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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

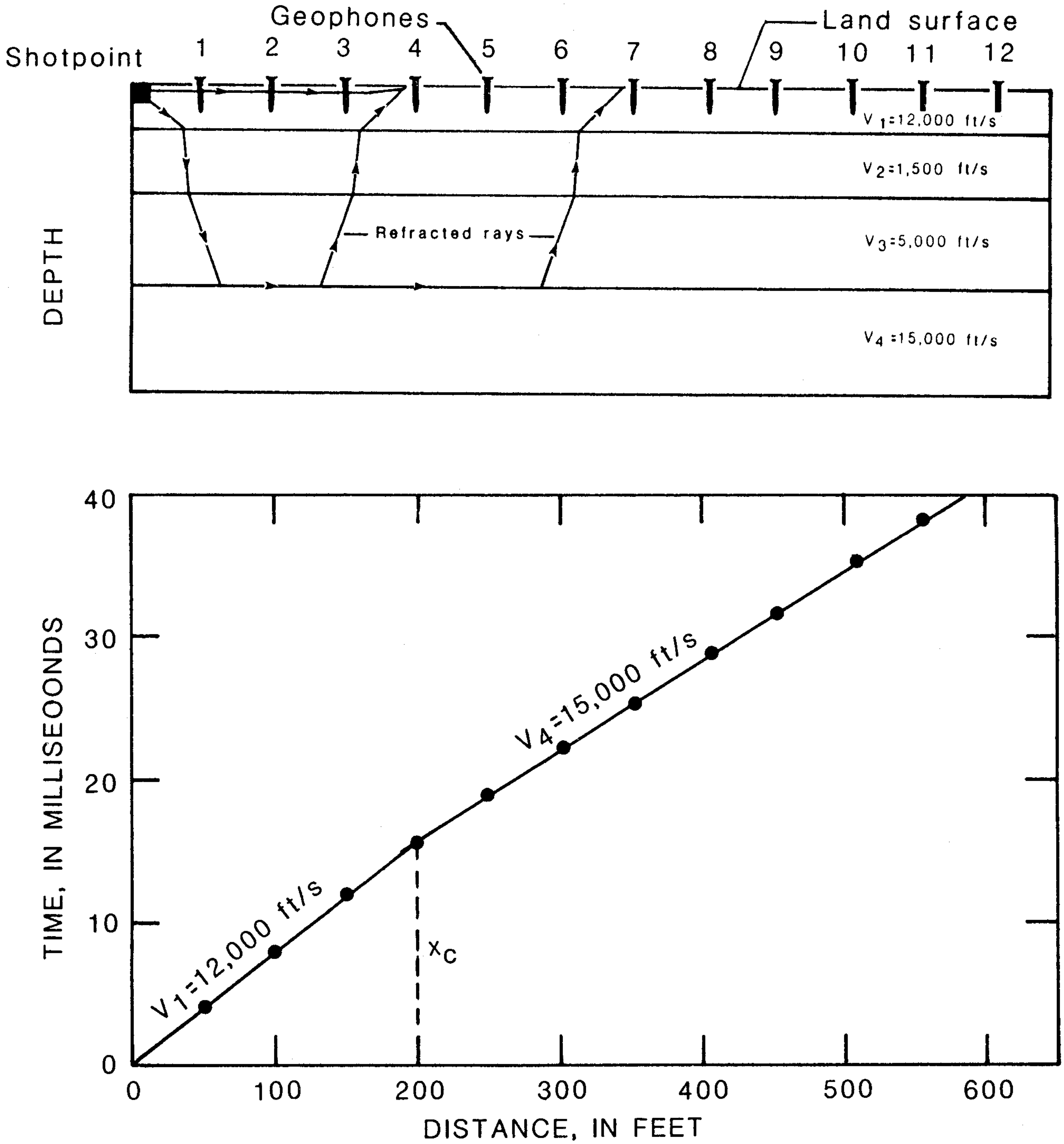

Figure 13.—Interpreted seismic section and time-distance plot for a four-layer model having frozen ground at the surface.

- 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references (Griffiths and King, 1965; Eaton and Watkins, 1967; Wallace, 1970; Zohdy and others, 1974) and the author's unpublished data indicate that the depth to a refractor can reasonably be determined to within 10 percent of the true depth.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

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[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.]

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[Changes in velocity of sound in saturated material shown to be independent of alluvial material present.]

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[Seismic-refraction techniques were evaluated for predicting the depth to rock with frozen ground at the surface.]

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[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.]

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[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.

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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.]

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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.]

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[A thorough handbook covering the theory and practical aspects of shallow refraction and reflection techniques.]

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Mota, L., 1954, Determination of dips and depths of geological layers by the seismic refraction method: Geophysics, v. 19, p. 242–254.

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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.]

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[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.]

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[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.
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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.
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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).

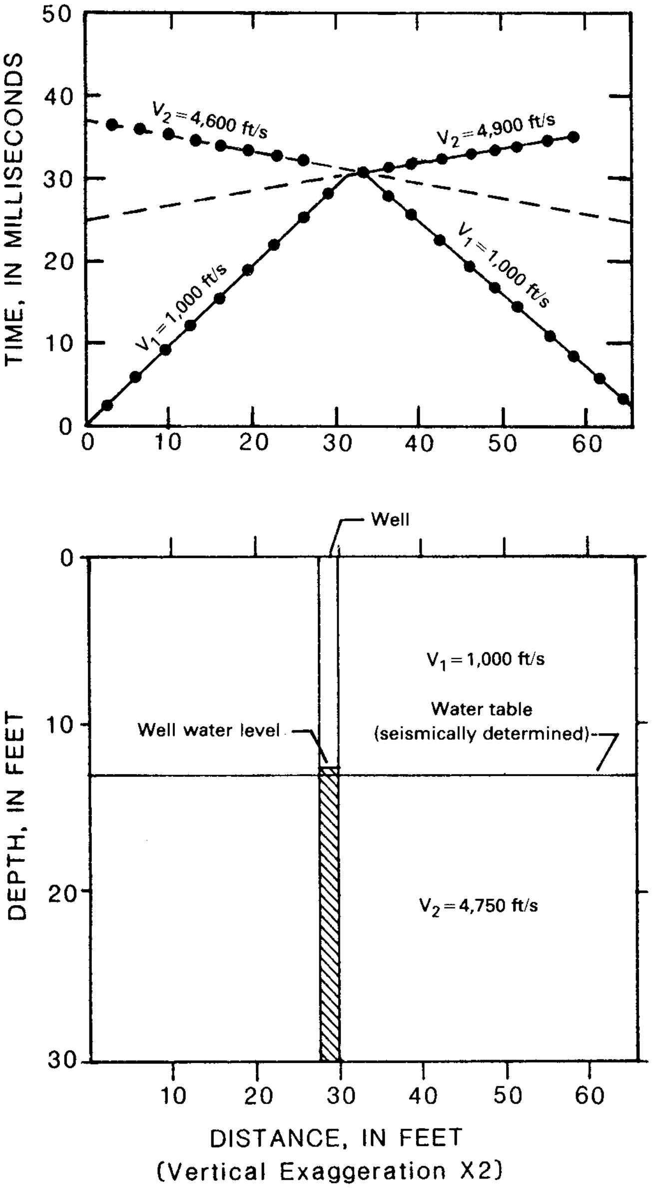


Figure 14.—Time-distance plot and interpreted seismic section from a ground-water study in Vertessomto, Hungary (modified from Galfi and Palos, 1970, p. 45).

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 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

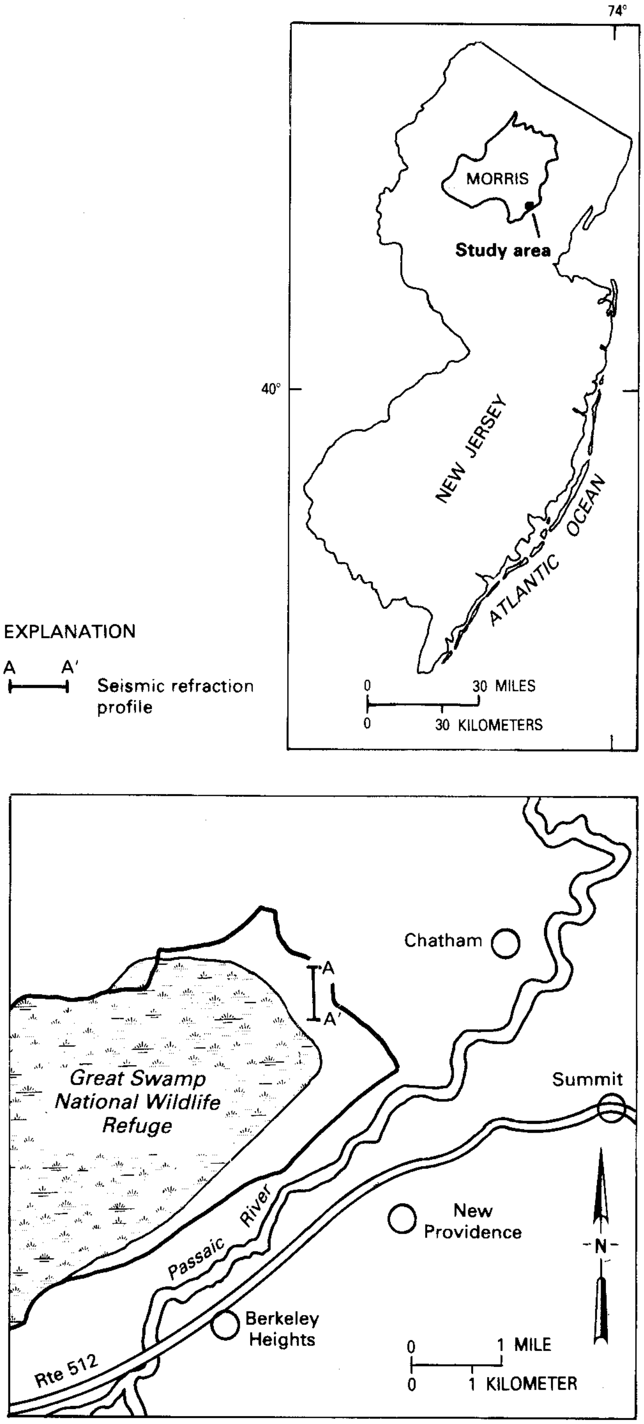


Figure 15.—Generalized location map of Great Swamp National Wildlife Refuge, N.J., and location of seismic-refraction profile A-A .

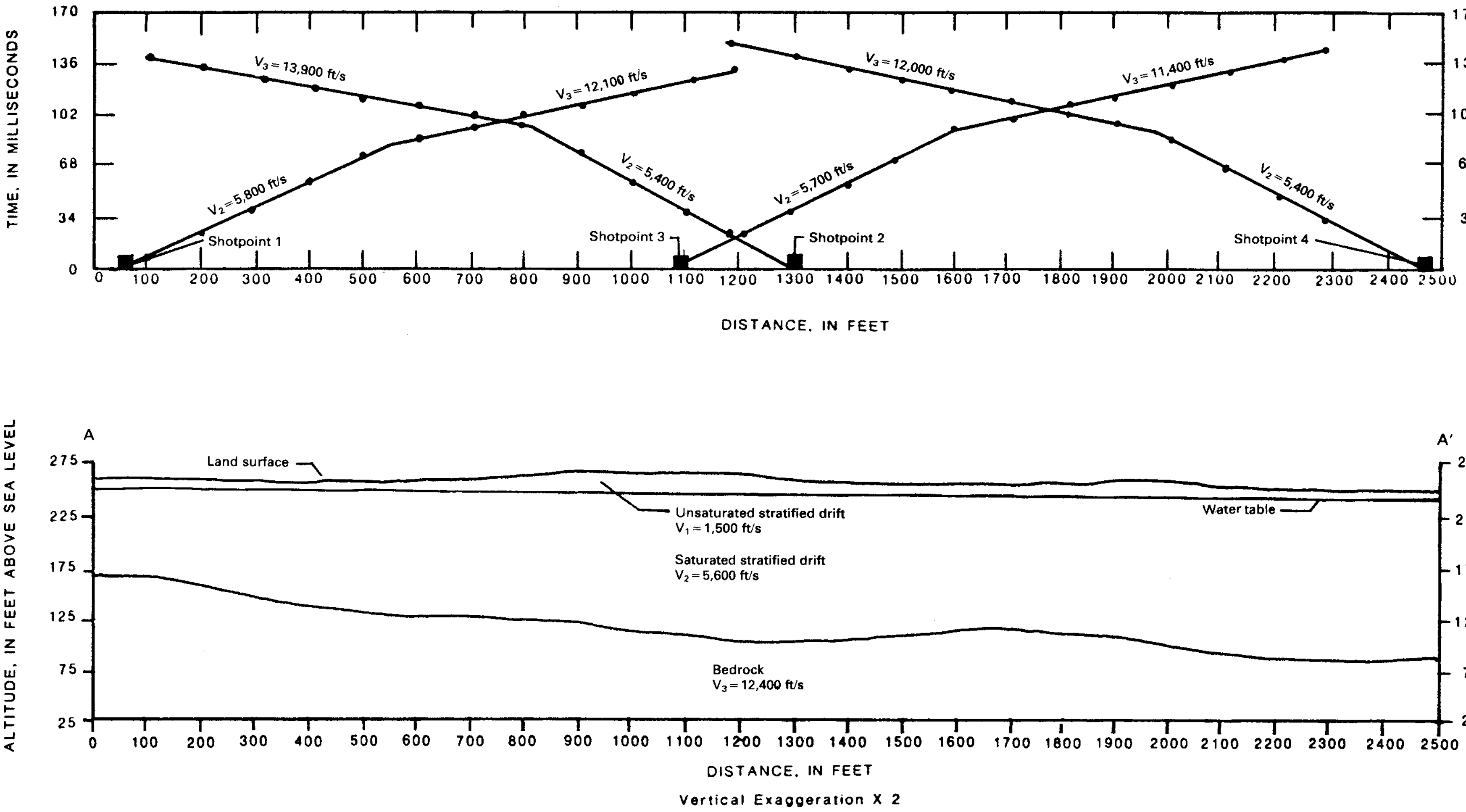


Figure 16.—Time-distance plot and interpreted seismic section near Great Swamp National Wildlife Refuge, Morristown, N.J.

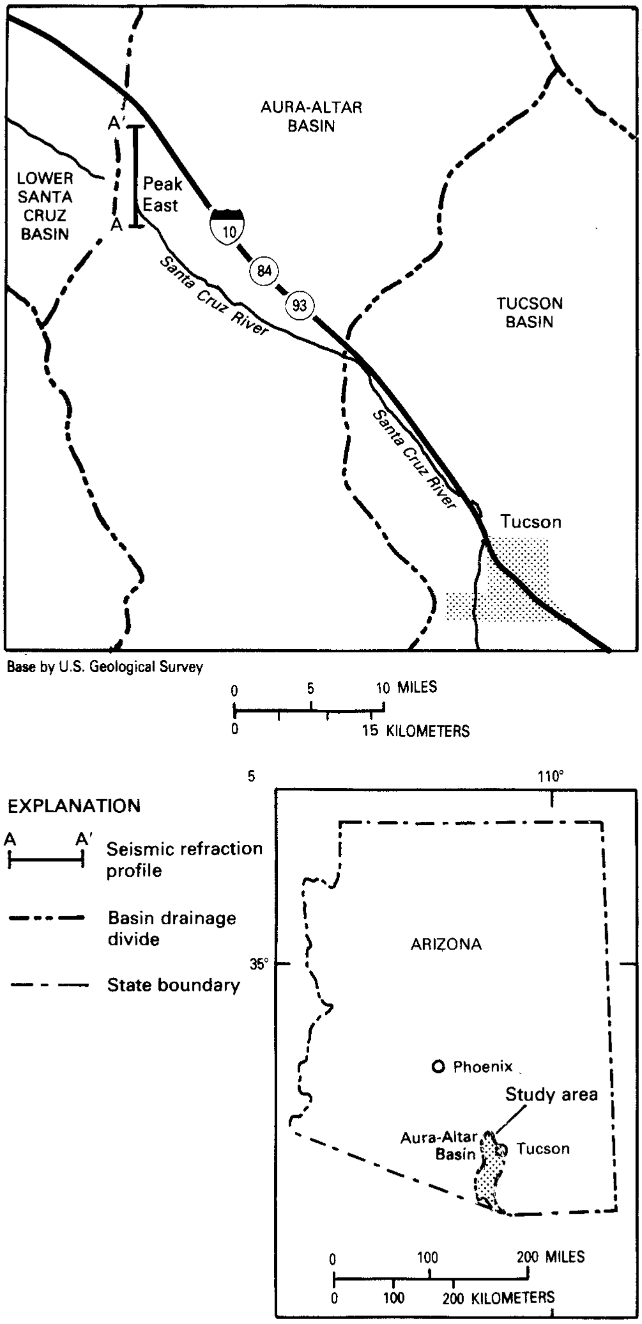


Figure 17.—Generalized location map of Aura-Altar basin, Arizona, and location of seismic-refraction profile A-A′.

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-

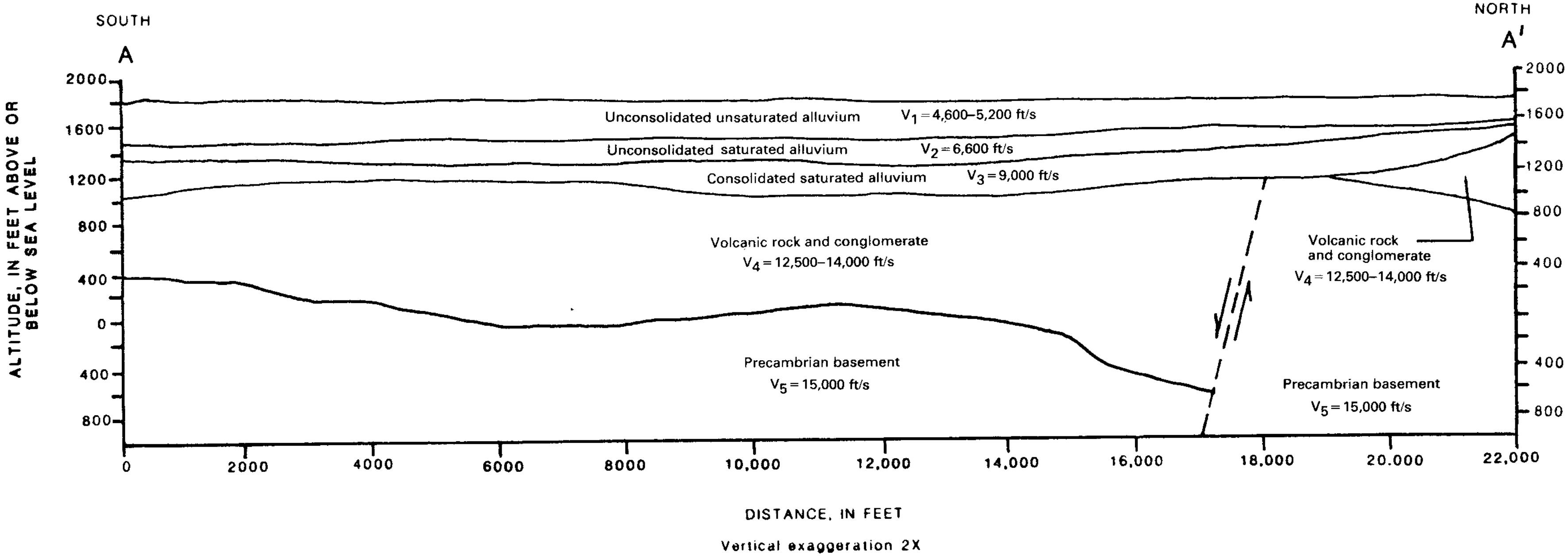


Figure 18.—Interpreted seismic section A-A′ in Aura-Altar basin, near Tucson, Ariz. (Patrick Tucci, written commun., 1981).

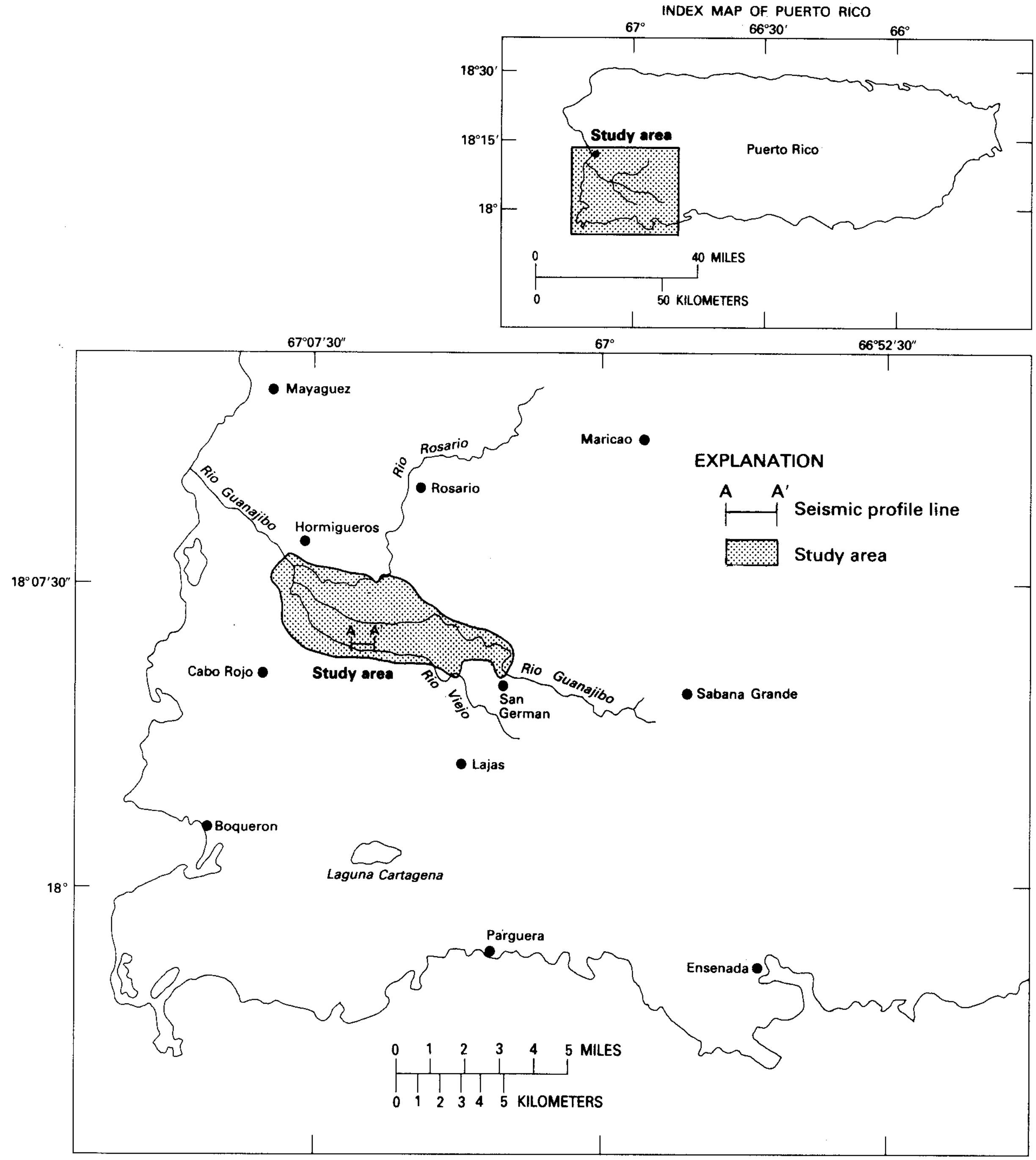


Figure 19.—Generalized location map of central Guanajibo Valley, Puerto Rico, and location of seismic-refraction profile A-A′ (from Colon-Dieppa and Quinones-Marquez, 1985).

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.

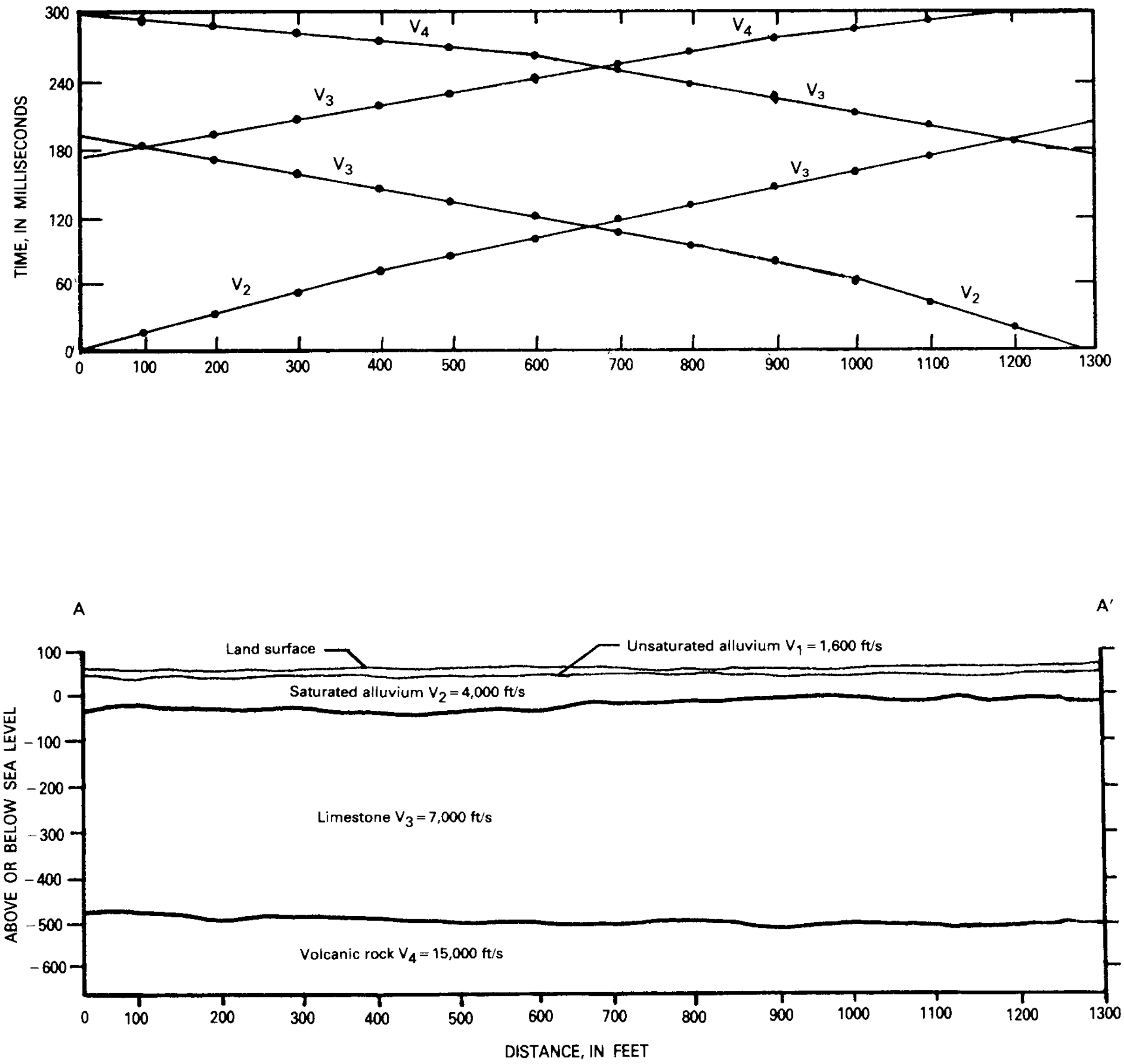
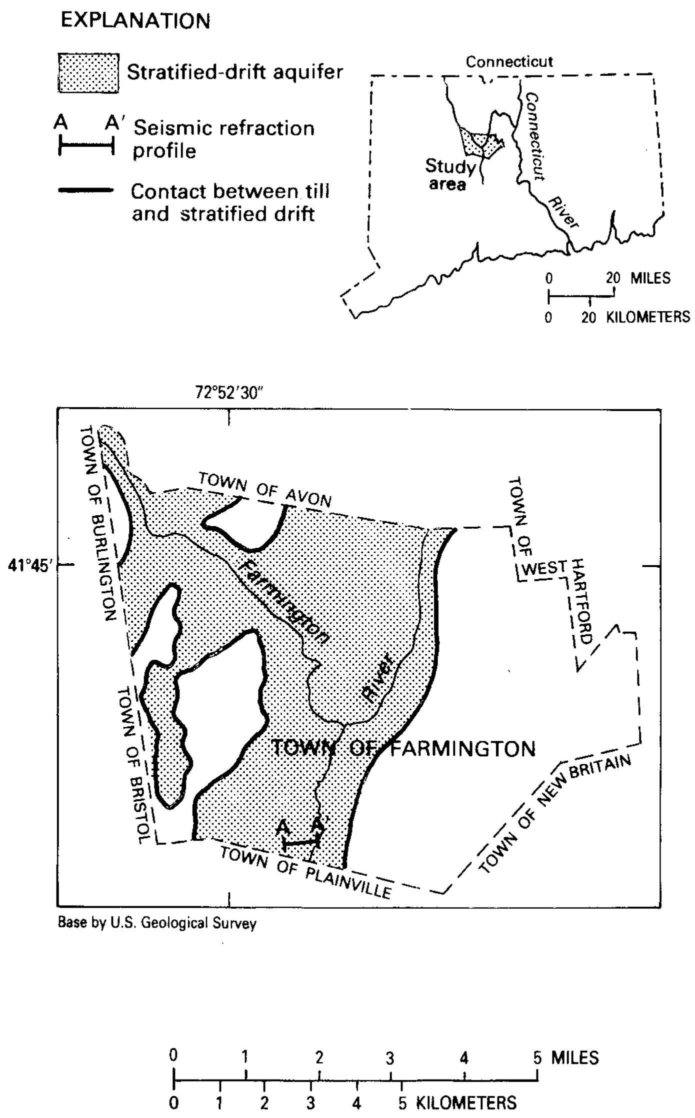


Figure 20.—Time-distance plot and interpreted seismic section at Guanajibo Valley, Puerto Rico.

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.



Base by U.S. Geological Survey

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

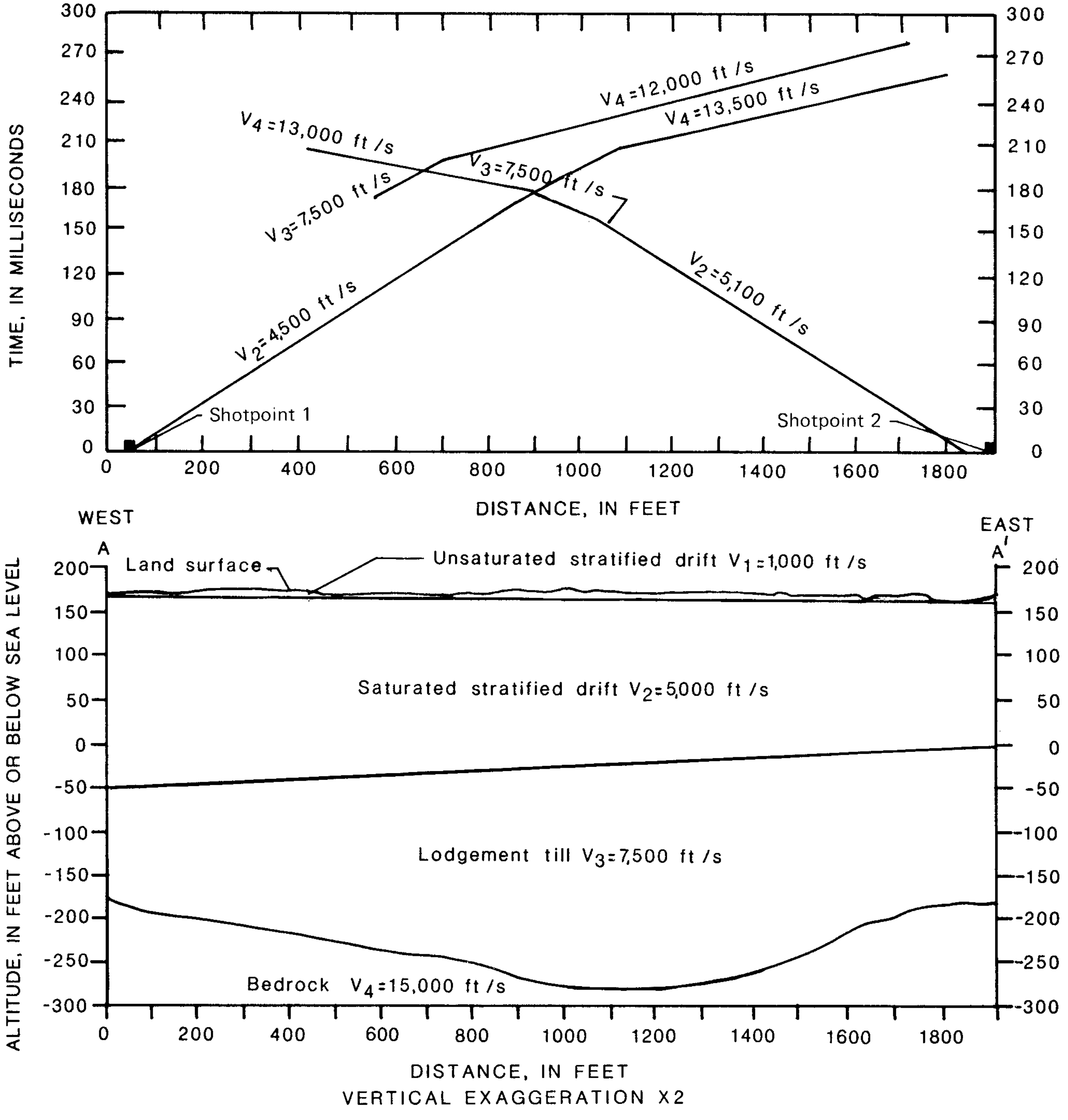
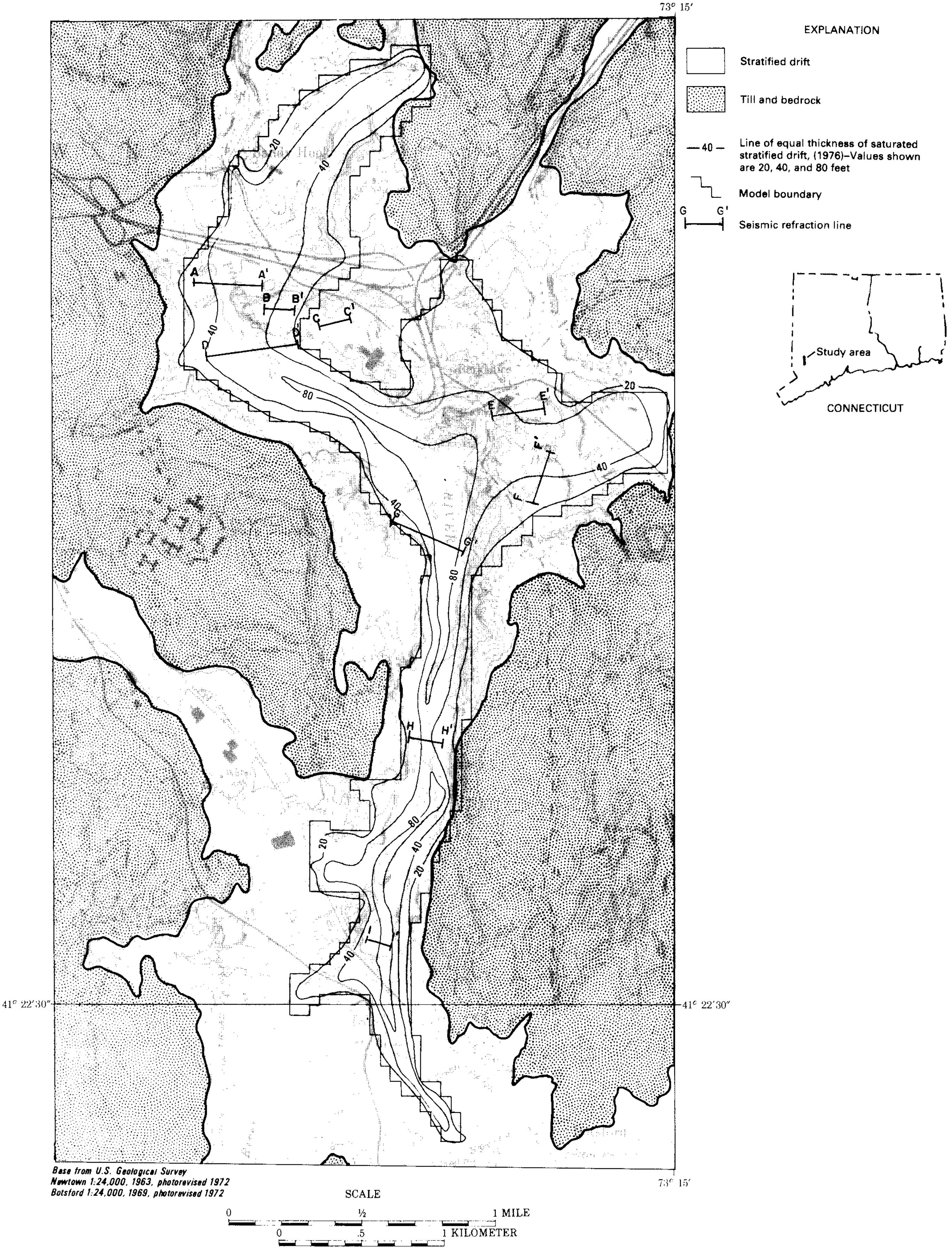


Figure 22.—Time-distance plot and interpreted seismic section near Farmington, Conn.

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;



Base from U.S. Geological Survey
Newtown 1:24,000, 1963, photorevised 1972
Botsford 1:24,000, 1969, photorevised 1972

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

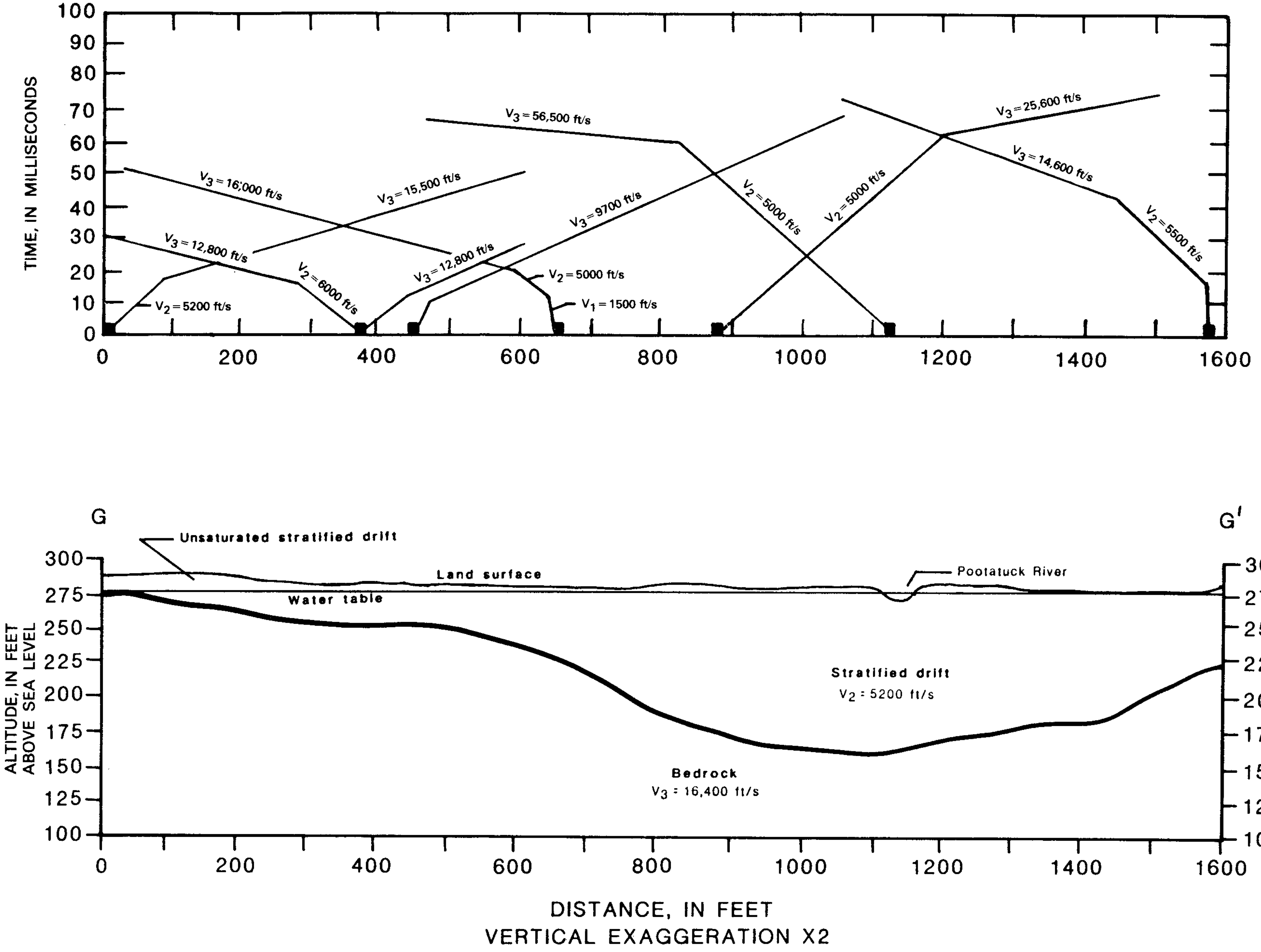


Figure 24.—Time-distance plot and interpreted seismic section of Pootatuck River valley, Newtown, Conn. (from Haeni, 1978).

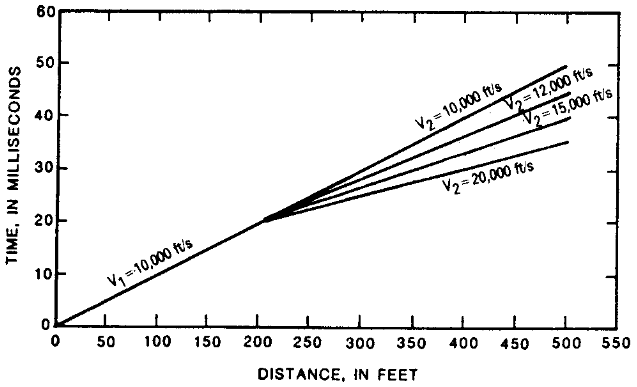


Figure 25.—Hypothetical time-distance plots resulting from different seismic velocities in the second layer.

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

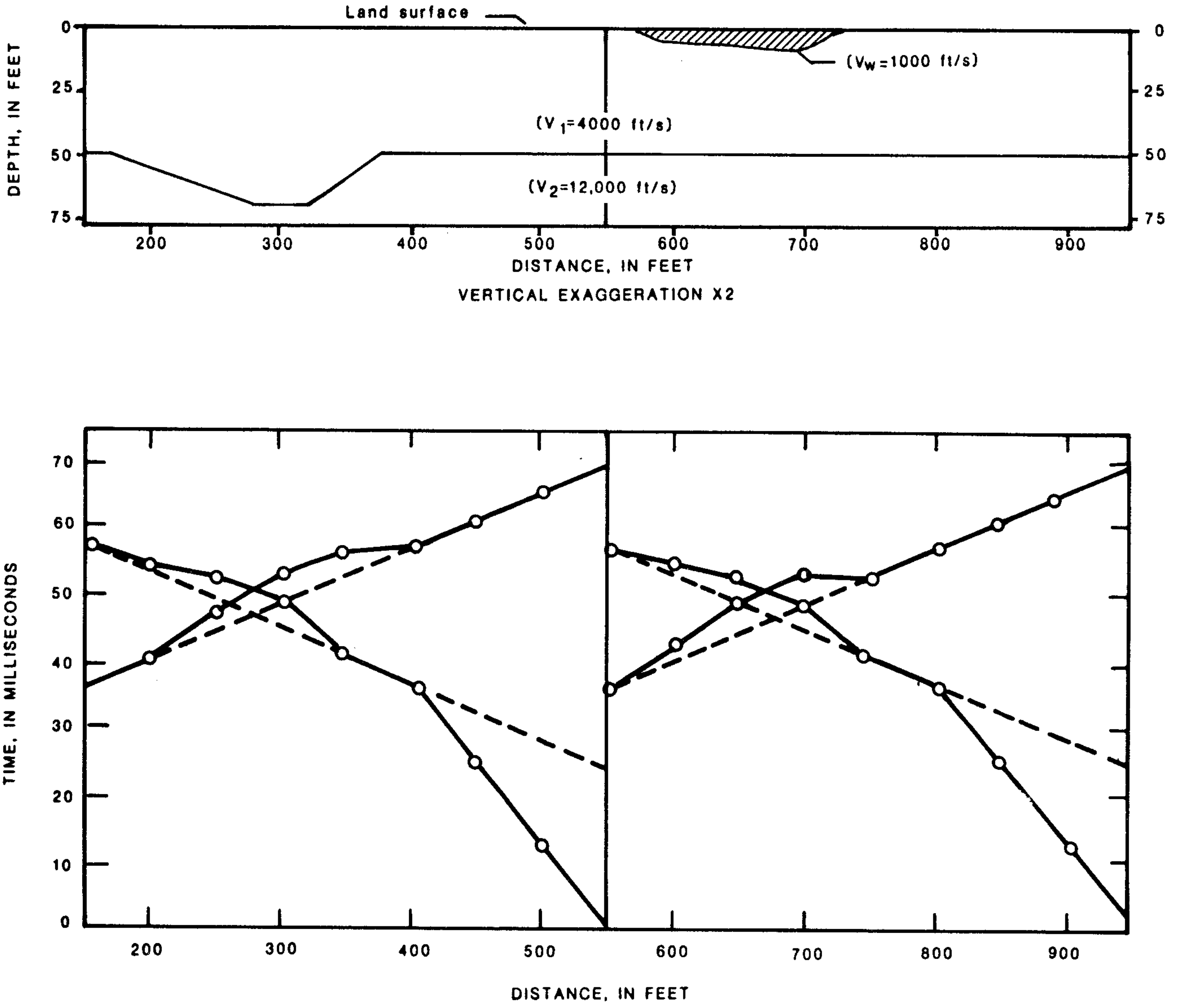


Figure 26.—Seismic section with shallow seismic-velocity discontinuities and relief on a refracting surface, and the resulting time-distance plot, Monument Valley area of Arizona and Utah (modified from Pakiser and Black, 1957).

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.

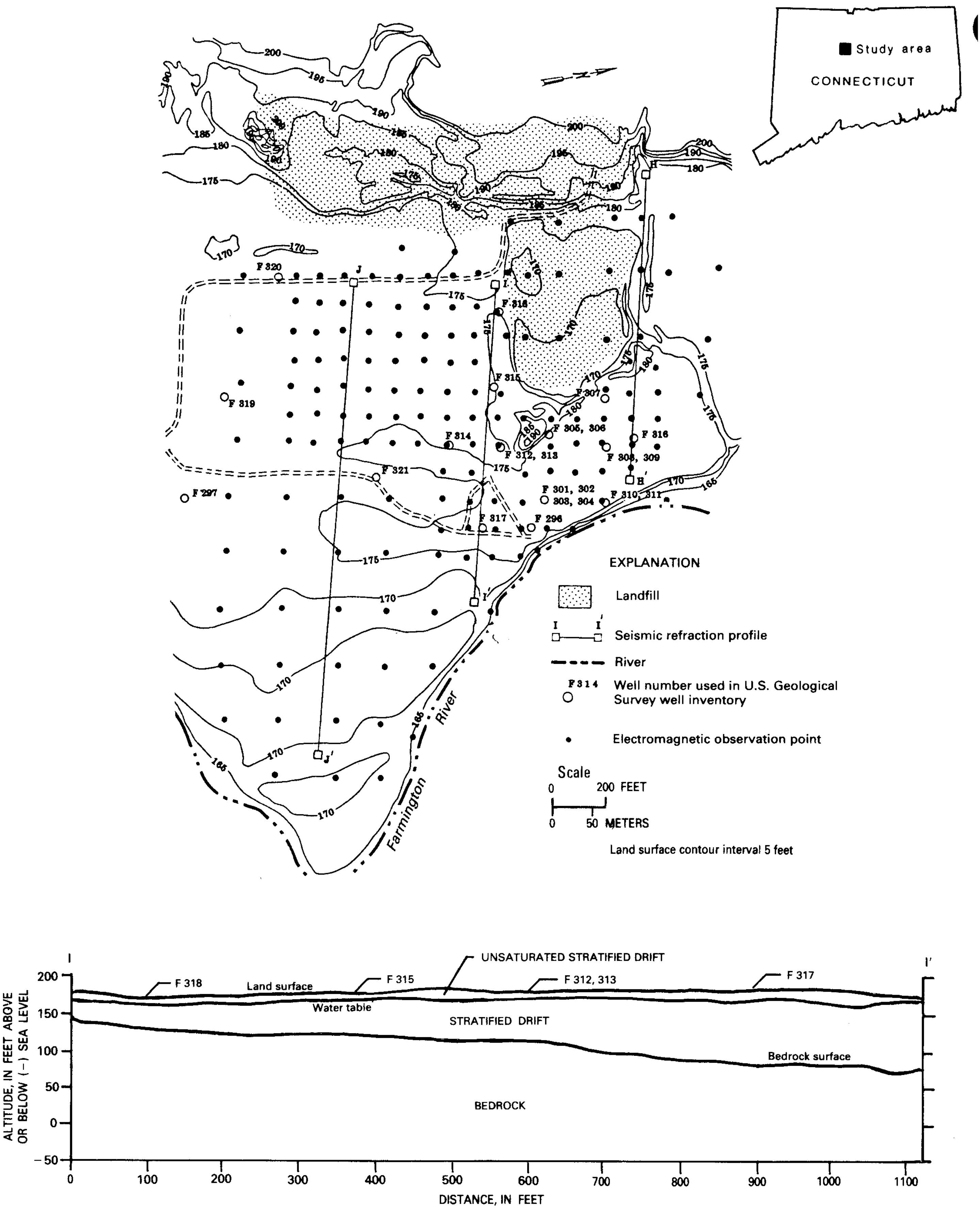


Figure 27.—Site diagram and seismic section of a sanitary landfill in Farmington, Conn. (from Grady and Haeni, 1984).

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.

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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)	Compressional velocity (ft/s)
Town of Cheshire					
CS 23 th	Sandstone, arkosic, white to buff, medium to very coarse grained, angular to subangular grains, poorly sorted and well cemented.	2.57	2.66	3.3	12,320
CS 27 th	Sandstone, arkosic, red and siltstone, very fine grained, and micaceous.	2.64	2.85	7.4	-
Town of North Branford					
NBR 7 th	Conglomerate, black and dark gray-green, very poorly sorted, with rounded to angular light-green volcanic fragments in a moderate to well-cemented matrix.	2.49	2.80	11.1	11,260
NBR 11 th	Volcanic agglomerate, green-gray; fragments of angular basalt; clasts of quartz in a fine-grained, weathered, green-white calcareous matrix.	2.51	2.77	9.3	13,080
NBR 17 th	Conglomerate, arkosic, gray-green (mostly very coarse sand to very fine gravel and some fine to medium pebble gravel).	2.48	2.74	9.5	13,640
Town of North Haven					
NHV 49 th	Sandstone, arkosic, red, medium to very coarse grained.	2.57	2.74	6.2	-
Town of Plainville					
PV 49 th	Siltstone, red-brown, very fine grained, dirty and mottled with gray-green spots.	2.64	2.72	2.9	13,900
PV 52 th	Sandstone, red, very fine to fine grained.	2.41	2.69	10.4	12,220
Town of Southington					
S 107 th	Sandstone, red, very fine to medium grained, with micaceous silt.	2.55	2.69	5.2	13,710
S 111 th	Sandstone, red, very fine grained, and siltstone, massive, micaceous and well-cemented.	2.63	2.72	3.3	13,790
S 115 th	Sandstone, red, very fine to fine grained.	2.62	2.73	4.0	13,790
S 116 th	Conglomerate, light-red to buff.	2.62	2.73	4.0	11,180
S 120 th	Sandstone, arkosic, tan to buff, and poorly sorted.	2.49	2.69	7.4	12,620
S 147 th	Sandstone, red, very fine to fine grained.	2.36	2.67	11.6	11,050
Town of Wallingford					
WLD 70 th	Sandstone, purple-red and buff-pink, coarse-grained and poorly sorted; with angular to subangular pink feldspars and a white bleached zone.	2.60	2.73	4.8	12,470

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[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.

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