HIGH RESOLUTION REFRACTION DATA ACQUISITION AND INTERPRETATION

by

Robert W. Lankston
Geo-Compu-Graph, Inc.
P. O. Box 1848
Fayetteville, AR 72702-1848

INTRODUCTION

Refraction and reflection seismic methods are named for a key element of the geometry of the ray paths in each method, respectively. Both methods are affected by the refraction of seismic rays at velocity contrast boundaries. However, the key geometrical element in the reflection method is that the rays incident on a target boundary are reflected back to the surface. In refraction surveying, the incident ray is critically refracted along the target boundary before it returns to the surface. Refraction seismic methods were employed in the petroleum industry before the reflection methods were developed, and the same evolution has been seen in the shallow-target application of the seismic methods.

The term shallow-target is more generic than terms such as engineering refraction (or reflection) seismic methods. Shallow-target encompasses the use of the seismic methods for engineering studies, groundwater exploration, waste site evaluations, industrial mineral and metals exploration, and exploration for certain energy materials. The common link among all of these is that the respective targets are close to the surface of the earth, generally less than 200m.

The modern era of shallow-target refraction surveying began to develop in the mid-1950's with the advent of the seismic timer. Seismic timers may still be purchased, but they remain difficult instruments to use because they have no waveform display. The user is forced to switch the polarity of the geophone signal and adjust a detection threshold level in an attempt to define the earliest arriving energy. The timer is not suitable for any modern refraction seismic work. A few years after the introduction of the seismic timer, a modified laboratory oscilloscope was used to give a short duration display of the full waveform. In the instant that the trace glowed on the CRT, the user would move a cursor to the position of the first break. Another hammer blow caused another waveform to be displayed, and the position of the cursor and the first break could be compared. This was a significant improvement over the timer.

However, the usefulness of the field oscilloscope was limited by the strength of the energy source. In the late 1960's, the field oscilloscope was replaced by an instrument still in widespread use, the single-channel, signal enhancement seismograph. This unit digitizes the incoming waveform and stores it in a computer-type memory. The trace is continuously displayed on a CRT screen by continuous reading of the memory. The user has ample time to make a decision about the location of the first break. Signal enhancement occurs when repeated hammer blows are made. The signal from each hammer blow is digitized and added to the memory. In principle, the coherent first break energy stacks or adds in phase, thereby increasing the magnitude of the values stored in memory, while non-coherent noise adds out of phase and decreases in amplitude. The signal enhancement feature of this type of seismograph was a major breakthrough for refraction methods, and, ultimately, for shallow-target reflection methods, because signals returning from greater depths could be recorded from relatively weak signal sources. However, all single-channel seismographs make inefficient use of the seismic source and allow a slow production rate in the field.

In the mid-1970's, the single-channel, signal enhancement seismograph was expanded into a multichannel system with the result that more data could be collected in a shorter time period. The additional data acquisition capability made continuous refraction profiling possible. The speed and efficiency afforded by the multichannel system allowed geophones to be closer together giving higher resolution of the refractor. By making shots from multiple offset distances into the same geophone spread, a higher level of quality control could be applied routinely and relatively inexpensively compared to the single-channel system. By 1980, an unrelated technological evolution had yielded the microcomputer. Also in 1980, the Generalized Reciprocal Method (GRM) (Palmer, 1980) of interpreting refraction seismic data was published. The multichannel seismograph could collect the continuous profile data, and the microcomputer could process these data rapidly through the GRM technique. The refraction method had matured to the sophistication necessary to address the geologic problems encountered in groundwater and engineering studies.

The same technology in seismographs and microcomputers affected the development of the shallow-target reflection seismic method, and by 1981, the common midpoint (CMP) method of collecting and processing data was available for use. Since 1981, therefore, the engineering or environmental geophysicist has been able to choose between refraction and reflection seismic methods. Each method has its relative strengths, and the refraction method is a clear choice for solution of certain types of problems. A statement by Dobecki and Romig (1985) that reflection methods will become the common seismic method in shallow-target studies within five years (i. e., by 1990) does not seem to be occurring and probably will not occur within another five years because the refraction method offers a means of obtaining certain subsurface information at a speed and at a cost much less than reflection methods. In studies of rippability of the bedrock, depth to the top of the bedrock (if less than 30m), depth to the water table in an alluvial aquifer (if less than 30m), and identification of buried fractures or shear zones in groundwater exploration in igneous and metamorphic terrains, the refraction seismic method will be hard to beat. As the depth to the target increases, the reflection method becomes more attractive and often a necessity.

This tutorial begins by reviewing seismic velocity and the basic geometry of seismic rays that follow the path that includes critical refraction along a planar boundary. This is the point at which many introductory geophysics texts and most seismograph manufacturer's literature regarding the refraction method end. Most of these works do not introduce continuous refractor profiling wherein the real power of the refraction method can be seen. The first phase of data interpretation is the assignment of first break arrivals to specific refracting horizons followed by the process of phantoming the data in order to construct the continuous time-distance profile along the survey line. These tasks are dependent upon successful completion of certain data acquisition procedures. Once continuous coverage of a target refractor is obtained, the power of the GRM can be employed to determine lateral changes in the refractor velocity and to obtain a cross section of the refractor migrated to its correct position in space. In addition to continuous coverage of the refractor, the GRM has certain requirements regarding reciprocal time and geophone spacing that must be addressed during field operations.

Continuous profile refraction data acquisition with modern multichannel, signal enhancement seismographs and data processing and interpretation with the aid of the GRM implemented on a microcomputer through readily available software will provide satisfactory resolution of the subsurface in a wide variety of geologic settings and at minimal cost. These field and office techniques will yield a resolution of the subsurface in direct proportion to the volume and quality of data that are obtained.

SEISMIC VELOCITY

The physical property of earth materials that is measured in seismic studies is the rate at which acoustic wave energy propagates through the various units of the subsurface. Of most importance in the refraction seismic method is p-wave energy. P-waves are compressional body waves that have the highest rate of propagation of any seismic waves. As a p-wave travels through the earth, it moves each particle it traverses in a direction colinear with the direction of propagation. The rate of propagation in a specific medium is generally called the velocity of the medium. The term velocity is used loosely. Velocity, to the physicist, is a vector quantity, but it is used by geophysicists to denote the scalar quantity speed. The use of the term velocity in the following will refer to the rate at which p-wave energy is propagated through the respective subsurface media. Each medium will also be assumed to be isotropic with respect to velocity.

Seismic velocity is not a function of the density of the earth material, but empirical observations show that the velocity of a denser material is generally higher than the velocity of a less dense material. For example, unconsolidated alluvium with a density of 2.0 gm/cc has a velocity of 300-600 m/s while a limestone with a density of 2.6 gm/cc could have a velocity of 5000 m/s. The velocity of a particular earth material can vary over a wide range as a function of its age, its depth of burial, its degree of fracturing or porosity, and whether water or air fills the voids (Telford et al., 1976). The velocity of limestone can be as low as 2500 m/s and as high as 7000 m/s (Telford et al., 1976). The velocity ranges of other rock types overlap this range. Consequently, velocity alone can not be used to specify the rock type. However, within a small study area, the range of velocity for a particular rock type is generally small, and certain rock types can be identified on the basis of their velocity.

ELEMENTARY REFRACTION RAYPATHS

The key geometrical element of raypaths in the refraction seismic method is critical refraction of the ray at some velocity contrast boundary in the subsurface. If a p-wave seismic ray is incident on a velocity contrast boundary, some of the p-wave energy is converted to s-wave energy and some remains as p-wave energy (Telford et al., 1976). Some of the p- and s-wave energy is reflected back into the medium from which the ray was initially incident. Some of the energy is transmitted below the boundary. Snell's Law defines the relationship between the angle that the incident ray and the angle that the transmitted (refracted) p-wave make with the normal to the boundary (Fig. la). Critical refraction is the condition in which the refracted angle is 90 degrees (Fig. lb). After being critically refracted, the signal travels in the lower medium at the velocity of the lower medium but essentially along the boundary between the two media. Snell's Law indicates that critical refraction can occur only at a boundary that shows an increase in velocity with depth across it.

This requirement is often used as a criticism of the refraction method, particularly when the reflection method is being promoted. In the near surface section, where the refraction seismic method has its greatest utility, the velocity commonly does increase with depth largely because of compaction of unconsolidated material or water saturation of the lower part of the unconsolidated section. The unconsolidated section is always underlain by bedrock, and the velocity virtually always increases from the unconsolidated section to the bedrock. Velocity inversions, i. e., the situation in which the velocity decreases across a boundary, is more common in the section below the surface of the bedrock. Velocity inversion can exist, however, in the unconsolidated section. For example, a caliche layer in an arid or semi-arid area can cause a velocity inversion. In mid-latitudes, the surface of the ground may be frozen to a depth of a meter or more during the winter. The frozen ground has a higher velocity than the unfrozen section below it. In higher latitudes, permafrost gives rise to the velocity inversion problem. Palmer (1986) states that the velocity inversion in the near surface section is generally the result of a layer with an anomalously high velocity rather than the presence of a layer with an anomalously low velocity.

Two Layer Case

Most geophysics texts (e. g., Dobrin, 1976, or Telford et al., 1976) begin their treatments of refraction methods by deriving the travel time equation for the critically refracted ray in the two layer case (Fig. 2). Deriving the travel time equation,

$$t = x/V_2 + 2h_1 \cos 1/V_1 \quad (1)$$

uses the straightforward procedure of ray tracing. Ray trace modeling, whether applied for refraction or reflection problems, generates ray paths by obeying Snell's Law at velocity contrast boundaries and applies the familiar relationship among distance, velocity, and time to calculate the travel time along each segment of the complete ray path. Equation 1 is in the form of the equation of a straight line. If t is plotted along the vertical axis and x is plotted along the horizontal axis (Fig. 2), the slope of the straight line is the reciprocal of the velocity of the medium in which the critical refraction

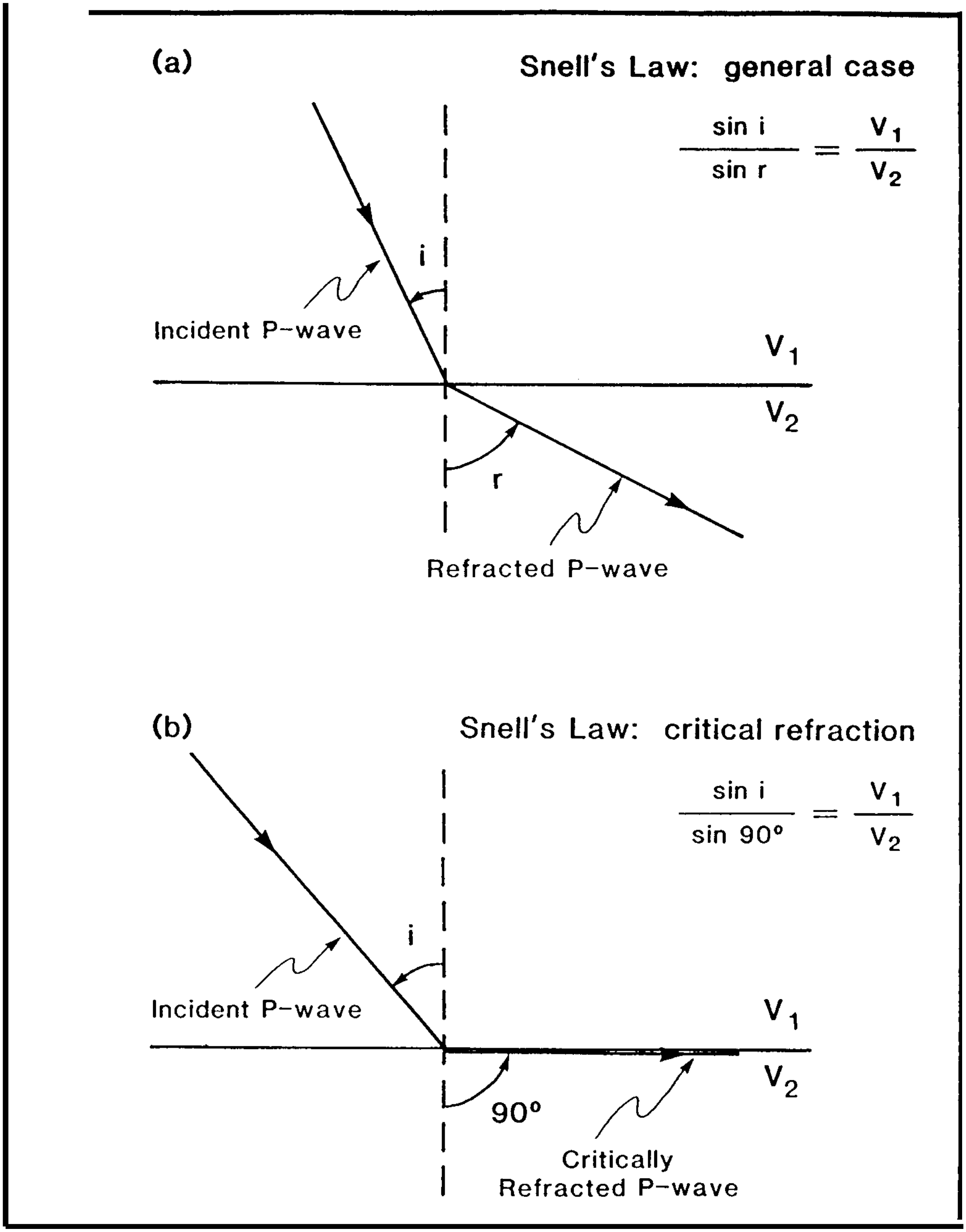


Figure 1. Raypath diagrams illustrating the terms in Snell's Law: a) the general case of incident and refracted rays at any velocity contrast boundary. b) the case of critical refraction.

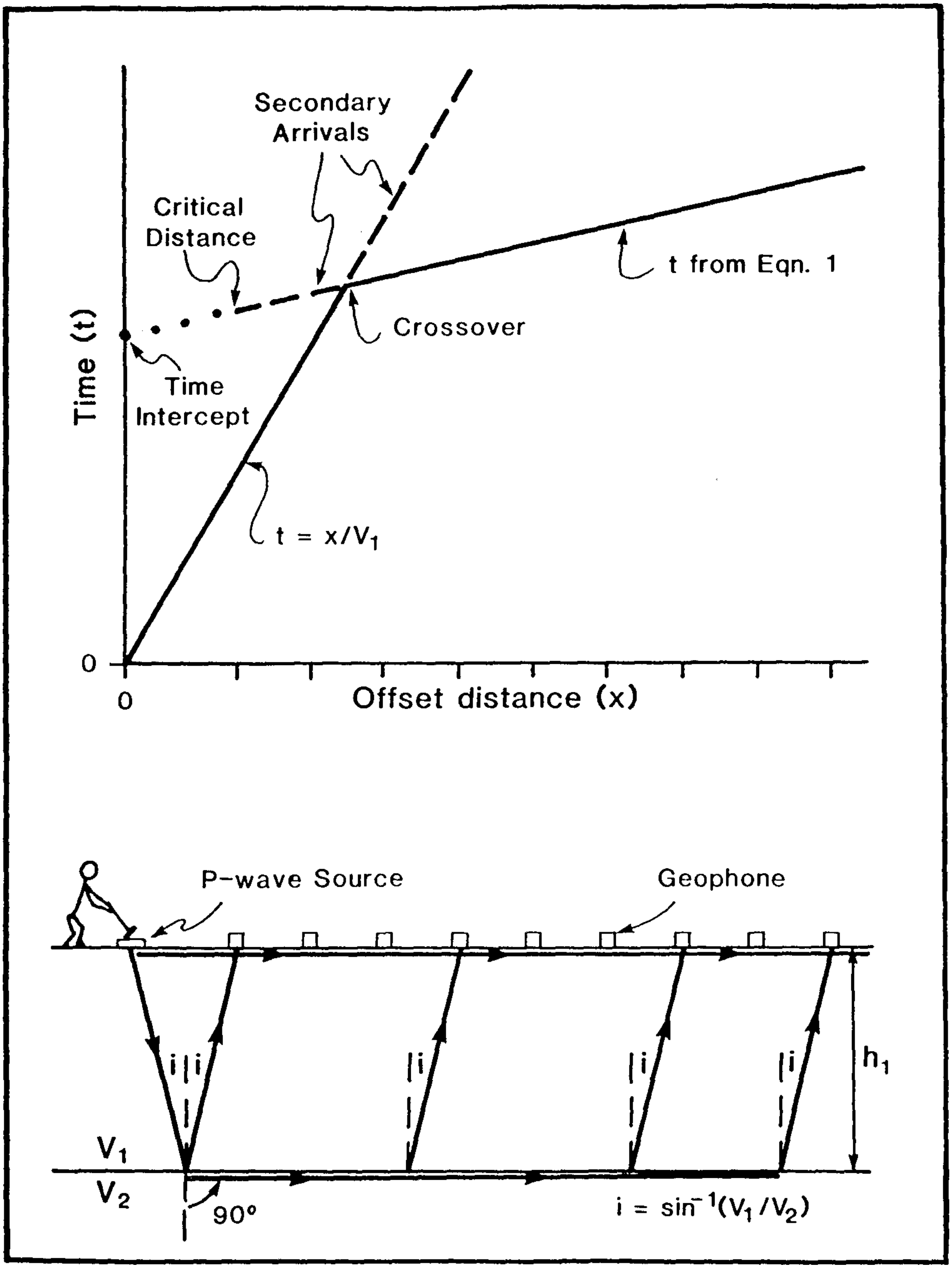


Figure 2. Direct and critically refracted raypaths and the time distance diagram showing the first and secondary breaks from these raypaths.

occurred. The remaining term in Equation 1 is known as the intercept time and defines the point at which the straight line intersects the time axis (Fig. 2).

The travel time equation also gives insight into the feature on the seismic trace that must be recognized and timed, the first break. Some simple algebra or plotting of travel-time curves (Fig. 2) will show that the p-waves that travel the critically refracted path will arrive earlier than the p-waves that travel the shorter, direct path across the surface of the earth at distances greater than a certain value. At shorter distances, the first breaks will be from the p-waves that travel the direct path. In the most elementary form of refraction surveying, a source and geophones are arranged as in Figure 2. The first break times are recorded and plotted on the t-x axes. Though rarely the case, if the earth consists of two layers bounded by a horizontal plane, two straight line segments will be visible in the travel time data. The velocities of the two layers can be determined by taking the reciprocal of the slopes of the two lines, respectively. As will be demonstrated below, this approach to refraction surveying and interpretation is very dangerous.

The first breaks on a seismic trace are unique in that they are, indeed, the first energy on the trace. This, in principle, makes them easy to identify and to time and is one of the strengths of the refraction seismic method with respect to the reflection method. Reflection events occur later in time and are often degraded by other seismic phases, in many cases, later-arriving phases of the multicyclic head wave wavetrain. Defining the arrival time of a reflection event is rarely as certain as defining the first break. The relative ease of recording refraction arrivals and in identifying and timing them on the records is a factor that will guarantee the refraction method a valued place in shallow-target geophysics for many years.

In addition to being based on an oversimplified model of the earth, Equation 1 has other problems. The intercept time is not a point that can be obtained by a physical refraction experiment. In fact, a zone exists between the source point and a position called the critical distance in which no energy that has followed the path of critical refraction can be observed (Fig. 2). Between the critical point and the crossover point, refracted arrivals may be recorded on the seismic record. However, they are rarely used because they are not first breaks, and timing these secondary arrivals is usually difficult. Although Equation 1 suggests that a travel time can be obtained for any offset distance, this does not occur because of physical or operational limitations. Equation 1 defines the times at which refraction signals should occur if they physically existed or if they could be identified, and this is an important consideration in continuous profiling of a refractor.

Multilayer Case

The ray tracing method can be employed to derive the equation that defines the travel time of rays that follow the critical refraction path through multiple, non-dipping layers:

$$t = x/V_n + \sum_{j=1}^{n-1} (2h_j \cos i_j / V_j) \qquad (2)$$

Figure 3 defines the terms in Equation 2 for the n equals four case. Equation 2 lends itself to two important activities, modeling and interpretation using the intercept time method (ITM). Modeling is important because the effects of velocity inversions and thin layers on the first break patterns on the time distance graph can be readily studied (Fig. 4). Modeling is critical in the survey design stage of a project, and it can be valuable in the interpretation stage of a project. Figure 4c indicates that the thickness of the second layer (h_2) in the three layer case could be so thin that no first break arrivals could be seen returning from the top of layer 2. In Figure 4b, the theoretical travel time curve shows that the second layer is visible in the first break arrivals. However, with the geophone spacing as indicated, only one arrival would actually be recorded along the V_2 line. Therefore, first breaks for a layer may be absent because the layer is too thin or because the geophone interval is too long.

The second use of this equation is in the interpretation of refraction data in cases in which the data were collected at a site at which the layers were of constant thickness and the boundaries between the layers were planes. The summation term in Equation 2 is the intercept time for the n'th layer. If n is two, Equation 2 reduces to Equation 1. In the two layer case, the velocities (V_1 and V_2) are known from the time distance graph, the incident angle (i_1) can be calculated from Snell's Law (Fig. 3), and h_1 can be calculated from Equation 1. Proceeding to the n equals three case, expansion of the summation term in Equation 2 shows that the only unknown value is h_2. This continues for the total number of layers identified in the travel time data, and the process is known as the intercept time method (ITM) of depth determination.

Lateral Versus Horizontal Velocity Changes

The problem with the layer cake approach to the refraction method is that it oversimplifies the real earth and potentially lulls users of the refraction method into a false sense of security. A single-ended refraction experiment as is illustrated by Figure 2 does not allow a multilayer case to be distinguished from a two layer case in which the refractor has lateral velocity changes (Fig. 5). Making this distinction is an important aspect of the qualitative interpretation of refraction seismic data. Fortunately, this problem has a readily attained solution. In addition to the shot point at the end of the geophone spread as in Figure 5, an additional shot point is added at a greater distance from the geophone spread (Fig. 6). All of the geophones remain in their initial positions.

Figure 6 shows the initial curves from the short offset shot (0) and the new curves from the long offset shot (-S) for the two cases. In the vertical velocity change model (Fig. 6a), the crossover point between the two segments of the travel time curve shifts laterally. In the lateral velocity change model (Fig. 6b), the crossover point does not shift laterally, but instead it shifts vertically, i. e., in time. In addition to the time shift in the lateral velocity change case, the travel time curves for the two shots are parallel to the left and to the right of the crossover point, i. e., the difference in time between the curves is a constant at each geophone location.

Identifying parallelism between the travel time curves for two or more shot points from the same end of each spread is an unequivocal method for

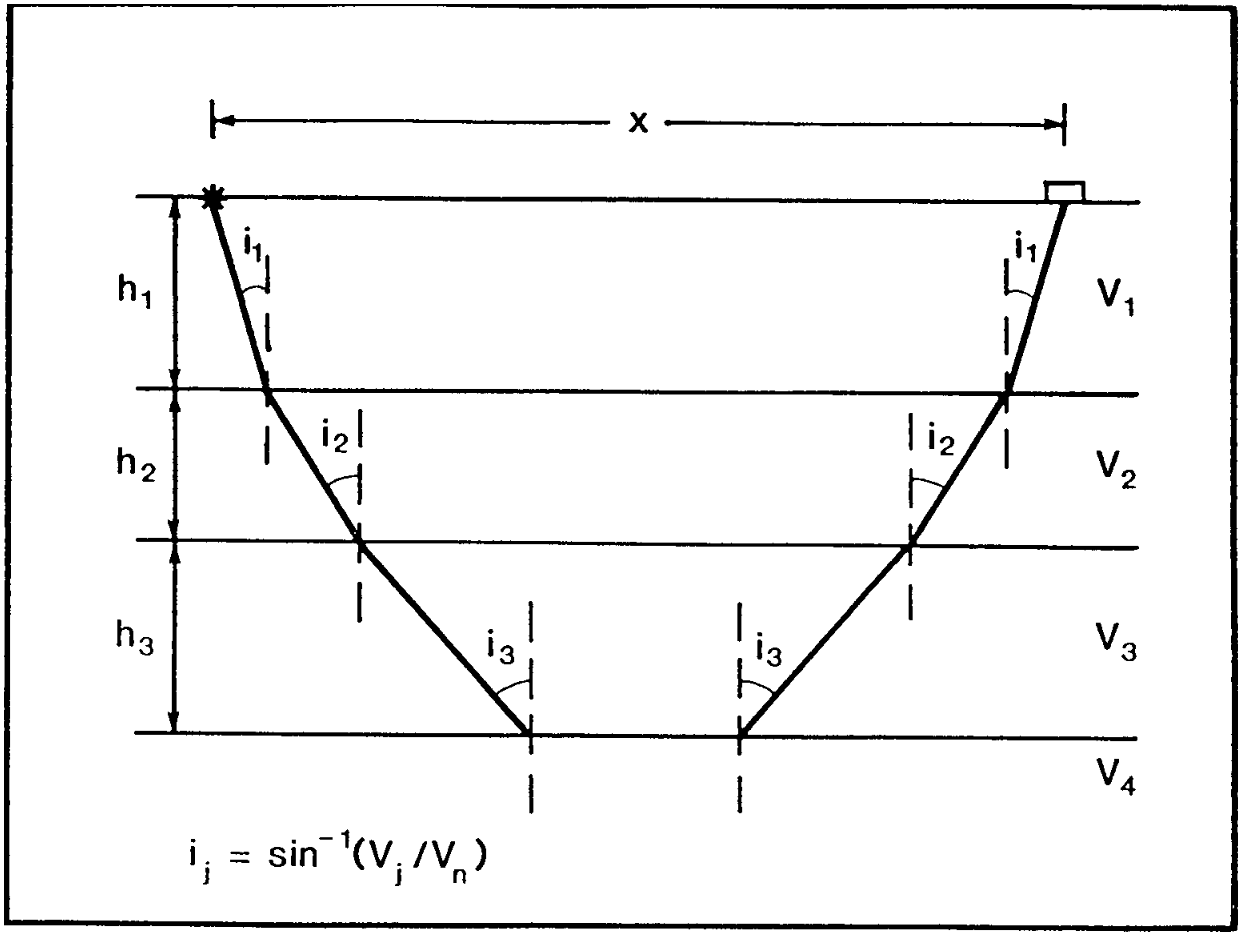


Figure 3. Definition of parameters for the multilayer case.

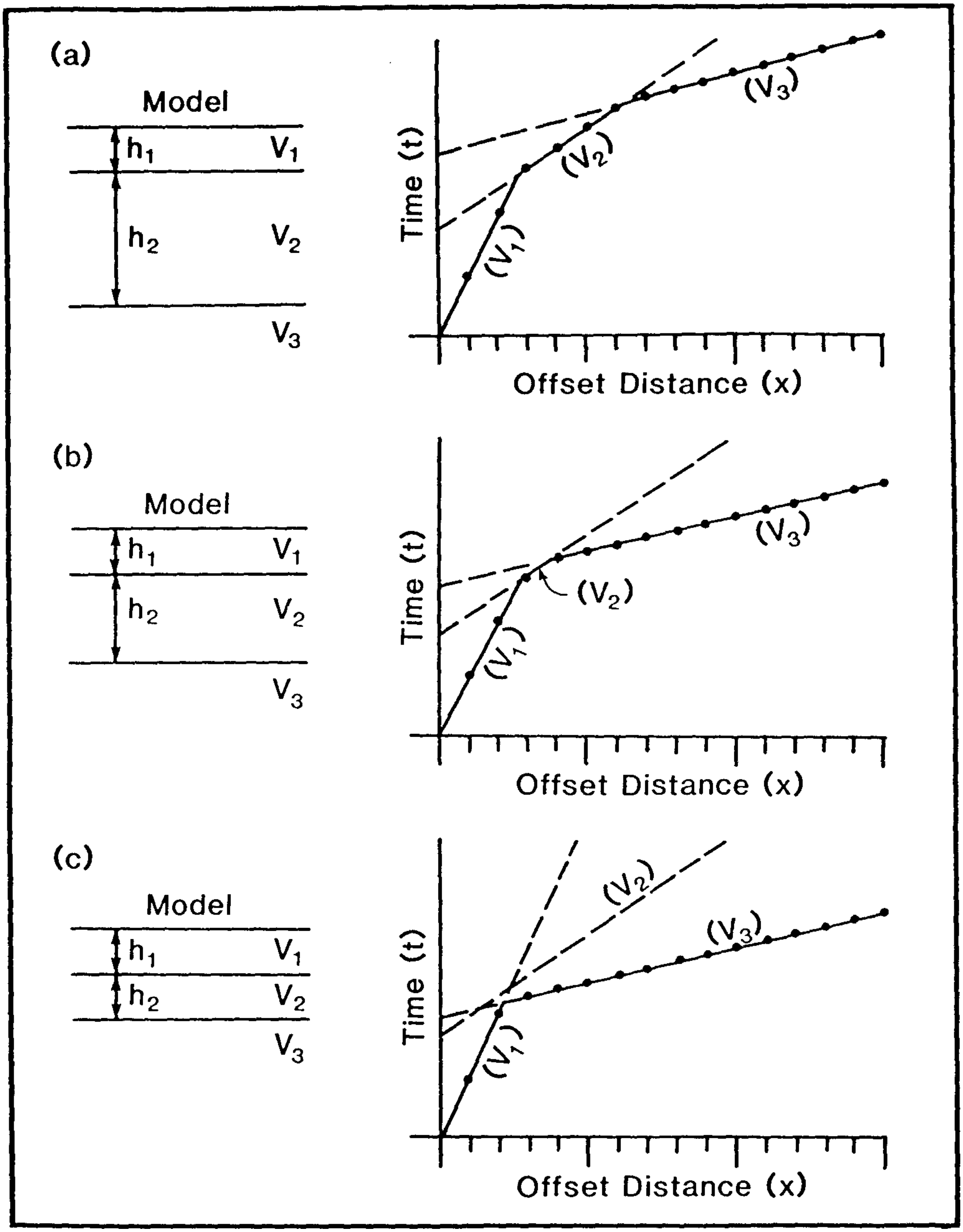


Figure 4. Travel time curves showing the effect of the thickness of the second layer.

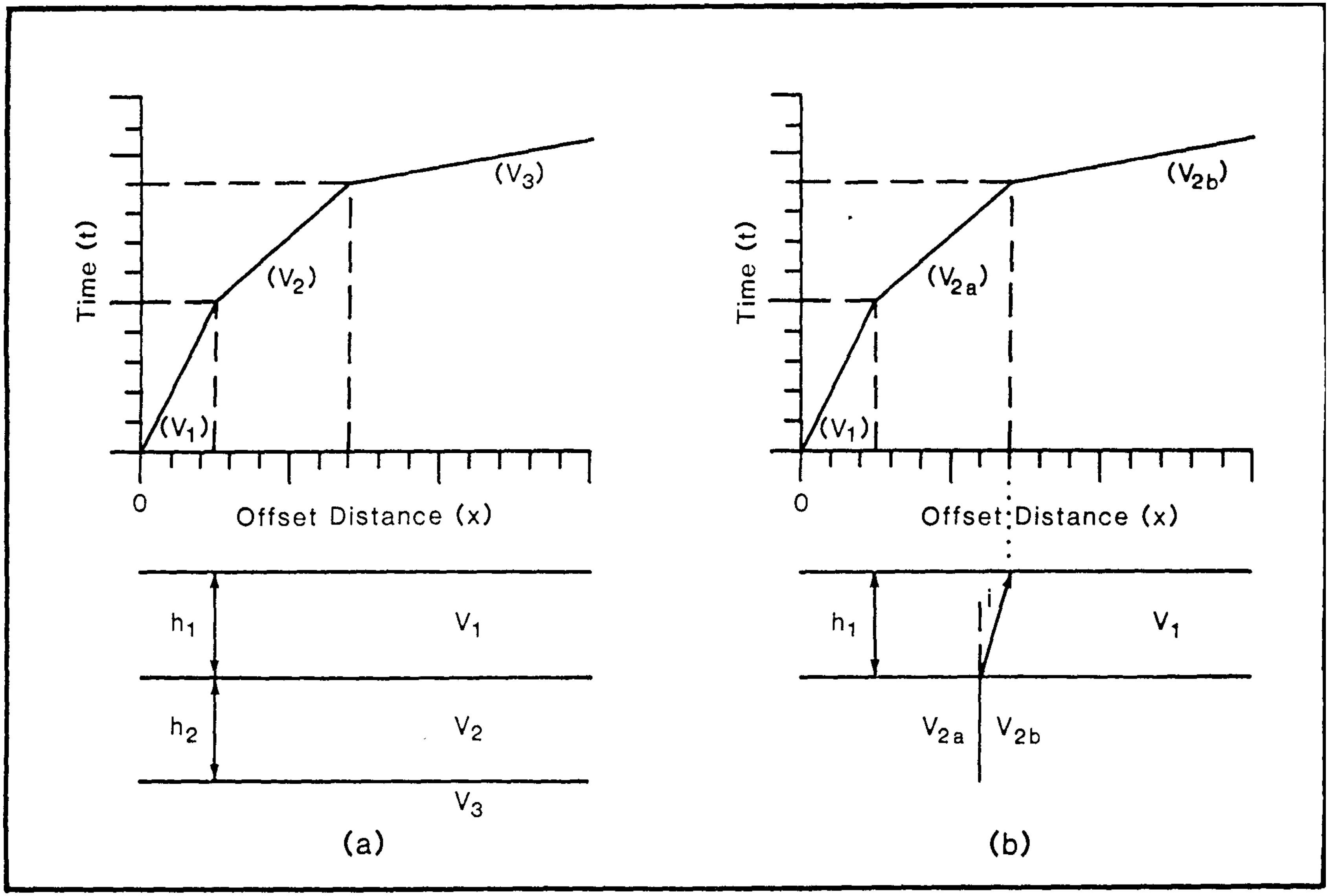


Figure 5. Identical travel time curves observed over a three layer earth and a two layer earth with a lateral velocity change in the second layer.

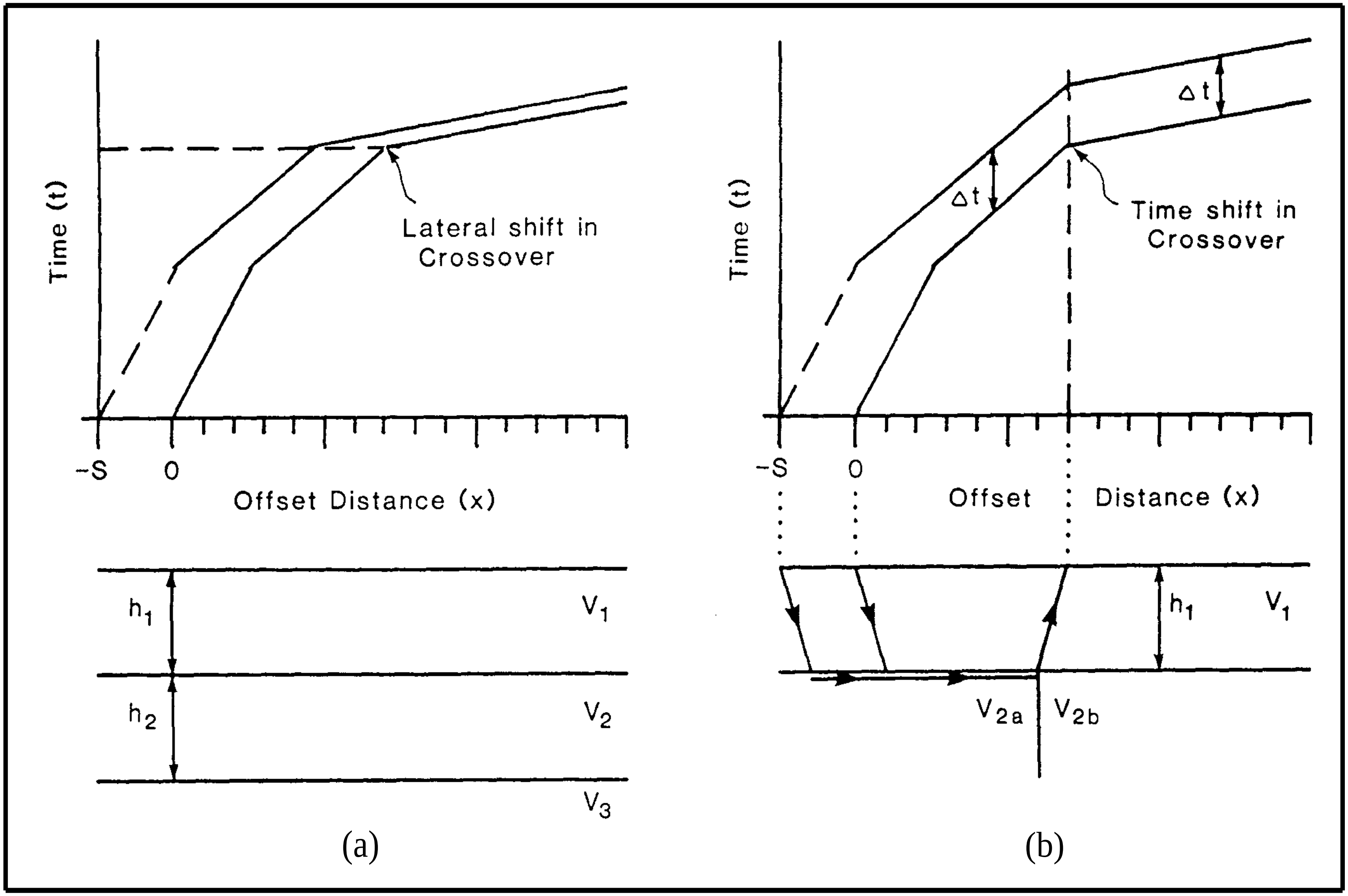


Figure 6. Additional off-the-end shot allows three layer case to be distinguished from two layer case with Lateral velocity change.

grouping first break arrivals according to the refractors at which the respective signals were critically refracted. Data acquisition techniques must be adopted that lead to the development of the volume of data that will allow the assignment decisions to be made with confidence. Practical considerations may preclude the definition of each refractor continuously along the survey line, but every target of the refraction survey must be continuously defined. The data available from multiple shots into a geophone spread can be considered from a quality control standpoint. Ideally, exactly parallel travel time curves would be generated. Typically, the curves are not everywhere parallel. This serves as a flag to the interpreter to review the field records in an attempt to resolve the lack of parallelism. The breakdown of parallelism may be the result of a simple timing error. However, background noise at the site and low energy sources can contribute to poor quality first breaks. Timing errors can be corrected, but problems associated with noise may not be removable from the data. Any uncertainties in the arrival time propagates into the final interpretation. The multiple shots at least allow these problems to be identified and allow limits to be placed on the quality of the final interpretation.

Two Layer Case With Dipping Refractor

Equation 2 was derived for the case of non-dipping planar boundaries. Figure 7 shows how the thickness of the upper layer at the source point (A) and the receiver point (C) is defined in the dipping, planar boundary case. Tracing the ray from A to C yields the travel time relationship in Equation 3:

$$t = AC(\cos\theta/V_2 + \cos i_1 \sin\theta/V_1) + 2Z_{1A}\cos i_1/V_1 \qquad (3)$$

Equation 3 readily reduces to Equation 1 when the dip (0) is zero. This equation is also in the form of the equation for a straight line, but the slope of the line is now a function of the velocity of the refracting medium, the velocity of the upper medium, and the sine and the cosine of the angle of dip of the refracting surface. However, the reciprocal of the slope of the line is in units of velocity (distance/time) and is called an apparent velocity. Equation 3 defines the forward direction experiment.

If the shotpoint is moved to B (the reverse direction experiment), the travel time equation is:

$$t = BC(\cos\theta/V_2 + \cos i_1 \sin\theta/V_1) + 2Z_{1B}\cos i_1/V_1 \qquad (4)$$

The slope of the reverse direction travel time curve is different from the forward direction curve because the dip of the boundary must be defined as -(Theta). The true refractor velocity can be obtained by calculating the harmonic mean of the forward and reverse apparent velocities. Forward and reverse direction shooting must be employed to properly define the velocity and the dip of the refractor. Reverse direction experiments must include multiple shots as in the forward direction case in order to make distinctions between lateral and vertical changes in the apparent velocity. Apparent velocity is used here because the travel time curves that are generated from field data rarely indicate the true refractor velocity. Equations are readily available for determining the angle of dip and the thicknesses Z_{IA} and Z_{1B} (e. g., Telford et al., 1976).

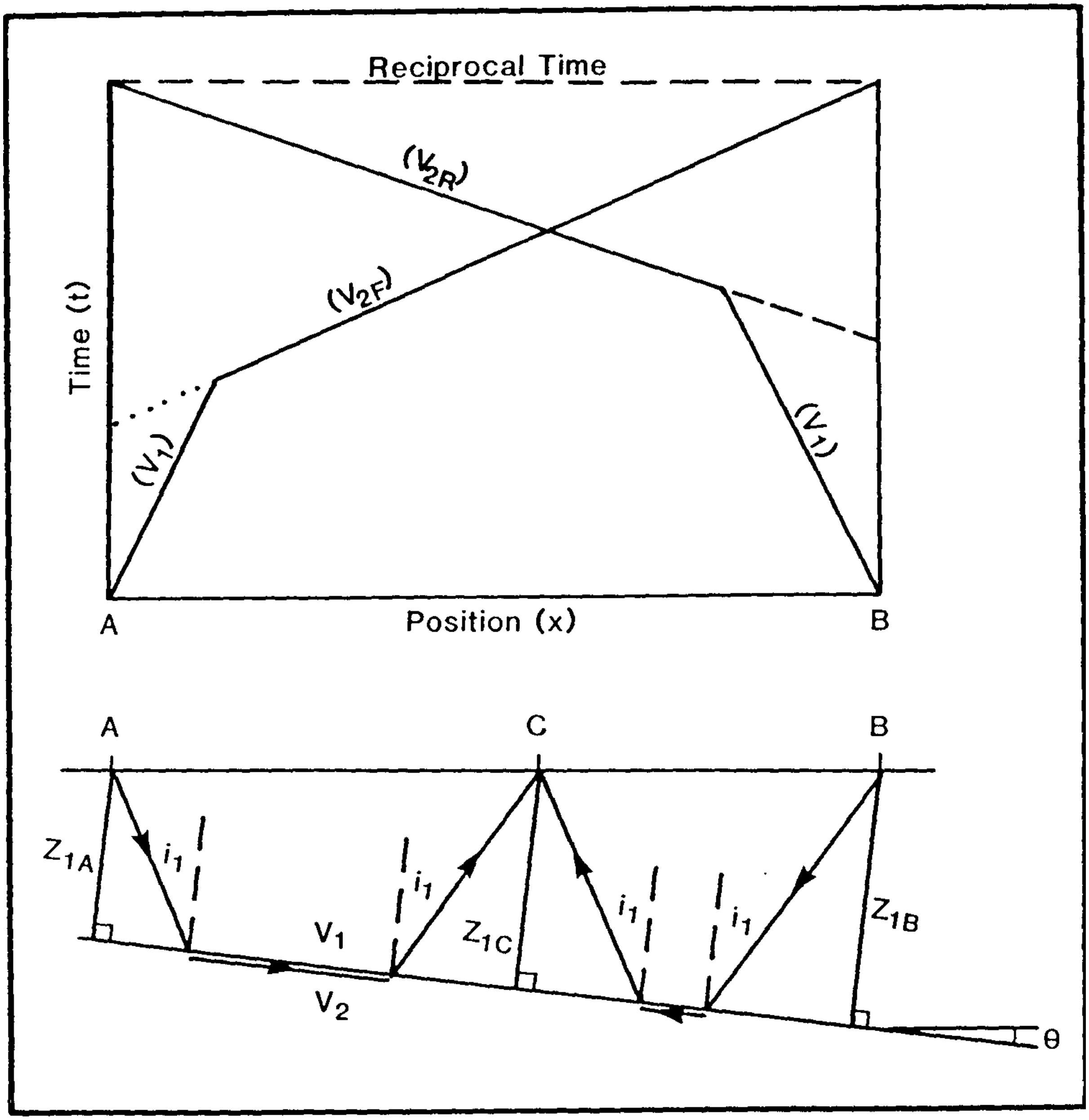


Figure 7. Raypath diagram and travel time curves for the forward direction (A to C) and the reverse direction (B to C) experiments. Forward and reverse direction intercept times and slopes are different. However, the reciprocal time, regardless of the direction of the measurement, is a constant.

The travel time graph in Figure 8b is prepared from the first breaks on the record in Figure 8a. This record and travel time graph illustrate several points. First, the straight line fit to the arrivals from the lower medium has a negative slope. This indicates that the dip of the refractor is steep and upward away from the shotpoint. A second feature in these data is the loss of the first break from the direct wave at the eighth geophone position. The true first break on trace eight probably occurs at about 50 msec. The record clearly shows that the amplitude of the direct wave first break decreases in amplitude with increasing distance. The first breaks from the refractor, however, seem to have a significantly higher amplitude. Two factors contribute to these observations. The first is the polarity of the geophones. The geophones are most sensitive to movement in the vertical direction and least sensitive to horizontal movement. The particle motion of the direct p-waves is perpendicular to the direction of greatest sensitivity of the geophones. The second factor is that the higher velocity material absorbs less energy than the low velocity material. Another item of interest in Figure 8b is the scatter in the first break arrivals with respect to the straight lines. In the case of the arrivals from the deeper horizon, these could be an indication of real geology. Knowing that the scatter is related to the geology can only be gauged by the degree of parallelism with a longer offset shot.

Multiple Dipping Refractors

The equation for the travel time through the multi-layer earth with arbitrarily-dipping planar boundaries was given by Palmer (1980), and Palmer (1986) describes the intercept time method (ITM) for interpreting data from multiple, dipping, planar refractors. This technique is essentially identical to the one implemented through a FORTRAN program described by Mooney (1977). Unfortunately, though the earth may be considered to be layered, the boundaries between the layers are rarely planes. To add to the complexity, the surface of the earth is also rarely a plane, and velocities may change laterally within the various layers. The greatest use for the theoretical travel time equations is in modeling. Through modeling, insight into the refraction method can be gained.

The insight afforded so far is that forward and reverse shooting must be employed in the field and more than one shot must be made at each end of the geophone spread. The travel time equations also offer a technique for interpreting the refraction data based on the intercept times, but this technique fails in the presence of non-planar refractors.

PHANTOMING ARRIVALS

Figure 9 presents forward and reverse travel time curves for a two layer, dipping-boundary case. Noted along the refractor are the areas for which coverage of the refractor is actually obtained from the forward and reverse direction experiments. The forward and reverse direction subsurface coverages overlap only along a segment of the refractor. Therefore, the apparent velocities that would be determined from the travel time graphs are based on rays that traveled through different parts of the refractor. If the refractor is planar and no lateral velocity changes are present, using the forward and reverse direction apparent velocities to calculate the true refractor velocity

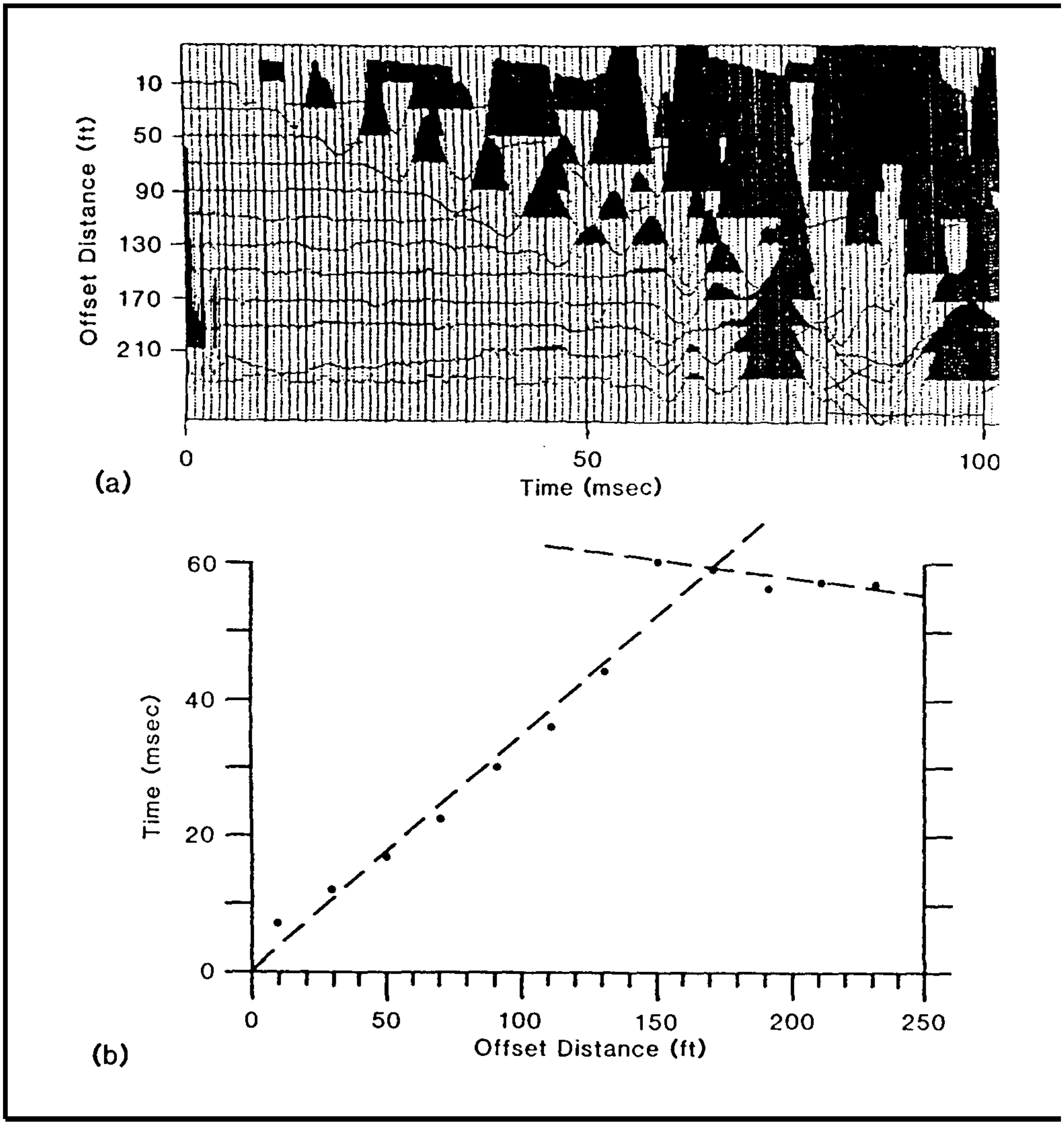


Figure 8. Field record (a) and corresponding time distance graph (b).

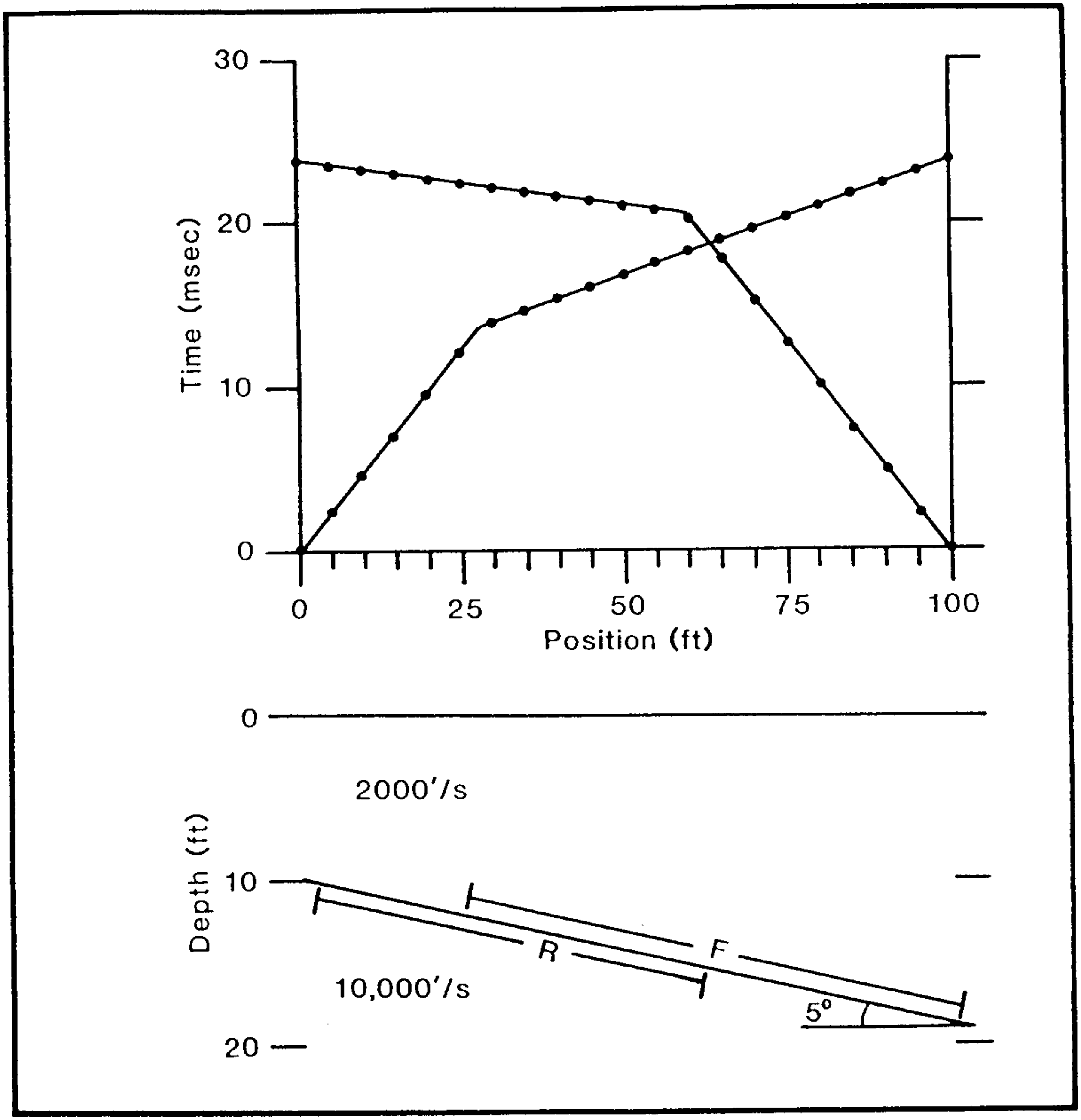


Figure 9. Subsurface model and forward and reverse travel time curves. The zones of subsurface coverage for the forward and reverse direction experiments are noted on the model.

is legitimate.

The subsurface coverage of a particular refractor is determined by the geology and by the shooting geometry. In order to sample a different segment of the refractor, the shotpoint and geophone points must be moved laterally. Figure 10 shows the subsurface coverage obtained from a different reverse direction shot and geophone spread. Some overlap of the two reverse direction coverage zones occurs along with a corresponding overlap of the travel time curves. In this zone of overlap, as expected from the discussion above, the travel time curves are parallel indicating head wave arrivals from the same refractor in both shots. Because the two curves are parallel, the time difference between the two curves is the same at each geophone point. If this time difference is subtracted from the second layer arrivals in the second shot, the resulting times are those that would have been recorded in the first shot if layer 2 had been thicker or if layer 3 did not exist at all. The time shifted arrivals are called phantom arrivals (Redpath, 1973). They are based on real first break arrivals, but they become associated with a shotpoint from which they could not be observed as first breaks. If layer 3 did not exist, Equation 4 would define the phantom arrival times.

The process of phantoming can be applied to obtain first break-type arrivals in the offset distance zone between the shotpoint and the crossover point (Fig. 10). Alternatively, the phantoming process could have been applied to shift the arrivals from the second layer from the shot at position 100 up to coincide with those from the shot at 140. The direction that arrivals are shifted depends on the objective of the phantoming. The same process can be applied to the forward direction data. By using overlapping geophone spreads and multiple shots per spread during field operations and by phantoming the data, first-break type arrival times can be obtained for each geophone position along the line. A line could be as short as one spread, but the phantoming process allows a line to reach any desired length. The phantomed travel time curve is, effectively, the result of an ideal experiment in which a very long geophone spread is used, in which no refractor exists below the target refractor, in which refracted signals can be recorded in the zone between the shotpoint and the critical distance, and in which first breaks can be recorded between the critical distance and the crossover distance. Once such data are in hand, deciding whether or not the refractor is planar and of constant velocity is possble.

VELOCITY ANALYSIS

In general, the target refractor will not be planar, and it will show lateral changes in velocity. The field procedures and phantoming described above yield two travel time curves, one from the forward direction experiment and one from the reverse direction experiment, that provide continuous coverage of a single target in the refraction study. If the study has more than one target, e. g., the water table and the surface of the bedrock, field operations and phantoming must yield continuous coverage, forward and reverse direction travel time curves for each target.

As part of the generalized reciprocal method (GRM) of interpreting refraction seismic data, Palmer (1980) presented the velocity analysis equation,

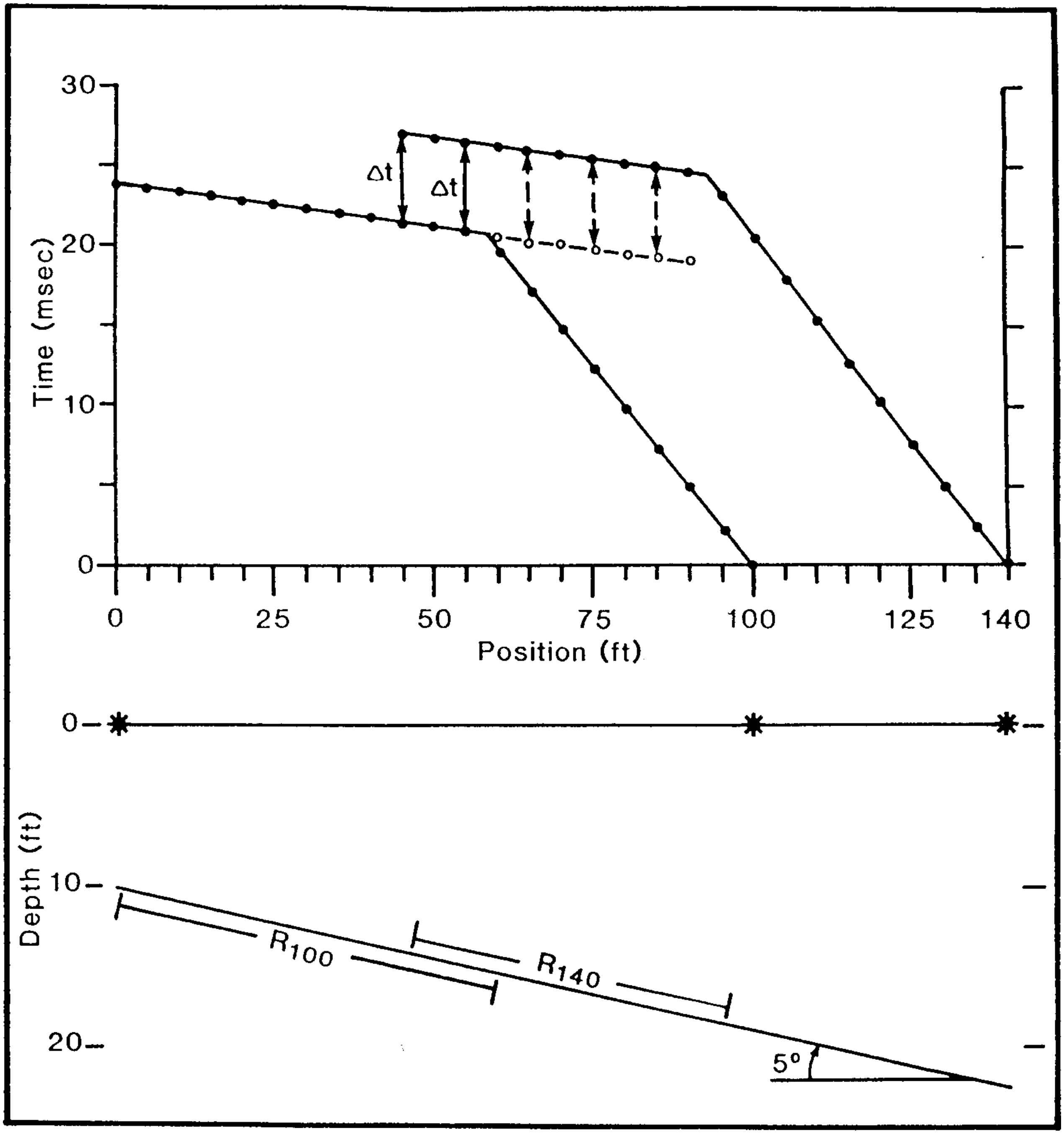


Figure 10. Travel time curves and subsurface coverages from two overlapping reverse direction spreads. Phantomed arrivals are indicated by open circles.

$$t_V = (t_{AY} - t_{BX} + t_{AB})/2 \quad (5)$$

where t_v is the velocity analysis function, and the other terms are travel times along the path of critical refraction from one point to another as indicated by the subscripts. The locations of A, B, X, and Y are illustrated in Figure 11a. The need for the reciprocal time (T_{AB}) places another constraint on field operations. Procedures must be adopted in the field such that the reciprocal Line is measured. Forward direction and reverse direction reciprocal time measurements must agree to within a few percent or less, another quality control feature. A reciprocal time must be obtained for each target refractor in the study. Obtaining the reciprocal time through direct measurement may be difficult in routine field operations. However, Lankston and Lankston (1986) note that phantoming can be used effectively to obtain reciprocal times.

Each t_v value is referenced to the G-position, which is half-way between the forward direction (Y) and reverse direction (X) geophone points. The velocity analysis value (t_v) is a function of the XY distance and position along the line. The velocity analysis value, which is in units of time, can be plotted with respect to distance along the line in the same manner as the travel time curves are plotted. The derivative of the velocity analysis function with respect: to position along the line is the reciprocal of the velocity at that position. The important point here is that the derivative (numerically, the slope of the velocity analysis function) can be taken at any point along the Line so that the velocity of the refractor can he determined as a function of position along the Line. Lateral velocity changes can be readily identified regardless of how many might occur along the line.

The t_v function is also related to the XY distance. In performing a velocity analysis using Equation 5, the XY distance is varied to yield a set of velocity analysis curves. According to Palmer (1980), the proper curve to use in determining the refractor velocities is the one that exhibits the least amount of irregularity. Selection of a particular curve defines the XY value that. is to be used in later stages of the GM processing.

Redpath's (1973) method for determining velocity is essentially identical to Palmer's (1980) method. However, Redpath only considered the XY equal zero condition. Physically, this condition can not occur. Figure lb indicates that for XY to be zero and for the forward and reverse traveling rays to emerge from the same point on the refractor, the incident (emergent) angle must be zero degrees. From Snell's Law (Fig. 1), this can occur only when the velocity of the lower medium is infinite. From a practical consideration, the Redpath (1973) method of determining velocity and the XY equal zero case often give satisfactory results. This occurs most often in settings in which a large velocity contrast exists such as an unsaturated alluvium or soil overlying an unfractured bedrock In such a setting, the velocity ratio in Snell's Law could he as low as .005, which yields an incident angle of less than one degree. Moreover, if the thickness of the overlying section is thin, the forward and reverse travelling rays do indeed emerge from essentially the same point on the refractor.

Figure 6 shows that a lateral change in the velocity of the refractor can

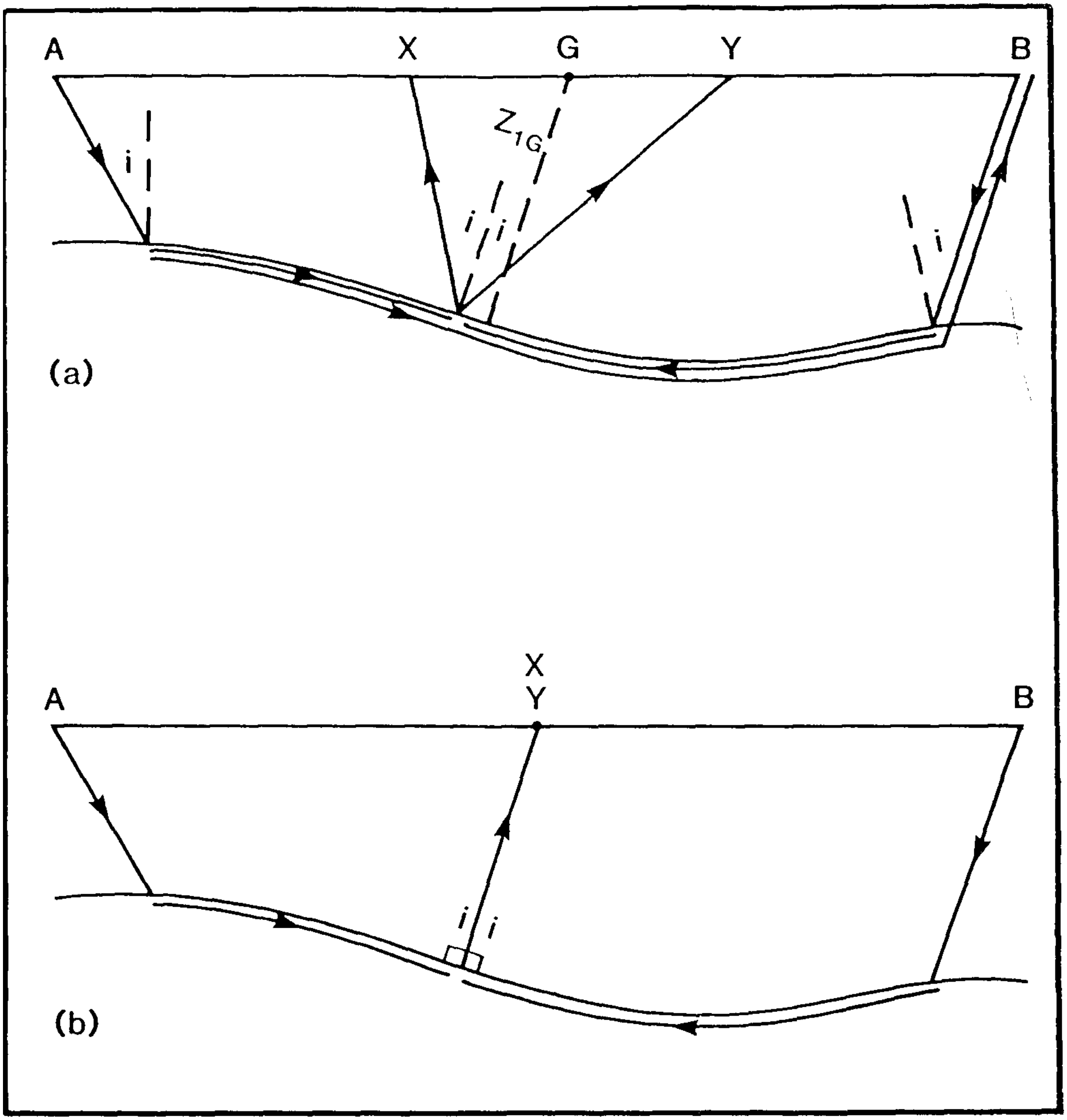


Figure 11. a). Raypath diagram for the optimum XY case. b) Raypath diagram for the XY equals zero case.

be identified from the travel time data. Single direction data, however, do not allow a lateral velocity change to he distinguished from a change in dip of the refractor or from the effects of a combination of dip and velocity change. In practical applications, the velocity analysis function (Eqn. 5) is not affected by the dip of the refractor, the dip or velocity of any overlying layer, or the surface topography (Palmer, 1980). The travel time data in Figure 6 show that the evidence for a lateral change (velocity or dip) in the refractor occurs at a point on the travel time curve that is shifted away from the shotpoint with respect to the location of the change in the subsurface. In contrast, any change in slope on the velocity analysis graph occurs at the lateral position of the velocity change in the subsurface.

TIME TO DEPTH MIGRATION

The process of migration is central to both refraction and reflection seismic data interpretation. It involves two stages. The first stage is a conversion of the data from units of time to units of distance. The distances calculated from velocity and time values are generally not vertical depths. Therefore, in the second stage, the depth point must be migrated from its position vertically below a surface point, i. e., a geophone point, to its correct position in space. The GRM accomplishes the time to depth migration in these two stages. The first stage is the calculation and interpretation of the time-depth function:

$$t_g = (t_{AY} + t_{BX} - t_{AB} - XY/V_n)/2 \qquad (6)$$

The forward direction and reverse direction travel times (t_{AY} and t_{BX}) and the reciprocal time are defined as they were during GRM velocity analysis (Fig. 11a). XY is an obvious variable in the time-depth equation, but it still occurs as a variable that affects which forward and reverse direction terms are selected for each calculation. The V_n term is the velocity of the refracting horizon at each G-position as determined in the velocity analysis stage. Evaluation of Equation 6 yields a suite of curves, one for each XY distance specified. Palmer (1980) states that the curve that defines the optimum XY is the one that shows the maximum amount of detail. This criterion is opposite to the minimum-detail criterion used in the velocity analysis case.

The principal objective of constructing the t_g curves is to confirm the XY value. Applying Palmer's (1980) criteria for selecting the optimum XY from both the velocity analysis and the time-depth functions should yield the same value. In general, this is the case. The time-depth curve for the optimum XY value does have physical significance, though. This curve gives the shape of the refracting horizon in time (Palmer, 1980). This curve is analogous to, but not equivalent to, the one-way travel time that is the starting point in the migration of reflection seismic data (Robinson, 1983). In reflection methods, the two-way reflection time is usually presented, but it is just twice the one-way time. In much reflection seismic work, the reflection section may illustrate the two-way travel times to many horizons. The interpreter must make the time to depth conversions and migrations, and, because of the volume of data, this is not a trivial task regardless of whether it is done manually or by the computer.

In refraction work, only a few horizons are of interest, usually because only a few can be identified from the first break data on the field records. From the continuous travel time data for each horizon, the lateral velocity changes can be quantified, and the optimum XY value can be selected. Palmer (1980) shows that the time-depth function (t_g) is related to the thicknesses and velocities of each layer overlying the target retractor at each G-position .through:

$$t_g = \sum_{j=1}^{n-1} Z_{Gj}((V_n{}^2 - V_j{}^2)^{\frac{1}{2}}/V_jV_n) \qquad (7)$$

The t_g values are determined through Equation 6 for the optimum XY case. Equation 7 is then employed in an iterative manner to determine each Z_{Gj}. In concept, the approach to determining each Z_{Gj} is analogous to the process that was followed using the ITM. Z_{G1} must be found first, then Z_{G2}, and so forth down through the section. The determination of Z_{Gj} has two distinct differences from the numbers determined using the ITM. First, Z_{Gj} can be determined under each point for which valid forward and reverse travel times are available, i. e., forward and reverse travel time pairs that are separated by the optimum XY distance. Second, Z_{Gj} is not a depth but a radius. The locus of points defined by the radius Z_{Gj}, i. e., a circular arc, defines all of the possible points from which the forward travelling and reverse travelling rays could have emerged, i. e., a wavefront. By having many close-spaced G-positions and calculating many radii, the refractor surface is readily visualized as the envelope of tangents to the arcs.

Thus, the final constraints on field operations can be stated. The definition of the refractor surface will be controlled by the spacing between the G-positions. Moreover, according to Palmer (1980), proper migration of the refractor is dependent upon the optimum XY parameter being selected and used. The choices for XY are limited to integer multiples of the geophone interval used in the field. Therefore, to increase the number of subsurface data points and to have the greatest confidence in them, close spaced geophones must he used in the field. Phantoming is used to obtain the necessary continuous coverage of each refractor and to obtain the reciprocal time for each refractor.

Geophone spacing, unfortunately, is often limited by the available budget. A shorter geophone interval will always yield better resolution of the optimum XY value and, consequently, of the refractor, but the cost will be higher and the data acquisition rate will be slower. Pre-survey modeling using Palmer's (1980) equation for multiple, dipping layers will often give clues to the maximum acceptable geophone spacing.

Palmer (1980) notes that if the optimum XY value can be determined with confidence from the velocity analysis and time-depth functions, the depth to the target refractor can be determined even if all of the thickness and velocity parameters for the overlying layers are not known. This is particularly useful in mapping sites at which velocity inversions occur or sites at which beds too thin to give rise to head wave refractions occur. The GRM parameters actually give an indication that undetected layers are present. This is an additional strength of the GRM. If the optimum XY is known, an average velocity (Palmer, 1980) can he determined for the section above the target refractor. This average velocity is analogous to the stacking velocity used in reflection seismic methods. In both cases, the thickness and velocity parameters from each overlying layer are not known, but satisfactory resolution of the target horizon is obtained if certain criteria in each seismic method, respectively, are met. The criterion in the refraction case is knowledge of the optimum XY. Errors in the XY value are propagated into the calculation of the average velocity and subsequently into the calculated Z_G value.

INTERPRETATION DEMANDS ON FIELD *OPERATIONS*

The optimum XY and the reciprocal time are crucial parameters in GRM processing. Consideration of these needs must be made during data acquisition. Reciprocal time can be measured directly for each target horizon, but it is more efficiently obtained through phantoming (Lankston and Lankston, 1986). The geophone interval must be as short as possble to give the greatest resolution of XY. A large volume of data must be collected in order to use the refraction seismic method to address the complexity of problems encountered in groundwater and engineering studies. However, the multiplicity of coverage minimizes the number of uncertainties in the interpretation.

Defining the shooting geometry and the number of shots per spread to use to obtain the necessary coverage during field operations can not be predicted through modeling or experience. Often, one short offset shot at each end of a spread, one long offset shot at each end of the spread, and one shot in the middle of the geophone spread (Fig. 12) will be sufficient to define the target refractor(s). However, first break data should be plotted on time distance axes in the field and evaluated for completeness of refractor coverage as a quality control measure. This adds a certain amount of time to field operations, but it is required for high resolution of the refractor. Modern seismographs that automatically pick first breaks can help in this effort, though manual picking is satisfactory.

Reflection seismic operations make use of roll-along shooting, and this is an efficient method for moving sources, geophone spreads, instrumentation, vehicles, and people along the survey line. Refraction methods may never benefit from this type of operation. That refraction methods can not (or do not) use roll-along shooting does not mean that they are inefficient. Each geophysical method has a certain amount of work associated with it, and once that work is being done as expeditiously as possible, the maximum in field efficiency is attained. Money saved in speedy field operations can be lost to a poor interpretation based on incomplete data.

EXAMPLE

A few years ago, a municipality was considering granting a permit for a waste disposal site. The proposed site was an isolated location adjacent to a major regional river. The bedrock at the site was basalt. The basalt was exposed along one boundary of the site, but the thickness of unconsolidated material over the rest of the site was unknown. The unconsolidated section was presumed to consist of alluvium deposited by the river though some loess layers were a possibility. The surface material was wind blown sand that formed small dunes, 1 to 2m high, that were marginally stabilized by brush and grass. The site was not visited by the seismic contractor prior to making a bid for the refraction survey. The project manager who requested the geophysical study described the site and explained what, geologic information was needed. The contractor designed the refraction survey and gave a fixed fee quotation on the basis of the manager's description.

The selection of the refraction method for the study of this site was a sound choice. The depth to the bedrock was the desired geologic information, and this is a classic use of the refraction method in shallow-target investigations. That the contractor did not visit the site and made a quotation based on verbal descriptions is not uncommon. Unfortunately, several data acquisition problems occurred as a function of the manager's descriptions. The site was described as basically flat and open, but the manager failed to mention the windblown sand. The contractor needed to know the surface conditions for several reasons, one of which relates to the source. Windblown sand, plowed fields, pastures (particularly in the spring), and forests and hogs with thick organic zones at the surface rapidly absorb seismic energy. At such sites, an explosive source may be the only way to obtain the necessary energy. Another reason for needing to know the surface conditions was for estimating the production rate of the field crew. If a site is brush-covered, in addition to other problems, cables become tangled, and production is slowed. If a site is not rugged and not brushy, equipment and personnel can be moved by vehicles thereby increasing productivity. Another factor in a site description is whether or not power lines are present. The 60Hz power line noise that is induced into the seismograph degrades the sharpness of the first breaks, and data acquisition that employs explosives can be safely conducted only so close to the lines. The proposed waste disposal site was crossed by high voltage transmission lines from a nearby power plant..

The manager suggested that the depth to the bedrock was in the 3 to 8 m range because he had augered to bedrock with a hand auger near the basalt outcrop and the depths were 3 to 5m. The project manager in this case was an engineer. However, some of the same survey startup problems could have occurred if the manager was a geologist unfamiliar with geophysical operations or even an elected official such as a zoning commissioner. If the project manager had known more basic geology and had a greater appreciation for the scope of modern refraction seismic methods, the site might have been better described for the geophysical contractor. The manager might also have anticipated that the bedrock surface would slope from the outcrop toward the river becoming more deeply buried by the unconsolidated sediment.. Perhaps the contractor should have been more familiar with the region and the site's potential problems for data acquisition. Regardless of what should have been the case, decisions were made that affected the data acquisition and the subsequent interpretation. Fortunately, the contractor's experience with refraction methods incorporating the strength of the GRM allowed a successful technical study to be completed.

Budget was a major consideration in this project. Fn an effort to shape the data acquisition program to accommodate the available budget, the contractor relied on the engineer's need for subsurface information and the anticipated geology. First, only one target was of interest, the top of the bedrock. Second, the target was believed to be within a few meters of the surface. Third, the refractor should show a high velocity contrast with respect to the overlying material. These three presumptions suggested that an XY value of zero would be satisfactory. Using an XY value of zero meant that the depth to the bedrock would be determined under each geophone position based solely on the forward and reverse direction arrival times at each geophone. Close spaced geophones would not be used to define an optimum XY. Although the lateral detail of the refractor would be reduced by the open geophone spacing, for the permitting and design process, the project manager only needed to know whether or not the bedrock sloped toward the river. A geophone interval of 50 ft (15.2m) was selected. This should have allowed a fairly rapid production rate along each survey line and should have yielded the overall configuration of the bedrock surface.

Not knowing about the windblown sand and anticipating a thin overburden and minimal background noise at the remote site, the contractor had hoped to use a sledgehammer source for much of the survey. Some use of explosives was anticipated, though, for the long offset shots. The sledgehammer proved to be insufficient even where the bedrock was less than 2m below the surface. The explosives, of course, solved this problem, but the production rate was immediately retarded because of the need to dig shot holes. Digging in the sand was easy, and the delay between shots allowed ample time for the first break data to be plotted in the field. Plotting the data in the field is necessary to insure continuous coverage of the target refractor. However, the extra cost for explosives and the extra field time consumed digging shot holes rapidly eroded the contractor's profit margin.

Figure 12 shows the shooting geometries for several spreads along part of one line. Each spread had one long offset shot and one short offset shot on each end of the spread and one mid-spread shot. Each spread overlapped the next one by two geophone positions. Figure 13 shows two typical field records. On Record 9, textbook quality first breaks can he timed on the near traces, but the breaks become less distinctive with increasing distance. Record 10 (Fig. 13) is from a long offset shot. Lower energy is expected in this case, and the seismograph gain was increased to account for that. Increasing the gain increased the amount of noise recorded. The spikiness on the traces is wind noise. On Record 10, no distinctive first breaks can be identified. However, on most of the traces, the trough that follows the first break can be seen. Timing this event is legitimate for the long offset shot because the objective is to obtain arrivals for phantoming to the near offset shot and because the trough often follows the first break by a fixed amount of time over much of a record. The troughs and the first breaks, therefore, would give parallel travel time patterns. Phantoming the trough arrivals would give the same results as phantoming true first breaks. Even using the troughs for the three or four most distant traces on Record 10 (Fig. 13) would be difficult. These are of less importance, though. In the present case, obtaining the first-break-type arrivals for the target refractor for the near traces on Record 9 is more important.

Figure 14 shows the forward direction travel. time data for this line. The travel time data essentially suggest a two layer case, and good parallelism can be seen in the high velocity, deeper layer arrivals. However, the paral-

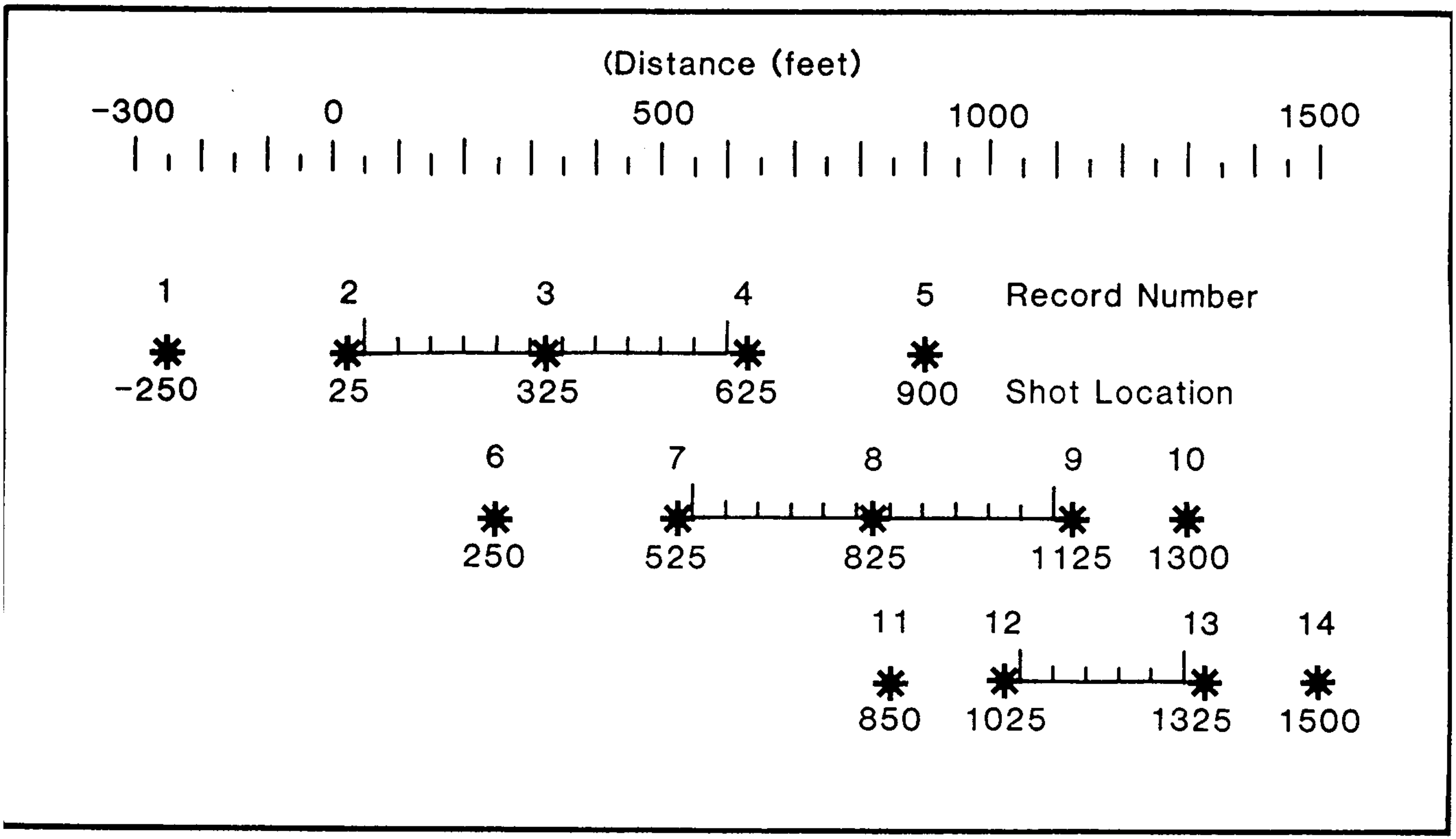


Figure 12. Geophone spreads and shot points. The two long spreads show a five-shots-per-spread geometry commonly used for obtaining continuous coverage along one subsurface refractor.

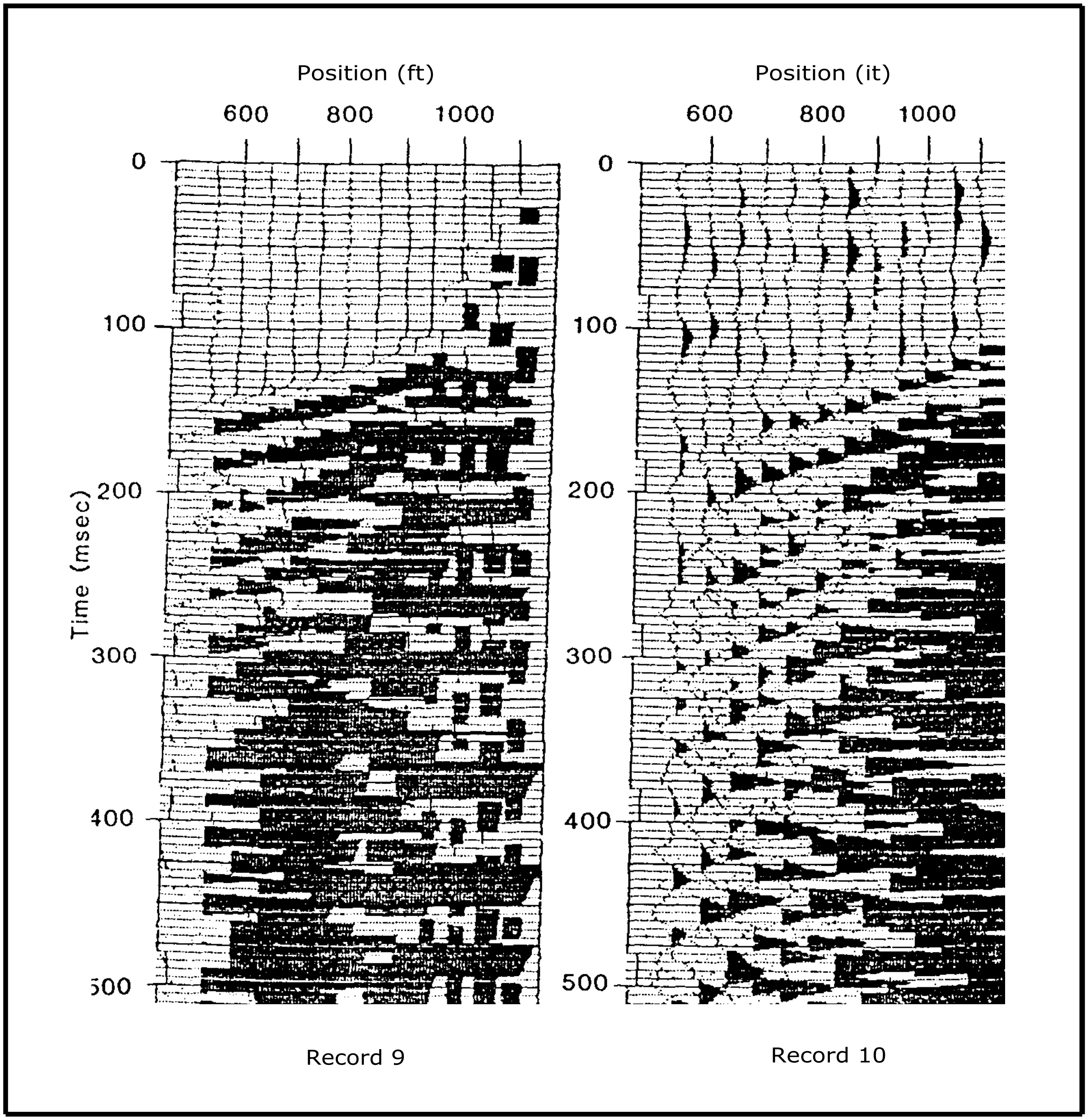


Figure 13. Field Records 9 and 10.

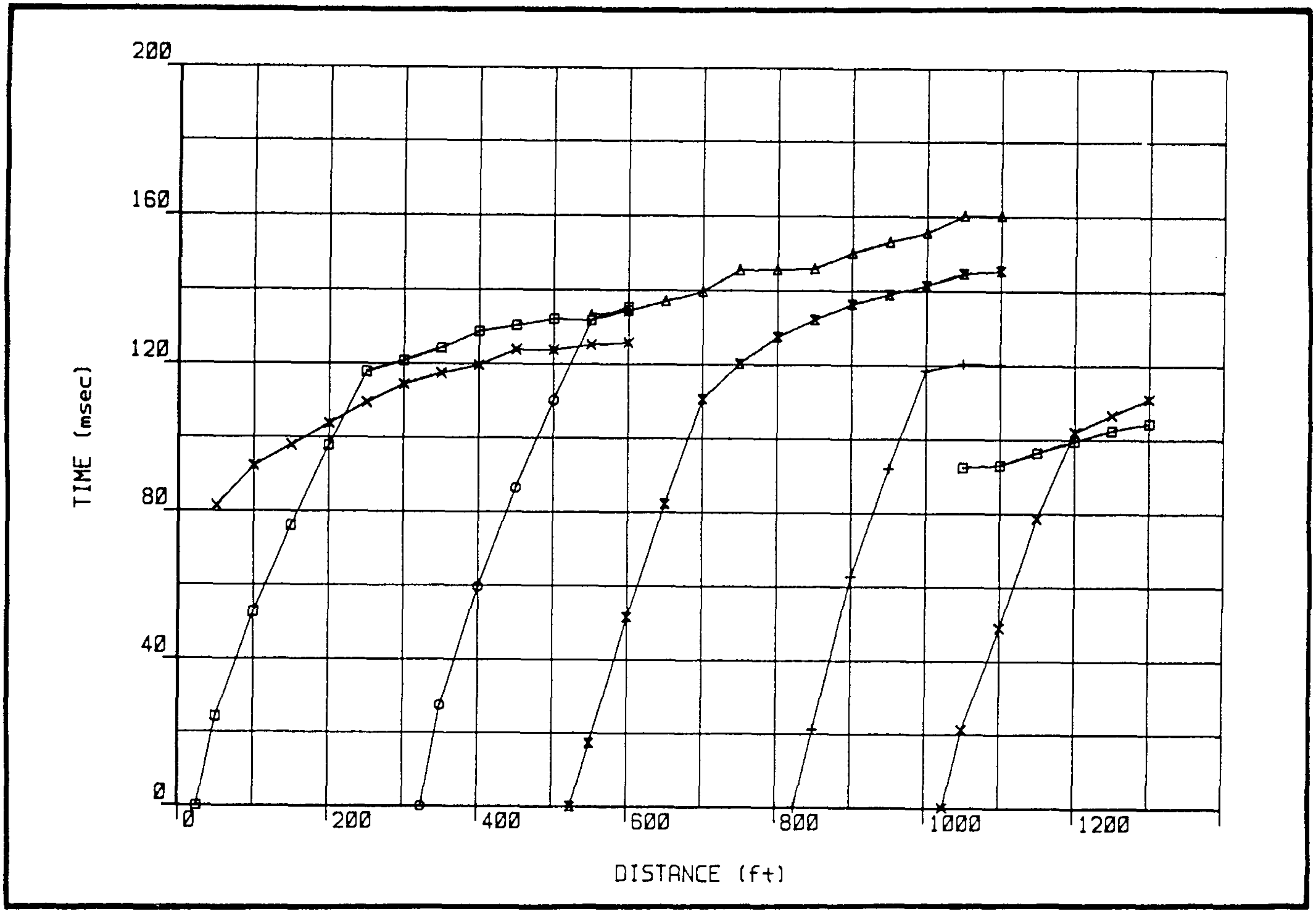


Figure 14. Travel time curves for forward direction shots. The first breaks for the far offset shot (X's) for the leftmost spread arrive earlier than those from the near offset shot (Shotpoint 25) (squares). This occurs when the distance between the shotpoint and the refractor decreases significantly between the near and the far offset shots.

lelism deteriorates between 700 and 800 ft (213 and 244 m) along the line This is the case that is illustrated in Figure 4b. A shorter geophone spacing would have resolved this zone better. The presence of this feature on the time distance curves acts as a reminder that hidden layers do exist. The interpreter is left with a question regarding the lateral extent of this feature. It could be a small erosional remnant of highly fractured basalt protruding upward from the main bedrock surface. Alternatively, the anomaly could be caused by a thickening of a laterally extensive layer with a velocity intermediate between the low velocity, unconsolidated section and the high velocity bedrock. The layer in question may be too thin to be seen across most of the line, but it happens to be thick enough to be seen in one first break at 750 ft (229 m). Presence of a continuous layer is geologically possible. It could be a saturated zone perched above the bedrock, it could be caliche zone, or it could be a zone of highly weathered basalt. Additional shots along the line in addition to closer spaced geophones are necessary to make any qualitative statements about this anomaly. A significant increase in the amount of data would be necessary to quantify the geologic source of the one point anomaly in Figure 14.

Figure 15 presents the reverse direction travel time data. These data offer no help in resolving the hidden versus discontinuous layer problem. The interpreter's only hope lies with the XY evaluation. However, that is effectively precluded in the present data set because of the broad geophone spacing.

The data were phantomed by applying the intra-line method described by Lankston and Lankston (1986) using the forward shot at position 325 ft (99 m) (Fig. 13) and the reverse shot at position 1125 ft (343 m) (Fig. 14). Between each observed (or phantomed) point on the travel time curves, a travel time has been interpolated (Fig. 16). This was done in an attempt to improve resolution of the XY value, but it is of debatable utility where lateral velocity changes occur and where the refractor is irregular. Figure 17 gives the velocity analysis curves. Applying Palmer's (1980) criterion of least detail, the curve for XY equals zero is probably the one to select. Apply Palmer's (1980) maximum detail criterion to the time-depth data in Figure 18, an XY value of zero is selected again. Of course, in generating the time-depth curves, the refractor velocity is needed. Three velocities were interpreted along the refractor. Figure 19 shows the interpreted straight lines and indicates the positions of the changes from one velocity to the next.

Selection of the optimum XY value from the velocity analysis and time depth curves is a somewhat subjective (interpretive) processes. In the pre sent case, because the bedrock surface was not as shallow as initially anticipated and because the depth varies considerably along the line (Fig. 20), the optimum XY value probably varies along the line from near zero on the right end of the profile to a greater value on the left end. Without closer spaced geophones, quantifying this change is impossible. However, computer software that implements the GRM must be able to accommodate both laterally changing velocities and laterally changing optimum XY values when they can be identified through the GRM velocity and time-depth function analyses.

In generating the final interpretation section for the target refractor i. e., performing the second stage in the time to depth migration process, the

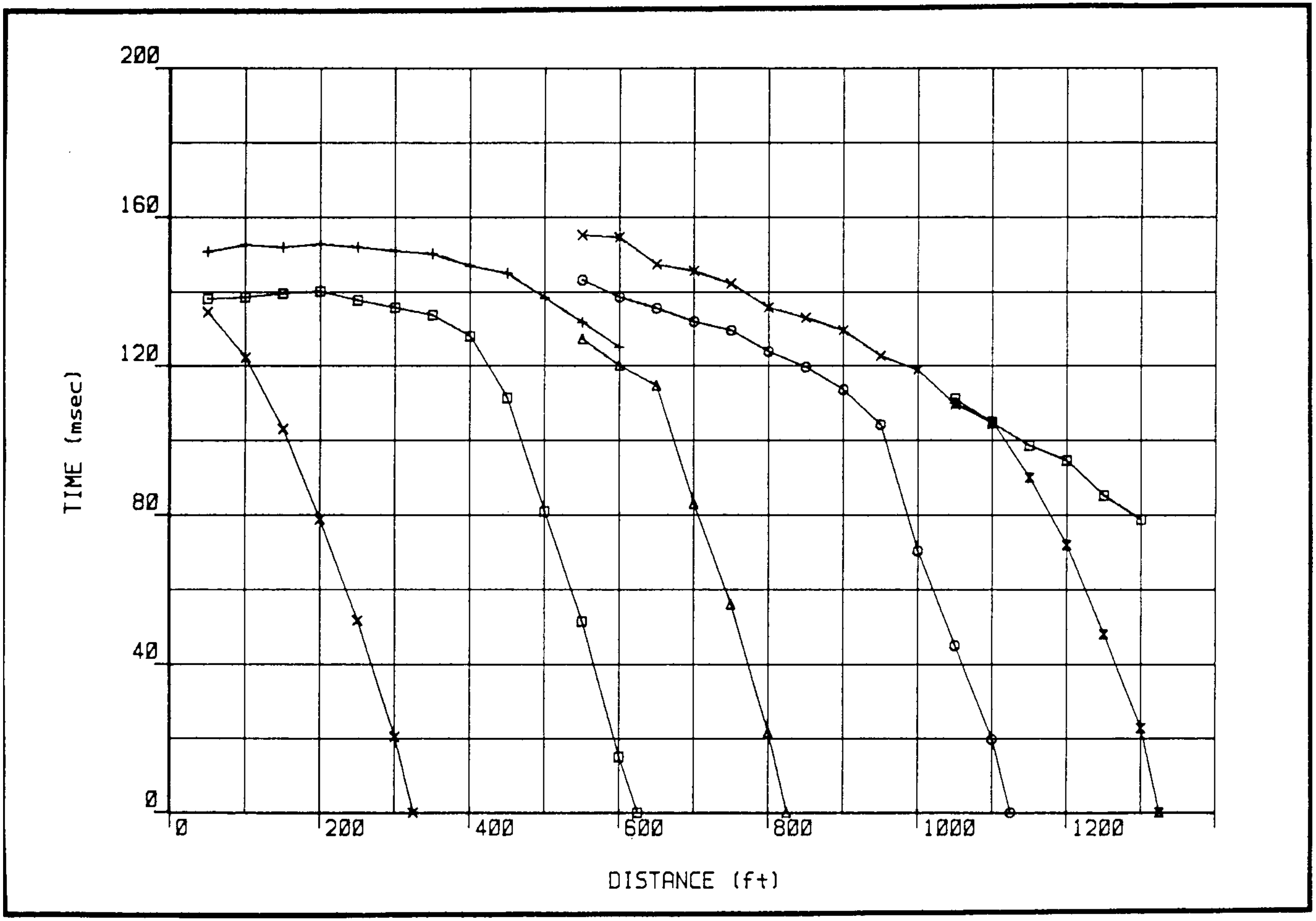
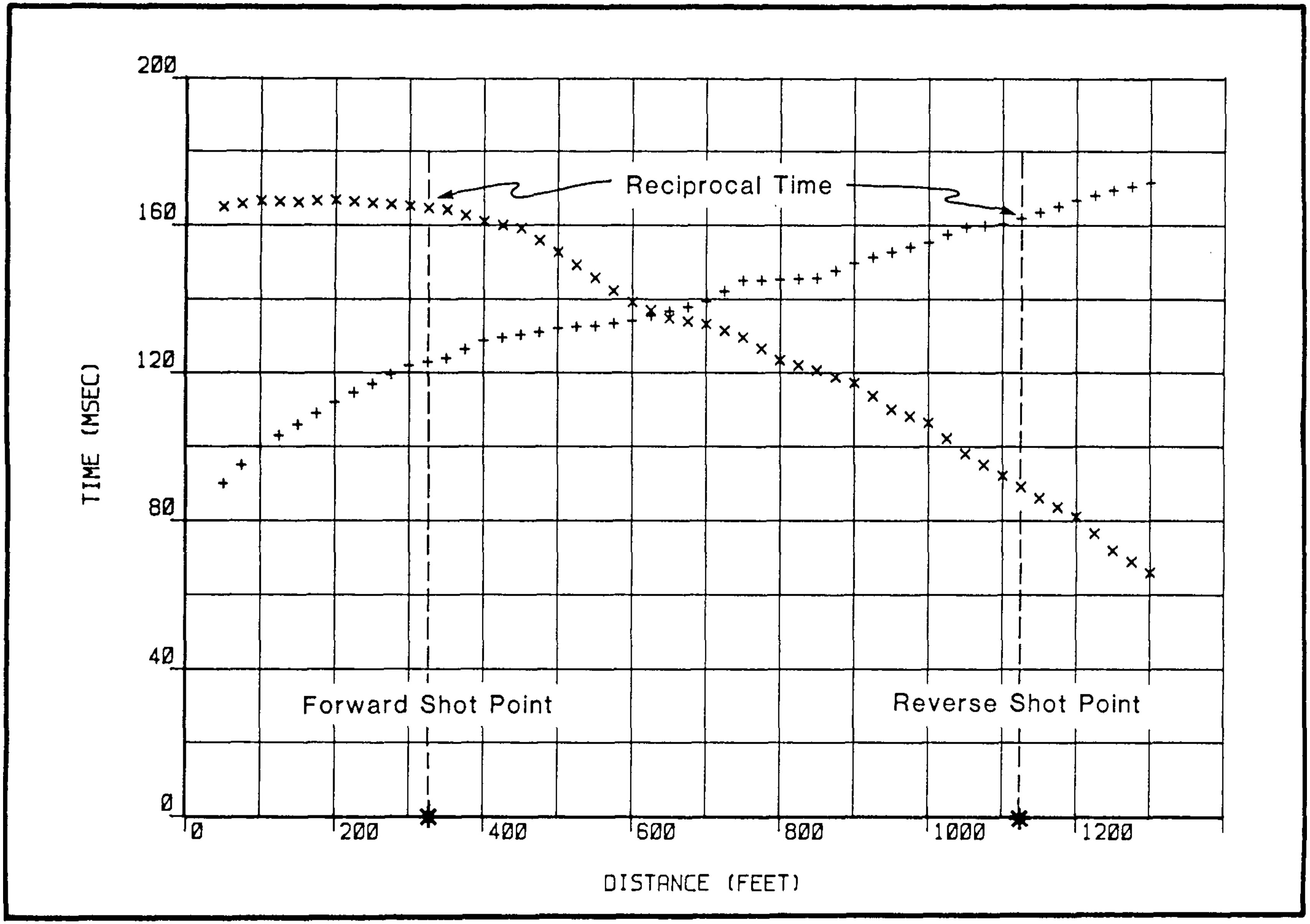


Figure 15. Travel time curves for the reverse direction shots.



TIME (MSEC)
200
160
120
80
40
Ø
Reciprocal Time
Forward Shot Point
Reverse Shot Point
Ø
200
400
600
800
1000
1200
DISTANCE (FEET)

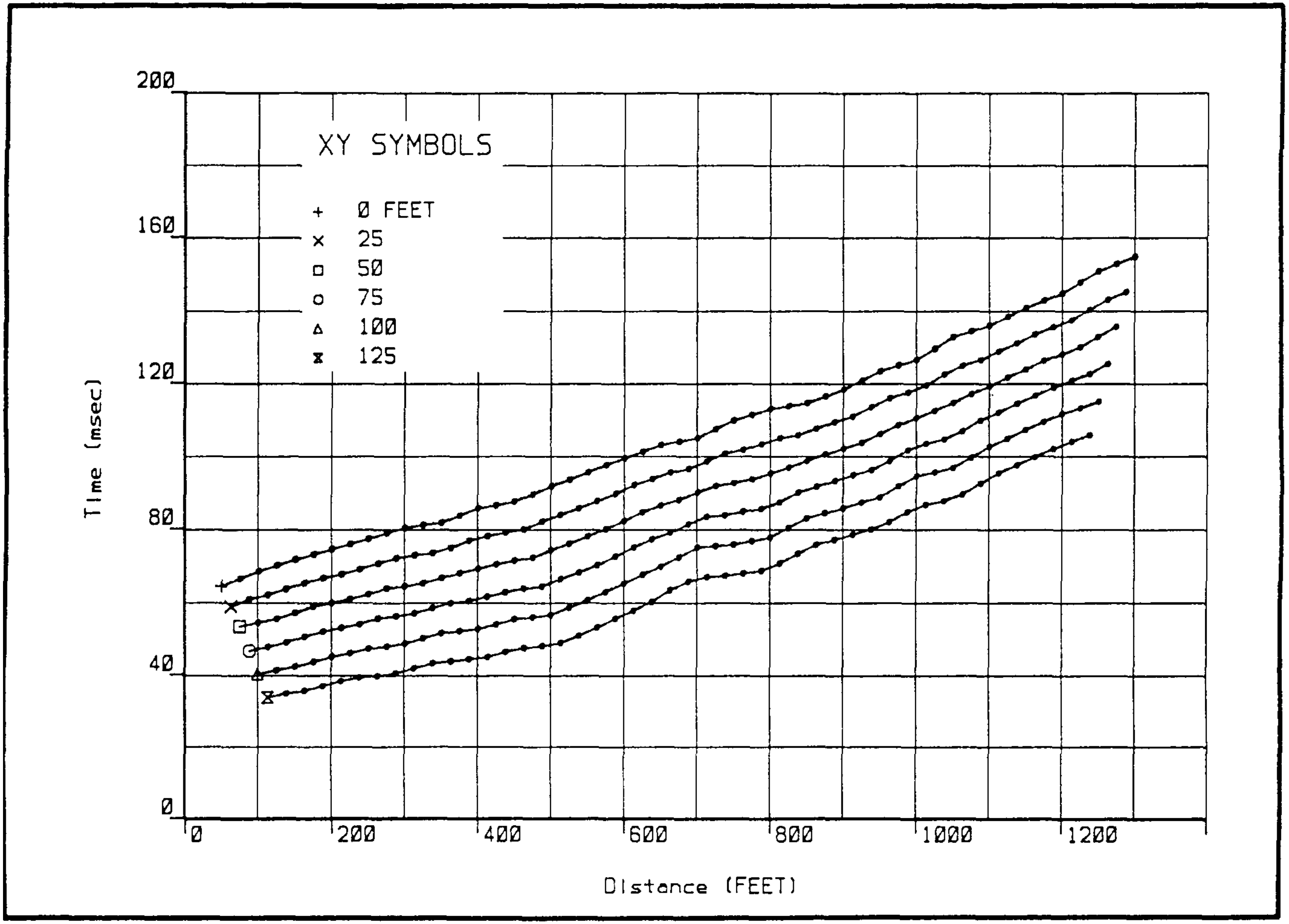


Figure 17. Velocity analysis curves for XY spacings from zero to 125 feet.

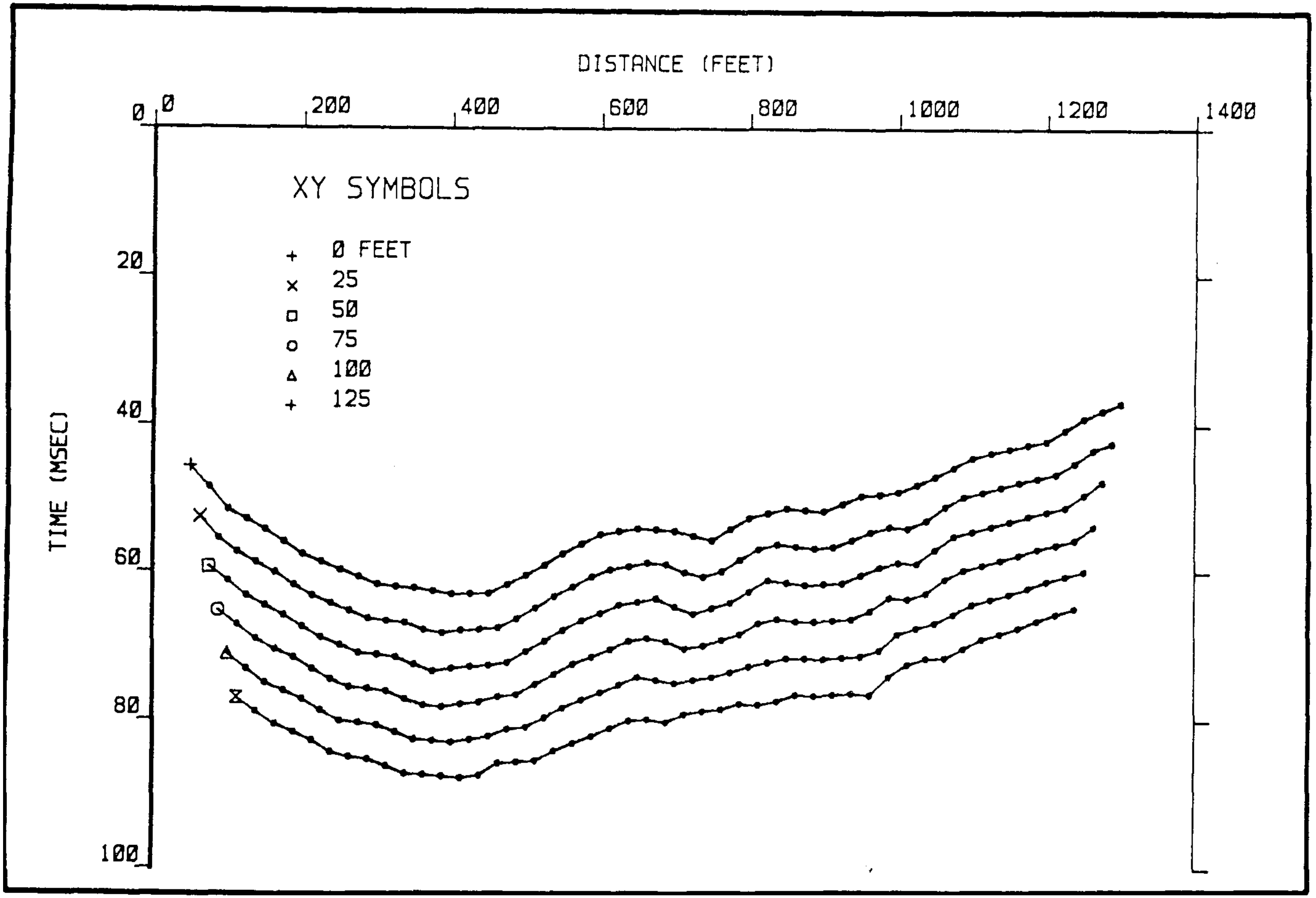


Figure 18. Time-depth curves for XY spaacing from zero to 125 feet. Refractor velocities used to generate these curves are noted in Figure 19.

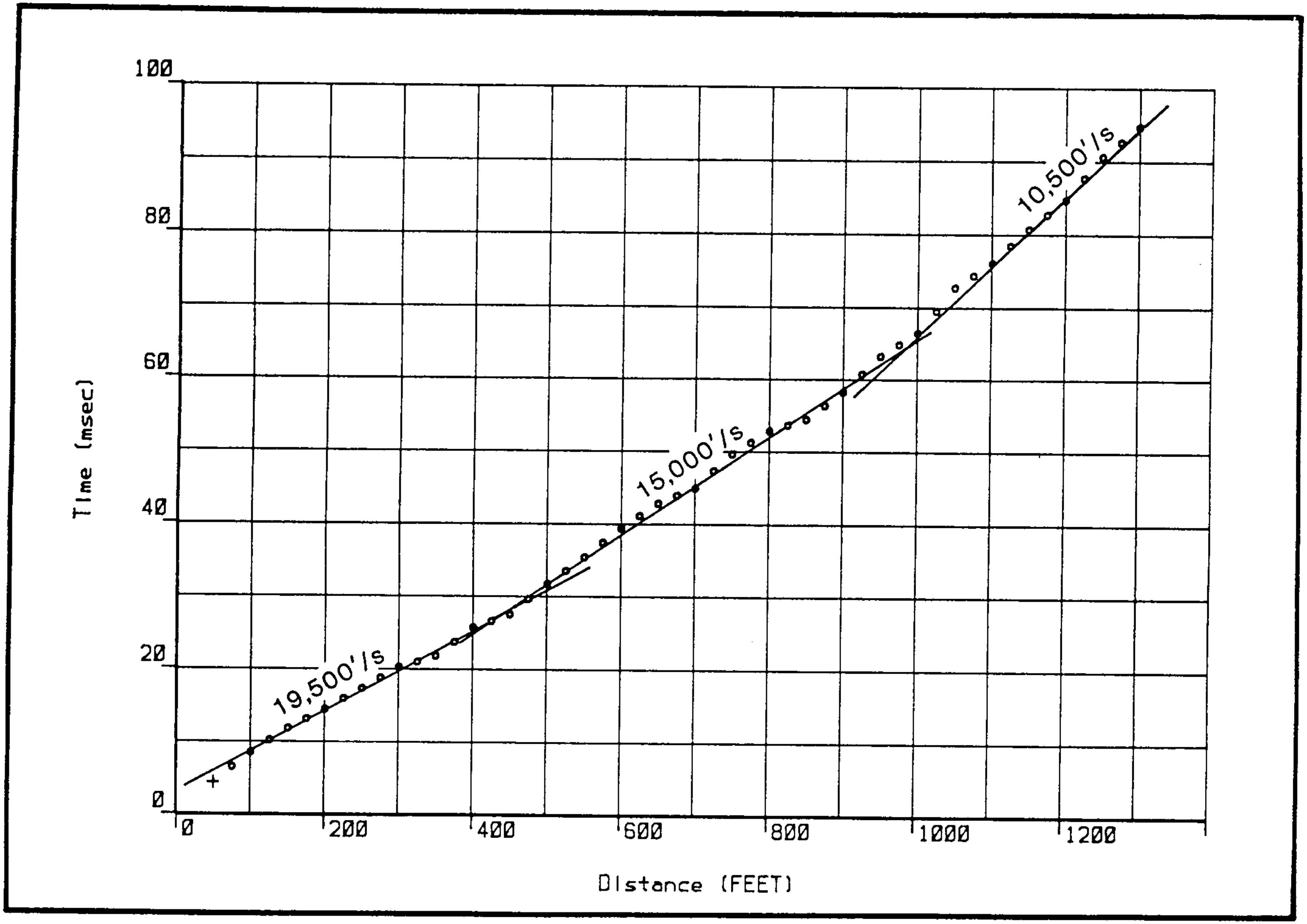


Figure 19. Velocity analysis curve for the XY equals zero case. The refractor is interpreted to exhibit two lateral velocity changes.

velocity of each layer above the target refractor must be known. The thickness of each layer except the one immediately overlying the target must be known. These data are often expensive to obtain continuously along the profile. This is the weakest link in GRM processing, but it adversely affects all refraction data interpretation schemes. The velocities and of overlying layers required for GRM processing are often based on ended shots (Fig. 2) and ITM interpretations. In the present case, the upper layer was assigned a uniform velocity of 1000 ft/sec (305 m/sec) and a thick ness of 10 ft (3.1 m) along the entire length of the line. The second layer was assigned a velocity of 1800 ft/sec (550 m/sec) along the entire length of the line. These velocities were based on means of the velocities determine(from single ended, forward or reverse direction shots for the respective layers. With such open geophone spacing, no more sophisticated velocity analysis of the two layers overlying the target is possible. Though not in the present case, GRM software must be able to accommodate laterally chang ing velocities and thicknesses in the layers overlying the target when the field data allow such changes to be identified.

In the final interpretation cross section (Fig. 20), the refractor surface is the envelope of tangents to the computer drawn circular arcs. The arcs not appear circular in Figure 20 because of vertical exaggeration. When the surface intervals between the G-positions (Fig. 11a) are small enough, as the present case, the arcs overlap considerably, and the surface of the refractor is easy to visualize. However, the positions of the lateral velocity changes along the refractor are indicated. Knowing that the bedrock basalt and that the basalt in this area is essentially flat lying, the interpretation suggested in Figure 20 is that the lateral velocity changes are the result of layering in the basalt.

The "final" interpretation cross section (Fig. 20) should be considerec another, but not necessarily final, stage in the processing. If sufficient data have been collected in the field, if they have been carefully timed and phantomed, if the reciprocal time is known to good accuracy, if the optimum value is determined with confidence, and if the interpretation has been mad(from the surface downward so that each layer thickness and velocity is known, the interpretation section is probably a good representation of the subsurface and can be considered the final interpretation. Evaluation of the depression in the refractor at 750 ft (229 m) is an example of ongoing interpretation in the present case. The depression occurs at the same positiot that a thin layer of intermediate velocity was suggested in the travel time data (Fig. 14). This layer has not been taken into account in generating Figure 20. Had it been taken into account, Equation 7 would have had another term in the summation, and the calculated depth to the target refractor would have been less. The depression that is present in Figure 20 would be less or absent. The observation of the dip on the refractor surface still does not answer the question of the lateral extent of the layer with the intermediate velocity, but processing the data without consideration of the intermediate velocity layer may give a suggestion as the the lateral extent of the anomalous feature.

The refraction survey at the proposed waste disposal site resulted in several profiles that were judged by the contractor to define the bedrock surface reasonably well. This judgement was made on the basis of the quality of the

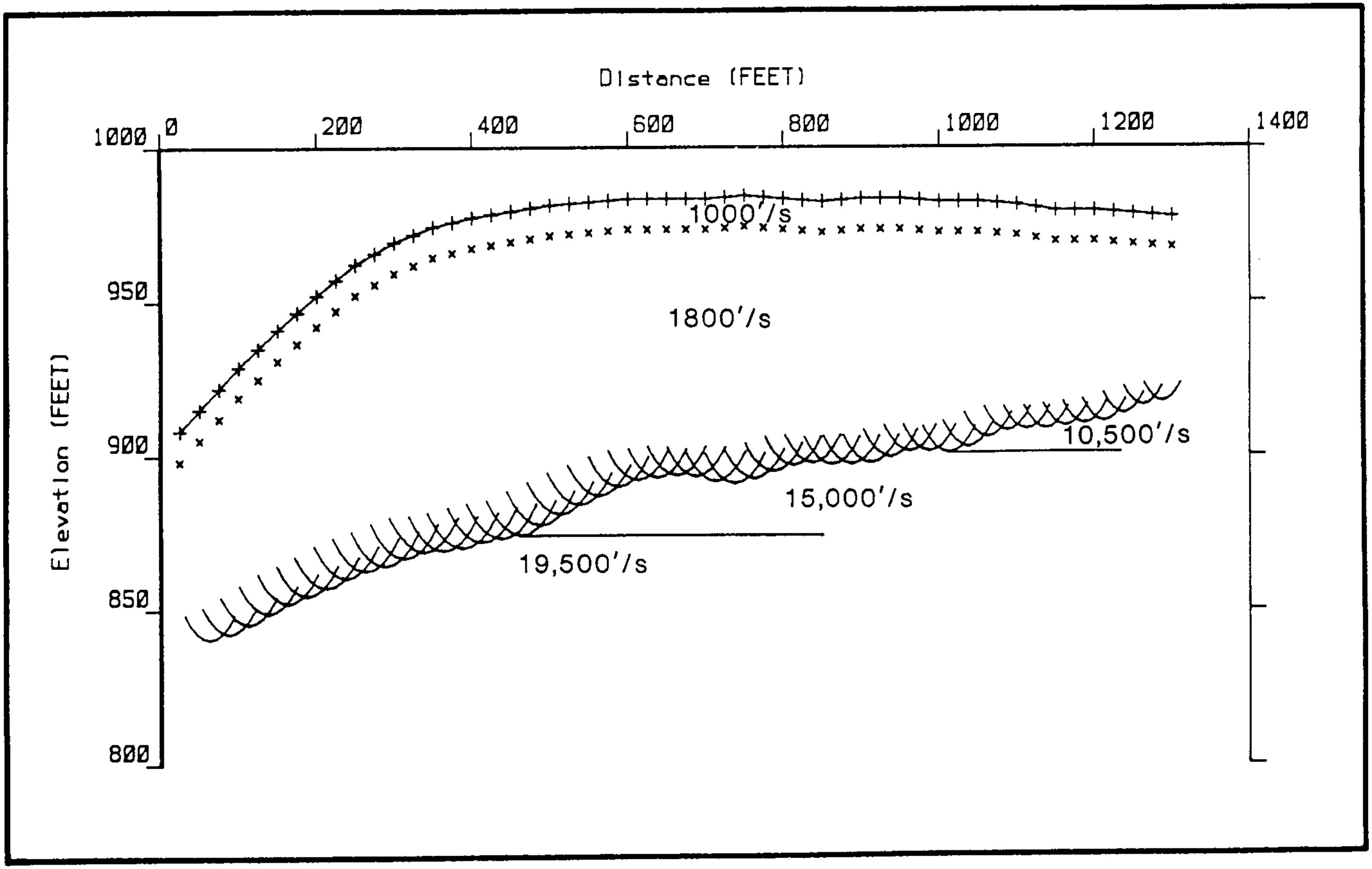


Figure 20. Final migrated section. The refractor surface is the envelope of tangents to the suite of arcs. The surface of the earth is noted by the continuous curve overprinted with +'s. The small x's represent the base the 1000 ft/sec unit and the top of the 1800 ft/sec unit.

first breaks and the multiplicity of coverage. The high velocity contras between the overburden and the bedrock invited the use of zero for the XY distance, and two GRM processing stages demonstrated this to be a choice. The project, however, could have had better results and within available budget if the project manager had been able to offer a description of the site. Insistence on a fixed-fee contract instead of a time and materials contract (with limits, of course) showed a lack of knowledge o the variability of the earth and of the strength of modern refraction methods in mapping that variability if field procedures can be varied response to the quick look at the data in the field. The quick look is actu ally a quality control feature of field operations and should be viewed as desirable aspect of the study and not as a luxury. In waste site evaluation and in ground water exploration, i. e., in studies in which high vertical an lateral resolution of near surface targets is important, the refraction mic method is one of the most powerful geophysical tools if appropriate car is taken during field operations. The refraction seismic tool of today orders of magnitude more powerful than it was twenty years ago. When it used properly and in the settings for which it is best suited, it has n equal.

SUMMARY

In all geophysical methods, equations are derived based on a model of the earth. These equations are used to develop methods of interpreting data an for generating synthetic anomalies as an aid in interpretation but more tantly as an aid in survey design. Selection of a particular method of inter- pretation places demands on the way the data are collected in the field.

In modern refraction seismic surveying, the data should be collected the objective of obtaining continuous coverage of the subsurface target. Wit forward and reverse direction continuous subsurface coverage of each refractor , the GRM can be used to interpret the data. The GRM offers greatest power in resolving refractor velocities, and these values and optimum XY value are used to generate a migrated subsurface section. In to collect field data such that continuous refractor coverage is obtained adjacent geophone spreads must overlap, and multiple shots must be from each end of each geophone spread. A reciprocal time must be recorded o be available through phantoming for each target horizon.

Field operations for collecting data to be interpreted with the GRM be more expensive than those that would yield data for intercept time or some other method of interpretation. However, the GRM requires relatively interaction by the interpreter. It can be implemented on any microcomputer including the relatively new laptop types, for ready use at field offices The interpreter's role becomes one of selecting suitable parameters subsequent processing. The computer does all of the computational and cal work. Though field operations to collect the necessary volume of data ma be more expensive, the data processing and interpretation, are not correspond ingly more expensive.

The refraction seismic method with the resolution afforded with an inter preter's aid like the GRM can be used to provide much subsurface information faster and less expensively than reflection seismic methods. It can not provide certain types of data that the reflection methods can, and the converse is true. Consequently, the respective method must be selected when it is the obvious choice. General criteria for selecting the refraction method and GRM data processing are a) the target is shallow, b) lateral velocity and dip changes on the target are expected or are themselves the anomaly of interest, and c) only a few targets are of interest. These criteria are often met in groundwater exploration and waste site evaluations.

REFERENCES CITED

Dobecki, T. L., and Romig, P. R., 1985, Geotechnical and groundwater geophysics: Geophysics, v. 50, p. 2621-2636.

Dobrin, M. B., 1976, Introduction to geophysical prospecting: McGraw-Hill, New York, 630p.

Lankston, R. W., and Lankston, M. M., 1986, Obtaining multilayer reciprocal times through phantoming: Geophysics, v. 51, p. 45-49.

Mooney, H. M., 1977, Handbook of engineering geophysics: Bison Instr., Minneapolis, 186p.

Palmer, D., 1980, The generalized reciprocal method of seismic refraction interpretation: Soc. Explor. Geophys., Tulsa, 104p.

, 1986, Refraction seismics, the lateral resolution of structure and seismic velocity: Geophysical Press, London, 269p.

Redpath, B. B., 1973, Seismic refraction exploration for engineering site investigation: NTIS, Springfield, VA, 51p.

Robinson, E. A., 1983, Migration of geophysical data: Int. Human Resources Development Corp., Boston, 208p.

Telford, W. M., Geldart, L. P., Sheriff, R. E., and Keys, D. A., 1976, Applied Geophysics: Cambridge Press, New York, 860p.

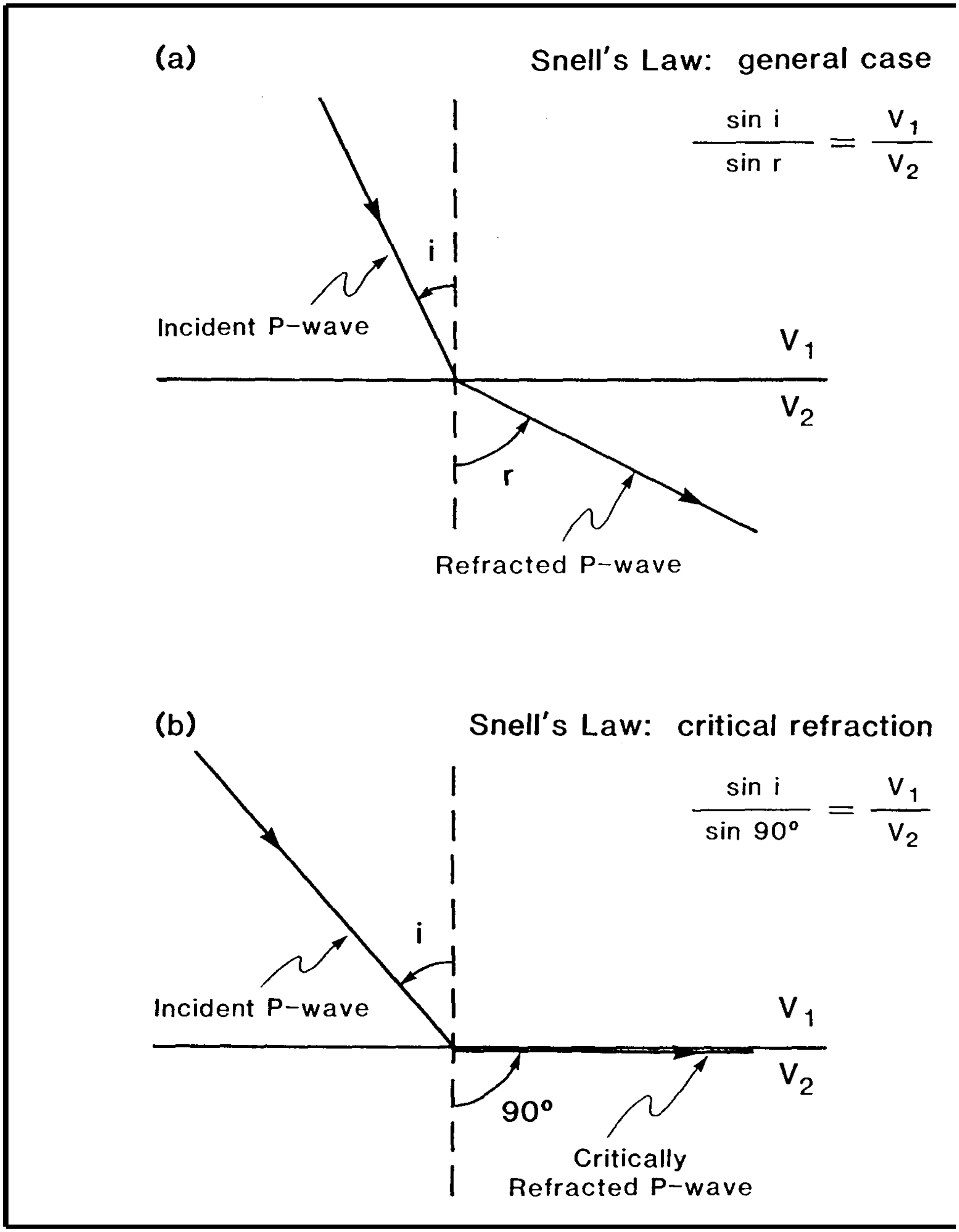


Figure 1. Raypath diagrams illustrating the terms in Snell's Law: a) the general case of incident and refracted rays at any velocity contrast boundary. b) the case of critical refraction.

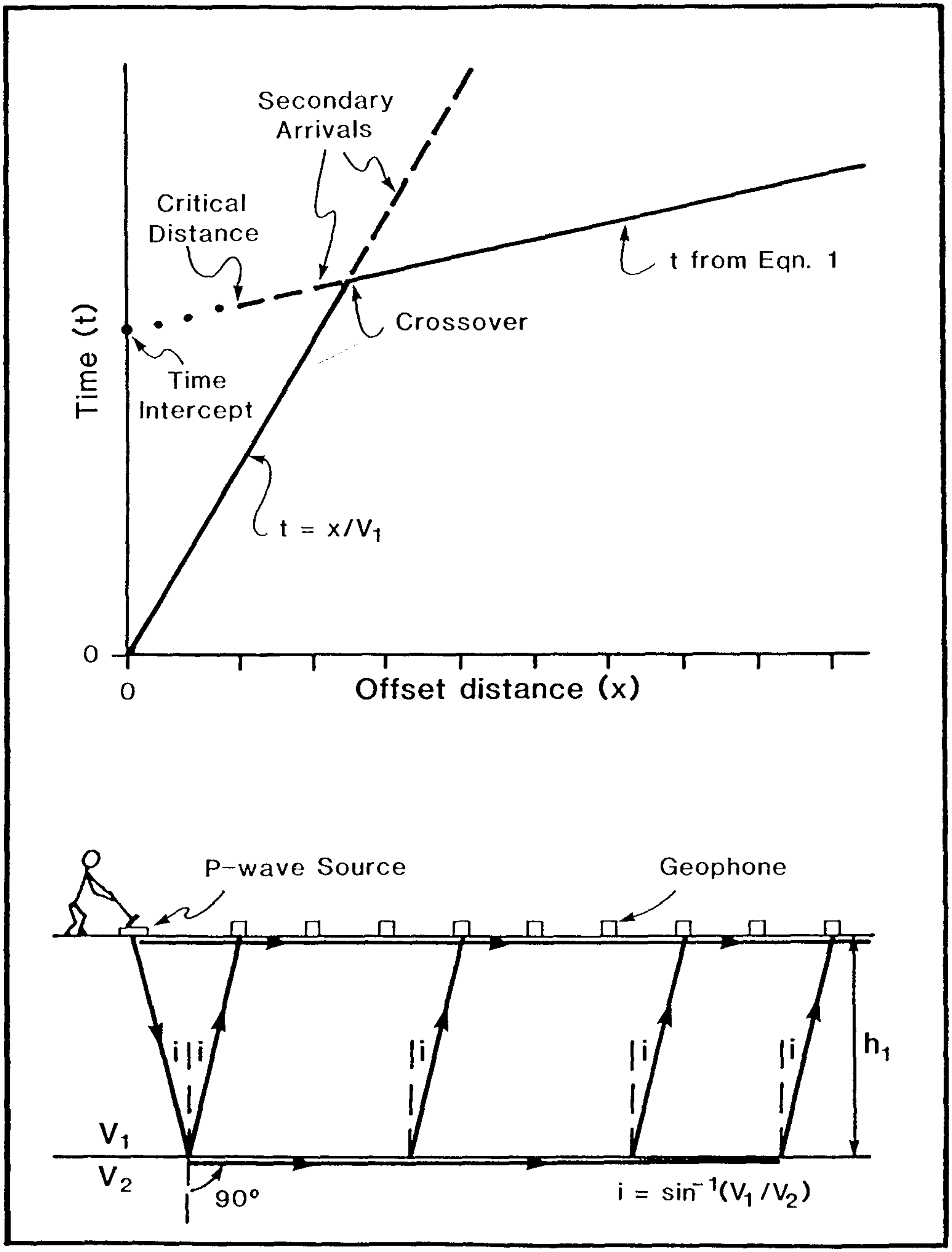


Figure 2. Direct and critically refracted raypaths and the time distance diagram showing the first and secondary breaks from these raypaths.

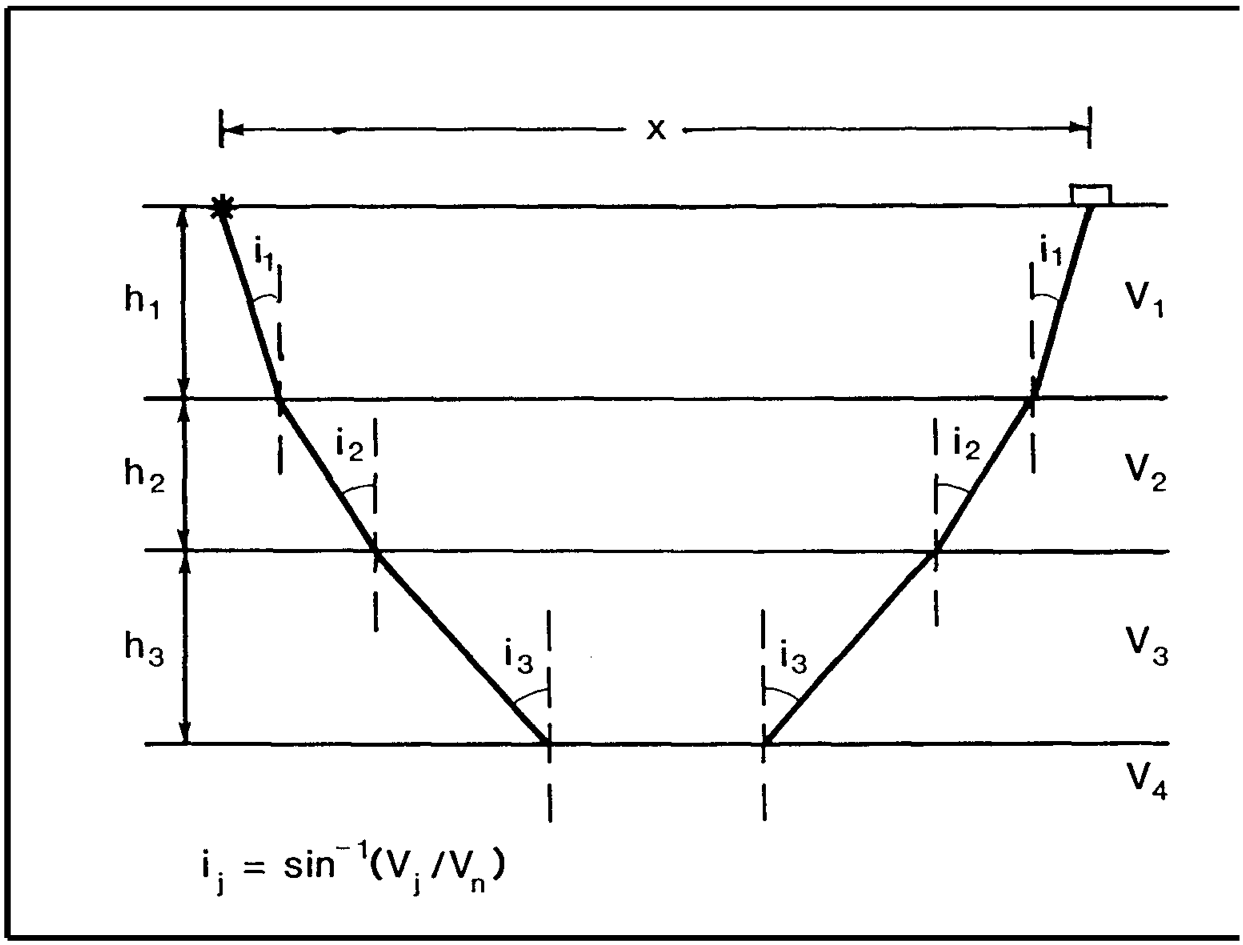


Figure 3. Definition of parameters for the multilayer case.

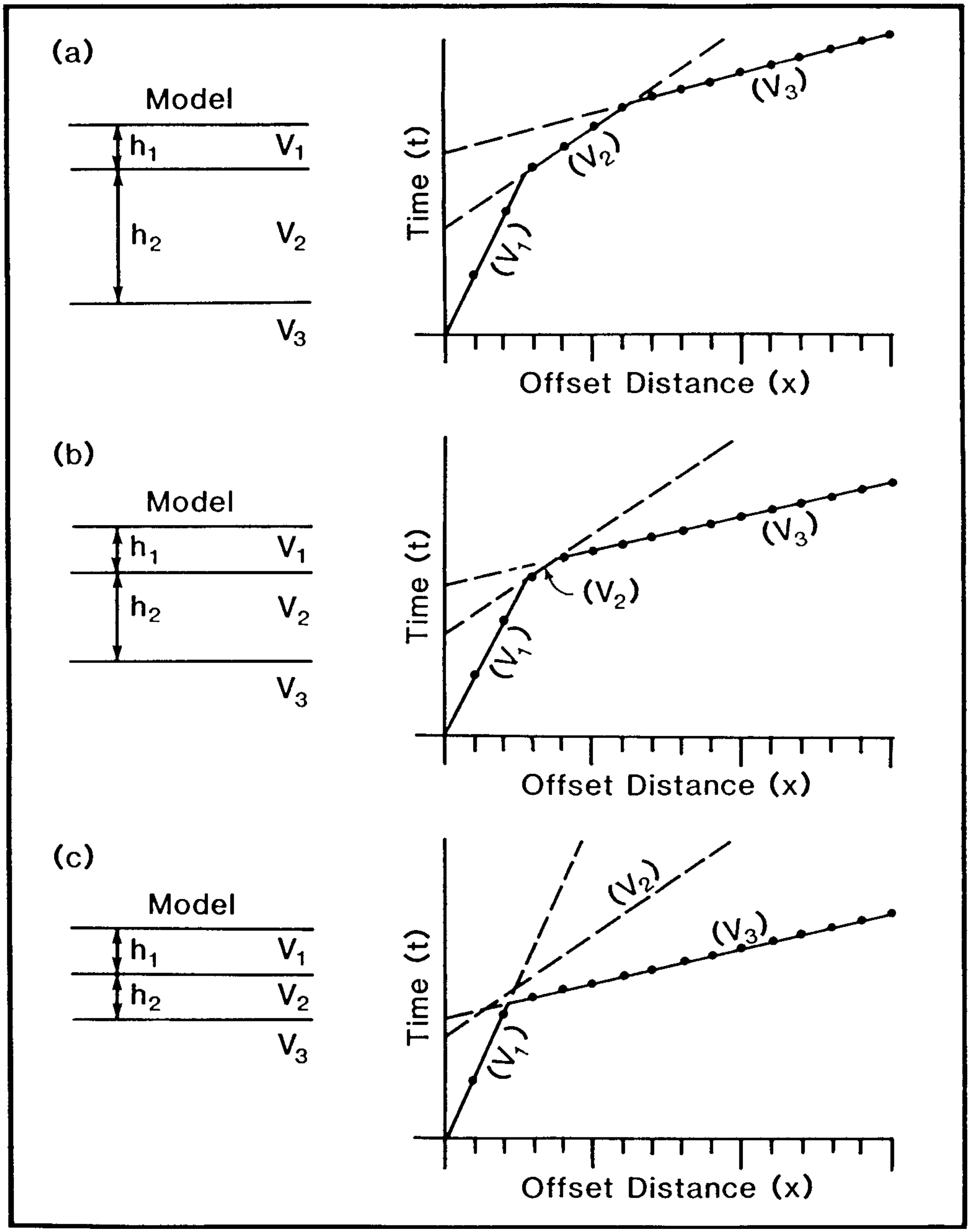


Figure 4. Travel time curves showing the effect of the thickness of the second layer.

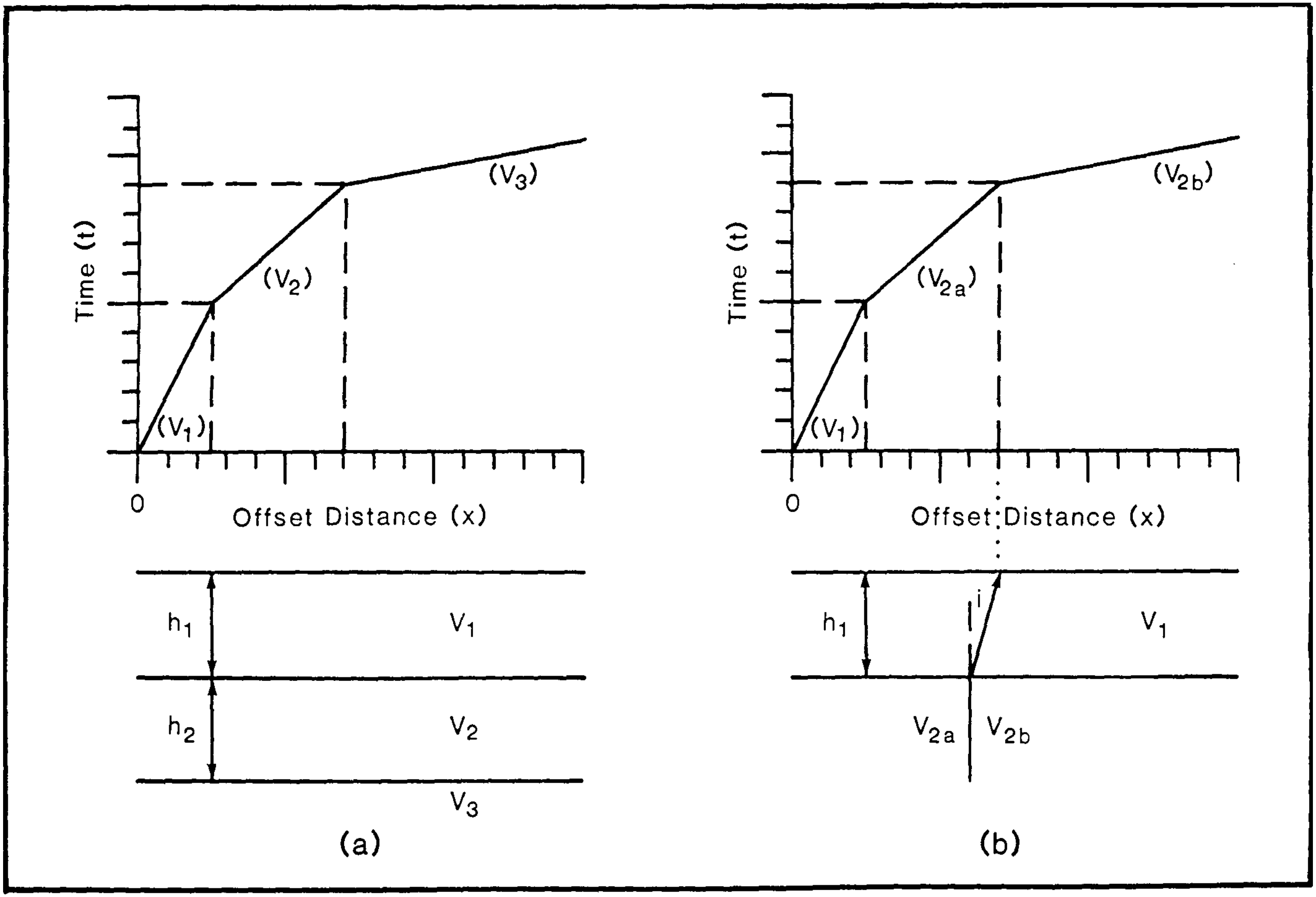


Figure 5. Identical travel time curves observed over a three layer earth and a two layer earth with a lateral velocity change in the second layer.

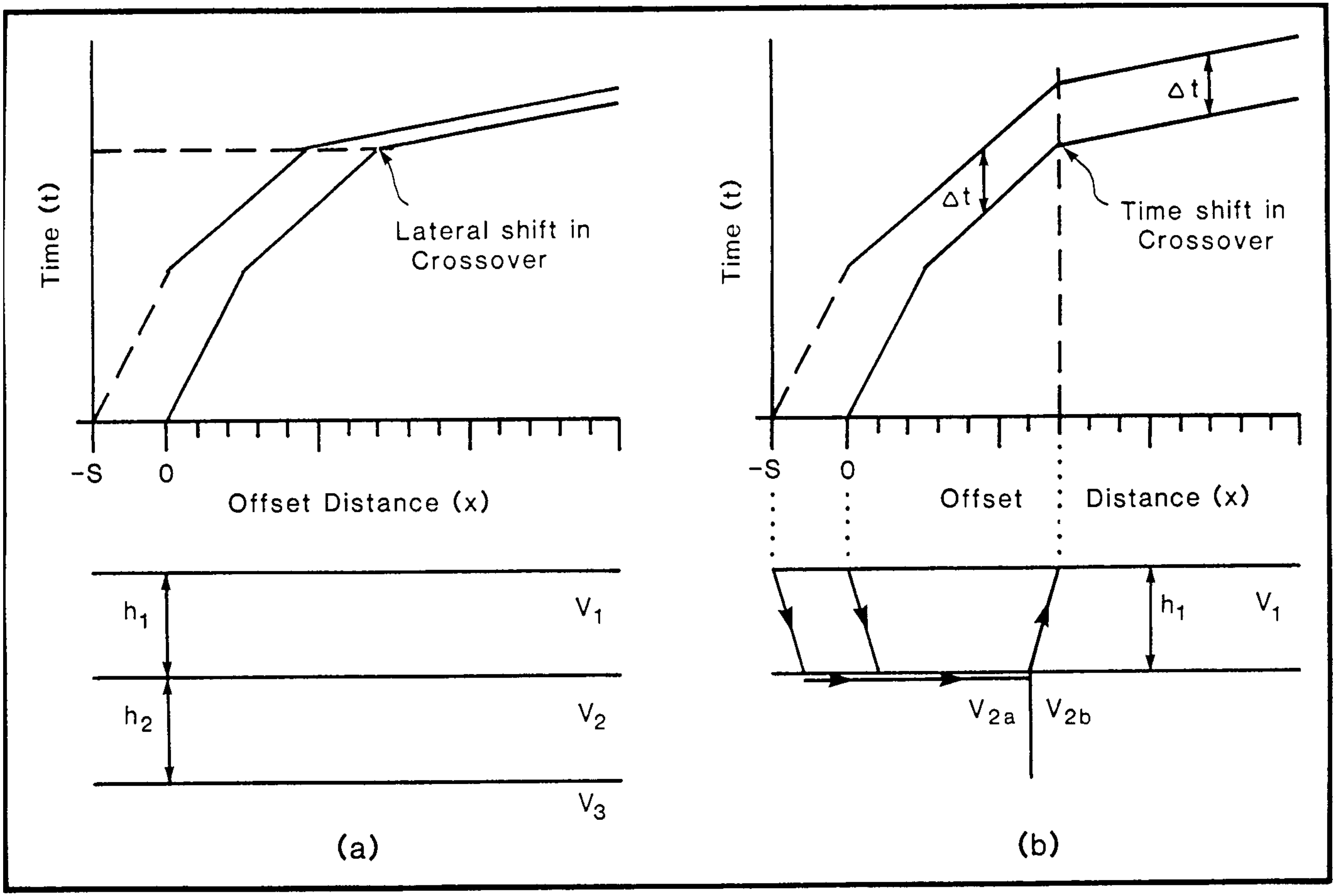


Figure 6. Additional off-the-end shot allows three layer case to be distinguished from two layer case with lateral velocity change.

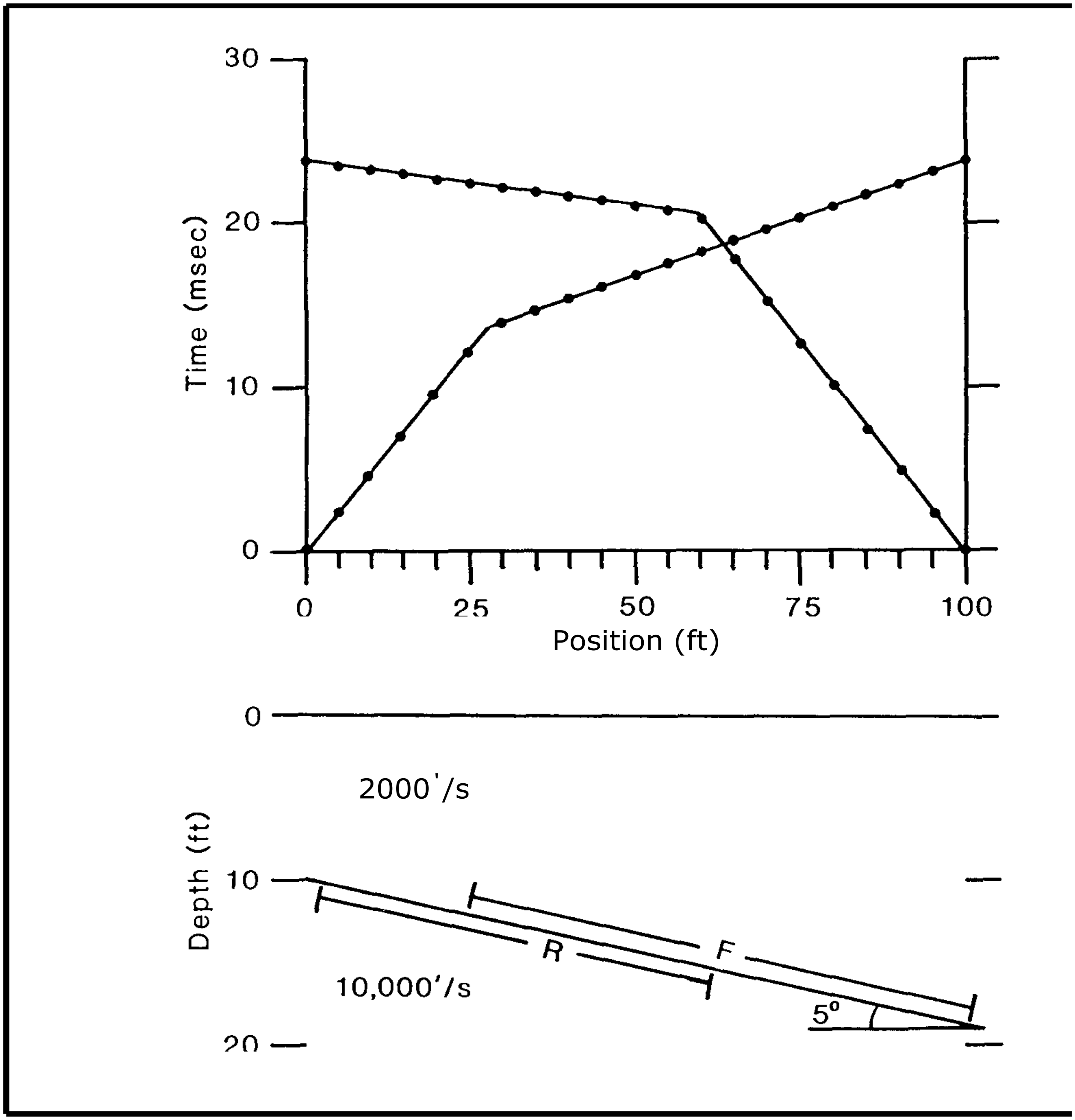


Figure 9. Subsurface model and forward and reverse travel time curves. zones of subsurface coverage for the forward and reverse direction experiments are noted on the model.

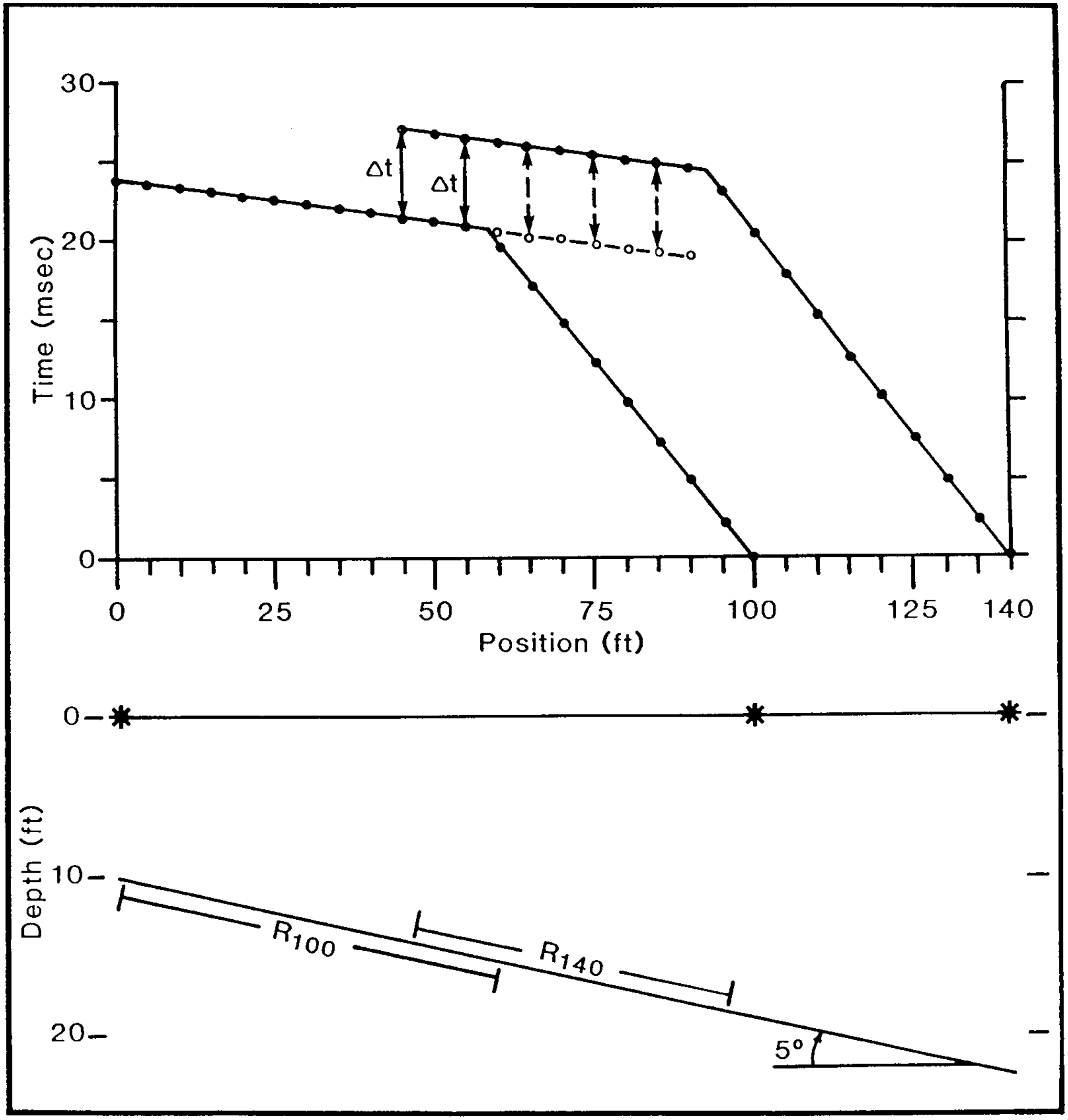


Figure 10. Travel time curves and subsurface coverages from two overlapping reverse direction spreads. Phantomed arrivals are indicated by open circles.

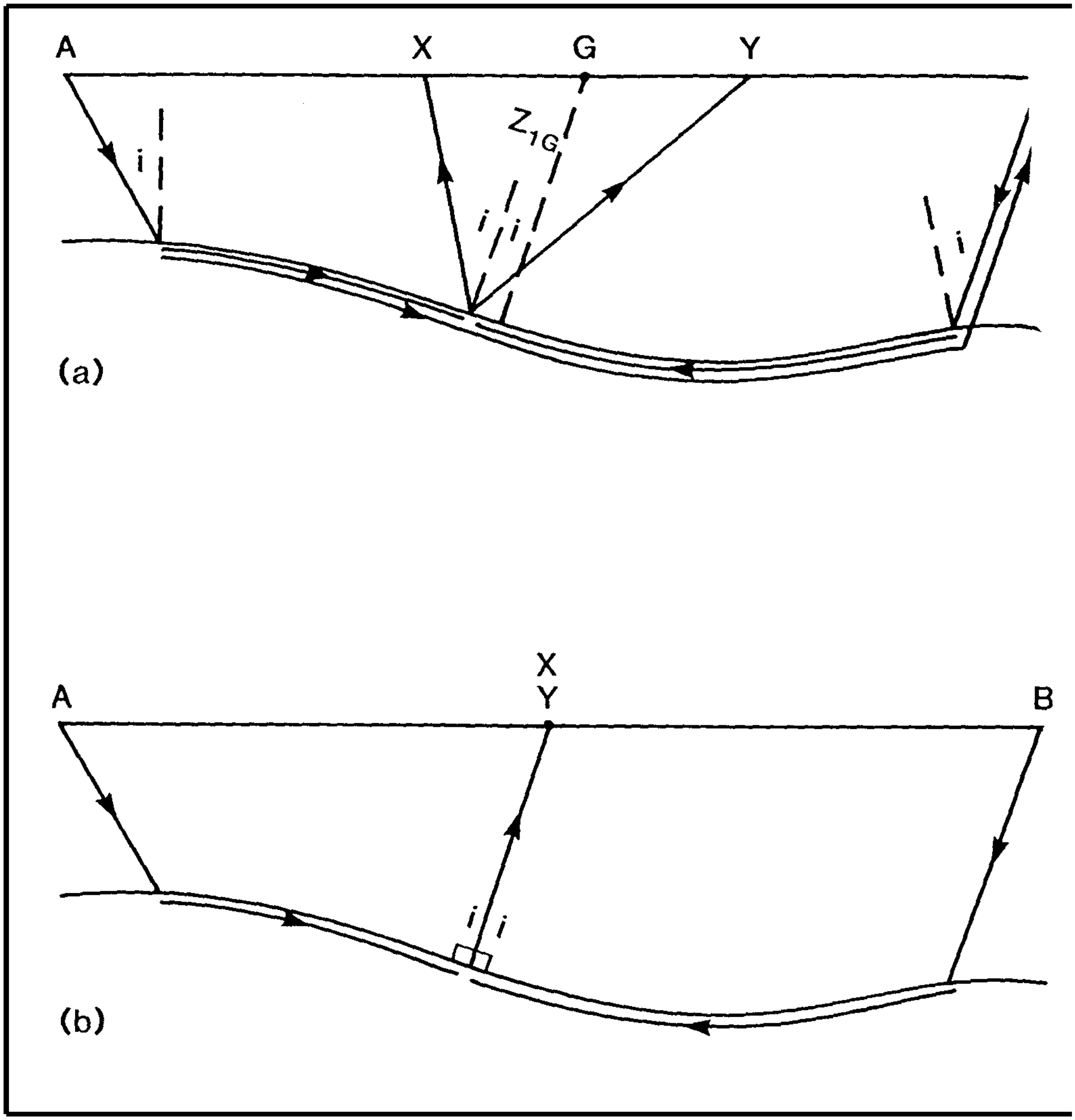


Figure 11. a). Raypath diagram for the optimum XY case. b) Raypath diagram for the XY equals zero case.

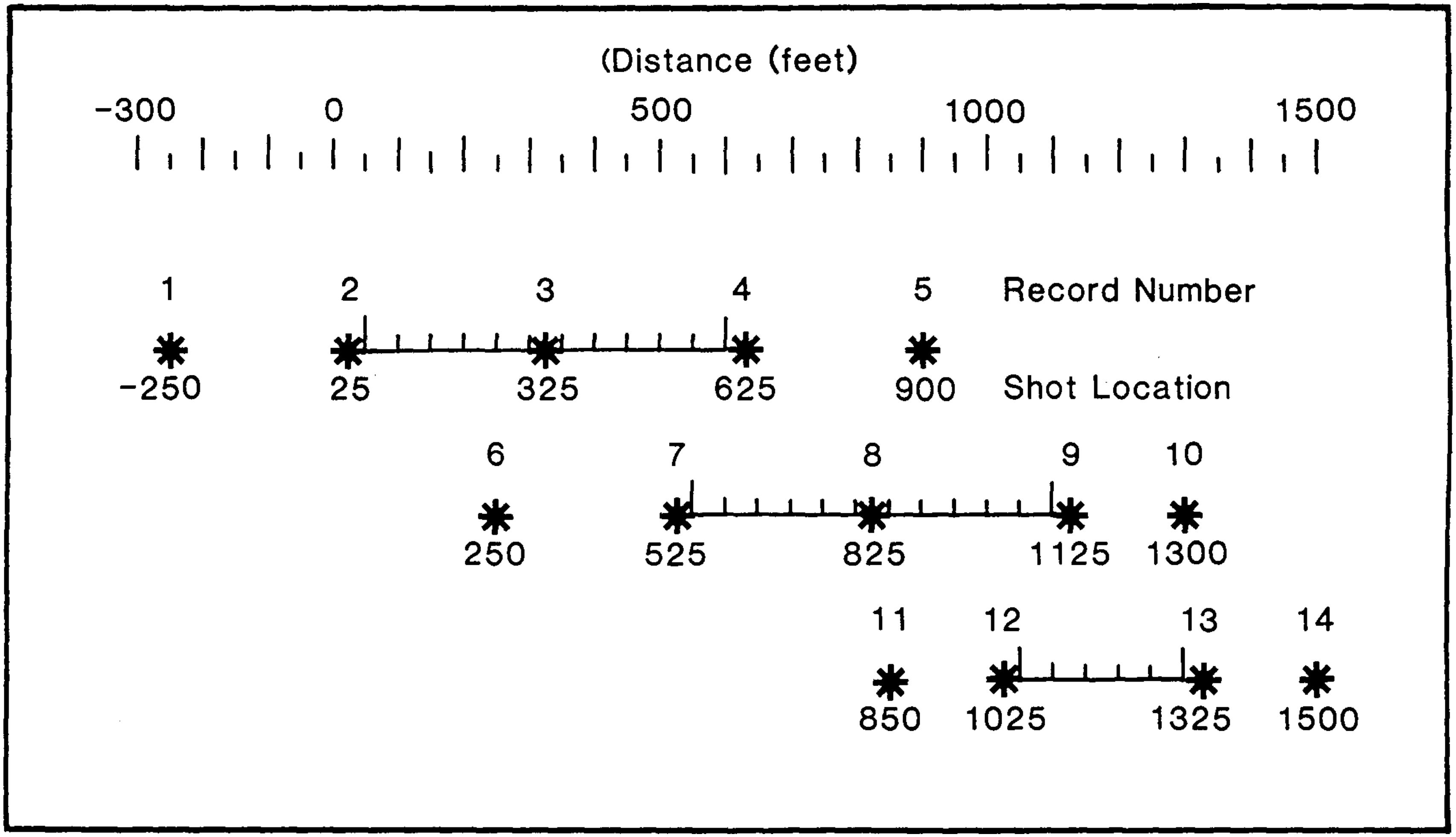


Figure 12. Geophone spreads and shot points. The two long spreads show a five-shots-per-spread geometry commonly used for obtaining continuous coverage along one subsurface refractor.

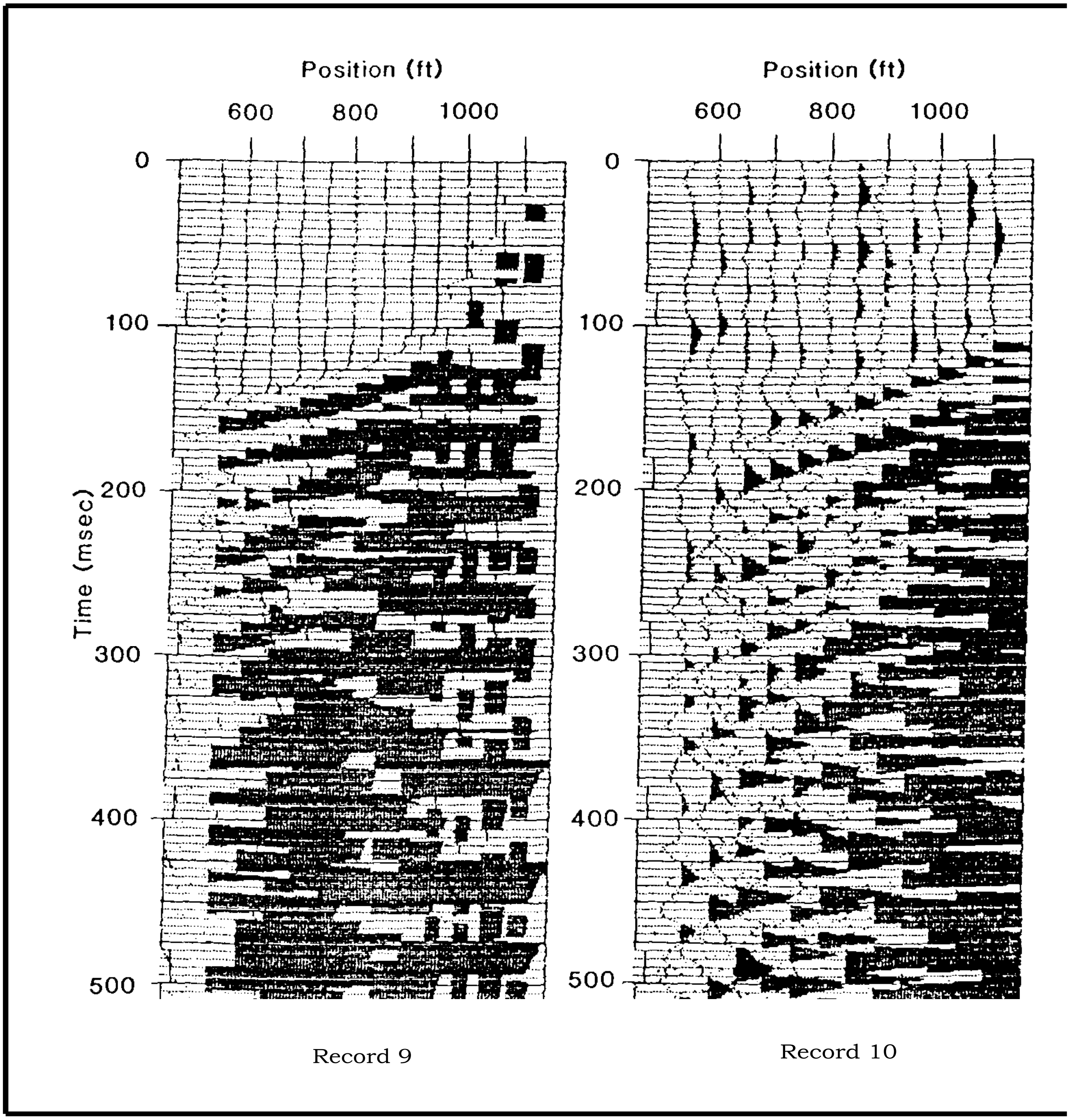


Figure 13. Field Records 9 and 10.

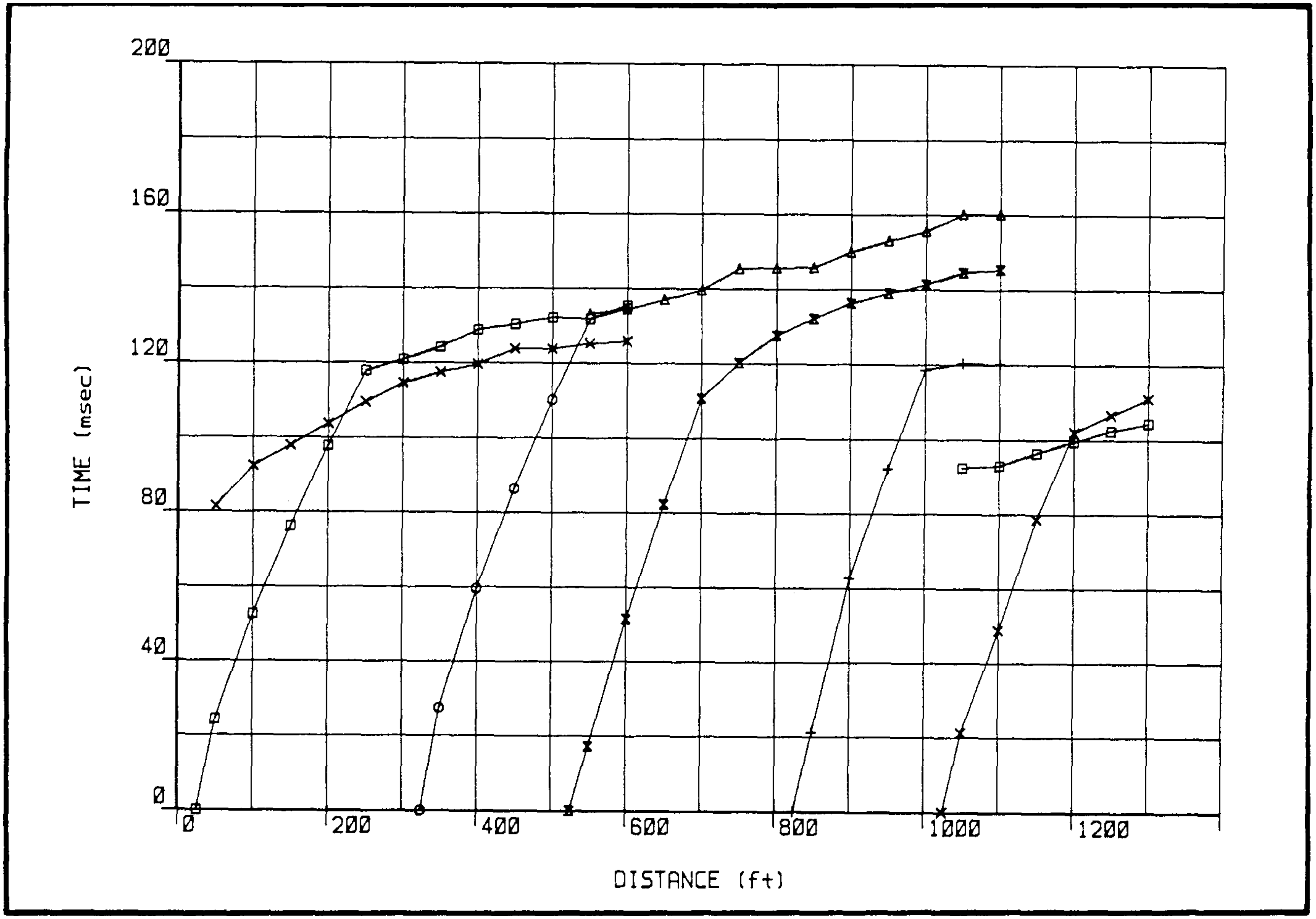
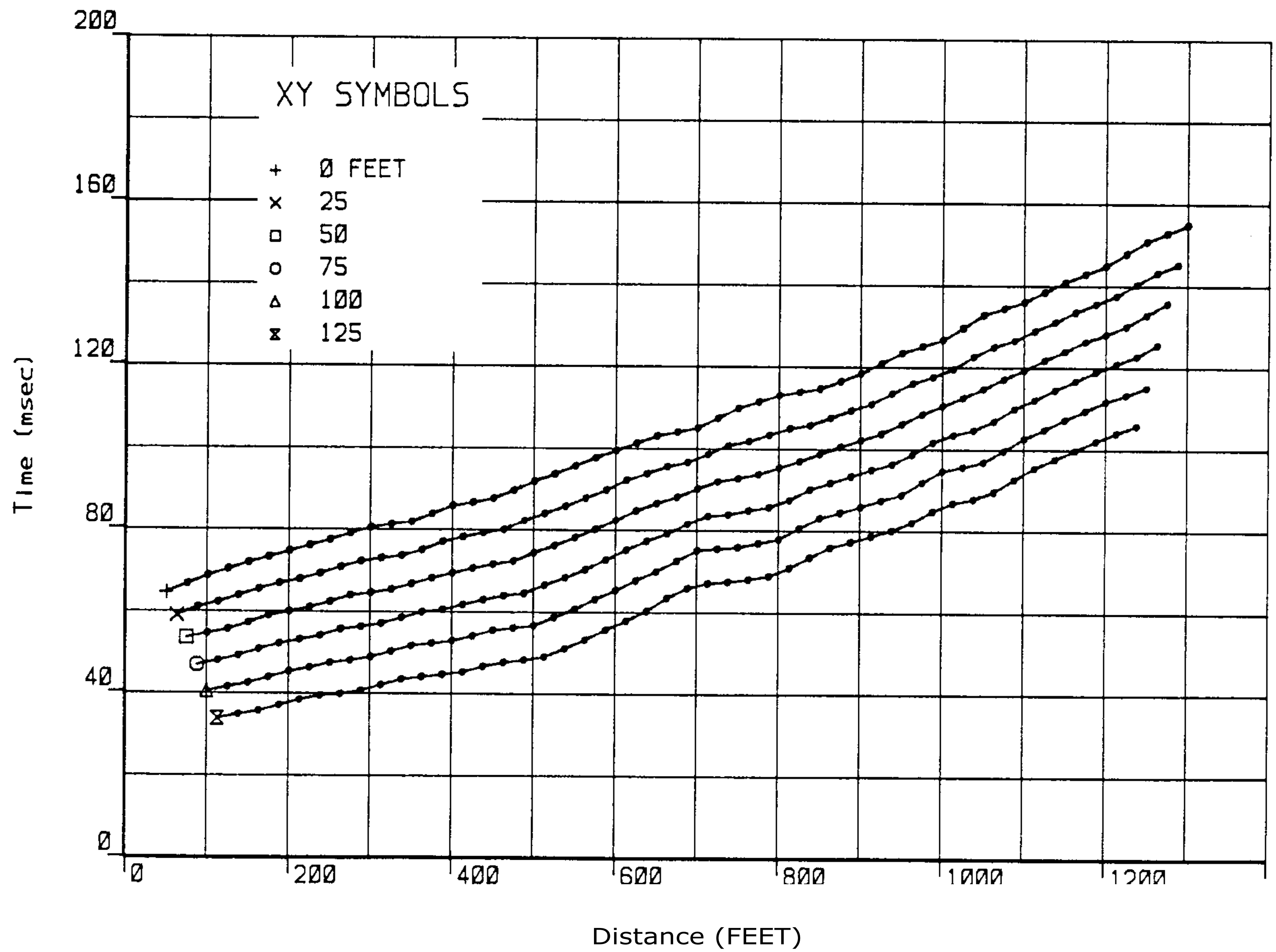


Figure 14. Travel time curves for forward direction shots. The first breaks for the far offset shot (X's) for the leftmost spread arrive earlier than those from the near offset shot (Shotpoint 25) (squares). This occurs when the distance between the shotpoint and the refractor decreases sig-



XY SYMBOLS
+ Ø FEET
× 25
□ 5Ø
○ 75
△ 1ØØ
⧗ 125
Time (msec)
2ØØ
16Ø
12Ø
8Ø
4Ø
Ø
Ø
2ØØ
4ØØ
6ØØ
8ØØ
1ØØØ
12ØØ
Distance (FEET)

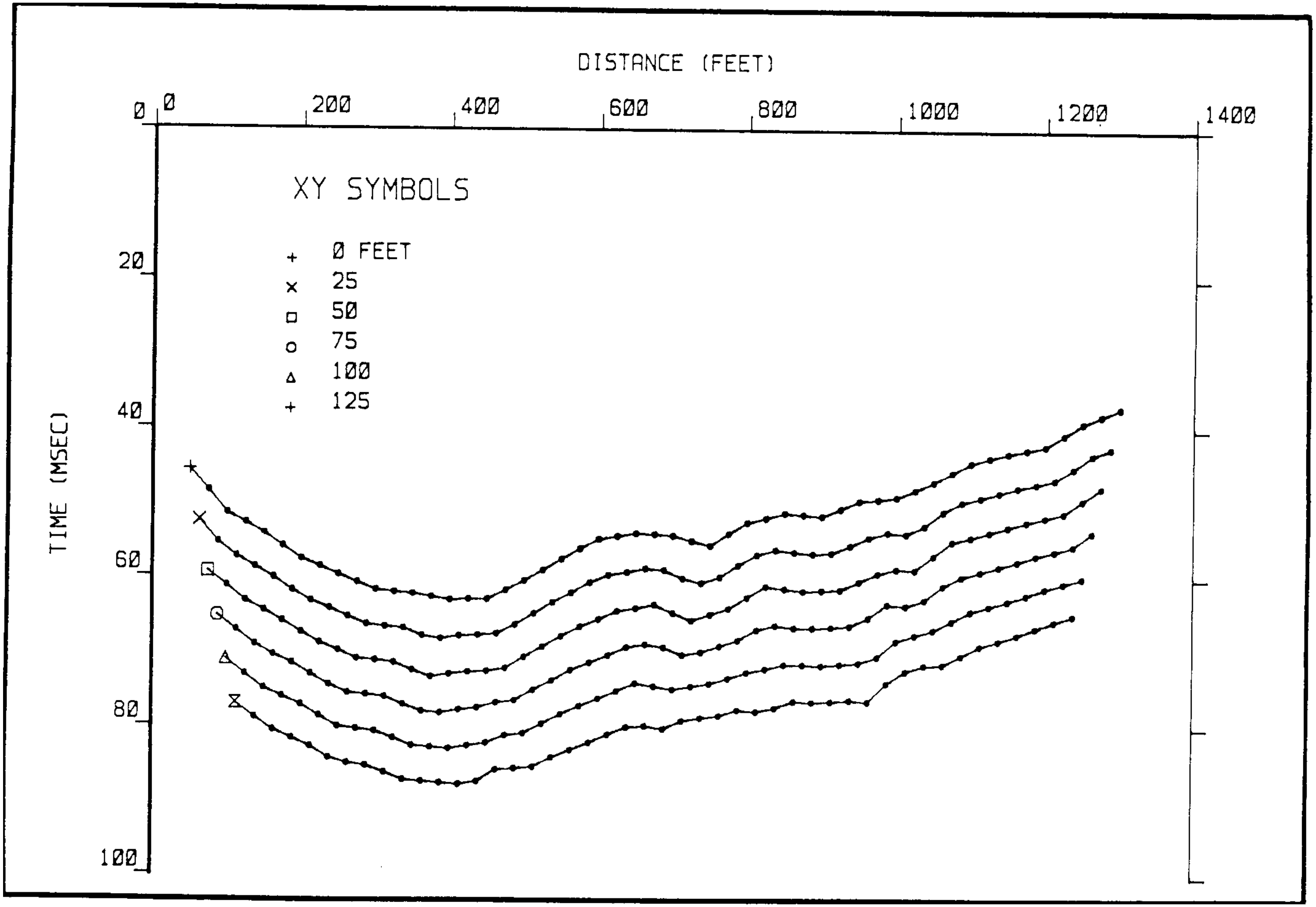
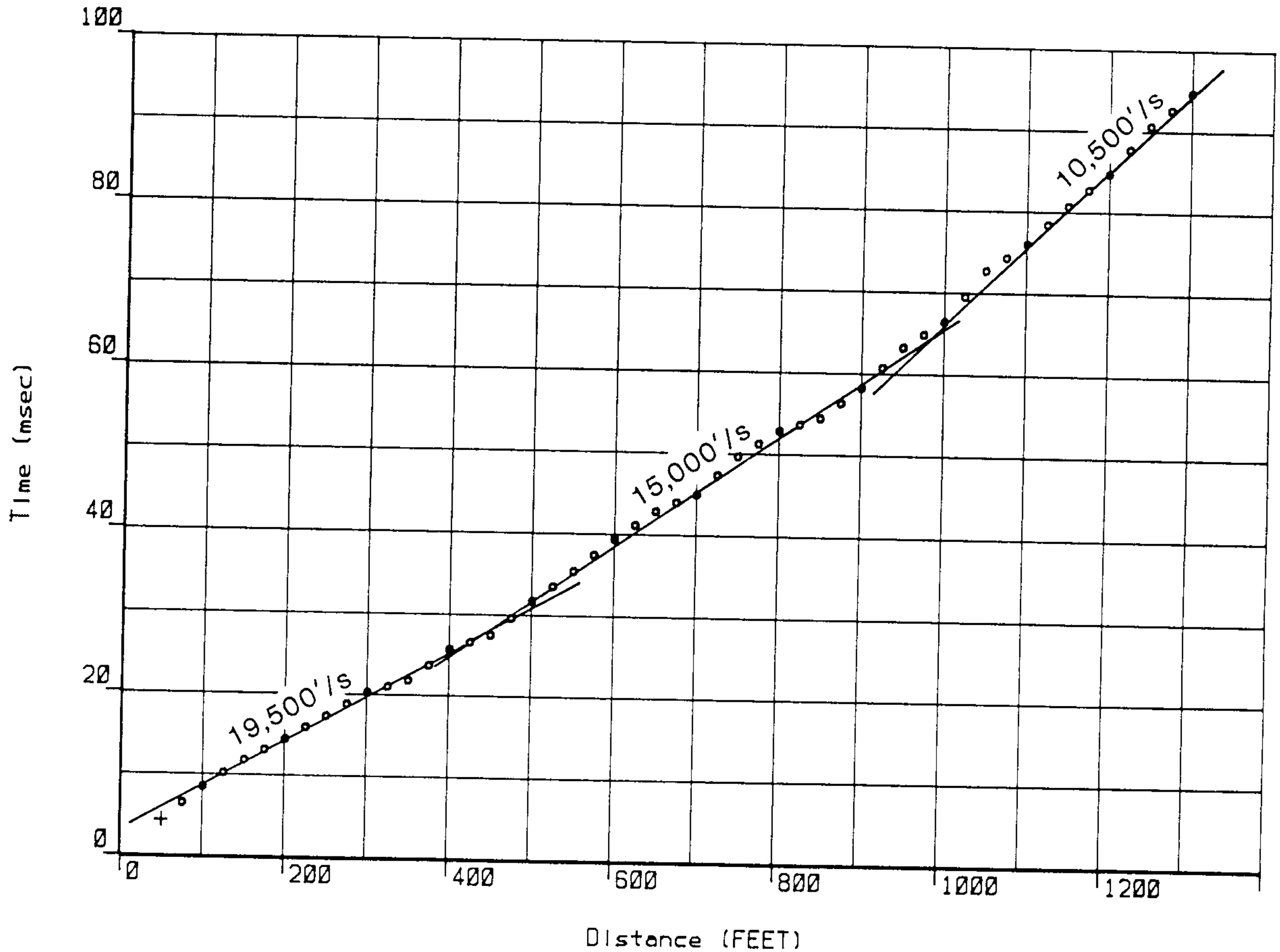


Figure 18. Time-depth curves for XY spaacing from zero to 125 feet. Refractor velocities used to generate these curves are noted in Figure 19.



100
80
60
40
20
0
0
200
400
600
800
1000
1200
Time (msec)
Distance (FEET)
19,500'/s
15,000'/s
10,500'/s

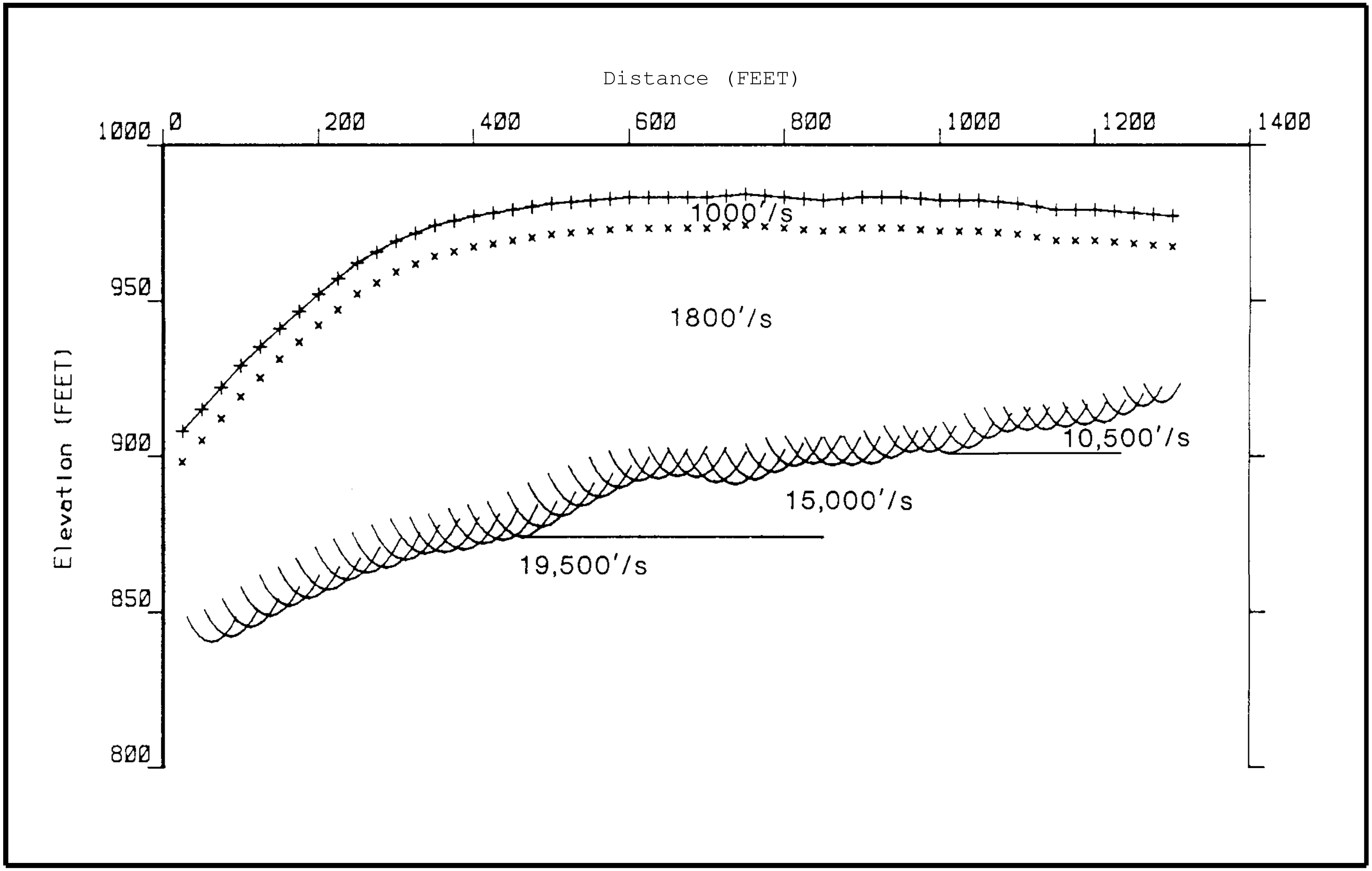


Figure 20. Final migrated section. The refractor surface is the envelope of tangents to the suite of arcs. The surface of the earth is noted by the continuous curve overprinted with + 's. The small x's represent the base the 1000 ft/sec unit and the top of the 1800 ft/sec unit.

BIOGRAPHY

Robert W. Lankston
Geo-Compu-Graph, Inc.
P. O. Box 1848
Fayetteville, AR 72702-1848
(501) 442-5004

Although Dr. Lankston spent two years with Gulf Research and Development Company after completing his Ph. D. research at the University of Montana, he had been interested in shallow-target geophysics since 1968. He left Gulf Research in 1976 to accept a post-doctoral appointment at Washington State Unviversity where he was instrumental in initiating a surface geophysics program to integrate with their program in borehole geophysics as applied to engineering and groundwater studies. In 1978, Dr. Lankston and his wife Marian formed Lankston Geophysical Company which worked with Bison Instruments to demonstrate the utility of expanding spread reflection seismic methods. Later in 1978, Lankston Geophysical merged with G-Cubed, Inc., in Spokane, WA. As their Chief Geophysicist, Dr. Lankston continued his work on shallow-targets, namely uranium exploration via the NURE program and groundwater contamination studies at uranium mill sites. Dr. and Mrs. Lankston left G-Cubed, Inc., in 1980 and formed Geo-Compu-Graph, Inc. This new enterprise continued the interest in shallow-targets and added an important element, the microcomputer. In 1980, the new company completed a 100% continuous profile reflection seismic survey for aquifer mapping in western Washington. This work is believed to be the first time that such data were collected with an "engineering" seismograph and processed with a microcomputer. Dr. Lankston continued to develop the shallow-target reflection method and software for processing CMP data was offered for sale in 1981. Also in 1981, Geo-Compu-Graph, Inc., offered another package that Dr. Lankston had developed. The GREMLIN* Package was the first commercially available implementation of the GRM for microcomputer installation. Within a year of its introduction, it had been purchased by placer gold explorationists, engineering firms, and petroleum service companies. Since 1983, Dr. Lankston has taught geophysics at the University of Arkansas emphasizing shallow-target technology. He continues to serve as a technical associate of Geo-Compu-Graph, Inc., and actively participates in reflection seismic software development and experiments with new field systems for both refraction and reflection surveying. Dr. Lankston's experiences with shallow-target methods have taken him from the big city environments of the major petroleum companies to the bush of The Yukon. His favorite region for study, however, is the intermountain West.

GREMLIN is a registered trademark of Geo-Compu-Graph, Inc.