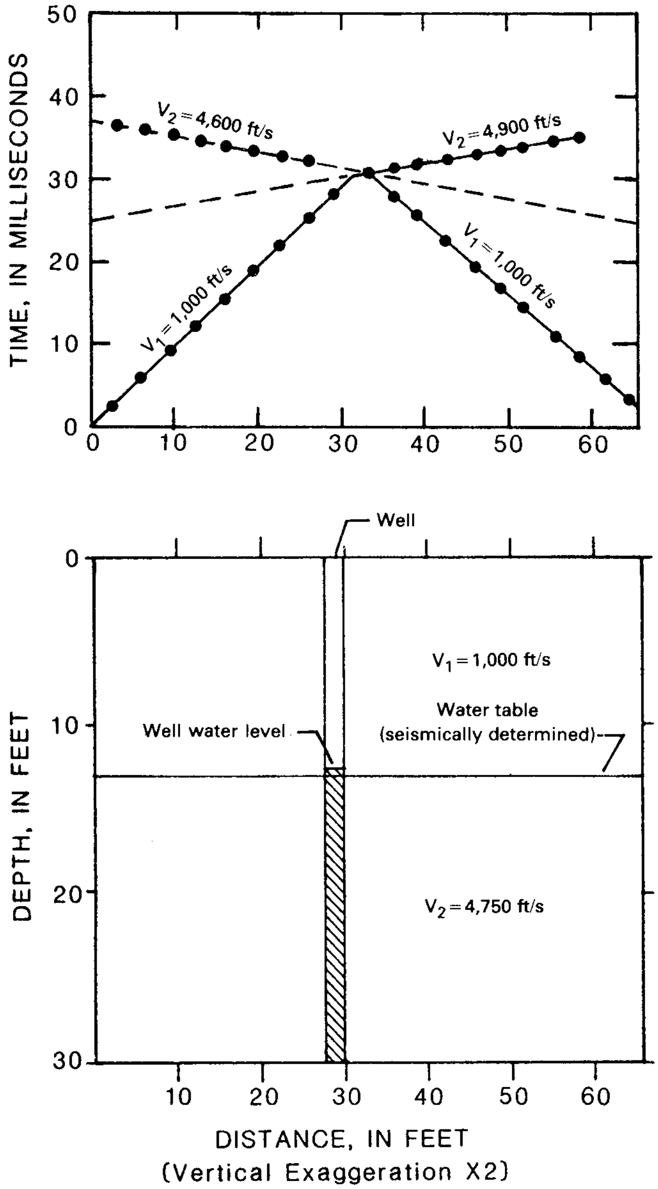


Figure 14.—Time-distance plot and interpreted seismic section from a ground-water study in Vertessomto, Hungary (modified from Galfi and Palos, 1970, p. 45).

Unconsolidated glacial or alluvial material overlying consolidated bedrock

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. Seismic-refraction techniques 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).

To map both a shallow refractor, such as the water table, and a deep refractor, such as the bedrock surface, careful consideration must be given to the choice of shotpoints, geophone spacing, and interpretation method used. Multiple shots, variable geophone spacings, and (or) test-hole data will be needed, depending on 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, N.J. (fig. 15). 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 because the water table was known to be close to the surface, only one shotpoint on each end of each geophone spread was used. The shots were 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 interpretation procedure to estimate, or "back out," the velocity of the thin unsaturated zone. The 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 those of Gill

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

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).

Thick, unconsolidated alluvial or sedimentary materials 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 layers are much thicker. As long as the successively deeper layers have a higher seismic velocity and are not thin, seismic-refraction techniques will work. As the depth to the water-table increases, however, the seismic velocity of the unsaturated layer increases, and this may prevent identification of the saturated zone as a separate refracting layer.

The U.S. Geological Survey conducted a seismic-refraction study near Tucson, Ariz. (H.D. Ackermann, U.S. Geological Survey, written commun., 1980), to determine the saturated thickness of the aquifer near the outlet of ground-water flow from the Aura-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 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 the geophones spaced 400 ft apart and one spread of 24 geophones with the geophones spaced 200 ft apart. Five to seven shots, each consisting of 15 to 80 lb 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).

Unconsolidated alluvial material overlying sedimentary rock, which in turn overlies volcanic or crystalline bedrock

In this type of setting, mapping the saturated thickness of the unconsolidated sand aquifer and the thickness of the sedimentary rock aquifer is a common exploration goal. Such goals can be achieved using seismic-refraction techniques 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 section on

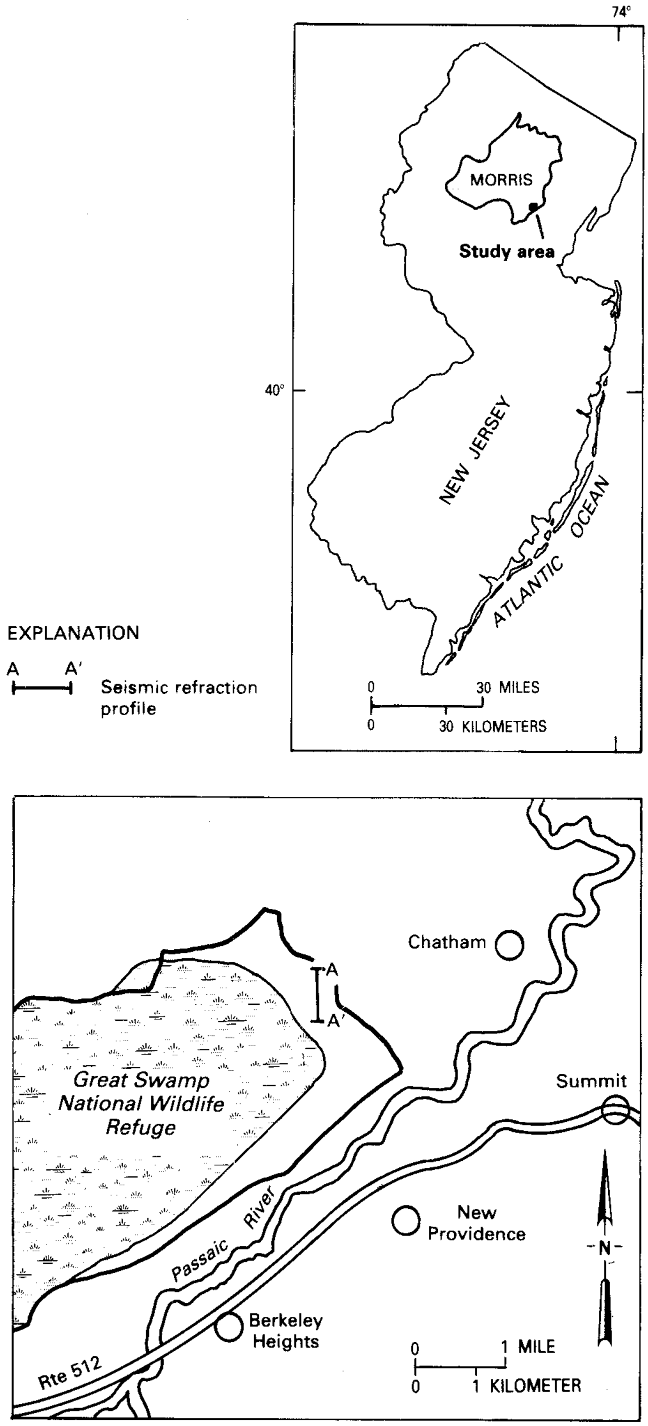


Figure 15.—Generalized location map of Great Swamp National Wildlife Refuge, N.J., and location of seismic-refraction profile A-A .

limitations of seismic-refraction techniques). 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

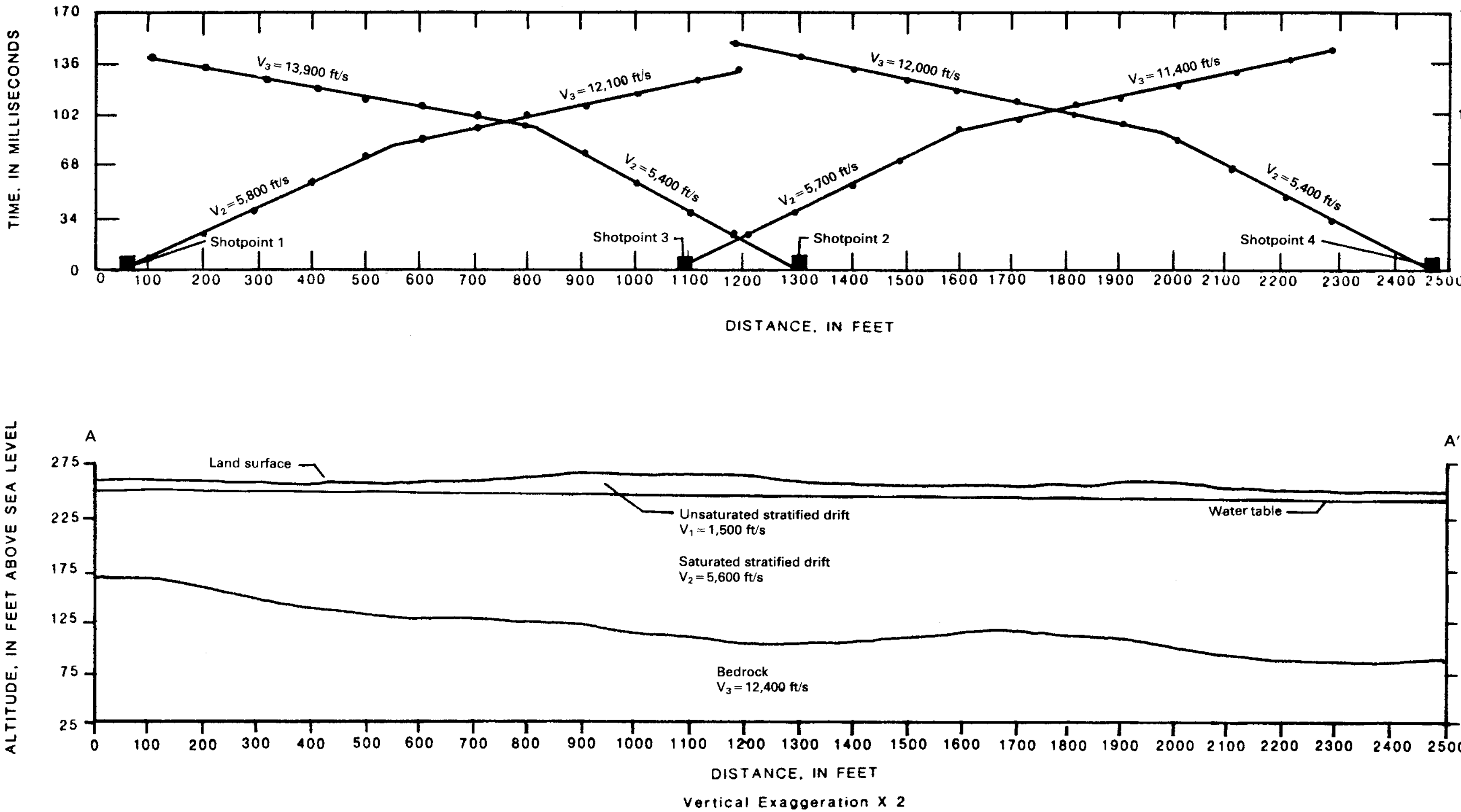


Figure 16.—Time-distance plot and interpreted seismic section near Great Swamp National Wildlife Refuge, Morristown, N.J.

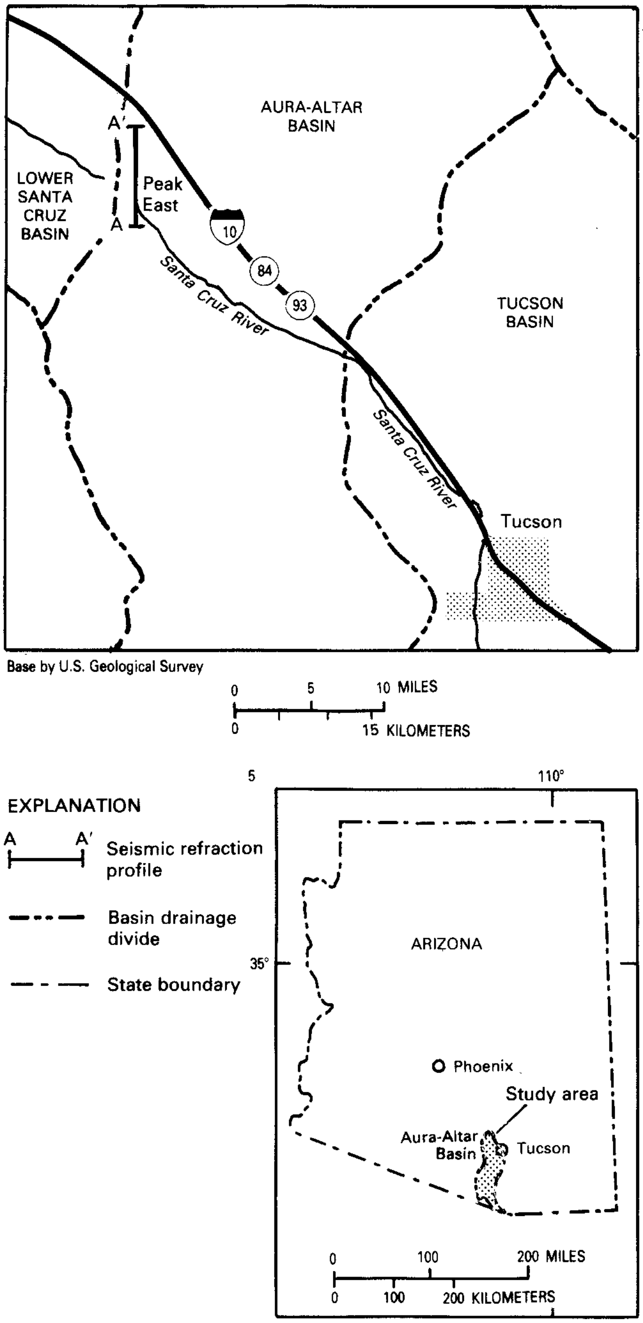


Figure 17.—Generalized location map of Aura-Altar basin, Arizona, and location of seismic-refraction profile A-A'.

profile. In this study, the alluvial aquifer was underlain by a thick limestone aquifer which in turn was underlain by volcanic basement rock.

To map both the shallow and deep refractors, multiple shotpoints were used for each geophone spread. One shotpoint was placed on each end of the geophone line, while others were offset 1,000 ft from each end. Each 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 shothole. 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 by Torres-Gonzalez, 1984.

Unconsolidated stratified-drift material overlying significant deposits of dense lodgement glacial till, which in turn overlie crystalline bedrock

The purpose of a refraction study in this hydrogeologic setting is 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 unsaturated 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 seismic-refraction techniques. Figure 21 shows the location of a seismic line from a study conducted in Farmington, Conn. (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 at this site (approximately 250 ft) is represented by a short segment on the time-distance plot. The till layer is an almost undetectable intermediate-seismic-velocity layer.

The field setup for the profile shown in figure 22 was limited by the physiographic setting and by 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 because the depth to the water table could be measured directly in each shothole. The seismic velocity of the unsaturated layer was subsequently determined using the interpretation program described by Scott and others (1972), and by 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 by Sander (1978).

Hydrogeologic settings in which seismic-refraction techniques may work, but with difficulty

The main limitations that may prevent 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 a thin, intermediate-

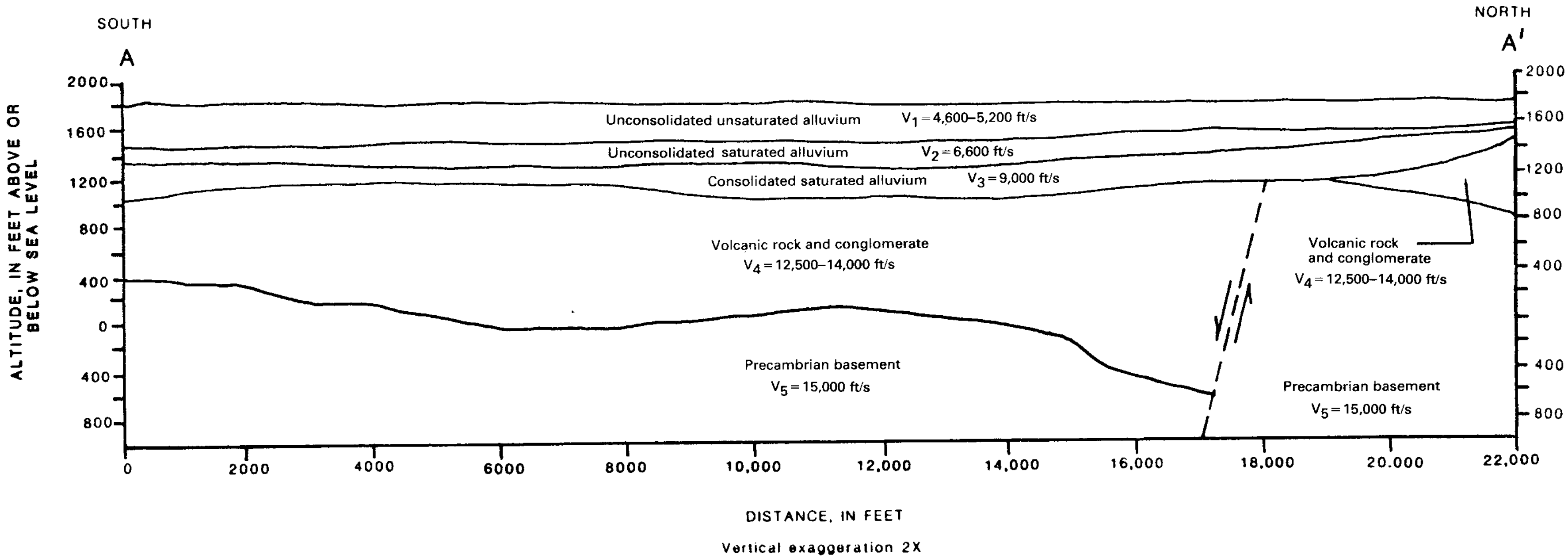


Figure 18.—Interpreted seismic section A-A′ in Aura-Altar basin, near Tucson, Ariz. (Patrick Tucci, written commun., 1981).

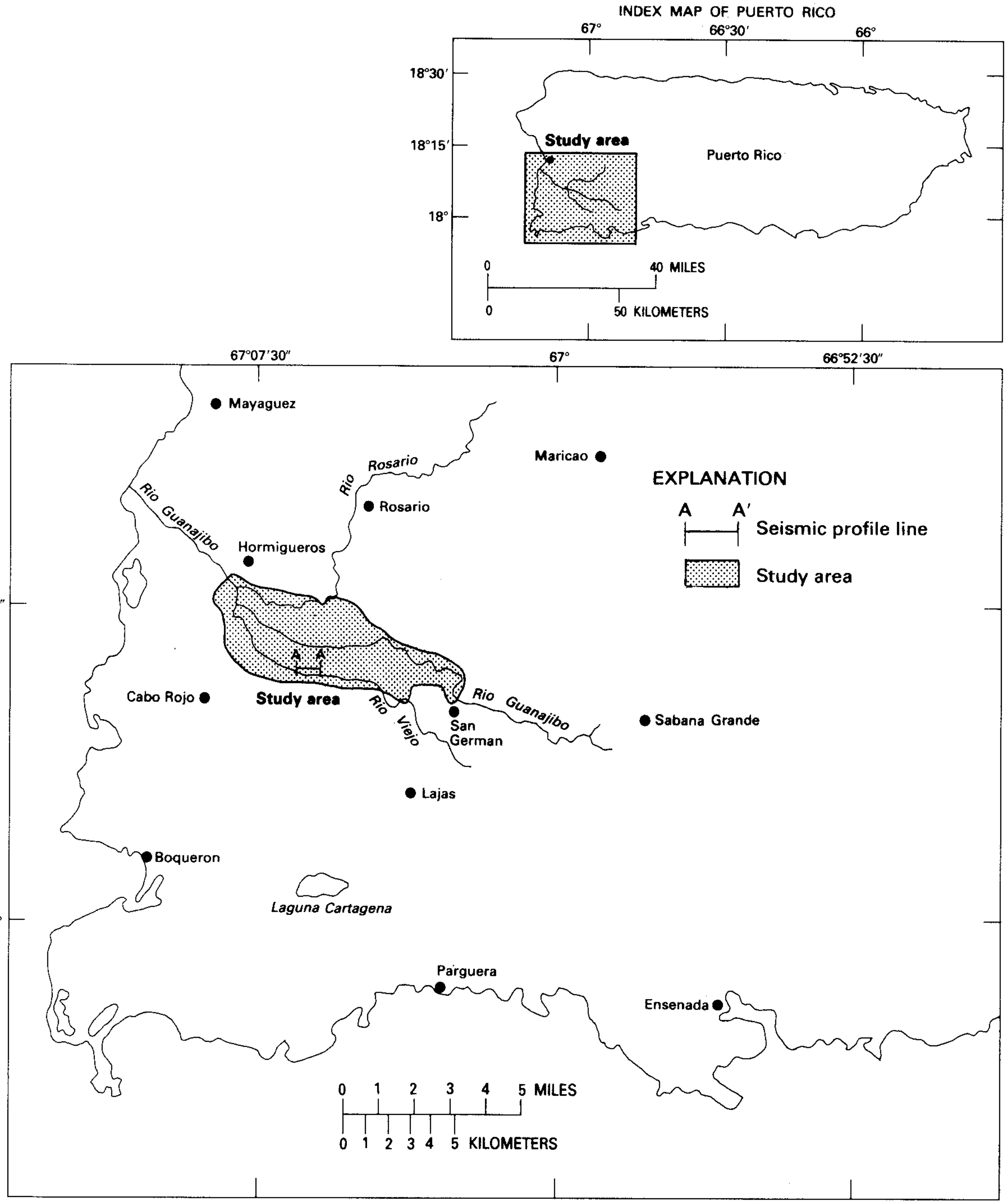


Figure 19.—Generalized location map of central Guanajibo Valley, Puerto Rico, and location of seismic-refraction profile A-A′ (from Colon-Dieppa and Quinones-Marquez, 1985).

seismic-velocity layer, 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 characterized by 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 situations in which it may be difficult to use seismic-refraction techniques are presented below.

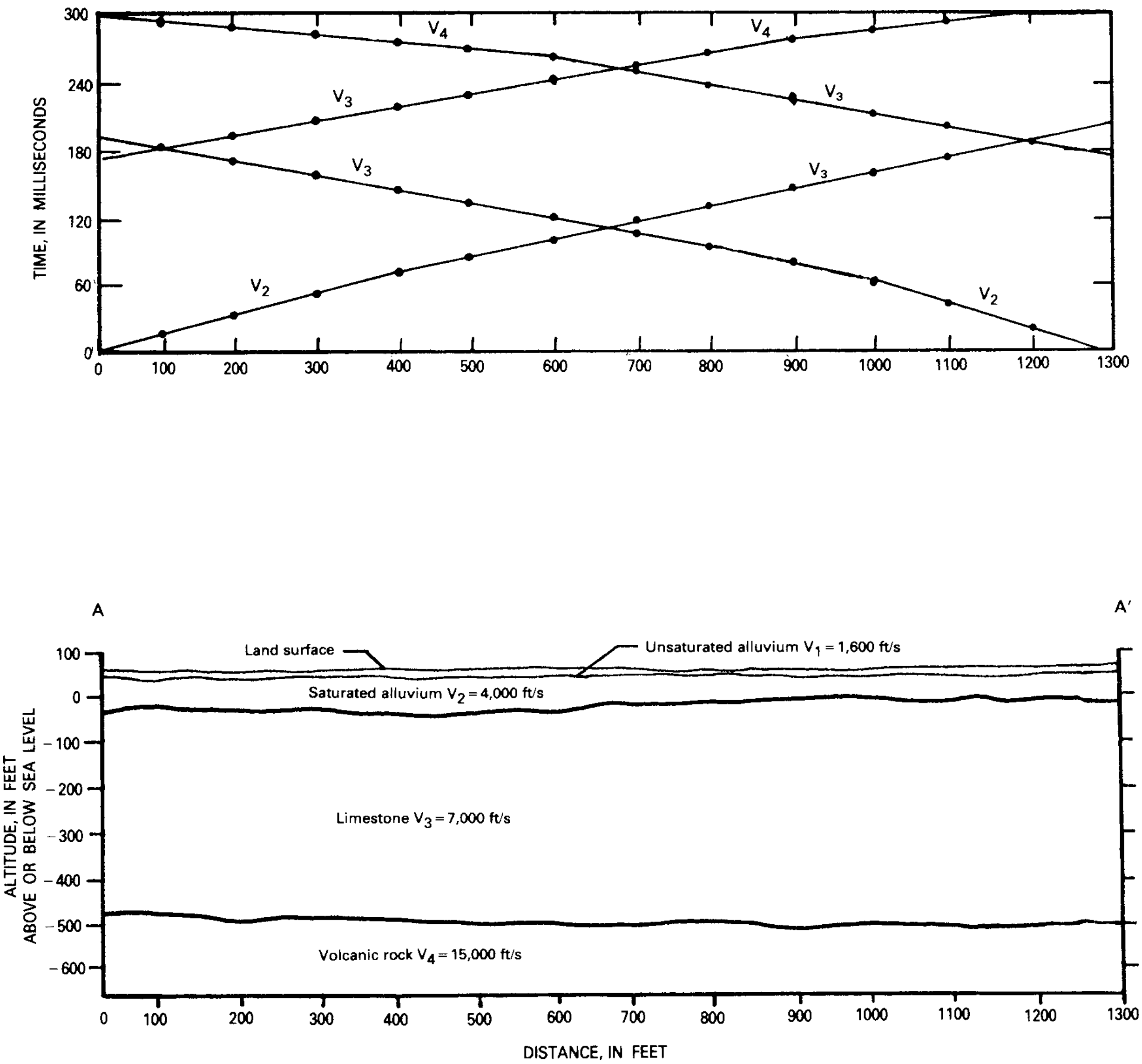


Figure 20.—Time-distance plot and interpreted seismic section at Guanajibo Valley, Puerto Rico.

Unconsolidated glacial sand and gravel overlying a thin till layer, which in turn overlies crystalline bedrock

Determining the aquifer's saturated thickness is a common hydrogeologic goal in glaciated areas. Because many basal till layers are 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 depth to bedrock, and thickness of the aquifer, can be determined accurately if the thickness of the till can be estimated from drill-hole or other data. Thin till layers, however, 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, Conn., seismic-refraction profiles (fig. 23) were used to determine the depth to bedrock and to help determine the saturated thickness of the aquifer (Haeni, 1978). Existing drill-hole data in this area indicated that the saturated aquifer material ranged from 10 to 100 ft in thickness and was underlain by 5 to 10 ft of till. Because the till was thin, its seismic velocity was close to that of the saturated material, 7,500 ft/s versus 5,000 ft/s, and because the accuracy of seismic-refraction methods is ±10 percent, the seismically determined depth to rock was considered to be the true depth to rock. The saturated thickness of the aquifer, determined from the refraction results, was arbitrarily decreased by 5 ft to account for the presence of the till.

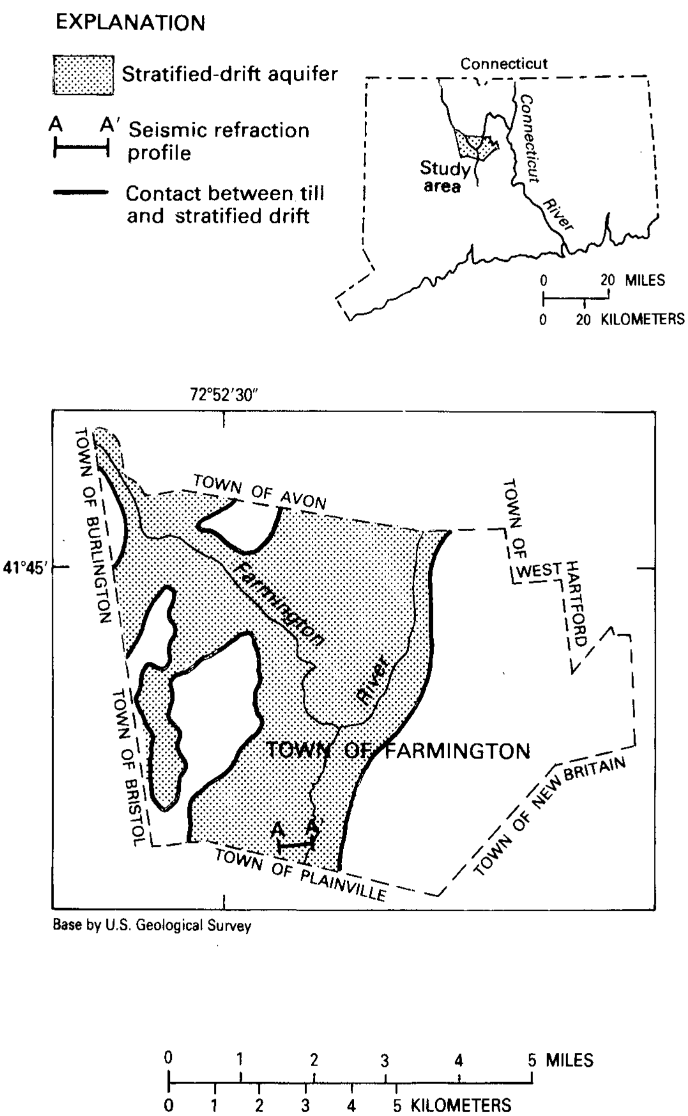


Figure 21.—Generalized location map of Farmington, Conn., and location of seismic-refraction profile A–A'.

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 shotpoints were used. Small explosive charges, weighing from 1/3 to 2 lb and placed at the water table, were used as energy sources. The depth to water was recorded in each shothole 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 using 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).

An aquifer underlain by bedrock having a similar seismic velocity

The exploration goal in this hydrogeologic setting is to determine the thickness of the upper aquifer. Because the seismic velocities of the two layers overlap, seismic-refraction methods may not yield useful information about the thickness of the upper aquifer. The success of a seismic-refraction survey in this setting will depend on the actual velocity of sound in the subsurface materials and the accuracy of seismograph and field data-collection activities.

Figure 25 shows hypothetical time-distance plots for a situation in which 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 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.

The problem of similar seismic velocities for adjacent layers has been reported for several hydrogeologic settings. Broadbent (1978) describes a problem in which alluvium overlies bedrock having an unusually low 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 having a surface layer that varies significantly in thickness or material composition

The exploration goal is to map the depth to the undulating surface of a high-velocity layer in an area that has discontinuous, shallow, low-seismic-velocity materials. 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 effects of the undulating refractor. Pakiser and Black (1957) describe how to differentiate between these effects in a simple geologic setting.

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 at any geophone caused by relief on the refracting

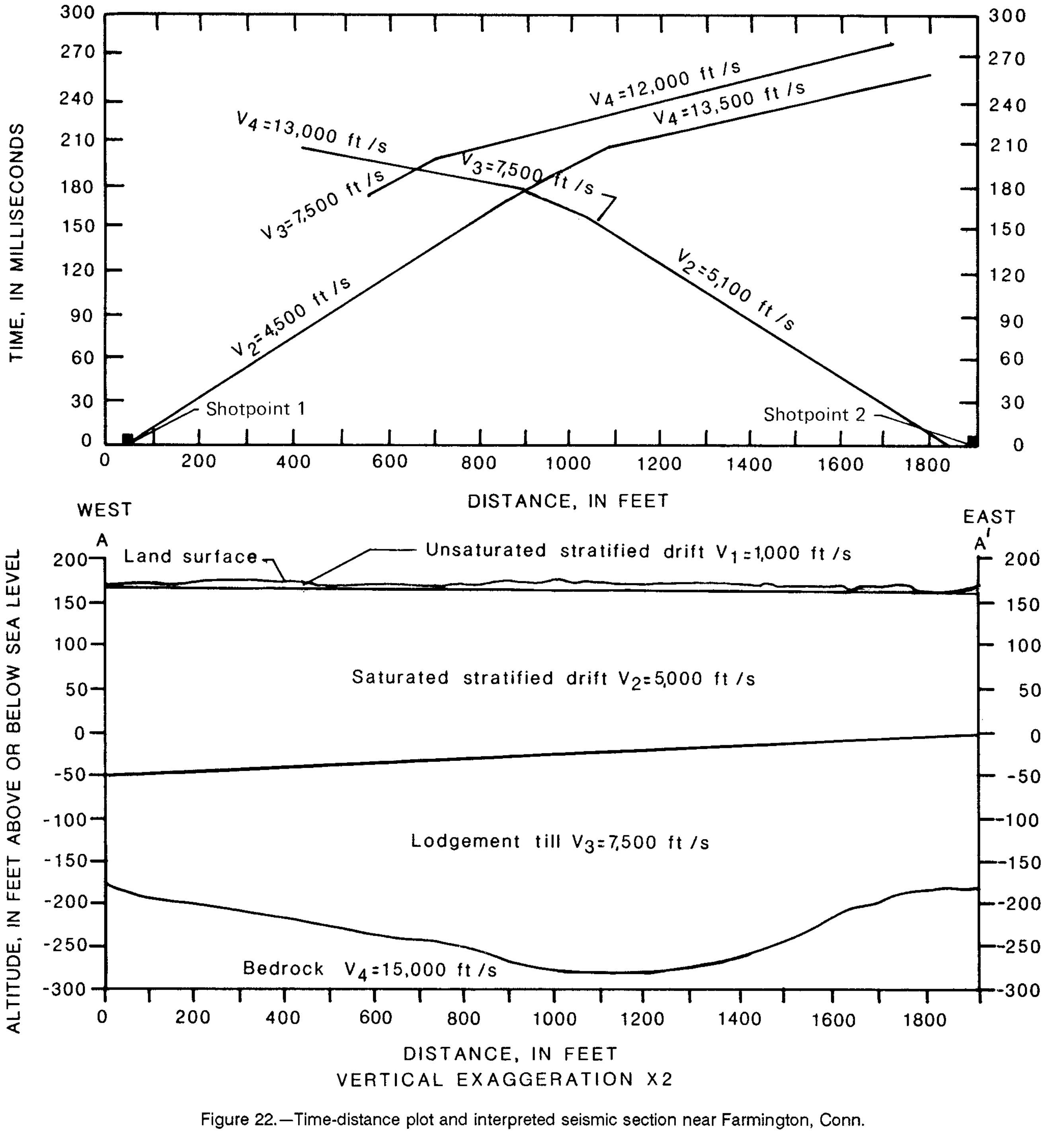


Figure 22.—Time-distance plot and interpreted seismic section near Farmington, Conn.

surface, on the other hand, will be different for shots from opposite ends of the spread. Shown is a very simple example; 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 such aquifer properties 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 seismic-refraction methods has been demonstrated in some studies (Eaton and Watkins, 1967; Wallace and Spangler, 1970; Watkins and Spieker, 1971; van Zijl and Huyssen, 1971; Barker and Worthington, 1973; Worthington, 1975; Worthington and Griffiths, 1975;

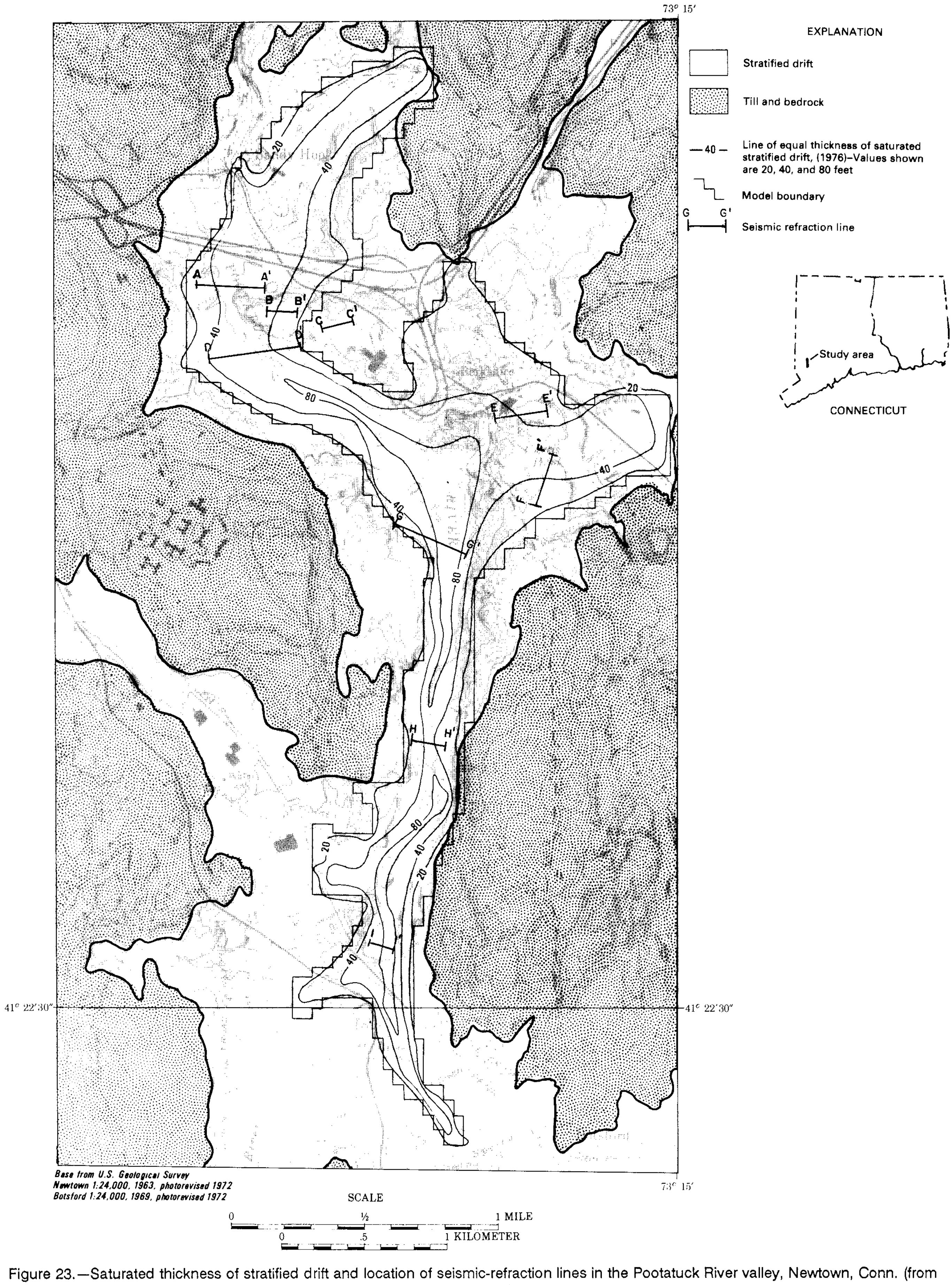


Figure 23.—Saturated thickness of stratified drift and location of seismic-refraction lines in the Pootatuck River valley, Newtown, Conn. (from Haeni, 1978).

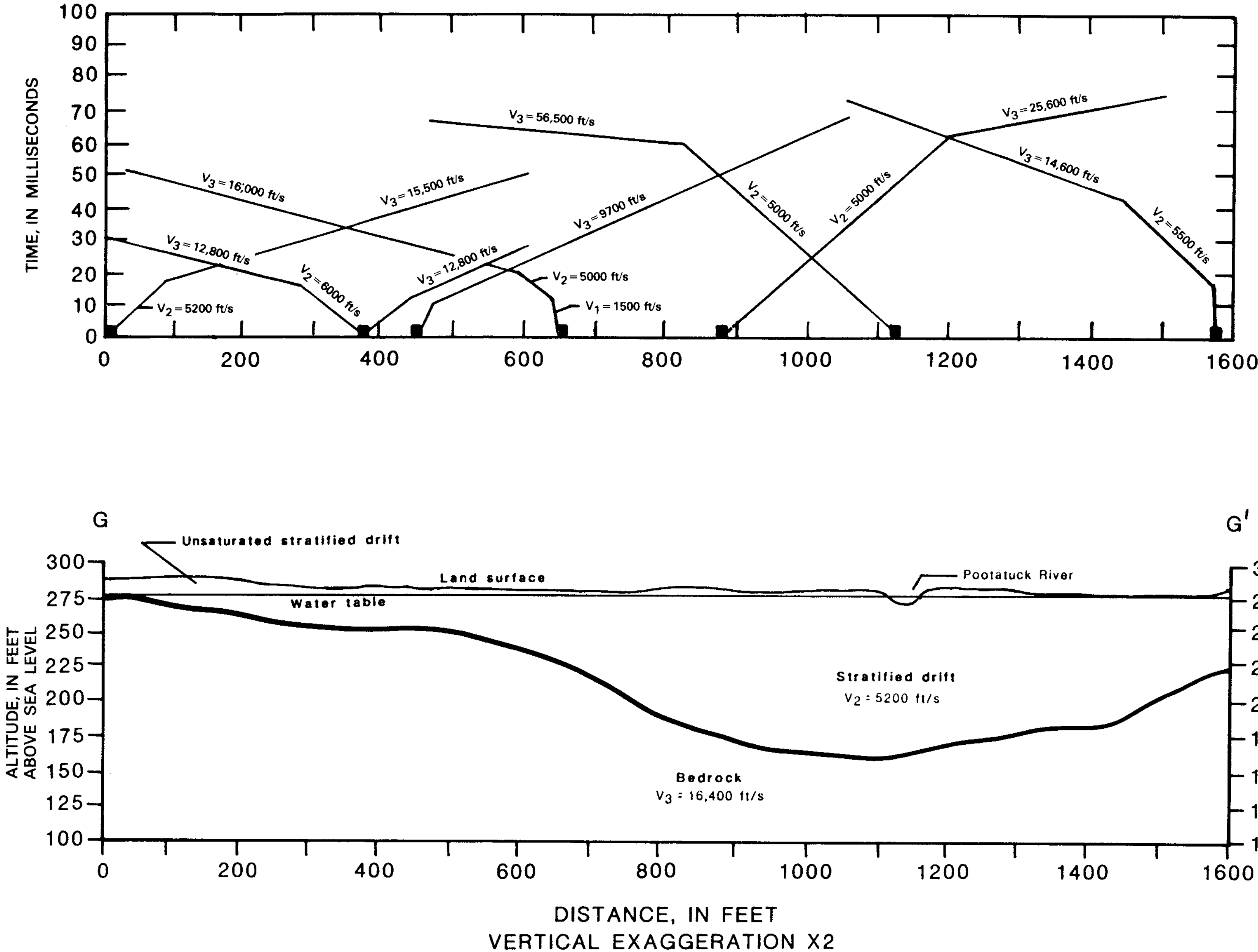


Figure 24.—Time-distance plot and interpreted seismic section of Pootatuck River valley, Newtown, Conn. (from Haeni, 1978).

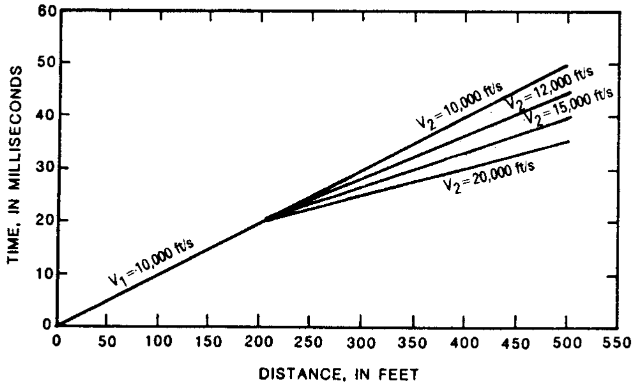


Figure 25.—Hypothetical time-distance plots resulting from different seismic velocities in the second layer.

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 valid for only a particular study area.

Ground-water contamination in unconsolidated materials

The initial phases of ground-water-contamination studies involve 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 these methods will not provide any direct information about the nature or extent of contamination of the ground

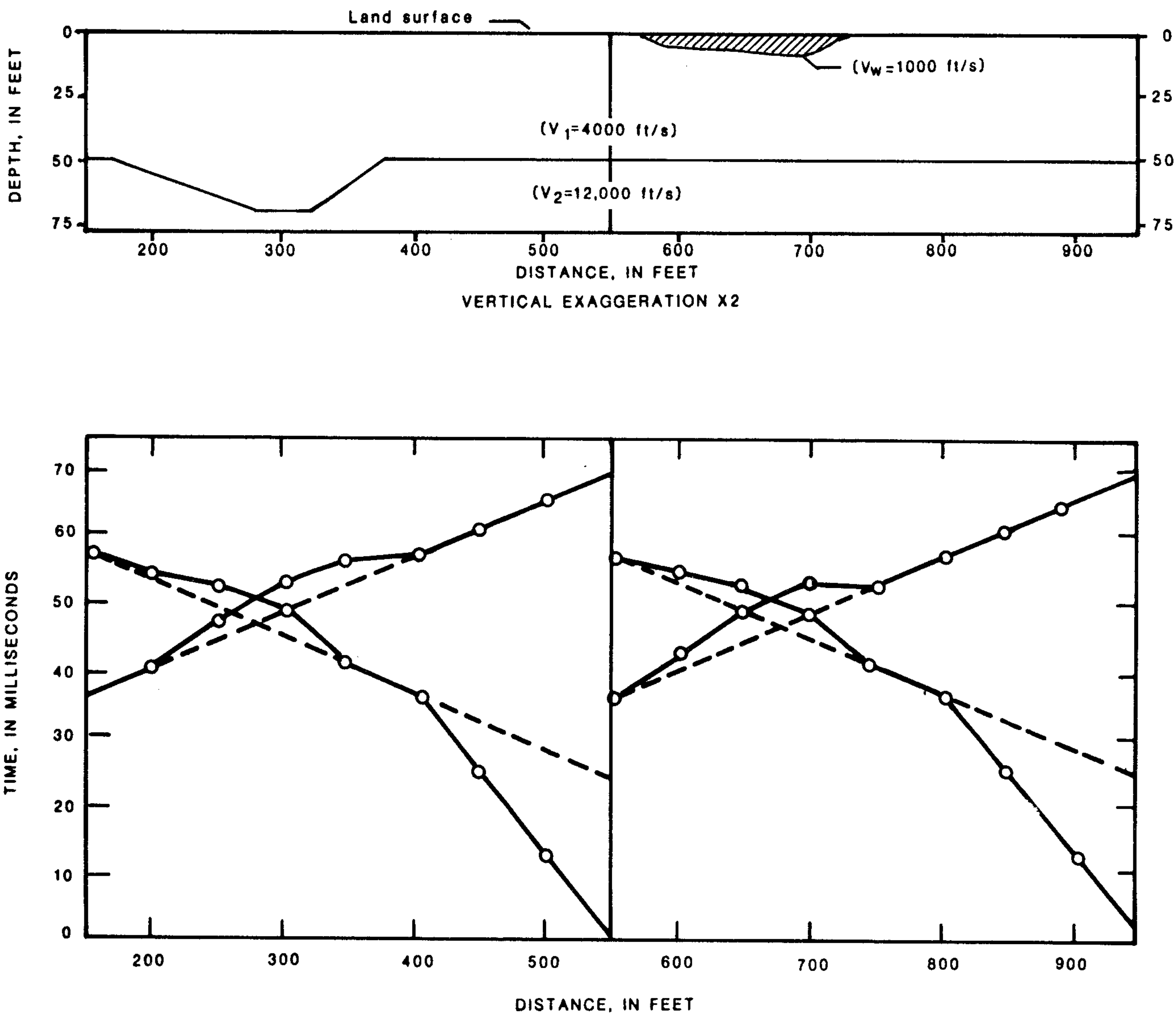


Figure 26.—Seismic section with shallow seismic-velocity discontinuities and relief on a refracting surface, and the resulting time-distance plot, Monument Valley area of Arizona and Utah (modified from Pakiser and Black, 1957).

water. 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, Conn., 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 shotpoints were used to provide tight control on the depth of the water table and to provide a continuous bedrock profile.

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

A multilayered Earth with a shallow, thin layer that has a seismic velocity greater than the layers below it

The exploration goal in this hydrogeologic setting 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 determination of the depth of a deep refractor underlain by a low-seismic-velocity refractor (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 determination of the depth 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 low-frequency arrivals from bedrock. In areas of thick frozen ground, however, 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 (9,500 ft/s) limestone 33 ft thick underlain by lower seismic-velocity (6,600 ft/s) aquifer material prevented determination of the depth to basement rock (seismic velocity 16,000 ft/s) and 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 settings

There are several other hydrogeologic settings in which seismic-refraction techniques have been used. Shields and Sopper (1969) used these techniques 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, N.H. 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 settings in which seismic-refraction techniques cannot be used

Seismic-refraction methods cannot be used successfully to detect (1) low-seismic-velocity layers overlain by high-seismic-velocity layers, (2) two hydrologically different units having the same seismic velocity, or (3) thin beds of intermediate seismic velocity in a sequence of beds whose seismic velocities increase with depth. Three examples of situations in which 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 exploration goal in this hydrogeologic setting 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 layer cannot be defined with seismic-refraction techniques.

Unconsolidated sand and gravel aquifer material underlain by silt and clay

The exploration goal in this hydrogeologic setting 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 hydrogeologic units cannot be differentiated on the time-distance plot. Resisitivity techniques may work in this setting.

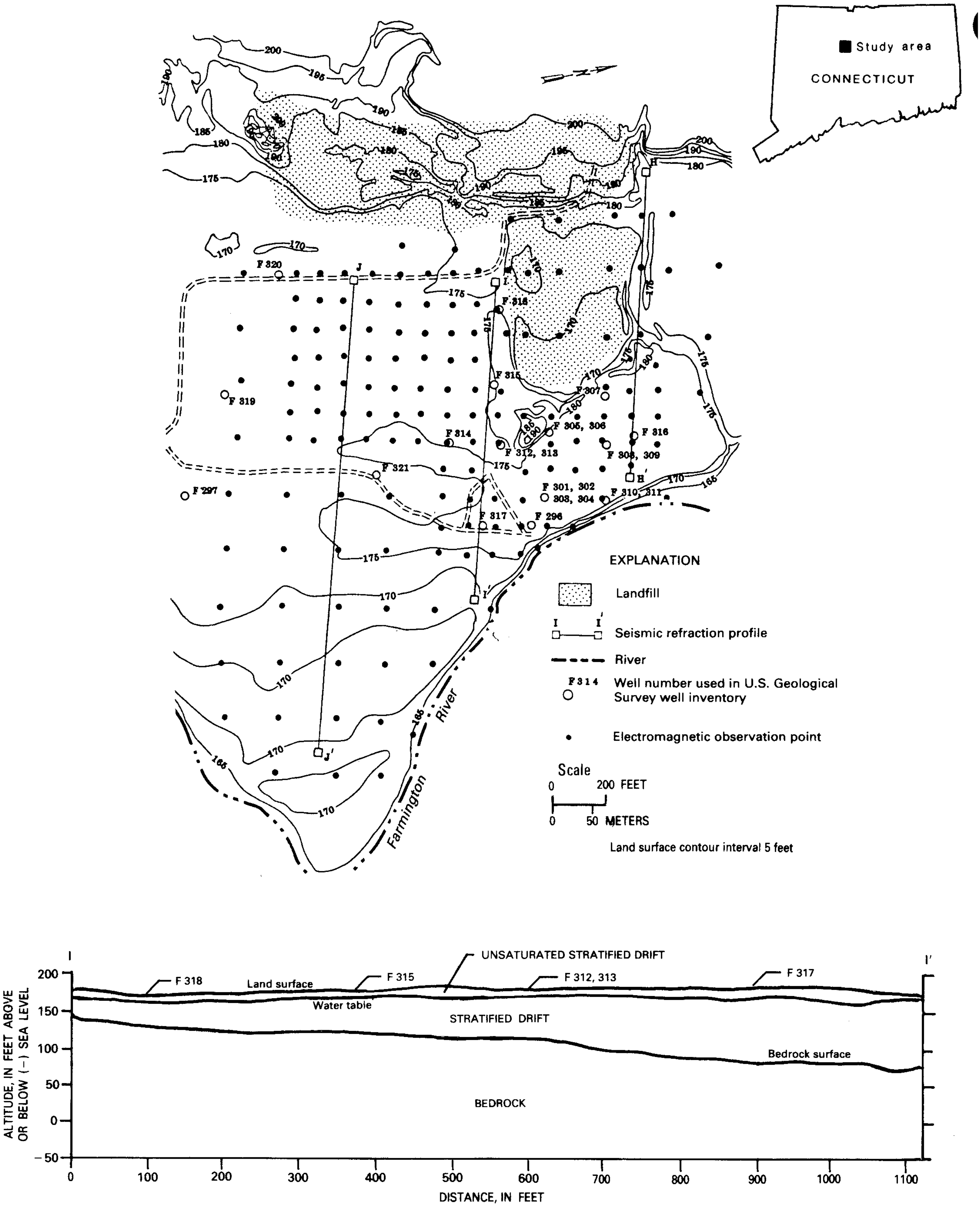


Figure 27.—Site diagram and seismic section of a sanitary landfill in Farmington, Conn. (from Grady and Haeni, 1984).

Saturated alluvium underlain by a thin confining shale, which in turn overlies a porous sandstone

The goal of a hydrogeologic study in this setting is to determine the depth and thickness of the confining shale layer. Again, one of the basic assumptions of seismic-refraction techniques 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 material overlying glacial or alluvial aquifers

Burwell, E.B., 1940, Determination of ground-water levels by the seismic method: Transactions of the 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, with emphasis 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 partially 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, Miss., 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 of the 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, Report of Investigation 7595, 95 p.
[Presents a computer program that uses seismic-refraction data to generate a two-dimensional model representing a layered geologic section.]

Sjogren, Bengt, and Wager, O., 1969, On a soil and ground-water investigation with the shallow refraction method at Mo I 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.]

Unconsolidated glacial or alluvial material overlying consolidated bedrock

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, N.J. 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 the bedrock surface in the Heflin area, Cleburne County, Ala.]

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, Albuquerque, 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 Mattick, 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 the thickness of sediments overlying consolidated bedrock in northern Nevada County, Calif.]

Wachs, Daniel, Arad, Arnon, and Olshina, Avi, 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 material 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: Bozeman, Montana University Joint Water-Resources Reseach Center Report 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 Watershed, Arizona: U.S. Agriculture Research Service, ARS 41–164, 14 p.
[Seismic-refraction methods were used to map bedrock and the depth to the water table in a deep alluvial valley near Tombstone, Ariz.]

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 that 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 determined partly on the basis of 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, 20 p.
[Six subsurface layers and three basement faults were identified by seismic-refraction methods.]

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, Ariz., where the depth to the water table ranged from 0 to 475 ft.]

Unconsolidated alluvial material overlying sedimentary rock, which in turn overlies volcanic or crystalline bedrock

Colon-Dieppa, Eloy, 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 aquifer.]

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 that used seismic-refraction data to generate a two-dimensional model representing a layered geologic section.]

Torres-Gonzalez, Arturo, 1985, Use of surface-geophysical techniques for ground-water exploration in the Canovanas-Rio Grande area, Puerto Rico: U.S. Geological Survey Water-Resources Investigations Report 83–4266, 29 p.
[Seismic-refraction techniques were used to map the depth and saturated thickness of unconsolidated alluvial aquifers and the 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 in turn overlie 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 of 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 Open-File Report 80–751, 68 p.
[A ground-water appraisal study that used seismic-refraction techniques to help 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 were used to map 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.]

Scott, J.H., Tibbets, B.L., and Burdict, R.G., 1972, Computer analysis of seismic-refraction data: U.S. Bureau of Mines Report of Investigation 7595, 95 p.
[Presents a computer program that uses seismic-refraction data to generate a two-dimensional model representing a layered geologic section.]

Unconsolidated glacial sand and gravel overlying a thin till layer, which in turn overlies 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 a mathematical model of a 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: University of Rhode Island, Rhode Island Water Resources Center 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 Investigations Report 83–4010, 56 p.
[Seismic-refraction profiles were used to determine the saturated thickness of selected stratified-drift aquifers.]

Haeni, F.P., 1978, Computer modeling of ground-water availability of the Pootatuck River valley, Newtown, Connecticut, *with a section on* Water quality by E.H. Handman: U.S. Geological Survey Water-Resources Investigations 78–77, 76 p.
[Seismic-refraction techniques were used to determine the depth to rock and the saturated thickness of the 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 National Water Well Association and Environmental Protection Agency conference on Surface and Borehole Geophysical Methods in Ground-Water Investigations, February 7–9, 1984, San Antonio, Texas: Worthington, Ohio, National Water Well Association, p. 237–256.
[Seismic-refraction profiles were used to determine the thickness of saturated stratified drift and 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, 68 p.
[Refraction methods were used to determine the topography of the bedrock surface for a ground-water appraisal study in Farmington, Conn.]

———1986, Ground-water availability and water quality at Southbury and Woodbury, Connecticut: U.S. Geological Survey Water-Resources Investigations Report 84–4221, 105 p.
[Seismic-refraction techniques were used to determine the thickness of saturated stratified drift and to 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, 87 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 seismic-refraction methods give incorrectly high values for saturated thickness where a blind-zone layer, such as till beneath a saturated aquifer, is present.]

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 that 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 to 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 pls.
[Seismic-refraction methods were used to determine the topography of the bedrock surface for a 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, 61 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 having 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 the layer in which 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 having a surface layer that 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.
[In the Monument Valley of Arizona and Utah, seismic-velocity variations in the upper layer (Shinarump Formation) were differentiated from erosion channels in the deeper refracting surface (Moenkopi Formation).]

Quantitative estimation of aquifer hydraulic properties

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 Department 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* Morey, L.W., ed., Mining and Ground Water Geophysics: Geological Survey of Canada Economic Geology Report 26, p. 544–568.

[Seismic-refraction methods were used to determine the three-dimensional geometry of the aquifer, the gross stratigraphy and local lithofacies 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, pt. 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, p. B1-B17.
[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.
[Seismic-refraction methods with an empirical relationship developed in the laboratory were used to estimate hydrologic conductivity in a Triassic sandstone in England.]

Ground-water contamination in unconsolidated materials

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., Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations, San Antonio, Tex., February 7–9, 1984, Proceedings: Worthington, Ohio, National Water Well Association, p. 338–367.
[Seismic-refraction techniques were used to define the saturated thickness of the aquifer material at a contamination site.]

Leisch, Bruce, 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 Corporation site in Bedford, Mass.]

A multilayered Earth with a shallow, thin layer that has a seismic velocity greater than the layers below it

Ackermann, H.D., 1976, Geophysical prospecting for ground water in Alaska: U.S. Geological Survey Earthquake Information Bulletin, v. 8, no. 2, p. 18–20.
[Seismic-refraction and resistivity techniques were used to locate water supplies in permafrost 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. (ed.), Canadian Regional Permafrost Conference, December 1–2, 1964, Proceedings: Ottawa, National Research Council of Canada, Associate Committee on Soil and Snow Mechanics, Technical Memorandum 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 of 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 having a higher seismic velocity than layers immediately below it were obtained near Redcliff Point on Spencer Gulf, Australia.]

Miscellaneous hydrogeologic settings

Shields, R.R., and Sopper, W.E., 1969, An application of surface geophysical techniques to the study of watershed hydrology, Water Resources Bulletin, v. 5, no. 3, p. 37–49.
[Seismic and resistivity techniques were used to determine the depth of soils, their volumes, the 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.]

Unconsolidated sand and gravel aquifer material underlain by silt and clay

Burwell, E.B., 1940, Determination of ground-water levels by the seismic method: Transactions of the 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, which in turn overlies 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 unit with an intermediate seismic velocity cannot be detected with seismic-refraction techniques.]

Planning the Investigation

Successful use of surface geophysical techniques in hydrogeologic 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

Table 3.—*Compressional 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];	4,600-18,000[2]
Shale	9,000-14,000[3];	11,700-20,000[2]
Limestone	7,000-20,000[3];	6,000-23,000[2]
Granite	15,000-19,000[3];	8,500-23,000[2]
Metamorphic rock	10,000-23,000[3]:	12,600-20,000[2]
Basalt	21,000[4]	; 10,000-19,000[2]
Ice	12,050[3]	
Freshwater at 13°C	4,800[1]	
Air	1,000[5]	

[1]Clark (1966, p. 204).
[2]Philip Powers and George VanTrump (written commun., 1982).
[3]Jakosky (1950, p. 660).
[4]Dobrin (1976, p. 50).
[5]Carmichael (1982, p. 134).

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 can yield disappointing results.

Local geology

Surface geophysical techniques measure the physical contrasts between 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 about whether or not to use seismic-refraction techniques and how to set up the equipment in the field.

Seismic-refraction techniques measure the velocity of sound in subsurface materials. Although the compressional velocity of sound in earth materials can be a good indicator of the type of subsurface material, it is not a unique indicator. As table 3 shows, each type of rock has a wide range of compressional velocities and the ranges of different rock types overlap. Seismic-refraction techniques measure the velocity of sound in earth materials, but it is the investigator who, on the basis of knowledge of the local hydrogeology, must interpret the data and arrive at a reasonable conclusion.

Available data

Before 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. Review of these data usually enables the investigator to determine whether there are significant velocity contrasts between the stratigraphic units of interest. The drill-hole or test-hole data also will serve as control points where indirect geophysical measurements can be correlated with actual geologic or hydrologic boundaries. Previous studies in similar geologic settings are a good indication of whether or not the refraction method can be used successfully in the hydrologic study.

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 hydrogeologic 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 section on "Applications of Seismic-Refraction Techniques to Hydrology"). 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. Compressional 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 compressional velocities for a wide range of sedimentary rock types from 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 compressional velocities of saturated unconsolidated materials from studies done by the U.S. Geological Survey. The velocity of saturated unconsolidated materials at shallow depths is relatively independent of their location or grain size.

When there is doubt as to whether there is a sufficient seismic-velocity contrast, detailed fieldwork (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 these need to be answered: Is this going to be a site-specific study or an 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 spreads are short, multiple shots are fired, geophone spacing is relatively close, elevations and locations of geophones and shotpoints are precisely determined, and test holes and wells are used for geologic control.

In areal hydrogeologic studies, geophone spacing is wide, seismic traverses are long, only a few shotpoints are used, and 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 select a site, complete field-site checking, and obtain clearance from utility companies before starting seismic field activities. Preliminary site selection, usually carried out through the use of topographic maps, should be based on the following criteria: (1) need for data at that location, (2) accessibility of the area to field crews, (3) ease of obtaining the necessary permits to conduct the survey, (4) proximity of wells or test holes for control data, and (5) absence of buried utility lines.

In many hydrogeologic 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 to or parallel to the axis of a valley. If the traverses are perpendicular to the axis of the valley, a series of valley cross sections will be obtained (Haeni, 1978, p. 48–51). These perpendicular traverses 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 it typically ranges from 0.5 to 1 mi 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 traversed using equipment brought in by backpack 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 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.

Table 4.—*Laboratory-determined physical properties of sedimentary rock samples from south-central Connecticut (from Haeni and Anderson, 1980)*

Test hole no.	Lithologic description[1/]	Bulk density (g/cm^3)	Grain density (g/cm^3)	Porosity (percent)	Compres-sional 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 velocities1/ (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.

3. Heavily developed areas are not good working sites if explosives are used.
4. Heavy vehicular traffic and operation of heavy equipment can cause background noise on seismograph records and may prevent successful seismic operations. If possible, arrangements should be made either to stop this machinery for the few moments needed to fire the shot or to schedule field activities for relatively quiet 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 and 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 on it.

Summary

A well-planned seismic-refraction study will result in smooth and efficient field-data acquisition and in 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.

References

Carmichael, R.S., 1982, ed., Handbook of physical properties of rocks, v. 2: Boca Raton, Fla., CRC Press, 368 p.

Clark, S.P., ed., 1966, Handbook of physical constants: Geological Society of America (New York), Memoir 97, 587 p.

Dobrin, M.B., 1976, Introduction to geophysical prospecting (3d ed.): New York, McGraw-Hill, 619 p.

Griffiths, D.H., and King, R.F., 1981, Applied geophysics for geologists and engineers (2d ed.): Oxford, England, Pergamon Press, 230 p.

Haeni, F.P., 1978, Computer modeling of ground-water availability in the Pootatuck River valley, Newtown, Connecticut, *with a section on* Water quality by E.H. Handman: U.S. Geological Survey Water-Resources Investigations 78–77, 64 p.

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

Institute of Makers of Explosives, 1981, Safety guide for the prevention of radio frequency radiation hazards in the use of electric blasting caps: Washington, D.C., Institute of Makers of Explosives Publication 20, 24 p.

Jakosky, J.J., 1950, Exploration geophysics: Los Angeles, Trija Publishing Co., 1,195 p.

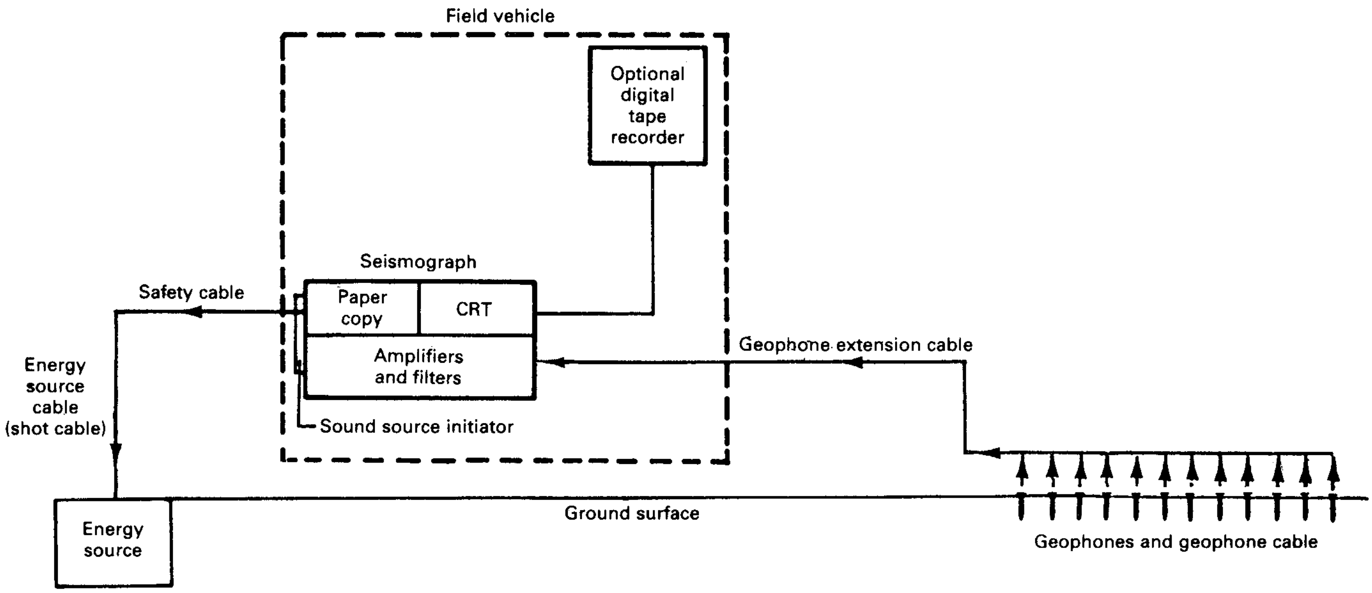


Figure 28.—Schematic diagram of a typical seismic-refraction system.

Equipment

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 and power supply	Shot cables
Geophones	Portable radios
Geophone cables and geophone extension cables	Field vehicles
Energy source and associated equipment	Hand level or transit, surveyor's rod, tape measure, and notebook
	Miscellaneous hand tools, shovels, and compass

Seismograph

A large variety of seismographs are available from different manufacturers. They range from relatively simple, inexpensive, single-channel equipment to very sophisticated, expensive, multichannel equipment like those used by the petroleum industry. Most modern seismographs 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 seismographs can be used with nonexplosive energy sources 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, 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 manufacturer and, therefore, is not 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 obtain 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 geophone positions 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 geophone cables except that no provision is made for connecting

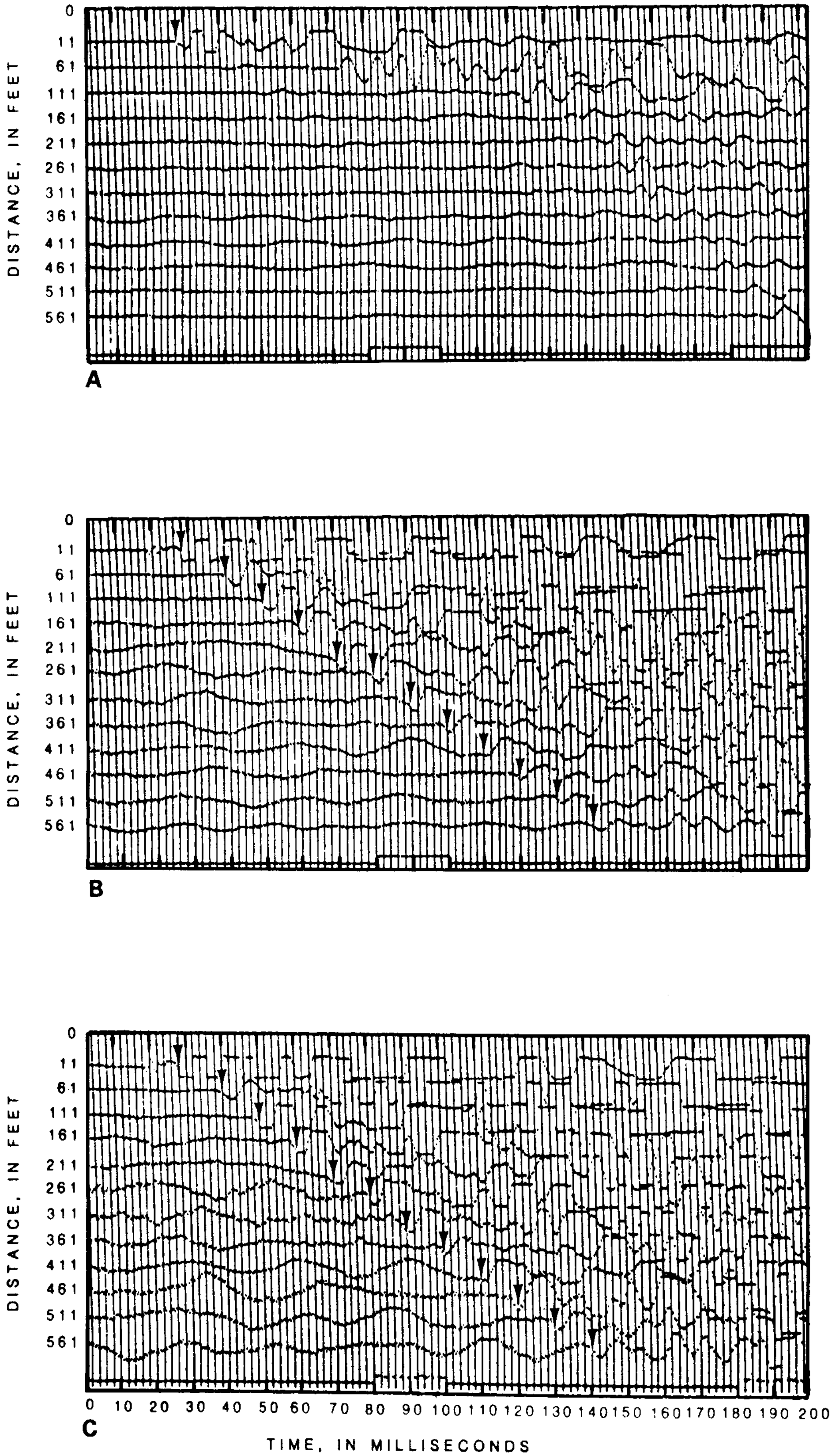


Figure 29.—Seismograms showing improvement in first breaks by stacking successive hammer impacts: A, 1 impact; B, 5 impacts; C, 10 impacts.

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	Excellent	Yes

geophones. These are used in refraction studies to obtain offsets of the shotpoint 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; 1981, p. 21-1—21-11) and in 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 energy sources used 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, 1981a). Other sources do not provide sufficient energy under most field conditions. A good alternative to the sole use of explosives, however, is use of a mechanical

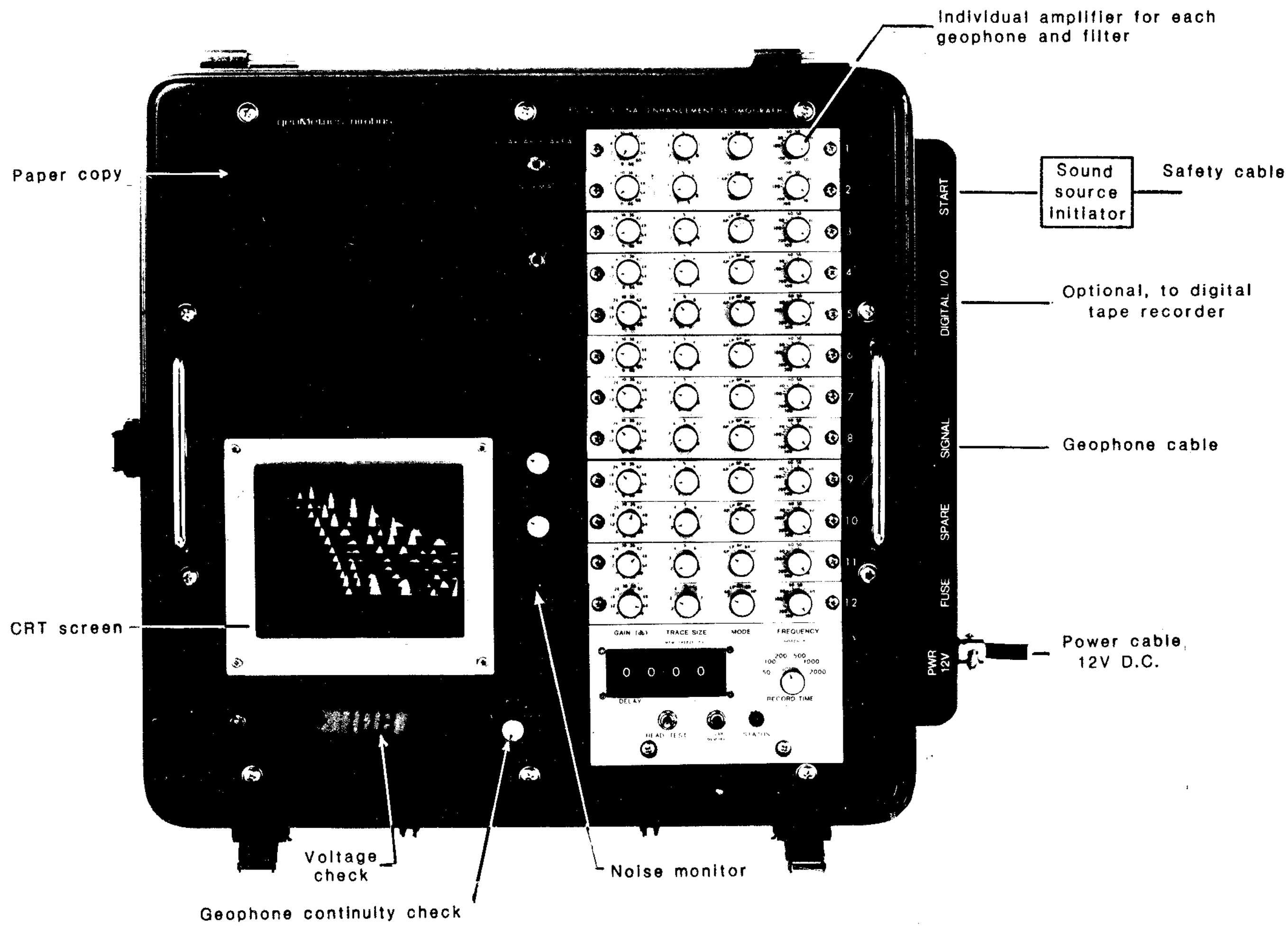
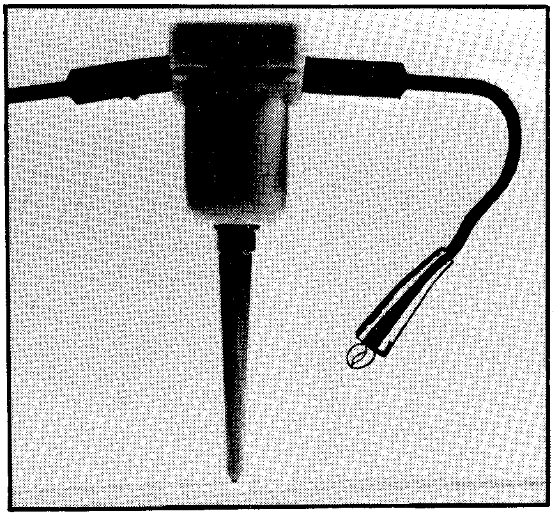
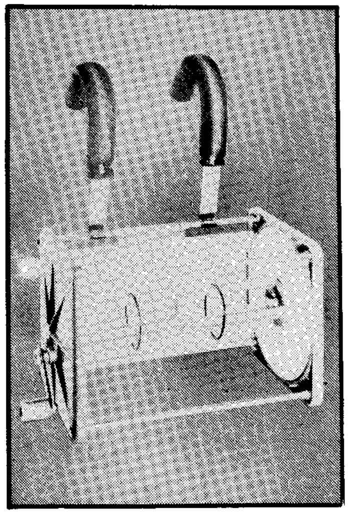


Figure 30.—Typical 12-channel seismograph.



Geophone

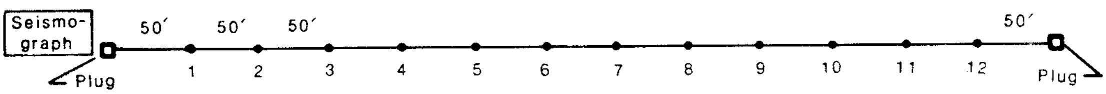


Breast reel

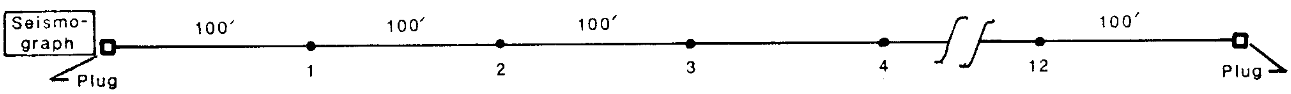
GEOPHONE CABLES

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.

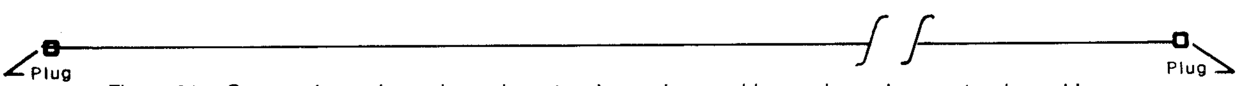


Figure 31.—Commonly used geophone, breast reel, geophone cables, and geophone extension cable.

or electrical source and selective use of explosives in areas where greater energy is needed.

For hydrogeologic 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), and
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

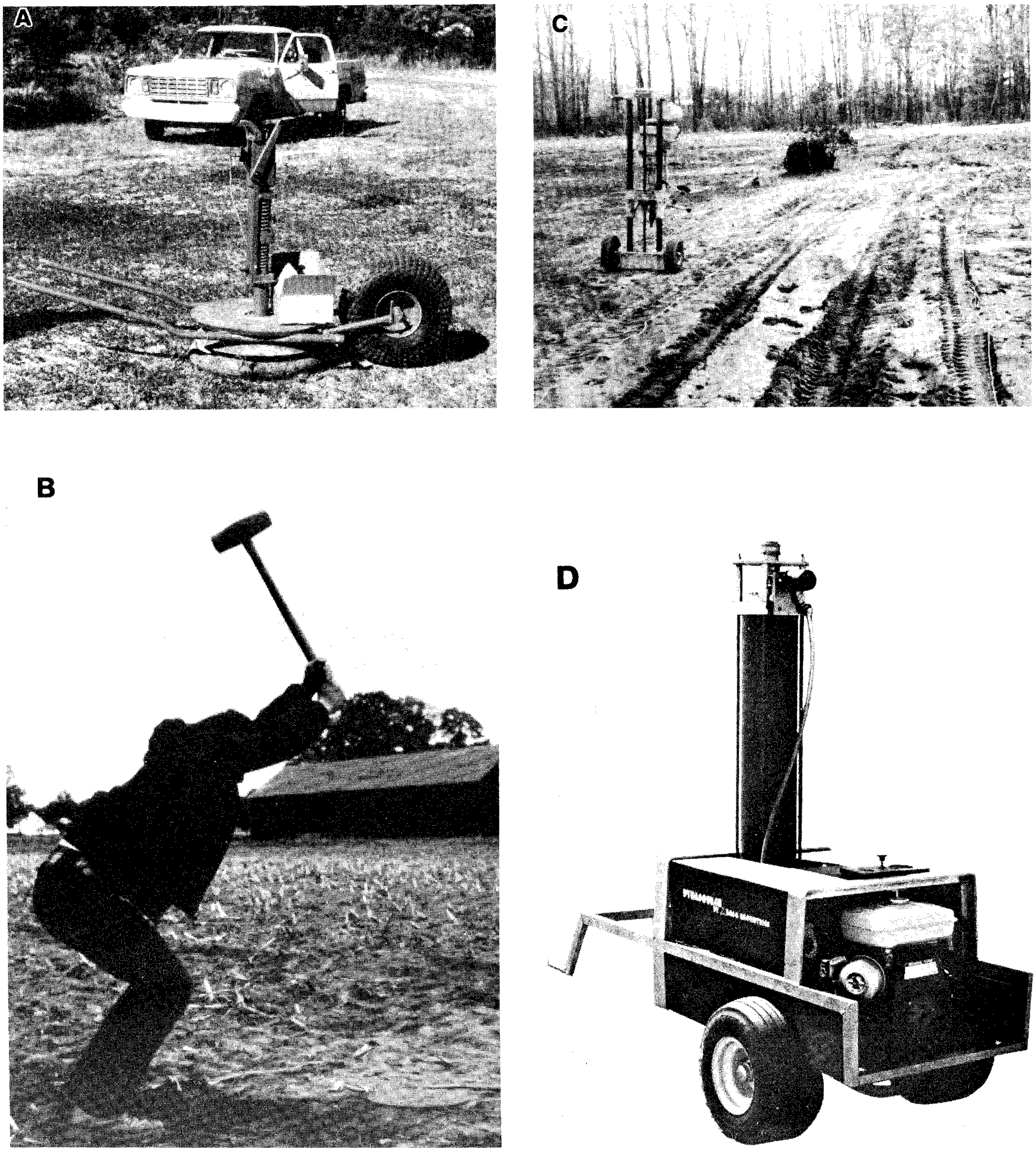


Figure 32.—Commonly used seismic energy sources: A, Shotgun; B, Sledge hammer; C, Explosives; D, Weight drop.

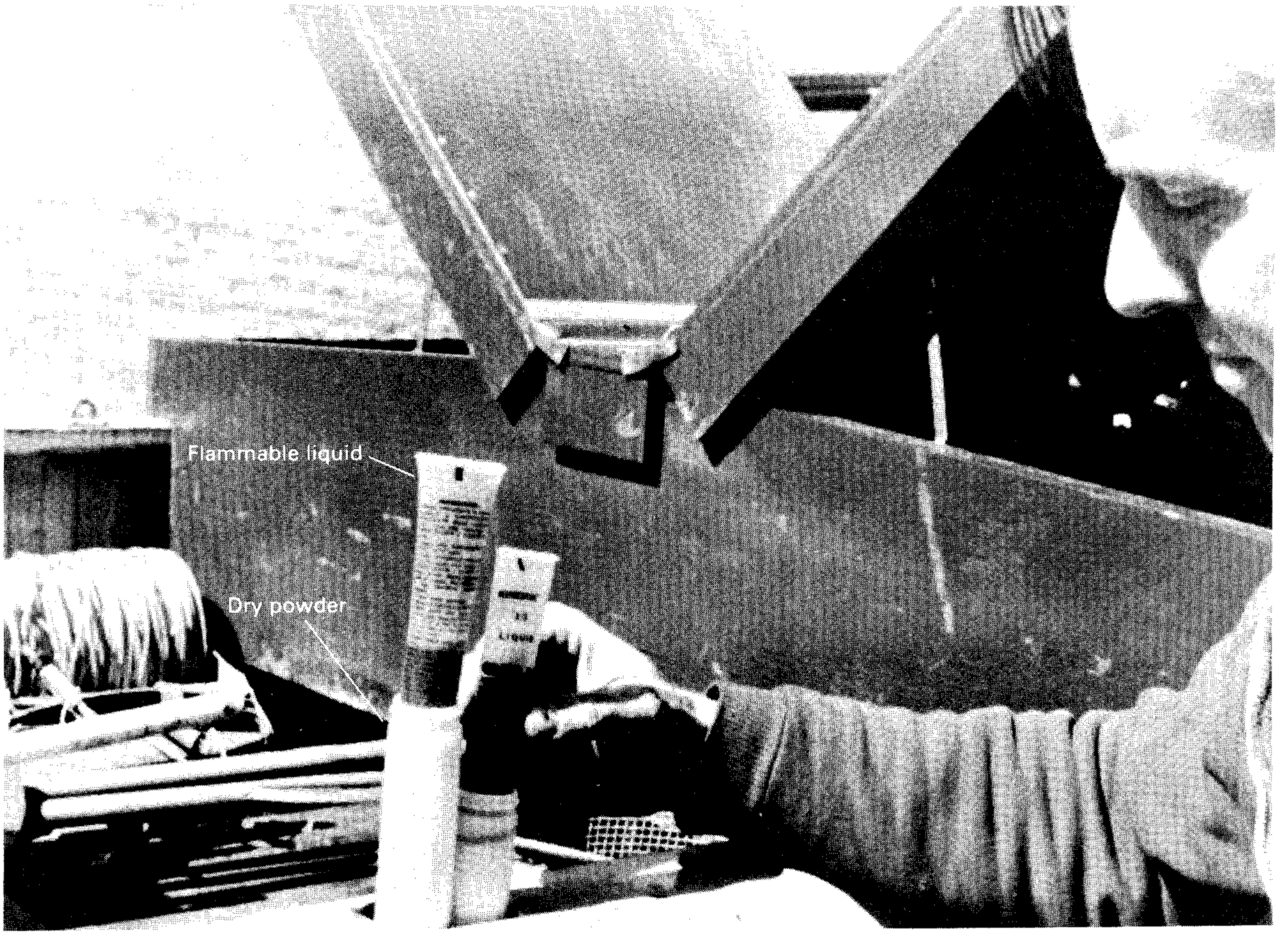


Figure 33.—Mixing two-component explosives in the field.

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. Electric 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 these 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 32C shows the detonation of these explosives after they were buried 5 feet in the ground.

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 32B.

Weight-drop (fig. 32D) and shotgun (fig. 32A) 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 wire can be installed to prevent 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 instead of long shot cables.

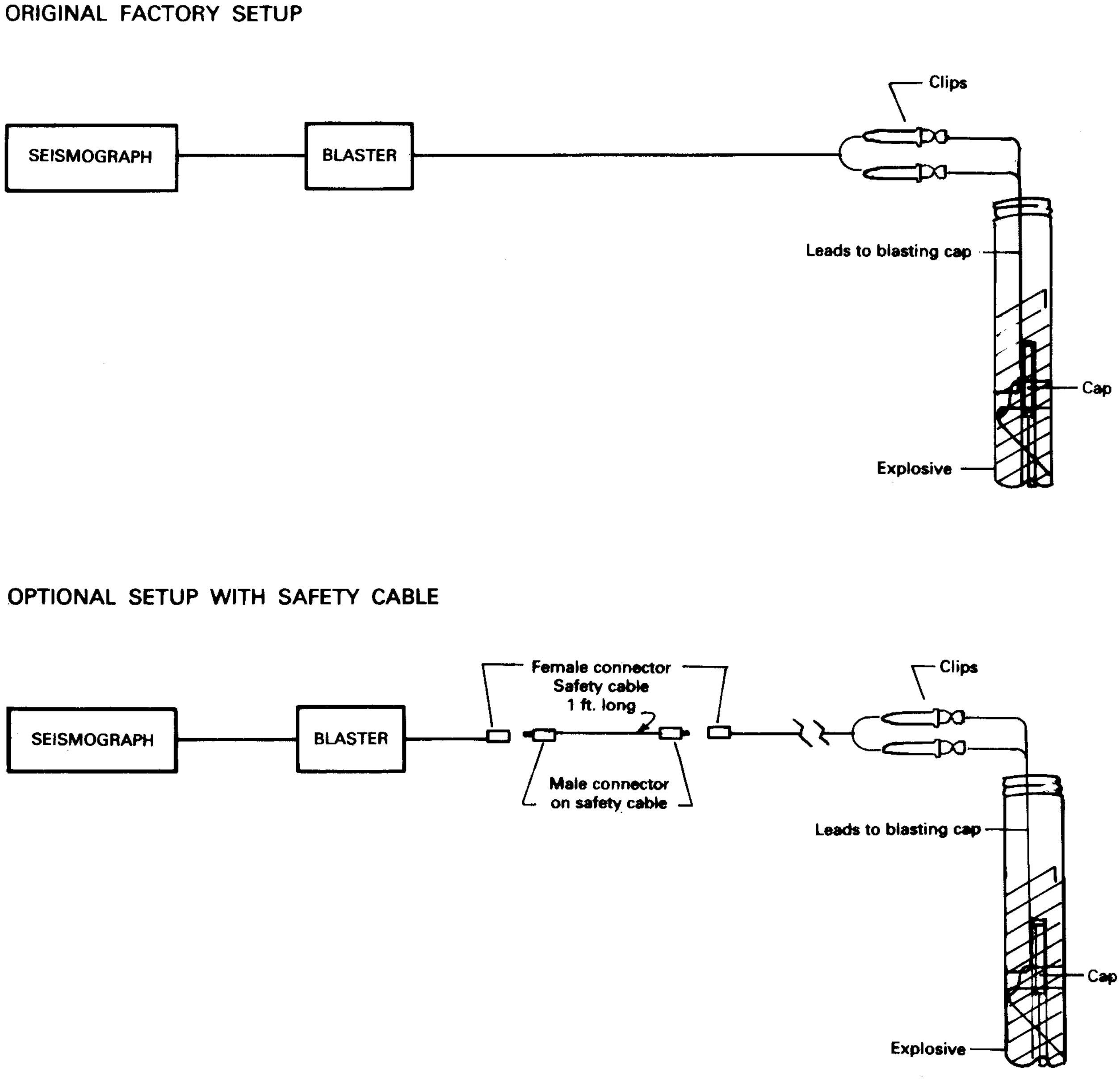


Figure 34.—Use of safety wire in explosive-firing circuit.

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 seismic array be set up near such transmitters (Institute of Makers of Explosives, 1981a).

Field 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 fieldwork. 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 shotholes (fig. 35). The shotgun and sparker

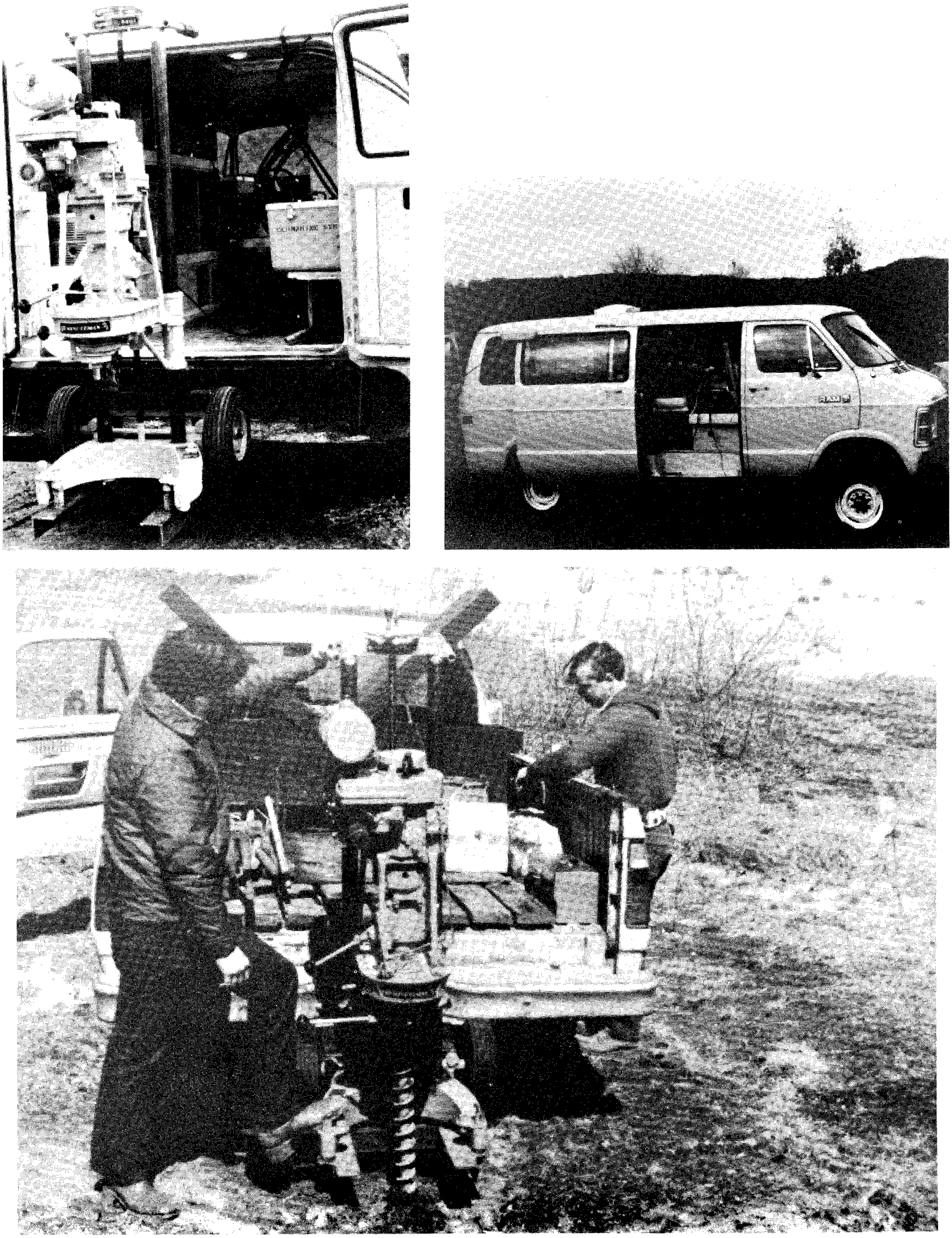


Figure 35.—Van and pickup truck used for seismic-refraction fieldwork.

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 handtools are helpful in seismic-refraction field operations. A canvas tarpaulin should also be carried for placing over the loaded shothole to help contain fly rock produced by the explosion.

References

Beggs, G., and Garriot, J.C., 1979, Shotgun surface source [abs.]: Society of Exploration Geophysicists annual international meeting and exposition, 49th, New Orleans, La., November 4–8, 1979, Abstracts of the Technical Program with Authors' Biographics, p. 38.

Bullock, S.J., 1978, The case for using multichannel seismic-refraction equipment and techniques for site investigations: Bulletin of the Association of Engineering Geologists, v. 15, no. 1, p. 19–35.

Institute of Makers of Explosives, 1980, Safety in the transportation, storage, handling and use of explosives: Washington, D.C., Institute of Makers of Explosives Publication 17, 61 p.

———1981a, IME standard for the safe transportation of class C detonators (blasting caps) in a vehicle with certain other explosives: Washington, D.C., Institute of Makers of Explosives Publication 22, 9 p.

———1981b, Safety guide for the prevention of radio frequency radiation hazards in the use of electric blasting caps: Washington, D.C., Institute of Makers of Explosives Publication 20, 24 p.

Mooney, H.M., 1976, The seismic wave system from a surface impact: Geophysics, v. 41, p. 243–265.

———1981, Handbook of engineering geophysics: Minneapolis, Bison Instruments, 220 p.

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 hydrogeologic 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 fieldwork. In this phase of the study, the investigator must be aware of field results that differ from the conceptual hydrogeologic 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 hydrogeologic section of interest. To accomplish this, the spacing between geophones should be selected so that first arrivals are obtained from each 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 on the depth of the refractors and the velocity of sound in each subsurface layer.

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 production 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, which 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 satisfactory only for rough field calculations and *not* 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 (eqs. 6–8):

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

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

$$-z_1\left(\frac{V_2\sqrt{(V_3)^2-(V_1)^2}-V_3\sqrt{(V_2)^2-(V_1)^2}}{V_1\sqrt{(V_3)^2-(V_2)^2}}\right),$$

and

$$z_3=z_1+z_2\ .$$

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

$$A=\sqrt{\frac{V_2-V_1}{V_2+V_1}}, \tag{23}$$

$$B=\frac{V_3-V_2}{\sqrt{(V_3)^2-(V_2)^2}}, \tag{24}$$

and

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

Now for the two-layer case,

$$z=x_c\frac{A}{2}, \tag{26}$$

and for the three-layer case,

$$z_1=x_{c1}\frac{A}{2}, \tag{27}$$

$$z_2=x_{c2}\frac{B}{2}-z_1C, \tag{28}$$

and

$$z_3=z_1+z_2\ . \tag{29}$$

Rearranging the above for the two-layer case,

$$x_c=\frac{2z}{A}, \tag{30}$$

and for the three-layer case,

$$x_{c1}=\frac{2z_1}{A} \tag{31}$$

and

$$x_{c2}=\frac{2(z_2+z_1C)}{B}. \tag{32}$$

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) before going into the field. Using these values, it is possible to estimate 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 seismic-refraction techniques 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 land surface and crystalline bedrock about 100 ft below land surface. The saturated thickness of the aquifer is 80 ft. 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 determine accurately the field velocities for layers 1, 2, and 3. Approximate values for x_{c1} and x_{c2} are needed to design the initial field setup to obtain these data. Figure 36 shows a general geologic section for this area and the time-distance plot that would be expected.

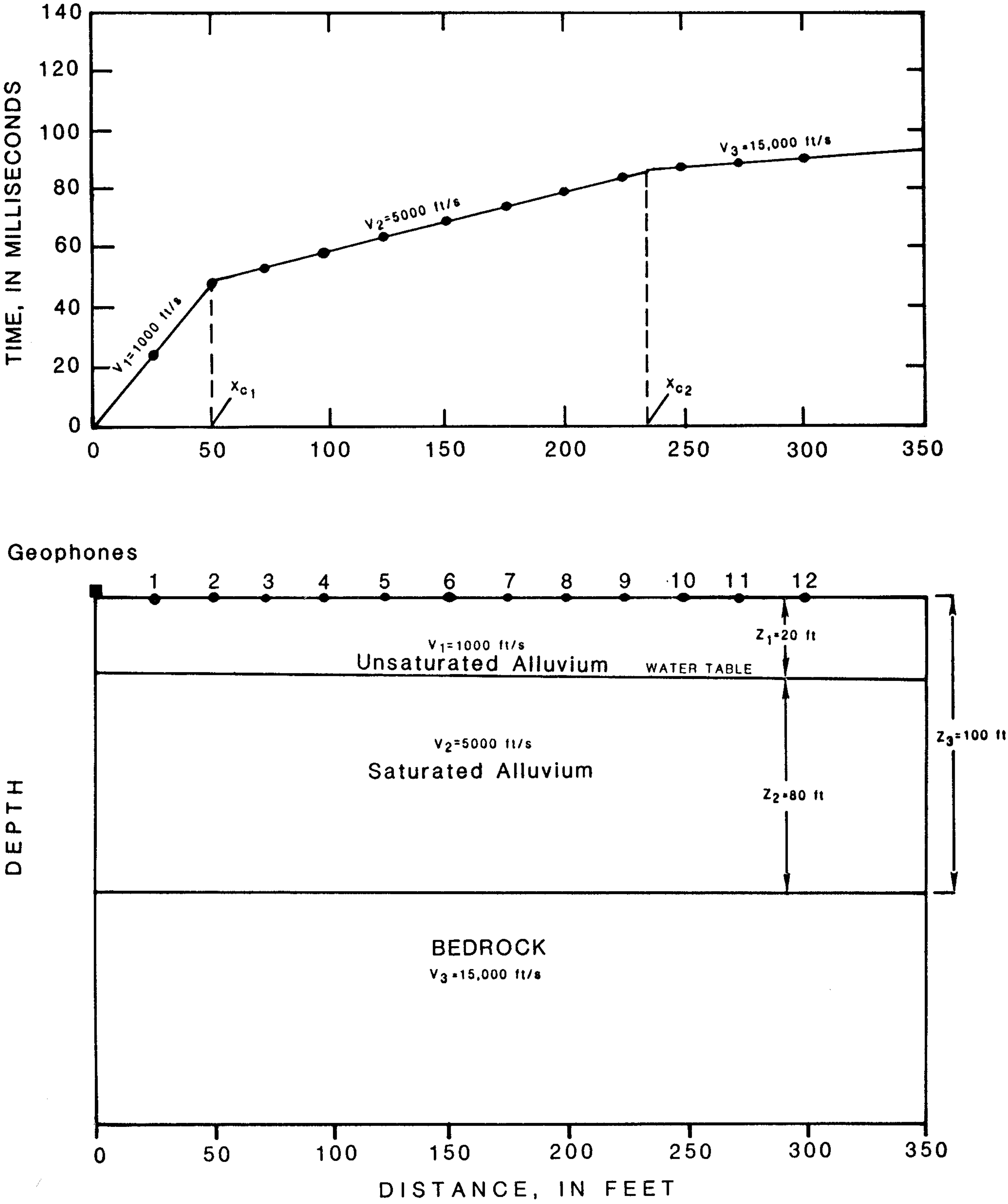


Figure 36.—Time-distance plot and interpreted seismic section for a three-layer problem.

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

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

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

and

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

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

$$=0.0953.$$

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

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

and

$$x_{c2}=(z_2+z_1C)\frac{2}{B}=[80+20(0.0953)]\ \frac{2}{0.7}=234 \text{ ft}.$$

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.

Considerations of spread design for example problem:

- 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. 37A).
- 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. 37B).
- To determine V3, most of the geophones should be placed more than 234 ft from the sound source (fig. 37C).

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 traveltime plots will differ from the expected one in figure 36, depending on 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 seismic-refraction techniques will delineate the interface of interest.

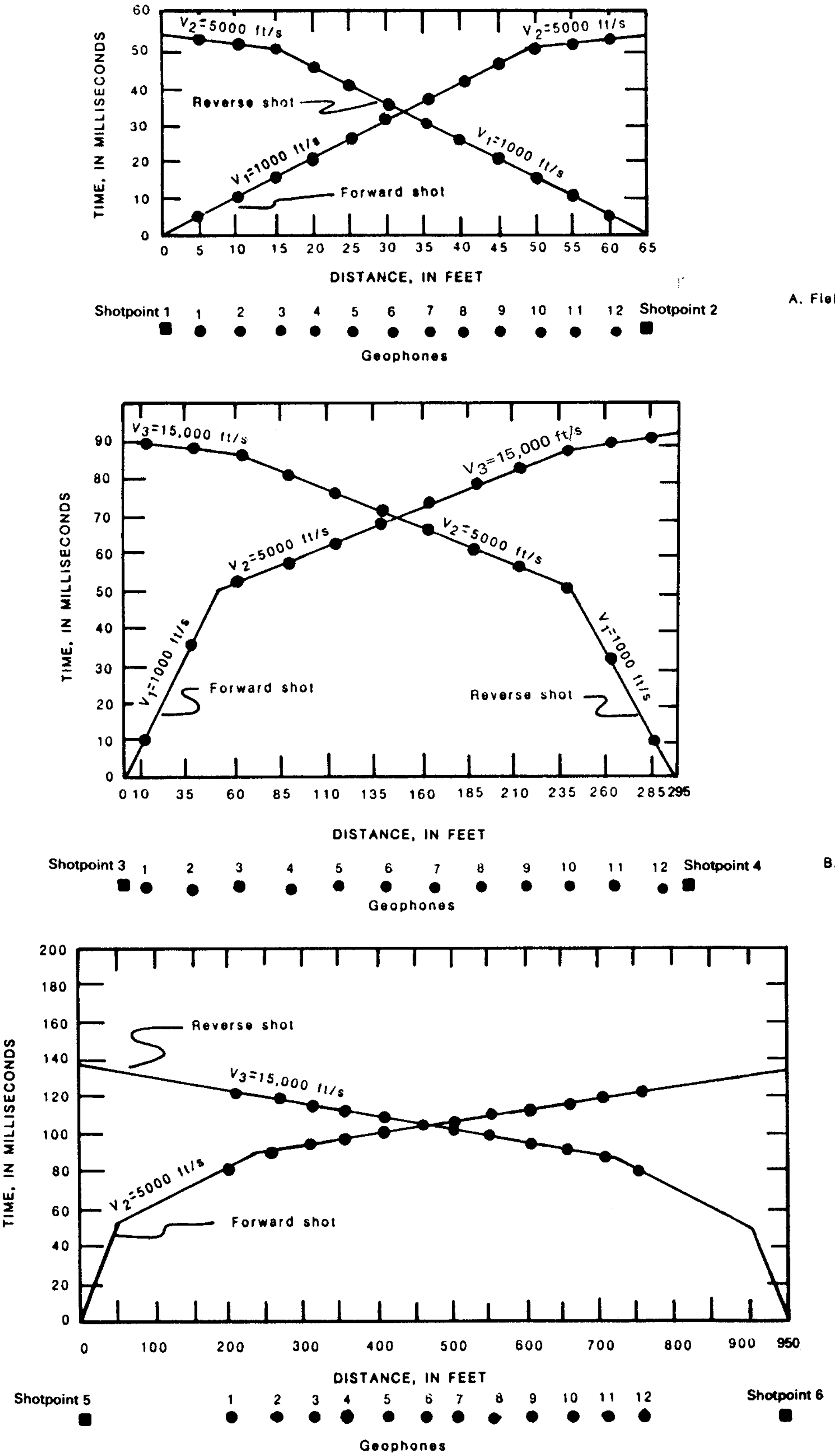
Quantity or quality of field data

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 are 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 and the resulting selected raypaths for the first three shotpoints are shown in figure 38. The resulting time-distance plot and interpreted cross section are shown in figure 39. This single arrangement of geophones allows accurate delineation of a shallow refractor (the water table in unconsolidated alluvium) and a deep refractor (bedrock) with five shotpoints. Figure 40 shows the time-distance plot and hydrogeologic section resulting from only two shotpoints using the same geophone spacing.

Comparison of figures 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.

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



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 200 feet between first geophone and shot point.

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

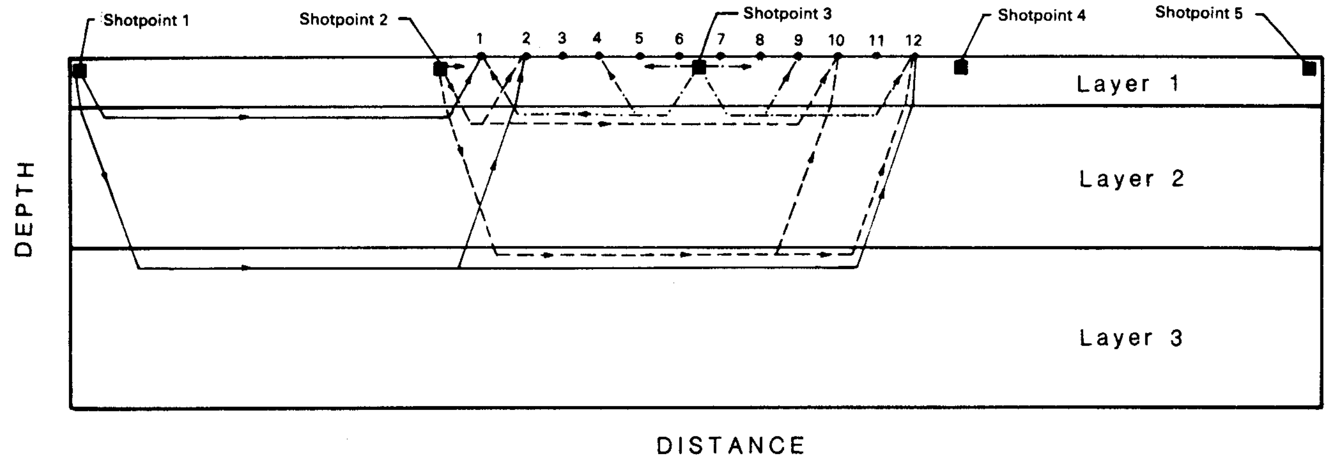


Figure 38.—Field setup of shotpoints and geophones for delineation of multiple-refracting horizons. Only selected raypaths for shotpoints 1, 2, and 3 are shown. The raypaths for shotpoints 4 and 5 are the mirror image (with respect to shotpoint 3) of the raypaths for shotpoints 2 and 1, respectively.

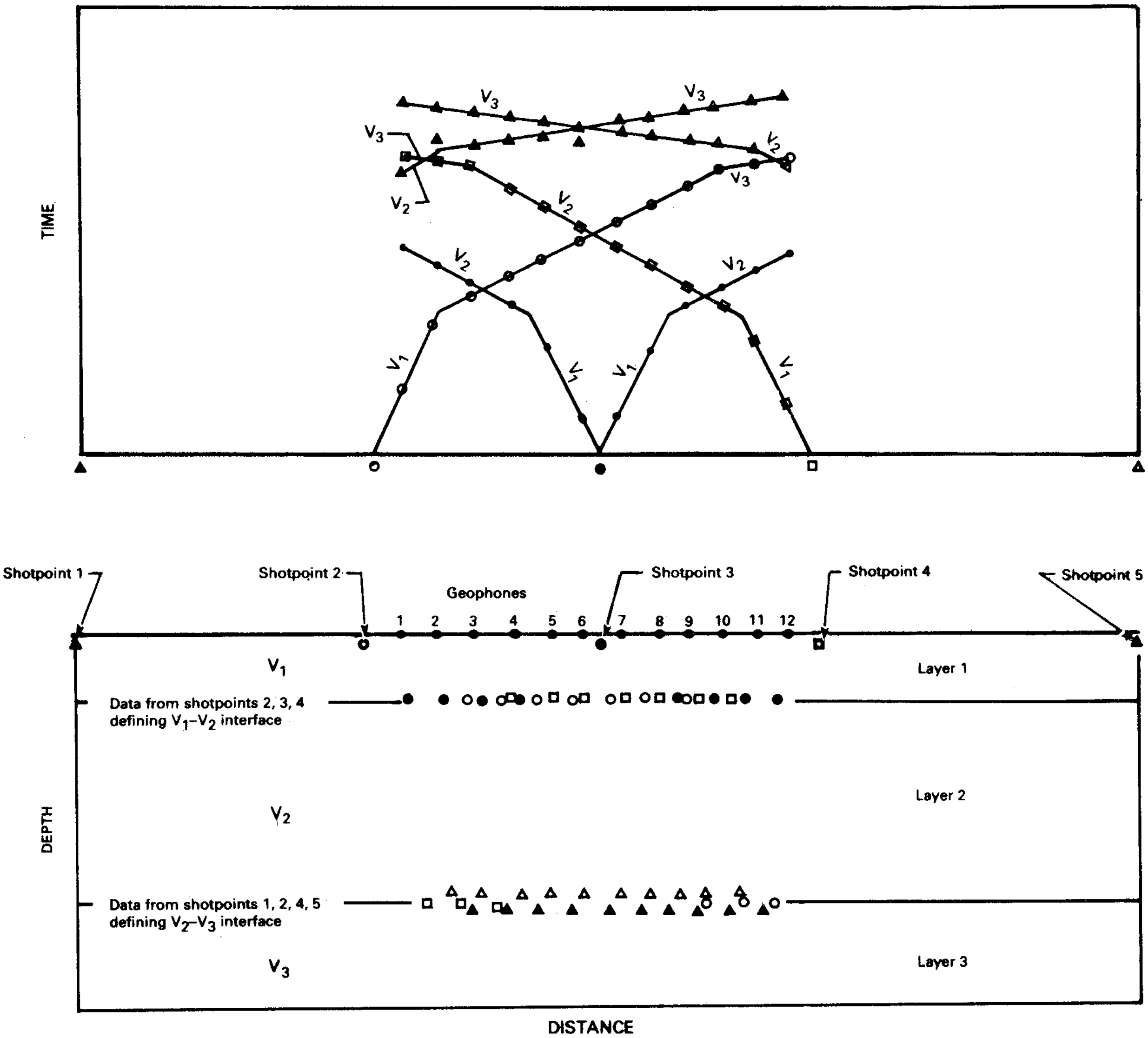


Figure 39.—Time-distance plot and interpreted seismic section resulting from a single geophone spread with five shotpoints.

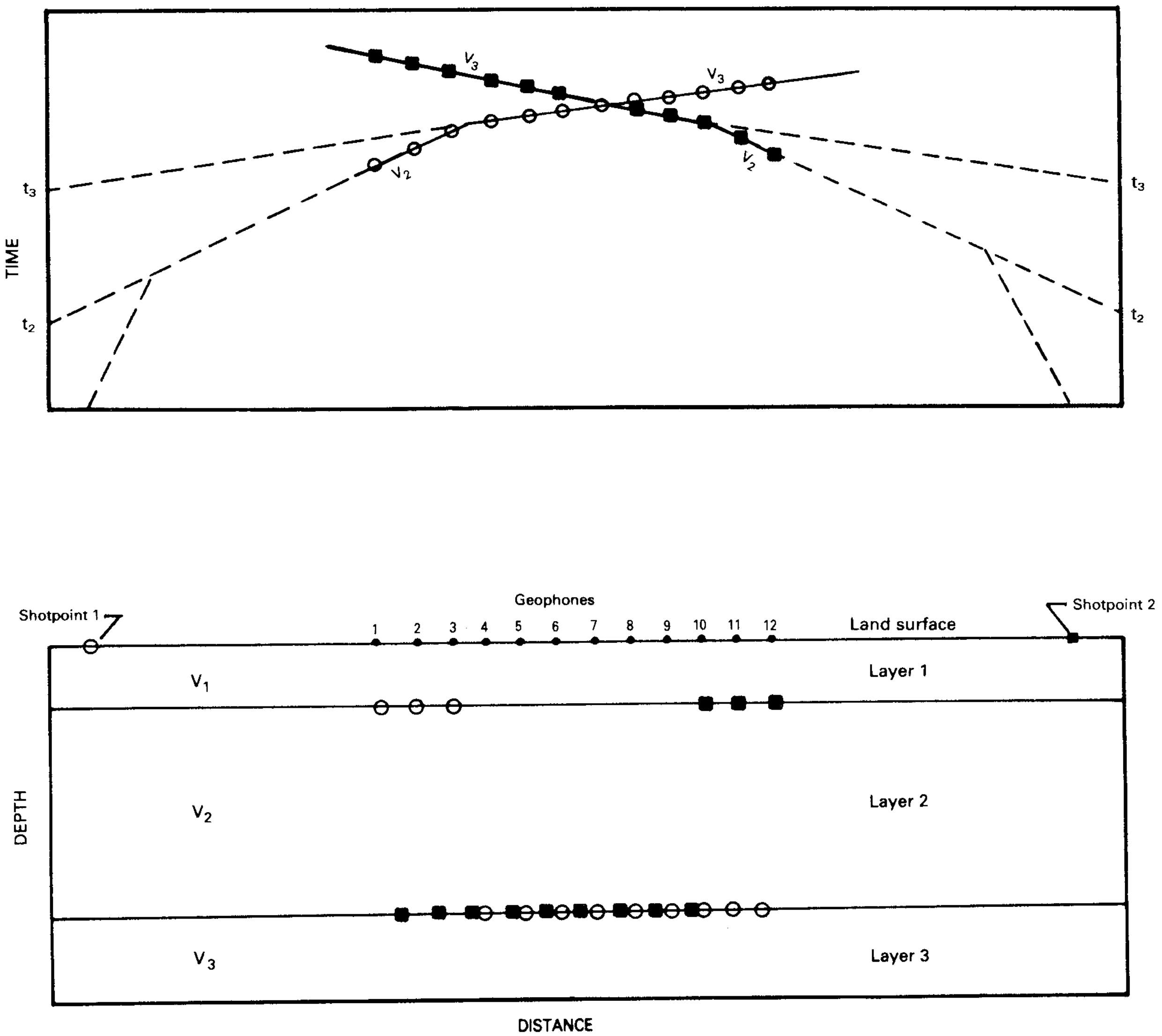


Figure 40.—Time-distance plot and interpreted seismic section resulting from a single geophone spread with two shotpoints.

by using 3 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 2 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 for interpreting seismic-refraction data. If the delay-time technique is used (see subsection on "Modeling Techniques"), the field setup 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 time-distance plots that would result from a number of shotpoint-geophone array geometries over several three-layer subsurface models in which the thickness and depth of layer 2 varies as indicated across the top and down the left side of the diagram. This figure illustrates the range of information acquired using different shotpoint-geophone array geometries for the various subsurface models. The figure assumes horizontal layers and seismic velocities of 1,000, 5,000, and 15,000 ft/s. These velocities are common in hydrogeologic studies and could represent a hydrogeologic 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/s 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 left side and the thickness of saturated material (100 ft) on the top, 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 were designed as indicated by the diagram below the plot (using the spacing distances a, b, and c listed above the plot). In this example, if a spread cable with 50 ft between geophones and two offset shotpoints (25 and 200 ft from the first geophone) were used, a time-distance plot similar to the one shown would be obtained. This shotpoint-geophone arrangement defines velocities V_1, V_2, and V_3 and the depths to layers 2 and 3. There are two different values for the depth to layer 3, which indicates that reversed shots must be used to reconcile the difference.

Reversed shots should always be made to determine if the assumption of a horizontally layered Earth is valid. If it is valid, the forward and reverse plots will be mirror images of one another. Figure 41 is only a guide to aid in the design of field geophone and shotpoint setups.

The issue of quantity versus quality arises in every seismic-refraction field investigation and should be clearly understood by any investigator. Specifically, the decision as to 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, it is time to begin production work. The organization and operation of a small field crew varies, depending on the number of people available, the type of equipment to be used, the terrain, and the objectives of the investigation.

Hydrogeologic seismic-refraction studies generally are directed toward shallow targets (less than 500 ft deep) 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 or four reversed seismic-refraction profiles in an 8-hr 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 of 0 to 500 ft) and four or more people for larger operations (target depths of 500 ft or more). Upon arrival at a site, the party chief should design the field layout of the geophones and shotpoints, 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 shotpoint, 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 equipment 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 are to be completed in order to conduct a seismic-refraction survey.

1. The truck is set up for fieldwork 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 hardhats 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 to 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 probability of encountering flying rock using different amounts of explosives under different field conditions.

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

Table 7.—*Typical field-crew work assignments for seismic studies*

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.		

canvas tarpaulin placed over the shotpoint 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 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 shotholes, and soft or loose surface material should be avoided. A shovel may be 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 hydrogeologic 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 geophone connection 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 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 wire or a safety key should be used to hook up the shot cable to the firing device. This cable or key should be in the possession of the person loading and wiring the explosive at the shothole. After the explosive is wired the shot cable should be attached to the firing device using the safety cable or safety key (see "Shot Cable" 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 into 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.

SAFETY NOTES:

- Do not place explosives in a hole that is still hot from drilling.
- Use only a wooden tamping pole.
- Mix explosive components and install cap just prior to loading hole. Manufacturer's instructions for mixing the explosives must be followed to prevent misfires.
- Check the cap with a blasting galvanometer, *not a standard voltmeter*.
- The cap should be on the bottom of the explosive.

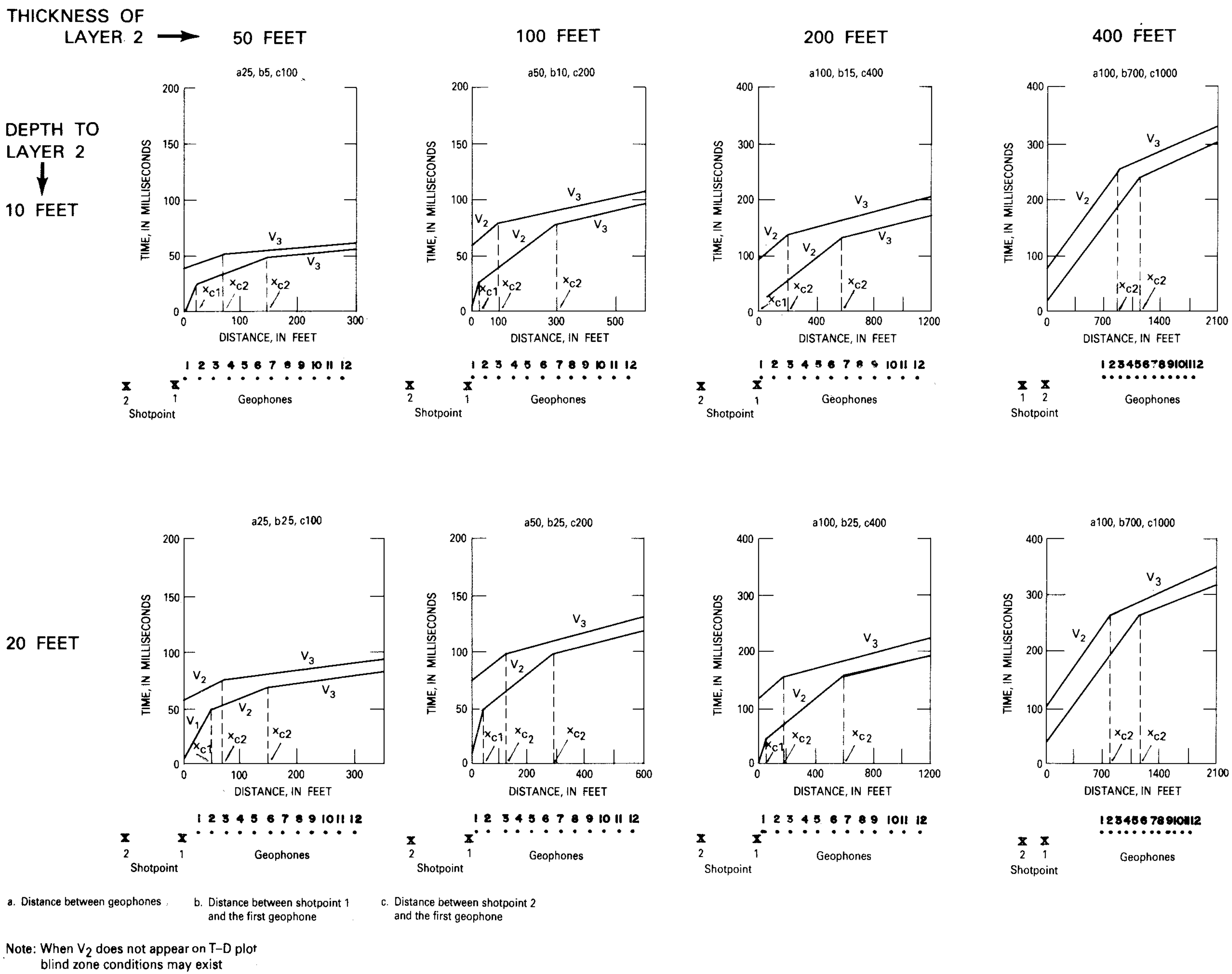
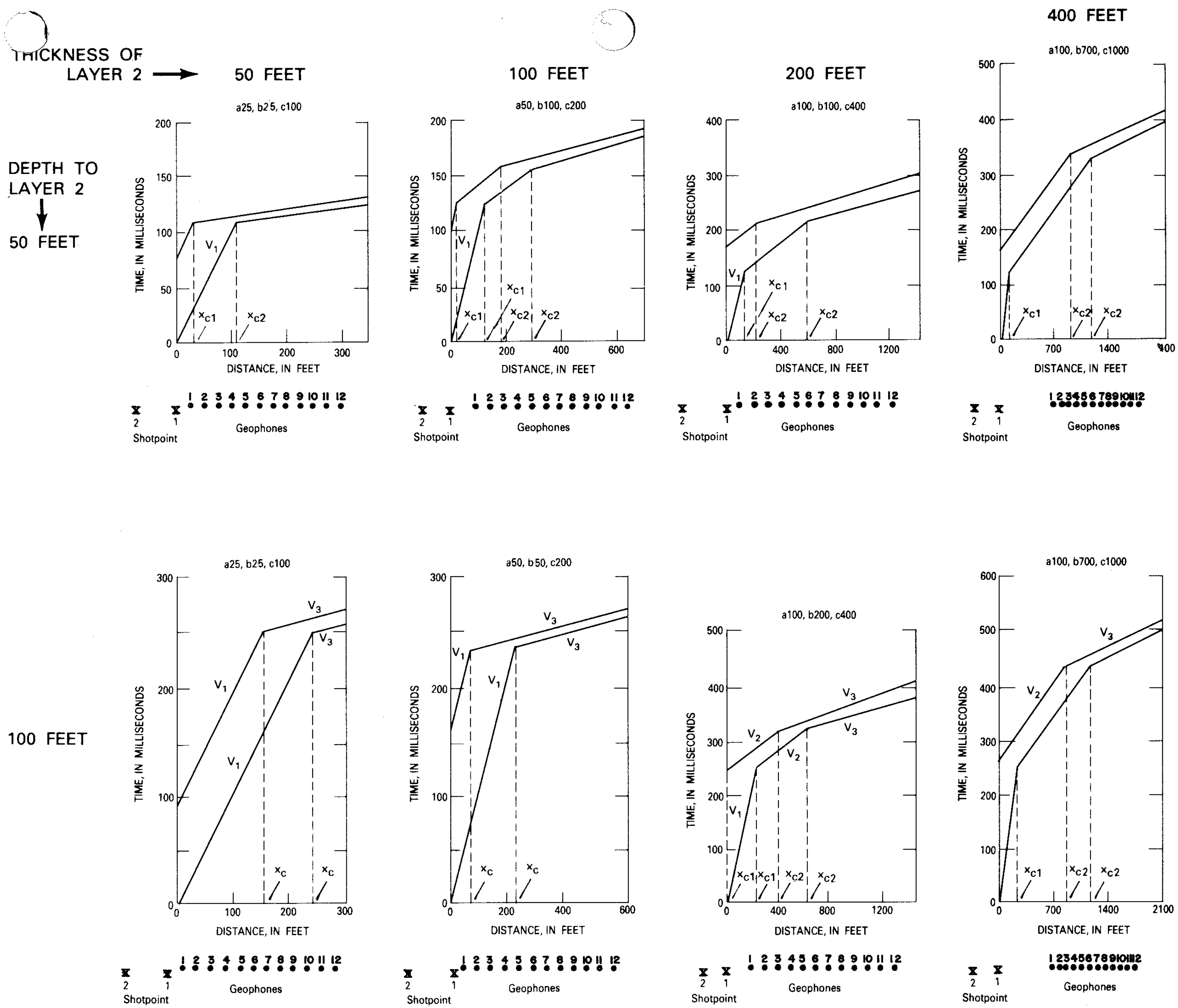


Figure 41.—Shotpoint and geophone geometries for various thicknesses and depths of layer 2 and the resulting time-distance plots.



a. Distance between geophones

b. Distance between shotpoint 1 and the first geophone

c. Distance between shotpoint 2 and the first geophone

Note: When V_2 does not appear on T–D plot, blind zone conditions may exist

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

[do., ditto]

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	do.
50	4 - 10	15	Medium.

- Record the depth of the top of the explosive and the depth of the hole in case of misfires (the explosive does not fire).
- Fill and tamp the hole with dirt or sand. Do not use grass, weeds, or cobbles.
- Always tape the cap wires to the explosive cartridges; the main reasons for misfires are separation of the cap from the explosive and electrical malfunction of the firing circuit.
- Personnel handling explosives should have special training and may need to be licensed.
- Local police and regulatory authorities should be notified if explosives are to be used.
- After detonation, do not inhale fumes, as they are often toxic.

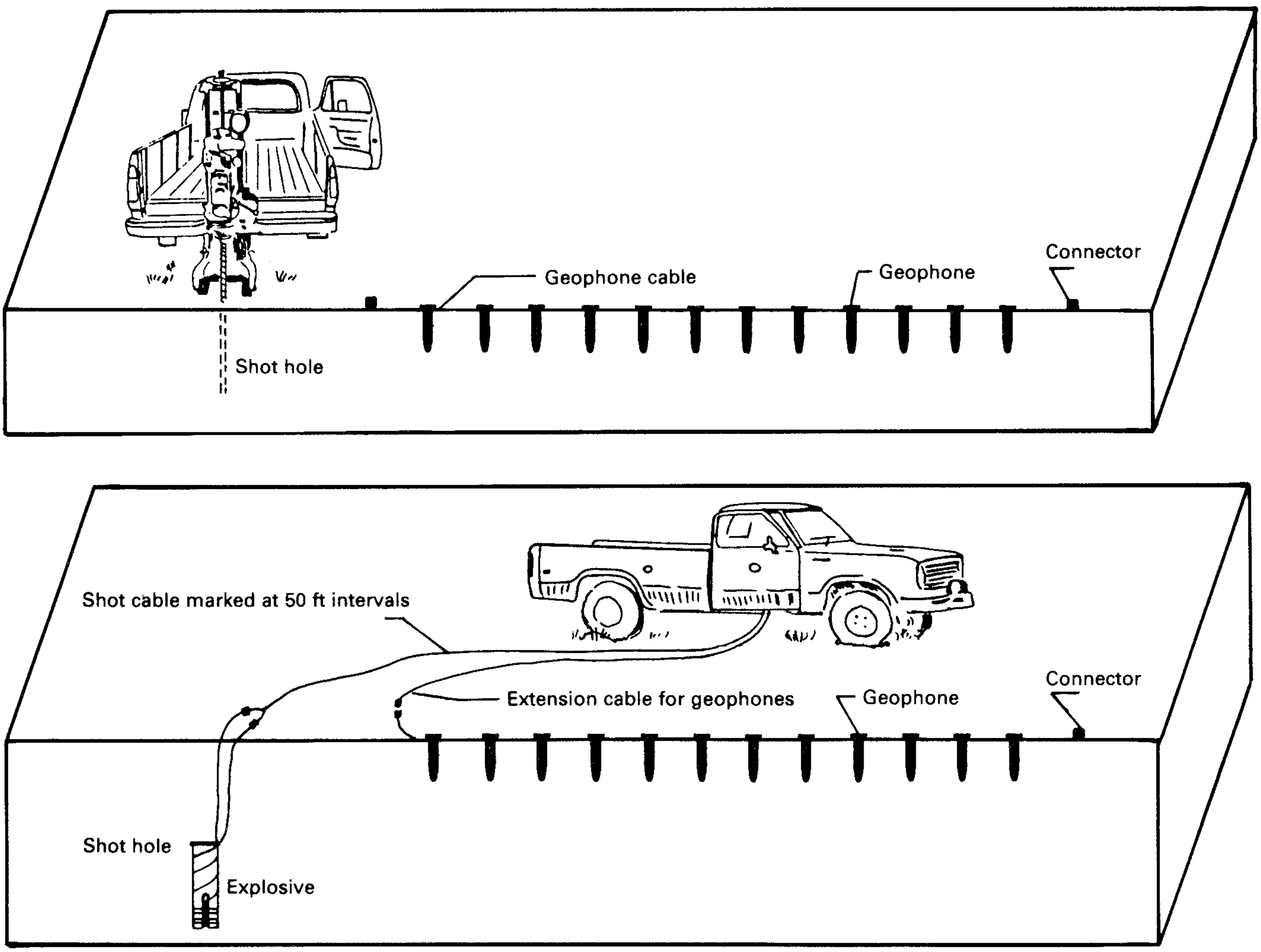


Figure 42.—Field setup of seismic truck, geophones, and shot hole.

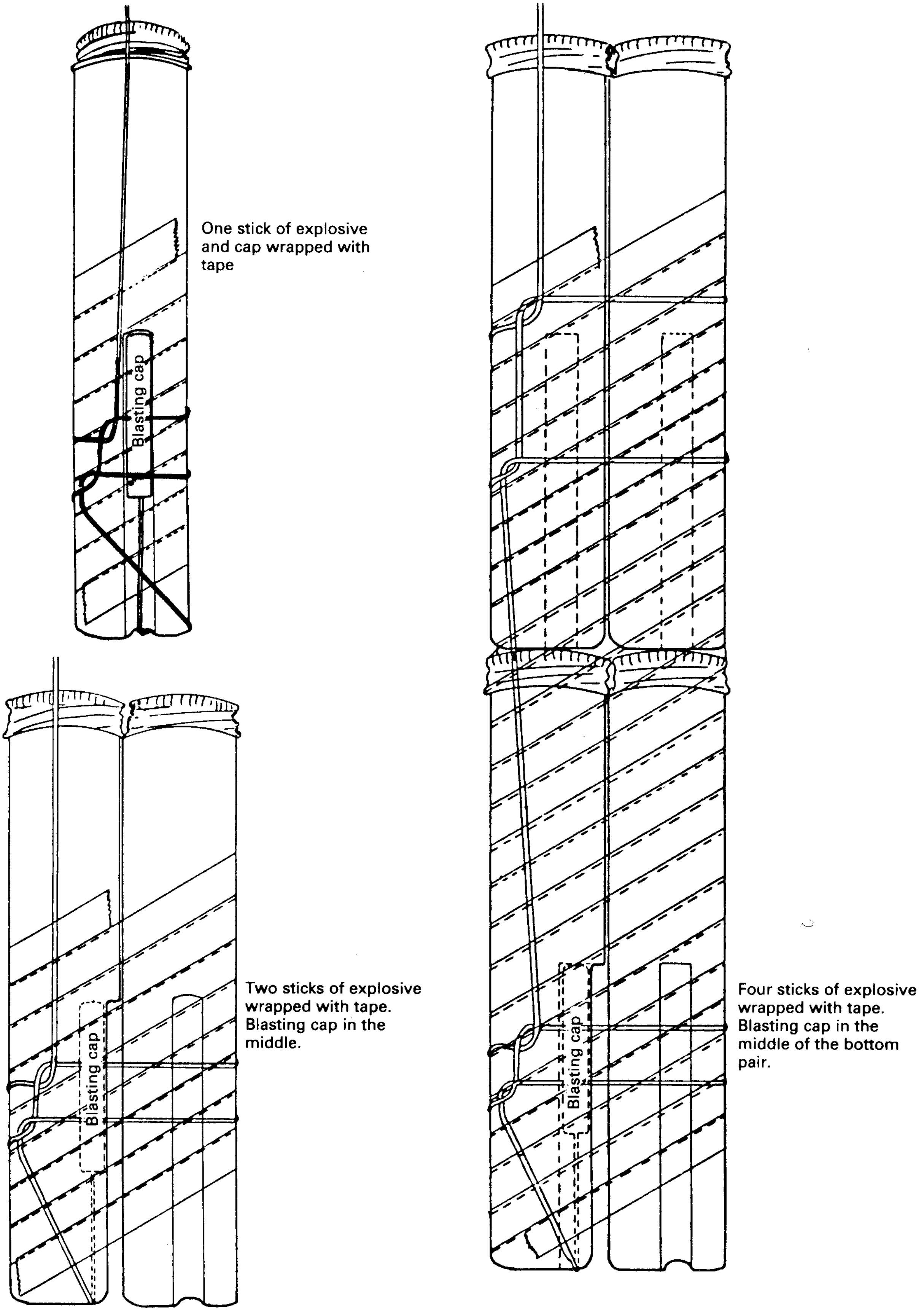


Figure 43.—Assembly of explosive cartridges and electric blasting caps.

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

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

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

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

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

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

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

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

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

Field records

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

Spread number (Which end of geophone cable is attached to seismograph?)
Location
Number of geophones
Distance between geophones
Elevation of each geophone
Remarks—location of outcrops; depth to water in ponds, streams, etc.; location of test holes or domestic wells

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

Shot number
Location
Distance to first geophone
Depth of shothole and explosives
Depth of water in shothole
Elevation of shothole
Description of materials in shothole
Spread number
Amount of explosives used (if applicable)

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

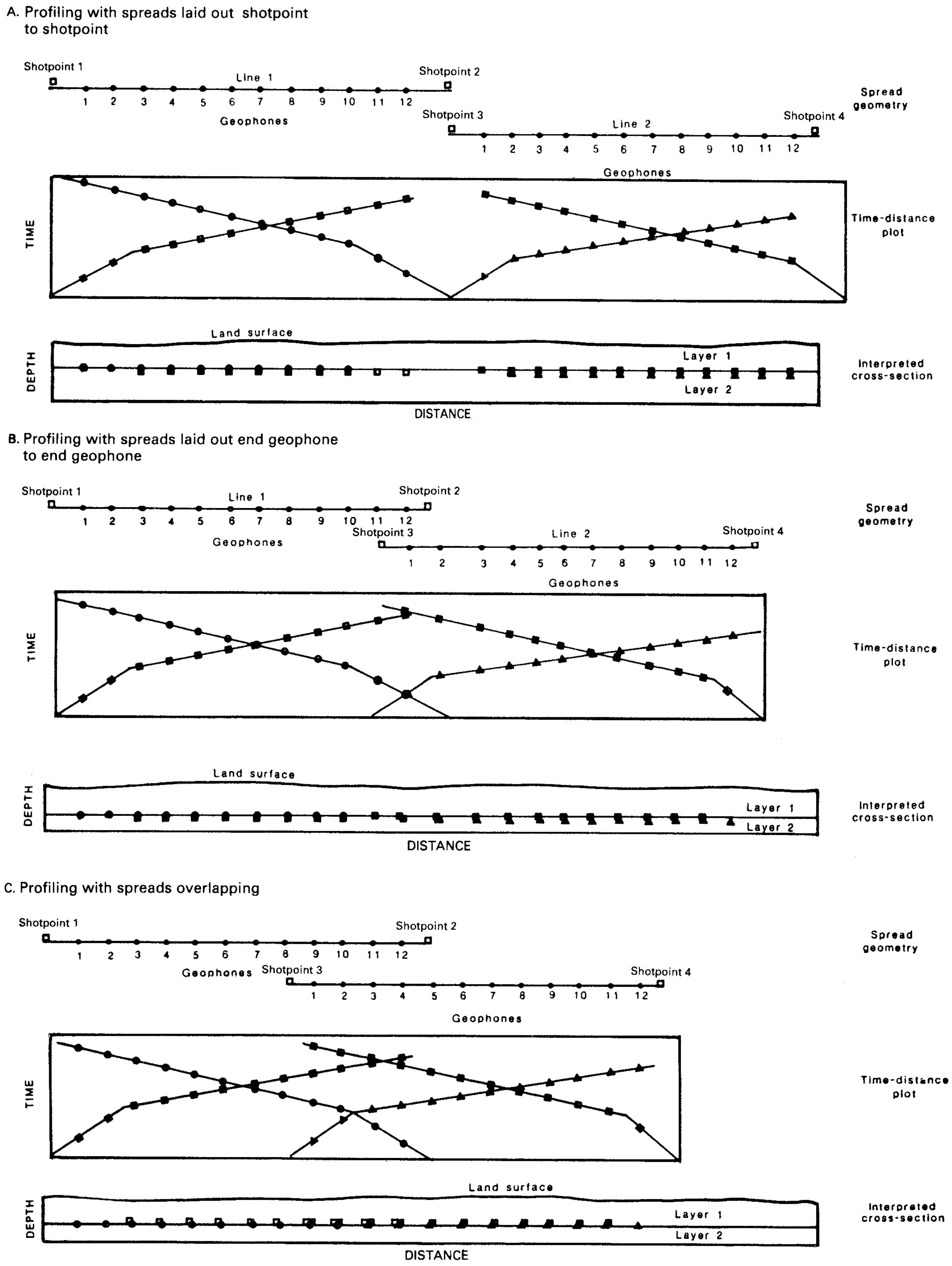


Figure 44.—Various field setups and resulting time-distance and depth plots for each geophone in a two-layer problem.

Town ______________________ Site ______________________

Location ______________________ Date & Time ______________________

Owner ______________________ Party ______________________

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

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

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.—Data sheet for recording field data.

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

References

Institute of Makers of Explosives, 1978, Do's and don'ts: Instructions and warnings: Washington, D.C., Institute of Makers of Explosives Publication 4, 13 p.

U.S. Geological Survey, 1979, Safety handbook: Reston, Va., U.S. Geological Survey, section 3.12, p. 1–10.

Interpretation Techniques

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

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

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

Seismograph records

The seismograph records obtained in the field contain data about the time it takes for compressional energy generated by the seismic source to travel (by different paths) through the subsurface and back up to the geophones on the surface. In most hydrogeologic studies, only the first arrival of compressional energy at each geophone is of interest, as this can be used to determine the position of refracting surfaces. Seismic-reflection techniques use subsequent energy arrivals on the seismic record. Figures 46 and 47 show typical seismograph records produced by twelve-channel seismographs.

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

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

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

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

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

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

Time-distance plots

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

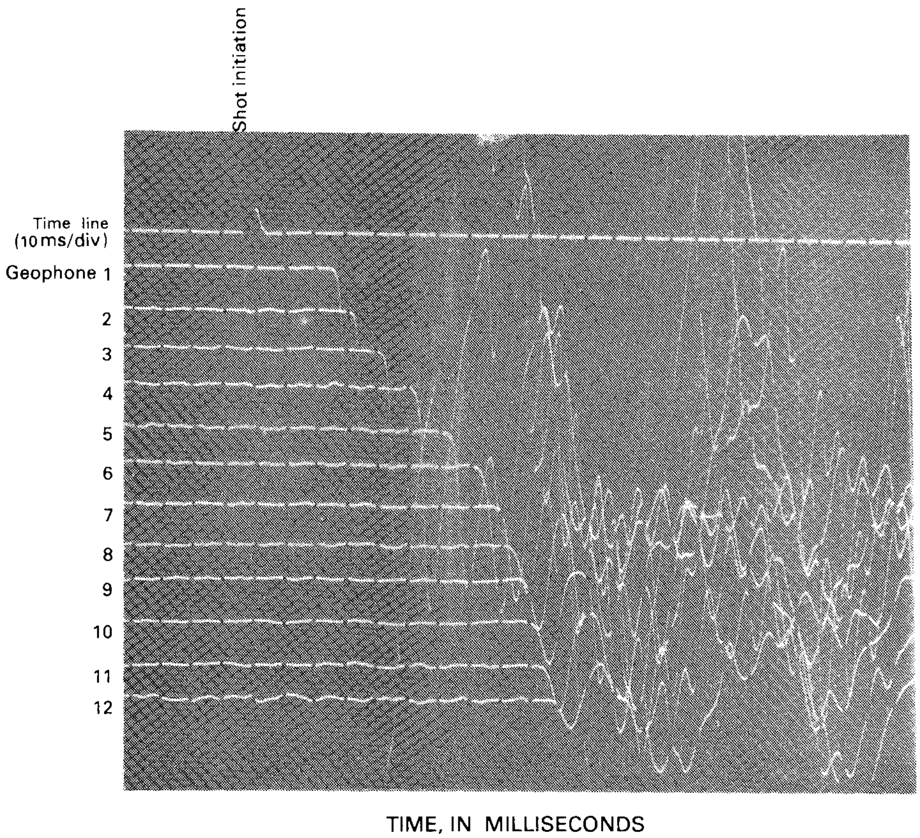


Figure 46.—Twelve-channel analog seismograph record showing good first breaks produced by an explosive sound source.

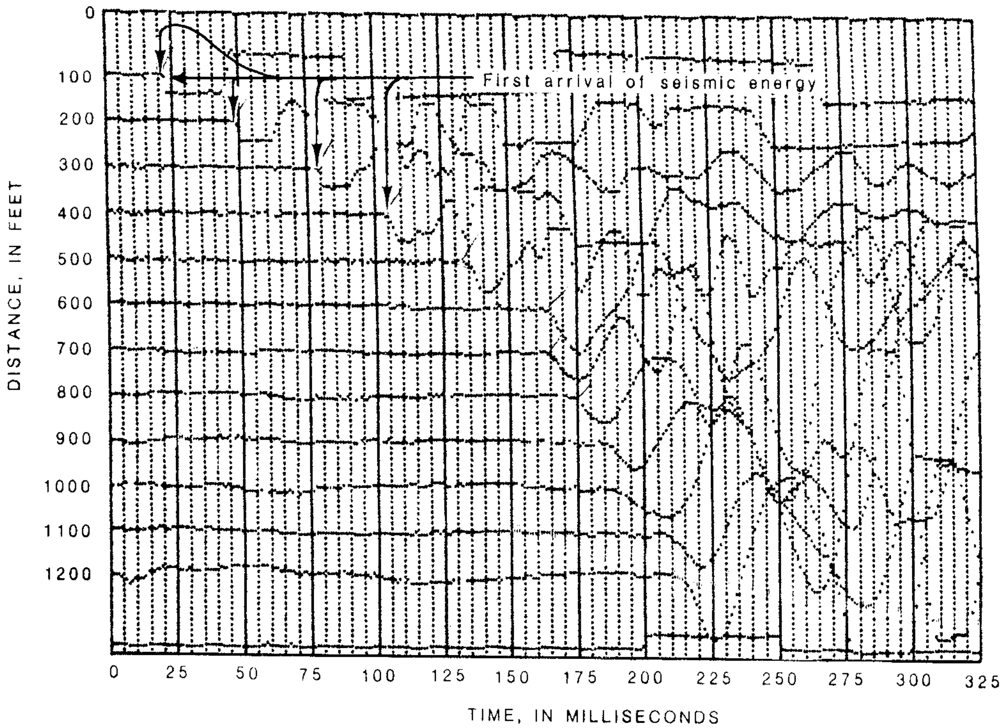


Figure 47.—Twelve-channel digital seismograph record from Little Androscoggin River valley, Maine, showing sharp first breaks produced by an explosive sound source in an area with low background noise.

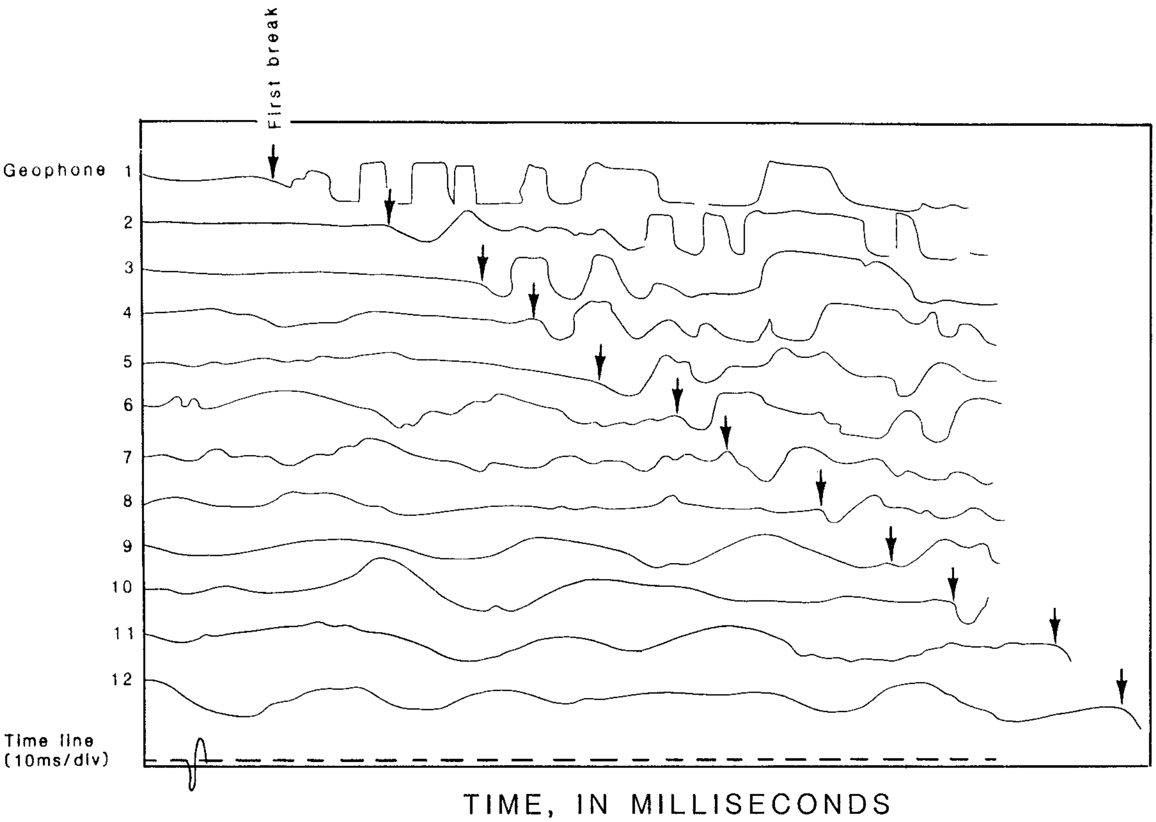


Figure 48.—Seismograph record with rounded first breaks produced by a sledge-hammer sound source in an area with high background noise. Signal stacked 10 times, with geophones spaced 50 ft apart.

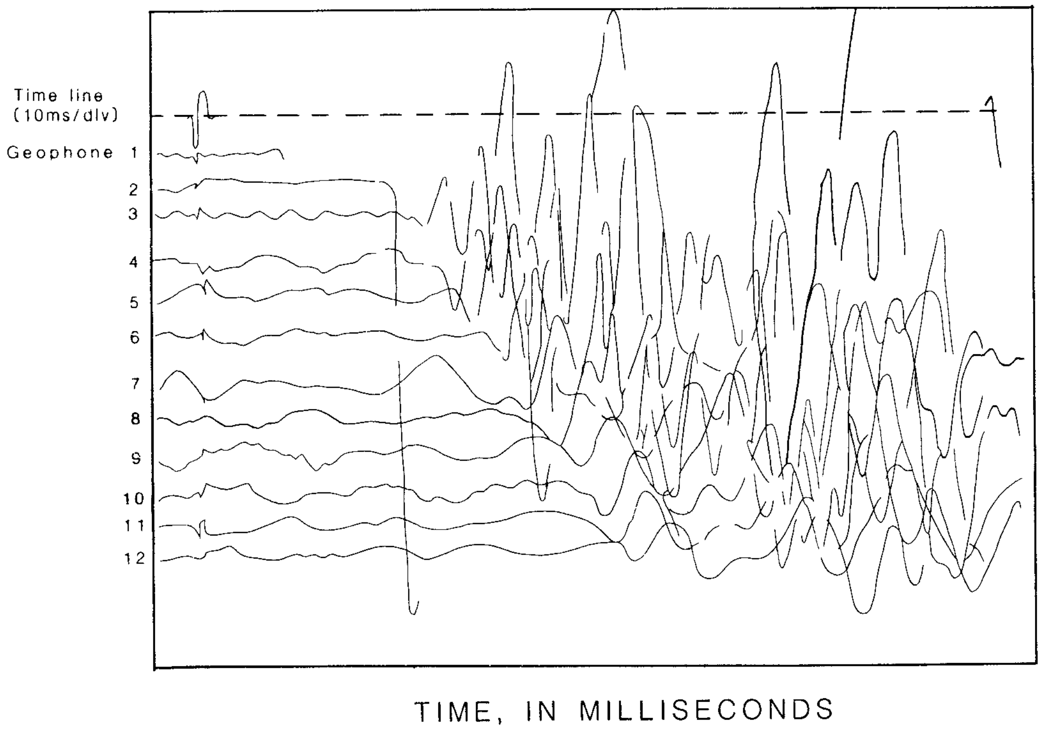


Figure 49.—Seismograph record with sharp first breaks produced by an explosive sound source in an area with high background noise. Geophones were spaced 50 ft apart.

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

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

Manual interpretation techniques

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

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

Computer-assisted interpretation techniques

Formulas

The same formulas used to interpret seismic-refraction data manually also can be solved by digital computers. Computer solutions of the formulas are given by Mooney (1981, chap. 11) and Hunter (1981).

Modeling techniques

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

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

The original FORTRAN IV source code and its documentation is for a program to do batch processing using a Burroughs 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

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

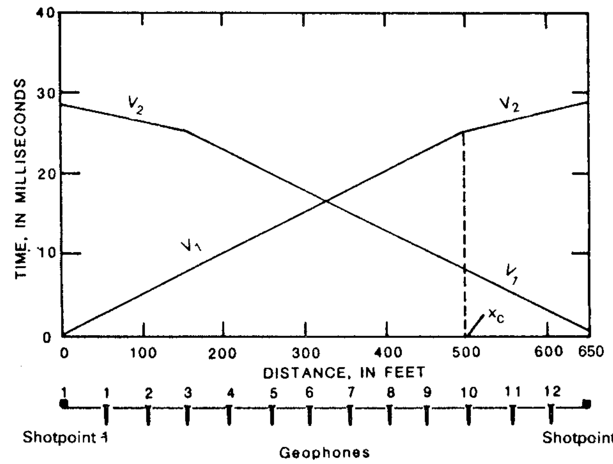


Figure 50.—Reversed seismic-refraction profiles with two velocity layers depicted on the time-distance plot.

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

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

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

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

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

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

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

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

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

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

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

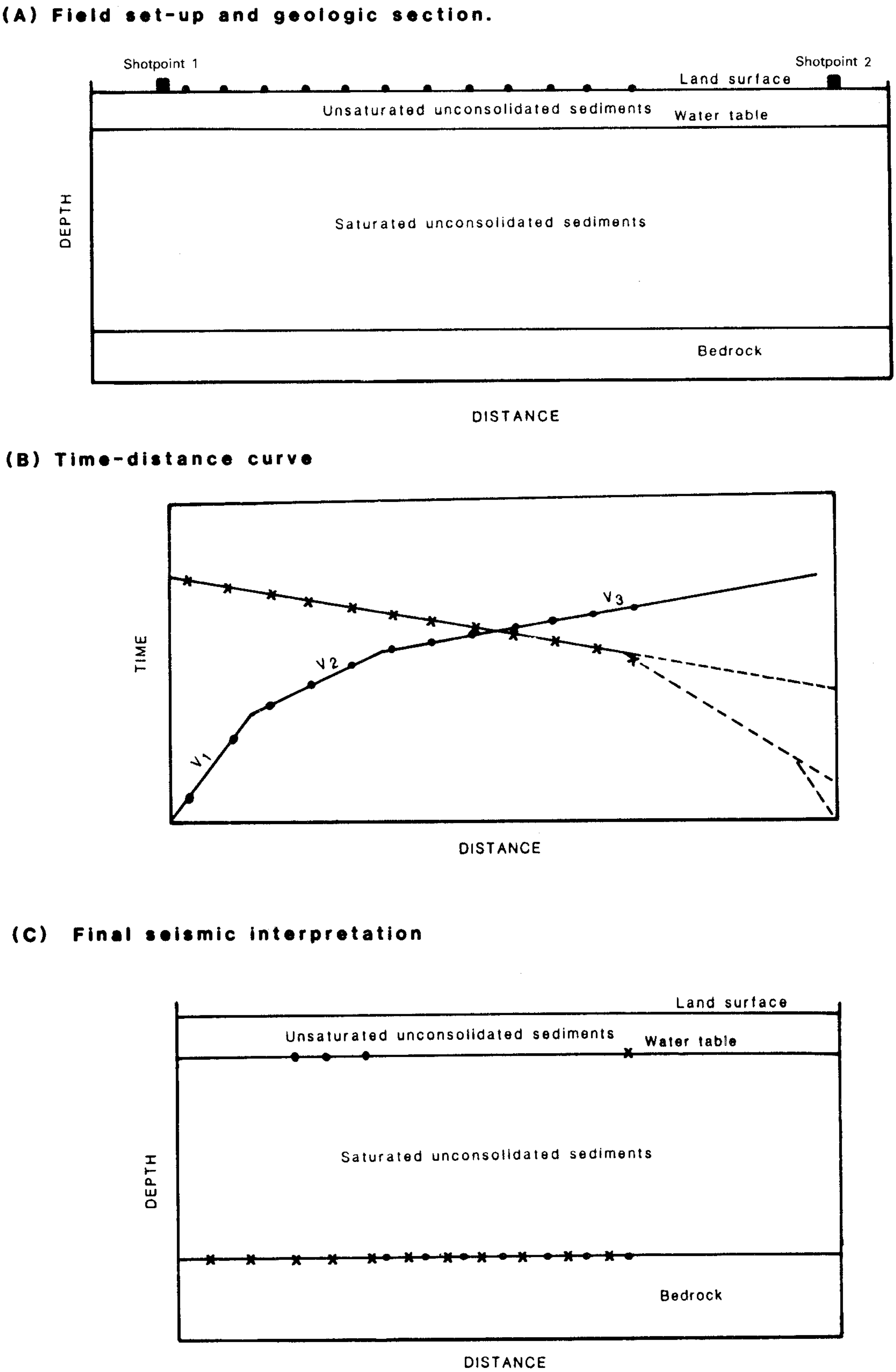


Figure 51.—Relationships between field setup, time-distance plot, and interpreted seismic section.

control to the choice assigned on the problem control line.

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

   T (response)

   Discussion: The table of input data should always be printed the first time through the program because the program has editing features that will flag typographic and other obvious data-entry errors. If this happens, the message "error on input cards" will be printed. Execution of the program will be terminated at this point, and the error can be corrected via the computer editor. The input geophone and shotpoint data table is now printed out. These data should be checked for typographic errors not caught by the editor.
7. T-D plot: 1 = raw, 2 = datum, 3 = Pre-D, 4 = L1 remvd: (prompt)

   1 (response)

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

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

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

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

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

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

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

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

Crossover distances:

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

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

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

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

Layer velocities:

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

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

SEISMIC REFRACTION FIRST ARRIVAL TIME RECORD SHEET

Site name ______________________________

Spread # ______________

Shot number ______________ Shot direction ______________

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

Shot number ______________ Shot direction ______________

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

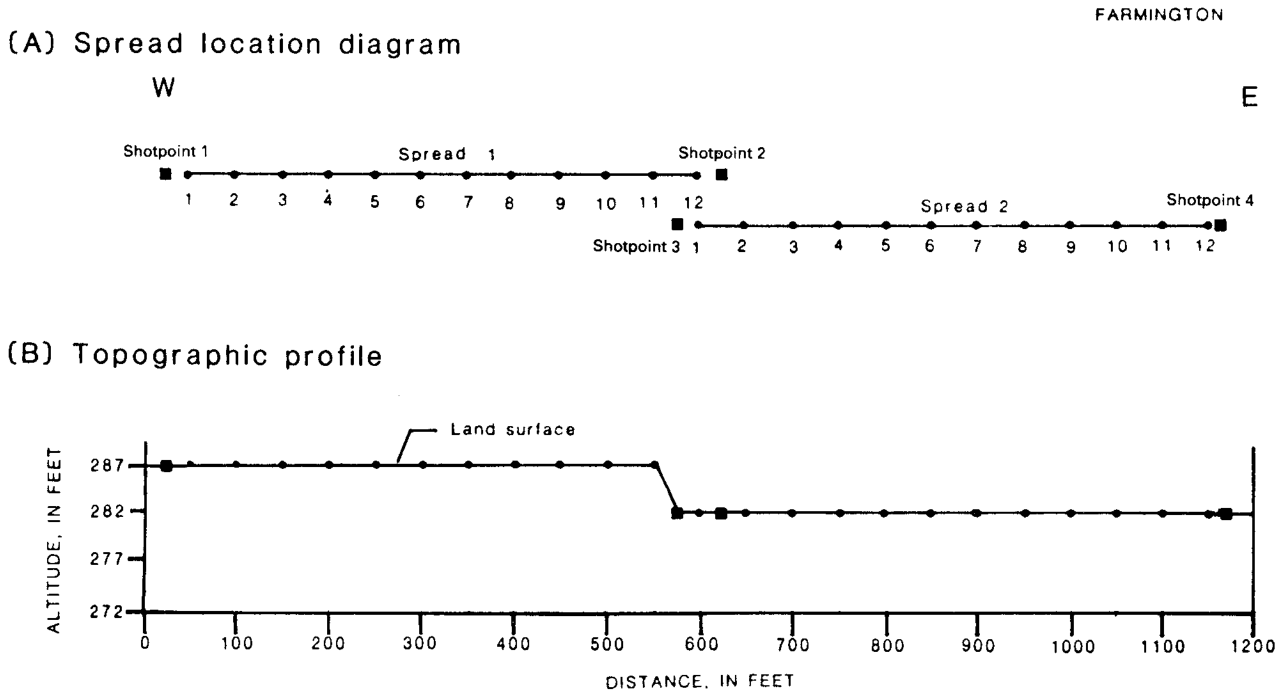


Figure 53.—Shotpoint and geophone locations and altitudes plotted to scale.

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

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

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

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

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

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

A. If the land surface is relatively flat, the first refracting surface is the water table. If the saturated zone has a significant thickness, a straight line segment with an inverse slope of about 5,000 ft/s can be aligned with several data points.

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

C. The remaining data points are used to construct line segments that represent refracted sound from deeper layers. It must be noted that if the deep refracting layers have little or no relief, the segments on the time-distance plots should be straight lines. If there is relief on these surfaces, or if the velocity of sound varies significantly in any of the overlying subsurface units, these data points will not form a straight line.

D. The principle of reciprocity also can be used to help construct time-distance plots. Examining figure 37A, the traveltime from shotpoint 1 to geophone 12 is the same as from shotpoint 2 to geophone 1. In general, the seismic traveltime from a source at point A to a geophone at point B is equal to that from a source at point B to a geophone at point A. For the arrangement shown in figure 37A, this criterion is not met but the offsets from shotpoint 1 to geophone 1 and from shotpoint 2 to geophone 12 are small. Hence, the reciprocity principle is applicable and constrains the traveltimes for the end geophones. Good examples of this principle

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

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 TEXT OR 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 i.e., two spreads would have 0,0,0,0)
		0,	0,0

One set per each spread

SPREAD CONTROL LINE

Spread number	Number of shotpoints	Number of geophones	
			0,0

SHOTPOINT LINES

Shotpoint number	Elevation of shotpoint	In-line coordinate	Transverse coordinate	Depth of shotpoint	
					0,0,0
					Multiple shotpoints must be listed in increasing in-line coordinate order

GEOPHONE LINES (Travel times from shotpoints must be in the same order as on shotpoint line)

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

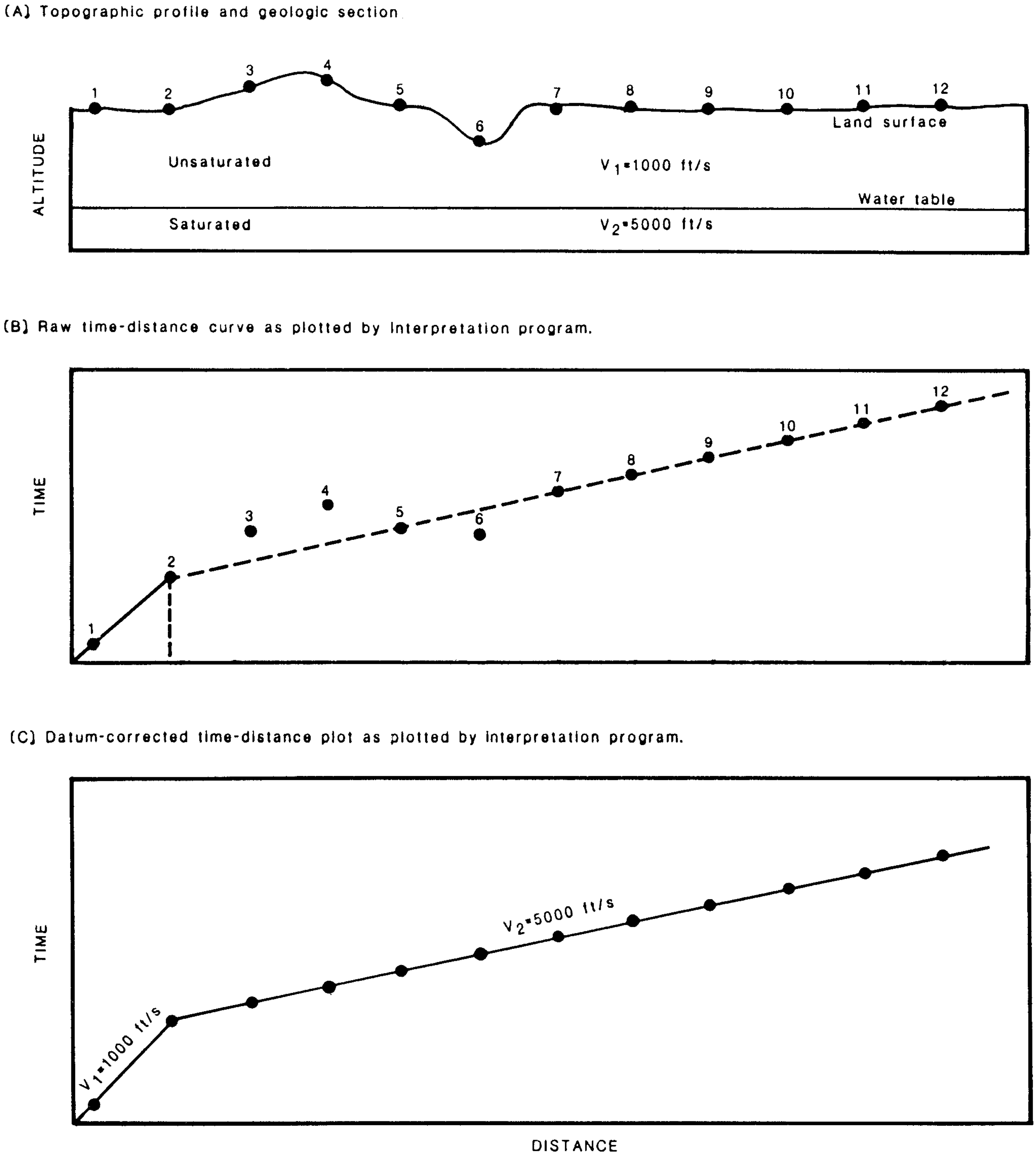


Figure 55.—Effect of topographic relief on raw and datum-corrected time-distance plots.

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

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

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

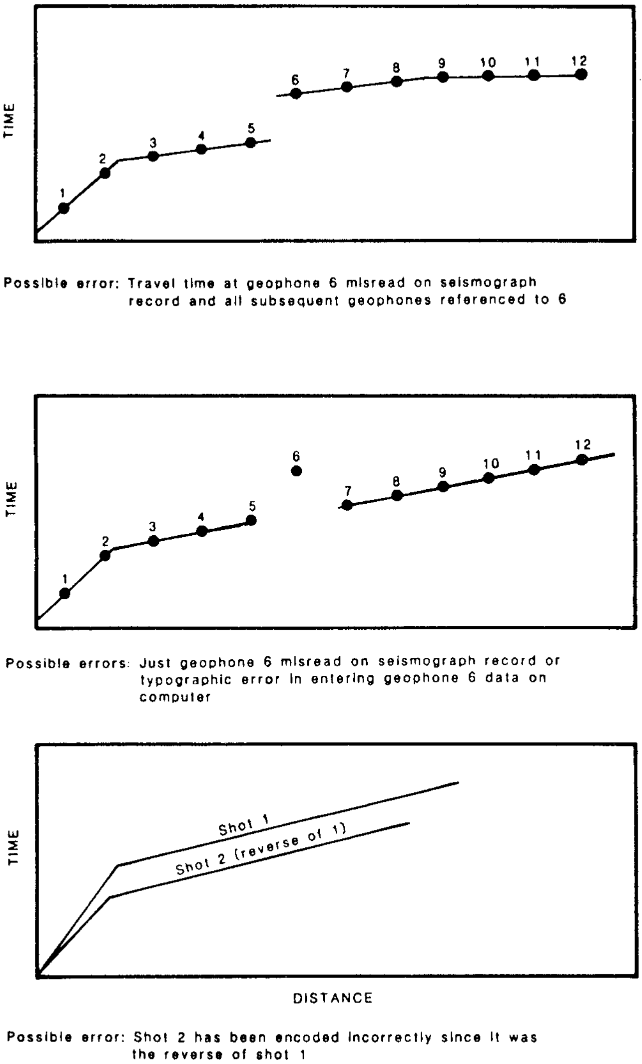


Figure 56.—Common errors indicated by unusual time-distance plots.

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

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

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

Because z, V_1, and V_2 are equal for both time-distance plots, the intercept times (t_i) also will be equal. Therefore, the line fit to the arrival times for the V_2 layer on each time-distance plot will meet the time axis at t_i for shotpoints 2 and 3. This property constrains the line fit to the arrival times. In general, then, for two geophone arrays laid in opposite directions for which the shotpoint is halfway between the arrays, the intercept times from common horizons will be equal. This property also is applied appropriately to shotpoints 4 and 5 in figure 57 and shotpoint 3 in figure 37B.

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

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

NOTE: It must be remembered that the velocities computed by regression are affected by dip and are the apparent velocities (see "Theory" section). Velocities computed by the "Hobson-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 troubleshooting the program and is not used in the interpretation process.
10. Depths beneath SPS & Geos: T to type, <CR> to suppress: (prompt)
    T (response)
    Discussion: This table is usually printed out because it lists depths to the individual refractors. If this is the first run, the interpreter should not be too concerned with the results. The obvious errors mentioned earlier have not been corrected and the solution presented here represents initial layer assignments and incorporates any data-entry error.
11. Depth plot: Enter T to type, <CR> to suppress: (prompt)
    T (response)
    Discussion: This is usually printed since it is the final plot of the interpreted geologic section. It can be suppressed on the initial run.
12. Enter input file name or <CR> to exit: (prompt)
    <CR> (response)
    Discussion: Enter file name for next run or <CR> to exit program. The final <CR> must be used to

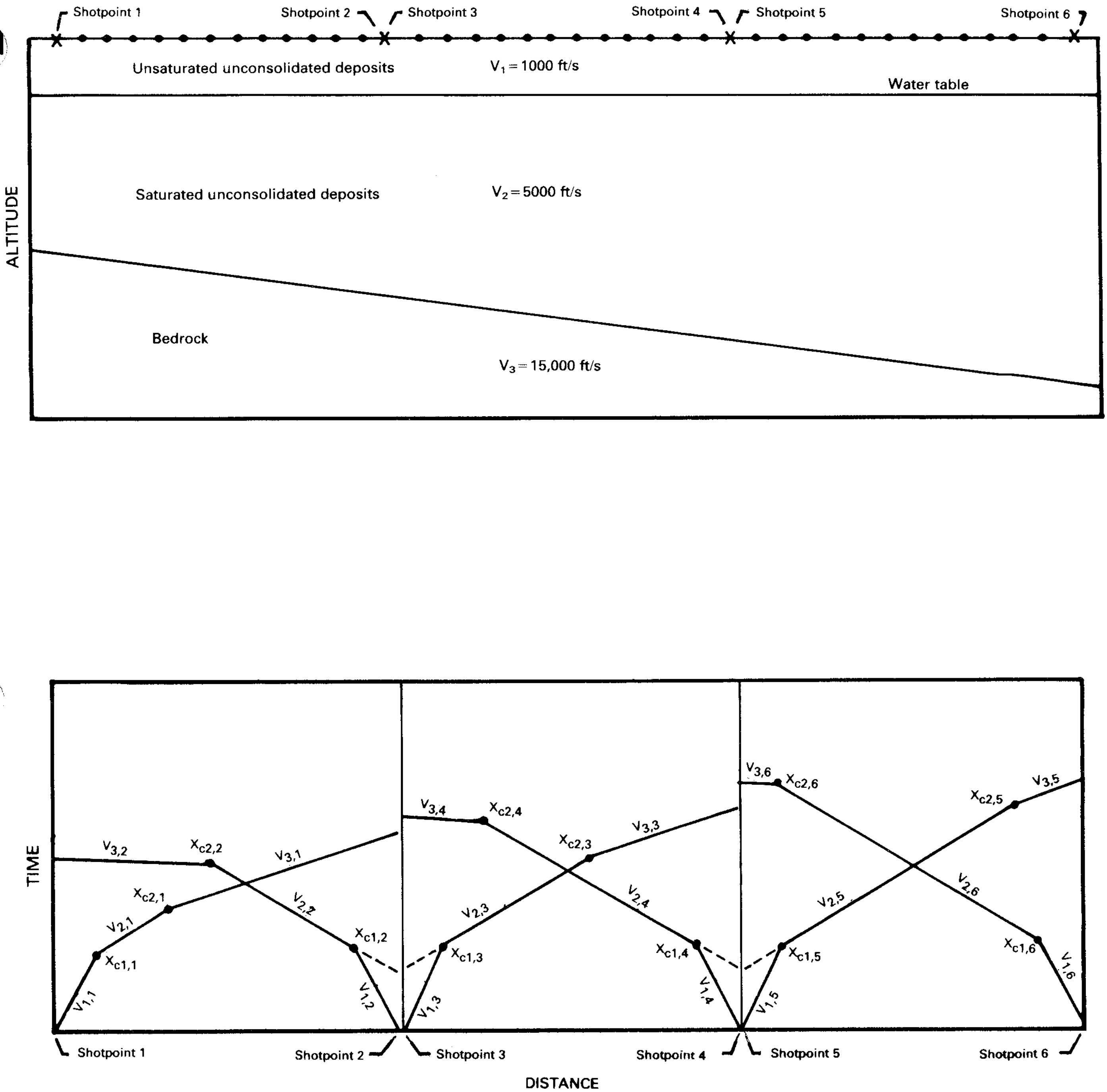


Figure 57.—Seismic section and time-distance plot showing the general relationships of seismic-layer velocities and crossover distances between three seismic-refraction spreads.

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

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

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

Format for input data to SIPT program	Explanation of data lines
Simsbury Minister Brook (Htfd. Fire Ins. Co.),	Title
2,6,3,1,5.0, 16.66,2.0,0,0,0,0,0,0,0,0,0,0,0 1,700,0,0,0	Problem control line Velocity override line
1,2,12,0,0 1,173.0,0,8,0,0,0 2,69,1000,0,8,0,0,0	Spread 1 control data Shot 1 data Shot 2 data
1,173,200,0,63,2,133,3 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	Spread 1, geophone locations, arrival times, and layer selection
2,2,12,0,0 3,173,400,0,10,0,0,0 4.155.1600.00.4.0.0.0	Spread 2 control data Shot 3 data Shot 4 data
1,171,750,0,94,2,152,3 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	Spread 2 geophone locations, arrival times and layer selection

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

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

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

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

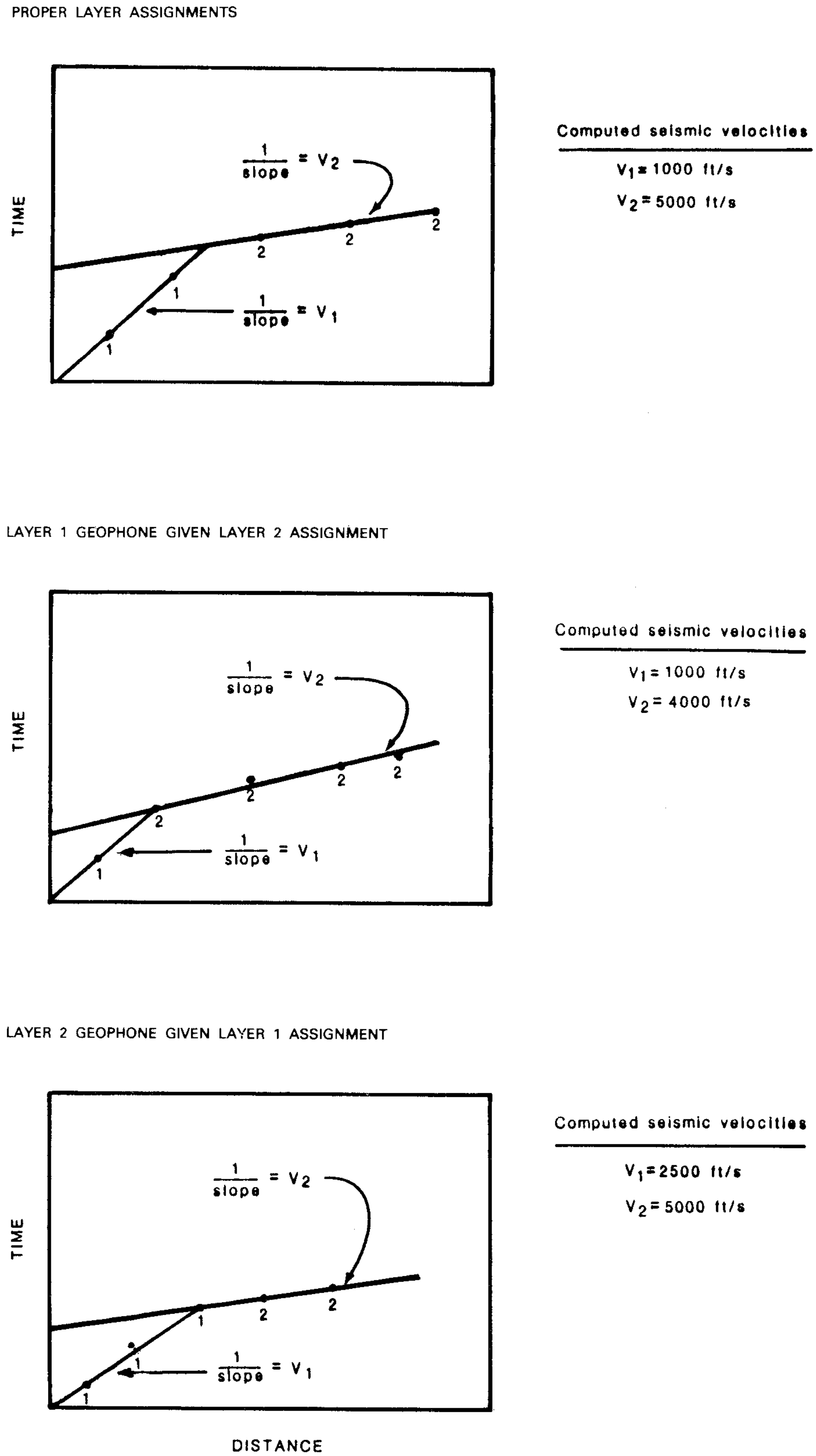
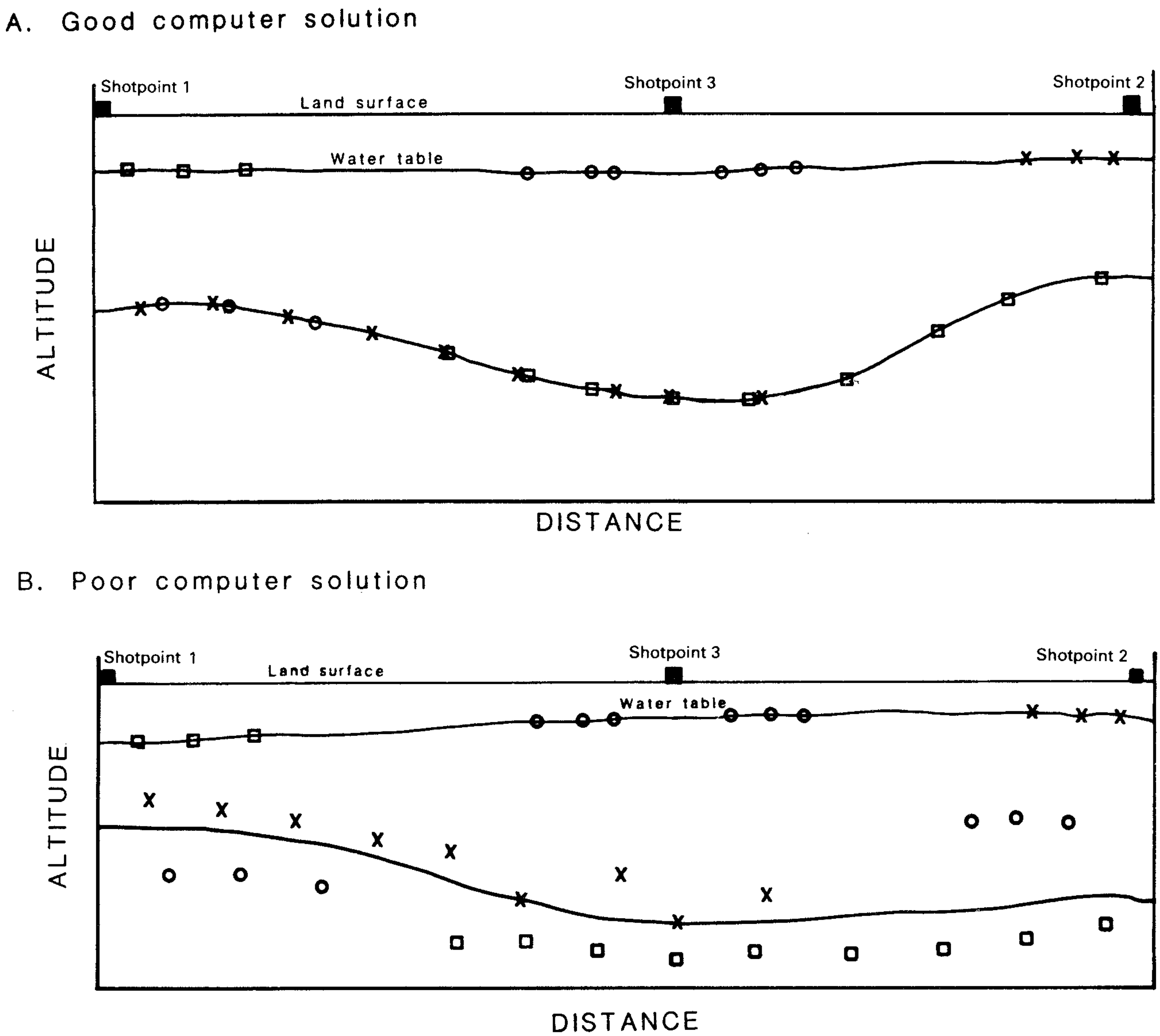


Figure 58.—Effects of incorrect layer assignments on the velocity of sound as computed by regression in the Seismic Interpretation Program (SIPT).



EXPLANATION

■ Shotpoint

□ Interpreted data from shotpoint 1

X Interpreted data from shotpoint 2

○ Interpreted data from shotpoint 3

— Final interpreted interface positions

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

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

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

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

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

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

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

The questionable layer assignments noted earlier on the time-distance plot near the crossover points can now be tested. The interpreter should make several computer runs, systematically varying the questionable layer 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 of where the problems are in the solution and whether or not the changes made in the runs have any effect. Under normal circumstances, the interpreter stops the computer-assisted interpretation process when little or no improvement is noted.

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

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

References

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, 268 p.

Ballantyne, E.J., Campbell, D.L., Mentemeier, S.H., and Wiggins, Ralphe, 1981, Manual of geophysical hand-held calculator programs, v. 2: Tulsa, Okla., Society of Exploration Geophysicists.

Barthelmes, A.J., 1946, Application of continuous profiling to refraction shooting: Geophysics, v. 11, no. 1, p. 24–42.

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

Hatherly, P.J., 1980, Computer methods for determining seismic first arrival times [abs.]: Society of Exploration Geophysicists annual meeting and exposition, 50th, Houston, Texas, v. 4, p. 1911–1932.

Hunter, J.H., 1981, Software listing of program for shallow seismic exploration using Apple components: Geological Survey of Canada Open File Report 552.

Mooney, H.M., 1981, Handbook of engineering geophysics: Minneapolis, Minn., Bison Instruments, Inc., 220 p.

Musgrave, A.W., ed., 1967, Seismic refraction prospecting: Tulsa, Okla., Society of Exploration Geophysicists, 604 p.

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

Palmer, D., 1980, The generalized reciprocal method of seismic refraction interpretation: Tulsa, Okla., Society of Exploration Geophysicists, 104 p.

Scott, J.H., 1973, Seismic-refraction modeling by computer: Geophysics, v. 38, no. 2, p. 271–284.

———1977a, SIPB—A seismic inverse modeling program for batch computer systems: U.S. Geological Survey Open-File Report 77-366, 40 p.

———1977b, SIPT—A seismic refraction inverse modeling program for timeshare terminal computer system: U.S. Geological Survey Open-File Report 77-365, 35 p.

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

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