UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

A computer program in BASIC for construction of two-layer, seismic refraction forward models within which elevation and thickness of the upper layer change and velocities vary laterally within both layers

by

Wilfred P. Hasbrouck[1]

Open-File Report 90-320

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards. Any use of trade names is for descriptive purposes only and does not imply endorsement by the USGS. Although the computer program in this report has been extensively tested, the USGS makes no guarantee whatever of correct results.

1990

[1]Golden, Colorado

ABSTRACT

This report presents a computer program in BASIC to construct two-layer, seismic-refraction forward models with elevation and thickness variations of the upper layer and lateral velocity changes within each layer. The program accomplishes this by dividing both the upper and lower layers into vertical zones with boundaries at each station location, constructing refracted ray paths within each zone, and summing the times to travel these paths from a source point to a detector position. A requirement is that rays refracted upward from the lower layer do not cross between zones within the upper layer. True scale plots of the model with ray paths drawn to each station are visually examined to see if this condition is met before computation of arrival times proceeds. The output includes traveltime curves (X/T plots) showing direct and refracted arrival times along both forward and reverse spreads, plots of delay times, and an option to produce elevation-corrected traveltime curves and delay-time plots.

INTRODUCTION

The program described and listed in this report was developed in response to the need to interpret seismic refraction data obtained along traverses which spanned a landfill boundary. One way to interpret these data is through the use of interactive forward modeling. In landfill areas, ground surface is not necessarily flat nor is thickness of the upper (lower velocity) layer necessarily constant. Also it is likely that the velocity of the material in the landfill is lower than that of the surrounding ground. Therefore, those refraction interpretation procedures using equations based on the assumptions of a flat ground surface, a plane interface at the base of the upper layer, and constant velocities within the layers are not applicable.

The purpose of this report is to present a computer program used to calculate theoretical refraction profiles for two-layer models that have variable surface elevations and upper-layer thicknesses and lateral changes in velocity. This is accomplished by dividing both the upper and lower layers into vertical zones with boundaries at each station location, constructing refracted ray paths within each zone, and summing the times to travel the paths through the zones from source points at each end of the spread to a given detector position. The following restrictions on the modeling procedure apply:

1. Only two-layer cases are considered; for example, overburden and bedrock.
2. Velocities within each partitioned zone are constant; that is, all ray segments are straight lines.
3. The refracted ray emerging from the lower (higher-speed) layer must not cross a zone partition within the upper layer.
4. The ray path in the lower layer follows the segmented top of the lower layer, and the ray path of the direct wave in the upper layer follows the segmented topography.

The program was developed for use by engineering geophysicists, and as such it uses units that though non-standard are more applicable in their field. For example; arrival times are in milliseconds (ms), distances are in meters (m), and velocities are expressed as m/ms. Option is provided for those who prefer to work in the English system, in which case, distances are in feet and velocities are entered as ft/ms.

Because the computing procedure is completely analytic, it operates very quickly on a desktop computer. The program was written to run on the Hewlett-Packard 9845B computer and it uses the Hewlett-Packard BASIC resident on that machine. With the exception of its graphics sections, this program language is sufficiently transportable that it can be modified to operate on most desktop computers.

In this report, after the conditions on the forward model are discussed, the computing scheme is developed, and a step-by-step description of the operation of the program is given. In the final section, examples of results produced by the program are presented. Two cases of practical importance are emphasized: seismic refraction surveys across landfills and stream beds.

CONDITIONS ON THE FORWARD MODEL

Shown on figure 1 is a sketch illustrating the conditions imposed upon the modeling procedure. The vertical dot-dash lines define the partitions at each station location, and the vertical, double solid lines separate the velocity zones within each layer. The source point (SP) is positioned far to the left side and the rays from it are shown traveling to the right along the top of the higher speed layer. The arrowed paths in the upper layer show selected ray paths to detectors at positions A, B, and C after being refracted from the lower layer.

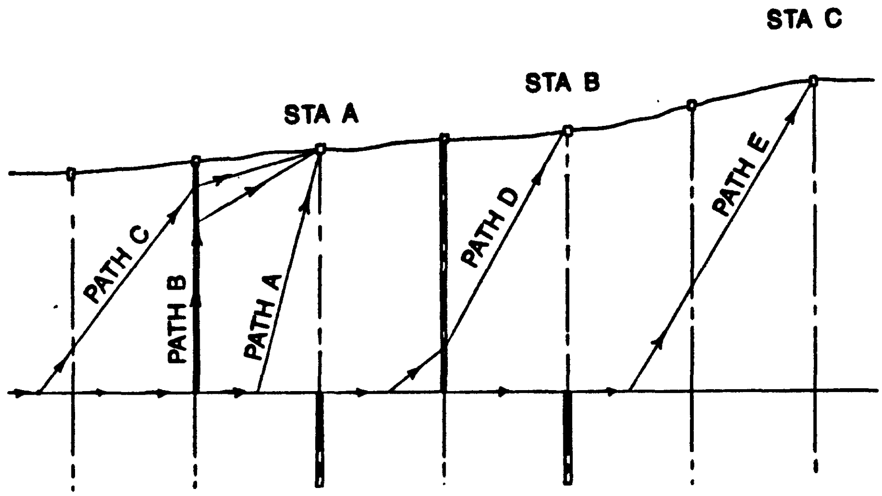

Figure 1. Sketch illustrating a prime condition imposed. Velocities zones are separated with double lines. Only those refracted rays that do not cross zone boundaries are allowed; therefore, path A to station A is acceptable, but paths B and C to station A, path D to station B, and path E to station C are not.

An important restriction on the model is that rays refracted from the lower layer are not permitted to cross partitions within the upper layer. For example, on figure 1, only the ray traveling to station A along path A is allowed. Unless this restriction is imposed, rays along alternate paths such as those of path B and C would have to be included in the calculation of the minimum arrival time (the first break time) at station A. The acceptance of these multiple paths would introduce unwanted complexity into the model. Once the door were opened to these type of arrivals, then one also would be obliged (for the sake of completeness) to include the flood of other arrivals such as those that have traveled diffracted and/or reflected paths.

In the computing procedure, the partition and velocity boundaries (such as shown on figure 1) are merely constructs--they do not represent actual boundaries within the section. One way to visualize the procedure is to recognize that we are only to be concerned with what happens within the region bounded by the partition lines. Path A to detector A falls totally within a partitioned region, whereas paths B and C to detector position A and those paths to detector positions B and C cross partitions. As will be shown later when the operation of the computer program is discussed, it is the user's responsibility to ascertain that the conditions of the modeling procedure are met.

DEVELOPMENT OF THE COMPUTATION SCHEME

The program is developed with use of Snell's law and the relation: velocity equals distance over time. Mathematics is limited to plane trigonometry. Model parameters include the number of stations, the station interval, the ground elevation at each station, the elevation at the top of the lower layer beneath each station, the velocity boundaries, and the velocities within these boundaries.

Once these parameters have been specified, the program partitions the model into zones whose widths equal the station spacing, Xd. Shown on figure 2 is Zone P with the following parameters:

Eg(p)	Elevation of the ground at station p
E(p)	Elevation of the base of the upper layer directly under station p
Eg(p+1)	Elevation of the ground at station p+1
E(p+1)	Elevation of the base of the upper layer directly under station p+1
V1(p)	Velocity of the upper layer in Zone P
V2(p)	Velocity of the lower layer in Zone P

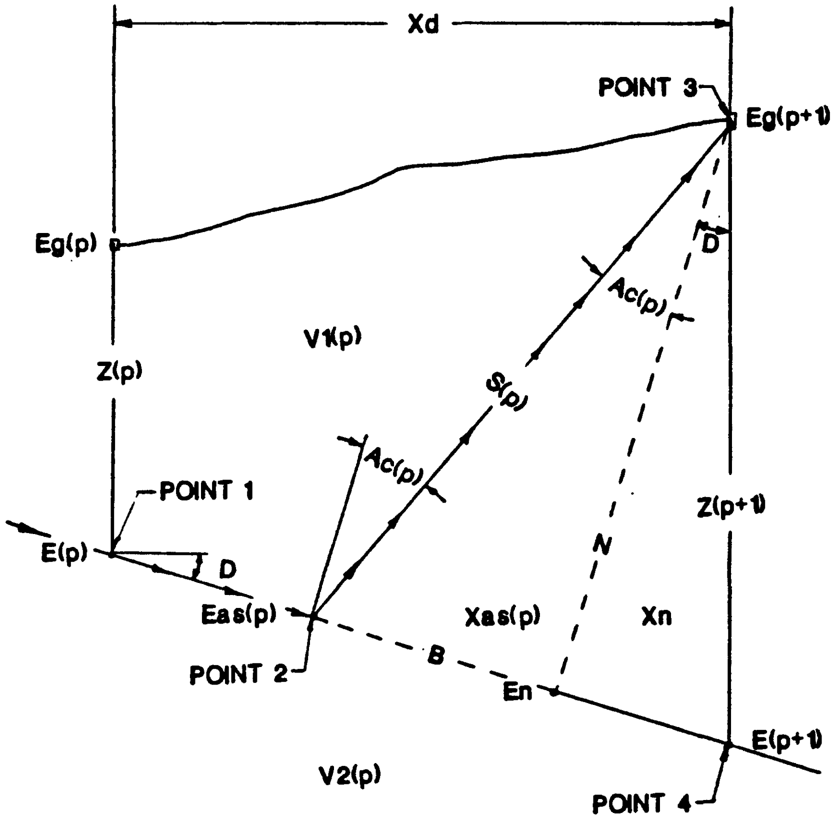

Figure 2. Sketch showing quantities used in development of the computing scheme. The arrowed line is the path of the refracted ray originating at a source point located far to the left.

In figure 2, SP A is positioned somewhere far to the left of zone P. What we want to do is compute:

1. Time from station p to p+1 at the top of the upper layer (the direct-ray time within the zone),

2. Refracted-ray time in the lower layer from Point 1 to Point 2,

3. Time in the upper layer from Point 2 (the refraction depth point) to Point 3 located at a station on the surface, and

4. Time in the higher speed (lower) layer from Point 1 to Point 4, a quantity used for subsequent zone calculations.

The direct-ray time along the surface of this zone is computed by taking the straight-line distance between stations p and p+1 and dividing it by the upper-layer velocity, V1(p).

Looking at the refracted-ray path, let us define Point 2 as the position along the top of the higher speed layer where the refracted ray emerges at the critical angle Ac(p) on its way to the station at Point 3. From Snell's law, the sine of the critical angle equals the ratio of V1(p) over V2(p).

Figure 2 shows the quantities used in the program to compute first arrival times. Many ways can be used compute these times: through the delay-time concept, employment of the law of sines, or use of the normal, N, and right triangles. The latter method is used in the program. The computational flow is as follows:

1. Determine N from the right triangle whose hypotenuse is Z(p+1) and whose interior angle is D, the dip of the interface.

2. Compute the coordinates of the intersection of N and the interface (Xn, En).

3. Using N and the critical angle, Ac(p), determine the distance B and the slant distance S(p).

4. Compute the coordinates of the refraction point, Point 2, using distance B and angle D.

5. Once these coordinates are known, compute the distance from Point 1 to Point 2 and then divided it by the velocity V2(p) to determine the ray time in the lower layer.

6. Compute the time in the upper layer from Point 2 to the detector at Point 3, this simply equals S(p)/V1(p).

7. Compute the time from Point 1 to Point 4 by determining the hypotenuse of the triangle with side Xd (station spacing) and interior angle D and then dividing this distance by V2(p).

The caption beneath the sketch in figure 3 describes how the quantities computed by the above procedure are combined to produce the direct and refraction times from SP A to stations 2, 3, and 4. A test is included in the program to assign a value of 999 to those arrivals at distances less than the critical distance; for example, when the horizontal distance from point b to c is negative. If a flag value of 999 is detected by the plot programs, then that point is skipped on the plots.

OPERATION OF THE COMPUTER PROGRAM

The computer program is written with liberal use of prompts; that is, it asks you questions and you respond from the keyboard. As an illustration of how to use the program, let us trace through calculation of arrival times for a model of a raised landfill within an excavated bedrock of constant velocity.

With the HP 9845B computer, the command "PRINTER IS" is used to select whether you want the printout on the internal printer, (PRINTER IS 0), or you want the print to be displayed on the monitor (PRINTER IS 16). Usually, hard copies are made only of the tabulated values and plots. You are given the option to select the print mode.

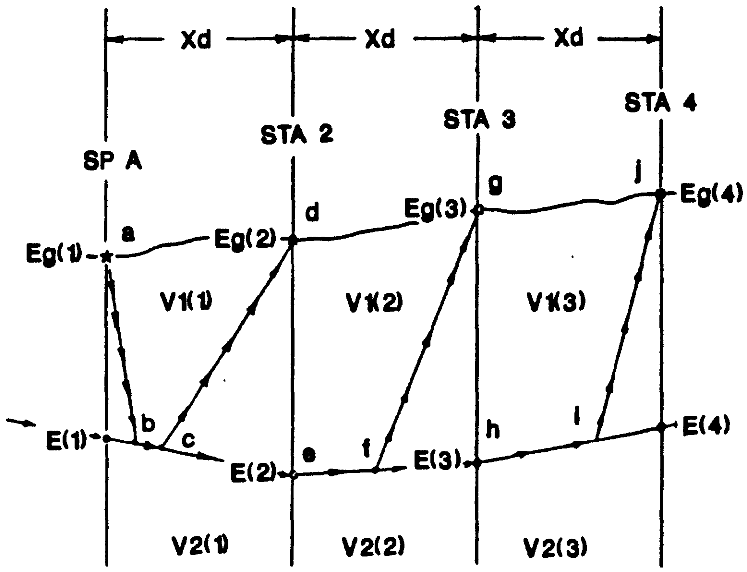

Figure 3. Sketch illustrating the ray-path times from SP A to detectors at locations 2 through 4 in zones 1 through 3, respectively. The ray from SP A to station 2 travels from a to b at V1(1), from b to c at V2(1), and from c to d at V1(1). For station 3, the ray is from a to b at V1(1), from b to e at V2(1), from e to f at V2(2), and from f to g at V1(2). The ray from SP A to station 4 travels from a to b at V1(1), b to e at V2(1), e to h at V2(2), h to i at V2(3), and i to j at V1(3). The direct ray time from SP A to station 2 is the straight-line distance between then divided by V1(1), and that from SP A to station 3 is the direct-ray time to station 2 plus the straight-line distance from station 2 to 3 divided by V1(2), and so on.

Once the program is loaded, either from tape or disk, operation of the program begins upon hitting the RUN key. You are first asked to give the year in which the program was run (default=1990) and to specify whether units are to be metric or English (default is metric). Note: regardless of which system you select, you must be consistent. In either system of units, times are in milliseconds (ms). If the English system is selected, distances are to be entered in feet and velocities in ft/ms; if metric, distances are to be entered in meters (m) and velocities in m/ms--the exact equivalent of km/s.

Then you are asked if you want to name the model; if yes, then the name (42 characters, maximum) is entered.

Next you are prompted to enter the model parameters. Shown on figure 4a is a hard copy of the parameters entered. In this example, the landfill is given a velocity of 0.4 m/ms, the upper layer is divided into three velocity zones (left sides of the zones being at stations 1, 4, and 10), and the bedrock is given a constant velocity of 1.0 m/ms.

After the elevations at each station on the surface and the elevations at the top of the lower (second) layer are entered, the display shown on figure 4b is produced. The model is shown at true scale (no vertical exaggeration), and the refracted rays to each detector are drawn. You are then asked if you want to accept this model. If you answer by entering an "N", then the program returns you to that section of the program wherein the model parameters are entered. If the default, "Y", is entered, the program computes, tabulates, and plots direct and refracted arrivals (dotted lines) at each station (figure 4c). The first arrivals are then connected by solid lines. From inspection of figure 4c it appears that an offset greater than about 7 m would be needed to have detectors beyond the crossover distance, defined as the distance at which direct and refracted arrival times are equal.

```
APPROXIMATION FORWARD MODEL FOR REFRACTION  COMPUTED:

Model: RAISED LANDFILL WITH EXCAVATED BEDROCK

MODEL PARAMETERS
              Station number at SP A = 1
    Number of detectors on spread = 12
                  Station spacing = 3
Offset from SP A to near detector = 3
       Distance from SP A to SP B = 36
           Station number at SP B = 13
               Number of stations  = 13
 Number of zones within 1st layer = 3
 Number of zones within 2nd layer = 1
      Number of partitioned zones = 12

FOR LAYER 1
NOTE: Zone boundaries must be at station locations
For zone 1 ,station number at left side of zone = 1
For zone 2 ,station number at left side of zone = 4
For zone 3 ,station number at left side of zone = 10
For zone 1 ,velocity within 1st layer = .5
For zone 2 ,velocity within 1st layer = .4
For zone 3 ,velocity within 1st layer = .5
       Constant velocity of 2nd layer = 1
```

Figure 4a. Copy of screen display showing model parameters entered from the keyboard for the model of a raised landfill within a partially excavated bedrock of constant velocity. Distances are in meters; velocities are in m/ms (km/s).

If you responded that you wanted to see a plot of delay times, then the tabulation and plot of figure 4d would have been produced upon supplying the requested value of V2. Although this plot is labeled and called a delay-time plot, it is actually an approximate delay time. Since all the necessary parameters needed to compute the precise delay time are entered, it would be possible to compute the actual delay time. However, when working with field data, all these input parameters (in effect, the answers) would not have been known--if they had been, there would have been no need to go to the field. In the procedure used, a value equal to the offset distance is divided by the entered V2 and then subtracted from each refraction time to give a reduced time which I call the delay time. With planar interfaces, these reduced times would be precisely the delay time. As written on the label at the top of the plot, delay time using values from SP A are plotted with dotted lines and those from SP B are shown with solid lines.

The program provides an option to compute and plot elevation-corrected, refracted-ray arrival times. A tabulation and traveltime plot of these times for the problem at hand is shown on figure 4e. Finally, you are asked if you want a plot of delay times using elevation-corrected refraction times. A tabulation and plot of these delay times is shown on figure 4f.

Model: RAISED LANDFILL WITH EXCAVATED BEDROCK   COMPUTED:

STATION NUMBER, OFFSET FROM SP A, AND ELEVATIONS

Sta Num	Offset	Surface Elev	Elev at Top of Layer 2
1	0	20.0	18.0
2	3	20.0	18.0
3	6	20.0	18.0
4	9	20.0	18.0
5	12	21.0	17.0
6	15	21.0	17.0
7	18	21.0	17.0
8	21	21.0	17.0
9	24	21.0	17.0
10	27	20.0	18.0
11	30	20.0	18.0
12	33	20.0	18.0
13	36	20.0	18.0

TRUE SCALE PLOT OF MODEL WITH REFRACTED RAYS

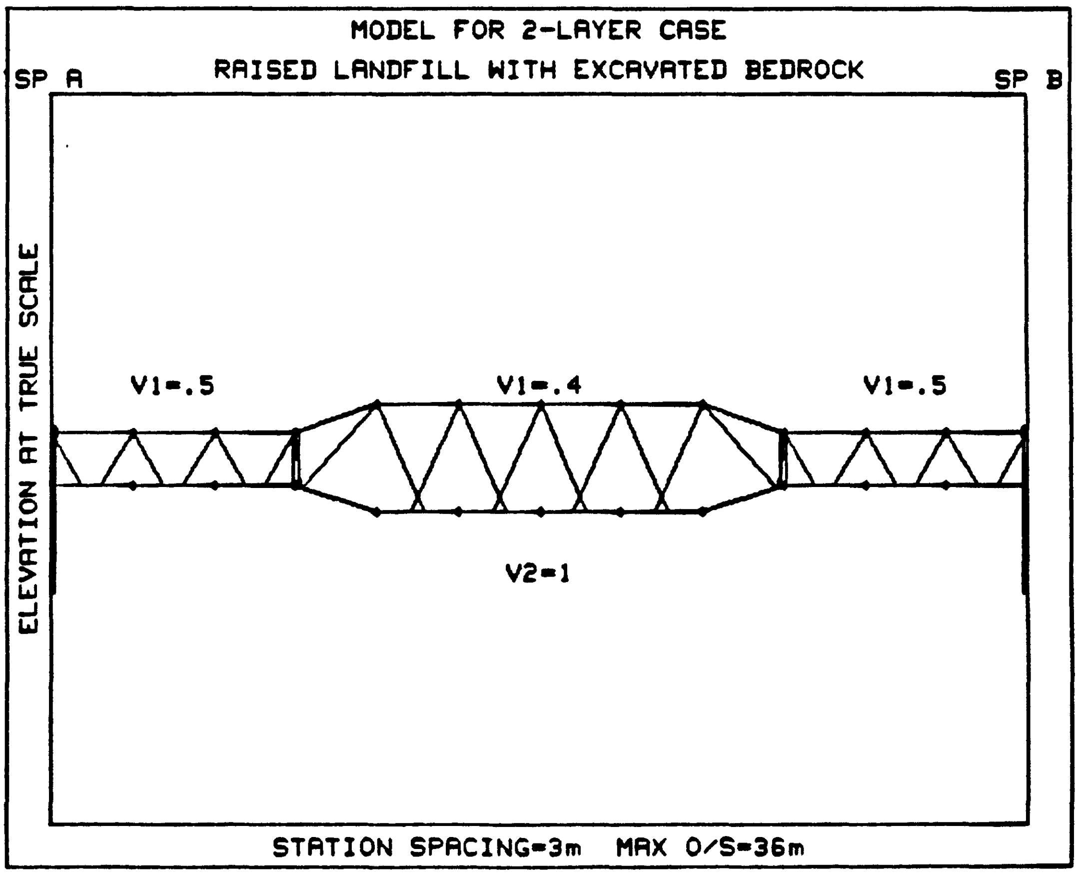

Figure 4b. Tabulation of station numbers, offsets of each station from SP A, station elevations, and elevations at the top of the lower layer together with a true-scale plot with ray paths drawn to each station.

Model: RAISED LANDFILL WITH EXCAVATED BEDROCK COMPUTED:

STATION NUMBER, OFFSET, AND ARRIVALS TIMES
NOTE: Refraction time = 999 indicates no refracted return

From SP A @ Station 1				From SP B @ Station 13			
Sta Num	& Offset	Tr	Td	Sta Num	& Offset	Tr	Td
1	0	999.0	0.0	1	36	43.3	81.0
2	3	9.9	6.0	2	33	40.3	75.0
3	6	12.9	12.0	3	30	37.3	69.0
4	9	15.9	18.0	4	27	35.0	63.0
5	12	23.1	25.9	5	24	36.0	55.9
6	15	27.0	33.4	6	21	33.0	48.4
7	18	30.0	40.9	7	18	30.0	40.9
8	21	33.0	48.4	8	15	27.0	33.4
9	24	36.0	55.9	9	12	23.1	25.9
10	27	35.0	63.0	10	9	15.9	18.0
11	30	37.3	69.0	11	6	12.9	12.0
12	33	40.3	75.0	12	3	9.9	6.0
13	36	43.3	81.0	13	0	999.0	0.0

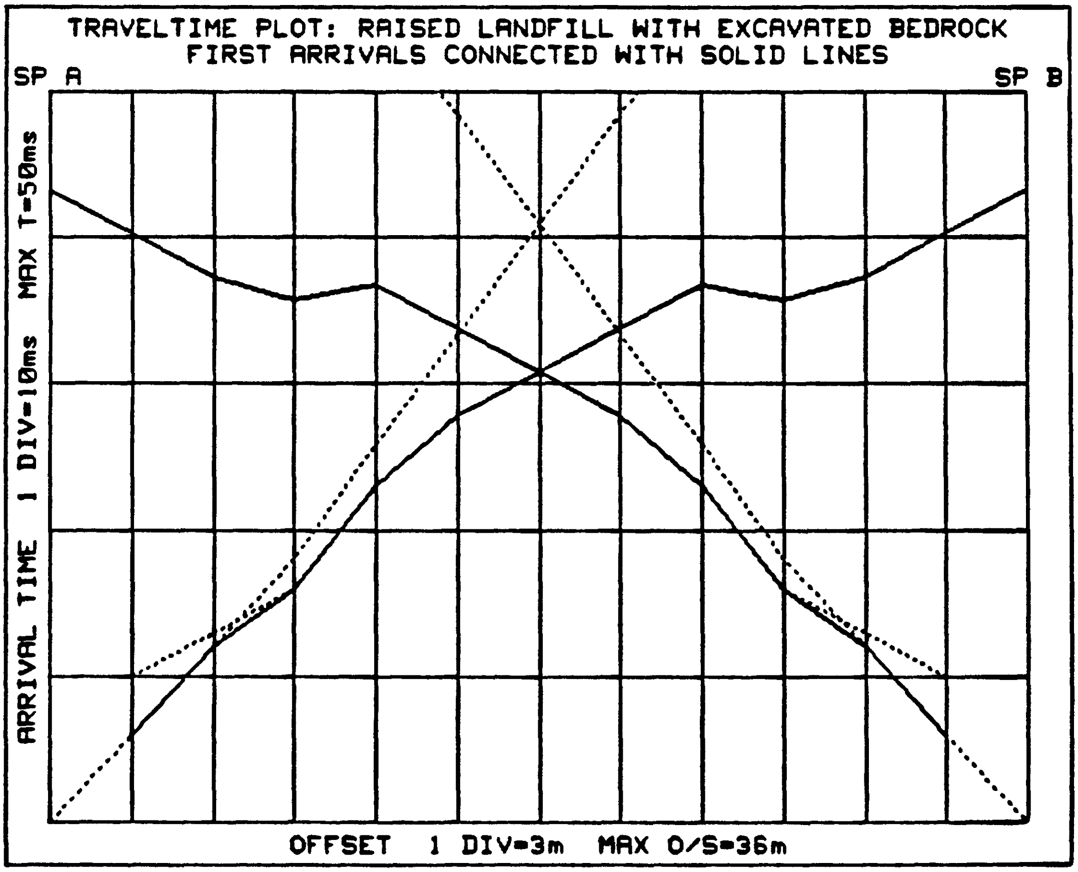

Figure 4c. Tabulation of computed refracted (Tr) and direct (Td) travel times together with traveltime curves. First arrival times are connected with solid lines; second arrivals and direct-ray times to the near detectors are connected with dotted lines.

Model: RAISED LANDFILL WITH EXCAVATED BEDROCK COMPUTED:

STATION AND APPROXIMATE DELAY TIMES
NOTE: Refraction time = 999 indicates no refracted return

From SP A		From SP B	
Station	Tar-X/V2	Station	Tbr-X/V2
1	999.00	1	7.25
2	6.93	2	7.25
3	6.93	3	7.25
4	6.93	4	8.77
5	11.06	5	12.79
6	12.79	6	12.79
7	12.79	7	12.79
8	12.79	8	12.79
9	12.79	9	11.06
10	8.77	10	6.93
11	7.25	11	6.93
12	7.25	12	6.93
13	7.25	13	999.00

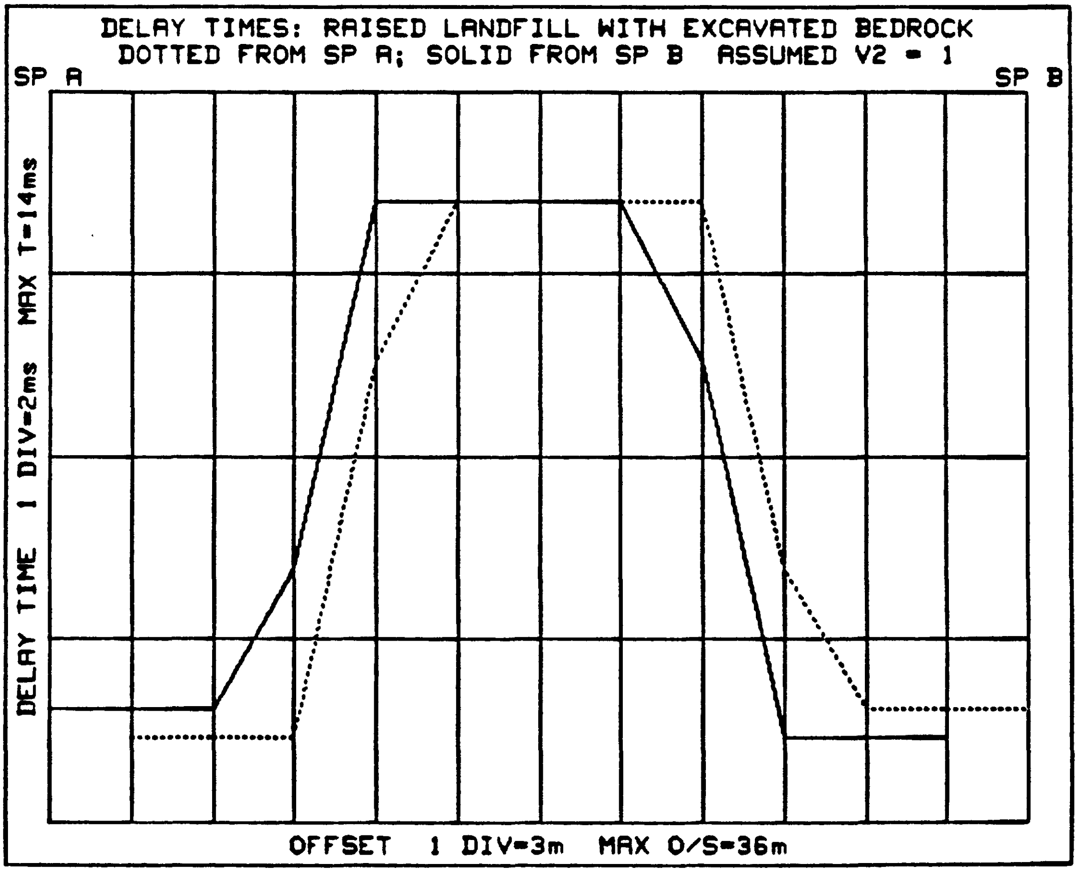

Figure 4d. Tabulation and plot of delay times. Solid lines connect delay times from SP B; dotted lines connect delay times from SP A. Delay time computation velocity = 1 m/ms.

Model: RAISED LANDFILL WITH EXCAVATED BEDROCK   COMPUTED:

STATION AND ELEVATION-CORRECTED TIMES Edatum= 20
NOTE: Refraction time = 999 indicates no refracted return

From SP A		From SP B	
Station	Tar-Ecorr	Station	Tbr-Ecorr
1	999.00	1	43.25
2	9.93	2	40.25
3	12.93	3	37.25
4	15.93	4	35.77
5	21.32	5	35.06
6	26.06	6	32.06
7	29.06	7	29.06
8	32.06	8	26.06
9	35.06	9	21.32
10	35.77	10	15.93
11	37.25	11	12.93
12	40.25	12	9.93
13	43.25	13	999.00

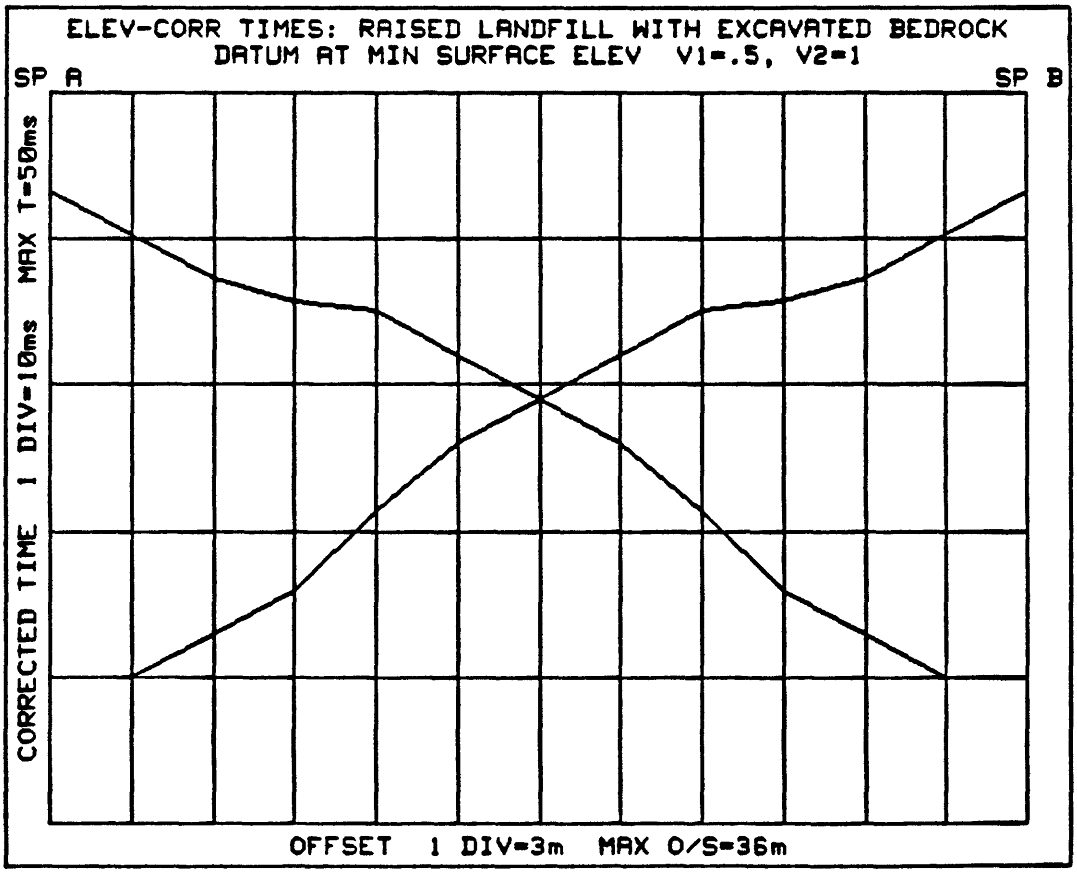

Figure 4e. Tabulation and plot of elevation-corrected refraction times. No elevation corrections are applied to direct-ray times.

Model: RAISED LANDFILL WITH EXCAVATED BEDROCK   COMPUTED:

STATION AND APPROX DELAY TIMES AFTER ELEVATION CORRECTION
NOTE: Refraction time = 999 indicates no refracted return

From SP A		From SP B	
Station	Tar-X/V2	Station	Tbr-X/V2
1	999.00	1	7.25
2	6.93	2	7.25
3	6.93	3	7.25
4	6.93	4	8.77
5	9.32	5	11.06
6	11.06	6	11.06
7	11.06	7	11.06
8	11.06	8	11.06
9	11.06	9	9.32
10	8.77	10	6.93
11	7.25	11	6.93
12	7.25	12	6.93
13	7.25	13	999.00

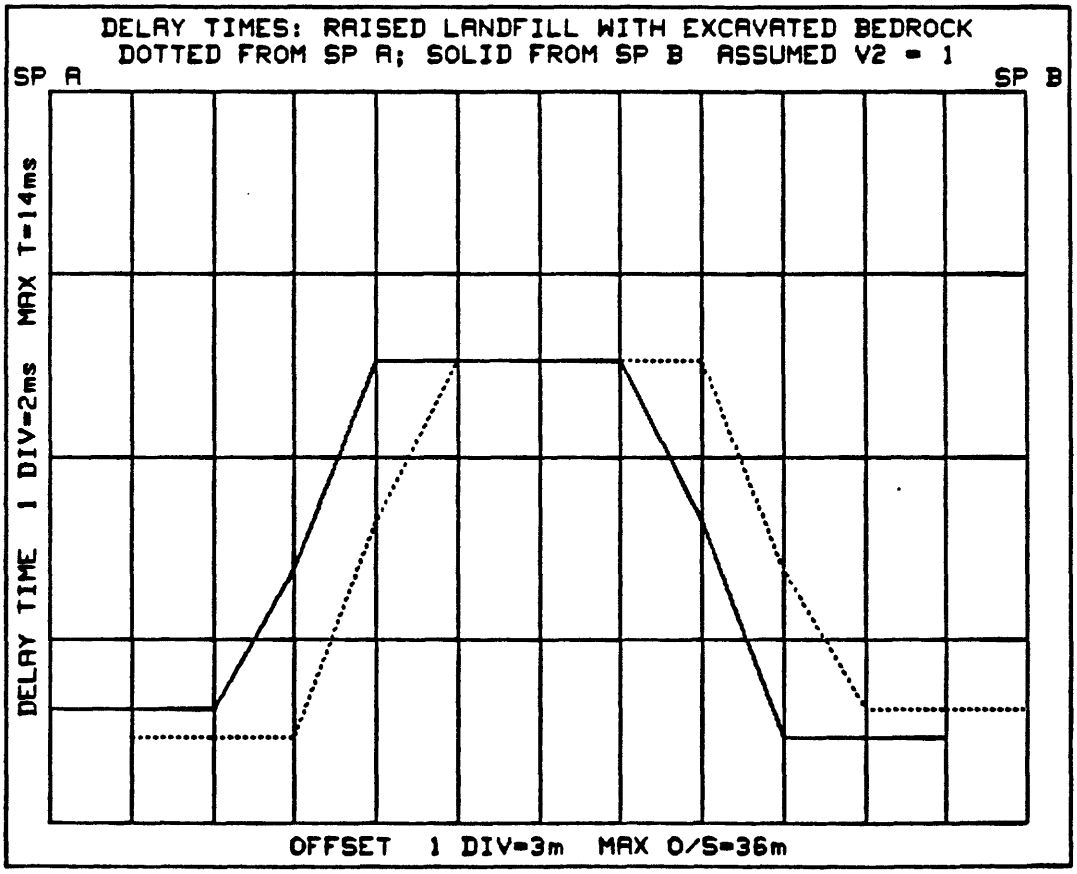

Figure 4f. Tabulation and plot of delay times computed using elevation-corrected refraction times.

A collected display of the plots produced in the above tutorial is shown on figure 15 as part of a set of models used to compare the effects of changing model parameters within the bedrock.

In the general procedure, after the model with superposed ray paths is drawn, you are expected to view the display and then decide whether you want to continue. In the figure 4 example, no violations of the program restrictions occurred. However, the model depicted in the upper left box of figure 5 does violate the conditions since the rays into station 2 cut across partitions.

Three courses of action can be followed when model conditions are not met:

1. The program can be stopped--the model abandoned.
2. The station numbers and the SP's for each spread at which the infraction occurs can be entered, after which the program assigns each of the arrival times at these locations a value of 999. Consequently these arrivals are skipped when plots are made. The results of this remedial action are displayed within the left column displays.
3. Model parameters can be changed. Shown in the right column of figure 5 is the result when the ratio of station spacing to depth is altered. In this case, depth to the lower layer was reduced. The same effect could have been realized by increasing the station spacing from 3 to 6 m but with maintenance of the same depth.

EXAMPLES OF APPLICATION OF THE MODELING PROGRAM

The examples given in this section display only the plots produced by the modeling program (tabulations excluded) with sufficient information shown on the model that the results can be reproduced. For example, velocities within each layer are given, and by scaling the station spacing values, elevations of the surface and at the top of the second layer can be determined. To reduce the number of pages in this report, plots have been reduced to approximately 38 percent of their original size, and five or six plots are placed on each page.

Shown on figure 6 are simple two-layer models with constant velocities and no elevation changes. The left column shows the zero-dip, plane-interface model; the right column shows the dipping plane-interface model. These two examples are the classic cases given in most introductory geophysics textbooks.

The models shown on figure 7 illustrate results over a shallow depression in the bedrock surface. The left column shows results when station 7 (the middle station of the spread between SP A and SP B) is located over the center of the bedrock valley. The right column shows results when the spread is shifted such that SP A is at station 7.

Note that if a refraction survey had been taken as in the left column, then the traveltime plot would indicate a zero-dip, three-layer subsurface. If interpreted as a three-layer case, the velocity of the second layer would be 1.71 m/ms (km/s) and the depth to its top would be 0.8 m; the velocity of the third layer would be 2.42 m/ms and the depth to its top would be 4.7 m. This model was suggested by H. D. Ackermann (oral communication) as an illustration of the need to take more than just the two profiles from the ends of the spreads. If off-end shotpoints had been used, the ambiguity of the left-column results would have been resolved. Although the traveltime curves of the left-column example of figure 7 indicate a three-layer case, the delay-time plot does not. Instead, there should be sets of constant value lines for the second layer (see the lower-left box in figure 6.)

The necessity of shifting the spreads in order to better the chances of a correct interpretation are shown by the model results displayed in the right column of figure 7. Here the spread has been shifted such that SP A is positioned at station 7 located directly over the thickest part of the bedrock valley. A traveltime plot bending upward with increased offset is a definite sign that a three-layer

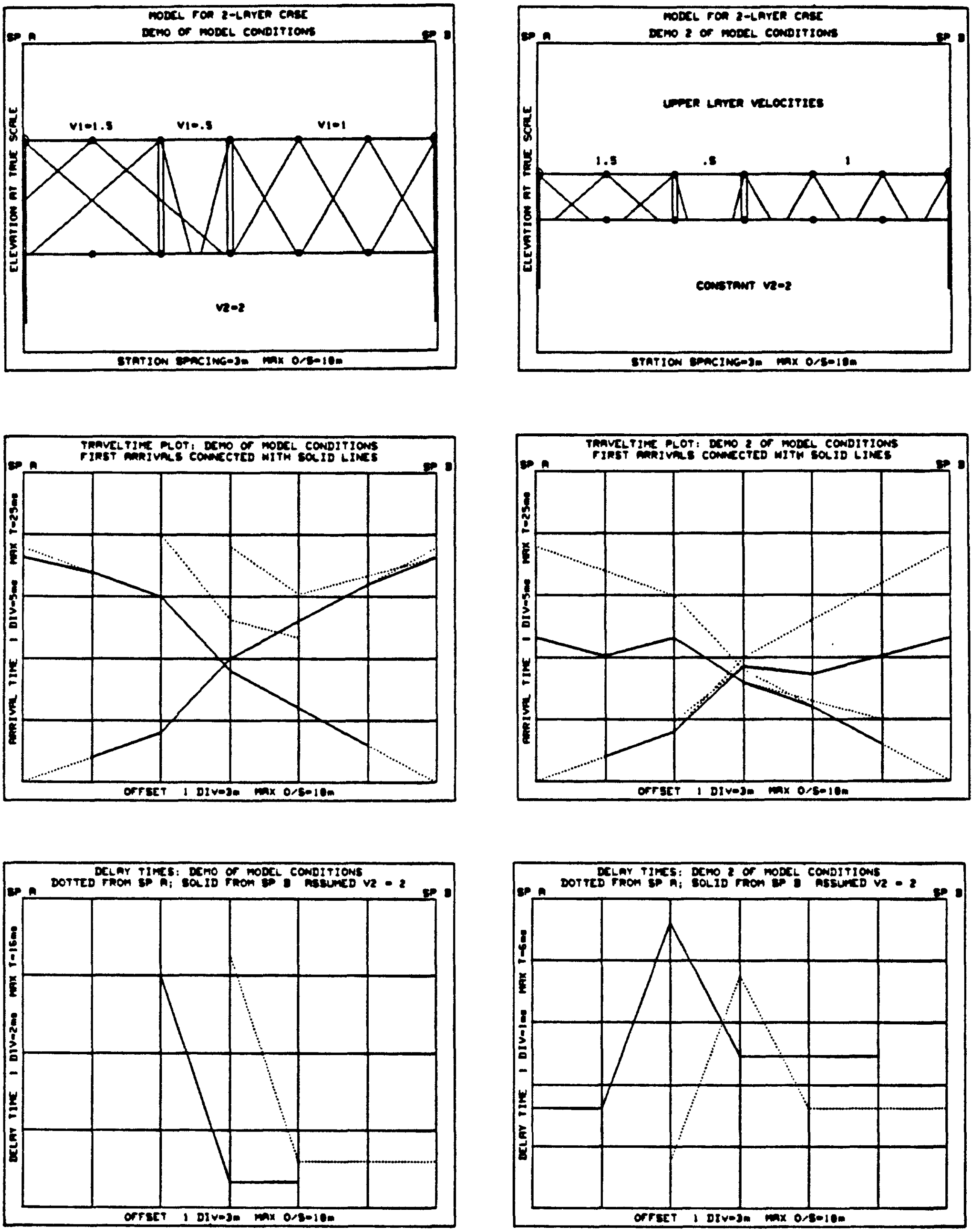

Figure 5. Demonstration of model conditions and remedial action taken. Left column shows results when refraction arrivals at station 2 are excluded; right column shows results of changing the station spacing-depth ratio.

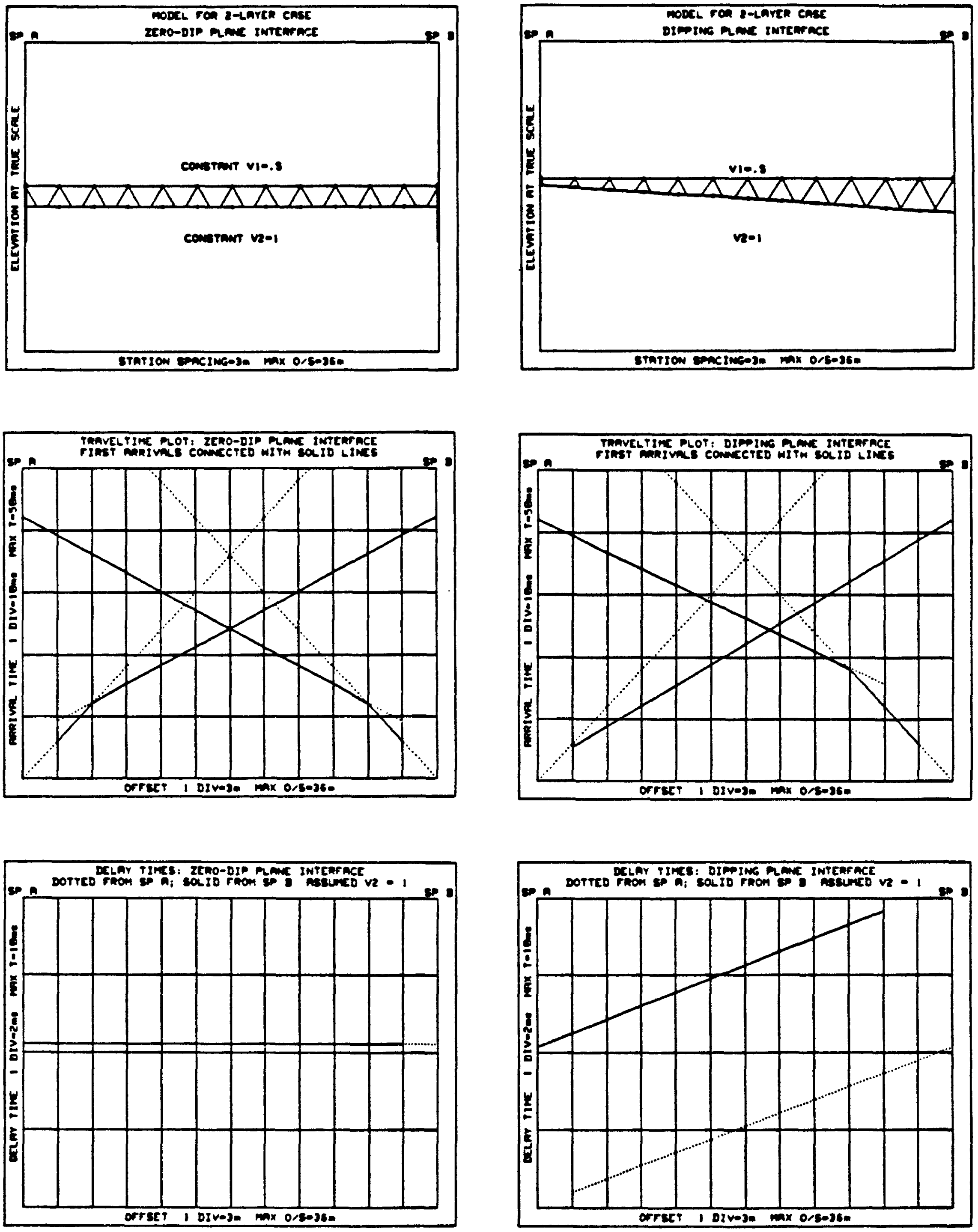

Figure 6. Simple two-layer models with constant velocities and no elevation changes. Left column shows the zero-dip, plane-interface model; right column shows the dipping interface model.

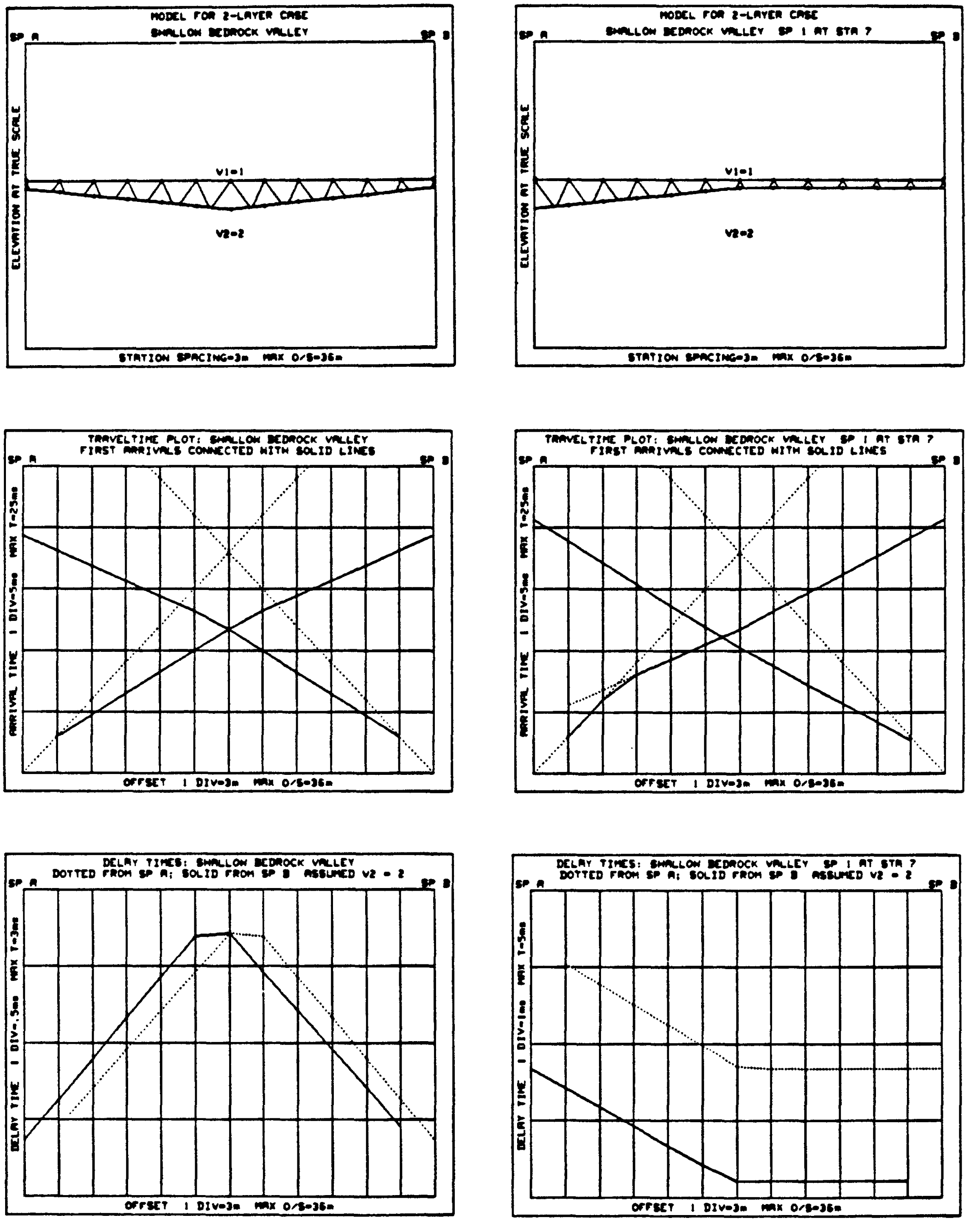

Figure 7. Models illustrating results over a bedrock depression. Left column shows results when middle station (station 7) is over the center of the depression. Right column shows results when SP's and spread are shifted such that SP A is at station 7.

case does not exist on these data since refraction returns require an increase in velocity with depth. Also, the delay-time plots clearly indicate an upper layer that thins from left to right and then becomes of constant thickness from about the center of the spread toward SP B (see the lower-right box in figure 6).

The purpose of the results shown on figures 8, 9, and 10, labeled LEARN #1, LEARN #2, AND LEARN #3, respectively, is to examine isolated effects so that their singular contributions to more complicated models can be studied.

The results shown in figure 8 illustrate the effect of elevation changes on first-arrival times. The right column shows traveltime and delay-time plots after elevation corrections have been applied. Note that the delay times computed with use of elevation-corrected first-arrival times are constant. Elevation corrections are made with respect to a fixed datum at the minimum elevation of the ground surface, and they require entry of an estimate of the average upper and lower layer velocities. Therefore, the depth computed using intercept time from the elevation-corrected, traveltime-plot data is relative to the fixed-datum elevation.

Shown on figure 9 are results that illustrate the effect of varying only the depth to bedrock; the surface elevation and layer velocities having been held fixed. Note that although the traveltime plot looks much like that of figure 8, the delay-time plots are significantly different. For completeness, elevation corrections were applied and results plotted in the right column.

It is instructive to compare the delay-time plots on figures 8 and 9. Two observations stand out:

1. The delay times mirror the upper-layer thicknesses,
2. The lateral shift between delay-time curves from the forward and reverse spreads is negligible when the base of the upper layer is level, but is pronounced when the base of the lower level varies. This shifting is known as migration of refraction arrivals.

Figure 10 shows results that illustrate what can be expected when the surface elevations vary but the depth to bedrock is constant. The consequences of applying elevation corrections are shown in the right column. Note that in the delay-time plot without elevation corrections (lower left plot), one division equals 0.1 ms, an amount of time within the uncertainty of picking first arrivals.

In general, elevation corrections are routinely applied. However, when doing so, it should be remembered that the elevation-corrected refraction times then become referenced to a fixed datum. For this reason elevation-corrected delay times are less at those stations at higher elevations and curvature is introduced into the elevation-corrected, traveltime-curve plots as illustrated in the right column of figure 10.

Let us now examine models with lateral variations in velocities. Double vertical lines are drawn by instructions from the program at those boundaries separating zones of different velocity. For clarity, velocities within the upper layer are labeled above the surface.

Figure 11 is a model constructed to show the combined effects of variable surface elevations, different thicknesses of the first layer, and lateral changes in velocity in both the upper and lower layers. In this case, a spread of six geophones was used with an offset of 6 m to the nearest geophone. Therefore, the spread shot from SP A extends from station 3 to 8, and the spread shot from SP B extends from station 1 to 6.

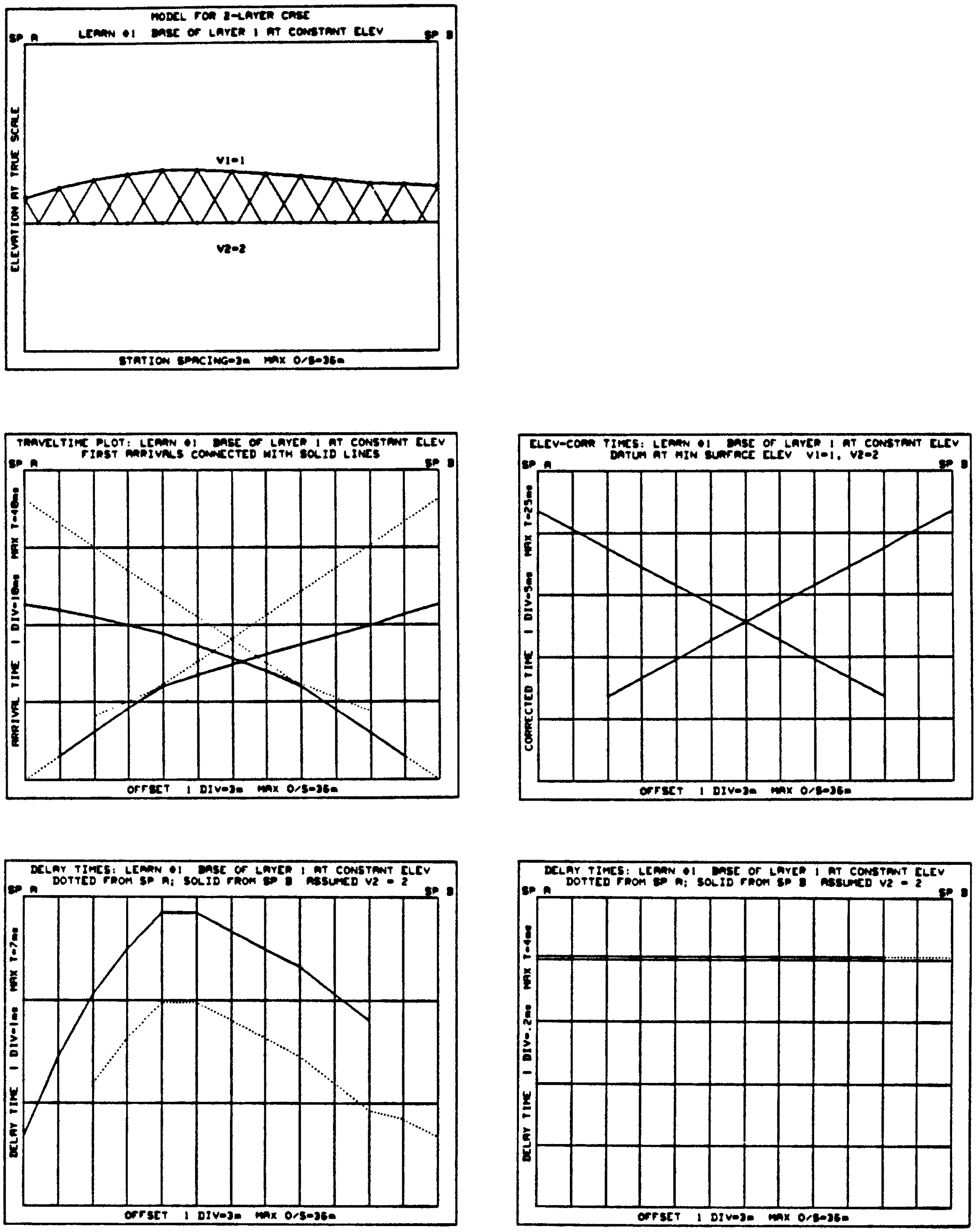

Figure 8. Model illustrating isolated effect of elevation changes on first-arrival times. Right column shows traveltime and delay-time plots after elevation correction.

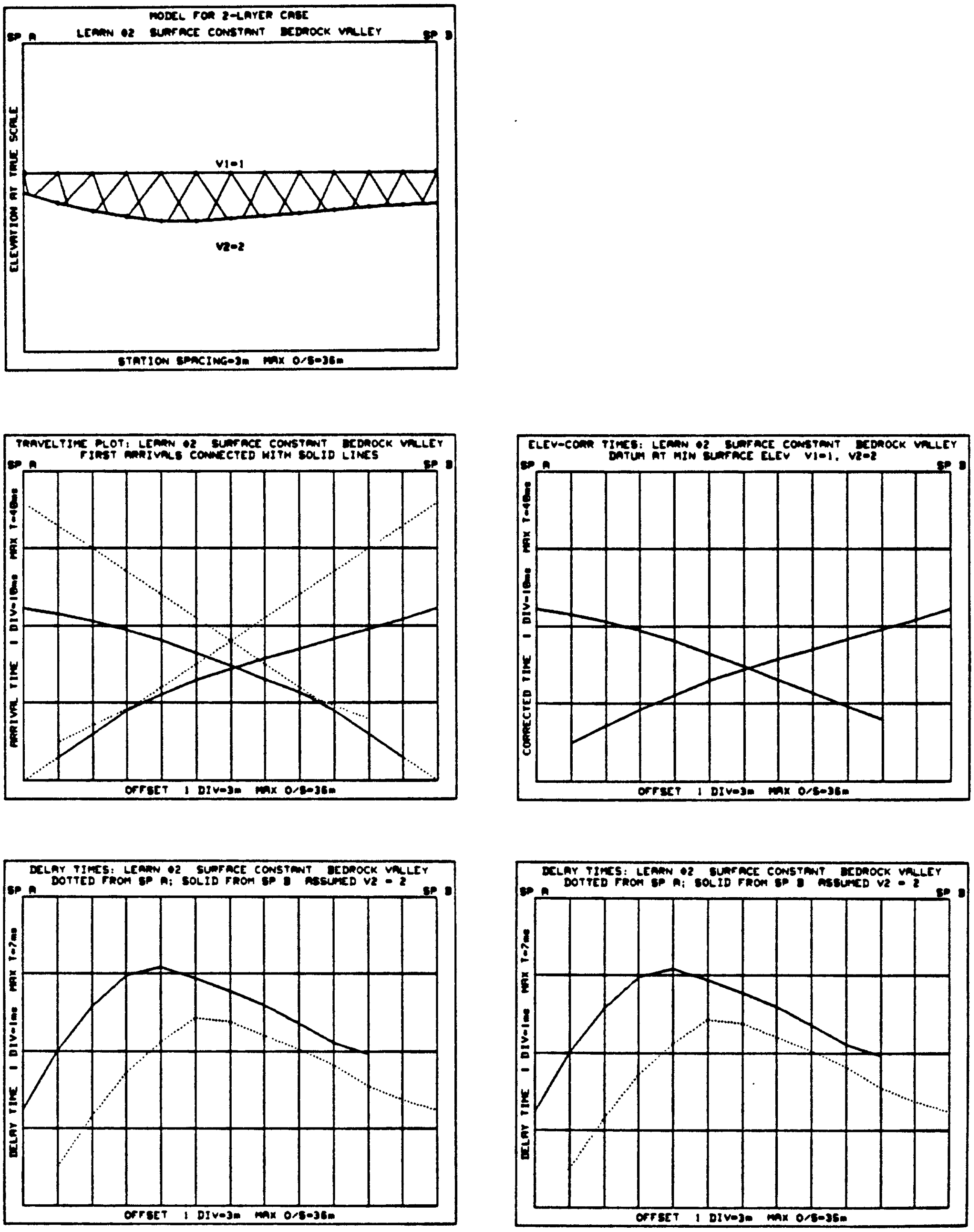

Figure 9. Model illustrating isolated effect of depth to bedrock on first-arrival times. Right column shows traveltime and delay-time plots after elevation correction.

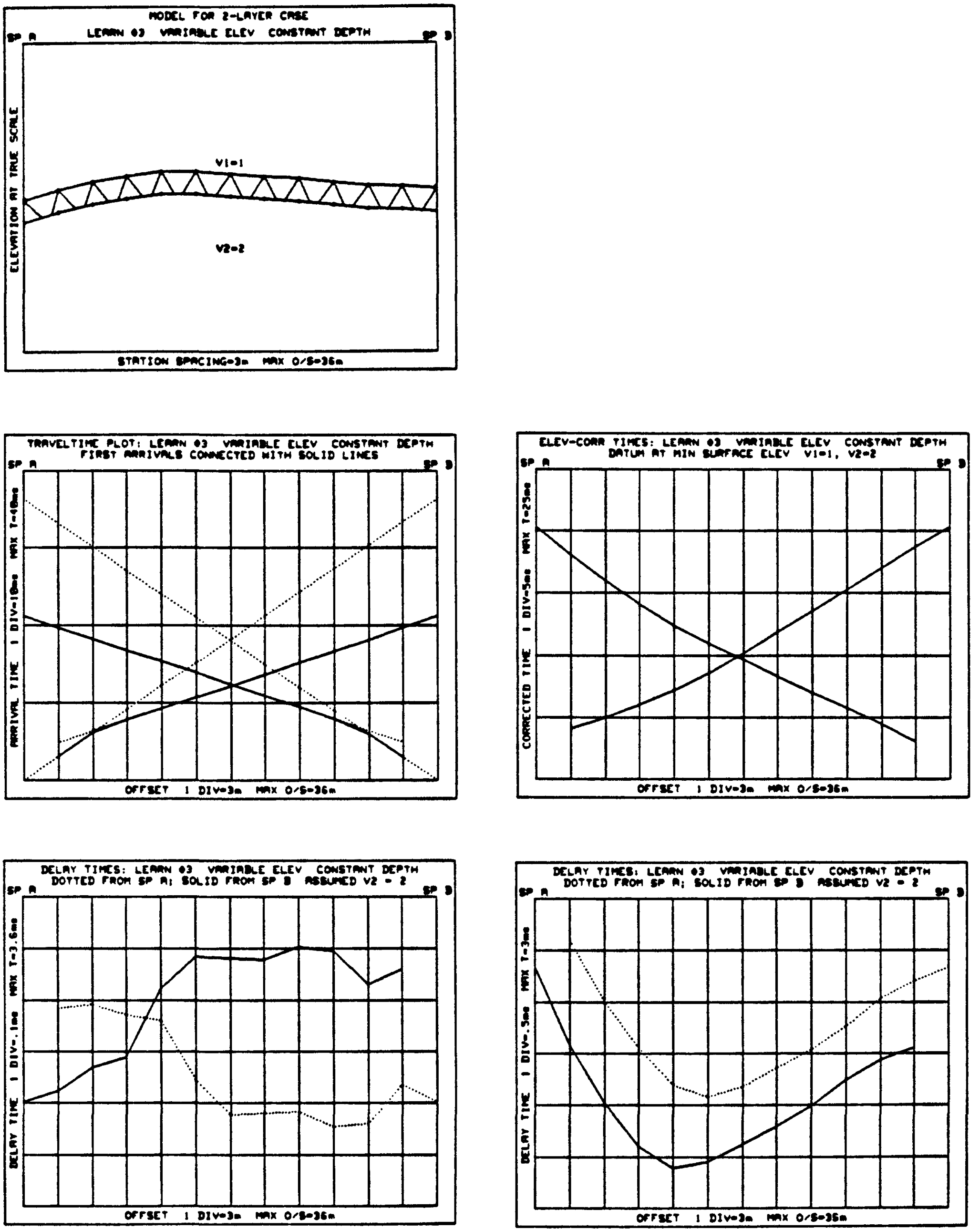

Figure 10. Model illustrating isolated effect of constant depth to bedrock on first-arrival times. Right column shows traveltime and delay-time plots after elevation correction.

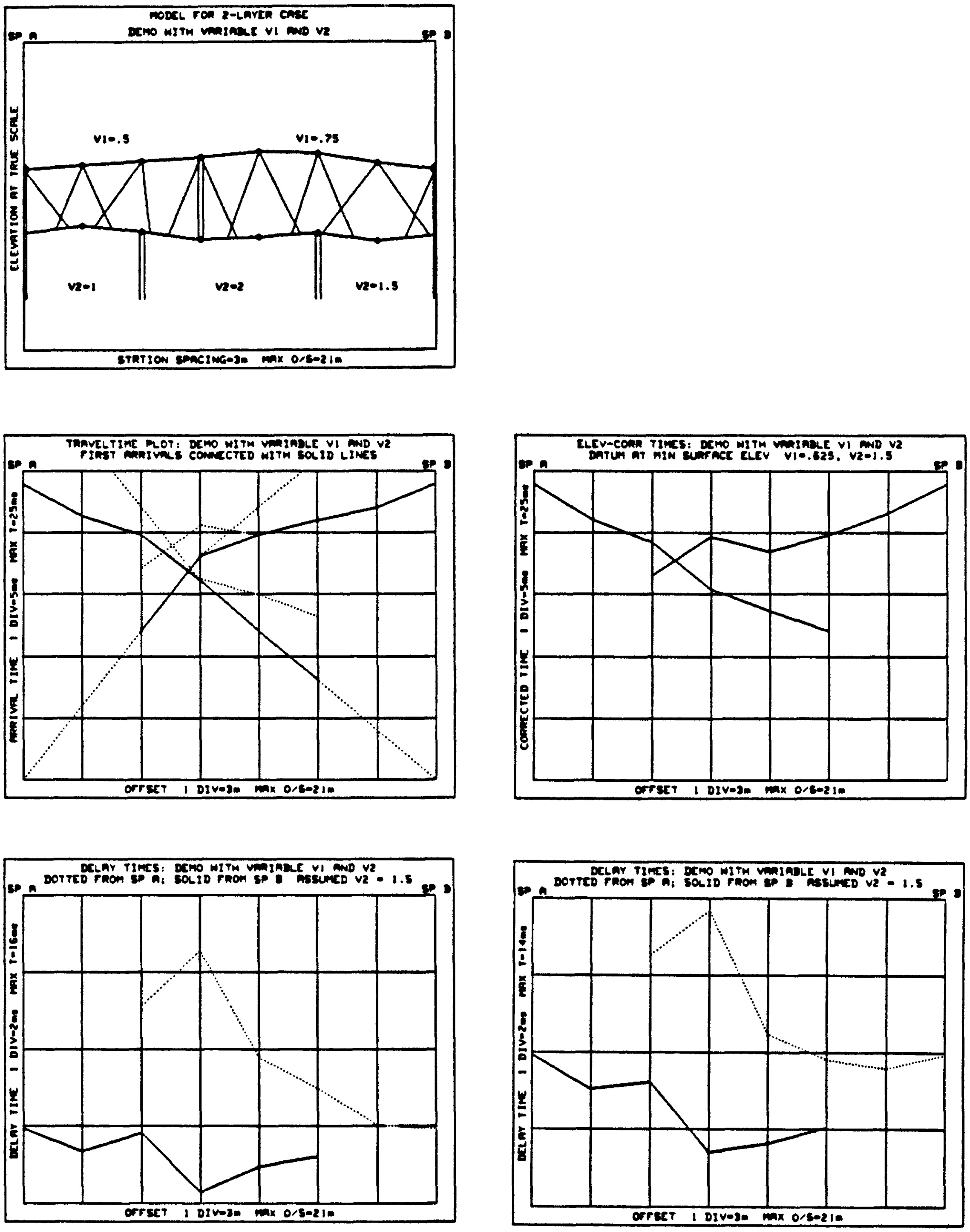

Figure 11. Model demonstrating combined effects of variable elevations, variable depths to second layer, and lateral changes in velocity within zones in both the upper and lower layers. Hand-drawn double lines connect obserable first-arrival times.

In the computing scheme, direct and permitted refracted arrival times are computed from each SP to each station location. On the traveltime curve display, all arrivals are initially plotted with dotted lines and later only those arrivals which are first arrivals are plotted with solid lines. First arrival times are shown only at locations at which geophones are positioned. Therefore, on the traveltime curve of figure 11, successive arrival times at SP A, station 2, and station 3 are connected by dotted lines, as are successive arrivals times at SP B, station 7, and station 6.

Delay times and elevation-corrected refraction times are computed without regard as to whether the refraction arrivals beyond the critical distance are first arrivals--the first arrivals may be direct-ray times. To emphasize this point, first-arrival refraction times and delay times derived from them are shown (hand drawn) on figure 11 with double lines.

As a final word of caution, when interpreting arrival time data it is important to remember that although arrival times are connected with straight lines, the inter-station arrival times may not fall along these straight lines. For example, figure 11 shows a solid straight line connecting SP A arrivals between stations 4 and 5. Since this straight line connects a direct and refracted arrival time, it should not be interpreted as a distinctive layer arrival.

The results shown in figure 12a illustrate the effects of stepped lateral changes in velocity of the lower layer (left column) and upper layer (right column). On the traveltime curves in the right column observe that if the offset was greater than the crossover distance (direct arrivals not recorded), then the initial interpretation would be that here we have a typical two-layer case with a dipping interface. Note the difference in intercept times and second-layer apparent velocities for spreads shot from SP A as contrasted to those from SP B (see figure 6, right column). However, if detectors had been deployed inside the critical distance, then the difference in upper-layer velocities at opposite ends of the spread would have been apparent, and a warning signal would have been flashed that more than a two-layer, planar-interface condition exists. This result from this model clearly demonstrates the need for selecting spread lengths sufficiently short so as to detect the direct arrivals.

In the left-column display of figure 12a, differences in slopes and intercept times between traveltime curves along spreads shot from SP A and SP B are not as pronounced as they are in the right column. On first glance, the results shown in the left column would have been interpreted as having been derived from a simple two-layer case with minor dip on the interface at the base of the upper layer. Only with the highest quality data would the convexity and concavity of the second-layer arrivals from SP's A and B, respectively, have been detected. This bending away from a straight line on the traveltime curves is well shown on the delay-time plots at the bottom of the left column. However, before jumping to the conclusion that the delay-time plots can be relied upon to detect lateral variations in second-layer velocity, note that the scale on the delay-time plots (1 ms/division) is only one-tenth that of the traveltime curves.

One of the pitfalls in working with results of the modeling technique of this report is that the results are noise free. And as a consequence, the traveltime curves are plotted as if first arrivals had been picked perfectly. My experience is that with the relatively weak seismic sources available to the engineering geophysicist and in consideration of the seismically noisy areas in which much of the work is done, precise picking of first arrivals to parts of milliseconds is an unwarranted expectation. Therefore, the tendency among interpreters is to draw straight lines on traveltime curves obtained from reciprocal spread surveys.

When the slopes, intercept times, and crossover distances obtained with straight-line fits to the traveltime curves of the results shown in the left and right columns in figure 12a are entered into a two-layer, planar-interface computing scheme, the solutions shown in figure 12b are obtained.

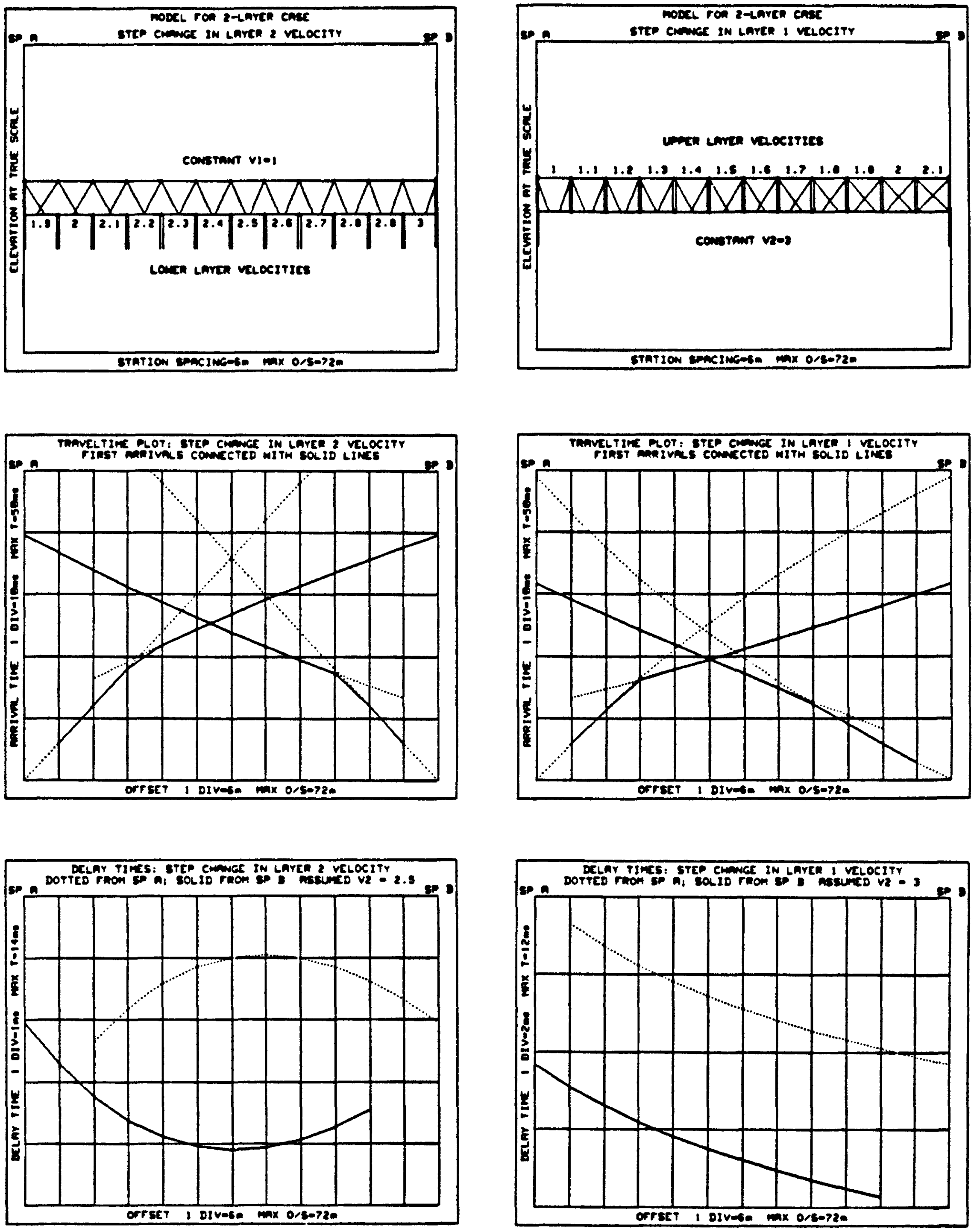

Figure 12a. Models demonstrating effects of stepped lateral changes in velocity of the lower layer (left column) and upper layer (right column).

```
TWO-LAYER CASE WITH DIP OF SECOND LAYER

INPUT VALUES
        Distance from SP A to SP B = 72
      First layer reciprocal time = 39.5
  Observed intercept time at SP A =  13
Observed crossover dist from SP A =  20.5
  Observed intercept time at SP B =  9.5
Observed crossover dist from SP B =  17.5
   Average velocity of first layer =  1
  Apparent 2nd-layer vel from SP A =  2.7
  Apparent 2nd layer vel from SP B =  2.4

COMPUTED VALUES USING OBSERVED VELOCITIES
    Mean velocity of second layer =  2.54
          Dip from SP A toward SP B = -1.4

COMPUTED VALUES USING INTERCEPT TIMES
Computed crossover dist from SP A =  20.6
Computed crossover dist from SP B =  16.3
          Computed reciprocal time =  39.6
          Observed reciprocal time =  39.5
 Depth to second layer under SP A =   7.1
 Depth to second layer under SP B =   5.2

COMPUTED VALUES USING CROSSOVER DISTANCES
          Computed reciprocal time =  39.9
          Observed reciprocal time =  39.5
  Computed intercept time at SP A =  12.9
  Computed intercept time at SP B =  10.2
 Depth to second layer under SP A =   7.0
 Depth to second layer under SP B =   5.6
```

```
TWO-LAYER CASE WITH DIP OF SECOND LAYER

INPUT VALUES
        Distance from SP A to SP B = 72
      First layer reciprocal time = 31.6
  Observed intercept time at SP A =  11.2
Observed crossover dist from SP A =  17
  Observed intercept time at SP B =  3
Observed crossover dist from SP B =  27
   Average velocity of first layer =  1.5
  Apparent 2nd-layer vel from SP A =  3.53
  Apparent 2nd layer vel from SP B =  2.52

COMPUTED VALUES USING OBSERVED VELOCITIES
    Mean velocity of second layer =  2.93
          Dip from SP A toward SP B = -5.7

COMPUTED VALUES USING INTERCEPT TIMES
Computed crossover dist from SP A =  29.2
Computed crossover dist from SP B =  11.1
          Computed reciprocal time =  31.6
          Observed reciprocal time =  31.6
 Depth to second layer under SP A =   9.8
 Depth to second layer under SP B =   2.6

COMPUTED VALUES USING CROSSOVER DISTANCES
          Computed reciprocal time =  31.4
          Observed reciprocal time =  31.6
  Computed intercept time at SP A =  6.5
  Computed intercept time at SP B =  7.3
 Depth to second layer under SP A =  5.7
 Depth to second layer under SP B =  6.4
```

Figure 12b. Depths and dips using a two-layer, planar-interface computing scheme. Results for the left-column displays of figure 12a are shown in the left-side listing; results for the right-column displays of figure 12a are shown on the right side.

One of the principal uses of forward modeling is to produce a data set that can be used as input to a computing scheme to test it against a known model. If the computing procedure fails completely to reproduce the model, then the scheme is suspect. However, if the computing method does produce the model, this does not necessarily mean that this method is correct--it only means that it is capable of producing results based on the same assumptions implicit in the forward modeling method. A fine piece of circular reasoning always lurks in test procedures, a trap that one must be careful to avoid. By analogy (looking back at your academic career), just because you passed a test did not mean that you knew all the course material--it only meant that you knew (or guessed) the right answers to the particular questions asked.

In the model used in figure 12a, the depth to the zero-dip planar interface is 6 m. The reciprocal-spread, two-layer, planar-interface computing scheme used to produce the results shown in figure 12b requires entry of the quantities listed under the INPUT VALUES heading. If no crossover distances are obtainable, crossover distances are entered as equal to zero. The data entered were taken directly from visual-best-estimate straight lines drawn on the traveltime curves shown on figure 12a.

For the left-column model results, the compute results shown on the left side of figure 12b are fairly close to the zero-dip, 6-m depth values of the model. Note that results obtained by computing the depths at SP A and SP B with the use of either intercept times or crossover distances are about the same, and that the computed crossover distances using entered intercept times and the computed intercept times using entered crossover distances are reasonably close to the input values. The conclusion here is that if the velocity within the upper layer were to remain fixed, then a simple, two-layer computation would give acceptable results. If opposing curvatures were observed on the second-layer arrivals, then some suspicion of these results would be aroused. Finally, if the spreads were shifted, say by four groups, across the traverse, then the different slope values of the refracted arrivals on these new spreads would be a strong indication of a lateral variation of the lower layer velocity.

The results listed on the right side of figure 12b show that a simple, two-layer, plane-interface computing scheme is not appropriate when the upper layer velocity varies laterally. Not only do the depths computed by the intercept and crossover methods disagree, but also the computed crossover distances and intercept times are not even close to the input values. If detector offsets were within the crossover distances, then it would have been obvious from inspection of the slopes of the direct arrivals from SP's A and B that severe changes in upper layer velocity were present. However, if data had been taken with spreads whose offset to the near geophone was beyond the crossover distance, then no cross checking between intercept-time and crossover-distance results could have been made. With hindsight, it would have been obvious that refraction data from both SP's can not sweep upward, as shown on the delay-time plot on the lower right of figure 12a.

Let us now examine models more representative of what might be encountered in practice. Two type of models are studied: a landfill and dry stream bed.

Figure 13 illustrates results what might be anticipated from traverses at constant surface elevation over a landfill at bedrock depth (left column) and over a landfill within excavated bedrock (right column). In these models it is assumed that the velocity within the landfill is 20 percent lower than the surrounding material.

As anticipated, the upward bump on the traveltime curve and the delay-time differences over the fill in the right column is greater than that in the left column since the fill is thicker and thus more lower velocity material is present. The delay-time plots clearly show the boundaries of the landfill and the need to take refraction migration effects into account when interpreting boundaries. Note that the fill extends from station 4 to 10, not from station 3 to 11. Although the limits of the landfill could be obtained just from examination of the traveltime curves, the model results show that it is easier to locate the edges of the fill from inspection of the delay-time plots.

These delay-time plots tell more about the landfill than just its extent. Observe that for the model with the landfill at bedrock depth, that the delay times at edges of the delay-time plot (stations 1, 2, 3, and 11, 12, 13) are equal for spreads shot from both SP A and SP B; whereas, when the fill is placed within an excavated bedrock, the delay times near the edges are not equal, even though the thickness of the overburden is the same at these locations. This observation suggests the nature of the base of the landfill may be inferred from study of the delay-time plots. In addition, the level line (equal time) across the top of the delay-time plot indicates that the base of the landfill is level (see left column on figure 6).

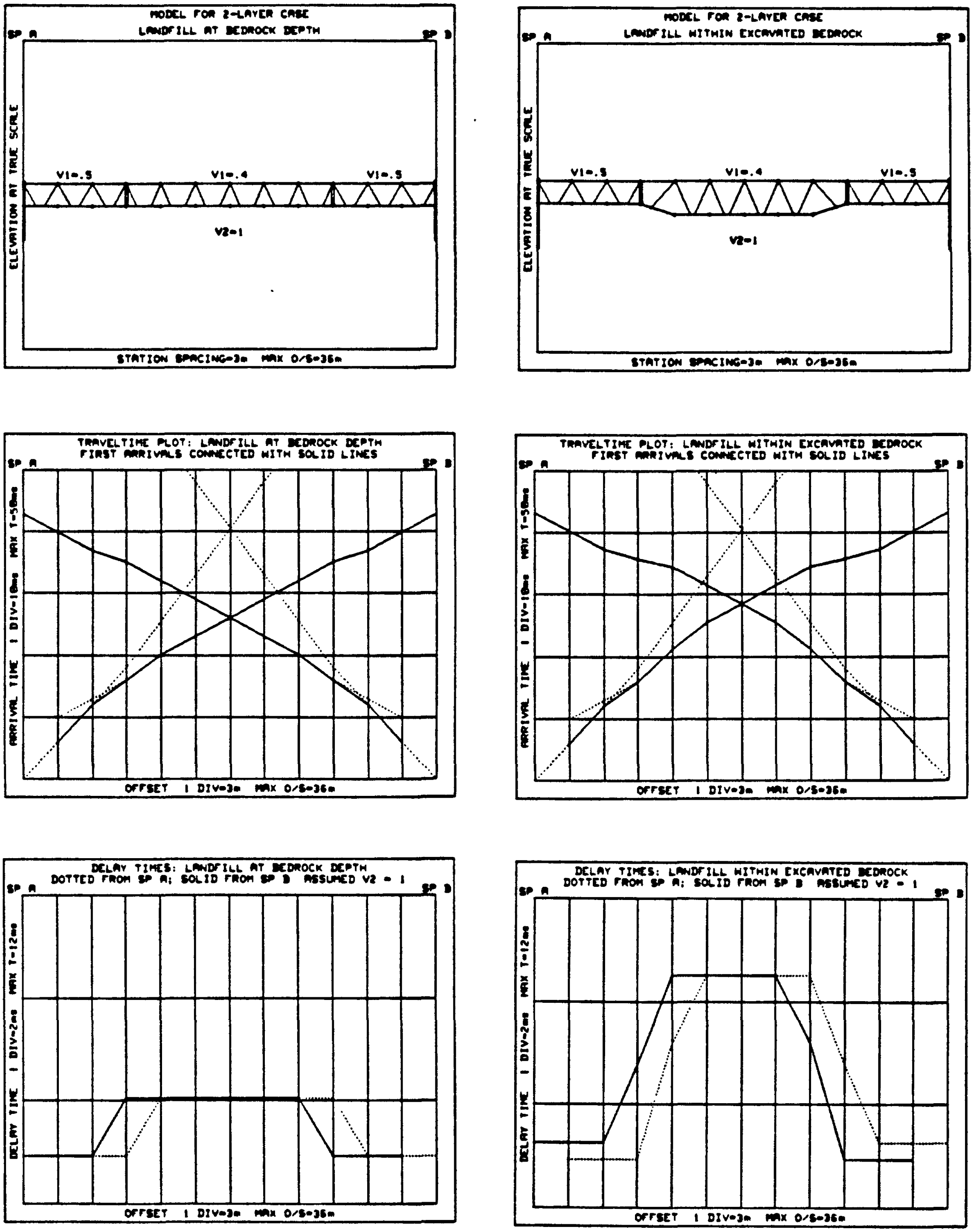

Figure 13. Models illustrating results obtained along traverses at constant surface elevation over a landfill at bedrock depth (left column) and over a landfill within excavated bedrock (right column).

Still more can be learned from these models. Note that the first-arrival plots (the solid lines) give no indication of the velocity of the landfill material. The slopes of the of the traveltime curves for direct-ray arrivals are the same for spreads shot from either SP A or SP B. The conclusion drawn from this observation is that the array of SP's and spreads would have to be shifted such that one of the SP's and several of its near geophones must be on the landfill before the velocity of the landfill could be determined. This illustrates the usefulness of modeling to guide establishment of field programs.

Although the modeling procedure of this report is limited to two-layer cases, one can imagine that the results derived from the flat-surface, landfill model (figure 13) would not be significantly altered if the filled area had been reclaimed by smoothing it, capping it with a thin soil cover, and then revegetating. Years after this work was done it would be difficult to visually detect the presence of the landfill, but as the model demonstrates, the landfill would not be invisible to seismic probing.

Let us now examine results for a landfill which rises above the surrounding ground. Figure 14 depicts a model of a raised landfill on level bedrock. Elevation corrected results are shown in the right column. Note that delay times for the forward and reverse spreads overlay when the top of the bedrock is level and no lateral changes occur within the bedrock.

Although the location of the landfill would have been obvious by just looking at the site, the thickness of the landfill could not have been determined by visual inspection. Since drilling is not recommended over landfills because of their possible toxic content and the danger of piercing the lower seal, a seismic survey may be a useful alternative. Models such as those shown in figures 14, 15, and 16 would be very useful in designing that seismic survey.

The results shown in figure 5 are repeated in figure 15. This display is in the same format as used in figures 14 and 16 to facilitate comparisons among three types of bedrock conditions under the landfill. In the figure 14 model, the fill is shown as having been deposited on a level bedrock surface, whereas in the model shown in figure 15, the bedrock (assumed to be at constant velocity) is shown as having been excavated prior to beginning the fill.

In figure 16, the bedrock is excavated, but it is assumed that a pit with sloping sides was dug only to an easily ripped depth. The effect of having sloping edges in the overburden is not considered in this model. With the upper surface of the bedrock having been removed, it is assumed that higher velocity material would be exposed at the base of the fill. Therefore, in the model of figure 16, a lateral variation in velocity is introduced within the modeled bedrock surface.

Comparing models of figures 14, 15, 16, note that the traveltime curves look about the same, but the delay-time plots exhibit the following significant differences:

1. When a velocity of 1 m/ms is entered as the bedrock velocity for computing the delay times, the slope of the distal ends of the delay-time plots is zero. However, if a velocity of 1.2 m/ms is used for the second layer (see plot in the upper right side of figure 16), the slopes at the edges of the plots are not zero. Note that these slope differences are not the results of dip of the bedrock surface.

2. When the bedrock surface remains level (figure 14) the delay times at the far ends of the forward and reverse spreads are equal, but if a change in elevation (figure 15) or a combined change in elevation and lateral change in velocity (figure 16) occurs, then a difference in far-end delay times is seen when the same delay-time computation velocity (1 m/ms) is used.

3. Over the central parts of the delay-time plots the slopes are zero when the bedrock velocity is constant and the surface is level beneath the landfill (figures 14 and 15), but slopes are not parallel when bedrock velocity varies. Although not shown in figure 16, if a delay-time computation velocity of 1.4 m/ms had been used, then these slopes would have been zero. As indicated by the model results of figure 6, if the bedrock surface dipped at a constant amount, then the slopes would

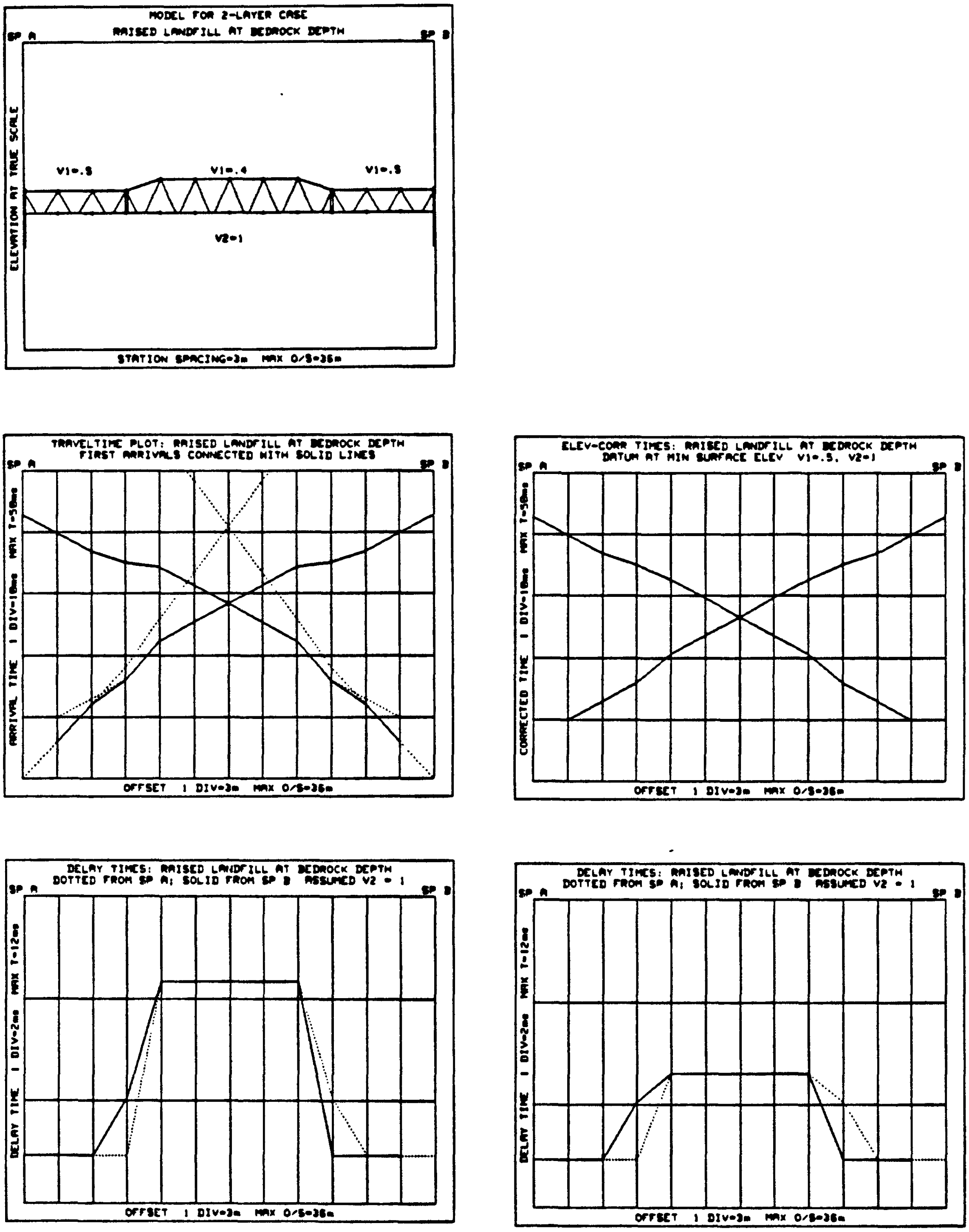

Figure 14. Model showing results across a raised landfill on level bedrock of constant velocity. Right column shows traveltime and delay-time plots after elevation correction.

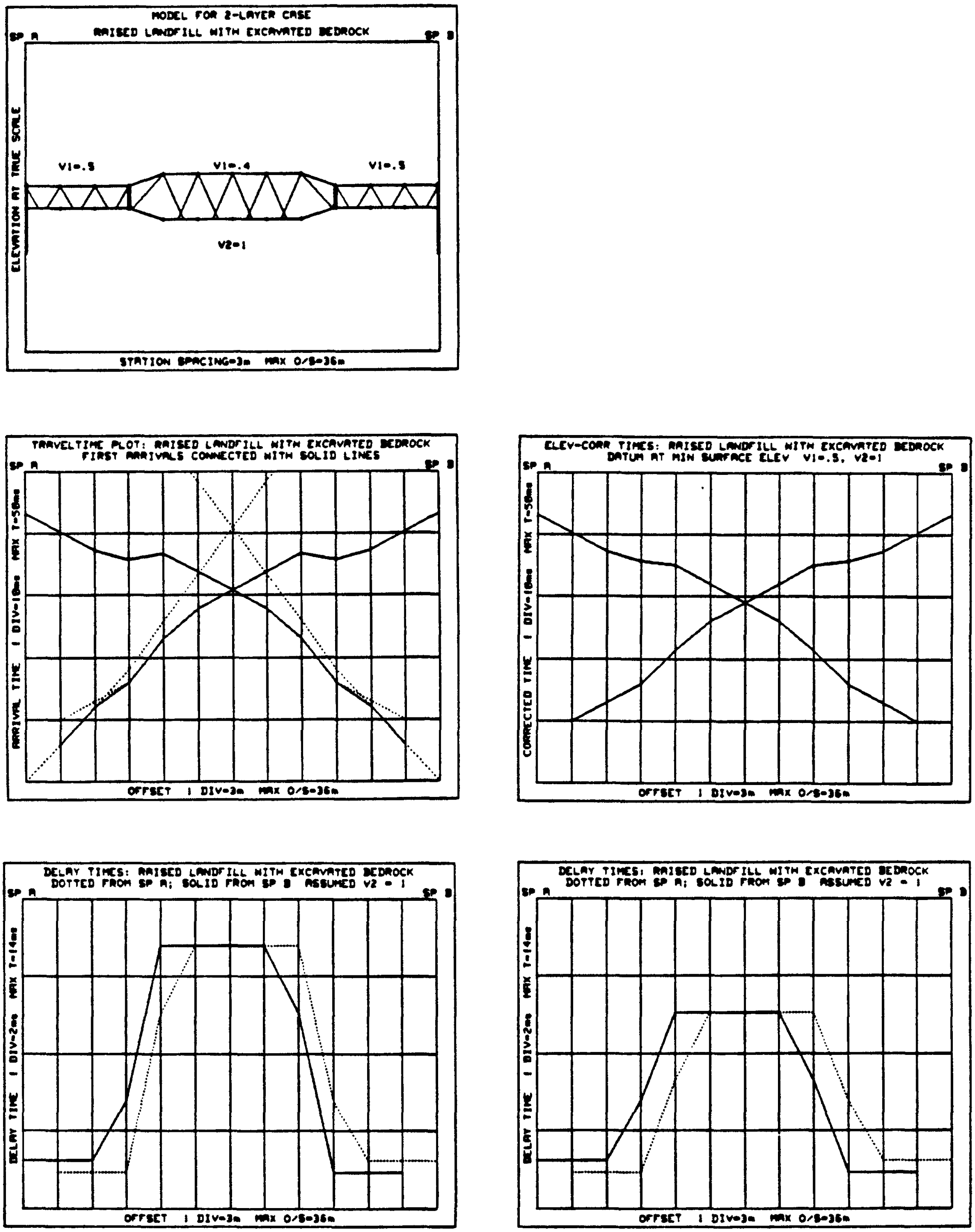

Figure 15. Model showing results across a raised landfill on excavated bedrock of constant velocity. Right column shows traveltime and delay-time plots after elevation correction.

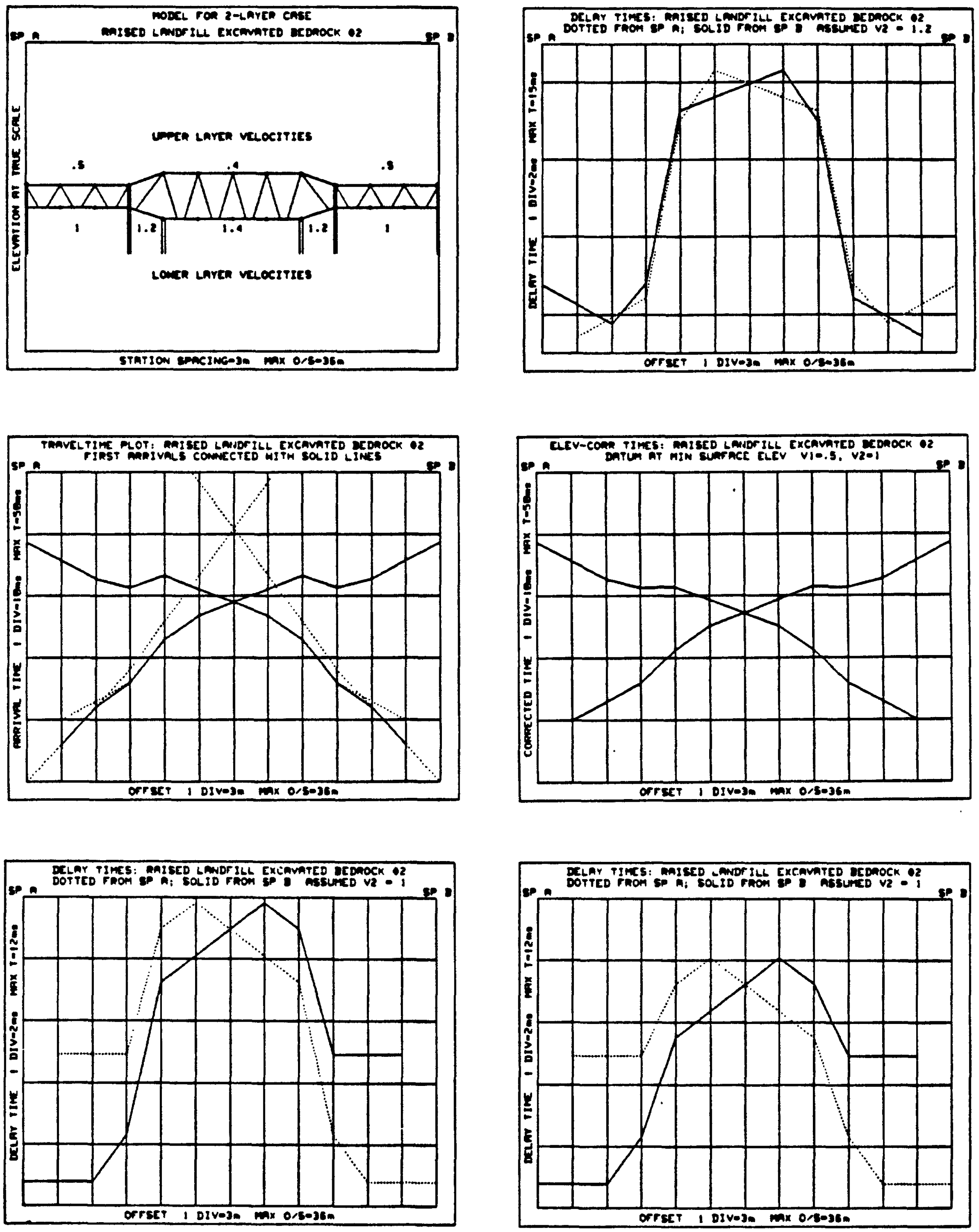

Figure 16. Model showing results across a raised landfill on excavated bedrock of variable velocity. Right column shows traveltime and delay-time plots after elevation correction.

have been parallel if the correct (arithmetic mean) velocity had been used as the computation velocity. The second-layer velocity that restores parallelism to the delay-time plots and the first-layer velocity (obtained from shiftted spreads) are the velocities to be used in computing the thickness of the landfill with the use of the ABC method (Heiland, 1940, Sherrif, 1984 and Sjögren, 1984).

A problem of interest in hydrology is illustrated by the next two models. Shown on figure 17 are model results when a refraction survey is taken across a stream bed containing lower velocity material than that in its banks. In this model, the bedrock velocity is constant, and both the ground and bedrock surfaces undulate. Elevation corrected results are shown in the right column.

This modeling results clearly demonstrate the complex nature of first arrivals that can arise from a relatively simple geologic case. The point of showing results derived from this model is to illustrate the effect of variable velocity within the upper layer. The thickness of the upper layer does not change much across the model. Therefore, it is instructive to compare the results shown on figure 10 (the constant depth model) and those in this figure. The model of figure 17 again illustrates the need to take more than just one set of reversed refraction profiles in order to arrive at an acceptable interpretation.

Shown on figure 18 are the results when a refraction survey is taken across a stream bed that followed a fractured zone within the bedrock. The surface and bedrock elevations as well as the lateral variations in velocity in the upper layer are the same as those used in the model of figure 17. Elevation corrected results are shown in the right column.

As was demonstrated for the landfill models, the traveltime curves on figures 17 and 18 have a somewhat similar appearance, but the delay-time plots are significantly different. As a learning exercise, I suggest that you use a set of delay-time computation velocities ranging from 3.0 to 1.5 m/ms, and observe the resulting delay-time plots over the central parts of the spreads. Rather than having to re-enter all model parameters, the program provides an option to chose another delay time computation velocity so that studies as recommended above can be executed simply and quickly.

SUMMARY AND CONCLUSIONS

The forward modeling program of this report does a fairly credible job of determining direct and refracted times for two-layer cases in which the elevation of the surface and the thickness of the upper layer vary and lateral changes in velocity occur. No diffracted or reflected arrivals are considered. The procedure is relatively fast (a couple of minutes per model on a desktop computer) and simple to use. However, as it is with all modeling techniques whether they are mental, mathematical, numerical, or physical, judgment must be exercised in interpreting modeling results in terms of real world structures.

The limitations of the modeling procedure must be considered when interpreting its results. One such limitation is that the model uses only straight ray segments; that is, within each zone, the velocity is constant. Another is that each zone is a quadrilateral with vertical sides. Two safeguards are included within the program: one prohibit the use of a ray that crosses a zone boundary, and another rejects second-layer arrivals within the critical distance.

The refraction forward model procedure has four principal uses:
1. To develop an understanding of the refraction method.
2. To produce input data to test computing schemes.
3. To assist in the design of field procedures.
4. To interactively interpret observed results.

Within its limitation, the modeling program of this report serves these functions.

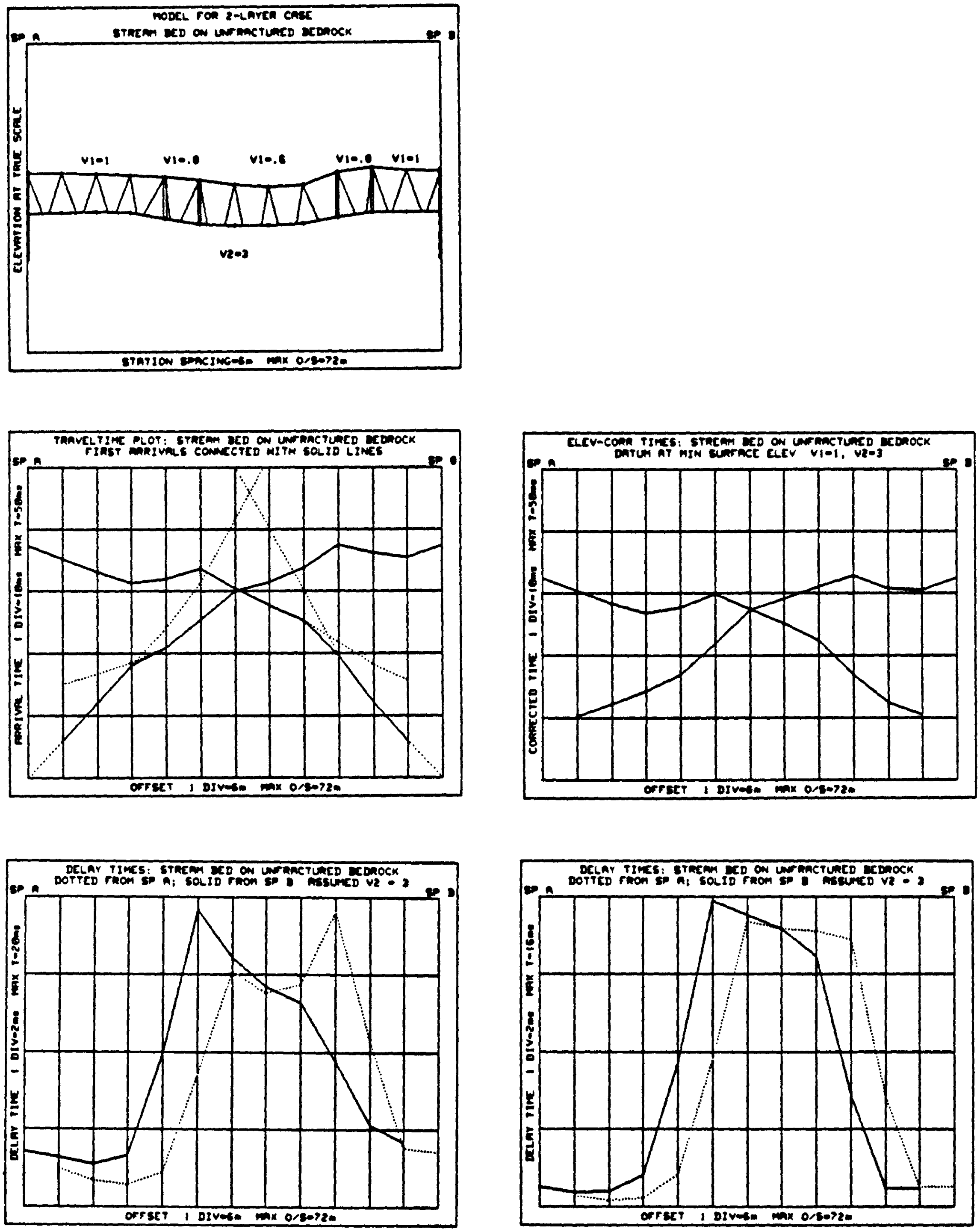

Figure 17. Model showing results across a stream bed on bedrock of constant velocity. Right column shows traveltime and delay-time plots after elevation correction.

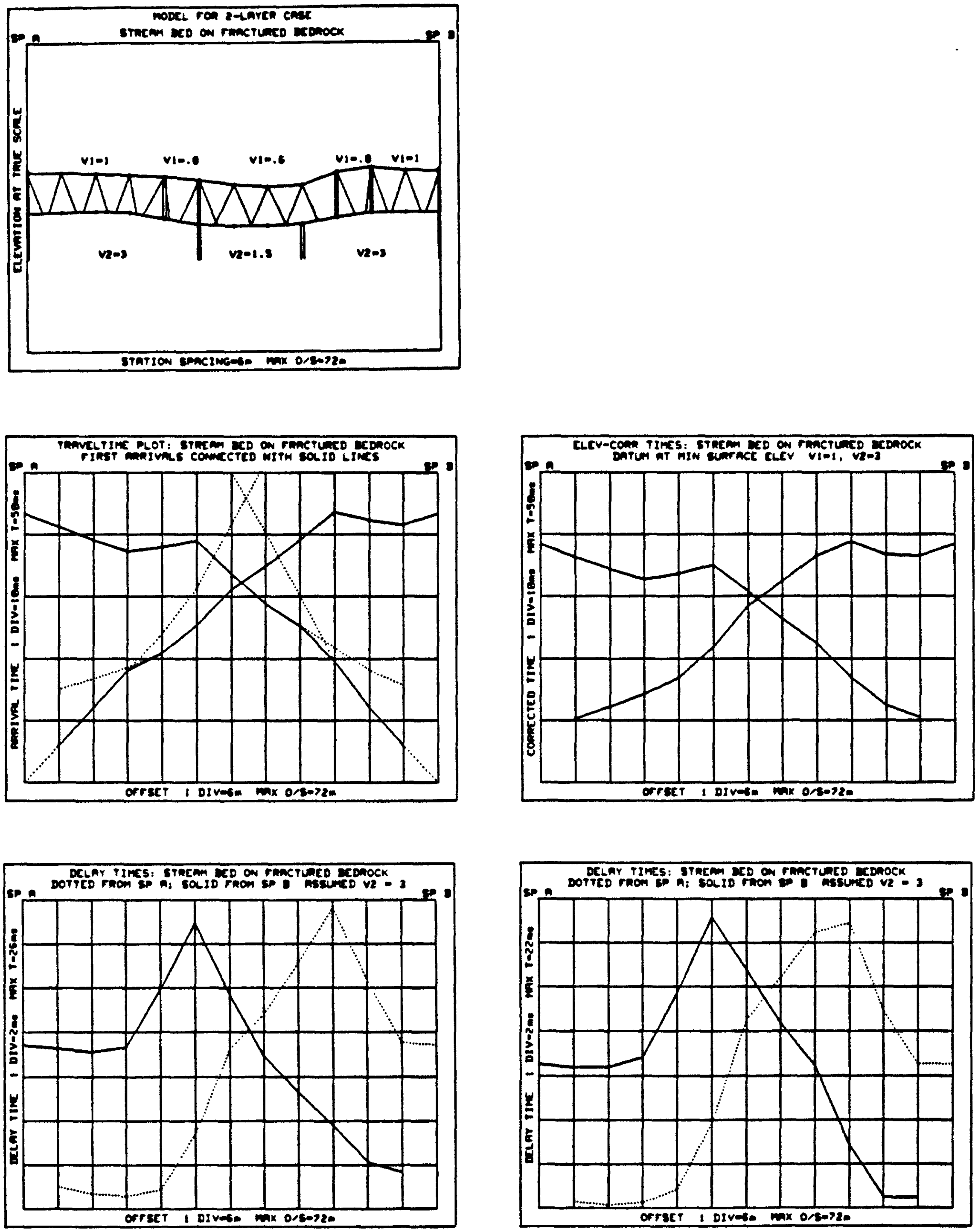

Figure 18. Model showing results across a stream bed on bedrock of variable velocity related to fracturing. Right column shows traveltime and delay-time plots after elevation correction.

Any forward modeling procedure is a "what if, then what" process. In this report, 19 different models were presented not only to demonstrate the capabilities of the modeling procedure, but also to see what could be expected with the seismic refraction method under the ideal conditions represented by the models.

As an example of the use of a model in design of a field procedure, let us consider the case of the raised landfill, as shown on figures 14, 15, and 16. To determine the thickness of this landfill with the use of the ABC procedure (Sjögren, 1984), the following requirements must be met (assuming acceptable first arrivals can be obtained):

1. First arrivals over the landfill must be refracted rays from the bedrock, and spreads must be sufficiently long that at a given detector position, refracted first arrivals can be obtained from both off-end SP's.
2. Refraction arrivals at stations on the landfill must meet the ideal triangle conditions (Sjögren, 1984); that is, the refracting surface must be planar between the refraction depth points to either side of the normal from the station, and the velocities both within the triangle and along its base must be constant.
3. Velocities within the upper and lower layers must be known to a reasonable level.

For the first condition on the ABC procedure, modeling can be used to determine the spread lengths for specified first-layer depths and upper and lower layer velocities. Compliance with the ideal triangle conditions can be confirmed by inspection of the traced rays on the drawing of the model (upper left box on figures 14, 15, and 16). In the worst case, only those arrivals at stations 6, 7, and 8 meet the ideal triangle conditions. Note: analysis of modeling results can be used to estimate the amount of error if the ideal triangle conditions are not met and to evaluate errors in ABC calculations for a range of assumed velocities. Finally, modeling can be used to determine station spacing so that a sufficient number of values can be determined within a segment to allow determination of second layer velocity.

NOTICE

Although the development of the procedure described in this report has been partially supported by the United States Environmental Protection Agency through Interagency Agreement Number DW14933103-01 to the United States Geological Survey, it has not been subjected to Agency review and therefore does not necessarily reflect the views of the Agency and no official endorsement should be inferred. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

REFERENCES

Heiland, C. A., 1940, Geophysical exploration, Prentice Hall, New York.

Sheriff, R. E., 1984, Encyclopedic dictionary of exploration geophysics (2nd ed), Soc. Exploration Geophysicist, Tulsa, Okla.

Sjögren, Bengt, 1984, Shallow refraction seismics, Chapman and Hall, New York.

```
10    PRINT "APPROXIMATION FORWARD MODELS FOR REFRACTION 'REFRM5' 19 MAR 90"
20    OPTION BASE 1
30    PRINTER IS 16                    ! Screen display
40    DEG                              ! Computations use angles in degrees
50    !
60    PRINT "NOTE: The program is for a two-layer case only"
70    PRINT "All times are in milliseconds (ms)";LIN(1)
80    !
90    DIM R$[55],Td$[40],Ac(25),Ae(25),Aed(25),Ced(25),Co(25),D(25),E(25)
100   DIM Eg(25),Esa(25),Esb(25),Sa(25),Sb(25),Sz1(25),Sz2(25)
110   DIM Tad(25),Tar(25),Tar_dt(25),Tbd(25),Tbr(25),Tbr_dt(25),Tda(25)
120   DIM Tdb(25),Teca(25),Tecb(25),Tma(25),Tmb(25),Tra(25),Trb(25),Tsw(25)
130   DIM V1(25),V2(25),Vz1(25),Vz2(25)
140   DIM Xa(25),Xb(25),Xg(25),Xsa(25),Xsb(25),Xz1(25),Xz2(25),Z(25)
150   !
160   GOSUB Begin                      ! Initial questions
170   GOSUB Model_param                ! Model parameters
180   GOSUB Plot_model                 ! Plot model at true scale
190   GOSUB Comp_direct                ! Compute direct-ray times
200   GOSUB Comp_refr                  ! Compute refracted-ray times
210   GOSUB Tabulate                   ! Tabulate results
220   GOSUB Plot                       ! Plot results
230   GOSUB Delay_time_plot            ! Compute and plot summed delay times
240   GOSUB Elev_corr_plot             ! Compute and plot elev-corrected times
250   PRINTER IS 0                     ! Hard copy
260   GOSUB Time_date                  ! Print time and data
270   PRINT LIN(3);Td$;LIN(2)
280   BEEP
290   PRINTER IS 16
300   DISP "PROGRAM COMPLETED"
310   END
320   !
330 Begin:                             ! Initial questions
340   PRINTER IS 16                    ! Screen display
350   Q1=1                             ! Flag for subsequent calculations
360   Y$="1990"                                                    ! DEFAULT
370   INPUT "Year computations made (default is 1990):",Y$
380   Qu=1                             ! Qu=1; flag for metric units
390   G$="Y"
400   INPUT "Are units in metric? (Y/N--default is Y)",G$
410   IF G$="Y" THEN 440
420   PRINT "English units (ft and ft/ms)"
430   GOTO 450
440   PRINT "Metric units (m and m/ms)"
450   PRINT "Enter model name (max length = 42 characters)"
460   INPUT "  ",R$
470   IF LEN(R$)<43 THEN 520
480   BEEP
490   PRINT "NAME TOO LONG  ENTER NEW NAME"
```

```
500   GOTO 450
510   PRINT "Model Name:";R$
520   RETURN
530   !
540 Time_date:                          ! Print time and data
550   OUTPUT 9;"R"                      ! Get time from internal clock
560   ENTER 9;T$
570   Td$="  COMPUTED: "&T$&", "&Y$
580   RETURN
590   !
600 Model_param:                        ! Model parameters
610   G$="N"
620   INPUT "Do you want hard copy of model parameters?(Y/N--default is N)",G$
630   IF G$="N" THEN 650
640   PRINTER IS 0                      ! Hard copy
650   GOSUB Time_date                   ! Time and data
660   PRINT LIN(2);"APPROXIMATION FORWARD MODEL FOR REFRACTION";Td$
670   PRINT LIN(1);"Model: ";R$;LIN(1)
680   PRINT "MODEL PARAMETERS"
690   Snspa=1                                                       ! DEFAULT
700   INPUT "Station number at SP A (default=1):",Snspa
710   PRINT "           Station number at SP A =";Snspa
720   Nd=12                                                         ! DEFAULT
730   INPUT "Number of detectors on spread (default=12):",Nd
740   PRINT "    Number of detectors on spread =";Nd
750   Xd=3                                                          ! DEFAULT
760   INPUT "Spacing between stations (default=3m):",Xd
770   PRINT "                  Station spacing =";Xd
780   Xa(1)=Xd                                                      ! DEFAULT
790   INPUT "Offset of near detector from SP A (default=sta spacing):",Xa(1)
800   PRINT "Offset from SP A to near detector =";Xa(1)
810   Xb(1)=0                           ! Far detector, spread B at SP A
820   FOR J=2 TO Nd                     ! FOR number of detectors
830     Xa(J)=Xa(J-1)+Xd                ! Detector offset spread A from SP A
840     Xb(J)=(J-1)*Xd                  ! Detector offset spread B from SP A
850   NEXT J
860   Xc=Xa(1)+(Nd-1)*Xd                ! Xc=SP A to SP B distance
870   PRINT "       Distance from SP A to SP B =";Xc
880   Snspb=Snspa+Xc/Xd
890   PRINT "           Station number at SP B =";Snspb
900   Ns=Xc/Xd+1                        ! Ns = number of stations
910   PRINT "               Number of stations  =";Ns
920   INPUT "Number of velocity zones within the first layer",Nz1
930   PRINT " Number of zones within 1st layer =";Nz1
940   INPUT "Number of velocity zones within the second layer",Nz2
950   PRINT " Number of zones within 2nd layer =";Nz2
960   Np=Ns-1                           ! Np=number of partitioned zones
970   G$="Y"
980   INPUT "Do you want to accept the above entries? (Y/N--default is Y)",G$
990   IF G$="Y" THEN 1010
```

```
1000  GOTO 680                         ! Branch; re-enter values
1010  REDIM Ac(Np),Ae(Np),Aed(Np),Ced(Np),Co(Np),D(Np),E(Ns),Eg(Ns)    ! REDIM
1020  REDIM Esa(Np),Esb(Np),Sa(Np),Sb(Np)                               ! REDIM
1030  REDIM Sz1(Nz1+1),Sz2(Nz2+1),Tad(Ns),Tar(Ns),Tar_dt(Ns)            ! REDIM
1040  REDIM Tbd(Ns),Tbr(Ns),Tbr_dt(Ns),Tda(Ns),Tdb(Ns)                  ! REDIM
1050  REDIM Teca(Ns),Tecb(Ns),Tma(Ns),Tmb(Ns),Tra(Nd),Trb(Nd),Tsw(Np)  ! REDIM
1060  REDIM V1(Nz1),V2(Nz2),Vz1(Np),Vz2(Np),Z(Ns)                      ! REDIM
1070  REDIM Xa(Nd),Xb(Nd),Xg(Np),Xsa(Np),Xsb(Np),Xz1(Nz1+1),Xz2(Nz2+1) ! REDIM
1080  IF Nz1>1 THEN 1150               ! More than one velocity in layer 1
1090  PRINT LIN(1);"FOR LAYER 1"
1100  INPUT "Constant velocity within first layer:",V1all
1110  PRINT "       Constant velocity of 1st layer =";V1all
1120  MAT V1=(V1all)
1130  MAT Vz1=(V1all)
1140  GOTO 1380
1150  PRINT LIN(1);"FOR LAYER 1"
1160  PRINT "NOTE: Zone boundaries must be at station locations"
1170  Sz1(1)=Snspa                     ! Zone 1 begins at SP A
1180  Sz1(Nz1+1)=Ns                    ! Last velocity zone in layer 1
1190  Xz1(1)=0                         ! Distance to left side of first zone
1200  Xz1(Nz1+1)=Xc                    ! Distance to left side of last zone
1210  PRINT "For zone 1 ,station number at left side of zone =";Sz1(1)
1220  FOR J=2 TO Nz1                   ! FOR vel zones within layer 1
1230    PRINT "For zone";J;
1240    INPUT "Station number at left side of zone:",Sz1(J)
1250    PRINT ",station number at left side of zone =";Sz1(J)
1260    Xz1(J)=(Sz1(J)-Sz1(1))*Xd      ! Distance of left side from SP A
1270  NEXT J
1280  FOR J=1 TO Nz1                   ! FOR vel zones within layer 1
1290    PRINT "For zone";J;
1300    INPUT "Velocity within zone:",V1(J)
1310    PRINT ",velocity within 1st layer =";V1(J)
1320  NEXT J
1330  FOR J=1 TO Nz1                   ! FOR vel zones within layer 1
1340    FOR K=1 TO Np
1350      IF (K>=Sz1(J)) AND (K<=Sz1(J+1)) THEN Vz1(K)=V1(J)
1360    NEXT K
1370  NEXT J
1380  IF Nz2>1 THEN 1450               ! More than one velocity in layer 2
1390  PRINT LIN(1);"FOR LAYER 2"
1400  INPUT "Constant velocity within 2nd layer:",V2all
1410  PRINT "       Constant velocity of 2nd layer =";V2all
1420  MAT V2=(V2all)
1430  MAT Vz2=(V2all)
1440  GOTO 1630
1450  PRINT LIN(1);"FOR LAYER 2"
1460  PRINT "NOTE: Zone boundaries must be at station locations"
1470  Sz2(1)=Snspa                     ! Zone 1 begins at SP A
1480  Sz2(Nz2+1)=Ns                    ! Last velocity zone in layer 2
1490  Xz2(1)=0                         ! Distance to left side of first zone
```

```
1500 Xz2(Nz2+1)=Xc                    ! Distance to left side of last zone
1510 PRINT "For zone 1 ,station number at left side of zone =";Sz2(1)
1520 FOR J=2 TO Nz2                   ! FOR vel zones within layer 2
1530   PRINT "For zone";J;
1540   INPUT "Station number at left side of zone:",Sz2(J)
1550   PRINT ",station number at left side of zone =";Sz2(J)
1560   Xz2(J)=(Sz2(J)-Sz2(1))*Xd      ! Distance of left side from SP A
1570 NEXT J
1580 FOR J=1 TO Nz2                   ! FOR vel zones within layer 2
1590   PRINT "For zone";J;
1600   INPUT "Velocity within zone:",V2(J)
1610   PRINT ",velocity within 2nd layer =";V2(J)
1620 NEXT J
1630 FOR J=1 TO Nz2                   ! FOR number of zones in layer 2
1640   FOR K=1 TO Np
1650     IF (K>=Sz2(J)) AND (K<=Sz2(J+1)) THEN Vz2(K)=V2(J)
1660   NEXT K
1670 NEXT J
1680 G$="Y"
1690 INPUT "Do you want to accept the above entries? (Y/N--default is Y)",G$
1700 IF G$="Y" THEN 1720
1710 GOTO 1080
1720 PRINTER IS 16                    ! Screen display
1730 G$="N"                           ! Surface elevations not equal
1740 INPUT "Are surface elevations constant? (Y/N--default is N)",G$
1750 IF G$="N" THEN 1800
1760 INPUT "Constant surface elevation:",Econ
1770 MAT Eg=(Econ)                    ! All Eg set equal to Econ
1780 PRINT "       Constant surface elevation =";Econ
1790 GOTO 1880                        ! Skip separate elevation inputs
1800 INPUT "Elevation of SP A (station 1):",Eg(1)
1810 PRINT "                Elevation of SP A =";Eg(1)
1820 PRINT "FOR STATIONS  FROM SP A TO SP B"
1830 FOR J=2 TO Ns
1840   PRINT "For station ";J;
1850   INPUT "Elevation of station:",Eg(J)
1860   PRINT ", elevation =";Eg(J)
1870 NEXT J
1880 MAT SEARCH Eg,MAX;Emax           ! Find maximum elevation of surface
1890 PRINT "        Maximum surface elevation =";Emax
1900 MAT SEARCH Eg,MIN;Egmin          ! Find minimum elevation of surface
1910 PRINT "        Minimum surface elevation =";Egmin
1920 G$="N"
1930 INPUT "Is top of layer 2 at constant elevation? (Y/N--default is N)",G$
1940 IF G$="N" THEN 2000
1950 INPUT "Elevation at top of layer 2:",Econ
1960 PRINT "Constant elevation at top layer 2 =";Econ
1970 MAT E=(Econ)                     ! All elev at base of layer 1 = Econ
1980 MAT Z=Eg-E                       ! Depth to top of 2nd layer
1990 GOTO 2070                        ! Branch, skip separate entries
```

```
2000 PRINT "FOR STATIONS FROM SP A TO SP B"
2010 FOR J=1 TO Ns                    ! FOR each station, enter base elev
2020   PRINT "For station ";J;
2030   INPUT "Elevation at top of layer 2:",E(J)
2040   PRINT ", elevation at top of layer 2 =";E(J)
2050   Z(J)=Eg(J)-E(J)                ! Depth to top of 2nd layer
2060 NEXT J
2070 MAT SEARCH E,MIN;Emin            ! Find min elev of top of 2nd layer
2080 PRINT "Min elevation at top of 2nd layer =";Emin
2090 PRINT "Default elevation of base of model = ";Emin-Xd
2100 Ebase=Emin-Xd                    ! Used to set V2 label
2110 INPUT "Elevation at base of model:",Ebase
2120 PRINT "       Elevation at base of model =";Ebase
2130 PRINTER IS 0                     ! Hard copy
2140 PRINT LIN(1)
2150 GOSUB Time_date                  ! Time and date
2160 PRINT "Model: ";R$;" ";Td$;LIN(1)
2170 IMAGE   2X,3D,5X,3D,10X,4D.D,14X,4D.D
2180 PRINT "STATION NUMBER, OFFSET FROM SP A, AND ELEVATIONS"
2190 PRINT LIN(1);"Sta Num & Offset     Surface Elev    Elev at Top of Layer 2"
2200 N=Snspa-1
2210 FOR J=1 TO Ns                    ! FOR number of stations
2220   Os=(J-1)*Xd                    ! Offset from SP A
2230   N=N+1
2240   PRINT USING 2170;N,Os,Eg(J),E(J)
2250 NEXT J
2260 G$="Y"
2270 INPUT "Do you want to accept the above entries? (Y/N--default is Y)",G$
2280 IF G$="Y" THEN 2300
2290 GOTO 1730                        ! Branch; re-enter values
2300 FOR J=1 TO Np                    ! FOR number of zones
2310   Ac(J)=ASN(Vz1(J)/Vz2(J))       ! Critical angle
2320   Co(J)=COS(Ac(J))               ! Cosine of critical angle
2330   D(J)=ATN((E(J+1)-E(J))/Xd)     ! Interface dip
2340   Xg(J)=SQR((Eg(J+1)-Eg(J))^2+Xd^2)   ! Slope distance on surface
2350   Ae(J)=ATN((Eg(J+1)-Eg(J))/Xd)  ! Topography dip
2360   Aed(J)=D(J)-Ae(J)              ! Combined surface and interface dip
2370   Ced(J)=COS(Aed(J))             ! Cosine of combined dips
2380 NEXT J
2390 FOR J=1 TO Np                    ! FOR zones along forward spread
2400   N=Z(J+1)*COS(D(J))             ! Normal distance to layer 2
2410   Sa(J)=N/COS(Ac(J))             ! Slant distance to layer 2
2420   B=-Sa(J)*SIN(Ac(J))            ! Distance along layer 2
2430   Xn=N*SIN(D(J))                 ! X dist of normal at layer 2
2440   En=Eg(J+1)-N*COS(D(J))         ! Elev of normal at layer 2
2450   Xsa(J)=B*COS(D(J))+Xn          ! Dist of S at layer 2 from partition
2460   IF Xsa(J)>=-Xd THEN 2490
2470   BEEP
2480   PRINT "Model condition not met--ray in zone";J;"from SP A crosses partition"
2490   Esa(J)=En+B*SIN(D(J))          ! Elev of S at layer 2
```

```
2500 NEXT J
2510 FOR J=1 TO Np                      ! FOR zones along reverse spread
2520   N=Z(J)*COS(D(J))                 ! Normal distance to layer 2
2530   Sb(J)=N/COS(Ac(J))               ! Slant distance to layer 2
2540   B=Sb(J)*SIN(Ac(J))               ! Distance along layer 2
2550   Xn=N*SIN(D(J))                   ! X dist of normal at layer 2
2560   En=Eg(J)-N*COS(D(J))             ! Elev of normal at layer 2
2570   Xsb(J)=B*COS(D(J))+Xn            ! Dist of S at layer 2 from partition
2580   IF Xsb(J)<=Xd THEN 2610
2590   BEEP
2600   PRINT "Model condition not met--ray in zone";J;"from SP B crosses partition"
2610   Esb(J)=En+B*SIN(D(J))            ! Elev of S at layer 2
2620 NEXT J
2630 RETURN
2640 !
2650 Plot_model:                        ! Plot model at true scale
2660 PRINT LIN(2);"TRUE SCALE PLOT OF MODEL WITH REFRACTED RAYS";LIN(1)
2670 PLOTTER IS 13,"GRAPHICS"
2680 GRAPHICS
2690 RESTORE 2700
2700 DATA 0,123,0,100
2710 READ B1,B2,B4,B5
2720 B3=B2-B1
2730 B6=B5-B4
2740 FRAME
2750 GOSUB Label_mod                    ! Print labels on plot of model
2760 LOCATE B1+5,B2-5,B4+5,B5-10        ! Plot border around results
2770 SCALE 0,Xc,Emin-1,Emax+1
2780 FRAME
2790 SHOW 0,Xc,Emin,Emax                ! Set true scale for plot
2800 MOVE 0,Eg(1)
2810 R=Xd/25                            ! R=radius of circle
2820 POLYGON 2*R                        ! Circle at SP A
2830 POLYGON R                          ! Station circle at SP A
2840 X=0
2850 FOR J=2 TO Ns                      ! DRAW topography
2860   X=X+Xd
2870   DRAW X,Eg(J)
2880   POLYGON R
2890   MOVE X,Eg(J)
2900 NEXT J
2910 POLYGON 2*R                        ! Circle at SP B
2920 X=0
2930 MOVE 0,E(1)
2940 POLYGON R                          ! Circle at point on interface
2950 MOVE 0,E(1)
2960 FOR J=2 TO Ns                      ! DRAW top of layer 2
2970   X=X+Xd
2980   DRAW X,E(J)
2990   POLYGON R
```

```
3000   MOVE X,E(J)
3010  NEXT J
3020  LORG 4
3030  IF Nz1>1 THEN 3070              ! Branch; velocity variation in layer 1
3040  MOVE Xc/2,Emax+Xd/2
3050  LABEL "CONSTANT V1="&VAL$(V1all)
3060  GOTO 3190
3070  Xz1(Nz1+1)=Xc
3080  Sz1(Nz1+1)=Ns
3090  MOVE Xc/2,Emax+Xd
3100  LABEL "UPPER LAYER VELOCITIES"
3110  FOR J=1 TO Nz1                  ! DRAW & LABEL velocity zones, layer 1
3120    MOVE Xz1(J)-R,Eg(Sz1(J))
3130    DRAW Xz1(J)-R,E(Sz1(J))
3140    MOVE Xz1(J)+R,E(Sz1(J))
3150    DRAW Xz1(J)+R,Eg(Sz1(J))
3160    MOVE (Xz1(J+1)+Xz1(J))/2,Emax+4*R
3170    LABEL VAL$(V1(J))
3180  NEXT J
3190  MOVE R,Eg(Ns)                   ! DRAW double lines at edges of model
3200  DRAW R,Ebase
3210  MOVE Xc-R,Eg(Ns)
3220  DRAW Xc-R,Ebase
3230  IF Nz2>1 THEN 3270              ! No velocity variation in layer 2
3240  MOVE Xc/2,Ebase
3250  LABEL "CONSTANT V2="&VAL$(V2all)
3260  GOTO 3380
3270  LORG 6
3280  MOVE Xc/2,Ebase-Xd/2
3290  LABEL "LOWER LAYER VELOCITIES"
3300  FOR J=1 TO Nz2                  ! DRAW & LABEL velocity zones, layer 2
3310    MOVE Xz2(J)-R,E(Sz2(J))
3320    DRAW Xz2(J)-R,Ebase
3330    MOVE Xz2(J)+R,Ebase
3340    DRAW Xz2(J)+R,E(Sz2(J))
3350    MOVE (Xz2(J+1)+Xz2(J))/2,Emin-4*R
3360    LABEL VAL$(V2(J))
3370  NEXT J
3380  FOR J=1 TO Np                   ! DRAW refracted rays from SP A
3390    MOVE J*Xd,Eg(J+1)
3400    DRAW J*Xd+Xsa(J),Esa(J)
3410  NEXT J
3420  FOR J=1 TO Np                   ! DRAW refracted rays from SP B
3430    MOVE (J-1)*Xd,Eg(J)
3440    DRAW (J-1)*Xd+Xsb(J),Esb(J)
3450  NEXT J
3460  DUMP GRAPHICS
3470  EXIT GRAPHICS
3480  PRINTER IS 16
3490  G$="Y"
```

```
3500  INPUT "Have conditions on the model been met? (Y/N--default is Y)",G$
3510  IF G$="Y" THEN 3650
3520  G$="Y"
3530  INPUT "Do you want to modify the model? (Y/N--default is Y)",G$
3540  IF G$="Y" THEN 170               ! Enter new set of model parameters
3550  INPUT "Number of stations from SP A at which conditions are not met",N
3560  FOR J=1 TO N
3570    INPUT "Station number:",K
3580    Tar(K)=999
3590  NEXT J
3600  INPUT "Number of stations from SP B at which conditions are not met",N
3610  FOR J=1 TO N
3620    INPUT "Station number:",K
3630    Tbr(K)=999
3640  NEXT J
3650  RETURN
3660  !
3670 Label_mod:                         ! Print labels on plot of model
3680  LORG 5
3690  MOVE B3/2,B5-2.5
3700  LABEL "MODEL FOR 2-LAYER CASE"
3710  MOVE B3/2,B5-7
3720  LABEL R$
3730  LORG 1
3740  MOVE 1,B5-9
3750  LABEL "SP A"
3760  LORG 7
3770  MOVE B2-1,B5-9
3780  LABEL "SP B"
3790  MOVE 2.5,B6/2
3800  LDIR 90
3810  LORG 5
3820  LABEL "ELEVATION AT TRUE SCALE"
3830  LDIR 0
3840  LORG 5
3850  MOVE B3/2,B1+2.5
3860  IF Qu=1 THEN 3890                 ! Metric units
3870  LABEL "STATION SPACING="&VAL$(Xd)&"m  MAX O/S="&VAL$(Xc)&"ft"
3880  GOTO 3900
3890  LABEL "STATION SPACING="&VAL$(Xd)&"m  MAX O/S="&VAL$(Xc)&"m"
3900  RETURN
3910  !
3920 Comp_direct:                       ! Compute direct-ray times
3930  Tad(1)=0
3940  FOR J=2 TO Ns                     ! Direct-ray time from SP A
3950    Tad(J)=Tad(J-1)+SQR((Eg(J)-Eg(J-1))^2+Xd^2)/Vz1(J-1)
3960  NEXT J
3970  FOR K=1 TO Nd                     ! FOR number of detectors, spd A
3980    Tda(K)=Tad(K+Xa(1)/Xd)
3990  NEXT K
```

```
4000  Tbd(Ns)=0
4010  FOR J=Ns-1 TO 1 STEP -1
4020    Tbd(J)=Tbd(J+1)+SQR((Eg(J+1)-Eg(J))^2+Xd^2)/Vz1(J)
4030  NEXT J
4040  FOR K=1 TO Nd                    ! FOR number of detectors, spd B
4050    Tdb(K)=Tbd(K)
4060  NEXT K
4070  RETURN
4080  !
4090 Comp_refr:                        ! Compute refracted-ray times
4100  ! Computation of refraction times from SP A
4110  FOR J=1 TO Np                    ! FOR partitoned zones
4120    Tsw(J)=SQR((E(J+1)-E(J))^2+Xd^2)/Vz2(J)
4130  NEXT J
4140  T1=Sb(1)/Vz1(1)+SQR((Xd-Xsb(1))^2+(Esb(1)-E(2))^2)/Vz2(1)
4150  Tar(1)=999                       ! 999 = flag to not plot refraction
4160  IF Xsb(1)-Xsa(1)<Xd THEN 4210    ! Test on critical distance
4170  BEEP
4180  PRINT "STATION 2 INSIDE CRITICAL DISTANCE"
4190  Tar(2)=999                       ! 999 is flag to not plot refraction
4200  GOTO 4240
4210  ! Compute refraction time to station 2
4220  IF Tar(2)=999 THEN 4240          ! Skip: model conditions not met
4230  Tar(2)=Xg(1)*Ced(1)/Vz2(1)+(Z(1)+Z(2))*COS(D(1))*COS(Ac(1))/Vz1(1)
4240  ! Compute refraction time to station 3
4250  IF Tar(3)=999 THEN 4280          ! Skip: model conditions not met
4260  Tar(3)=SQR((Xd+Xsa(2))^2+(E(2)-Esa(2))^2)/Vz2(2)
4270  Tar(3)=T1+Tar(3)+Sa(2)/Vz1(2)
4280  ! Compute refraction times for station 4 to last station
4290  T=T1
4300  FOR J=4 TO Ns
4310    IF Tar(J)=999 THEN 4350        ! Skip: model conditions not met
4320    T=T+Tsw(J-2)
4330    Tar(J)=SQR((Xd+Xsa(J-1))^2+(E(J-1)-Esa(J-1))^2)/Vz2(J-1)
4340    Tar(J)=T+Tar(J)+Sa(J-1)/Vz1(J-1)
4350  NEXT J
4360  ! Computation of refraction times from SP B
4370  T1=Sa(Np)/Vz1(Np)+SQR((Xd+Xsa(Np))^2+(E(Np)-Esa(Np))^2)/Vz2(Np)
4380  Tbr(Ns)=999                      ! Tbr at SP B
4390  IF Xsb(Np)-Xsa(Np)<=Xd THEN 4440
4400  BEEP
4410  PRINT "STATION";Ns-1;"INSIDE CRITICAL DISTANCE"
4420  Tbr(Np)=999
4430  GOTO 4470
4440  ! Compute refraction time to station Ns-1
4450  IF Tbr(Np)=999 THEN 4470         ! Skip: model conditions not met
4460  Tbr(Np)=Xg(Np)*Ced(Np)/Vz2(Np)+(Z(Np)+Z(Np+1))*COS(D(Np))*Co(Np)/Vz1(Np)
4470  ! Compute refraction time to station Ns-2
4480  IF Tbr(Np-1)=999 THEN 4510       ! Skip: model conditions not met
4490  Tbr(Np-1)=T1+Sb(Np-1)/Vz1(Np-1)
```

```
4500  Tbr(Np-1)=Tbr(Np-1)+SQR((Xd-Xsb(Np-1))^2+(Esb(Np-1)-E(Np))^2)/Vz2(Np-1)
4510  T=T1
4520  FOR J=Ns-3 TO 1 STEP -1
4530    T=T+Tsw(J+1)
4540    IF Tbr(J)=999 THEN 4570        ! Skip: model conditions not met
4550    Tbr(J)=SQR((Xd-Xsb(J))^2+(Esb(J)-E(J+1))^2)/Vz2(J)
4560    Tbr(J)=T+Tbr(J)+Sb(J)/Vz1(J)
4570  NEXT J
4580  FOR K=1 TO Nd                    ! FOR number of detectors, spd A
4590    Tra(K)=Tar(K+Xa(1)/Xd)
4600  NEXT K
4610  FOR K=1 TO Nd                    ! FOR number of detectors, spd B
4620    Trb(K)=Tbr(K)
4630  NEXT K
4640  FOR K=1 TO Nd                    ! Determine minimum times
4650    Tma(K)=MIN(Tra(K),Tda(K))
4660    Tmb(K)=MIN(Trb(K),Tdb(K))
4670  NEXT K
4680  RETURN
4690  !
4700 Tabulate:                         ! Tabulate  results
4710  PRINTER IS 0                     ! Hard copy
4720  GOSUB Time_date                  ! Time and date
4730  PRINT LIN(3);"Model: ";R$;" ";Td$;LIN(1)
4740  PRINT "STATION NUMBER, OFFSET, AND ARRIVALS TIMES"
4750  PRINT "NOTE: Refraction time = 999 indicates no refracted return"
4760  IMAGE 7X,"From SP A @ Station ",3A,16X,"From SP B @ Station ",3A
4770  PRINT USING 4760;VAL$(Snspa),VAL$(Snspb)
4780  PRINT "Sta Num & Offset    Tr        Td       Sta Num & Offset    Tr        Td"
4790  IMAGE 3X,2D,4X,3D,6X,3D.D,5X,3D.D,9X,2D,4X,3D,6X,3D.D,5X,3D.D
4800  N=Snspa-1
4810  FOR J=1 TO Ns
4820    N=N+1
4830    Osa=(J-1)*Xd
4840    Osb=Xc-(J-1)*Xd
4850    PRINT USING 4790;N,Osa,Tar(J),Tad(J),N,Osb,Tbr(J),Tbd(J)
4860  NEXT J
4870  RETURN
4880  !
4890 Plot:                             ! One-page, quick plot of results
4900  PRINTER IS 16
4910  INPUT "Maximum arrival time wanted on plot",Max_at
4920  Gy=INT(Max_at/5)                                          ! DEFAULT
4930  PRINT "Default grid spacing =";Gy
4940  INPUT "Grid spacing for arrival times wanted on plot:",Gy
4950  Gx=Xd                            ! Grid spacing = station spacing
4960  PRINTER IS 0
4970  PRINT LIN(2)
4980  PLOTTER IS 13,"GRAPHICS"
4990  GRAPHICS
```

```
5000 RESTORE 5010
5010 DATA 0,123,0,100
5020 READ B1,B2,B4,B5
5030 B3=B2-B1
5040 B6=B5-B4
5050 FRAME
5060 GOSUB Labels                     ! Print labels on graph
5070 LOCATE B1+5,B2-5,B4+5,B5-10      ! Plot border around results
5080 SCALE 0,Xc,0,Max_at
5090 FRAME
5100 GRID Gx,Gy                       ! Plot grid lines
5110 LINE TYPE 3                      ! Plot arrivals at all stations
5120 MOVE 0,Tad(1)                    ! using dashed lines
5130 FOR J=2 TO Ns                    ! Plot all direct-ray arrivals from SP A
5140   DRAW (J-1)*Xd,Tad(J)
5150 NEXT J
5160 MOVE 0,Tbd(1)
5170 FOR J=2 TO Ns                    ! Plot all direct-ray arrivals from SP B
5180   DRAW (J-1)*Xd,Tbd(J)
5190 NEXT J
5200 FOR J=1 TO Np                  ! Plot all refraction arrivals from SP A
5210   IF Tar(J)=999 THEN 5250
5220   MOVE (J-1)*Xd,Tar(J)
5230   IF Tar(J+1)=999 THEN 5250
5240   DRAW J*Xd,Tar(J+1)
5250 NEXT J
5260 FOR J=1 TO Np                    ! Plot all refraction arrivals from SP B
5270   IF Tbr(J)=999 THEN 5310
5280   MOVE (J-1)*Xd,Tbr(J)
5290   IF Tbr(J+1)=999 THEN 5310
5300   DRAW J*Xd,Tbr(J+1)
5310 NEXT J
5320 LINE TYPE 1                      ! Solid line plot
5330 MOVE Xa(1),Tma(1)                ! Plot first arrivals from SP A
5340 FOR K=2 TO Nd                    ! FOR detectors along spread A
5350   DRAW Xa(K),Tma(K)
5360 NEXT K
5370 MOVE Xb(1),Tmb(1)                ! Plot first arrivals from SP B
5380 FOR K=1 TO Nd                    ! FOR detectors along spread N
5390   DRAW Xb(K),Tmb(K)
5400 NEXT K
5410 DUMP GRAPHICS
5420 EXIT GRAPHICS
5430 PRINTER IS 16
5440 G$="N"
5450 INPUT "Do you want to replot? (Y/N--default is N)",G$
5460 IF G$="N" THEN 5480
5470 GOTO 4900
5480 RETURN
5490 !
```

```
5500 Labels:                          ! Print labels on plot
5510  LORG 5
5520  MOVE B3/2,B5-2.5
5530  LABEL "TRAVELTIME PLOT: "&R$
5540  MOVE B3/2,B5-5.5
5550  LABEL "FIRST ARRIVALS CONNECTED WITH SOLID LINES"
5560  LORG 1
5570  MOVE 1,B5-9
5580  LABEL "SP A"
5590  LORG 7
5600  MOVE B2-1,B5-9
5610  LABEL "SP B"
5620  MOVE 2.5,B6/2
5630  LDIR 90
5640  LORG 5
5650  LABEL "ARRIVAL TIME  1 DIV="&VAL$(Gy)&"ms  MAX T="&VAL$(Max_at)&"ms"
5660  LDIR 0
5670  LORG 5
5680  MOVE B3/2,B1+2.5
5690  IF Qu=1 THEN 5720               ! Metric units
5700  LABEL "OFFSET  1 DIV="&VAL$(Gx)&"m  MAX O/S="&VAL$(Xc)&"ft"
5710  GOTO 5730
5720  LABEL "OFFSET  1 DIV="&VAL$(Gx)&"m  MAX O/S="&VAL$(Xc)&"m"
5730  RETURN
5740  !
5750 Delay_time_plot:                 ! Plot delay times and elevations
5760  IF Q1=2 THEN 5800               ! Branch; delay time after elev corr
5770  G$="N"
5780  INPUT "Do you want to plot delay times? (Y/N--default is N)",G$
5790  IF G$="N" THEN 6580
5800  INPUT "Assumed layer 2 velocity:",V2avg
5810  PRINT "Assumed layer 2 velocity =";V2avg
5820  IF Q1=1 THEN 5940               ! Delay time with raw data
5830  FOR J=1 TO Ns                   ! Compt delay time after elev corr
5840    Tar_dt(J)=Teca(J)-(J-1)*Xd/V2avg
5850    IF Tar(J)=999 THEN Tar_dt(J)=999
5860    Tbr_dt(J)=Tecb(J)-(Xc-(J-1)*Xd)/V2avg
5870    IF Tbr(J)=999 THEN Tbr_dt(J)=999
5880  NEXT J
5890  PRINTER IS 0
5900  GOSUB Time_date                 ! Time and date
5910  PRINT LIN(3);"Model: ";R$;" ";Td$;LIN(1)
5920  PRINT "STATION AND APPROX DELAY TIMES AFTER ELEVATION CORRECTION"
5930  GOTO 6040
5940  FOR J=1 TO Ns
5950    Tar_dt(J)=Tar(J)-(J-1)*Xd/V2avg
5960    IF Tar(J)=999 THEN Tar_dt(J)=999
5970    Tbr_dt(J)=Tbr(J)-(Xc-(J-1)*Xd)/V2avg
5980    IF Tbr(J)=999 THEN Tbr_dt(J)=999
5990  NEXT J
```

```
6000 PRINTER IS 0
6010 GOSUB Time_date                   ! Time and date
6020 PRINT LIN(3);"Model: ";R$;" ";Td$;LIN(1)
6030 PRINT "STATION AND APPROXIMATE DELAY TIMES"
6040 PRINT "NOTE: Refraction time = 999 indicates no refracted return"
6050 PRINT "      From SP A                   From SP B"
6060 PRINT "Station      Tar-X/V2       Station      Tbr-X/V2"
6070 IMAGE 2X,2D,9X,3D.D,12X,2D,9X,3D.D
6080 FOR J=1 TO Ns
6090   PRINT USING 6070;J,Tar_dt(J),J,Tbr_dt(J)
6100 NEXT J
6110 PRINTER IS 16                     ! Screen display
6120 INPUT "Minimum delay time on plot",Min_rt
6130 INPUT "Maximum delay time on plot",Max_rt
6140 Gy=INT((Max_rt-Min_rt)/5)
6150 PRINT "Default grid spacing for delay times =";Gy
6160 INPUT "Grid spacing for delay times:",Gy
6170 Gx=Xd                             ! Grid spacing = station spacing
6180 PRINTER IS 0
6190 PRINT LIN(2)
6200 PLOTTER IS 13,"GRAPHICS"
6210 GRAPHICS
6220 RESTORE 6230
6230 DATA 0,123,0,100
6240 READ B1,B2,B4,B5
6250 B3=B2-B1
6260 B6=B5-B4
6270 FRAME
6280 GOSUB Dt_labels                   ! Print labels on graph
6290 LOCATE B1+5,B2-5,B4+5,B5-10       ! Plot border around results
6300 SCALE 0,Xc,Min_rt,Max_rt
6310 FRAME
6320 GRID Gx,Gy                        ! Plot grid lines
6330 LINE TYPE 3                       ! Dotted lines for times from SP A
6340 FOR J=1 TO Np                     ! Plot delay times from SP A
6350   IF Tar(J)=999 THEN 6390
6360   MOVE (J-1)*Xd,Tar_dt(J)
6370   IF Tar(J+1)=999 THEN 6390
6380   DRAW J*Xd,Tar_dt(J+1)
6390 NEXT J
6400 LINE TYPE 1                       ! Solid line for times from SP B
6410 FOR J=1 TO Np                     ! Plot delay times from SP B
6420   IF Tbr(J)=999 THEN 6460
6430   MOVE (J-1)*Xd,Tbr_dt(J)
6440   IF Tbr(J+1)=999 THEN 6460
6450   DRAW J*Xd,Tbr_dt(J+1)
6460 NEXT J
6470 DUMP GRAPHICS
6480 EXIT GRAPHICS
6490 PRINTER IS 16
```

```
6500  G$="N"
6510  INPUT "Do you want to replot? (Y/N--default is N)",G$
6520  IF G$="N" THEN 6580
6530  G$="Y"
6540  INPUT "Do you want to use different velocities (Y/N--default is Y",G$
6550  IF G$="N" THEN 6570               ! Replot with scale change only
6560  GOTO 5800                         ! Re-select layer 2 velocity
6570  GOTO 6110
6580  RETURN
6590  !
6600 Dt_labels:                         ! Print labels on delay time plot
6610  LORG 5
6620  MOVE B3/2,B5-2.5
6630  LABEL "DELAY TIMES: "&R$
6640  MOVE B3/2,B5-5.5
6650  LABEL "DOTTED FROM SP A; SOLID FROM SP B  ASSUMED V2 = "&VAL$(V2avg)
6660  LORG 1
6670  MOVE 1,B5-9
6680  LABEL "SP A"
6690  LORG 7
6700  MOVE B2-1,B5-9
6710  LABEL "SP B"
6720  MOVE 2.5,B6/2
6730  LDIR 90
6740  LORG 5
6750  LABEL "DELAY TIME  1 DIV="&VAL$(Gy)&"ms  MAX T="&VAL$(Max_rt)&"ms"
6760  LDIR 0
6770  LORG 5
6780  MOVE B3/2,B1+2.5
6790  IF Qu=1 THEN 6820                 ! Metric units
6800  LABEL "OFFSET  1 DIV="&VAL$(Gx)&"m  MAX O/S="&VAL$(Xc)&"ft"
6810  GOTO 6830
6820  LABEL "OFFSET  1 DIV="&VAL$(Gx)&"m  MAX O/S="&VAL$(Xc)&"m"
6830  RETURN
6840  !
6850 Elev_corr_plot:                    ! Comp and plot elev-corrected times
6860  G$="N"
6870  INPUT "Do you want to plot elevation-corrected times? (Y/N--default is N)",G$
6880  IF G$="N" THEN 7680
6890  INPUT "Assumed layer 1 velocity:",V1avg
6900  PRINT "Assumed layer 1 velocity =";V1avg
6910  INPUT "Assumed layer 2 velocity:",V2avg
6920  PRINT "Assumed layer 2 velocity =";V2avg
6930  Acrit=ASN(V1avg/V2avg)            ! Critical angle with assumed velocities
6940  Ccrit=COS(Acrit)                  ! Cosine of critical angle
6950  Ed=Egmin                          ! Datum taken at minimum elevation
6960  Eca=-(Eg(1)-Ed)*Ccrit/V1avg       ! Elevation correction at SP A
6970  Ecb=-(Eg(Ns)-Ed)*Ccrit/V1avg      ! Elevation correction at SP B
6980  Teca(1)=999                       ! Elev corrected time at SP A
6990  FOR J=2 TO Ns
```

```
7000   Teca(J)=Tar(J)-(Eg(J)-Ed)*Ccrit/V1avg+Eca
7010   IF Tar(J)=999 THEN Teca(J)=999
7020 NEXT J
7030 Tecb(Ns)=999                      ! Elev corrected time at SP B
7040 FOR J=1 TO Ns-1
7050   Tecb(J)=Tbr(J)-(Eg(J)-Ed)*Ccrit/V1avg+Ecb
7060   IF Tbr(J)=999 THEN Tecb(J)=999
7070 NEXT J
7080 PRINTER IS 0                      ! Hard copy
7090 GOSUB Time_date                   ! Time and date
7100 PRINT LIN(3);"Model: ";R$;" ";Td$;LIN(1)
7110 PRINT "STATION AND ELEVATION-CORRECTED TIMES  Edatum=";Ed
7120 PRINT "NOTE: Refraction time = 999 indicates no refracted return"
7130 PRINT "      From SP A                 From SP B"
7140 IMAGE 2X,2D,9X,3D.2D,10X,2D,9X,3D.2D
7150 PRINT "Station     Tar-Ecorr      Station     Tbr-Ecorr"
7160 FOR J=1 TO Ns
7170   PRINT USING 7140;J,Teca(J),J,Tecb(J)
7180 NEXT J
7190 PRINTER IS 16
7200 INPUT "Minimum corrected time on plot",Min_rt
7210 INPUT "Maximum corrected time on plot",Max_rt
7220 Gy=INT((Max_rt-Min_rt)/5)
7230 PRINT "Default grid spacing for elev corrected times =";Gy
7240 INPUT "Grid spacing for corrected times:",Gy
7250 Gx=Xd                             ! Grid spacing = station spacing
7260 PRINTER IS 0
7270 PRINT LIN(2)
7280 PLOTTER IS 13,"GRAPHICS"
7290 GRAPHICS
7300 RESTORE 7310
7310 DATA 0,123,0,100
7320 READ B1,B2,B4,B5
7330 B3=B2-B1
7340 B6=B5-B4
7350 FRAME
7360 GOSUB E_labels                    ! Print labels on graph
7370 LOCATE B1+5,B2-5,B4+5,B5-10       ! Plot border around results
7380 SCALE 0,Xc,Min_rt,Max_rt
7390 FRAME
7400 GRID Gx,Gy                        ! Plot grid lines
7410 FOR J=1 TO Np                     ! Plot corrected times from SP A
7420   IF Tar(J)=999 THEN 7460
7430   MOVE (J-1)*Xd,Teca(J)
7440   IF Tar(J+1)=999 THEN 7460
7450   DRAW J*Xd,Teca(J+1)
7460 NEXT J
7470 FOR J=1 TO Np                     ! Plot corrected times from SP B
7480   IF Tbr(J)=999 THEN 7520
7490   MOVE (J-1)*Xd,Tecb(J)
```

```
7500    IF Tbr(J+1)=999 THEN 7520
7510    DRAW J*Xd,Tecb(J+1)
7520  NEXT J
7530  DUMP GRAPHICS
7540  EXIT GRAPHICS
7550  PRINTER IS 16
7560  G$="N"
7570  INPUT "Do you want to replot with different scales? (Y/N--default is N)",G$
7580  IF G$="N" THEN 7600
7590  GOTO 7190                        ! Re-select scale values for plot
7600  G$="N"
7610  INPUT "Do you want to replot with different V1? (Y/N--default is N)",G$
7620  IF G$="N" THEN 7640              ! Re-plot with scale change only
7630  GOTO 6890
7640  G$="N"
7650  INPUT "Do you want to plot elev-corrected delay times? (Y/N--default is N)",G$
7660  IF G$="N" THEN 7680
7670  GOSUB Datum_dt_plot
7680  RETURN
7690  !
7700 E_labels:                         ! Print labels on plot
7710  LORG 5
7720  MOVE B3/2,B5-2.5
7730  LABEL "ELEV-CORR TIMES: "&R$
7740  MOVE B3/2,B5-5.5
7750  LABEL "DATUM AT MIN SURFACE ELEV  V1="&VAL$(V1avg)&", V2="&VAL$(V2avg)
7760  LORG 1
7770  MOVE 1,B5-9
7780  LABEL "SP A"
7790  LORG 7
7800  MOVE B2-1,B5-9
7810  LABEL "SP B"
7820  MOVE 2.5,B6/2
7830  LDIR 90
7840  LORG 5
7850  LABEL "CORRECTED TIME  1 DIV="&VAL$(Gy)&"ms  MAX T="&VAL$(Max_rt)&"ms"
7860  LDIR 0
7870  LORG 5
7880  MOVE B3/2,B1+2.5
7890  IF Qu=1 THEN 7920                ! Metric units
7900  LABEL "OFFSET  1 DIV="&VAL$(Gx)&"m  MAX O/S="&VAL$(Xc)&"ft"
7910  GOTO 7930
7920  LABEL "OFFSET  1 DIV="&VAL$(Gx)&"m  MAX O/S="&VAL$(Xc)&"m"
7930  RETURN
7940  !
7950 Datum_dt_plot:                    ! Plot delay times after elev correction
7960  Q1=2                             ! Flag for delay time from datum
7970  GOSUB Delay_time_plot
7980  RETURN
7990  !
```