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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

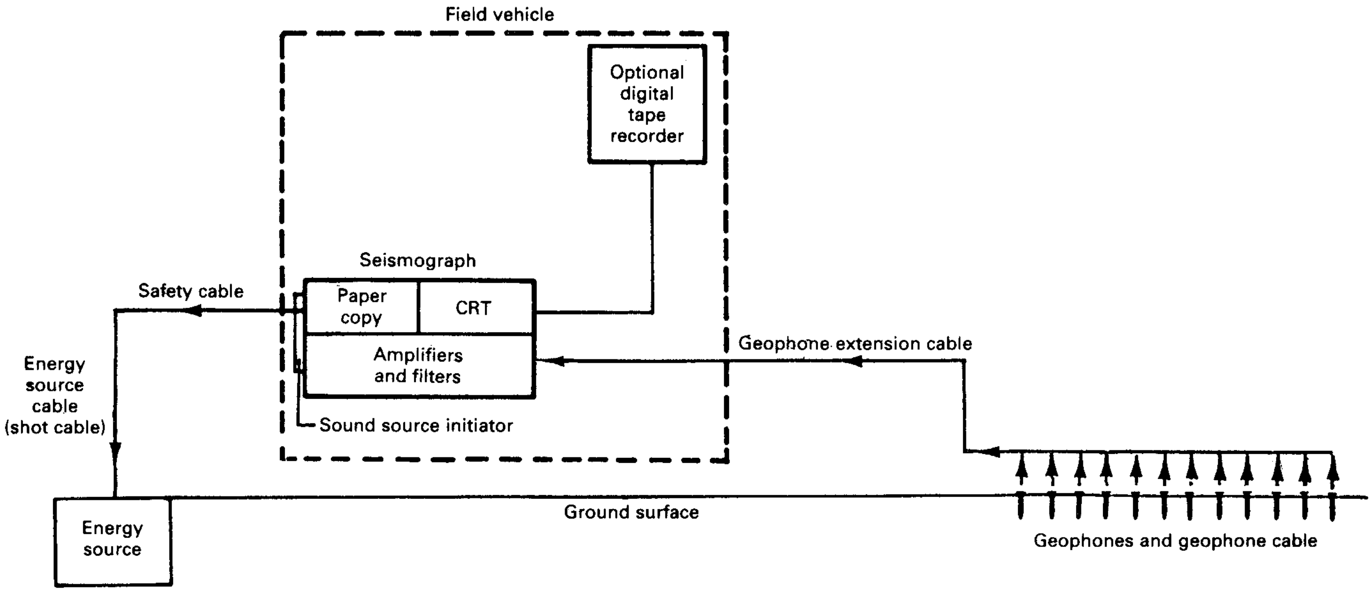


Figure 28.—Schematic diagram of a typical seismic-refraction system.

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
- Geophones
- Geophone cables and geophone extension cables
- Energy source and associated equipment
- Shot cables
- Portable radios
- Field vehicles
- 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

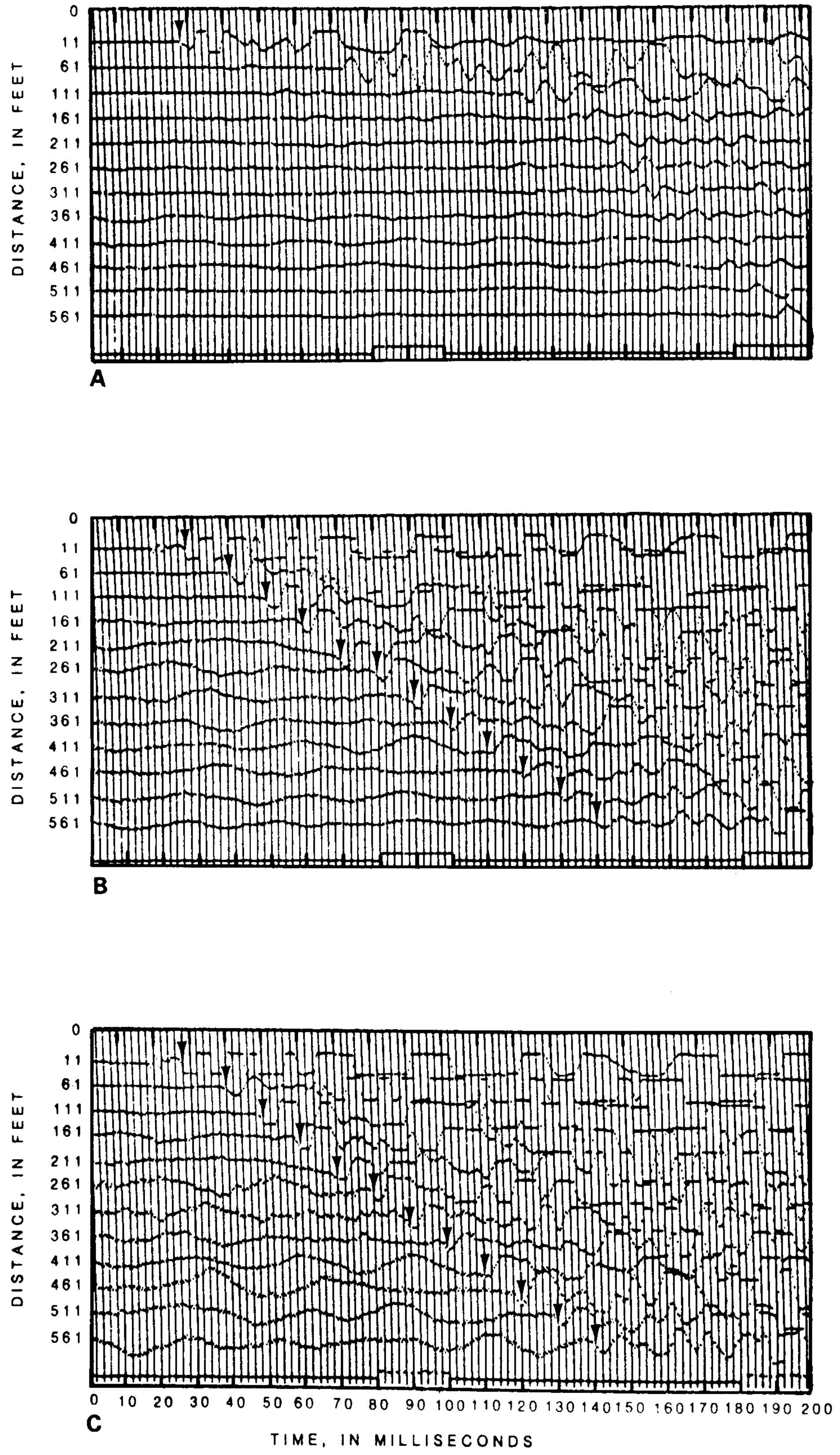


Figure 29.—Seismograms showing improvement in first breaks by stacking successive hammer impacts: A, 1 impact; B, 5 impacts; C, 10 impacts.

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

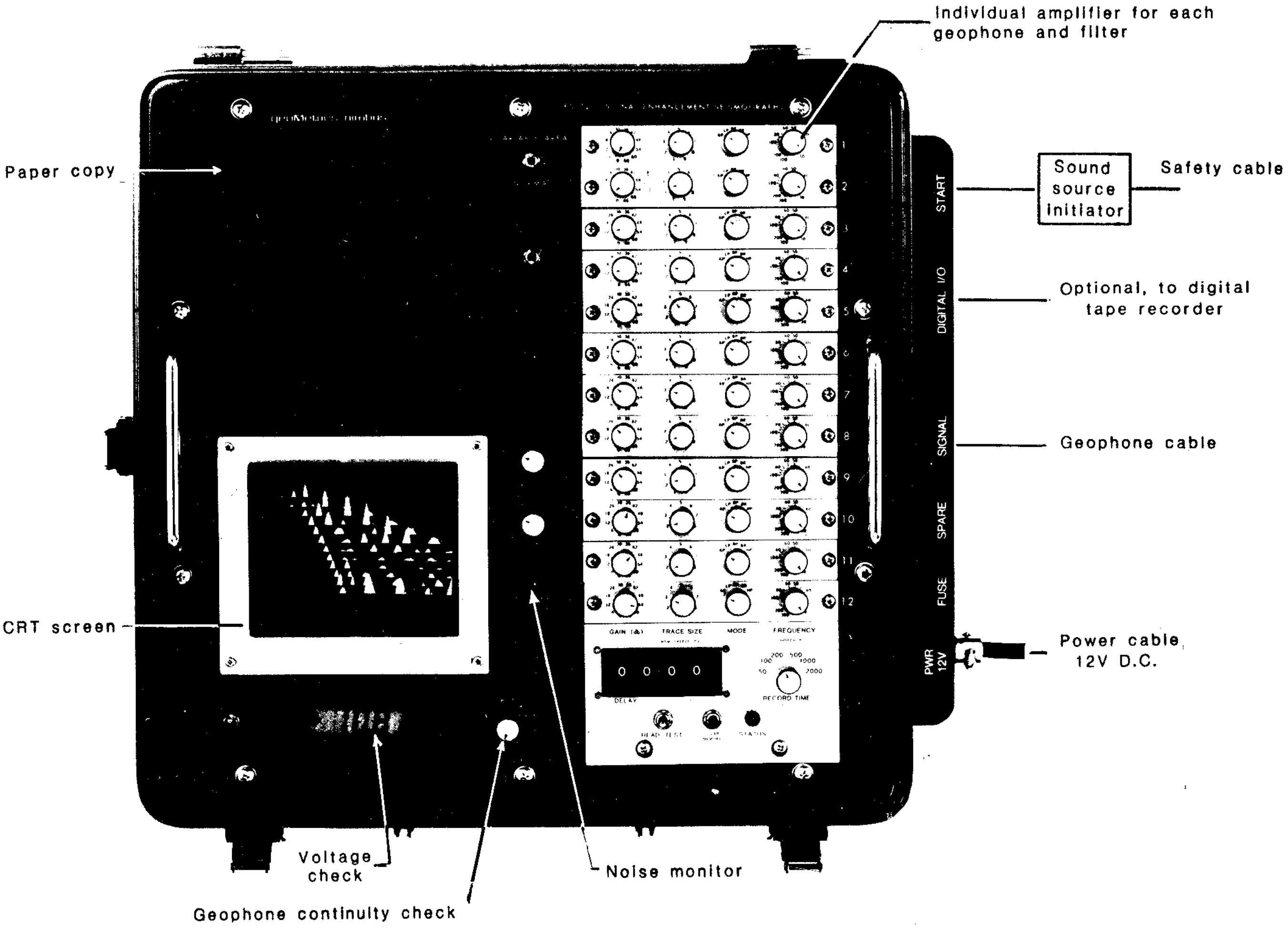
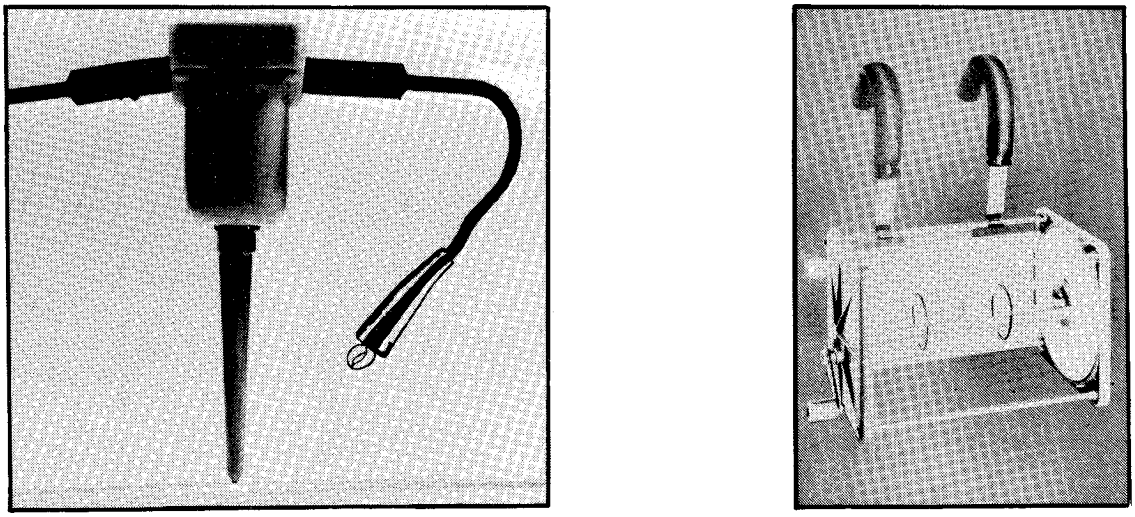


Figure 30.—Typical 12-channel seismograph.

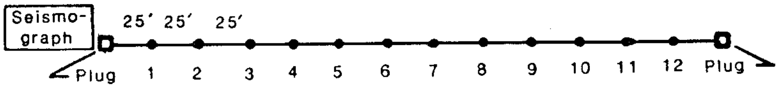


Geophone

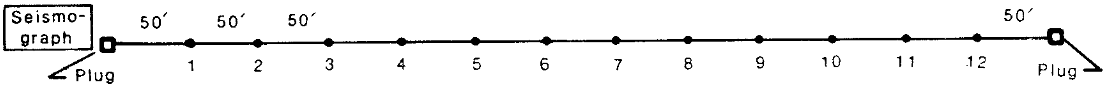
Breast reel

GEOPHONE CABLES

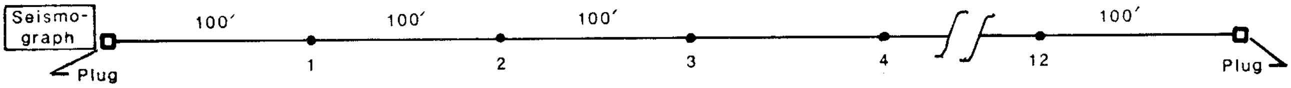
Cable with 25 feet between geophone takeouts. Total length 325 feet



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

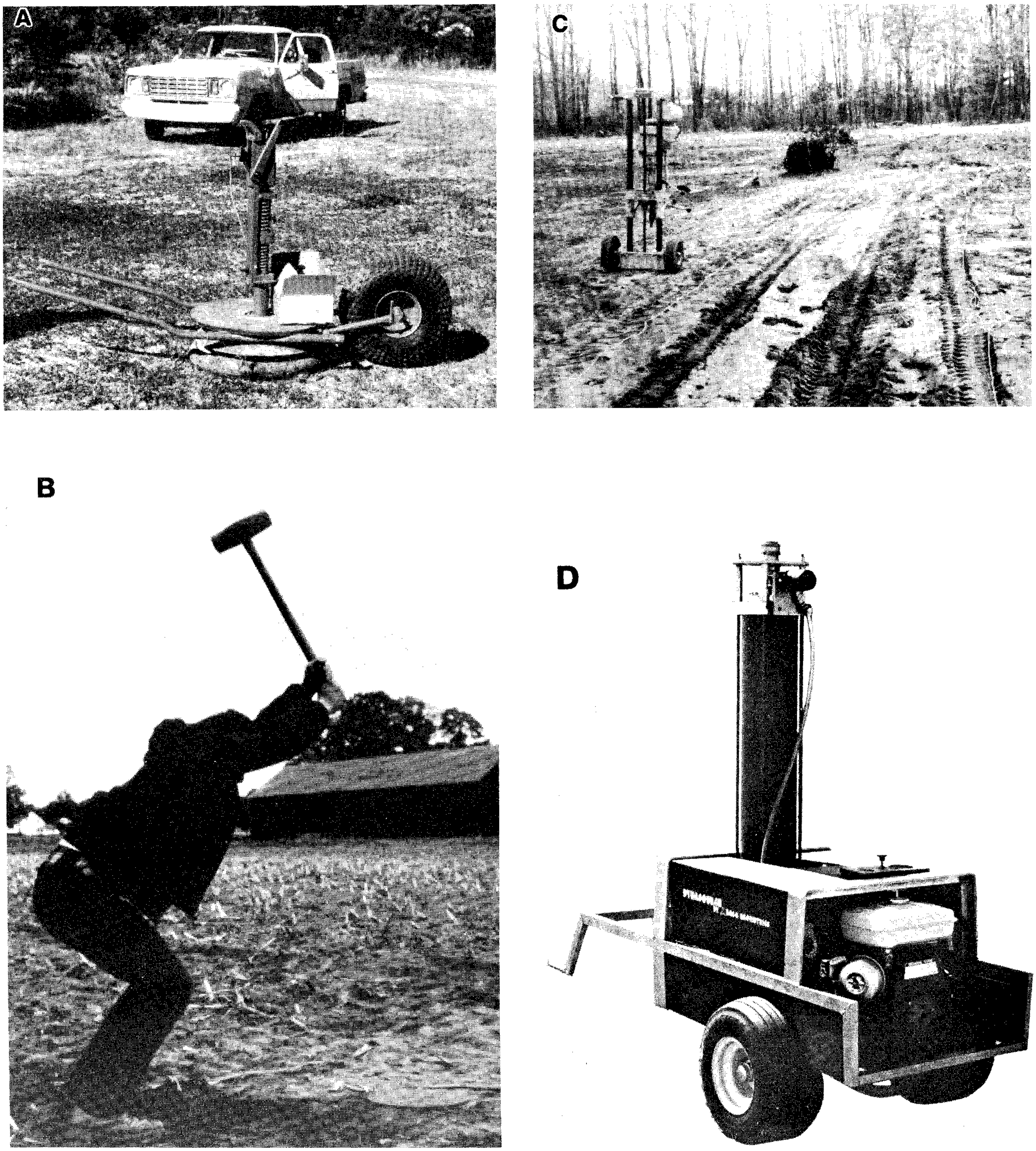


Figure 32.—Commonly used seismic energy sources: A, Shotgun; B, Sledge hammer; C, Explosives; D, Weight drop.

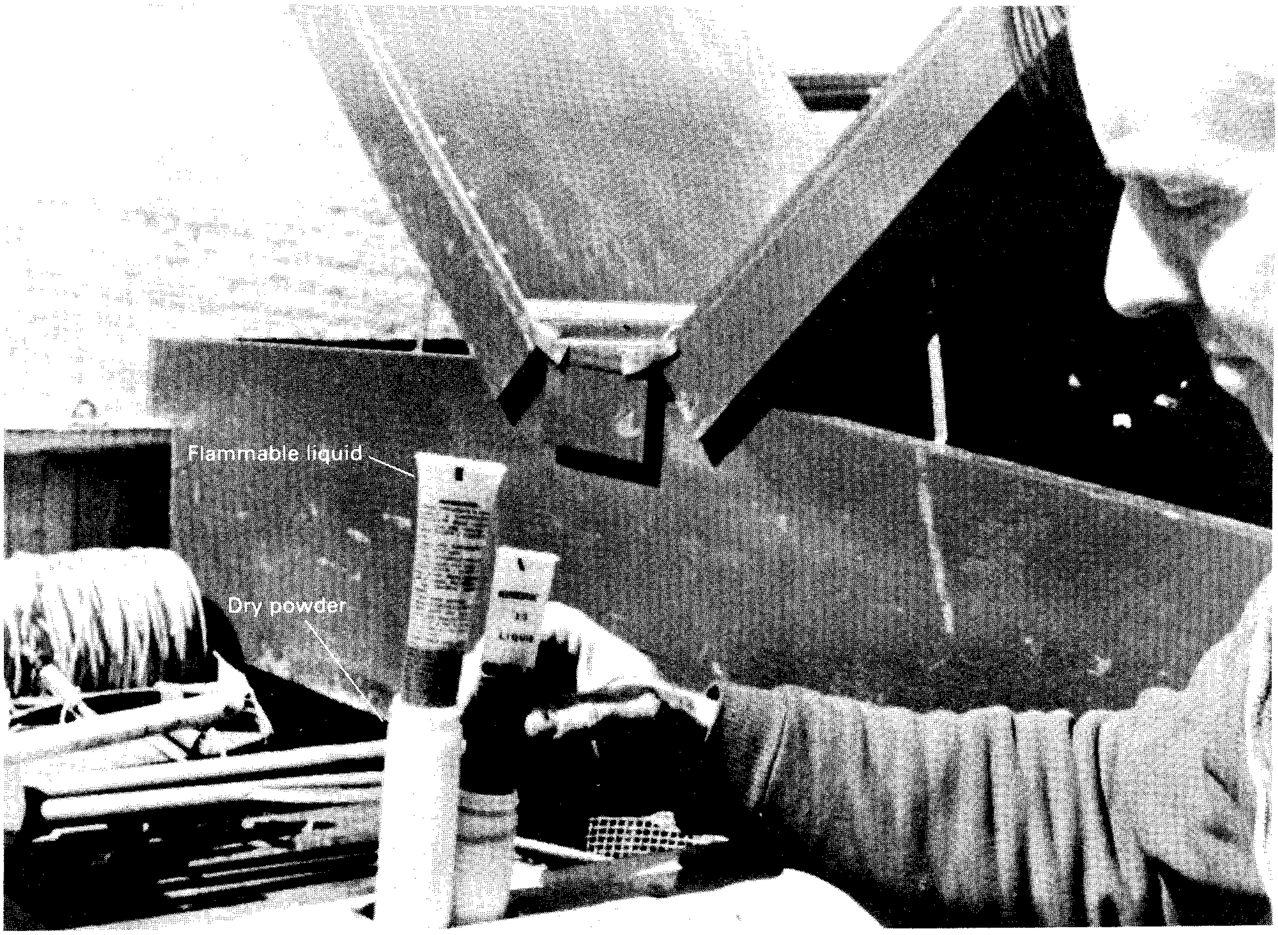


Figure 33.—Mixing two-component explosives in the field.

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.

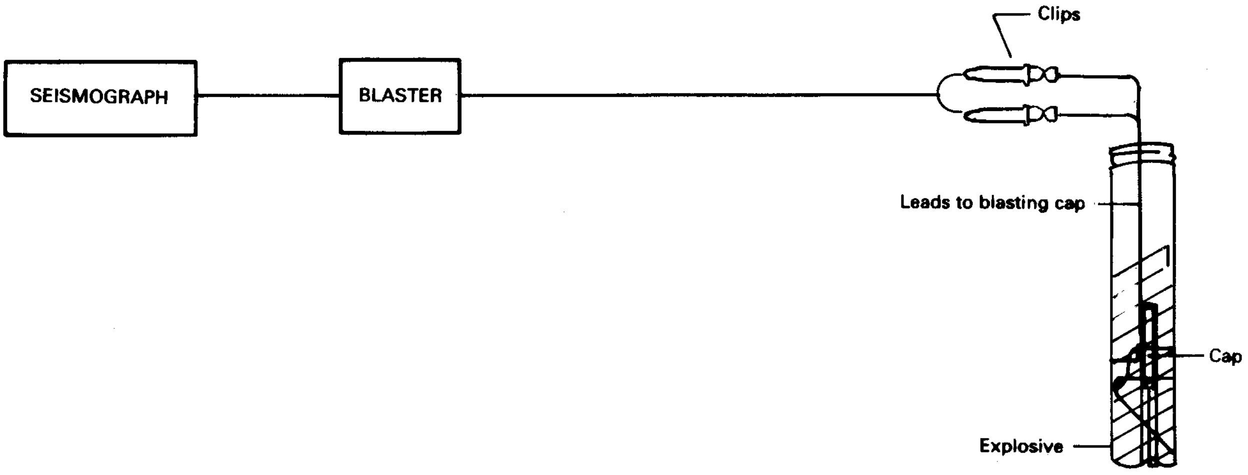
Weight-drop (fig. 32D) and shotgun (fig. 32A) systems provide intermediate energy levels. Both these sources have approximately two to five times the energy of a sledge hammer but significantly less energy than explosives.

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.

ORIGINAL FACTORY SETUP



OPTIONAL SETUP WITH SAFETY CABLE

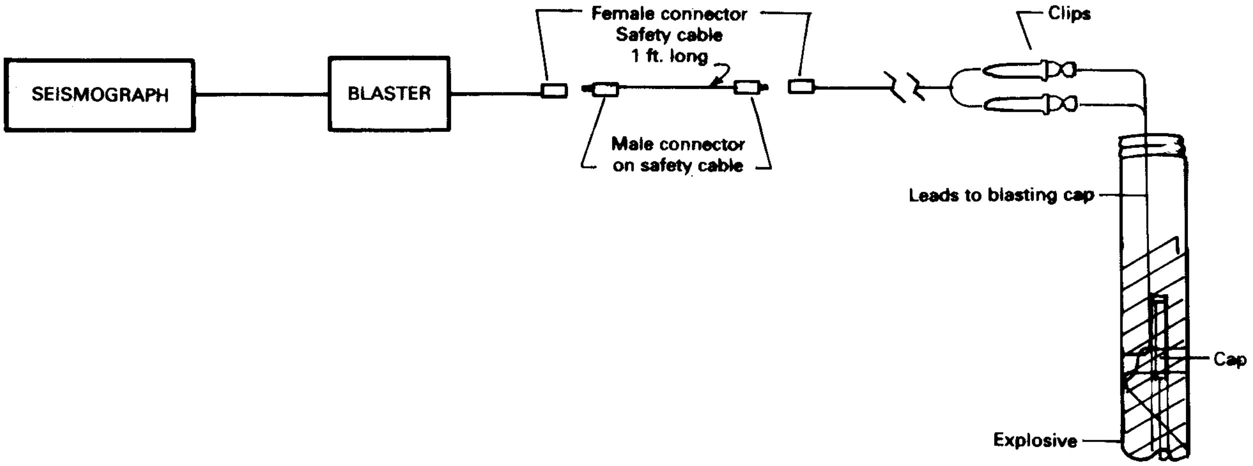


Figure 34.—Use of safety wire in explosive-firing circuit.

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

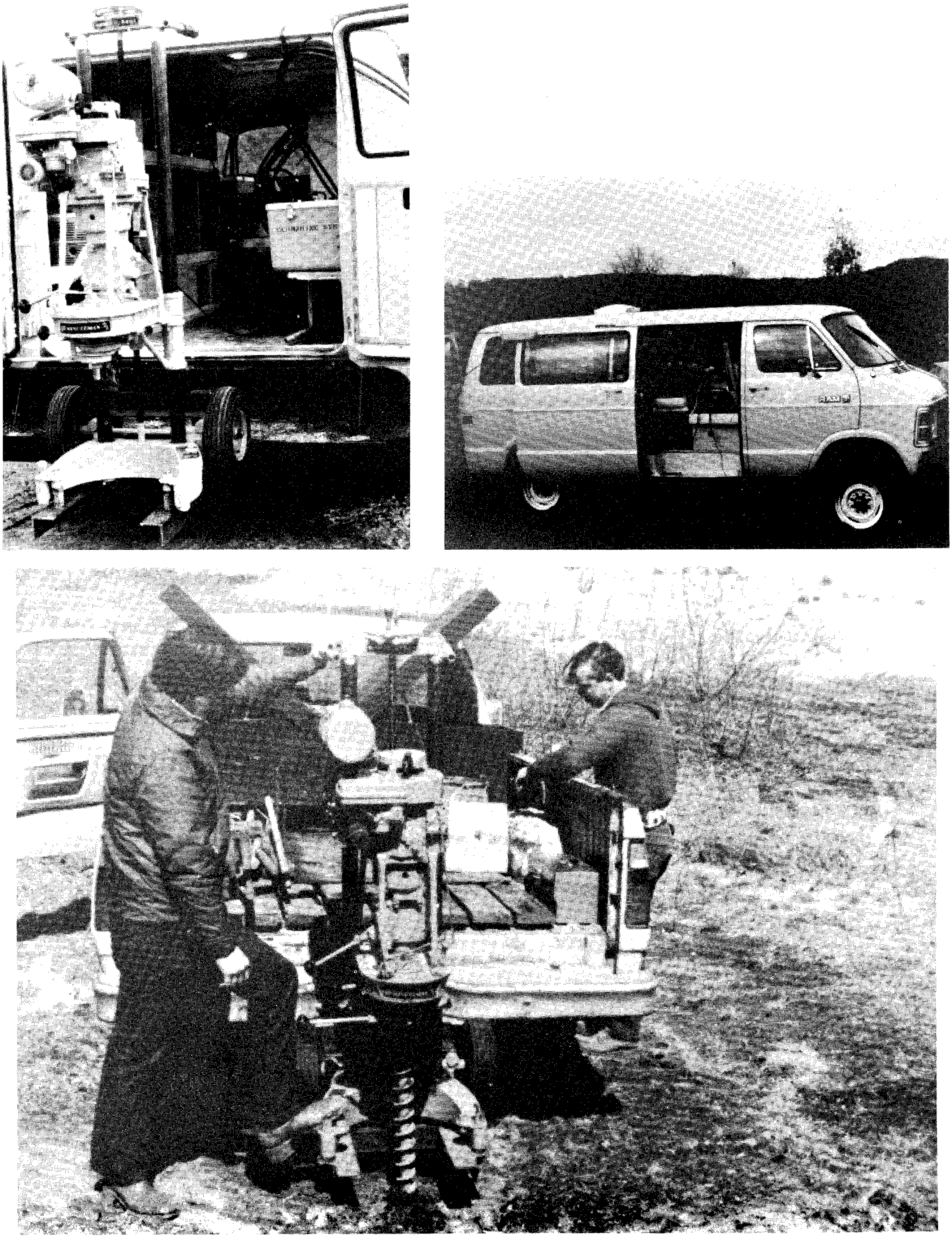


Figure 35.—Van and pickup truck used for seismic-refraction fieldwork.

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

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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.

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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

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

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

and

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

Now for the two-layer case,

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

and for the three-layer case,

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

$$z_2=x_{c2}\frac{B}{2}-z_1C, \qquad (28)$$

and

$$z_3=z_1+z_2 . \qquad (29)$$

Rearranging the above for the two-layer case,

$$x_c=\frac{2z}{A}, \qquad (30)$$

and for the three-layer case,

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

and

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

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.

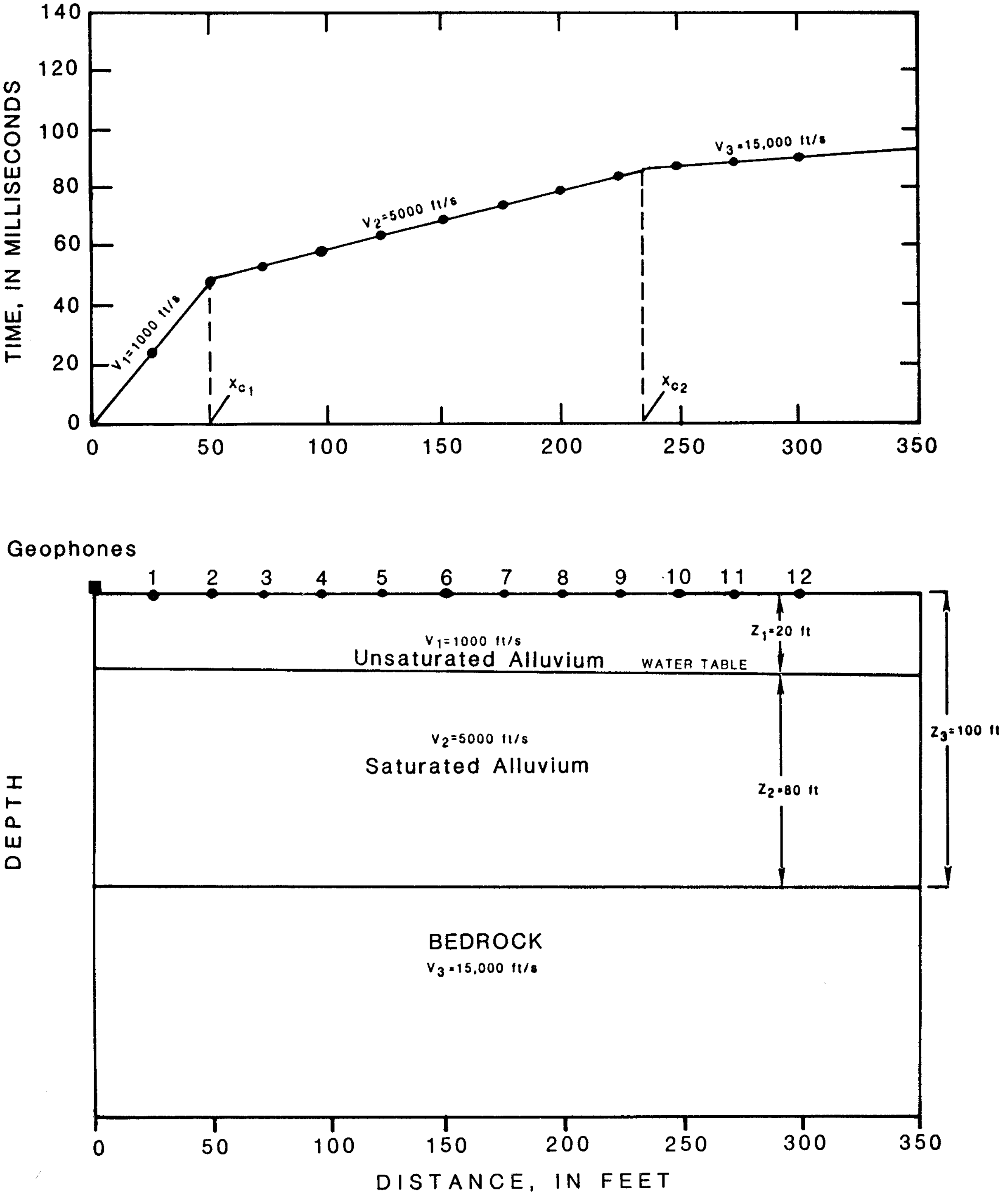


Figure 36.—Time-distance plot and interpreted seismic section for a three-layer problem.

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.

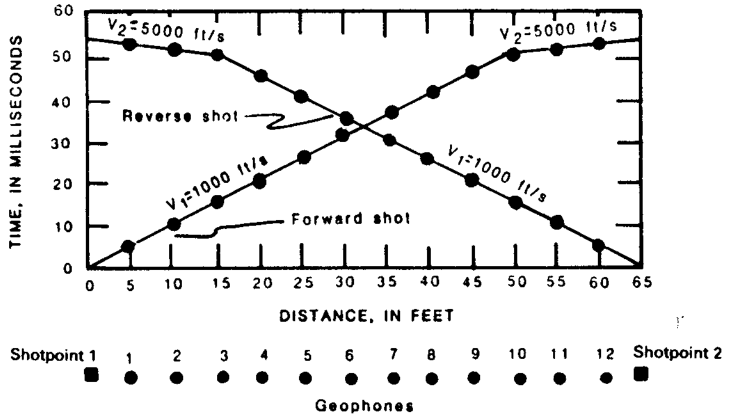
Quantity or quality of field data

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.

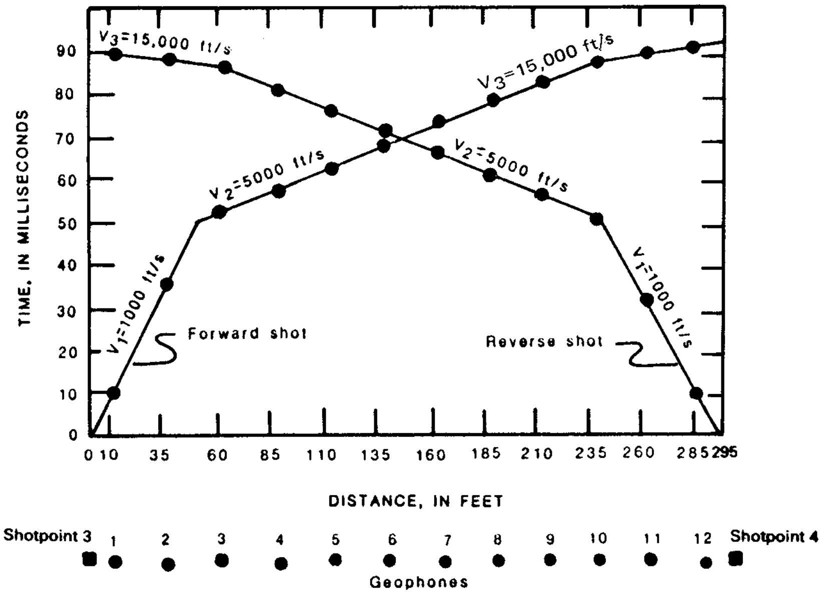
One pattern of shotpoints and geophones that can be used effectively in field production work and the resulting selected raypaths for the first three shotpoints are shown in figure 38. The resulting time-distance plot and interpreted cross section are shown in figure 39. This single arrangement of geophones 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.

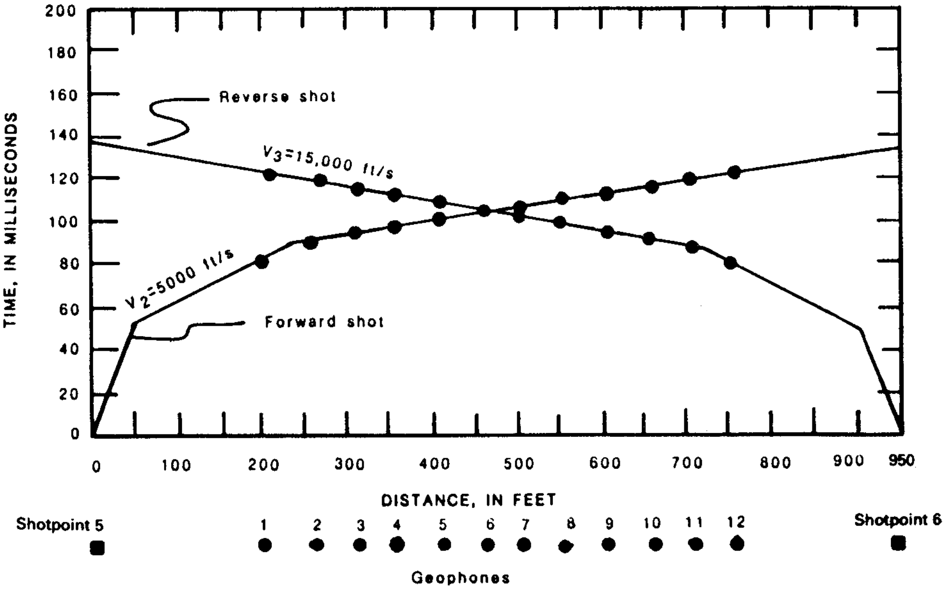
In figure 39, the velocity of sound in layer 1 is calculated by determining the inverse slope of a line formed by data from two geophones from shotpoints 2, 3, and 4. Likewise, the velocity of sound in layer 2 is calculated by using seven points from shots 2 and 4 and eight points from shot 3. The velocity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

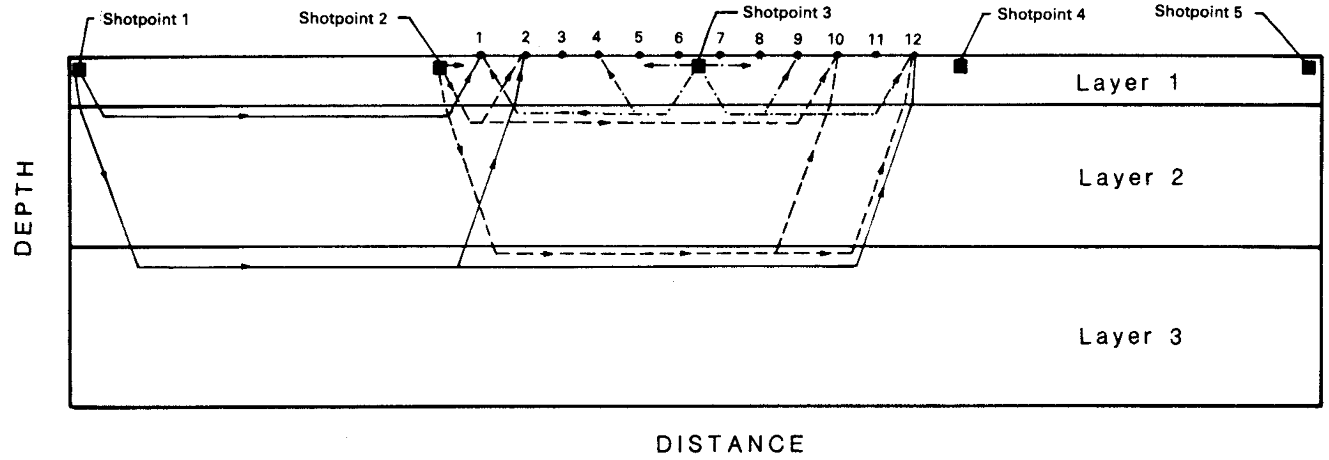


Figure 38.—Field setup of shotpoints and geophones for delineation of multiple-refracting horizons. Only selected raypaths for shotpoints 1, 2, and 3 are shown. The raypaths for shotpoints 4 and 5 are the mirror image (with respect to shotpoint 3) of the raypaths for shotpoints 2 and 1, respectively.

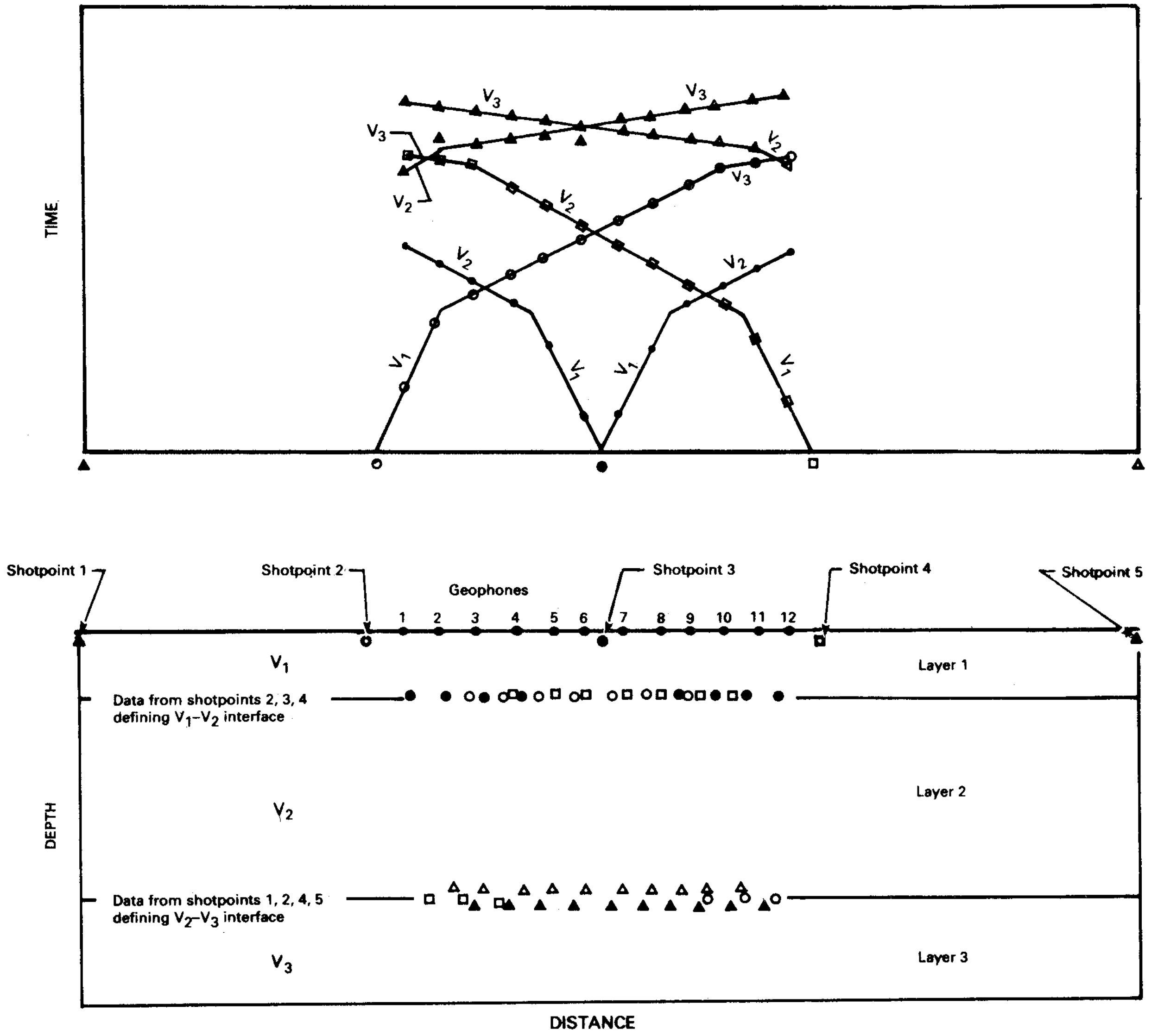


Figure 39.—Time-distance plot and interpreted seismic section resulting from a single geophone spread with five shotpoints.

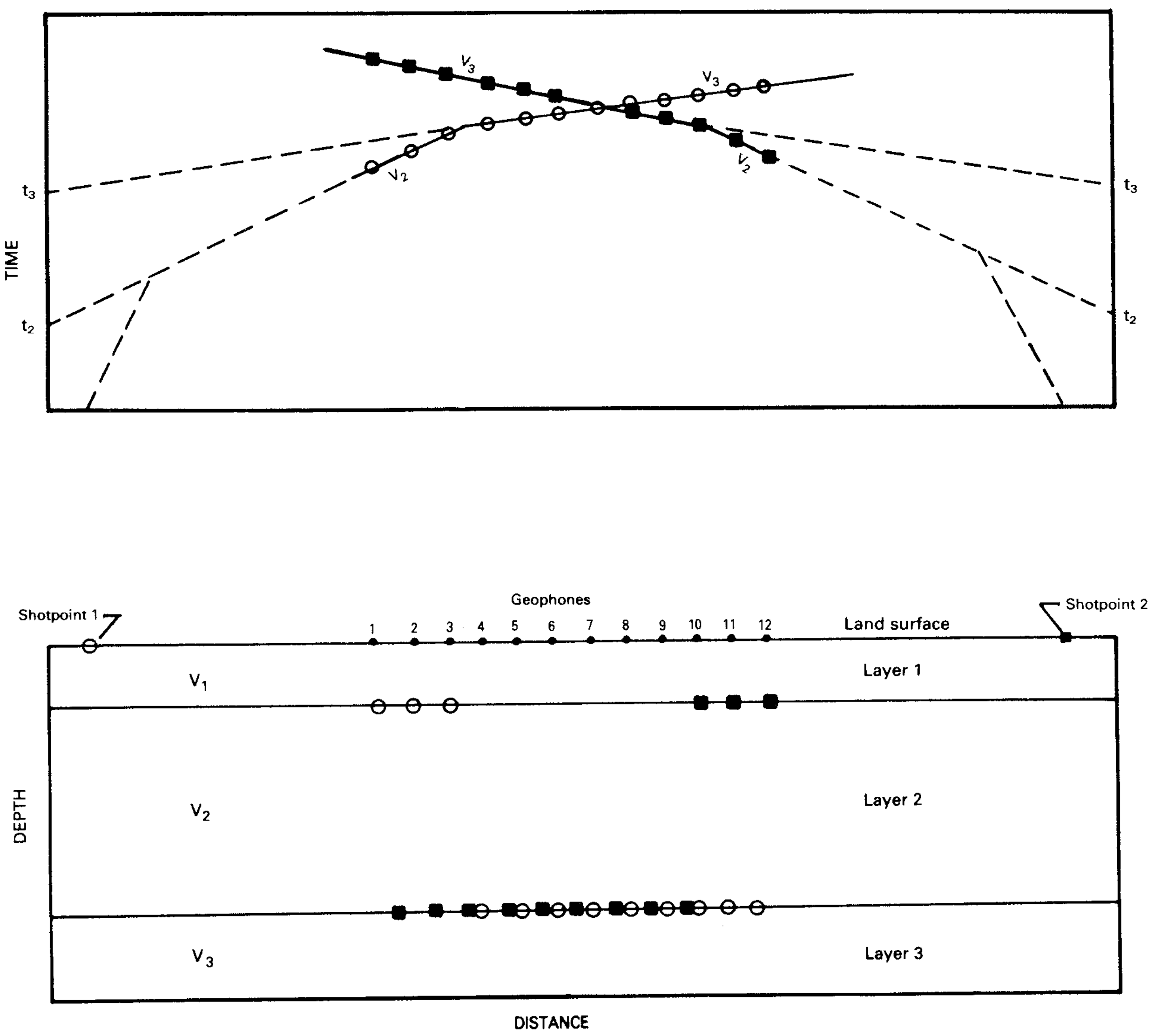


Figure 40.—Time-distance plot and interpreted seismic section resulting from a single geophone spread with two shotpoints.

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.

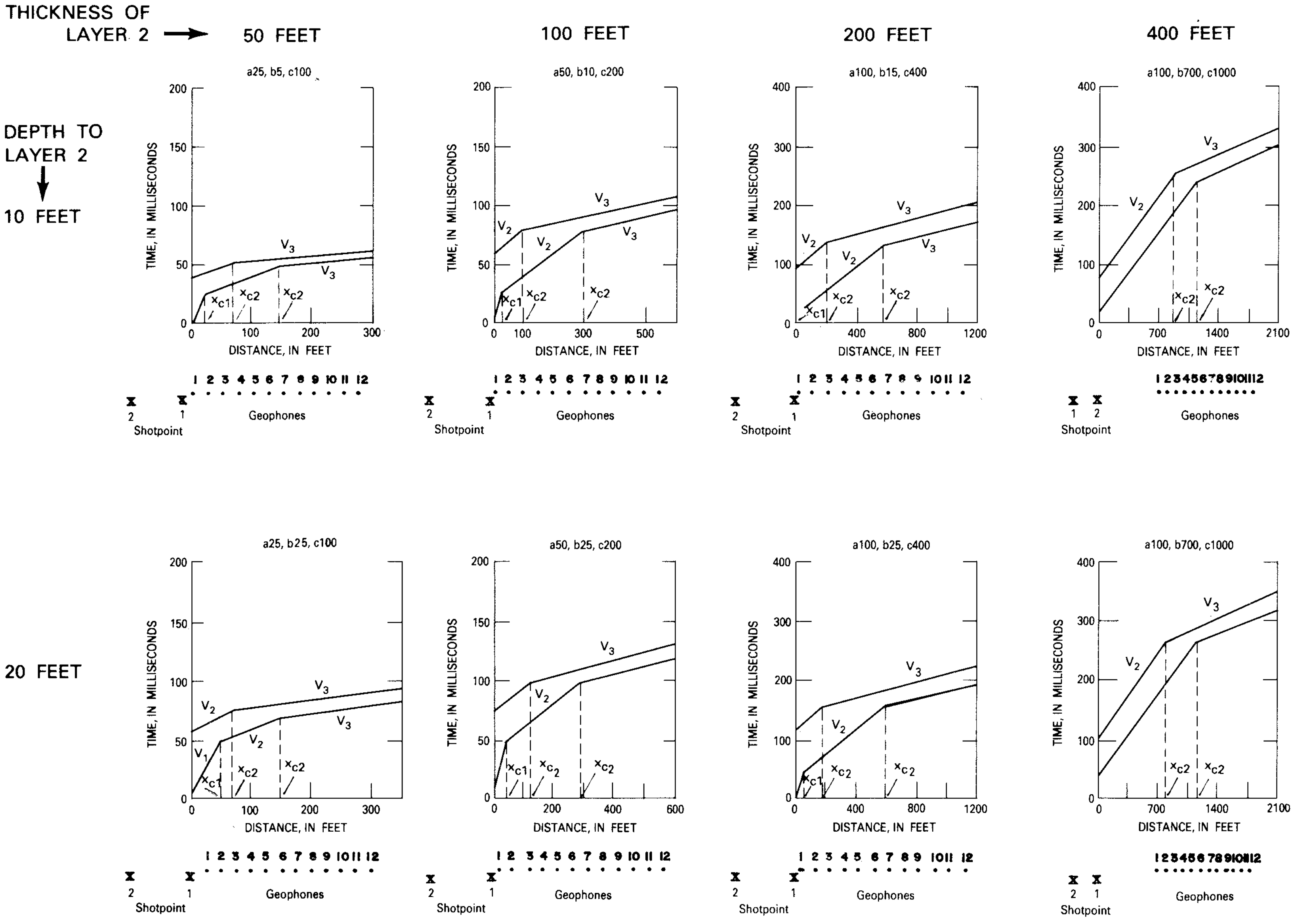
4. The seismograph is set up in the truck. If the unit is to remain in the truck, it is probably most convenient to use the truck's 12-volt direct current system to power the seismograph. Adapters are available to connect the seismograph to this power supply through the truck's cigarette lighter receptacle.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



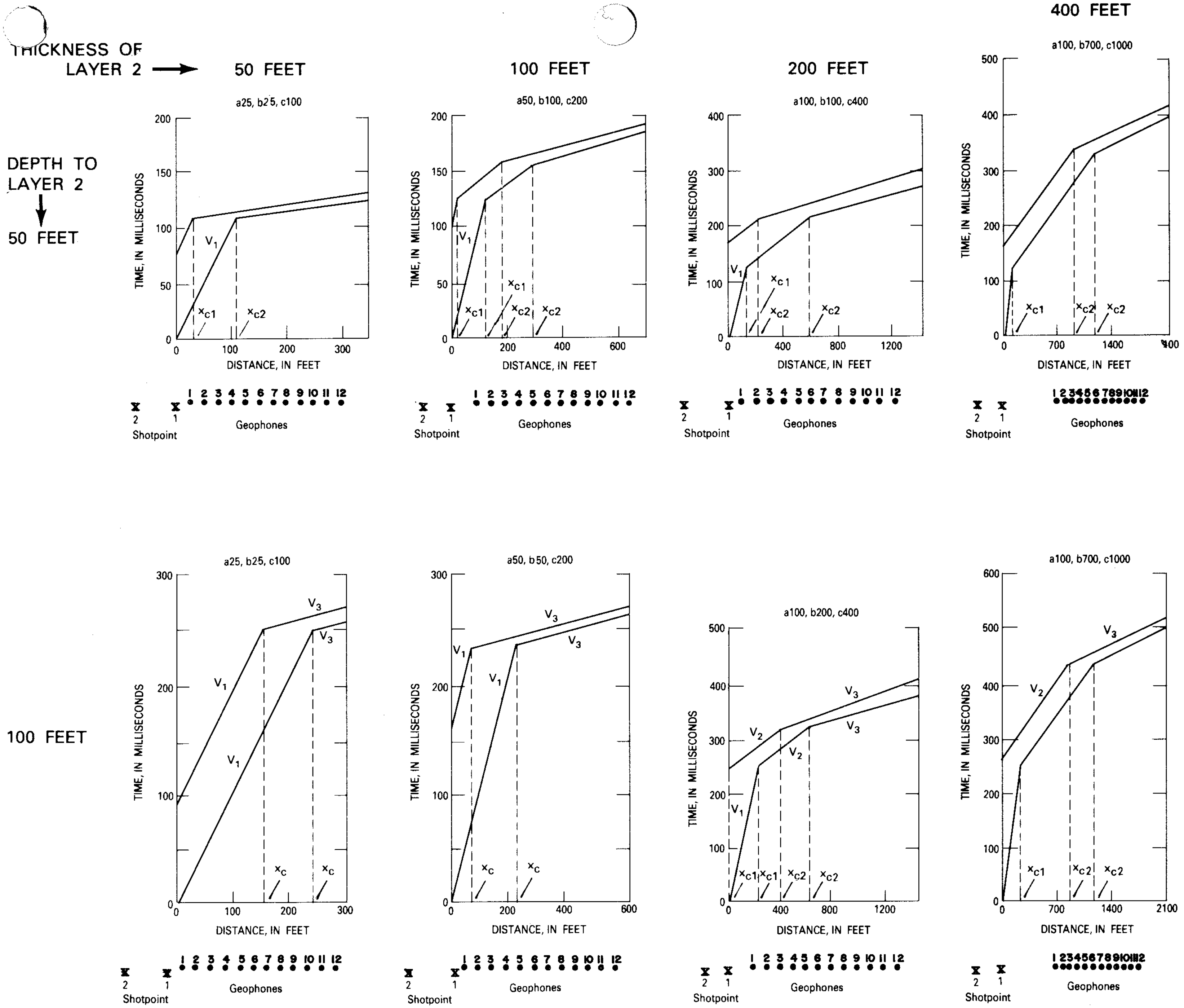
a. Distance between geophones

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

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.

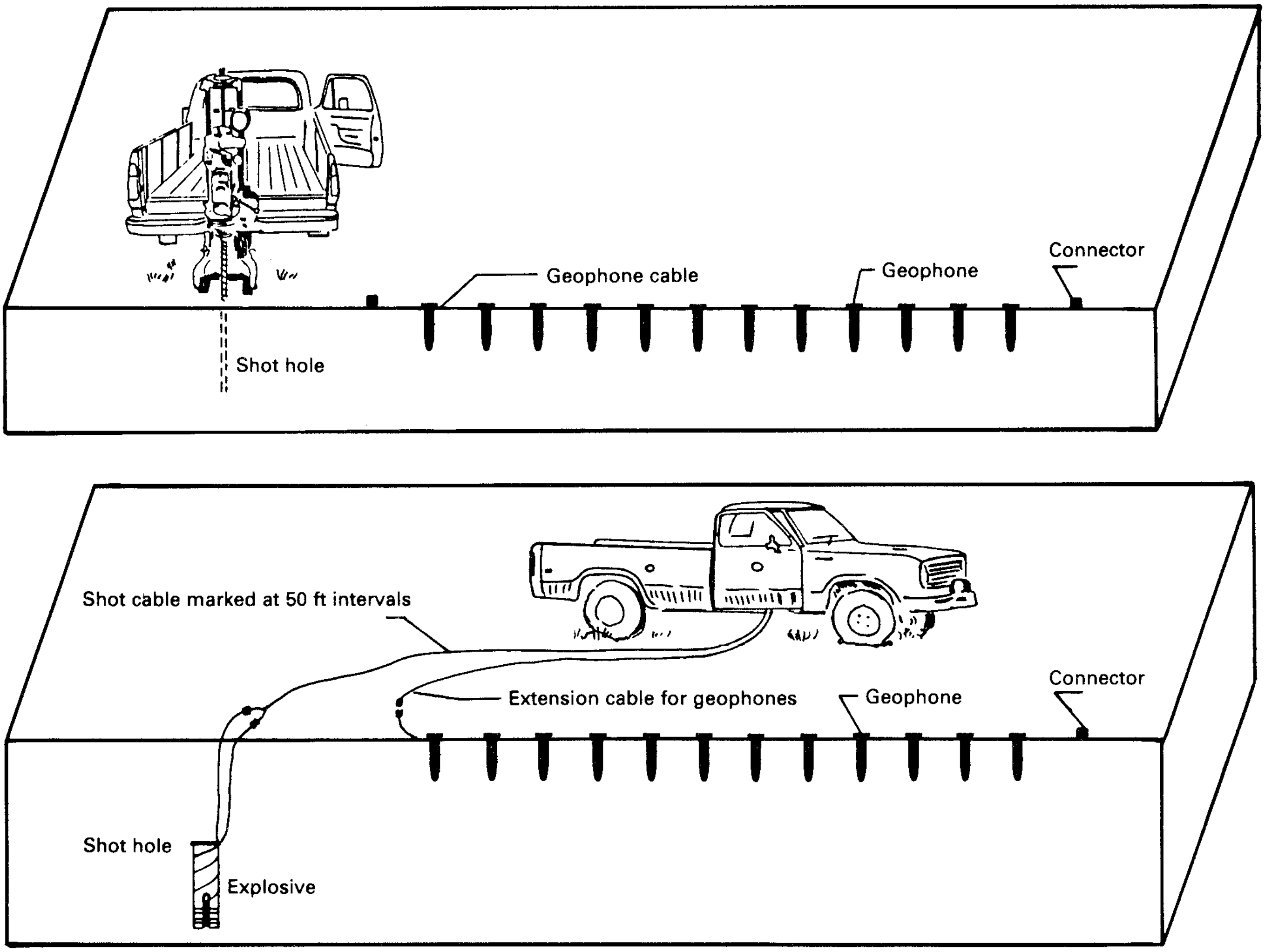
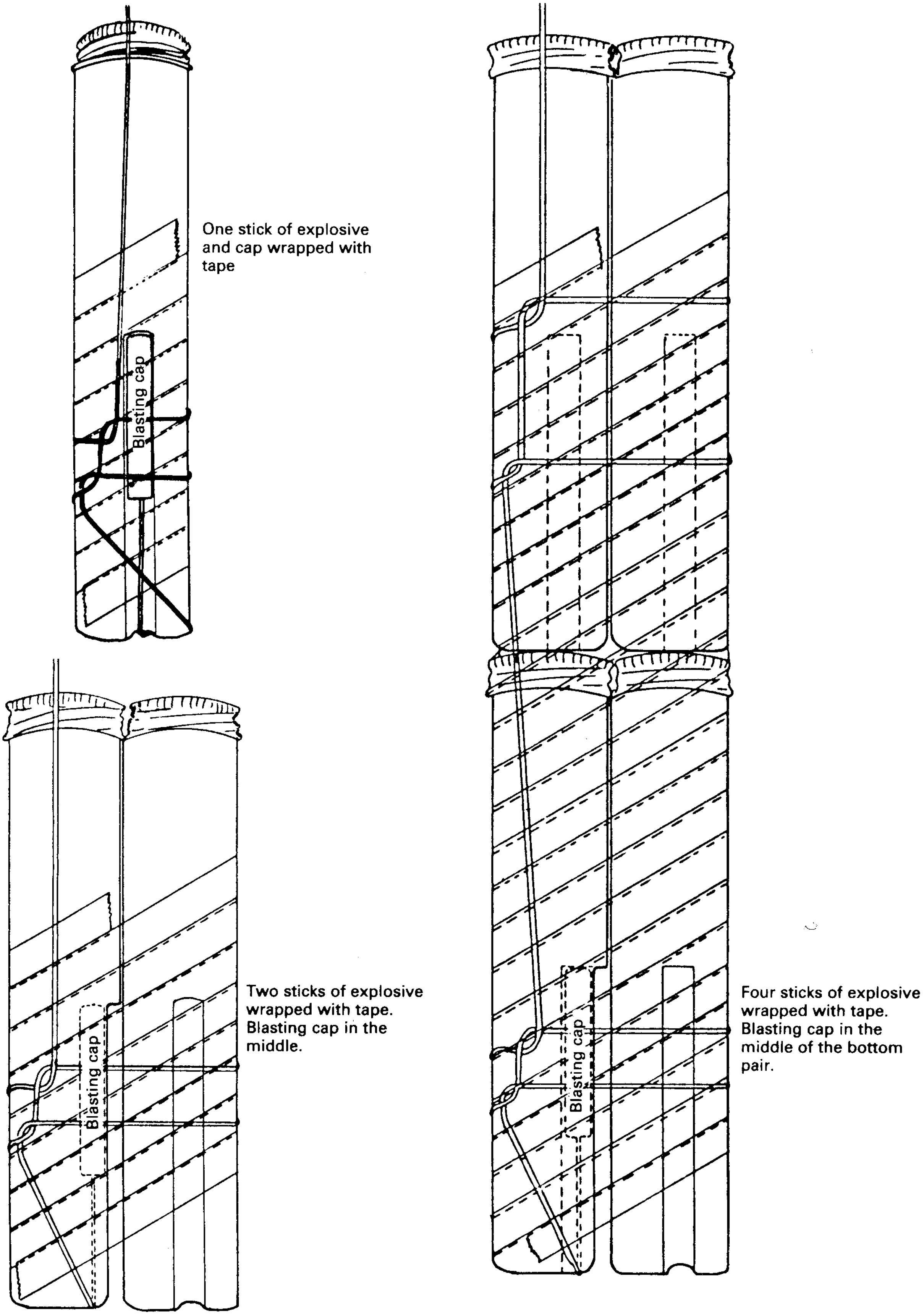


Figure 42.—Field setup of seismic truck, geophones, and shot hole.



One stick of explosive and cap wrapped with tape

Two sticks of explosive wrapped with tape. Blasting cap in the middle.

Four sticks of explosive wrapped with tape. Blasting cap in the middle of the bottom pair.

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