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CONTINUOUS REFRACTION PROFILING: A NEW STANDARD FOR SEISMIC REFRACTION SURVEYS

by

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ABSTRACT

Seismic refraction surveys are normally carried out with a conventional three- or five-shot reversed spread. Study indicates that the conventional survey design yields results which are far from optimal. Shot and geophone spacings are determined prior to data acquisition using the conventional approach. As a result, the inadequate spacings do not provide enough coverage of each refractor to ensure accurate velocity and depth calculations throughout the entire spread.

It has long been known that complete coverage of each refractor is required to determine interval velocities and thicknesses. However, shallow seismic studies are usually conducted by engineering firms or government agencies which operate on a very limited budget. As a result, the conventional approach has been used primarily because it is relatively inexpensive in terms of field time and data processing expense. However, with the power and affordability of personal computers, it is now possible to gather and process more complete refraction data with about the same effort as the conventional approach.

Continuous Refraction Profiling, or CRP, is a data acquisition method designed to provide complete coverage of each interface in the geologic section. CRP is a roll-along approach similar to CDP reflection data acquisition, where a forward shot is recorded at each geophone station. With the CRP approach, shot pair

combinations that provide the best coverage of each refractor can be determined in analysis after data acquisition.

This thesis will introduce the Continuous Refraction Profiling approach. A methodology will be presented that shows how CRP data can be acquired and processed with about the same amount of time and effort as the conventional approach. A case study will then be presented to compare results of conventional and CRP surveys carried out on the same refraction line.

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SECTION 1

Introduction of the Continuous Refraction Profiling Approach

The idea for Continuous Refraction Profiling came as a result of trying to answer the question, "what would be the best possible refraction survey design?" This question was asked when trying to define a set of guidelines describing how to conduct a seismic refraction survey. The intention was to use these guidelines to instruct inexperienced personal in the use of seismic refraction for groundwater exploration. It was necessary to explain how to gather data in a way that the processing and interpretation could be defined in a set of rules as well.

To begin with, the effort centered on describing the conventional five-shot reversed spread, which is commonly used to gather seismic refraction data. It was found that no set of rules could be defined that would allow optimal results to be obtained with the conventional survey design. The conventional approach is limited in that there is a lack of complete coverage of each refractor. Key design decisions, like shot locations and spacings are made prior to data acquisition. Finally, the conventional field procedure tends to be very inefficient because of the complicated shot patterns.

This thesis proposes a refraction data acquisition method specifically designed to provide complete coverage of each refractor. Continuous Refraction Profiling, or CRP, allows for complete coverage of each interface by allowing shot spacings that determine maximum refractor coverage to be determined after data acquisition. CRP also provides redundant coverage of each refractor, which allows statistical improvement of refraction survey results. Finally, CRP is a roll-along approach, so it tends to be more efficient in the field. It is easier for the field personal to roll-along shooting at each station than to shoot the more complicated conventional shot patterns. This thesis will show that the CRP approach can be used to provide much more complete data with about the same amount of time and effort as the conventional approach.

1.1 Lack of Complete Coverage

Most three- or five-shot reversed spreads do not provide enough coverage of each refracted arrival to guarantee accurate velocity and depth calculations. Complete coverage is provided where arrival times overlap on the same refractor from shot points which were recorded at opposite ends of the geophone array. Any extrapolation of velocity segments through zones of incomplete coverage will tend to induce errors in depth calculations (Redpath, 1973).

These limitations are pointed out in the following example. FIGURE 1.1 through FIGURE 1.3 show a string of 12 geophones laid out on the surface of a simple, three-layer geologic model.

The first step in the conventional method is to record a shot at each end of the geophone array. As can be seen in FIGURE 1.1, the

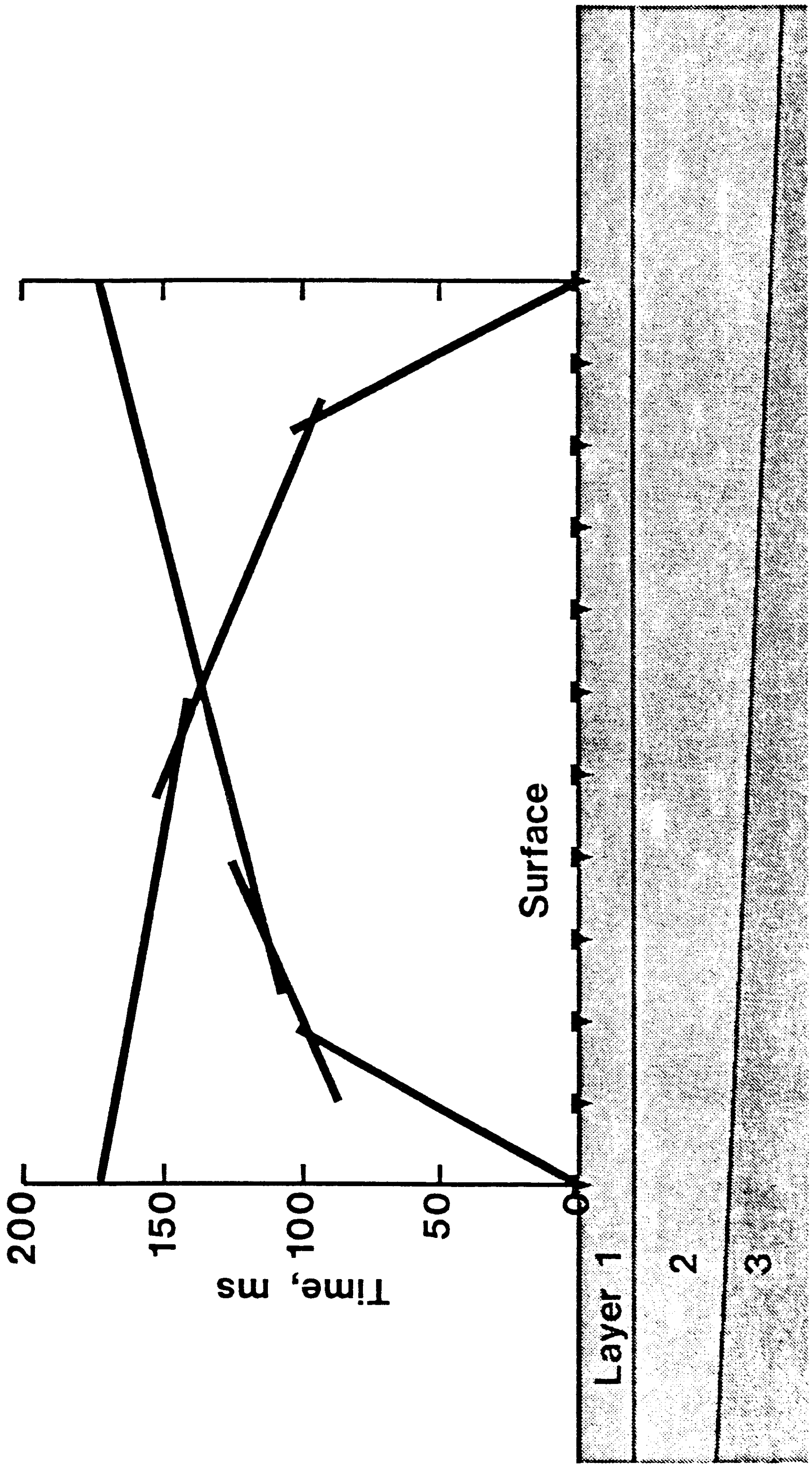

FIGURE 1.1
Time/distance plot showing end shots of the conventional spread.

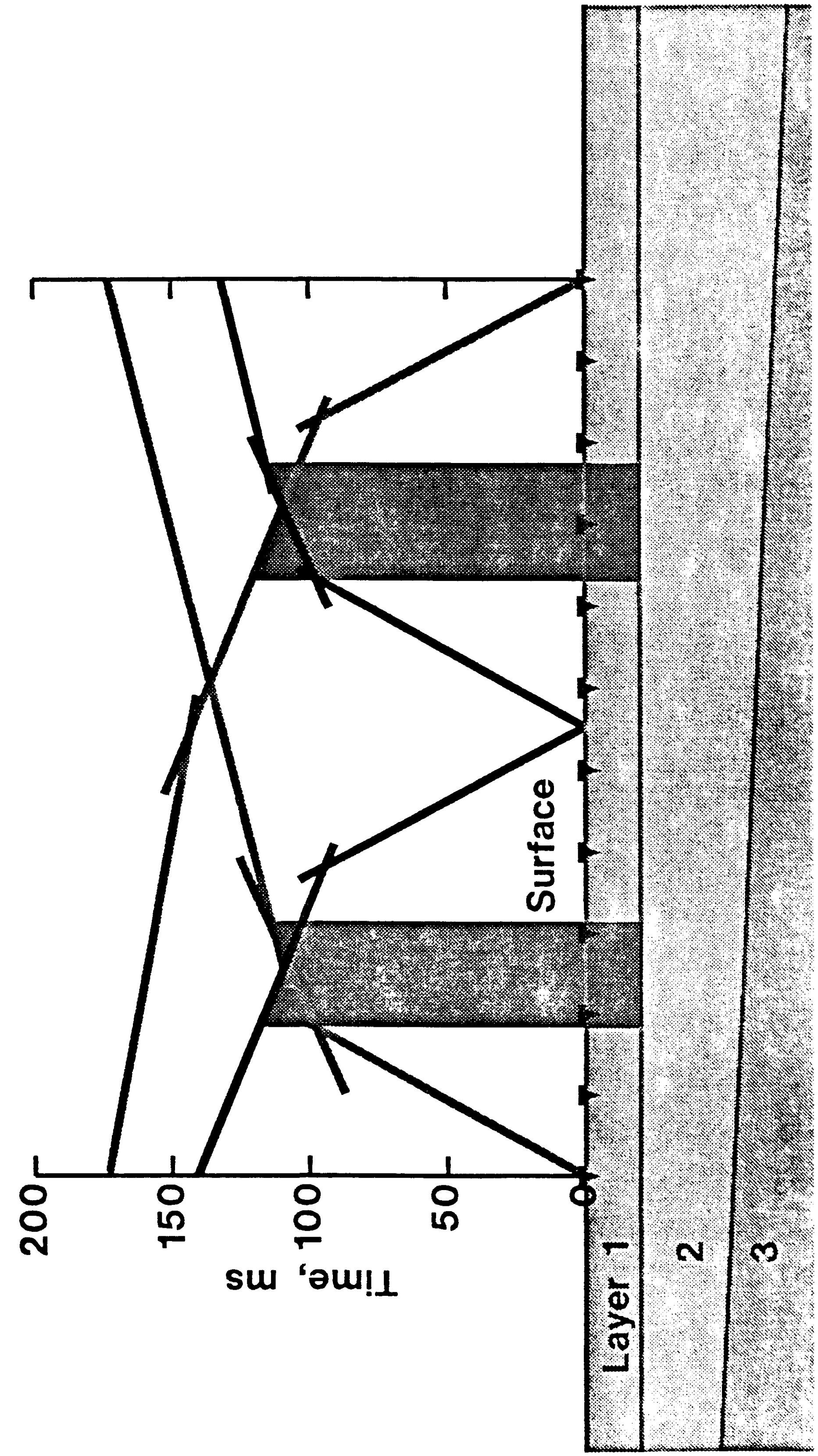

FIGURE 1.2
Time/distance plot showing intermediate shot in the center of the geophone array.

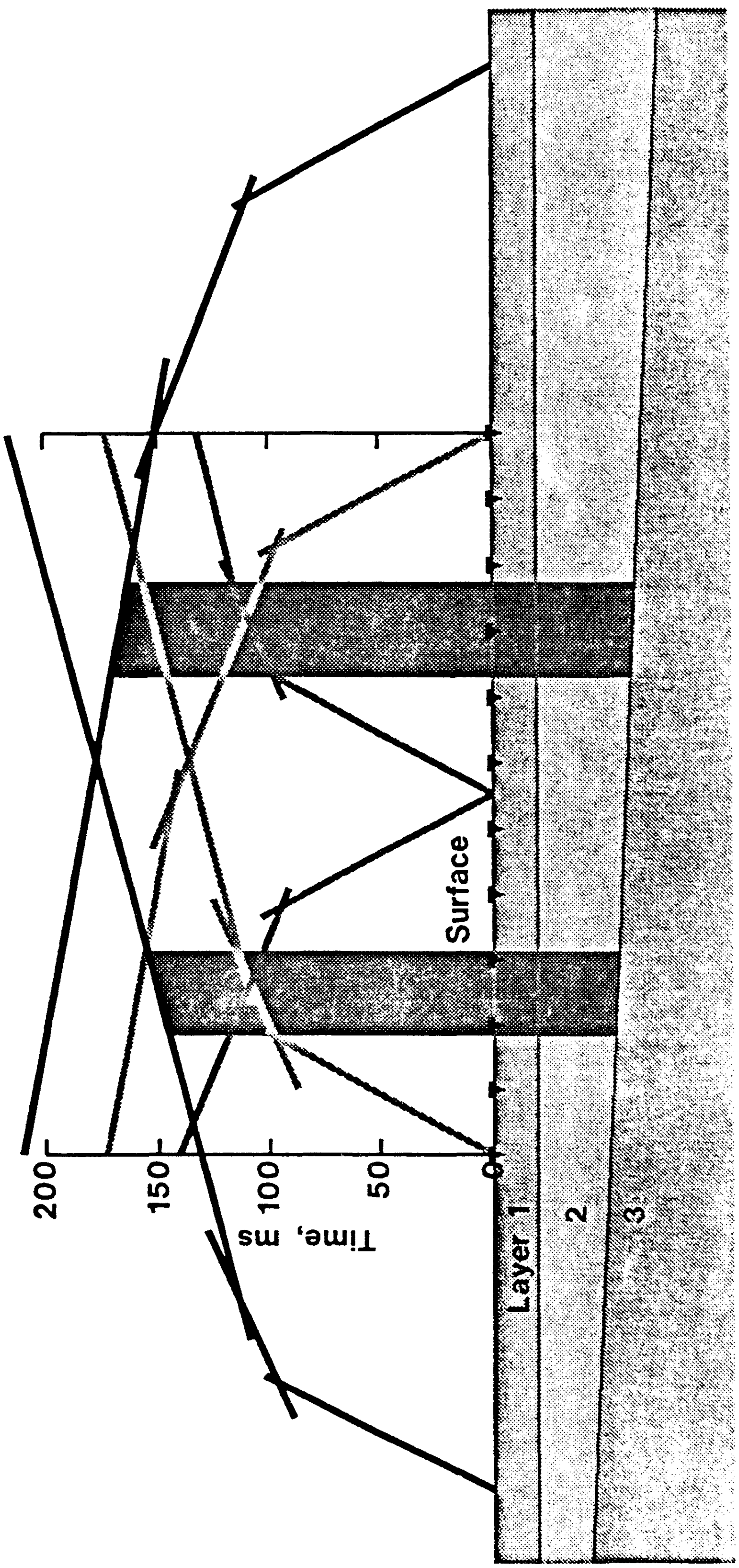

FIGURE 1.3
Time/distance plot showing off-end shots which comprise the rest of the five-shot conventional spread.

two end shots do not provide any overlapping coverage of the first refracted arrival. To obtain better coverage, the next step is to record an intermediate shot in the center of the spread (FIGURE 1.2). Then, the final step to obtain as much coverage of the deeper layers as possible, for the goal of most refraction surveys is to map the bedrock surface. The deeper layer coverage is obtained by recording shots off of each end of the geophone array, as shown in FIGURE 1.3.

Analysis of FIGURES 1.1-1.3 show the drawbacks associated with the conventional survey design. As stated before, it is desirable to make depth calculations only where there is overlap of arrival times. The intermediate shot seen in FIGURE 1.2 does provide more near-surface information. However, only a small portion of the spread shows overlap of arrival times from the first interface. This limits proper depth calculations to the shaded regions as shown in FIGURE 1.2.

The off-end shots shown in FIGURE 1.3 do provide overlapping arrival times from the top of layer 3 for the entire spread length. However, as shown in FIGURE 3, depth calculations are still limited to the shaded region. This is because the depth calculations to the second interface depend on the depth to the first interface. Extrapolation of depth calculations to the first interface may not accurately represent true depth, and could induce error in the second interface interpretation.

1.2 Limited Survey Design Control

The conventional survey provides inadequate coverage primarily because the shot spacings are determined prior to data acquisition. This limitation is the main reason that no set of rules could be determined to define an optimal five-shot spread. Spacings for the five shots shown in the example had to be chosen prior to recording. Unfortunately, the spacings chosen do not provide adequate coverage of the near surface refractors. It can be seen from this example that only a trial-and-error procedure will allow a maximum amount of coverage to be obtained from the five shots. Even if a few more shot points were added to the conventional survey, it would still be impossible to guarantee complete coverage of each interface.

The need for a trial-and-error approach indicates that some refraction data information is required before any useable data is obtained. The optimal situation would be that the shot spacings that provide maximum overlap of each refractor are known before data acquisition. Since this is not possible, the next best solution is to have enough shot points recorded so that the optimal shot spacings can be determined after the data has been acquired.

1.3 Error Magnification With Depth

The possibility of inducing error with extrapolation is another important consideration. Not only does extrapolation induce error in the depth calculations, but this error is magnified for deeper layers.

This is easily shown by observing the depth equation for the second interface. A general equation for the thickness of the second layer can be written as:

$$thickness_2 = velocity_2 \cdot A \cdot (\Delta Time - thickness_1 \cdot B \div velocity_1)$$

where A and B are constants related to other parameters.

The actual thickness equations are developed in detail in SECTION 3. From the generalized equation listed above, it can be seen that any error associated with thickness of the first layer will be multiplied by a ratio of velocities. For refraction analysis to be valid, the second layer velocity must be greater than the first layer velocity. This means that the ratio of velocities is always greater than one. Thus, the error associated with depth to the first interface is magnified by the ratio of velocities when calculating depth to the second interface.

1.4 Conventional Approach is Inefficient

Another problem with the conventional survey design is the general inefficiency of the method. With the conventional design, key design decisions like shot location and geophone spacing are made prior to data acquisition. Even though the suspected geology is usually modeled prior to field study, it is often necessary to conduct several test surveys to find adequate spacings which allow usable data to be recorded. This is an inefficient use of field time. Furthermore, spacings determined from one test survey may not be applicable to other portions of the survey. This is especially true for areas with inhomogeneous or steeply dipping layers (see Domalski, 1956). The field operation also tends to be inefficient due to the complicated shot patterns. The seismic source must be carried to the long offset shot points, as well as the intermediate shot positions for each geophone array. This often requires carrying the source several times over the same portion of the survey.

1.5 CRP Provides Complete Coverage

To overcome the aforementioned conventional survey design limitations, it was necessary to define a new refraction data acquisition procedure. Continuous Refraction Profiling, or CRP, is an efficient acquisition procedure that provides complete coverage of each layer in the geologic section. Similar to CDP reflection data acquisition, CRP is a roll-along approach where a shot is recorded at every geophone station. FIGURE 1.4 shows the same geologic model and geophone string as seen in FIGURES 1.1 through 1.3, but a forward shot is recorded at each geophone station.

When a forward shot is recorded at each station, reverse shots can be generated from the forward data at each station as well. For each corresponding reverse shot, a single geophone ground position may be considered as the "source," while the many shot points with that particular ground position within their spread length may be considered receiver positions (McGaughey, 1986).

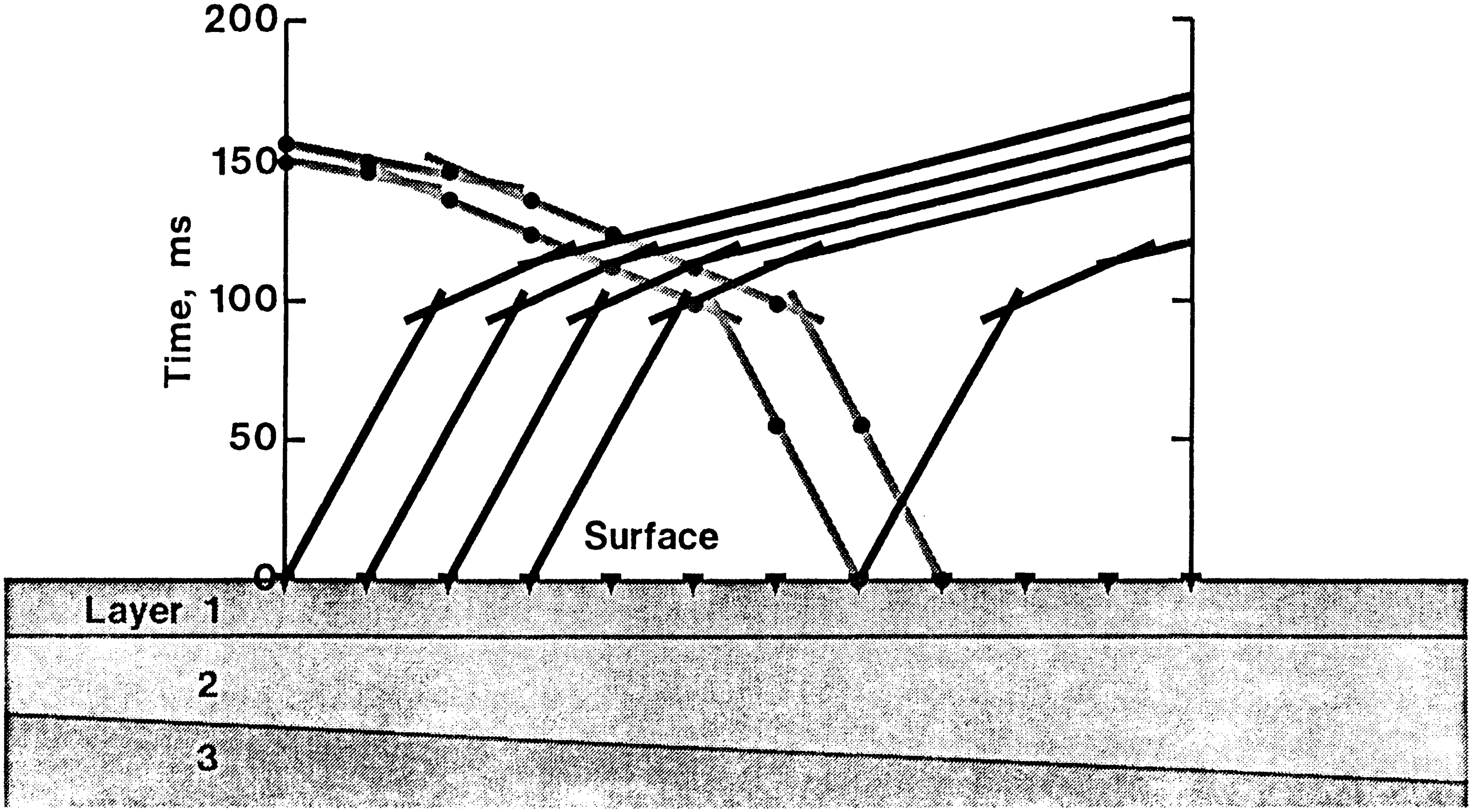

FIGURE 1.4
Time/distance plot showing the recording of forward shots at each geophone station with the CRP approach.

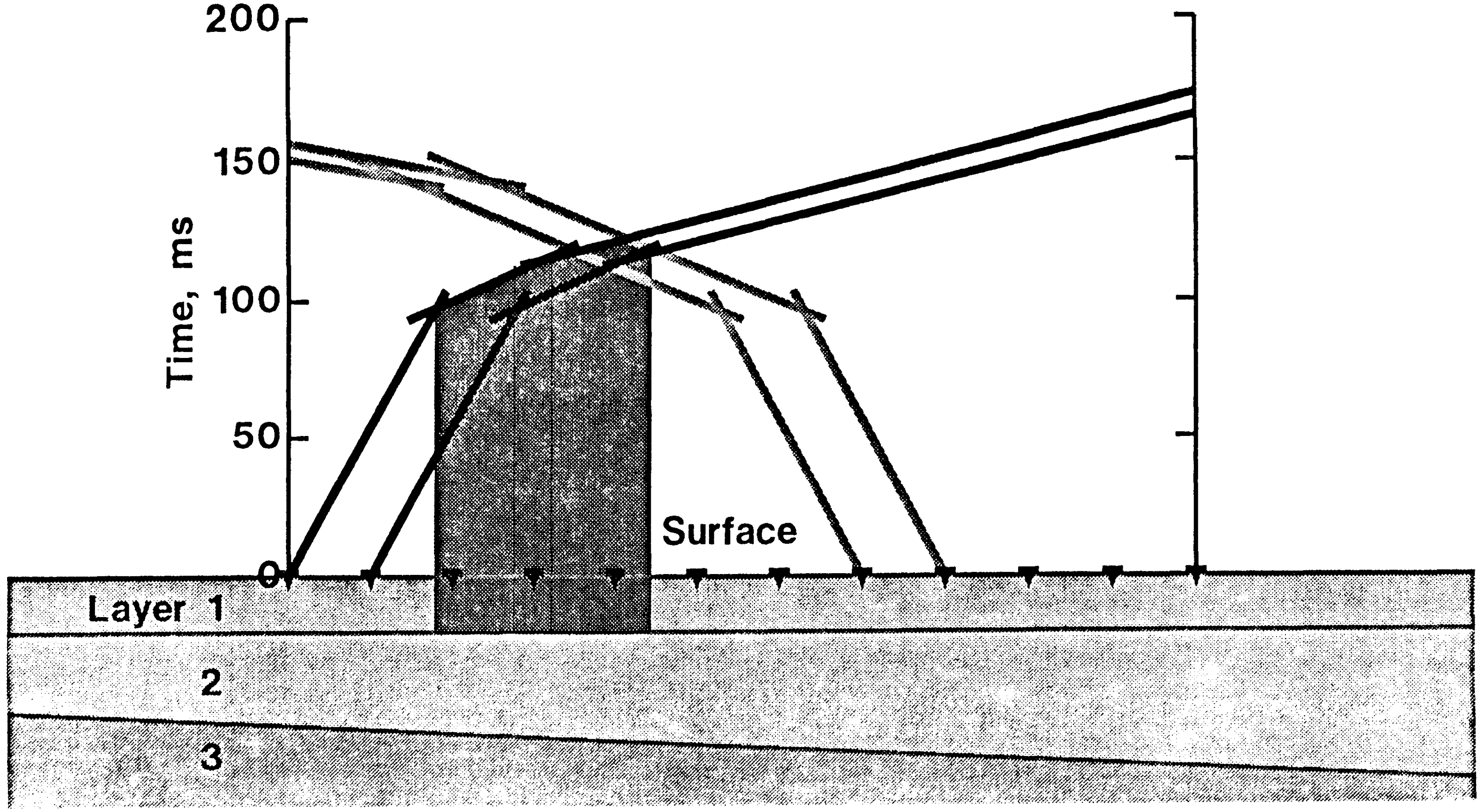

FIGURE 1.5
Time/distance plot showing overlapping coverage from reverse shot recording which are derived from the forward data.

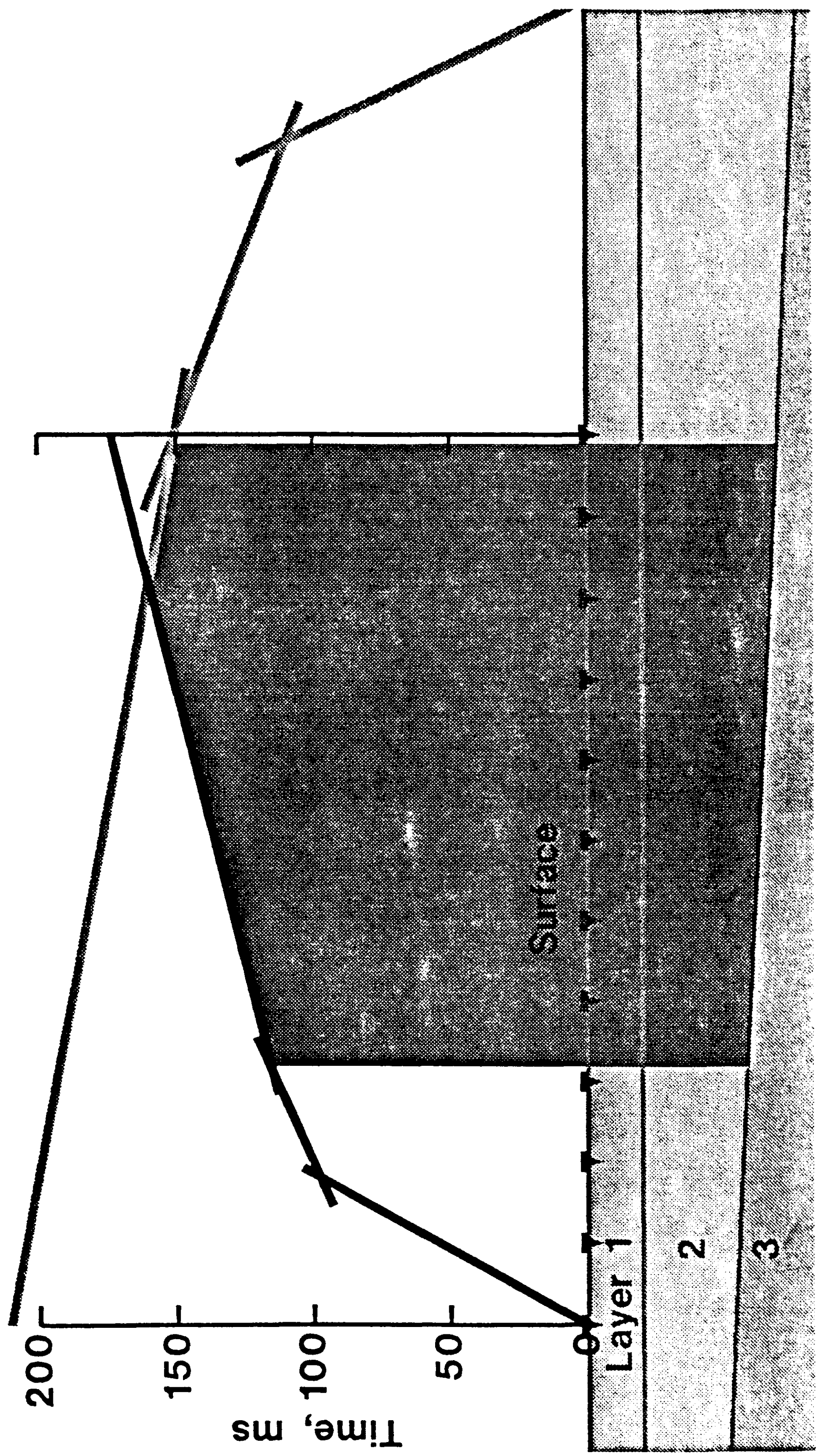

FIGURE 1.6
Time/distance plot showing how the longer offset shots can now be used to calculate depths with no extrapolations.

Since forward and reverse travel time information is available throughout the entire spread, shot pair combinations that provide maximum overlap of the first interface can be chosen (FIGURE 1.5). This shot spacing can be used to provide overlapping coverage of the first interface throughout the survey. Then, the larger shot spacings can be used to obtain complete coverage of deeper layers, as shown in FIGURE 1.6. Every overlapping arrival time from the same refractor can be used to calculate depths. Unlike with the conventional survey design, none of these calculations are made using extrapolated values.

1.6 Shot Spacings Determined During Processing

The CRP approach was designed so that optimal shot spacings could be chosen from the many possible forward and reverse shot combinations. As can be seen in this example, the shot pair combinations that provide the best coverage of each interface are determined after the data has been acquired. Unlike the conventional method, where shot spacings are determined before acquisition, CRP allows these critical decisions to be made during data processing. This is a very important consideration, because as long as the geophone spacing is dense enough, any changes in dip, or lateral velocity changes will be detected using the CRP approach.

1.7 Redundancy in Data

Using a CRP approach has other important advantages. For instance, the many different possible shot pair combinations allow several independent depth calculations to be made at each geophone position for each interface. This data redundancy will allow statistical methods to be applied the refractor velocity analysis and subsequent depth calculations. This will tend to reduce some of errors associated with seismic refraction surveys (see Domalski, 1956).

1.8 Increased Efficiency

Continuous Refraction Profiling is also a very efficient field procedure. The field crew simply records a shot at each geophone station. No complicated shot patterns are involved, so the source need simply roll-along, shooting at each station. Even though there are many more shots to be recorded, a CRP survey takes about the same amount of field time as a conventional survey.

This is an important consideration, because time as well field effort constraints are what kept methods like CRP from being used in the past. Although there is much more data involved in the CRP survey, technology today is such that the additional amounts of data can be gathered, precessed, and interpreted in approximately the same amount of time as conventional surveys.

Another reason that the conventional survey has been used for so long is simply cost. Although the CRP survey can be run with about the same field time, there is additional expense associated with obtaining more data. There is the cost of the additional explosives or shells depending on the source, and the extra equipment could be expensive to acquire (see SECTION 2 for necessary equipment). Although the CRP field acquisition will be more expensive than the conventional survey, the improvement in data quality should be enough to justify the cost.

SECTION 2

Continuous Refraction Profiling Feasibility Study

This section will document the Continuous Refraction Profiling feasibility study conducted at the 1988 Colorado School of Mines Geophysics Summer Field Session. The seismic refraction study at this field camp was designed to determine the optimum field equipment and methodology required to obtain refraction data with the CRP approach. This section will contain a discussion of the refraction study, including field parameters and equipment used, and a comparison of the conventional and CRP acquisition procedures.

The CRP feasibility study took place on the Colorado School of Mines' 40 acre parcel in Park County, Colorado (SW 1/4 of the SE 1/4 of Sec. 29 T75W R10S). Over an eight working-day period, the refraction crew, consisting of a graduate Teaching Assistant and three undergraduate students, completed two lines of CRP data. The two lines are shown in map view in FIGURE 2.1. The North-South line runs approximately parallel to the ridge which covers the eastern third of the property. The East-West line starts at the SW corner of the property and runs perpendicular to the ridge.

The refraction data were recorded using the EG&G ES2420 24 channel seismograph and Mark Products 50 Hertz geophones. The source was an eight-gauge Betsy Seisgun, set up to fire a lead slug when signaled by a high-voltage firing switch. Each shot point was recorded on both magnetic tape, using the EG&G tape recorder, and on

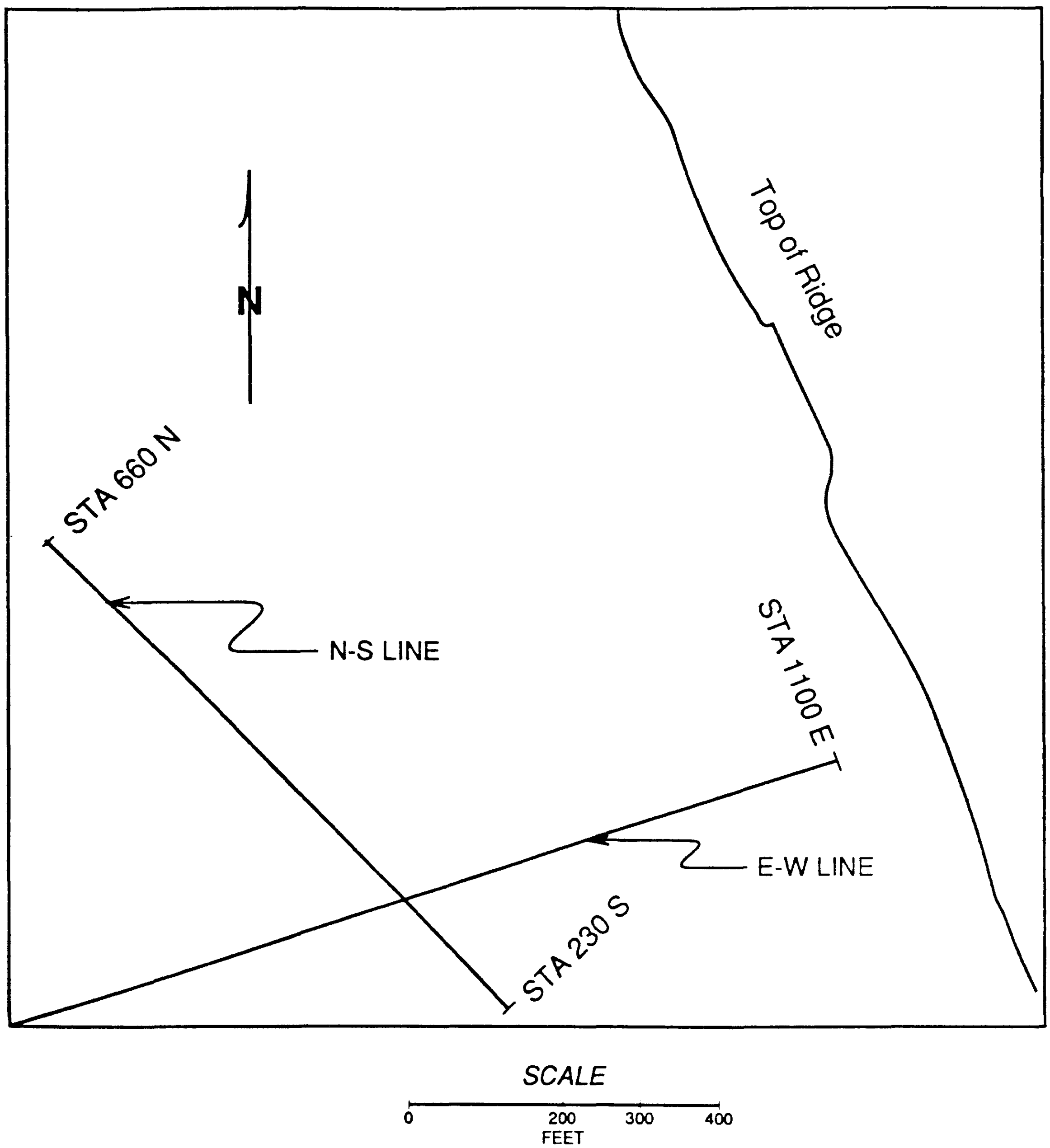

FIGURE 2.1
Map of CSM property showing two refraction lines
(SW 1/4 of the SE 1/4 of Sec. 29 T75W R10S).

paper, using the EG&G printer. This equipment configuration is shown in schematic form in FIGURE 2.2.

Power for this system was provided by two 12 Volt marine batteries, which were continually recharged by the recording truck's generator. It was found that the recording truck needed to be running constantly to keep the amperage high enough to run the hardware for a full day. Because of this, it was necessary to use a 300 foot cable extension to keep the recording truck away from the line. The geophone noise test feature on the seismograph showed that with the cable extension, the truck engine did not produce any significant noise as measured by the geophones.

After having determined that the field equipment was functioning properly, several test shot points were recorded to determine the proper geophone spacing for the survey. It was found that a geophone spacing of 10 feet would provide adequate coverage of the near-surface layers while still extending far enough to obtain coverage of deeper layers. Therefore, the two lines shown in FIGURE 2.1 were defined with a station interval of 10 feet.

The geophone cable and geophones were then laid out with a geophone at each station and the recording truck as far away from the line as the cable extensions would allow. The cables were connected to the seismograph through a 96 pin roll-along box.

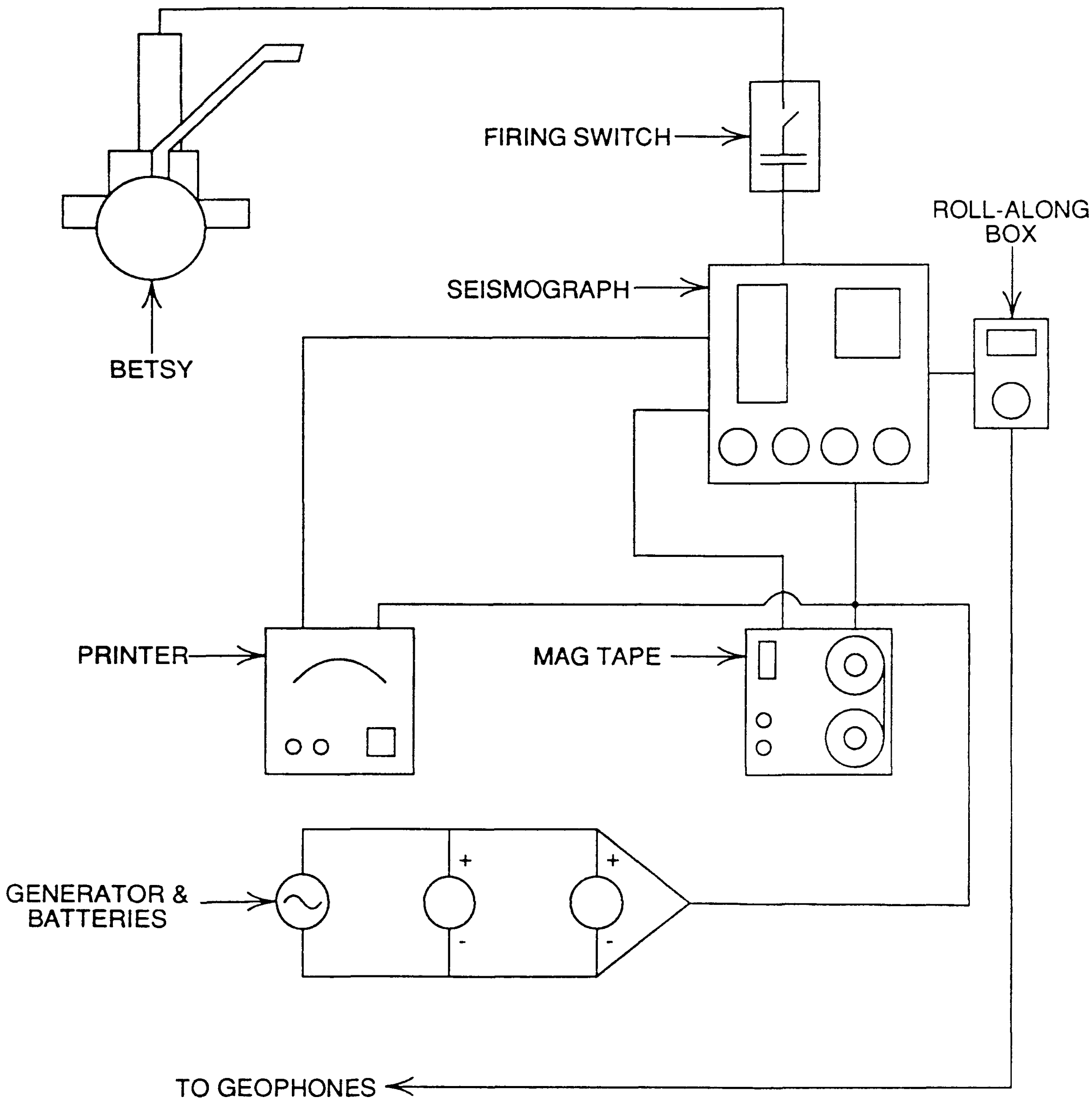

FIGURE 2.2
Schematic showing CRP survey hardware.

Therefore, the truck could be placed between two 48 take-out geophone cables as shown in FIGURE 2.3. The choice of the 24 channels recorded for each shot was controlled with the roll-along box.

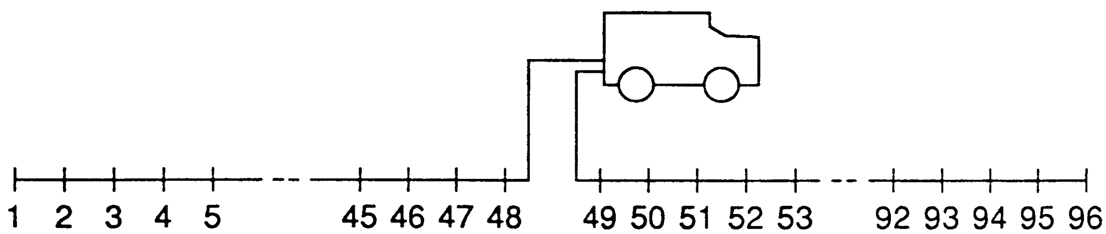

FIGURE 2.3
Recording truck and 96 station geophone array.

With the field equipment in place and operational, the data acquisition proceeded by recording a shot 10 feet off the end of each 24 channel spread (this is done to effectively add another channel to the spread, 0 seconds at 0 offset). This procedure was repeated by simply switching the roll-along box and moving the Betsy Seisgun to the next position. Before the live channels would roll off the end to the geophone cable, the truck was moved ahead and geophones and cable at stations that had already been recorded were moved ahead and laid out. This routine was followed until shot points had been recorded at each station along the line.

A good deal of front-end time was required to establish the field routine described above. In addition to problems encountered configuring the system, the students needed to be trained on proper field techniques. However, once the bugs were worked out of the system and the students became familiar with the routine, the CRP approach rolled along very efficiently. Towards the end of the refraction study, the students could move the Betsy to the next station and be set up in the time it took to write the previous shot to magnetic tape and obtain a paper record.

This field procedure became so efficient that there was almost no time difference between completing this CRP survey and completing conventional surveys in previous field camps (based on experience with refraction crews in the 1986 and 1987 field camps). There is about the same amount of time spent laying cable and planting geophones for both methods. There is more time involved in the actual shooting of the CRP survey, because of the additional shot points involved. However, an experienced crew can roll-along, shooting at each station almost as fast as a conventional crew can traverse the spread, shooting at intermittent points. The Betsy requires a long cable which connects it to the firing switch in the recording truck, it is also quite heavy, and can be difficult to move over rough terrain. It is therefore easier to move the Betsy along in short increments, rather than over the longer shot spacings required in a conventional survey.

To summarize, the CRP data acquisition during the 1988 CSM Field Session showed that the equipment configuration and the methodology outlined in this section can be used to efficiently gather seismic refraction data. Also, it was found that the field effort required to conduct the CRP survey is comparable to the conventional approach. The result being that the efficiency of the CRP method allows more and more useful refraction data to be acquired with about the same amount of time spent on the field.

It should be mentioned here that several of the field equipment items shown in this configuration are essential for CRP data acquisition. It would be next to impossible to gather CRP data without a roll-along switch and roll-along cables. The CRP data acquisition would be much too inefficient without roll-along capability. Also, a portable, repeatable source, like the Betsy, is recommended. Other explosive sources may be considered, but the added time of drilling shot points will tend to impede field performance. Finally, although not required, it is recommended to use at least a 24 channel seismograph. The additional channels make it easier to record an adequate number of arrival times for each refractor at each station.

SECTION 3

Continuous Refraction Profiling Data Processing

The field session CRP survey data were processed and interpreted with two goals in mind. First, a basic methodology for processing and interpreting CRP data needed to be established. Second, for evaluation purposes, a portion of a refraction line was interpreted using both conventional and CRP survey designs. This section will discuss the methodology used in processing the CRP data. The steps necessary to take the raw field data and produce a depth section will be presented with an emphasis on making the processing possible from a production standpoint.

The processing of CRP data can be divided into three steps: first break picking, velocity analysis, and depth calculations. These steps are shown in flow-chart form in FIGURE 3.1.

3.1 First Break Picking

The first step in processing the CRP data is to pick the first arrival times from the shot records. For this study, all of the first arrival times were picked by hand from the paper plot of each recorded shot point. The refraction study at the 1988 field session consisted of two lines with 89 shot points on one line and 110 shot points on the other (see FIGURE 2.1). Each shot was recorded with the 24 channel seismograph, so a total of 4776 first arrival times

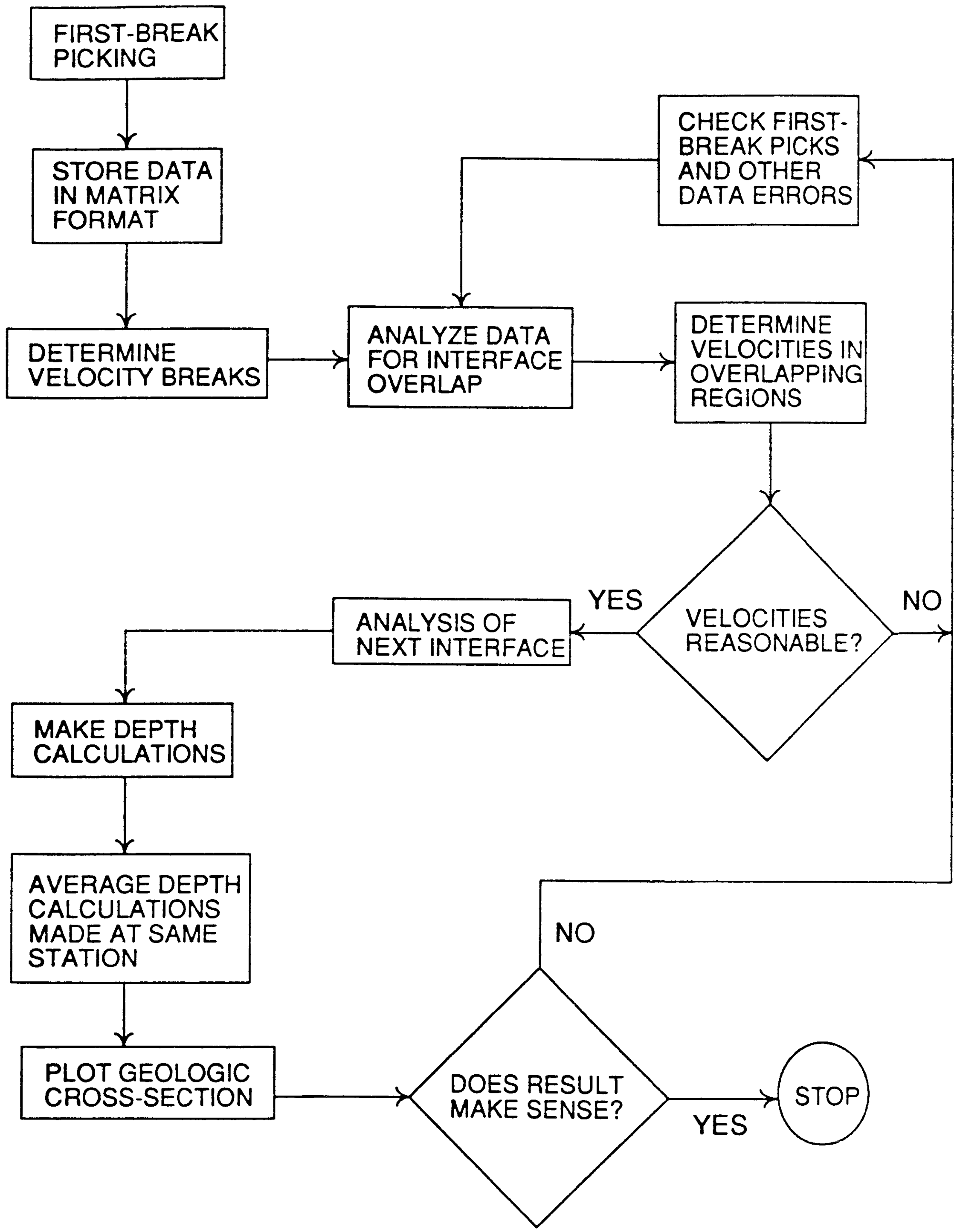

FIGURE 3.1
Flow chart showing CRP processing.

was recorded in this study. The 24 arrival times associated with each shot point can be manually picked and documented in about five minutes, so to pick all of the first arrival times for this study would take about 16.5 hours.

In an experimental study like this, time spent picking arrival times is not an issue. However, an engineering geophysicist conducting a refraction survey may not be able to justify the time expense in manually picking the first arrival times. Therefore, for larger scale, production refraction studies, the use of an automated first break picking computer program is recommended.

3.2 Velocity Analysis

With all of the first arrival times for the study area picked and documented, the next step is to get the data in a form so that the shot spacings that provide maximum coverage of each interface can be chosen. It was found that the shot spacing analysis could be conducted quickly and efficiently using spreadsheets (Microsoft Excel was used for this study, but other programs like Lotus 123 could be used as well). With the arrival time data input to the spreadsheet, the interactive graphics capabilities are used to quickly plot any forward and reverse shot pair along the line.

To analyze the data, the arrival times are input to the spreadsheet in the following format. The arrival times for the first forward shot along the line is input as the first row of the spreadsheet. The next shot is input to the second row, but the first arrival time in the second row is shifted one column to the right. Each shot point along the line is input by shifting one row down and one column to the right from the previous shot point. FIGURE 3.2 shows an example of the data in spreadsheet form. The arrival times from the forward shot recorded at geophone station -10 are in ROW 3. The arrival times from the forward shot recorded at geophone station 0 are in the ROW 4, and so on.

This particular spreadsheet format is used to take advantage of the inherent symmetry of CRP data in matrix form. With the arrival times in this form, the reverse shot travel times at each station are located in the spreadsheet columns. This relationship is based on the assumption that the theory of reciprocity holds for this refraction study (Stated simply, the reciprocal relationship means that a shot at station A and a recording at station B will be equivalent to a shot at station B and a recording at station A.).

For example, a reverse shot at geophone station 30 is created as follows. The first arrival time recording from a reverse shot at station 30 would be at station 20. Using the reciprocal relationship, this is equivalent to a shot at station 20 and a recording at station 30. Note that the shot at station 20 and recording at station 30 is located in ROW 6 COLUMN F of the spreadsheet (FIGURE 3.2). The second arrival time recording from a shot at station 30 would be at station 10. Again, using the reciprocal relationship, this is

	A	B	C	D	E	F
1		-10	0	10	20	30
2						
3	-10	0.000	0.013	0.021	0.027	0.030
4	0		0.000	0.010	0.018	0.022
5	10			0.000	0.010	0.017
6	20				0.000	0.010
7	30					0.000
8						
9						
10						
11						
12						
13						
14						
15						
16						

Forward data in rows →

↑ Reverse data in columns

FIGURE 3.2
Example Excel worksheet. Arrival times in seconds are shown for the stations listed in COLUMN A and ROW 1 of the worksheet.

equivalent to a shot at station 10 and a recording at station 30. The shot at station 10, recorded at station 30, is located in ROW 5 COLUMN F of the spreadsheet (FIGURE 3.2). It can be shown in this fashion that all of the arrival times for the reverse shot at station 30 are located in COLUMN F of the spreadsheet. The important result is that forward and reverse travel times for any shot pair are located in the corresponding row and column in the spreadsheet. This result is used to plot shot pairs using the interactive graphics capabilities in Excel.

Excel has the capability of creating a plot of any portion of a row or column in the spreadsheet. The plot of a particular shot pair is created by first making a chart of the forward shot arrival times, located in a spreadsheet row. Then, the column containing the reverse shot arrival times is pasted on the chart. An example plot showing a forward shot at station -10 and a reverse shot at station 30 is shown in FIGURE 3.3. This plot was created by plotting ROW 3 and COLUMN F of the spreadsheet (FIGURE 3.2).

This method is an extremely fast way of examining shot pairs. The plot in FIGURE 3.3 took about one minute to make. Thus, all of the possible combinations of forward and reverse shot pairs throughout the survey can be examined in a relatively short period of time.

This graphical analysis method can be used to determine the number of layers covered by the refraction survey. Also, this

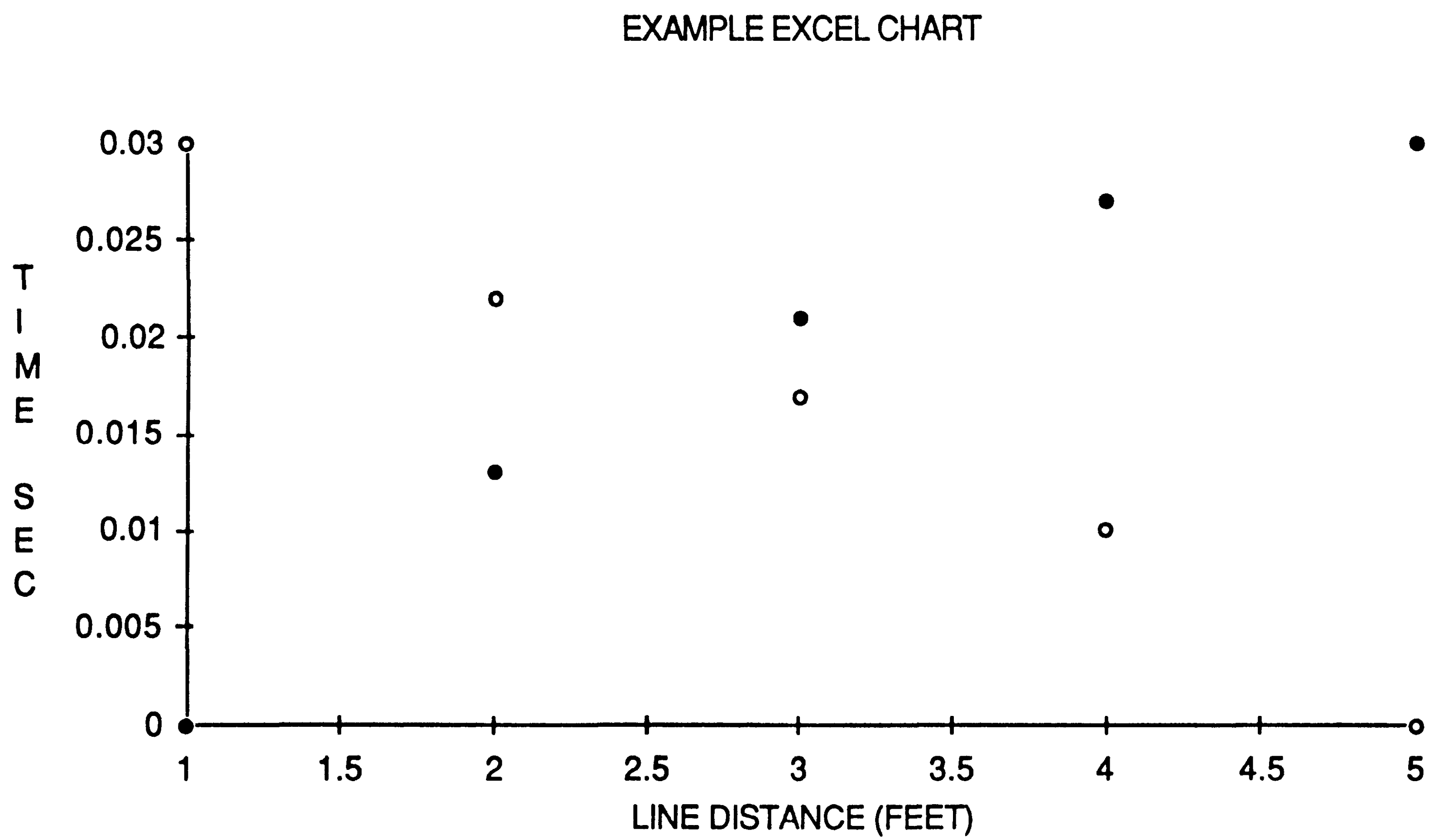

FIGURE 3.3
Example Excel Chart. This chart was made by plotting ROW 3 versus COLUMN F of the worksheet shown in FIGURE 3.2.

procedure provides a means of analyzing the CRP data to determine the shot spacings that will provide optimal coverage of each refractor.

3.3 Depth Calculations

Once the optimal shot spacing is determined for each refractor, the rest of the data processing is very straightforward. The only step remaining is to use the overlapping arrival times to solve for velocities and thicknesses of each layer. Velocities and thicknesses can be determined using the method-of-differences, first introduced by Edge and Laby (1931). The method-of-differences equations used to solve for thickness of each layer are described as follows:

$$h_{1x} = V_1(T_a + T_b - T_{ab}) \div 2\cos\alpha_{12}$$

$$h_{2x} = V_2[(T_a + T_b - T_{ab}) - 2h_{1x}\cos\alpha_{13} \div V_1] \div 2\cos\alpha_{23}$$

$$h_{3x} = V_3[(T_a + T_b - T_{ab}) - 2h_{2x}\cos\alpha_{24} \div V_2 - 2h_{1x}\cos\alpha_{14} \div V_1] \div 2\cos\alpha_{14}$$

where

- h_{nx} is the thickness of the nth layer at geophone station x
- V_n is the velocity of the nth layer
- T_a is the arrival time from the forward shot A, recorded at station x
- T_b is the arrival time from the reverse shot B, recorded at station x

T_{ab} is the total end-to-end travel time (A to B, or B to A)

$\alpha_{mn} \equiv \sin^{-1}(V_m \div V_n)$

Note that these equations were derived for the non-dipping layer case. For a development of these travel time equations that account for dip, refer to Hollister (1974).

Each layer velocity used in these equations are determined from the difference times, or the difference between forward and reverse shot recordings at the same station. This method is described in detail by Redpath (1973). The result is that for regions where refractions from the same interface overlap, the difference times will fall on a straight line. Also, the slope of the line is directly related to true velocity of the refractor. An example of determining true velocities from difference times is shown in FIGURE 3.4.

A flow chart showing the methodology used to calculate depths from CRP data is shown in FIGURE 3.5. Once the shot spacing is determined that provides the best coverage of the first refractor, the maximum number of geophone stations with overlapping arrival times is defined. Then, velocities and thicknesses for the first layer are determined in the overlapping regions for all of the shot pairs along the line at the optimal spacing. The velocities and thicknesses for the first layer at each station are then used in conjunction with the overlapping arrival times from the second refractor to solve for second layer thicknesses and velocities along

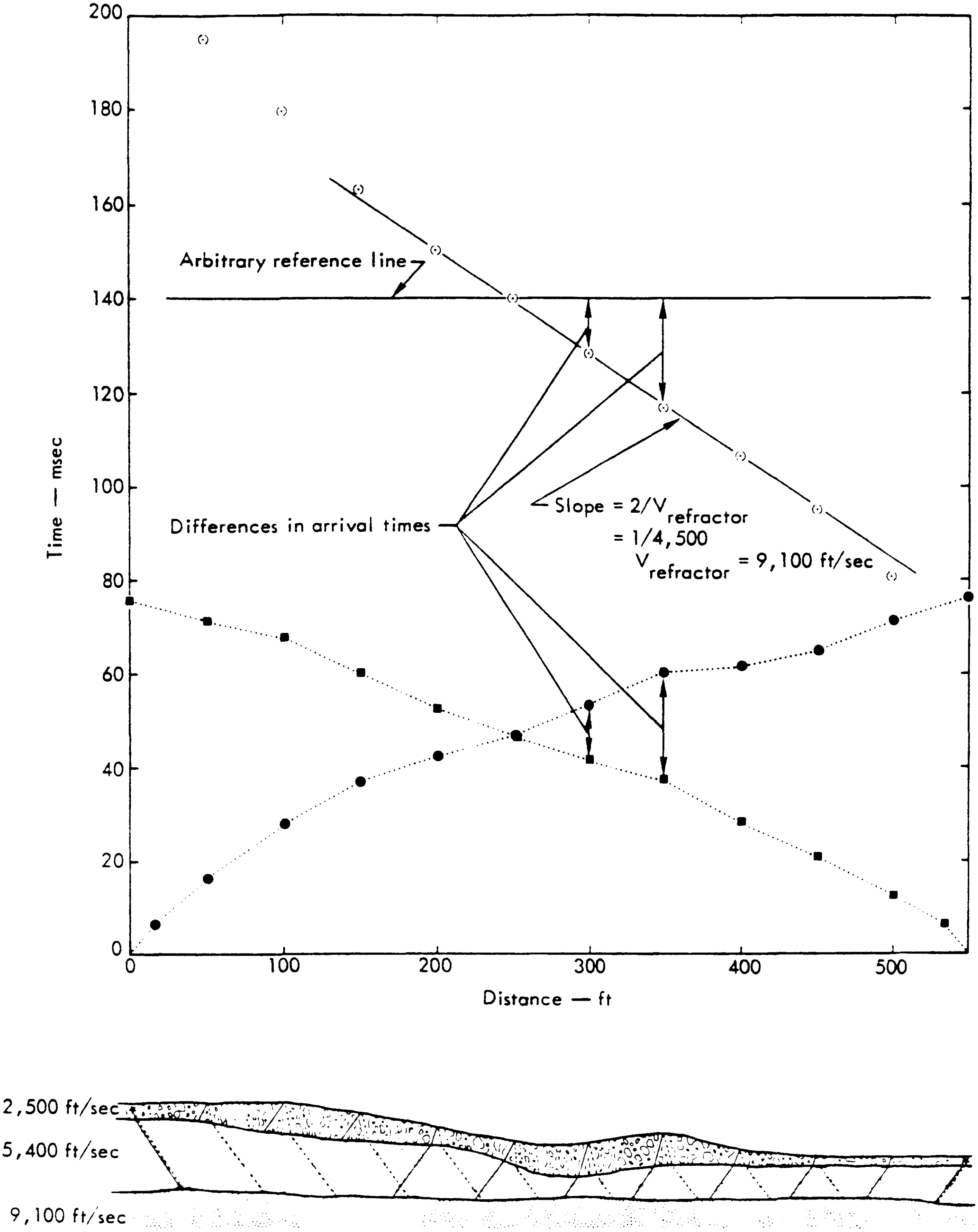

FIGURE 3.4
Determining true refractor velocities using the method-of-differences (after Redpath, 1973).

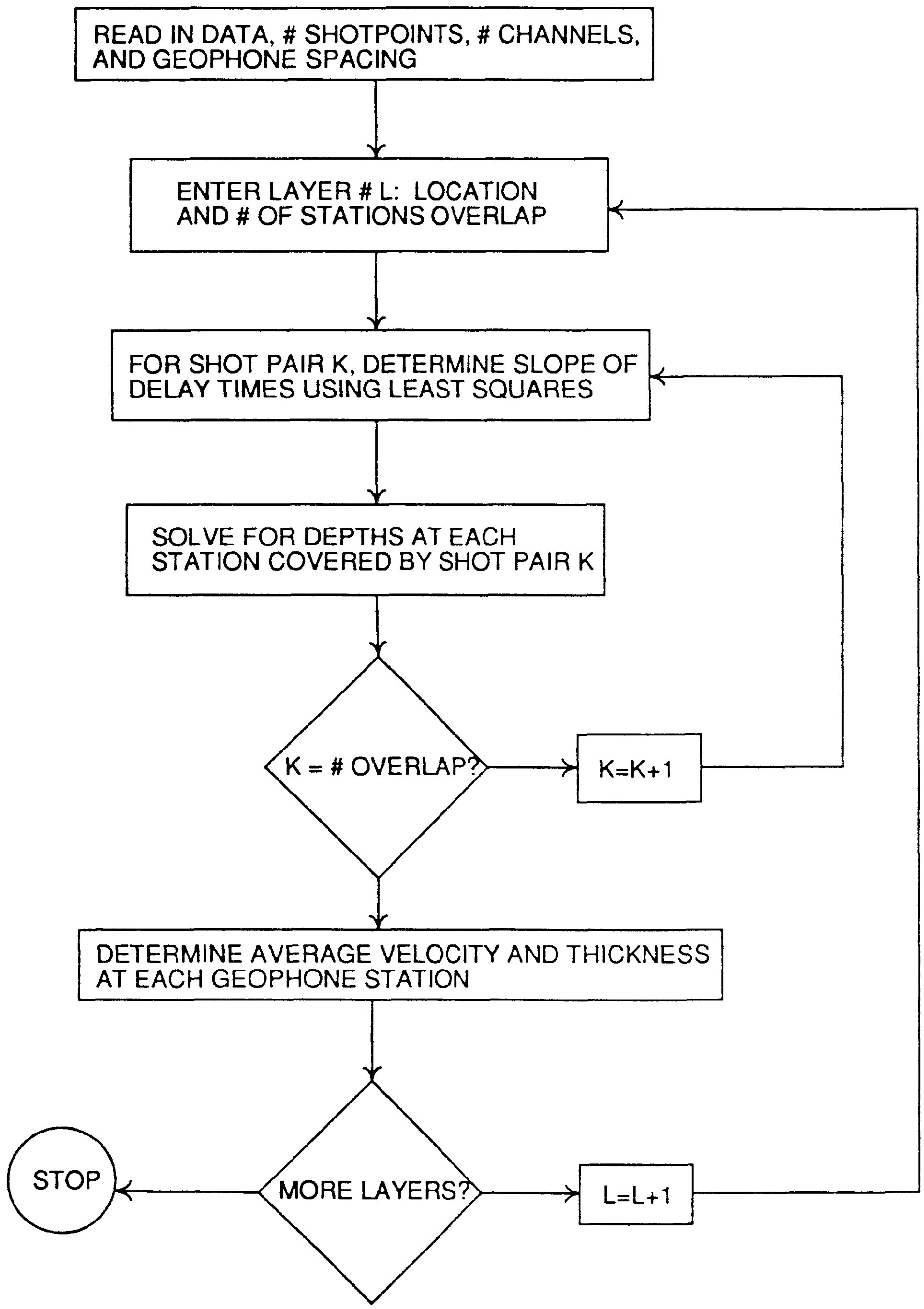

FIGURE 3.5
Flowchart showing depth calculation program.

the line. This process continues until velocities and thicknesses for each layer are defined.

A FORTRAN program designed to sort through CRP data and solve for thicknesses and velocities of up to four layers is listed in APPENDIX A. The program prompts the user to input the arrival times for each of the forward shots. The forward shots are then stored in an array with exactly the same format as the spreadsheet in FIGURE 3.2. The program then prompts the user for the shot spacing, the location and number of stations of overlap for coverage of the first interface. Depths and velocities of the first interface are computed and stored in a data file. The user is prompted for information on the second and third interfaces and the thickness and velocity calculations are made and stored in data files.

It took about 20 minutes to enter into the program all of the arrival times for one of the field camp lines. Once the arrival times were input, the depth calculations for four layers along the line were made almost instantaneously. This program was run on a Macintosh SE personal computer, with the total time required to input arrival times and make the calculations for one line of about 25 minutes (note that most of the time was spent entering data; the actual program run time was only a few seconds).

This section presented the proposed methodology for processing CRP data. All of the steps necessary to take the raw field data and determine depths and velocities for each refracting interface has been discussed in detail. With the exception of picking the first break times, the time required for the processing procedure outlined in this section is comparable to any conventional survey precessing scheme. From a production standpoint, if some first break picking algorithm was utilized in this procedure, it would be possible to process CRP data in almost real-time. This leads to the conclusion that even though there is much more data involved in a CRP survey, it is possible to acquire, process, and interpret CRP data in about the same amount of time as a conventional survey.

SECTION 4

Comparison of CRP and Conventional Survey Data

This section will document the comparison of results from a CRP survey and a conventional survey on the same refraction line. This study was undertaken with two goals in mind. First, the CRP data were processed with the intention of defining a standard processing procedure. The procedure described in detail in SECTION 3 was the result of processing the CRP data which will be presented here. Second, this study was designed to compare conventional and CRP survey results on actual refraction data from the same line.

A 24 station interval on the North-South refraction line was chosen for the study area. The North-South line was chosen because it runs basically parallel to the ridge, and had no topographic difficulties. Thus, static corrections did not need to be applied to the data. If statics had been an issue, each station could be brought to a datum using the "complete" first layer velocity control (assuming elevations at each station are known). The 24 station interval was chosen so that two 12 station conventional survey spreads could be compared to the same 24 stations shot with the CRP approach. Data gathered at geophone stations 50 through 280 were used to conduct this study (refer to the study area map, FIGURE 2.1).

4.1 Conventional Survey Results

The two five-shot spreads that were used for the conventional survey analysis were derived from the CRP data. The reverse shots required for the five-shot spreads were derived using the forward data shot at each station along the line. The 12 geophone stations, 50 through 160, recorded shots at stations -10, 50, 100, 160, and 220 for the first conventional spread FIGURE 4.1). The second spread consisted of shot points at stations 110, 170, 220, 280, and 340 which were recorded at geophone stations 170 through 280 (FIGURE 4.2).

The first step in processing the conventional survey data is to pick the velocity breaks on each of the time/distance plots (FIGURES 4.1 - 4.2). The result of this analysis is shown in FIGURES 4.3 - 4.4. The guidelines used for picking the apparent refractor velocities off of time/depth plots is described in detail by Mooney (1984).

With the apparent refractor velocities chosen, the next step is to solve for depths to each refractor. As shown in SECTION 1, it is desirable to solve for depths only where forward and reverse arrival times overlap. However, even though there is a shot recorded in the center of each spread, the refracted arrivals from the second interface do not overlap anywhere on either spread. This left no alternative but to solve for depths to the first interface using intercept time formulas (see Mooney, 1984). This method basically assumes a constant second-layer velocity with a flat boundary, and

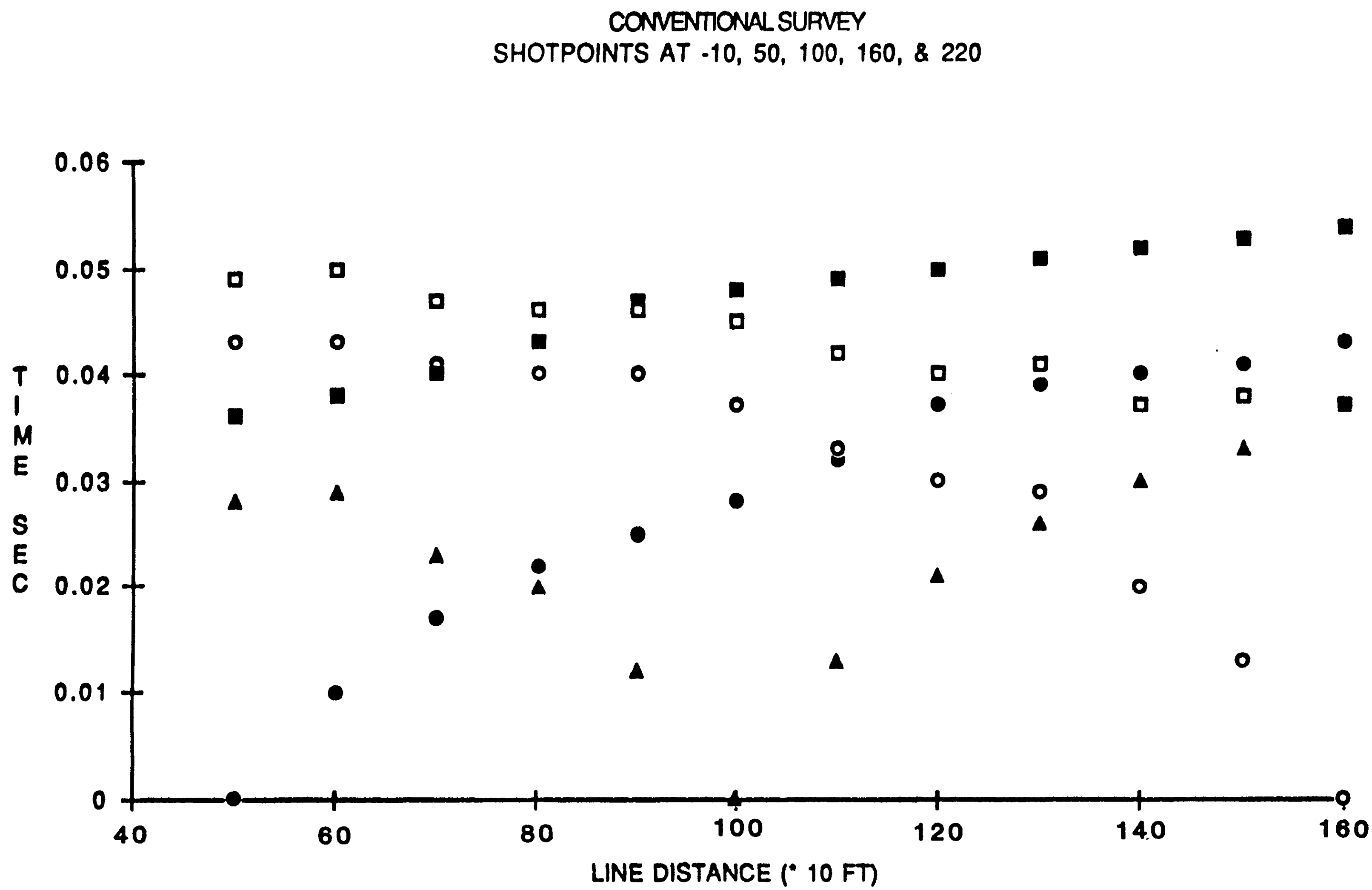

FIGURE 4.1
Uninterpreted first portion of the conventional survey.

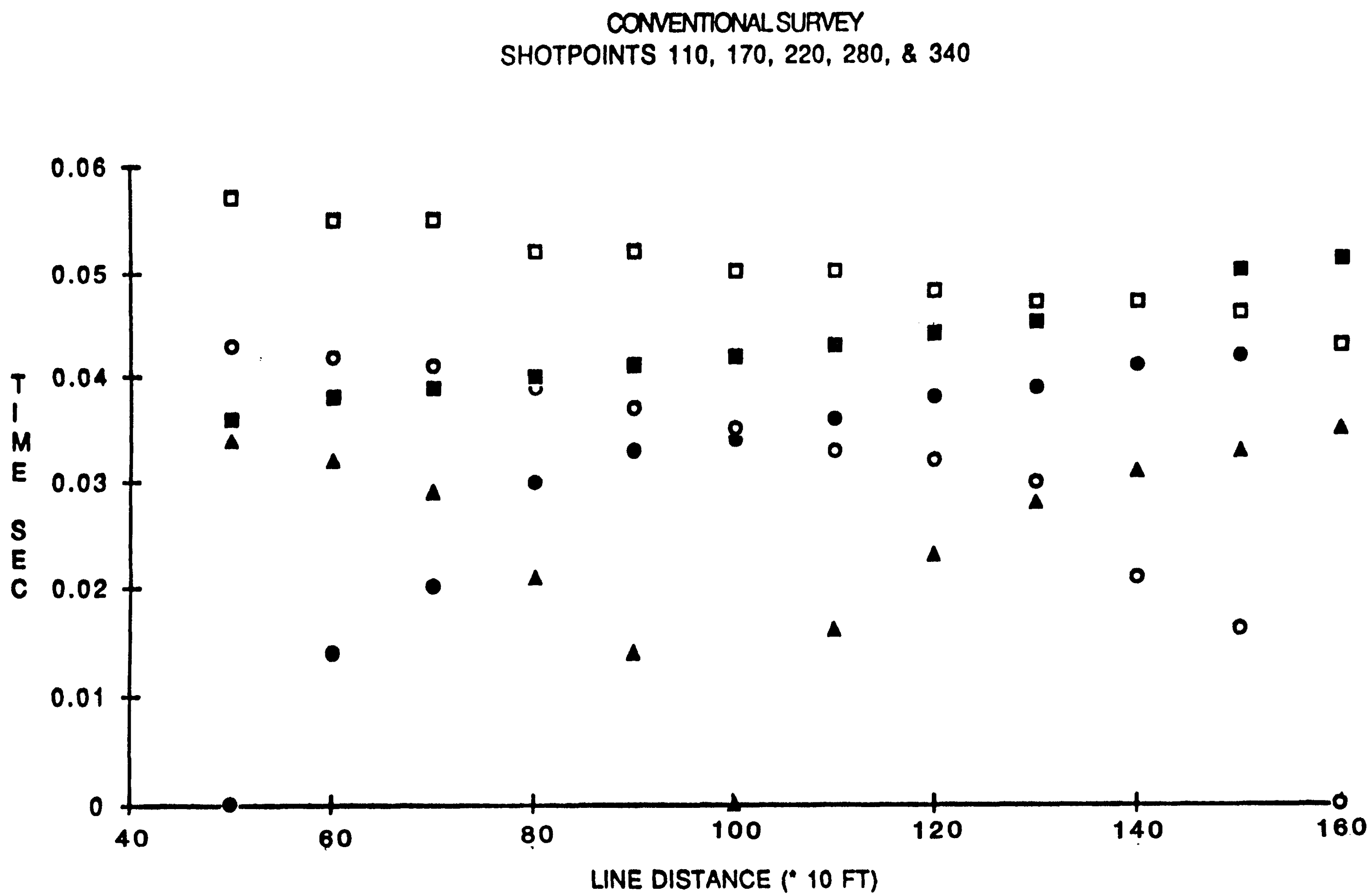

FIGURE 4.2
Uninterpreted second portion of the conventional survey.

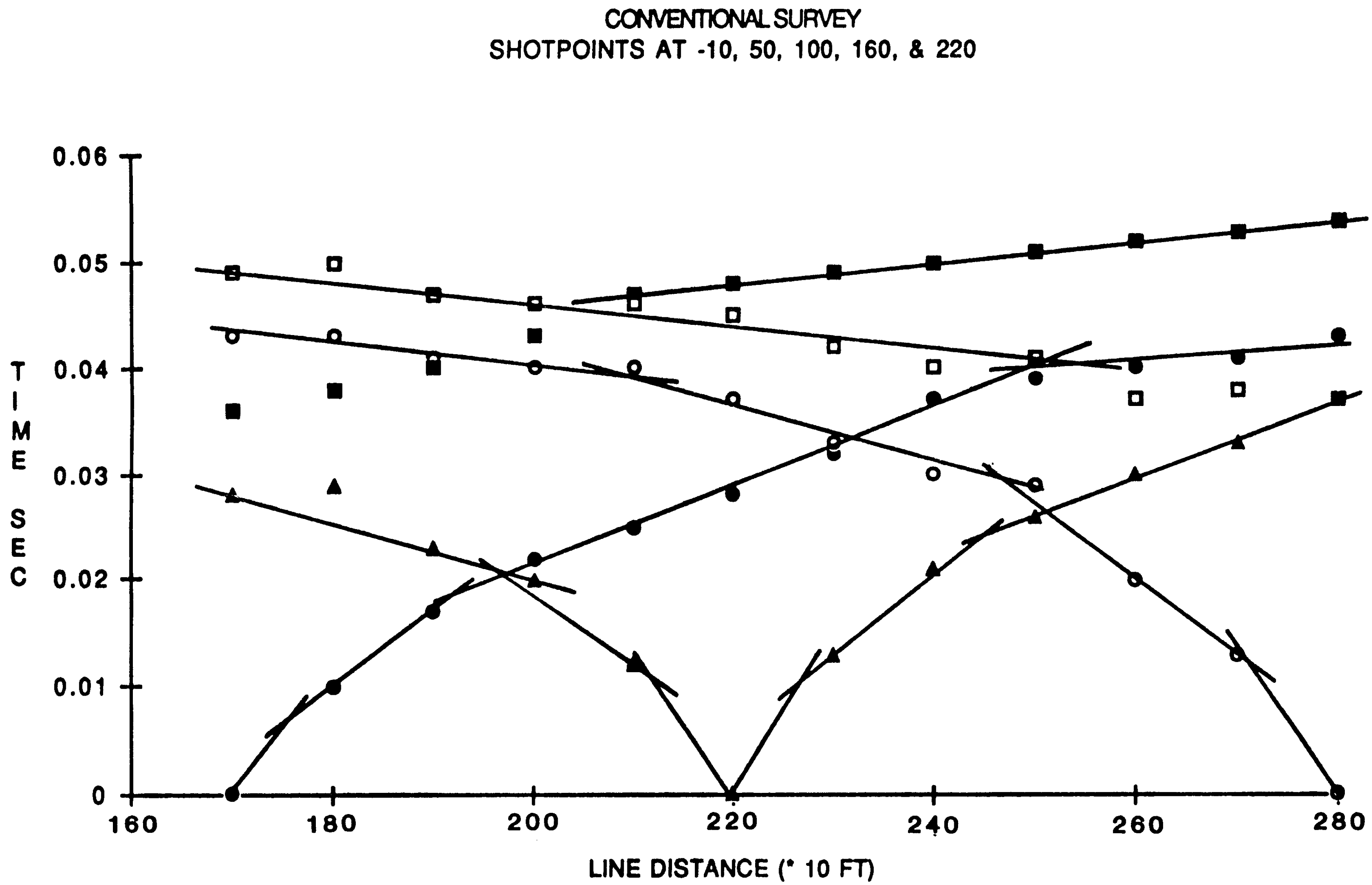

FIGURE 4.3
First portion of the conventional survey showing velocity picks.

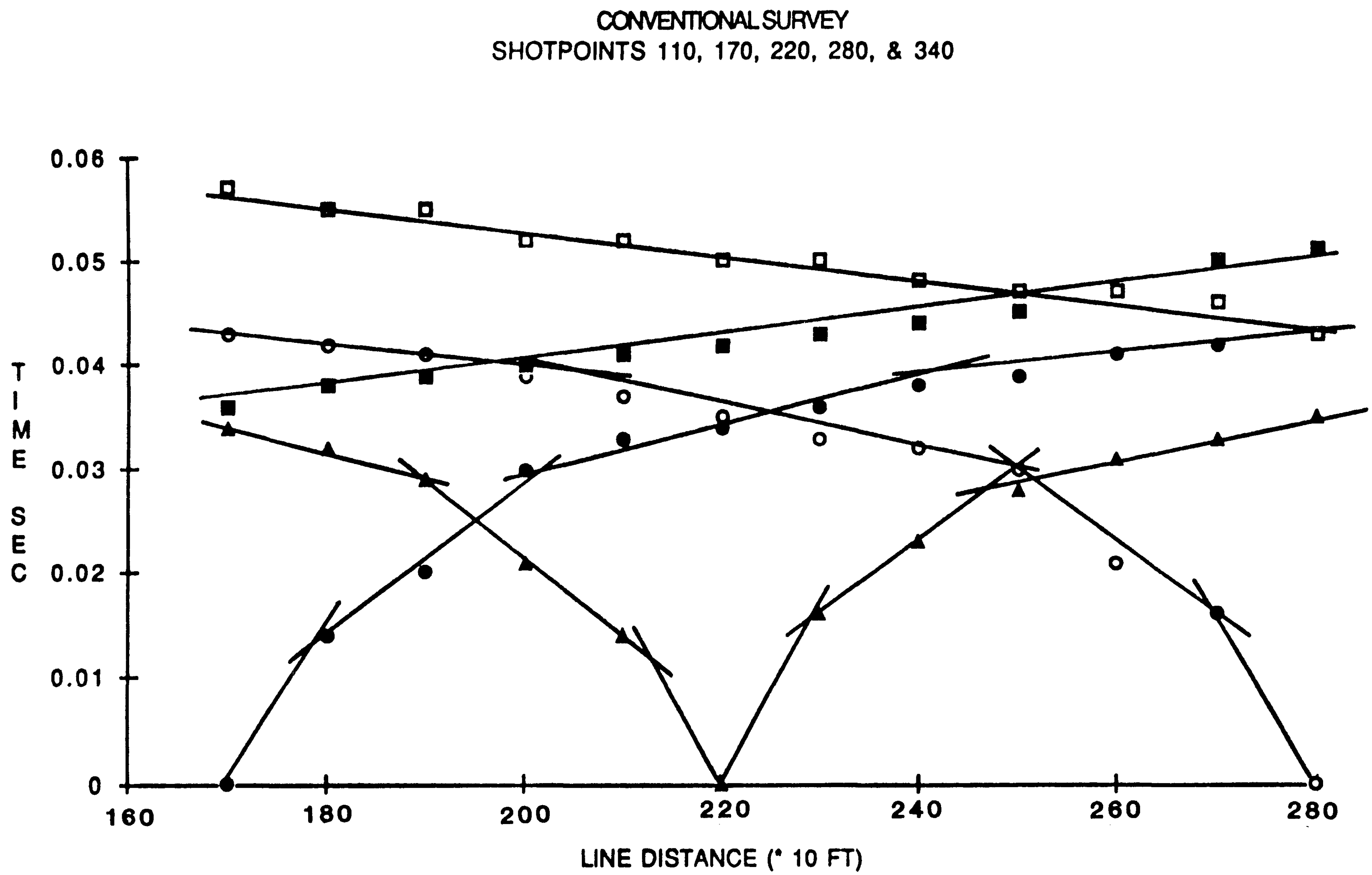

FIGURE 4.4
Second portion of the conventional survey showing velocity picks.

projects the depth to the first interface back to the origin, the shot points. So, using the intercept time formulas, depths to the first interface were computed at stations 50, 100, 160, 170, 220, and 280. Depths to the first interface for the rest of the geophone stations were found with linear interpolation between these points.

Refracted arrivals from the second interface do overlap some in the center of each spread. The method-of-differences equations listed in SECTION 3 were applied to determine true refractor velocity and solve for depths to the second interface where the overlap occurs (stations 90 through 120, and 200 through 220). Depths to the second interface for the rest of the geophone stations were found by interpolation.

The off-end shots for each spread provide refracted arrivals from the third interface. The method-of-differences was again applied, and velocities and depths were determined for the third interface in the overlapping zones (stations 70 through 120, and 190 through 250). It is possible to obtain an estimate of the depth to the third interface using intercept times. However, because the intercept is the one position on the line where there is no data (Hollister 1974), intercept times were not used here. The depth to the third interface at each spread end point could just as easily be found by interpolating between depths that were determined using method-of-differences.

The results of the depth calculations based on the two five-shot spreads are displayed as a depth section in FIGURE 4.5. Numerical velocity and thickness values determined in the conventional survey analysis are shown in TABLE 4.1. The depth section in FIGURE 4.5 demonstrates a common problem found when using a conventional five-shot spread on a long refraction line: the depths to each interface do not quite line up where the two spreads meet. The zone between stations 120 and 190 shows a difference of almost 10 feet in depth to the third interface. Also, as seen in the depth section, the right side of the zone ends with an upward trending interface while the left side after the zone begins with an upward trend. Because of the lack of data in this region, depths to the third interface can only be estimated by interpolating between sections where the method-of-differences was used to calculate depths. Another problem with the depth calculations is that there was no overlapping coverage of the first interface. This means that every calculation made to arrive at the depth section in FIGURE 4.5 was made using extrapolated velocity and thickness values.

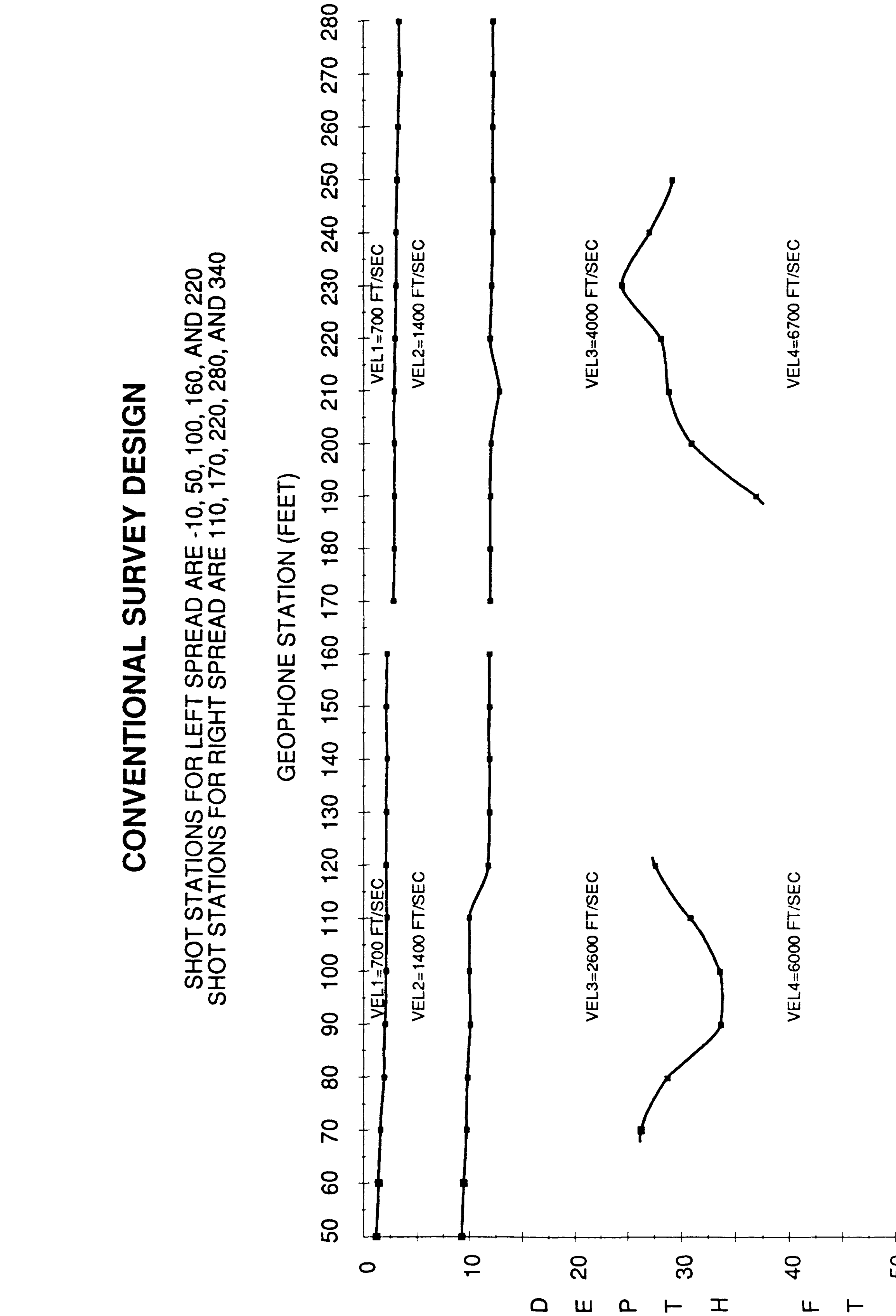

FIGURE 4.5
Depth section showing results of the conventional survey design.

TABLE 4.1

Conventional Survey Thickness and Velocity Summary

STA #	VEL1*	DEPTH1**	VEL2	DEPTH2	VEL3	DEPTH3	VEL4
50	700	1.2	1428	9.3	2608	--	6000
60	700	1.4	1428	9.5	2608	--	6000
70	700	1.6	1428	9.7	2608	26.3	6000
80	700	1.8	1428	10.1	2608	28.7	6000
90	700	2.0	1428	10.0	2608	33.7	6000
100	700	2.1	1428	10.0	2608	33.6	6000
110	700	2.1	1428	11.7	2608	30.7	6000
120	700	2.1	1428	11.7	2608	27.6	6000
130	700	2.1	1428	11.7	2608	--	6000
140	700	2.1	1428	11.7	2608	--	6000
150	700	2.1	1428	11.7	2608	--	6000
160	700	2.1	1428	11.7	2608	--	6000
170	700	2.7	1428	11.8	4000	--	6667
180	700	2.8	1428	11.9	4000	--	6667
190	700	2.8	1428	11.9	4000	36.1	6667
200	700	2.9	1428	12.0	4000	30.8	6667
210	700	2.9	1428	12.7	4000	28.8	6667
220	700	3.0	1428	11.8	4000	28.1	6667
230	700	3.1	1428	12.1	4000	24.5	6667

TABLE 4.1

Conventional Survey Thickness and Velocity Summary

STA #	VEL1*	DEPTH1**	VEL2	DEPTH2	VEL3	DEPTH3	VEL4
240	700	3.1	1428	12.1	4000	27.0	6667
250	700	3.2	1428	12.2	4000	29.2	6667
260	700	3.2	1428	12.2	4000	--	6667
270	700	3.3	1428	12.3	4000	--	6667
280	700	3.3	1428	12.3	4000	--	6667

*Depths are in feet.

**Velocities are in feet/second.

4.2 CRP Survey Results

CRP data along the North-South line was processed over the same 24 station interval, stations 50 through 280. For this analysis, the arrival times for forward shots at each geophone station in the interval from -10 to 340 were input to an Excel spreadsheet as described in SECTION 3. The spreadsheet showing the first arrival times for these forward shots is included as PLATE 1. Analysis of various shot pair combinations showed that for the first interface, a five station shot spacing (40 feet) provided overlapping arrivals from the first interface for the central three stations. A shot spacing of 11 stations, or 100 feet provided a 5 station overlap of refracted arrivals from the second interface. For the third interface, a shot spacing of 20 stations, or 190 feet provided a 6 station overlap. The time versus depth plots for all of the combinations of these shot spacings that provide coverage of each interface from stations 50 to 280 are included in APPENDIX B.

The forward shot arrival times, the geophone spacings and number of stations of overlap were input to the CRP.FOR program listed in APPENDIX A. The velocities and thicknesses determined by the program are listed in TABLE 4.2. The depth section resulting from analysis of the CRP data is shown in FIGURE 4.6. This depth section shows that a depth calculation to each interface was made at every geophone station. Also, every depth calculation was made

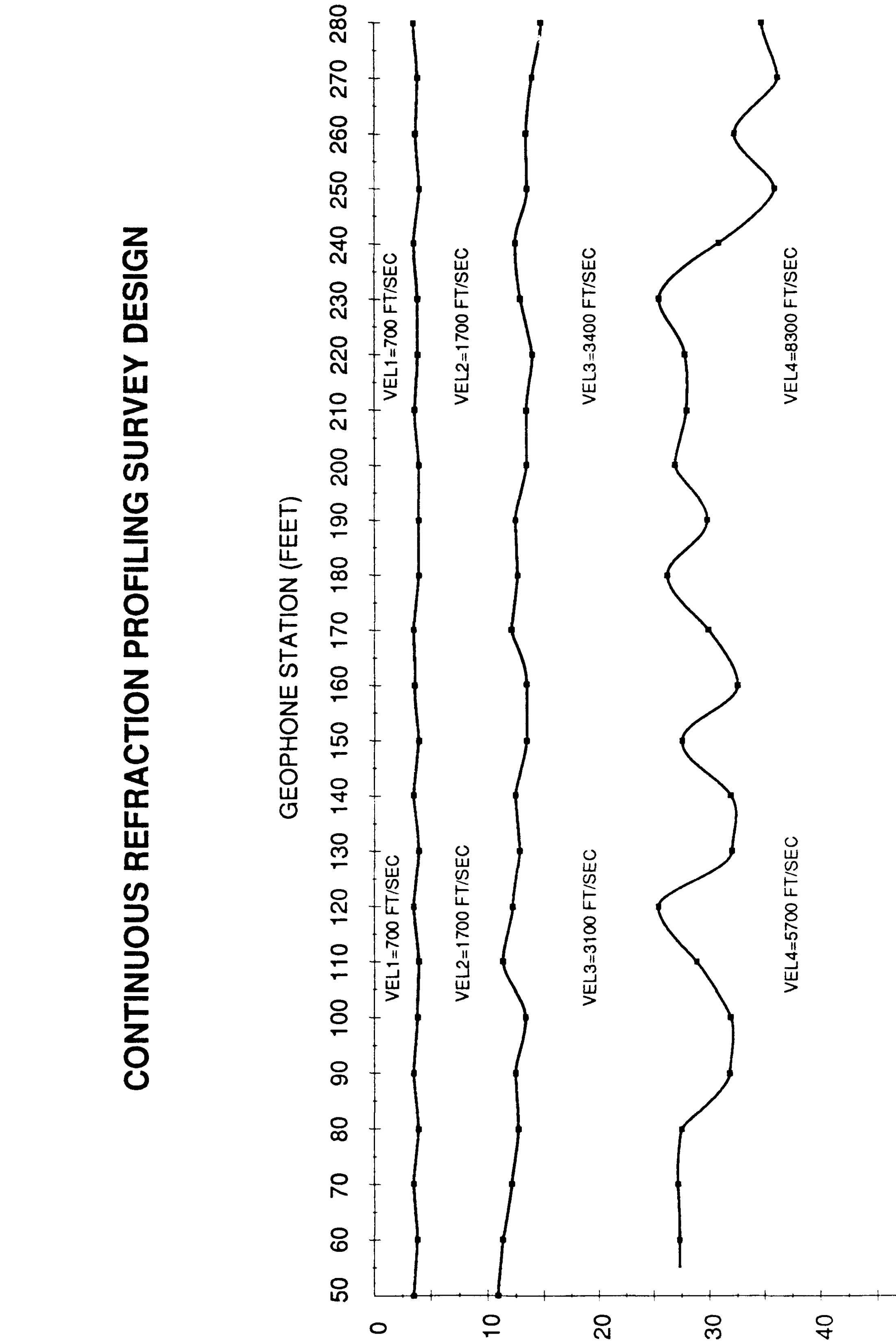

FIGURE 4.6
Depth section showing results of CRP survey.

TABLE 4.2

CRP Survey Thickness and Velocity Summary

STA #	VEL1*	DEPTH1**	VEL2	DEPTH2	VEL3	DEPTH3	VEL4
50	700	3.5	1670	10.8	3075	--	--
60	700	3.8	1656	11.3	3053	27.3	5645
70	700	3.5	1757	12.1	3070	27.1	5763
80	700	3.8	1705	12.7	3114	27.5	5724
90	700	3.5	1670	12.5	3189	31.8	5650
100	700	3.8	1656	13.3	3314	31.8	5879
110	700	3.5	1656	11.3	3053	28.8	6240
120	700	3.5	1756	12.1	3070	25.3	6814
130	700	3.8	1706	12.7	3114	32.0	7274
140	700	3.5	1670	12.5	3189	31.8	8000
150	700	3.8	1656	13.3	3314	27.5	8501
160	700	3.6	1649	13.4	3455	32.5	8695
170	700	3.5	1756	12.1	3070	29.7	8621
180	700	3.8	1705	12.7	3114	26.7	8389
190	700	3.5	1670	12.5	3189	29.7	8304
200	700	3.8	1656	13.3	3314	26.7	8214
210	700	3.6	1649	13.4	3457	27.9	8249
220	700	3.8	1705	14.0	3614	27.7	8400
230	700	3.8	1705	12.7	3114	25.3	8347

TABLE 4.2

CRP Survey Thickness and Velocity Summary

STA #	VEL1*	DEPTH1**	VEL2	DEPTH2	VEL3	DEPTH3	VEL4
240	700	3.5	1670	12.5	3189	30.8	8244
250	700	3.8	1656	13.3	3314	35.9	8031
260	700	3.6	1649	13.4	3457	32.2	7895
270	700	3.8	1705	14.0	3614	36.1	7796
280	700	3.5	1670	14.8	3752	34.7	7615

*Depths are in feet.

**Velocities are in feet/second.

COMPARISON OF BOTH METHODS

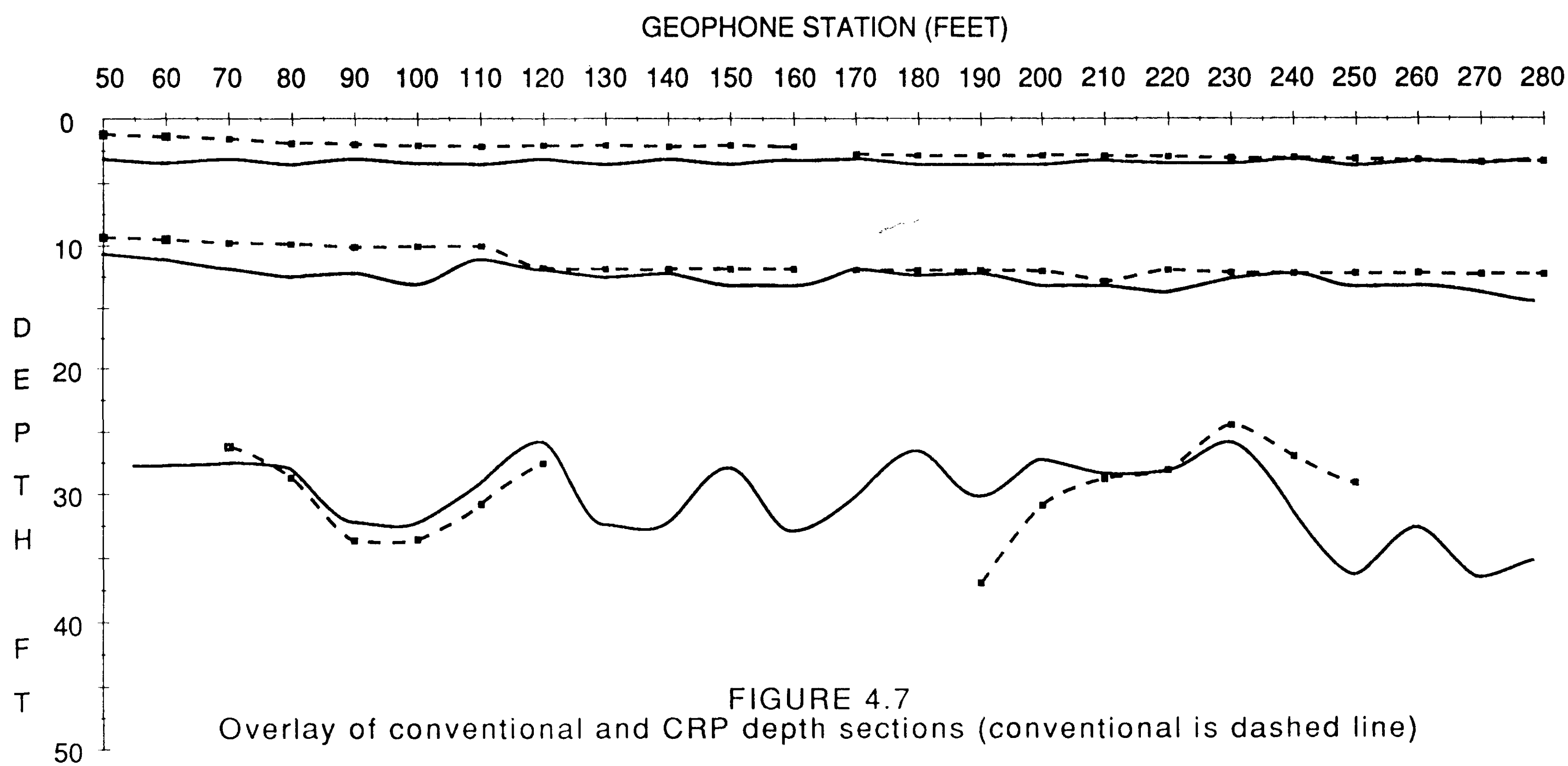

FIGURE 4.7
Overlay of conventional and CRP depth sections (conventional is dashed line)

using only data-derived values; no extrapolations were needed to solve for depths.

The difference between the data-derived depth section from the CRP survey and the depth section from the conventional survey can be seen in FIGURE 4.7. This figure is the superposition of both depth sections (FIGURES 4.5 and 4.6). Some of the character of the third interface is represented by the conventional survey depth section, however, there is some discrepancy in depth to the third interface. More importantly, the zone between the two conventional spreads which was unresolved in the conventional survey is completely covered by the CRP data.

Another interesting result of this analysis is pointed out in TABLE 4.2. The velocities determined in the CRP analysis at each geophone station are slightly different laterally. The velocities represented in TABLE 4.2 are actually the average of all the velocities which were determined from the many different shot pairs covering the same geophone station. There is no reason to assume that the material velocity of each layer changes laterally, although this is always a possibility. More likely, the change in velocities laterally can be attributed errors in first break picking.

Consider the following example. At best, the first break times can be picked off the paper shot records to within plus or minus one millisecond. So, in the most extreme case, the error in the arrival time difference at any given geophone station could be two milliseconds. Now consider attempting to use the difference method to determine true refractor velocity. For three stations of overlap, as shown in FIGURE 4.8, refractor velocity could possibly vary from 3334 feet per second to 10000 feet per second.

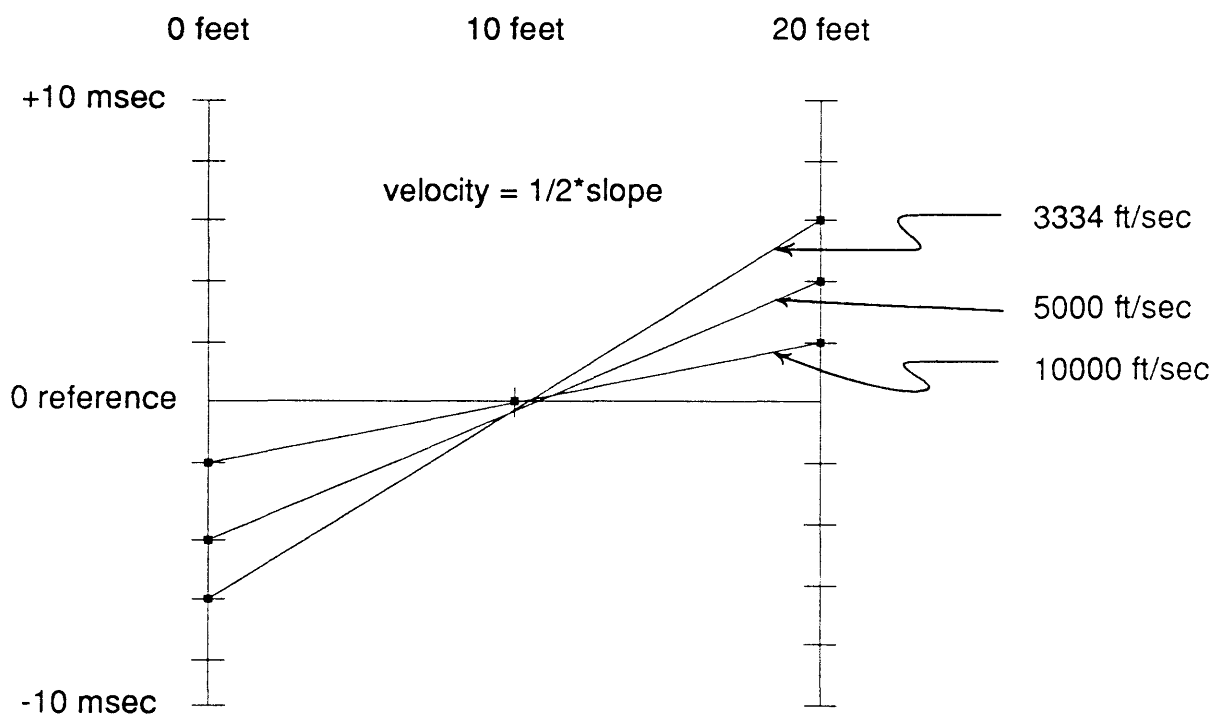

FIGURE 4.8
Possible changes in velocity using method-of-differences, with 2 msec error at end points.

The example and the tables showing refractor velocities emphasize the need for using as many shot pairs as possible to define velocities. Averaging of several values helps to reduce the errors associated with erroneous data. As was shown in TABLE 4.2 the redundant data provides much more control on refractor velocities. One expects this kind of velocity variation for the near surface layers in this area. Although there is a comparatively large variance in fourth layer velocity, much more confidence can be placed in the CRP because of the added statistics in the velocity determinations. Thus, the redundant CRP data allows much more reliable velocity determinations to be made.

This section showed some of the positive aspects associated with the use of the CRP method. The conventional survey results showed some similarity to the CRP survey results. However, the CRP depth calculations were made using only data-derived values, whereas each conventional survey depth calculation was made using extrapolated data. The CRP results showed far superior depth control to each interface. Also, analysis of the range of velocities possible within the resolution of the first break picks showed the need for the redundancy in data inherent with the CRP approach. The added statistical enhancement of the data allows much more reliable interpretations to be made.

SECTION 5

Conclusions

This study was intended to introduce the Continuous Refraction Profiling approach for engineering seismic refraction surveys. The CRP method was developed specifically to eliminate the drawbacks associated with the conventional five-shot reversed spread, which is used almost exclusively in seismic refraction studies.

SECTION 1 introduced the Continuous Refraction Profiling approach. It was pointed out in this section that the conventional survey design did not provide adequate coverage of each refractor. Complete coverage is required to ensure that only data derived values, as opposed to extrapolated values, are used in the depth calculations. Also, Continuous Refraction Profiling allows key design decisions, such as shot location and geophone spacing, to be made after the data has been acquired. The conventional survey spacings are determined before or during acquisition.

SECTION 2 consists of a description of the Continuous Refraction Profiling feasibility study which took place at the 1988 CSM Geophysics Summer Field Session. Two refraction lines were shot using the CRP approach. It was found that once the hardware was functioning properly and the students were trained in the field procedure, CRP was very efficient as a data acquisition method. The CRP survey does require more shot points than the conventional survey. However, the efficiency added with a roll-along approach is such that CRP data could be acquired in about the same amount of time as conventional data.

Continuous Refraction Profiling data processing steps are presented in SECTION 3. The procedure from first-break picking to velocity analysis and depth calculations is discussed in detail. The additional amount of data acquired in a CRP survey does present some bookkeeping problems. Each shot point must be documented carefully to keep track of the shot location and which geophones were recording the shot. Picking the first arrival times for all of the shots in a CRP survey can be very time consuming. It is not recommended to pick all of the first-breaks by hand. An automatic first-break picking algorithm would make processing CRP data more time efficient. The software tools presented in SECTION 3 provide a means to rapidly analyze shot pairs throughout the survey and determine refractor velocities and calculate depths. With software to provide first-break picking, the CRP data could be processed quite effectively from a production standpoint.

A comparison of results of CRP and conventional data on the same refraction line are presented in SECTION 4. A 24 station interval on one of the CSM filed session refraction lines is processed for both survey designs. The conventional survey consisted of two five-shot spreads, recorded with 12 geophone stations each. Also, CRP data were processed at these same 24 stations. The result, as shown in FIGURE 4.7, is that the conventional survey depth section shows similar character to the CRP section in the center of each spread. However, where the two five-shot meet, there is only extrapolated data from the conventional survey. It is not clear how to interpret the zone between the two conventional spreads. The CRP depth section has no extrapolated values, and several independent depth calculations are averaged to arrive at each depth calculation shown. Thus, a much higher degree of confidence can be placed in the CRP results.

This study was intended to present a basic methodology for acquisition and processing of Continuous Refraction Profiling data. The CRP approach, when applied to actual field data, did provide complete coverage of each refractor. The results show that, compared to the conventional approach, CRP provides a much more detailed picture of near surface geology. Also, the statistical enhancement made possible by the redundant CRP data increases the reliability of refraction survey results.

Analysis of the CRP method also included a comparison of the additional time and effort associated with the additional amounts of data. It was found that the efficient roll-along approach made it possible to gather CRP data with about the same amount of field time as conventional data. With the exception of picking first-break times, it was found that the software tools presented here make it possible to process CRP data quickly and efficiently.

This study showed that it is possible conduct, process, and interpret Continuous Refraction Profiling data with a time frame similar to a comparable conventional survey. Therefore, it is possible to gather more complete and more reliable refraction data without significant additional time or expense.

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APPENDIX A

Fortran Code for CRP Velocity and Depth Calculations

```
C    CRP.FOR
C      Written By:  Michael O. Bower
C      January 1989
C
C      This program was written in MACTRAN PLUS FORTRAN for the
C     Macintosh SE.  The code has been written with due care, and
C     has been tested on the data used in this thesis.  I assume no
C     liability for the use of this code in other applications.
C
C     This program will analyze refraction data gathered using the
C     Continuous Refraction Profiling approach.
C
C
C     DELGP = geophone spacing in feet (must be equal spacings)
C     DELSP = shot spacing (must be an integer number of geophone
C     spacings)
C     FOLAP = number of stations from left (forward) before overlap
C     begins
C     ROLAP = number of stations from left before overlap ends
C     NSHOT = number of total shot points in survey
C
C
C
C
C
C


      DIMENSION DATA(100,100), H1X(500,3), H2X(500,5),
     &           H3X(500,7)

      INTEGER DELSP2, FOLAP2, NOLAP2, DELSP3, FOLAP3, NOLAP3

      INTEGER NSHOT, NCHAN, DELGP, ANS, DELSP, FOLAP, NOLAP,
     &        N2SHOT, L
```

```
C
C Set up data file and variables necessary to find depths and
C  velocities to the first interface.
C

      WRITE(*,*)'How many shotpoints to be analyzed for this line?'

      READ(*,*) NSHOT

      N2SHOT = ((NSHOT*2)-1)

      WRITE(*,*)'How many channels were recorded at each
                    shotpoint?'

      READ(*,*) NCHAN

      WRITE(*,*)'What is the geophone spacing?'

      READ(*,*) DELGP

      WRITE(*,*)'Do you have a defined data file? (1=yes,0=no)'

      READ(*,*)ANS

      IF(ANS.EQ.1) THEN

         DO 21 I=1,NSHOT

            DO 22 J=1,NCHAN+1

               L = J-1

                READ(15,*) DATA(I,I+L)

22          CONTINUE

21       CONTINUE
```

```
      ELSE
         DO 10 I=1,NSHOT
            WRITE(*,30)I
30             FORMAT('Enter the arrival times for shotpoint',I2)
            DO 20 J=1,NCHAN+1
               N = J - 1
               WRITE(*,35)J
35                FORMAT(5X,'Enter arrival #',I2)
               READ(*,*)DATA(I,I+N)
               WRITE(15,*)DATA(I,I+N)
20          CONTINUE
10       CONTINUE
      ENDIF
      WRITE(*,*)'How many stations (from left) is the reverse shot?'
      READ(*,*)DELSP
      WRITE(*,*)'How many stations (from left) until overlap
      begins?'
      READ(*,*)FOLAP
      WRITE(*,*)'How many stations of overlap to analyze?'
```

```
      READ(*,*)NOLAP

      CALL FINDH1(DATA,NSHOT,FOLAP,NOLAP,DELSP,DELGP,H1X)

C
C Now set up to solve for second interface depths and velocities.
C
      WRITE(*,*)'For the second interface - how many stations'

      WRITE(*,*)'(from the left) is the reverse shot?'

      READ(*,*)DELSP2

      WRITE(*,*)'How many stations (from left) until overlap
               begins?'

      READ(*,*)FOLAP2

      WRITE(*,*)'How many stations of overlap to analyze?'

      READ(*,*)NOLAP2

      CALL

      FINDH2(DATA,NSHOT,FOLAP2,NOLAP2,DELSP2,DELGP,H1X,H2X)

C
C Now set up to solve for third interface depths and velocities.
C
      WRITE(*,*)'For the third interface - how many stations'

      WRITE(*,*)'(from the left) is the reverse shot?'

      READ(*,*)DELSP3
```

```
      WRITE(*,*)'How many stations (from left) until overlap
                begins?'

      READ(*,*)FOLAP3

      WRITE(*,*)'How many stations of overlap to analyze?'

      READ(*,*)NOLAP3

      CALL

      DO 25 I = 1,NSHOT

            WRITE(20,*) (H3X(I,J),J=1,7)

            WRITE(21,*) (H2X(I,J),J=1,5)

            WRITE(22,*) (H1X(I,J),J=1,3)

25    CONTINUE

      END

C
C     Subroutine FINDH1 defines the depth to the first interface and
C     the velocity at each geophone station.
C


      SUBROUTINE

      FINDH1(DATA,NSHOT,FOLAP,NOLAP,DELSP,DELGP,H1X)


C
C      Dimension arrays and initialize variables.
C
```

```
      DIMENSION TA(200), TB(200), DIFF(200), VEL2(200),
               XDATA(200)

      DIMENSION H1X(500,3), VEL1(200), SIG(200), DATA(100,100)

      DIMENSION X(200), H(200), V2(200)

      INTEGER DELSP, DELGP, FOLAP, NOLAP, ROLAP, NSHOT, NUMSP

      INTEGER COUNT, XN

      REAL TAB, ALPH12, H1, NP, HAVG, HSUM,  VAVG, VSUM, QUO

     COUNT = 0

C
C     Define the x-distance array and the standard deviations.
C

      DO 70 M = 1,NSHOT

         VEL1(M) = 700.

         XDATA(M) = (M-1)*DELGP

         SIG(M) = .001

70    CONTINUE

C
C     Calculate velocities and depths at each geophone station for
C     each of the overlapping regions and write to data file.
C
```

```
      M = (NSHOT - (NOLAP + FOLAP)) + 2
       DO 100 I = 1,M
C
C     Determine difference times for the overlapping regions.
C
          DO 80 J = 1,NOLAP
             N = (I+J-2) + FOLAP
             L = (I-1) + DELSP
             TA(J) = DATA(I,N)
             TB(J) = DATA(N,L)
             DIFF(J) = TA(J) - TB(J)
80        CONTINUE
C
C     Call subroutine FIT to determine the best fit slope of
C     difference times.
C
          MWT = 0
          CALL FIT(XDATA,DIFF,NOLAP,SIG,MWT,A,B,SIGA,SIGB,CHI2,Q)
```

```
C
C     Compute velocity (from inverse slope), intercept time, and
C     incident angle.
C

          VEL2(I) = 2.0/(ABS(B))

          TAB = DATA(I,DELSP+I-1)

          QUO = VEL1(I)/VEL2(I)

          ALPH12 = (ASIN(QUO))*(180./3.1415926)

C
C     Determine depth to first interface and write depth, velocity,
C     and the geophone station (in feet) to data file.
C

        DO 90 K = 1,NOLAP

            N = (K+I-2) + FOLAP

          COUNT = COUNT+1

             H1 = (VEL1(I)*((TA(K)+TB(K))-
                    TAB))/(2.0*COSD(ALPH12))

            WRITE(12,*) XDATA(N), H1, VEL2(I)

85          FORMAT(G10,5X,G10,5X,G10)

90      CONTINUE

100   CONTINUE
```

```
      CLOSE(12,STATUS='KEEP')

C
C     Analyze depths and velocities at each station and define final
C     values.
C

      DO 115 I = 1,COUNT

         READ(13,*) X(I), H(I), V2(I)

115   CONTINUE

      XN = 0

      DO 120 I=1,NSHOT

        NP = 0.0

        HSUM = 0.0

        VSUM = 0.0

        DO 110 J = 1,COUNT

          IF(X(J).EQ.XN) THEN

            HSUM = HSUM + H(J)

            VSUM = VSUM + V2(J)

            NP = NP + 1.0

          ENDIF
```

```
110     CONTINUE
        IF(NP.NE.0.0) THEN
            VAVG = VSUM/NP
            HAVG = HSUM/NP
            H1X(I,1) = XN
            H1X(I,2) = HAVG
            H1X(I,3) = VAVG
        ELSE
            H1X(I,1) = XN
            H1X(I,2) = 0.0
            H1X(I,3) = 0.0
        ENDIF
        XN = XN + DELGP
120   CONTINUE
      RETURN
      END

      SUBROUTINE FIT(X,Y,NDATA,SIG,MWT,A,B,SIGA,SIGB,CHI2,Q)

C
```

```
C     Given a set of NDATA points X(I), Y(I) with standard deviations
C     SIG(I), fit them to a straight line y = a + bx by minimizing
C      x**2.
C

      DIMENSION X(NDATA), Y(NDATA), SIG(NDATA)

      SX = 0.

      SY = 0.

      ST2 = 0.

      B = 0.

      IF(MWT.NE.0) THEN

         SS = 0.

         DO 11 I=1,NDATA

               WT = 1./(SIG(I)**2)

            SS = SS+WT

            SX = SX+X(I)*WT

            SY = SY+Y(I)*WT

11       CONTINUE

      ELSE

         DO 12 I=1,NDATA

            SX = SX+X(I)

            SY = SY+Y(I)
```

```
12        CONTINUE
            SS = FLOAT(NDATA)
          ENDIF
          SXOSS = SX/SS
          IF (MWT.NE.0) THEN
              DO 13 I=1,NDATA
                  T = (X(I)-SXOSS)/SIG(I)
                  ST2 = ST2+T*T
                  B = B+T*Y(I)/SIG(I)
13        CONTINUE
          ELSE
              DO 14 I=1,NDATA
                  T = X(I)-SXOSS
                  ST2 = ST2+T*T
                  B = B+T*Y(I)
14        CONTINUE
          ENDIF
          B = B/ST2
          A = (SY-SX*B)/SS
```

```
      SIGA = SQRT((1.+SX*SX/(SS*ST2))/SS)
      SIGB = SQRT(1./ST2)
      CHI2 = 0.
      IF(MWT.EQ.0) THEN
          DO 15  I=1,NDATA
                CHI2 = CHI2+(Y(I)-A-B*X(I))**2
15        CONTINUE
          Q = 1.
          SIGDAT = SQRT(CHI2/(NDATA-2))
          SIGA = SIGA*SIGDAT
          SIGB = SIGB*SIGDAT
      ELSE
          DO 16 I=1,NDATA
                CHI2 = CHI2+((Y(I)-A-B*X(I))/SIG(I))**2
16        CONTINUE
          Q = 1.
      ENDIF
      RETURN
      END
```

```
C
C Subroutine FINDH2 finds the depth to the second interface based on
C average depths and velocities found in FINDH1.
C

      SUBROUTINE
      FINDH2(DATA,NSHOT,FOLAP,NOLAP,DELSP,DELGP,H1X,H2X)

C
C      Dimension arrays and initialize variables.
C

      DIMENSION TA(200), TB(200), DIFF(200), VEL2(200),
      XDATA(200)

      DIMENSION H1X(500,3), H2X(500,5), VEL1(200), SIG(200)

      DIMENSION DATA(100,100), HX(200), H1A(200)

      DIMENSION X(200), H1(200), VEL3(200), V2(200), V3(200)

      INTEGER DELSP, DELGP, FOLAP, NOLAP, ROLAP, NSHOT, NUMSP

      INTEGER COUNT, XN

      REAL TAB, ALPH13, ALPH23, H2, NP, HAVG, HSUM, VAVG, VSUM

      REAL PROD1, PROD2, QUO1, QUO2

     COUNT = 0

C
```

```
C     Define the x-distance array, standard deviations, and velocity
C     functions.
C

      DO 70 M = 1,NSHOT

         VEL1(M) = 700.

        IF (M.GE.2) THEN

           VEL2(M) = (H1X(M-1,3) + H1X(M,3) + H1X(M+1,3))/3.

           H1A(M) = (H1X(M-1,2) + H1X(M,2) + H1X(M+1,2))/3.

        ELSE

           VEL2(M) = H1X(M,3)

           H1A(M) = H1X(M,2)

        ENDIF

         XDATA(M) = (M-1)*DELGP

         SIG(M) = .001

70    CONTINUE

C
C     Calculate velocities and depths at each geophone station for
C     each of
C     the overlapping regions and write to data file.
C

      M = (NSHOT - (NOLAP + FOLAP)) + 2
```

```
      DO 100 I = 1,M
C
C     Determine difference times for the overlapping regions.
C
         DO 80 J = 1,NOLAP
            N = (I+J-2) + FOLAP
            L = (I-1) + DELSP
            TA(J) = DATA(I,N)
            TB(J) = DATA(N,L)
            DIFF(J) = TA(J) - TB(J)
80       CONTINUE
C
C     Call subroutine FIT to determine the best fit slope of
C     difference times.
C
         MWT = 0
         CALL FIT(XDATA,DIFF,NOLAP,SIG,MWT,A,B,SIGA,SIGB,CHI2,Q)
C
C     Compute velocity (from inverse slope), intercept time, and
C     incident angle.
```

```
C
      VEL3(I) = 2.0/(ABS(B))
      TAB = DATA(I,DELSP+I-1)
      QUO1 = VEL2(I)/VEL3(I)
      ALPH23 = (ASIN(QUO1))*(180./3.1415926)
      QUO2 = VEL1(I)/VEL3(I)
      ALPH13 = (ASIN(QUO2))*(180./3.1415926)
C
C    Determine depth to first interface and write depth, velocity,
C    and the geophone station (in feet) to data file.
C
      DO 90 K = 1,NOLAP
        N = (K+I-2) + FOLAP
        COUNT = COUNT+1
        PROD1 = VEL2(N)/(2.*COSD(ALPH23))
        PROD2 = (2.0*H1A(N)*COSD(ALPH13))/VEL1(N)
        H2 = PROD1*(((TA(K)+TB(K))-TAB)-PROD2)
        WRITE(16,*) XDATA(N), H1A(N), VEL2(N), H2, VEL3(I)
90    CONTINUE
```

```
100   CONTINUE

      CLOSE(16,STATUS='KEEP')

C
C     Analyze depths and velocities at each station and define final
C     values.
C

      DO 115 I = 1,COUNT

          READ(17,*) X(I), H1(I), V2(I), HX(I), V3(I)

115   CONTINUE

      XN = 0

      DO 120 I=1,NSHOT

         NP = 0.0

         HSUM = 0.0

        VSUM = 0.0

        DO 110 J = 1,COUNT

           IF(X(J).EQ.XN) THEN

              HSUM = HSUM + HX(J)

               VSUM = VSUM + V3(J)

               NP = NP + 1.0
```

```
         ENDIF
110     CONTINUE
        IF(NP.NE.0.0) THEN
            VAVG = VSUM/NP
            HAVG = HSUM/NP
            H2X(I,1) = XN
            H2X(I,2) = H1(I)
            H2X(I,3) = V2(I)
            H2X(I,4) = HAVG
            H2X(I,5) = VAVG
        ELSE
            H2X(I,1) = XN
            H2X(I,2) = H1(I)
            H2X(I,3) = V2(I)
            H2X(I,4) = 0.0
            H2X(I,5) = 0.0
        ENDIF
       XN = XN + DELGP
120   CONTINUE
```

```
      RETURN
      END
C
C  Subroutine FINDH3 defines the velocities and depths to the third
C  interface based on the velocity and depth values determined in
C  FINDH1 and FINDH2.
C
      SUBROUTINE
      FINDH3(DATA,NSHOT,FOLAP,NOLAP,DELSP,DELGP,H2X,H3X)
C
C        Dimension arrays and initialize variables.
C
      DIMENSION TA(100), TB(100), DIFF(100), VEL2(200),
      DIMENSION H3X(500,7), H2X(500,5), VEL1(200), SIG(200)
      DIMENSION DATA(100,100), HX(200), VEL4(200), V4(200),
     &           H2A(200)
      DIMENSION X(200), H1(200), H2(200), VEL3(200), V2(200),
     &           V3(200)
      INTEGER DELSP, DELGP, FOLAP, NOLAP, ROLAP, NSHOT, NUMSP
      INTEGER COUNT, XN, X1
      REAL TAB, ALPH14, ALPH24, ALPH34, H3, NP, HAVG, HSUM,
     &     VAVG, VSUM
```

```
      REAL PROD1, PROD2, PROD3, QUO1, QUO2, QUO3
      REAL HA1, HA2, HA3, VA1, VA2, VA3
      COUNT = 0
C
C     Define the x-distance array, standard deviations, and velocity
C     functions.
C
      DO 70 M = 1,NSHOT
         VEL1(M) = 700.
         VEL2(M) = H2X(M,3)
         IF(M.GE.2) THEN
            VEL3(M) = (H2X(M-1,5) + H2X(M,5) + H2X(M+1,5))/3.
            H2A(M) = (H2X(M-1,4) + H2X(M,4) + H2X(M+1,4))/3.
         ELSE
            H2A(M) = H2X(M,4)
            VEL3(M) = H2X(M,5)
         ENDIF
         XDATA(M) = (M-1)*DELGP
         SIG(M) = .001
70    CONTINUE
```

```
C
C     Calculate velocities and depths at each geophone station for
C     each of the overlapping regions and write to data file.
C

      M = (NSHOT - (NOLAP + FOLAP)) + 2

      DO 100 I = 1,M

C
C     Determine difference times for the overlapping regions.
C

         DO 80 J = 1,NOLAP

            N = (I+J-2) + FOLAP

            L = (I-1) + DELSP

            TA(J) = DATA(I,N)

            TB(J) = DATA(N,L)

            DIFF(J) = TA(J) - TB(J)

80       CONTINUE

C
C     Call subroutine FIT to determine the best fit slope of
C     difference times.
C
```

```
      MWT = 0

      CALL FIT(XDATA,DIFF,NOLAP,SIG,MWT,A,B,SIGA,SIGB,CHI2,Q)

C
C   Compute velocity (from inverse slope), intercept time, and
C    incident angle.
C

       VEL4(I) = 2.0/(ABS(B))

       TAB = DATA(I,DELSP+I-1)

       QUO1 = VEL1(I)/VEL4(I)

        ALPH14 = (ASIN(QUO1))*(180./3.1415926)

       QUO2 = VEL2(I)/VEL4(I)

        ALPH24 = (ASIN(QUO2))*(180./3.1415926)

       QUO3 = VEL3(I)/VEL4(I)

        ALPH34 = (ASIN(QUO3))*(180./3.1415926)

C
C   Determine depth to first interface and write depth, velocity,
C   and the geophone station (in feet) to data file.
C

      DO 90 K = 1,NOLAP

         N = (K+I-2) + FOLAP
```

```
            COUNT = COUNT+1
              PROD1 = VEL3(N)/(2.*COSD(ALPH34))
              PROD2 = (2.0*H2A(N)*COSD(ALPH24))/VEL2(N)
              PROD3 = (2.0*H2X(N,2)*COSD(ALPH14))/VEL1(N)
              H3 = PROD1*(((TA(K)+TB(K))-TAB)-PROD2-PROD3)
             X1 = XDATA(N)
             HA1 = H2X(N,2)
             VA2 = VEL2(N)
             HA2 = H2A(N)
             VA3 = VEL3(N)
              WRITE(18,*) X1, HA1, VA2, HA2, VA3, H3, VEL4(I)
90        CONTINUE

100   CONTINUE
      CLOSE(18,STATUS='KEEP')

C
C     Analyze depths and velocities at each station and define final
C     values.
C

      DO 115 I = 1,COUNT
```

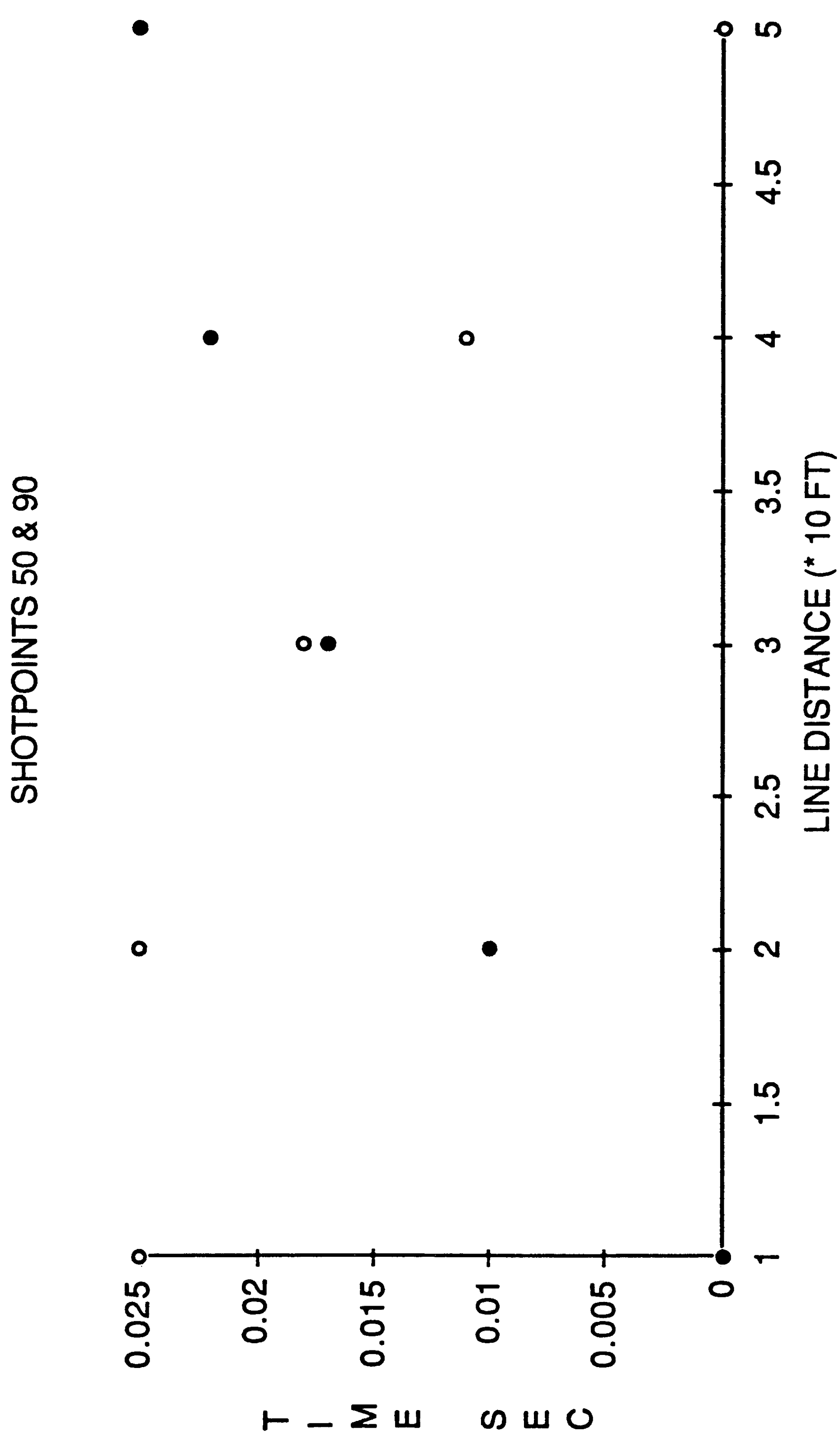
```
      READ(19,*) X(I), H1(I), V2(I), H2(I), V3(I), HX(I), V4(I)
115   CONTINUE
      XN = 0
      DO 120 I=1,NSHOT
        NP = 0.0
        HSUM = 0.0
        VSUM = 0.0
        DO 110 J = 1,COUNT
          IF(X(J).EQ.XN) THEN
            HSUM = HSUM + HX(J)
            VSUM = VSUM + V4(J)
            NP = NP + 1.0
          ENDIF
110     CONTINUE
        IF(NP.NE.0.0) THEN
          VAVG = VSUM/NP
          HAVG = HSUM/NP
          H3X(I,1) = XN
          H3X(I,2) = H1(I)
```

```
        H3X(I,3) = V2(I)
        H3X(I,4) = H2(I)
        H3X(I,5) = V3(I)
        H3X(I,6) = HAVG
        H3X(I,7) = VAVG
     ELSE
        H3X(I,1) = XN
        H3X(I,2) = H1(I)
        H3X(I,3) = V2(I)
        H3X(I,4) = H2(I)
        H3X(I,5) = V3(I)
        H3X(I,6) = 0.0
        H3X(I,7) = 0.0
     ENDIF
     XN = XN + DELGP
120  CONTINUE
     RETURN
        END
```

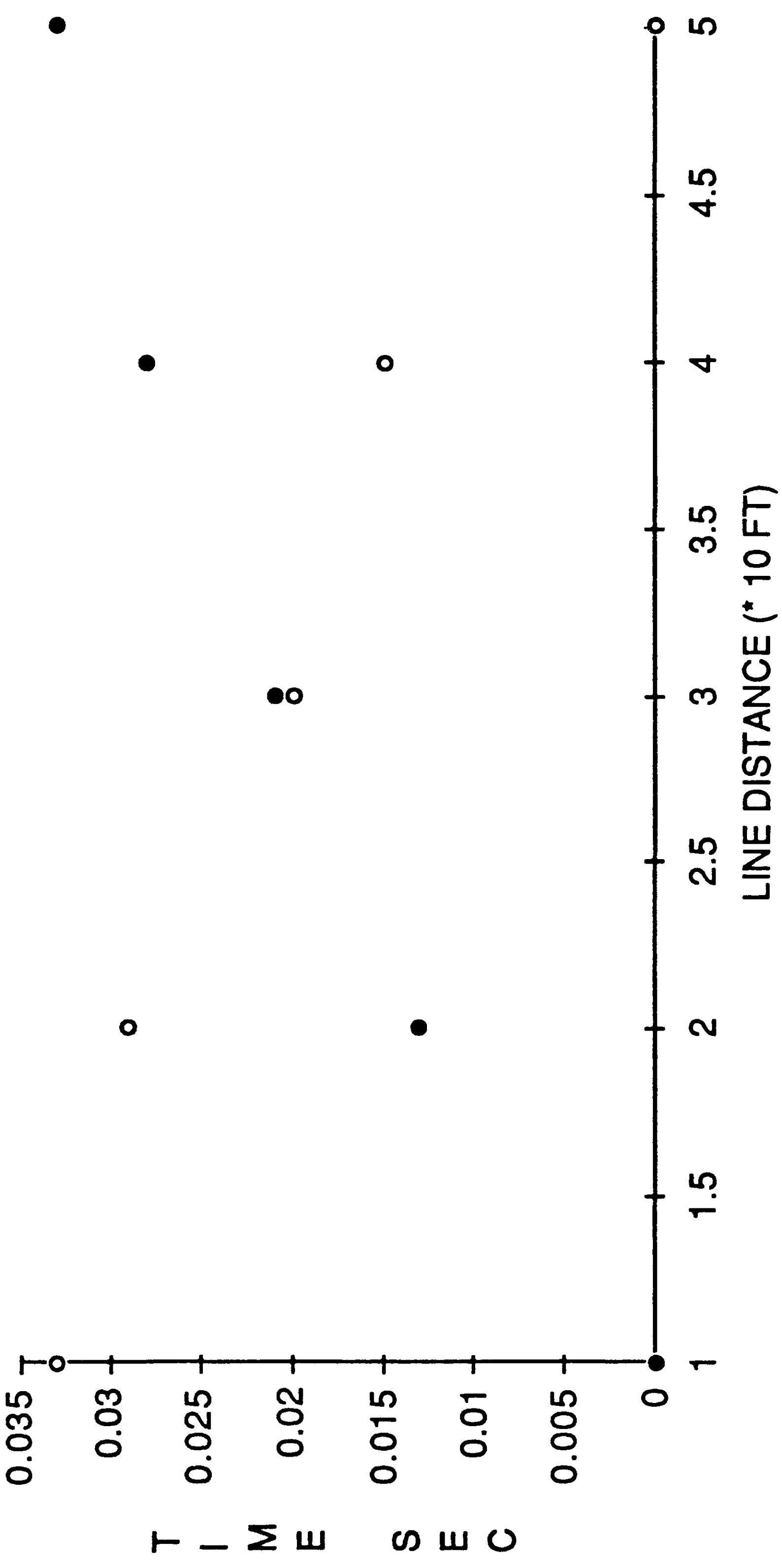
APPENDIX B

Example Figures Showing Shot Pair Analysis

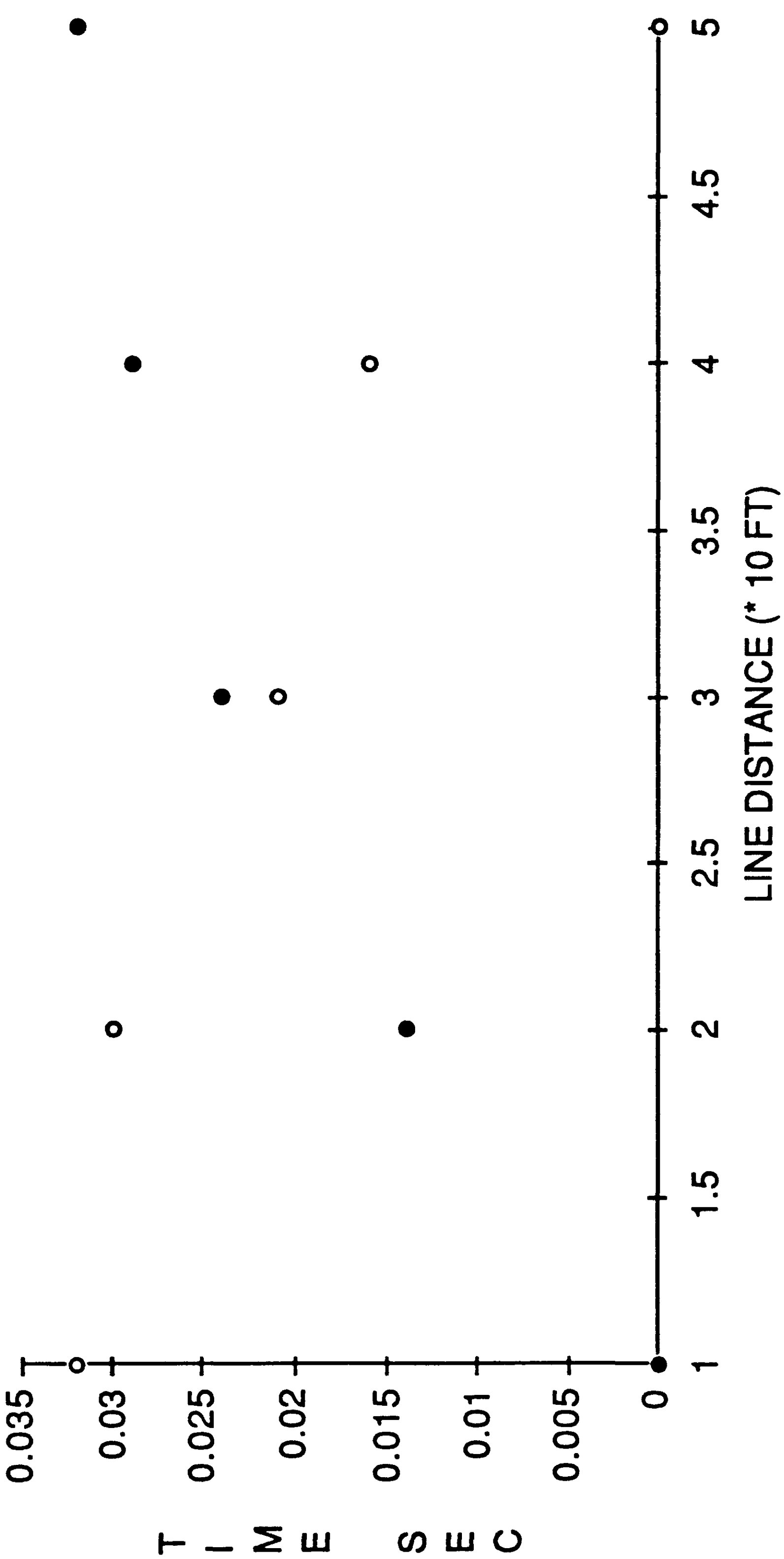
First Interface Overlap



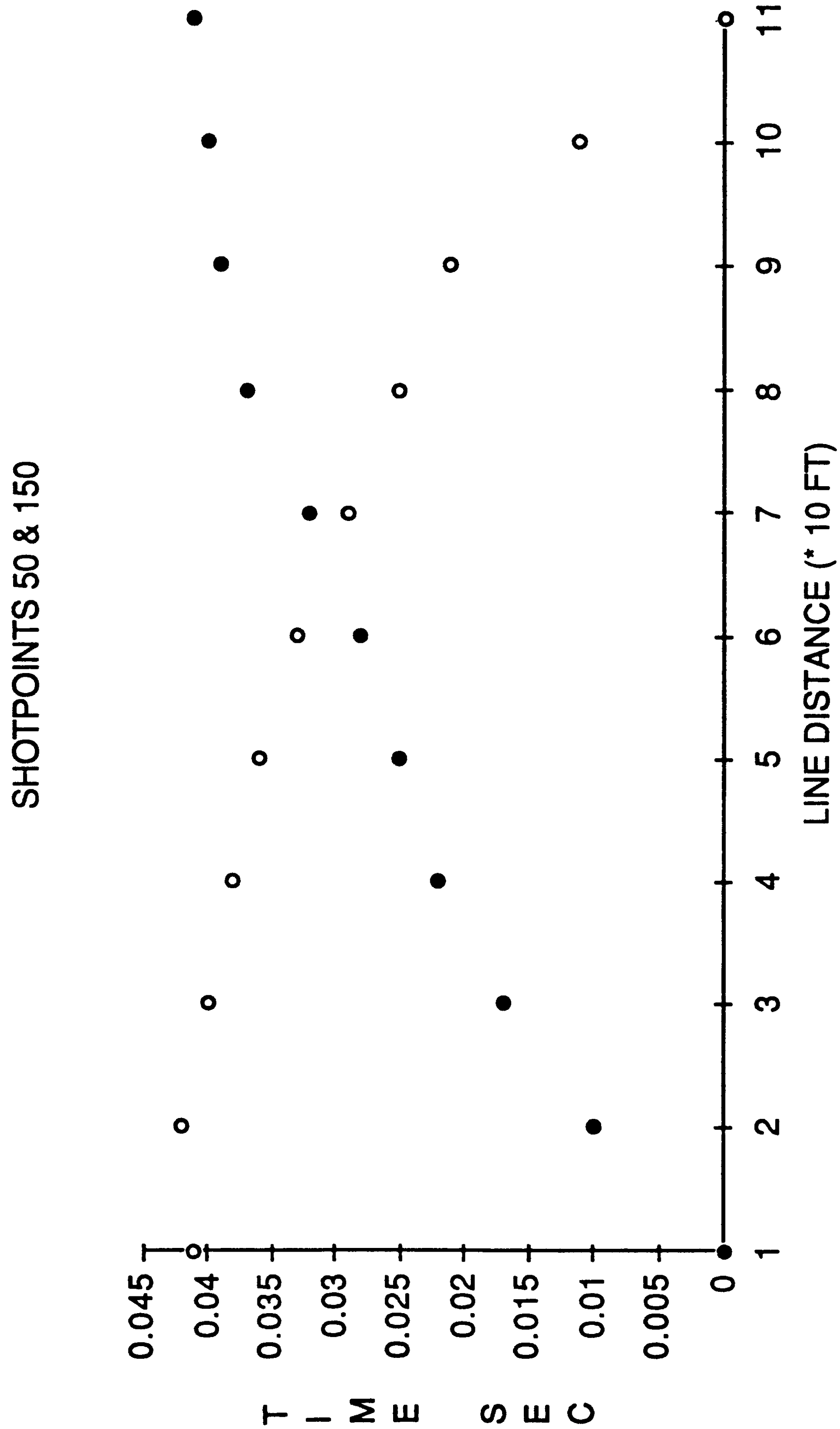
First Interface Overlap



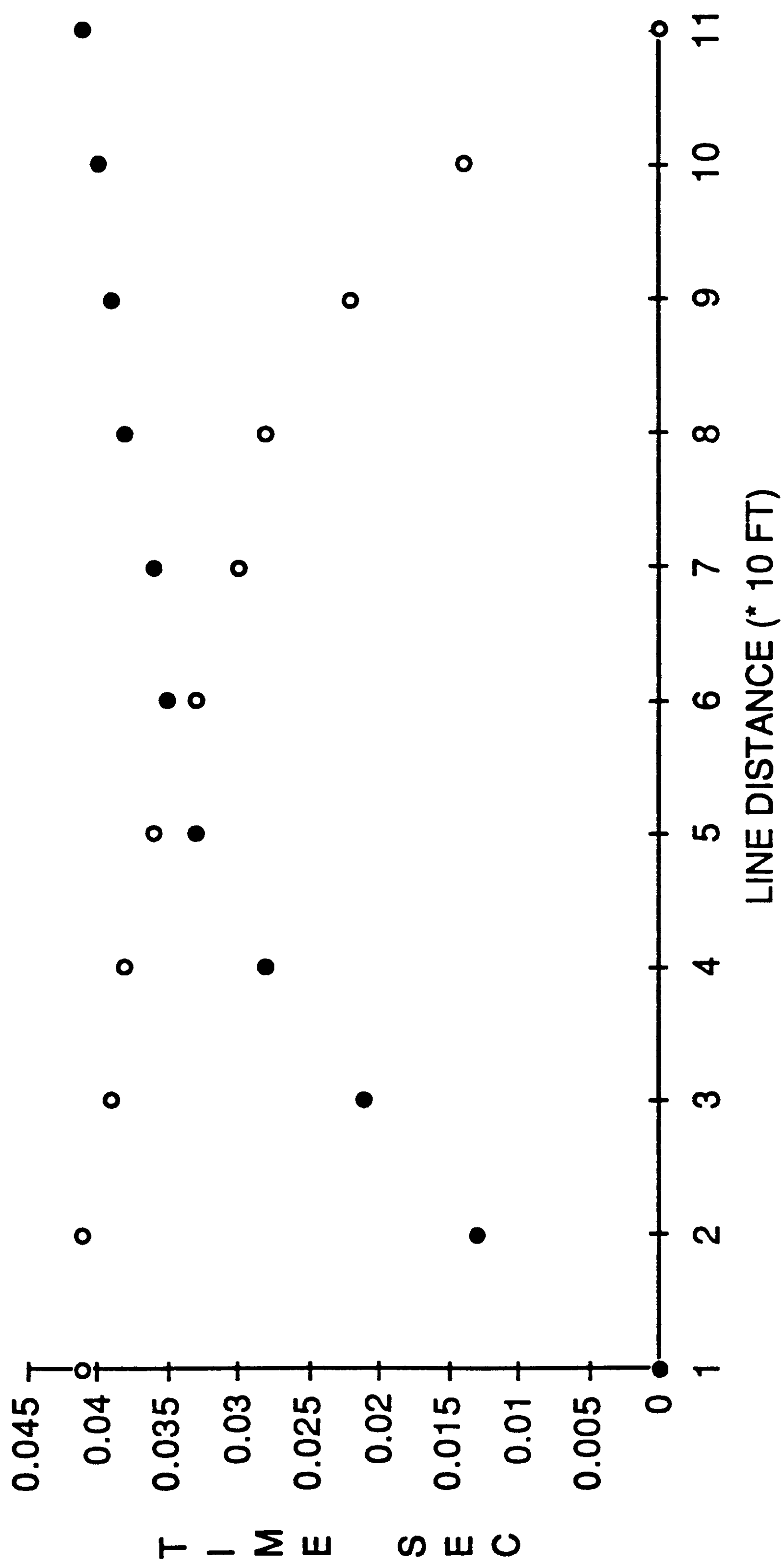
First Interface Overlap



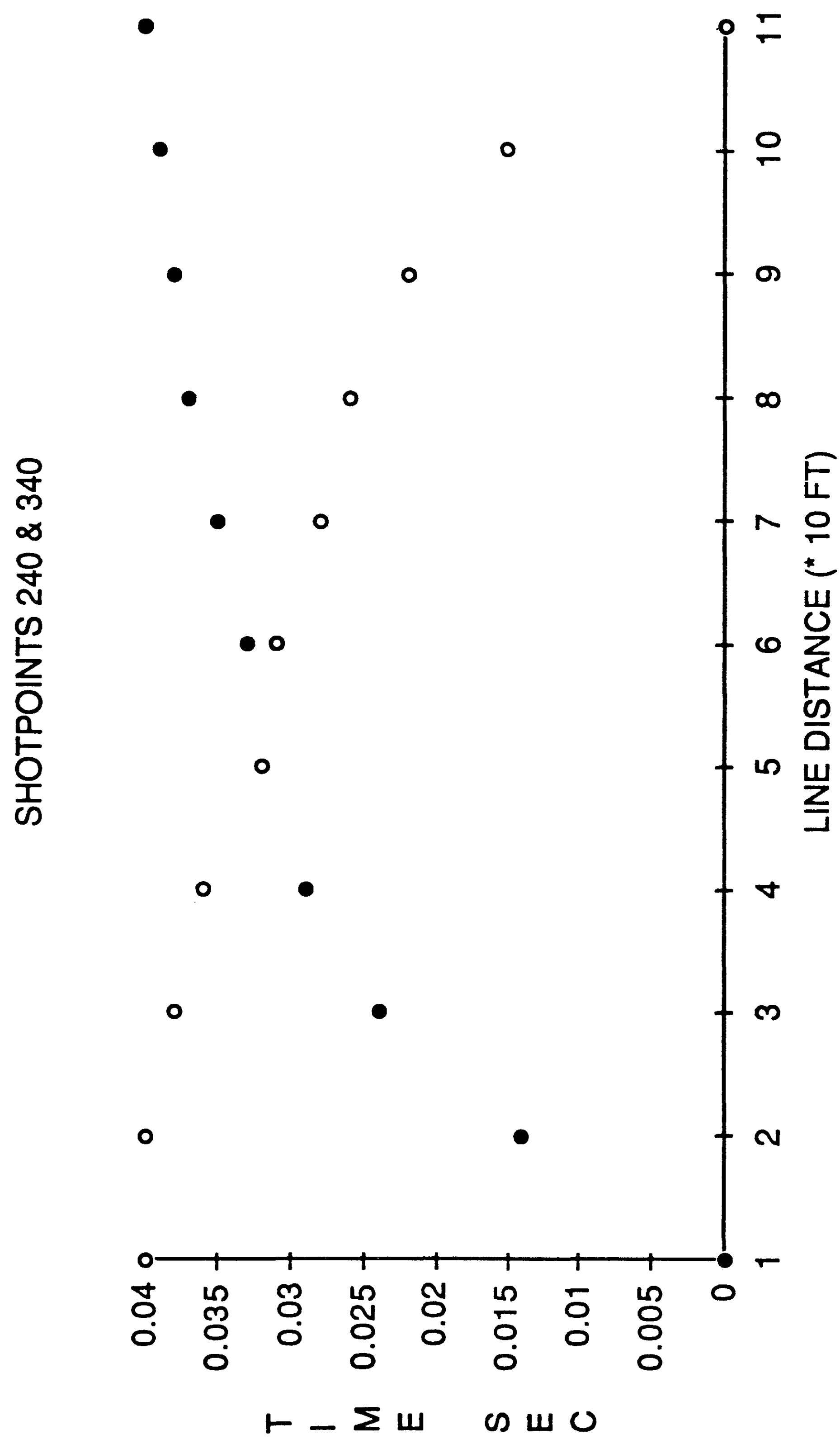
Second Interface Overlap



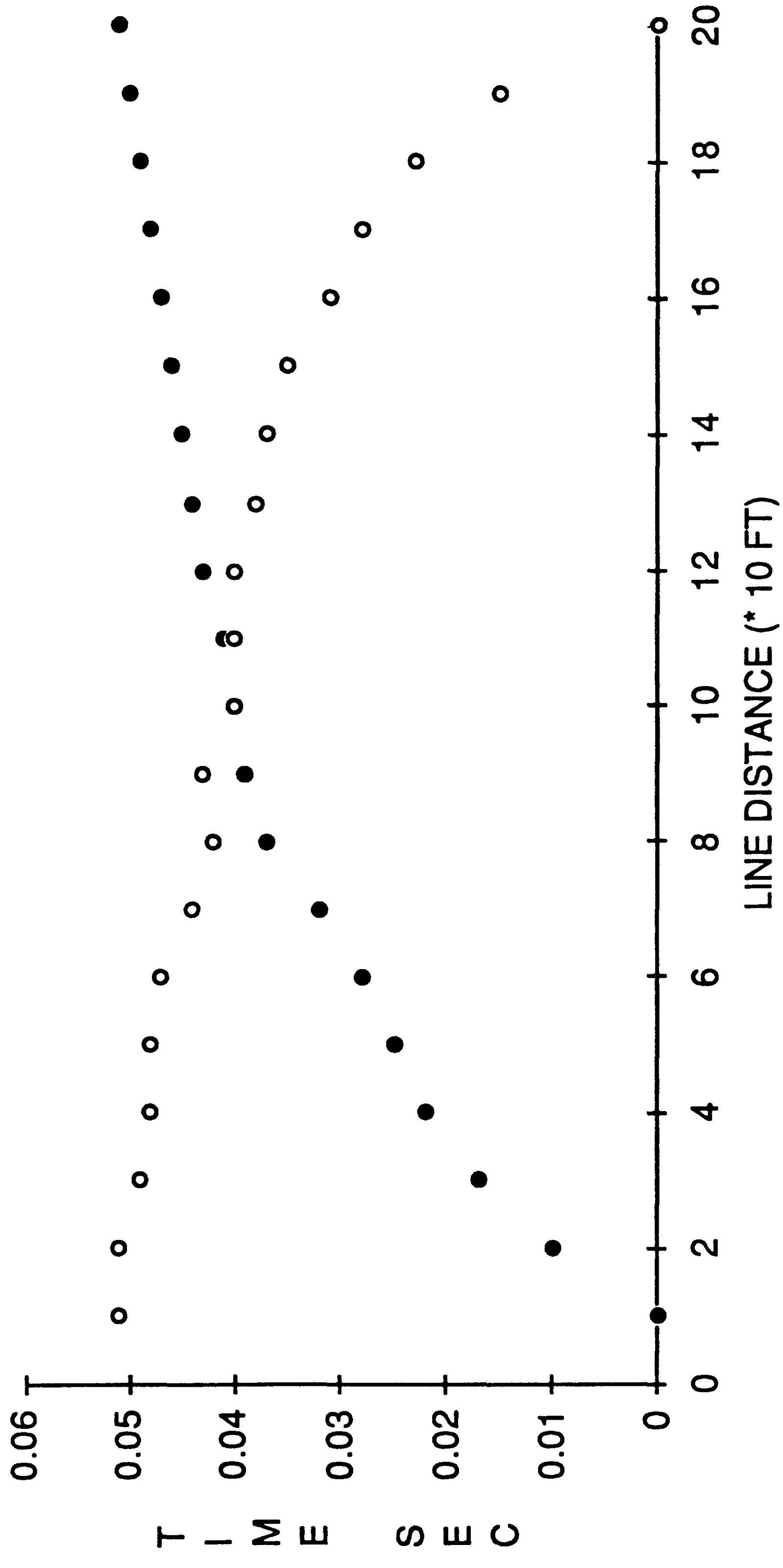
Second Interface Overlap



Second Interface Overlap



Third Interface Overlap



Third Interface Overlap

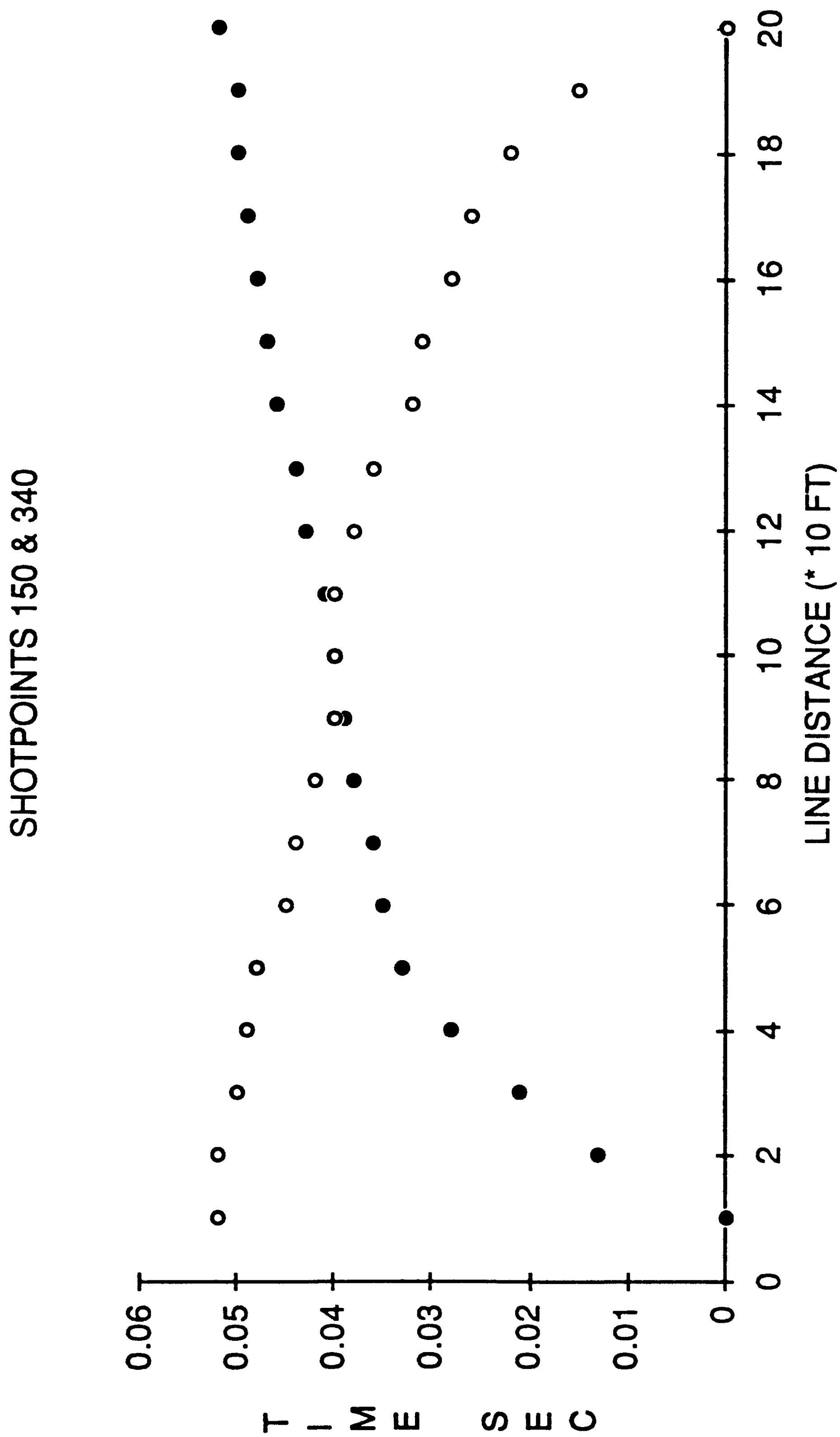


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PLATE 1
CRP Data in Excel Worksheet Format
Michael O. Bower

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1															
2															
3					-10	0	10	20	30	40	50	60	70	80	90
4															
5			-10		0.000	0.013	0.021	0.027	0.030	0.032	0.036	0.038	0.040	0.043	0.047
6			0			0.000	0.010	0.018	0.022	0.025	0.029	0.033	0.035	0.037	0.039
7			10				0.000	0.010	0.017	0.022	0.025	0.029	0.032	0.035	0.038
8			20					0.000	0.010	0.017	0.021	0.025	0.028	0.032	0.035
9			30						0.000	0.011	0.019	0.023	0.026	0.030	0.033
10			40							0.000	0.013	0.021	0.025	0.028	0.031
11			50								0.000	0.010	0.017	0.022	0.025
12			60									0.000	0.013	0.021	0.025
13			70										0.000	0.011	0.018
14			80											0.000	0.011
15			90												0.000
16			100												
17			110												
18			120												
19			130												
20			140												
21			150												
22			160												
23			170												
24			180												
25			190												
26			200												
27			210												
28			220												
29			230												
30			240												
31			250												
32			260												
33			270												
34			280												
35			290												
36			300												
37			310												
38			320												
39			330												
40			340												

	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC
1														
2														
3	100	110	120	130	140	150	160	170	180	190	200	210	220	230
4														
5	0.048	0.049	0.050	0.051	0.052	0.053	0.054	0.054	0.055	0.055	0.056	0.057	0.060	0.060
6	0.042	0.043	0.044	0.045	0.047	0.049	0.050	0.050	0.050	0.051	0.052	0.053	0.055	0.055
7	0.040	0.042	0.044	0.045	0.046	0.047	0.048	0.049	0.050	0.050	0.051	0.052	0.053	0.054
8	0.038	0.040	0.042	0.043	0.045	0.046	0.047	0.047	0.048	0.048	0.049	0.050	0.051	0.052
9	0.037	0.040	0.041	0.043	0.044	0.045	0.046	0.046	0.048	0.048	0.049	0.050	0.052	0.053
10	0.035	0.038	0.041	0.044	0.045	0.046	0.047	0.047	0.048	0.050	0.050	0.051	0.053	0.052
11	0.028	0.032	0.037	0.039	0.040	0.041	0.043	0.044	0.045	0.046	0.047	0.048	0.049	0.050
12	0.029	0.032	0.035	0.038	0.040	0.042	0.043	0.044	0.045	0.046	0.047	0.048	0.050	0.050
13	0.023	0.026	0.030	0.035	0.038	0.040	0.041	0.042	0.043	0.044	0.045	0.046	0.047	0.048
14	0.020	0.025	0.027	0.030	0.035	0.038	0.040	0.041	0.042	0.043	0.044	0.045	0.046	0.047
15	0.012	0.020	0.025	0.030	0.033	0.036	0.040	0.041	0.042	0.043	0.044	0.045	0.046	0.047
16	0.000	0.013	0.021	0.026	0.030	0.033	0.037	0.040	0.041	0.042	0.043	0.044	0.045	0.046
17		0.000	0.012	0.020	0.025	0.029	0.033	0.036	0.038	0.039	0.040	0.041	0.042	0.043
18			0.000	0.011	0.020	0.025	0.030	0.033	0.035	0.036	0.037	0.039	0.040	0.040
19				0.000	0.013	0.021	0.029	0.033	0.035	0.036	0.038	0.039	0.041	0.042
20					0.000	0.011	0.020	0.029	0.031	0.033	0.035	0.036	0.037	0.039
21						0.000	0.013	0.021	0.028	0.033	0.035	0.036	0.038	0.039
22							0.000	0.014	0.021	0.029	0.033	0.035	0.037	0.039
23								0.000	0.014	0.020	0.030	0.033	0.034	0.036
24									0.000	0.015	0.021	0.028	0.032	0.034
25										0.000	0.015	0.021	0.029	0.032
26											0.000	0.014	0.021	0.027
27												0.000	0.014	0.021
28													0.000	0.016
29														0.000
30														
31														
32														
33														
34														
35														
36														
37														
38														
39														
40														

	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN
1											
2											
3	240	250	260	270	280	290	300	310	320	330	340
4											
5											
6	0.056										
7	0.055	0.056									
8	0.053	0.055	0.056								
9	0.054	0.055	0.056	0.057							
10	0.054	0.055	0.055	0.057	0.057						
11	0.051	0.052	0.053	0.054	0.055	0.056					
12	0.051	0.051	0.052	0.053	0.054	0.055	0.056				
13	0.049	0.050	0.051	0.052	0.053	0.053	0.055	0.056			
14	0.048	0.048	0.049	0.051	0.053	0.053	0.055	0.056	0.057		
15	0.048	0.050	0.050	0.052	0.053	0.054	0.055	0.056	0.057	0.058	
16	0.047	0.048	0.049	0.052	0.053	0.054	0.055	0.056	0.057	0.058	0.060
17	0.044	0.046	0.047	0.050	0.051	0.052	0.053	0.054	0.055	0.056	0.057
18	0.042	0.043	0.045	0.047	0.048	0.049	0.050	0.051	0.052	0.054	0.055
19	0.043	0.044	0.046	0.048	0.049	0.050	0.052	0.052	0.053	0.054	0.055
20	0.040	0.040	0.042	0.043	0.044	0.046	0.047	0.048	0.049	0.050	0.052
21	0.040	0.041	0.043	0.044	0.046	0.047	0.048	0.049	0.050	0.050	0.052
22	0.040	0.041	0.042	0.044	0.045	0.047	0.048	0.049	0.050	0.051	0.050
23	0.038	0.039	0.041	0.042	0.043	0.045	0.046	0.047	0.048	0.049	0.050
24	0.037	0.038	0.040	0.041	0.042	0.043	0.044	0.045	0.047	0.048	0.048
25	0.035	0.036	0.038	0.040	0.041	0.042	0.043	0.043	0.045	0.046	0.047
26	0.031	0.033	0.035	0.038	0.039	0.040	0.041	0.042	0.042	0.043	0.047
27	0.028	0.030	0.032	0.035	0.037	0.038	0.040	0.040	0.041	0.042	0.046
28	0.023	0.028	0.031	0.033	0.035	0.037	0.038	0.039	0.040	0.041	0.043
29	0.015	0.022	0.028	0.031	0.033	0.035	0.036	0.037	0.038	0.039	0.040
30	0.000	0.014	0.024	0.029	0.032	0.033	0.035	0.037	0.038	0.039	0.042
31		0.000	0.017	0.026	0.030	0.033	0.035	0.037	0.038	0.039	0.039
32			0.000	0.013	0.021	0.029	0.030	0.031	0.032	0.035	0.039
33				0.000	0.016	0.024	0.028	0.030	0.031	0.033	0.039
34					0.000	0.015	0.023	0.027	0.028	0.030	0.036
35						0.000	0.015	0.022	0.026	0.028	0.034
36							0.000	0.015	0.021	0.027	0.032
37								0.000	0.015	0.023	0.027
38									0.000	0.015	0.021
39										0.000	0.016
40											0.000