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REPORT OF INVESTIGATIONS No. 16

APPLICATION OF GEOPHYSICS TO HIGHWAY DESIGN IN THE PIEDMONT OF DELAWARE

BY
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ABSTRACT

The feasibility of using geophysical techniques in determining the amount of overburden and the nature of the subsurface along a proposed highway was tested in the Piedmont area of Delaware. The area is underlain by crystalline rocks capped by varying amounts of unconsolidated material or regolith. Seismic refraction and surface resistivity methods were used at selected stations and the interpretations were later compared to results from test holes and to the material exposed in road cuts.

In general, interpretation of the seismic refraction results compared quite well with test borings and with field observations made after construction was started. Resistivity data were inconclusive in themselves but provided some additional control points when correlated with seismic refraction data. With proper control, it is concluded that such techniques could be useful in the Piedmont of Delaware for highway planning.

INTRODUCTION

Purpose

Delaware is at present one of the fastest growing areas in the nation and during 1960-70 ranked eighth among the states in percentage increase of population growth (22.8% increase). For states on the Atlantic seaboard only Maryland and Florida exceeded Delaware in this growth rate (State Planning Office, personal communication). Concurrent with this development is the need for improved highways and transportation systems particularly to link suburbs with inner city areas and to provide access to and from growth areas. Part of highway planning routinely includes investigation of the underlying geology, usually by means of borings. Such borings help in determining the depth of overburden, possible borrow areas, ground-water levels and the rippability of rock encountered. The rippability is the degree to which construction equipment can disintegrate or remove rock in place without the aid of explosives. One of the disadvantages of borings, however, is the expense and time necessary to explore large areas. Although borings will probably remain the primary control, other methods can be used to decrease the number of borings necessary to define the geology of a project site. Two geophysical methods in common use today are the refraction seismic technique and the electrical resistivity survey. These methods measure certain physical properties of the rocks which in turn are correlated to the local geology.

Recently the Delaware Division of Highways (Department of Highways and Transportation) sought to test the feasibility of using such geophysical techniques in their highway planning. An area in the Piedmont portion of the State west of Wilmington and northeast of Newark was chosen as a pilot area (see Figure 1). Drill hole results were available along the proposed roadway and preliminary construction was soon to begin. The Delaware Geological Survey was asked to cooperate in a geophysical survey along the line of the proposed roadway and to interpret the results in terms of rock type to be expected. Shortly thereafter the interpretations could be compared with the actual field conditions encountered during construction and with previous test borings. It was agreed that the results of the test borings would not be made available until after the geophysical results were interpreted. Thus the interpretations presented in this study are based on the geophysical data alone.

Acknowledgments

The Delaware Division of Highways assisted in nearly all portions of the investigation. Particular thanks are due W. E. Kickery, J. W. Simpson, and M. E. Morgan of the Highways Materials and Research Section, and B. J. Bilas of the Survey staff for their assistance in the field. Mr. A. D. Donofrio, Soils Engineer with the Division of Highways coordinated the study and the exchange of ideas between the two State agencies.

The refraction seismograph used in the study is the property of the Department of Geology, University of Delaware.

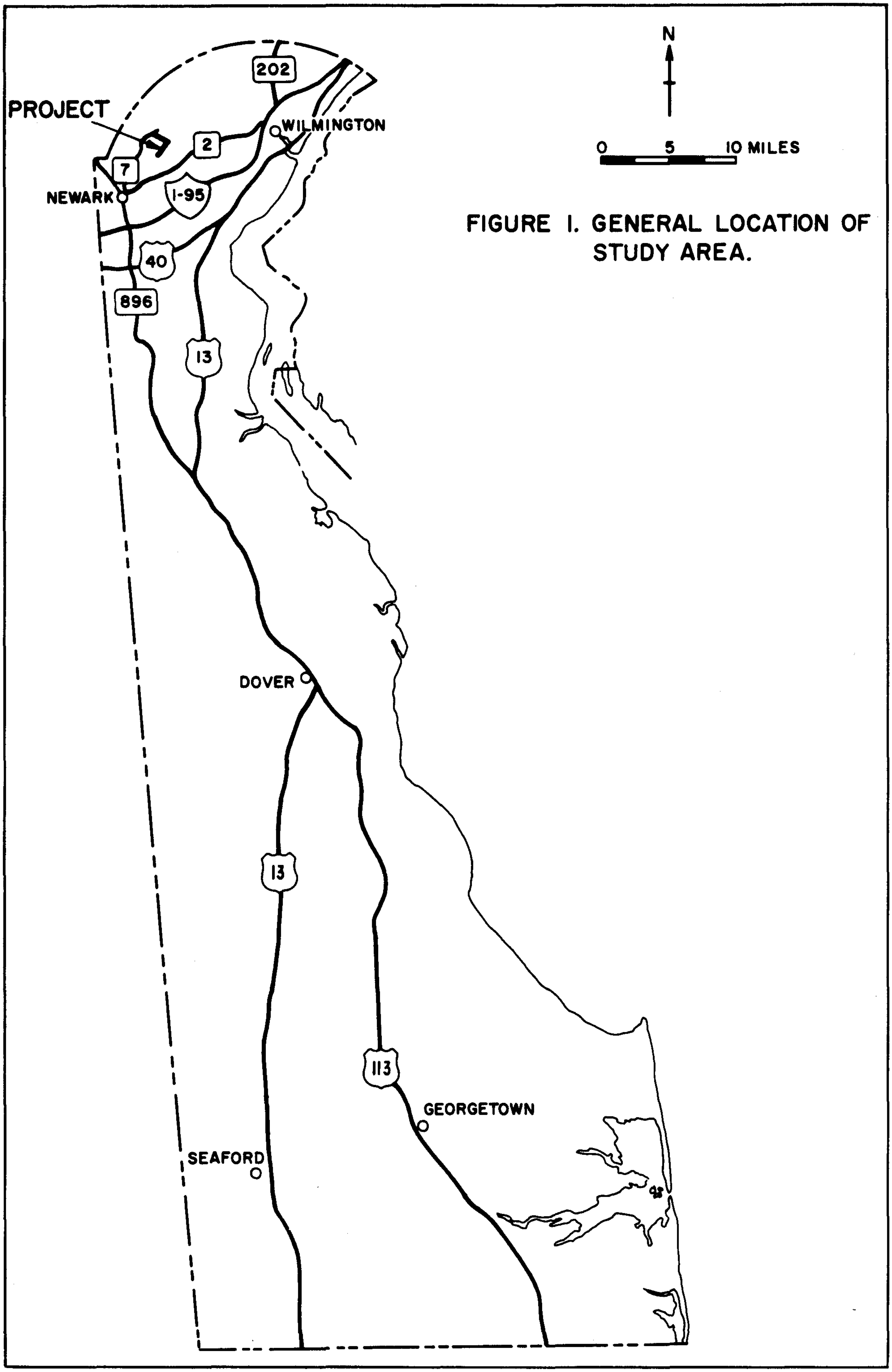

FIGURE I. GENERAL LOCATION OF STUDY AREA.

J. C. Miller, hydrologist with the Delaware Geological Survey, made field investigations of the outcrops and road-cuts (Appendix B). The interpretation of the data, however, is solely that of the author.

R. R. Jordan, State Geologist, first suggested publication of the study as an aid to others contemplating similar work and reviewed the manuscript.

SEISMIC REFRACTION TECHNIQUE

The detailed theory of the seismic refraction methods has been covered in several publications. An especially thorough explanation is given by Dobrin (1952) and Johnson (1954). Basically, energy is released into the subsurface by detonating a blasting cap, dynamite, or similar energy source. The energy source for some small seismic instruments may be a hammer or "thumper" which is struck on the ground or a metal plate to produce a sound wave. The energy transmitted away from the source or shot-point contains several components. One component, known as the direct wave, travels just beneath the ground, along the top of the first layer. Other components travel deeper into the subsurface and upon passing through a boundary between two different rock types are partly refracted and reflected back to the surface. The path of the refracted component is governed by Snell's Law (see Appendix A) which determines the amount of bending that will take place as the wave front passes between two media of different physical properties. The velocities of the waves are dependent on several factors which include depth of burial, water content, porosity, composition, and density of the material. Table 1 relates seismic velocities of various rock types to their rippability. Such data are useful in preliminary interpretations for a new area of investigation.

Table 1. Seismic velocities related to rippability of rock for a D9G - No. 9 Series B Ripper (Modified after Caterpillar Tractor Co., 1966).

	Rippable	Marginal	Non-Rippable
top soil	1-2	-	-
clay	1.5-6.5	-	-
igneous rock	3-7	7-8.5	8.5-12

Table 1. Continued

	Rippable	Marginal	Non-Rippable
shale	3-8.5	8.5-10	10.5-12
sandstone	3-8.5	8.5-10.5	10.5-12
limestone	3-8.5	8.5-10.5	10.5-12
schist	3-7.5	7.5-9.5	9.5-12
slate	3-7.5	7.5-9.5	9.5-12

velocities in feet per second x 1000

At some horizontal distance from the shot-point the direct wave and the refracted wave arrive simultaneously. This distance is known as the critical distance and is used in calculating the depth to the first seismic interface.

In actual practice, a number of geophones are spaced in some regular manner, generally a straight line for highway work, at known distances from the shot-point. The arrival time at each geophone of the sound waves produced by a single detonation is then recorded by the instrument. An alternative procedure is to employ only a single geophone and to move the shot-point for each recording. For both procedures the arrival time at each geophone is then plotted on linear graph paper against the distance of the detector from the shot-point. Velocities of the underlying materials are found from the slope of the straight-line plots thus produced and the depth to seismic discontinuities are calculated from the general equation:

$$Z = \frac{Xc}{2}\sqrt{\frac{V2-V1}{V2+V1}}$$

Where: Z = depth to interface

Xc = critical distance

V1 = velocity of top layer

V2 = velocity of bottom layer.

The critical distance is also obtained from the graphical plot by extrapolating the intersection of the two velocity curves (V1, V2) back to the distance axis.

The refraction technique is valid as long as the upper layer (in a two layer model) has the slower velocity. If the first layer has a faster velocity than underlying material, then this faster velocity will mask all other arrivals that have had to travel a slower path. In such a case nothing can be told about the velocity of the second slower layer. The refraction technique is also able to distinguish three layers having successively increasing velocity with depth. This is a common situation and the formula above is again used for depth calculations with slight modifications.

Derivation of the general equation will be found in Appendix A for those interested in its proof.

The instrument used in this study was a Geo Space Corp. GT-2A portable refraction unit equipped with six recording channels. In most cases the energy source was a Du Pont electric blasting cap (seismic 000) although in a few shots a charge of black powder was used in an attempt to gain more energy in areas of high background noise. Data from each shot is automatically recorded on Polaroid film by a series of light-beam galvanometers each driven by one of the six geophones. Vertical timing lines, 10 milliseconds apart, and the time of detonation are automatically traced on the film by the instrument. Plate 1 is a fairly typical recording made in this study.

Seismic profiles were run along the center line of proposed road cuts for the Linden Hill Road project (see Figure 2). The shot-point usually corresponded to a 50 or 100 foot surveying station and was moved approximately 50 feet at a time, always in the same direction until the entire length of the proposed cut was traversed. In most cases the direction of traverse was then reversed and the profiles run in the opposite direction. Spacing between each geophone varied from 10 feet to 20 feet depending on conditions of terrain, weather, and the depth to which information was desired.

Usually, the electric cap provided enough energy to give an adequate signal at the geophone most distant from the shot-point. However, under adverse conditions, as mentioned above, the signal from a cap is easily lost and a higher energy source is needed. At present, local regulations and lack of suitable storage areas prevent the use of higher energy explosives.

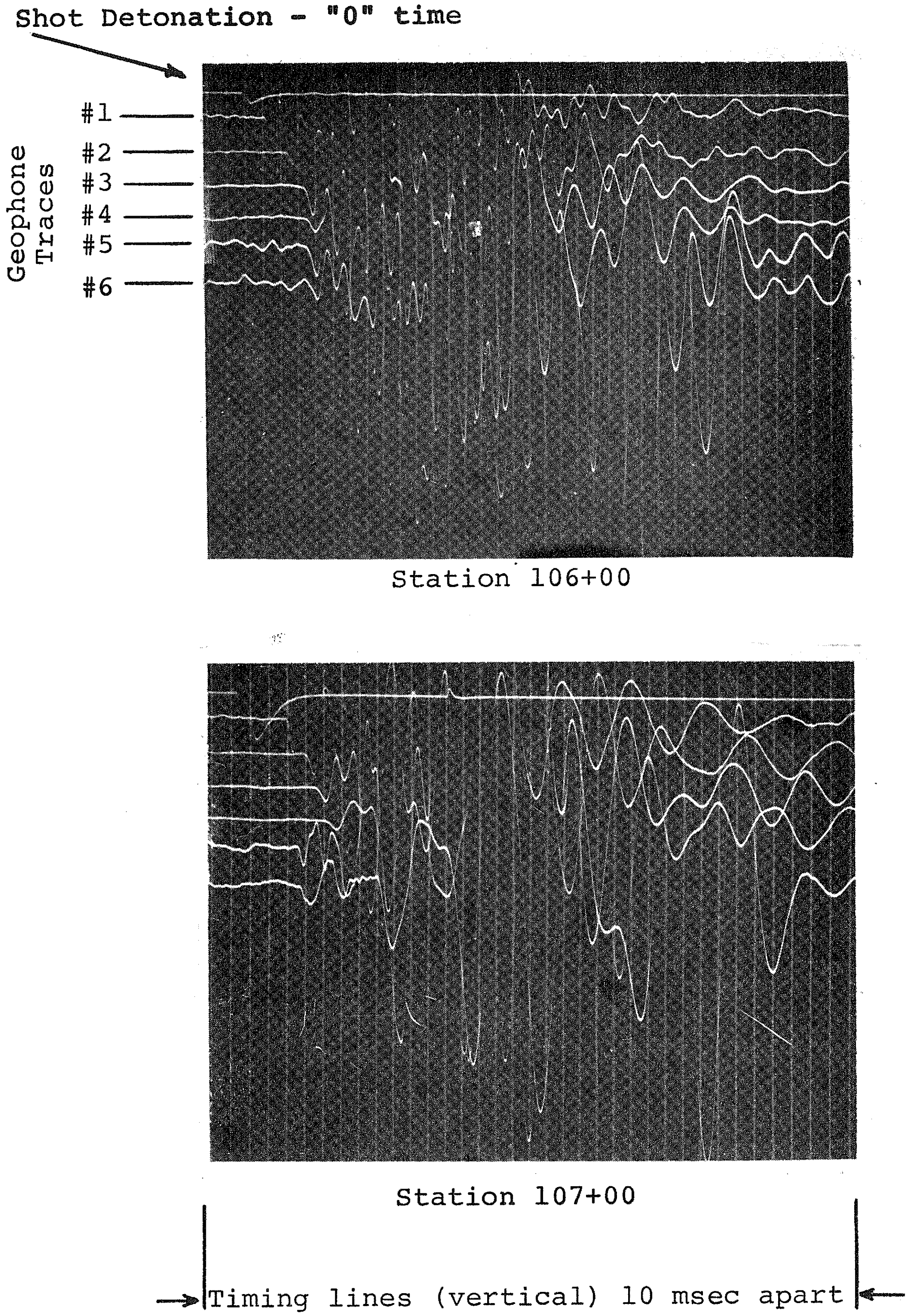

Plate 1. Example of actual seismic record obtained with electric blasting cap and fifteen-foot geophone spacing. (Note early arrivals recorded by geophones 5 and 6 at station 107.)

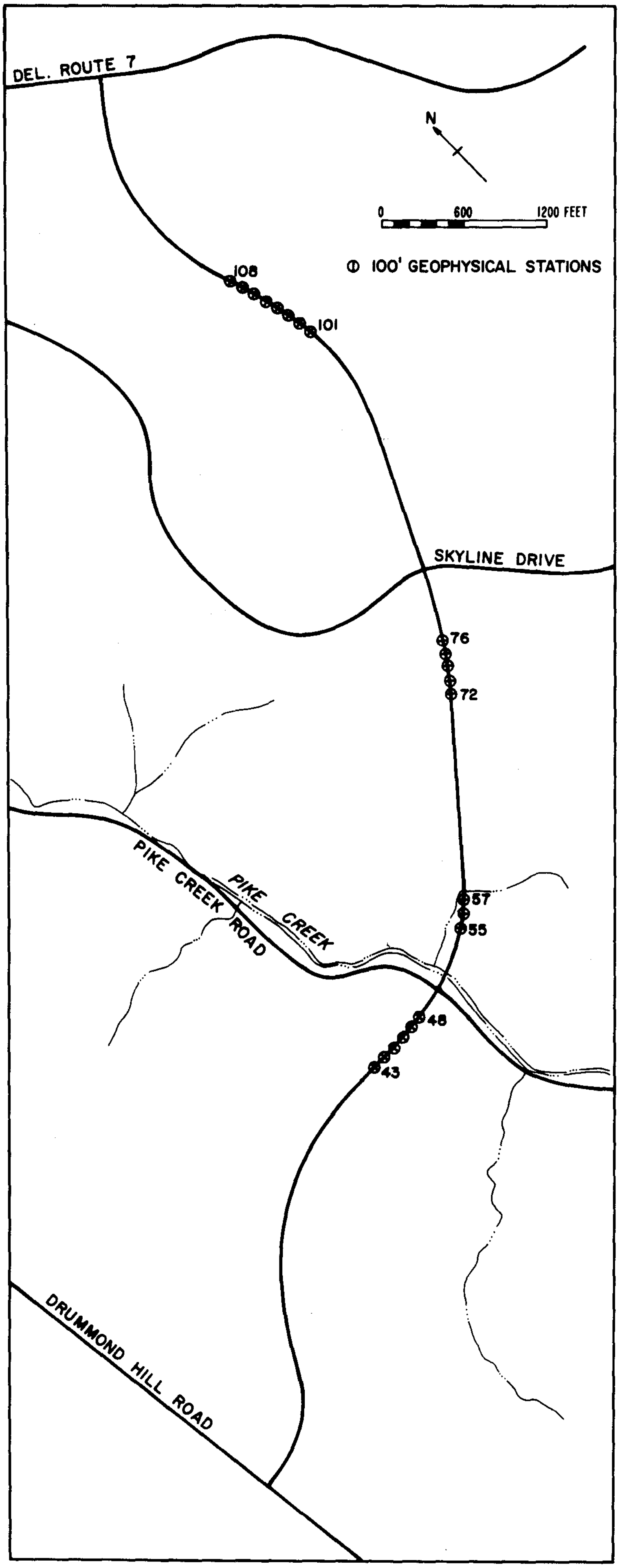

FIGURE 2. LOCATION OF GEOPHYSICAL STATIONS.

RESISTIVITY SOUNDING TECHNIQUE

Resistivity soundings were also made at intervals of 50 feet along the same center-line sections as the seismic profiles. The Wenner electrode configuration (Wenner, 1915-16) was used in all cases and data were plotted and interpreted by means of the Moore Cumulative Method (Moore, 1945). Basically, in sounding techniques, four electrodes are set in the ground in a straight line, the spacing, known as the "A spacing", is the same between all electrodes. A current is passed through the two outer electrodes and the resultant voltage drop that takes place within the earth is measured by the two inner electrodes. The spacing is then changed in some regular manner, with the spacing between electrodes always remaining equal, and readings are again made. The results in ohm-meters are plotted against "A spacing" on either log-log, semi-log, or linear graph paper. The often used Moore method plots cumulative resistivities against electrode spacing on linear paper and it is assumed that changes in slope of the straight lines obtained are due to changes in lithology. The Moore method is empirical and has no mathematical or theoretical basis. However, it is capable of giving good results when used with caution and where some drilling or other geologic control is available. In all methods of interpretation the depths at which changes occur are assumed to be beneath the center of the electrode spread.

A Soil Test ER-2 Earth Resistivity Meter was used in this investigation. Modifications were made to the original instrument to allow more rapid handling of the electrode cable and to permit easier setting up in the field.

The centers of resistivity soundings were made at the same stations as used for the shot-points in the seismic surveys. The "A spacing" was changed in 4-foot intervals with an "A spacing" range from 4 feet to 68 feet for each sounding. Because the sounding centers were moved 50 feet at a time, there was some overlap from one sounding to the other.

AREA OF INVESTIGATION

The project area includes Linden Hill Road (New Castle County Road 323) and Rankin Road (New Castle

County Road 321) and is located about five miles northeast of Newark, Delaware, and about nine miles west of Wilmington in the Piedmont Province (see Figures 1 and 2). The area is underlain predominantly by schist of the Wissahickon Formation (Early Paleozoic age). Pegmatites containing quartz, feldspar, and mica are common and faulting, folding, and jointing are often seen in outcrops. Common weathering products are both clays and sands of varying thickness. The regolith seems to average about 15 feet in depth in the study area. Some Holocene sands and gravels are present in the flood plain of Pike Creek which traverses part of the study area.

RESULTS

About thirty-five seismic refraction shots and about twenty-six resistivity soundings were made in the study. After all data were plotted, it was apparent that the seismic technique provided better definition and more consistent results than did the resistivity work. Nevertheless, the resistivity work did, in some cases, give a reasonable check with the seismic results and provided some additional control points. Both techniques gave valuable background data on the pertinent physical properties of the local rocks. Up until the present, most work of this kind had been done only in the Coastal Plain portion of the State (Barnes, 1951; Bonini, 1967; Spoljaric and Woodruff, 1970). The results for individual stations are discussed below. Station numbers both in the text and on the illustrations refer to standard surveying stations as designated by the Delaware Division of Highways.

Stations 43+00 to 48+00

Seismic velocities in this section (see Figure 2 for location) vary from less than 2000 feet per second (fps) to 25,000 fps. At least three distinct zones and sometimes four general "seismic velocity" zones can be recognized (see Figure 3). The top-most zone is interpreted to be soil and highly weathered rock, generally under ten feet in depth. This is underlain by moderately weathered rock with a seismic velocity from 2000 - 5000 fps. Breaks between these first two zones were quite distinct on the seismic record and no trouble was had in making the timing picks. The third zone occurs about 20 feet below land surface and is distinguished by a

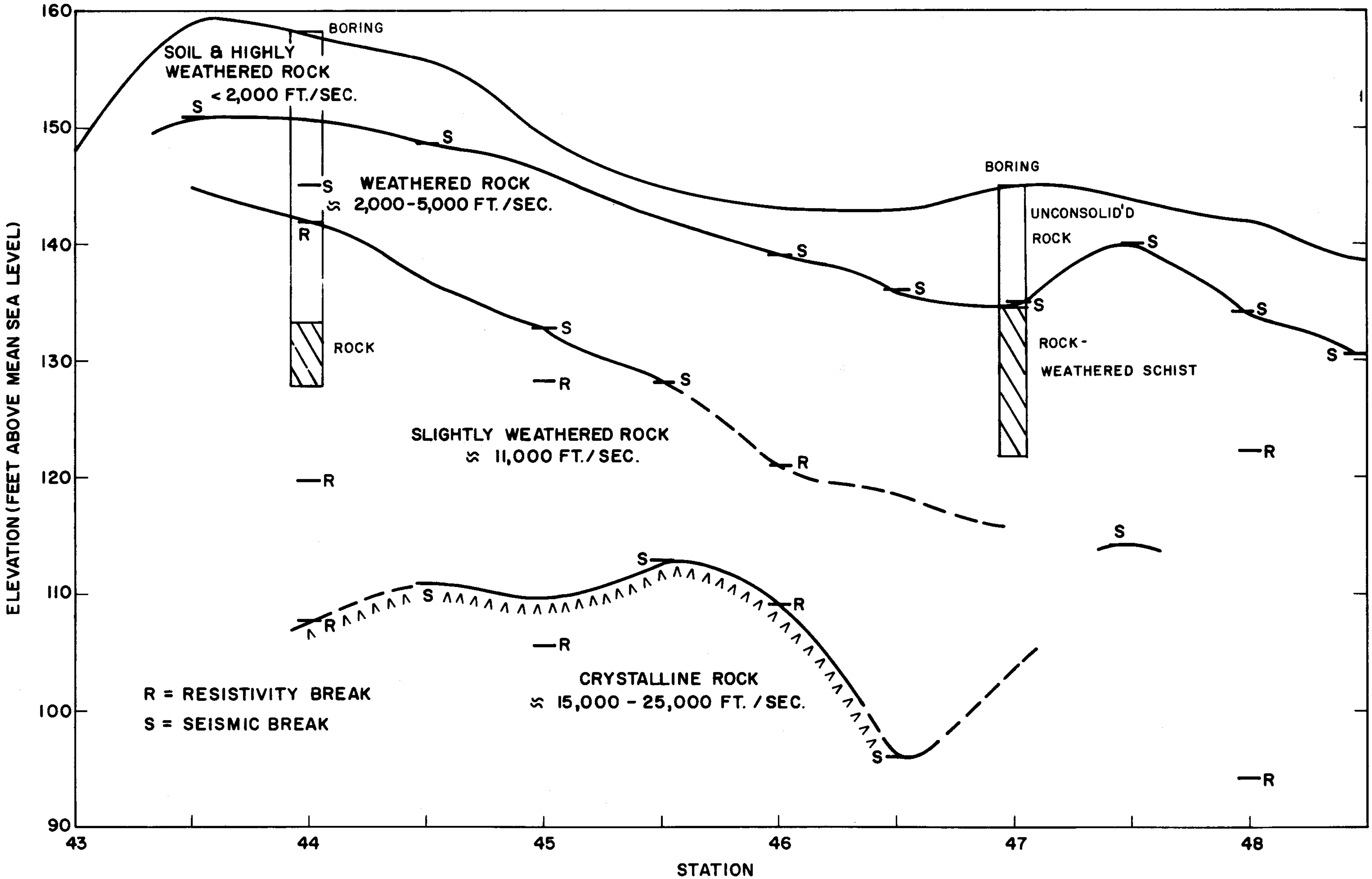

FIGURE 3. INTERPRETATION OF GEOPHYSICAL DATA AT STATIONS 43+00 TO 48+00.

velocity of around 11,000 fps except at the eastern end of the profile where the 11,000 fps velocity material is absent. Extremely high velocities, from 15,000 to 25,000 fps are found beneath the middle section of the profile and give depth solutions of about 30 feet and greater. This zone is thought to be fresh crystalline rock with no major fracturing. Field observations in the banks of a small stream near station 50+00 later verified the presence of the high velocity layer which was described as a massive, dense, quartz, biotite schist. Exposed cuts, after ripping was completed, showed that the geophysical interpretations were essentially correct.

Resistivity breaks determined by the Moore cumulative method were rather indistinct and resistivity data were generally not conclusive enough to be used as the only means of interpretation. Two resistivity depth solutions did, however, come within four to five feet of seismic solutions.

Stations 55+00 to 57+00

Very low first layer seismic velocities, some under 1000 fps are encountered in this profile. The wooded area through which the profile was run and the loose, organic top soil are both characterized by abnormally low seismic velocities. Only a small area of fresh or nearly fresh rock is inferred to be present from the seismic work and no velocities approach that of the dense rock recorded at depth in the previous profile (stations 43+00 to 48+00). The indication of slightly weathered rock at station 56+50 may be a large boulder rather than bedrock. Two deep resistivity breaks were obtained (see Figure 4) and were tentatively correlated with fresh crystalline rock. Neither borings or the later cuts reached to the depth of the breaks and thus no confirmation was available. However, if the two deeper breaks are extrapolated back to the solutions obtained by both seismic and resistivity work at stations 43+00 to 48+00 a rather consistent picture is obtained. Unaltered bedrock apparently becomes increasingly deeper to the east and it may be that resistivity methods were better able to define these deeper lithologic changes than were the refraction techniques. Ripping later did expose Wissahickon schist with considerable fracturing and deformation, possible a fault or fracture zone. This probably accounts for some of the lower velocities that were originally attributed to weathered rock.

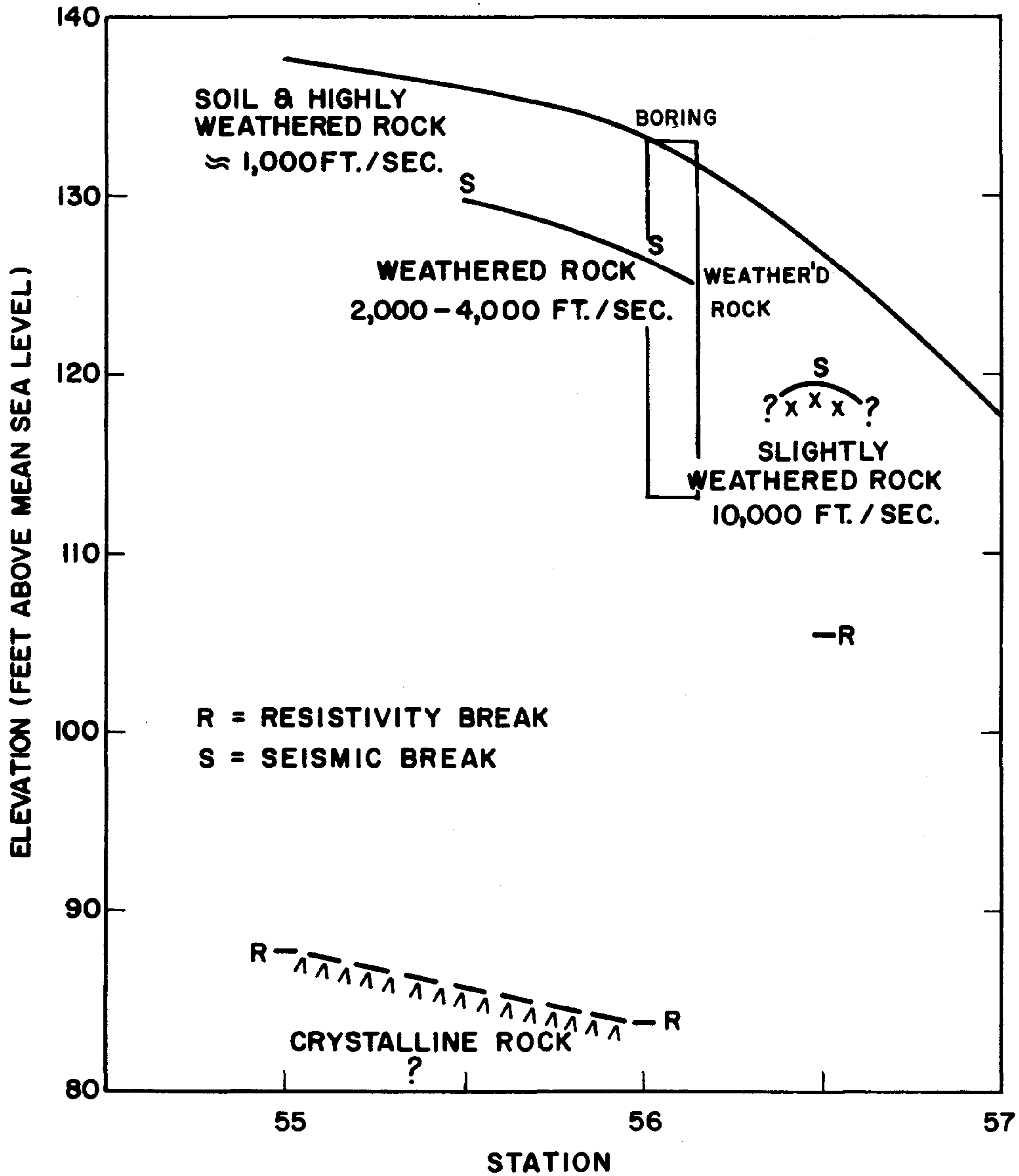

FIGURE 4. INTERPRETATION OF GEOPHYSICAL DATA AT STATIONS 55+00 TO 57+00.

Stations 72+00 to 76+50

Interpretation of this section showed the greatest thickness of overburden for any of the areas investigated. The zone interpreted as weathered rock could again be consistently picked from the seismic record. Extremely high velocities were detected only at stations 75+50 and 76+50. The resistivity break at station 73+00 (see Figure 5) was correlated with the unaltered bedrock. One resistivity solution and one seismic solution could not be reasonably correlated with other breaks and were ignored in the interpretation. Note that at station 74+00 both the seismic and resistivity depth solutions were in excellent agreement. Investigation of the later cuts showed the exposed material to be thinly bedded, moderately weathered Wissahickon schist with some small pegmatites. At a few locations denser, less altered schist was observed to protrude into the surrounding rock. Such an occurrence was interpreted correctly at station 74+00, although other such occurrences were not detected from the basic data.

Stations 101+00 to 108+50

At the eastern end of the proposed road-cut four distinct lithologies were postulated but only two lithologies could be detected at the western end. Part of this difference was due to external noise at the western end of the profile which masked the energy of the seismic shot. The resistivity correlation with the seismic data was slightly better for this profile than for the others. At station 107+00 two deeper resistivity depth solutions were obtained but could not be correlated with any known feature. Investigation of the later road-cuts showed that the "slightly weathered rock" (see Figure 6) should indeed extend west to station 103+00. Ripping was reported to be easy in the upper portion of the road-cut but difficult in the lower part. Again, some "knobs" of relatively fresh rock protruded through the weathered material.

CONCLUSIONS

Seven borings were available in the study area. Lithology as determined by geophysical means agreed within one to two feet of the drilling records for two holes, within five feet for one hole, and matched the

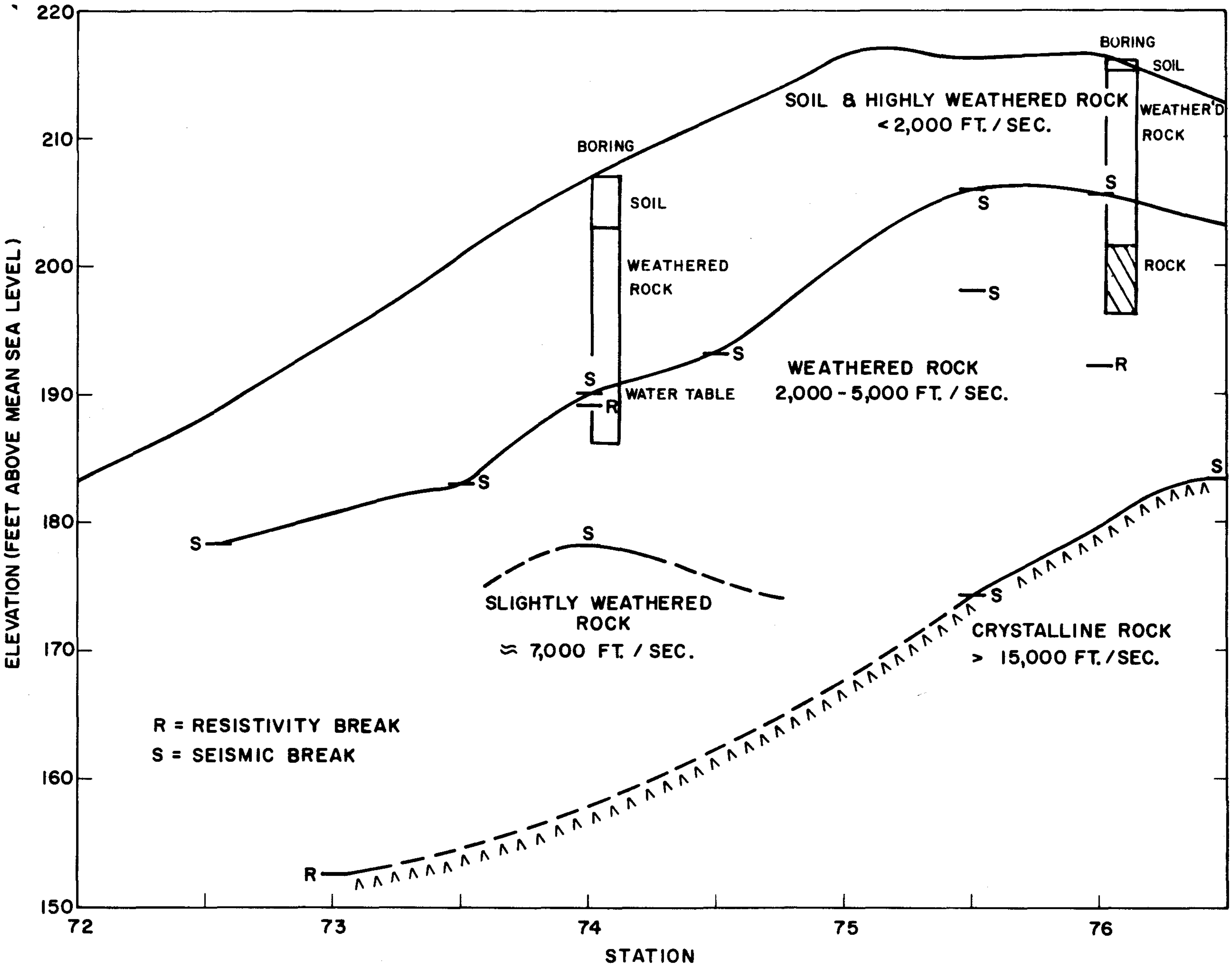

FIGURE 5. INTERPRETATION OF GEOPHYSICAL DATA AT STATION 72+00 TO 76+50.

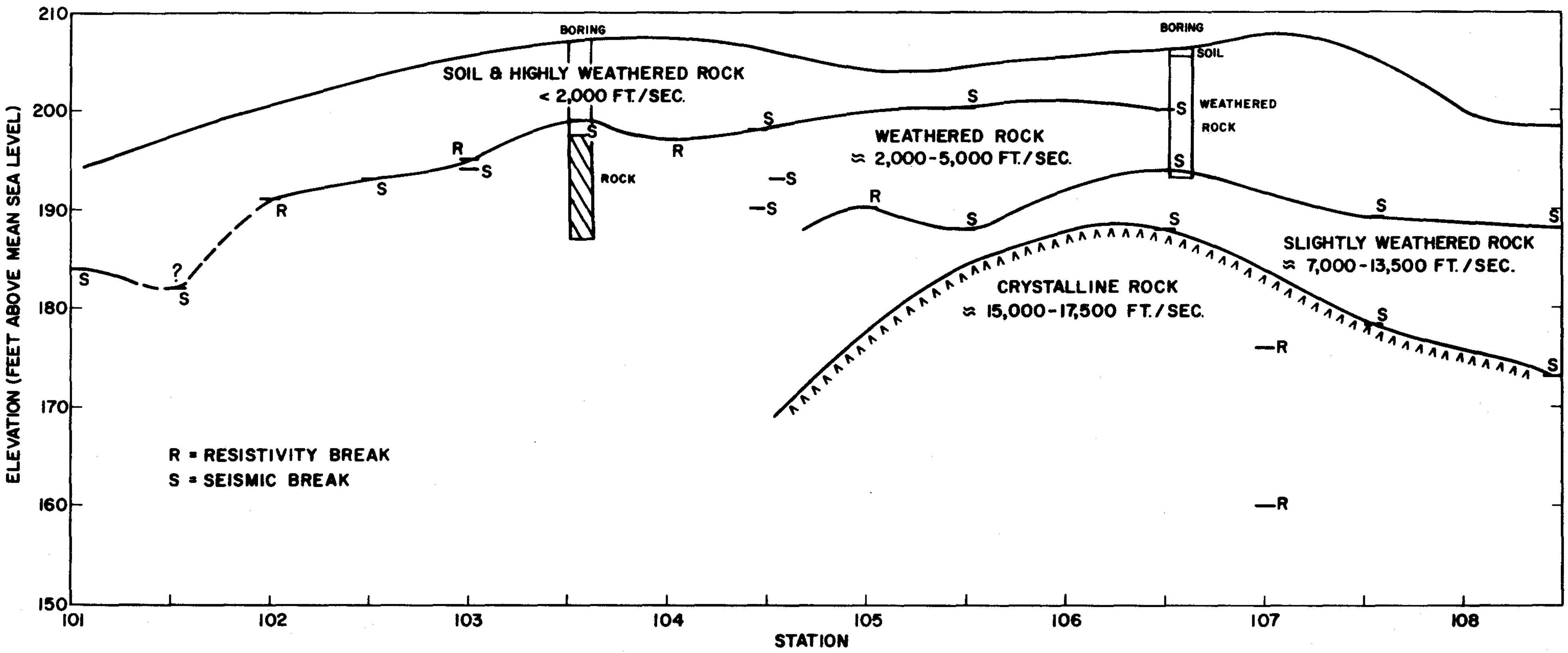

FIGURE 6. INTERPRETATION OF GEOPHYSICAL DATA AT STATION 101+00 TO 108+50.

general lithology in two holes where only a single lithology was recorded. Correlation with drilling logs in the remaining two holes was poor. Part of the difficulty in correlating with driller's logs was due to terminology. Material having a seismic velocity of about 2000-5000 feet per second and designated as "weathered rock" in the geophysical studies (see Figures 3, 4, 5, 6) was often described simply as "rock" on the drilling log. In general more detail could be inferred from the geophysical work but the detail was not always meaningful in terms of highway construction practices. The trend of the top of unweathered crystalline rock matched very well with the trend as defined by drilling and by the later road-cuts.

It is estimated that a three man crew could run approximately 1500 feet of seismic line with reversals (or 3000 feet one way) with shot-points every 50 feet in an eight-hour day.

This study generally showed that geophysical refraction methods can be quite successful in determining the depth of overburden and the distance to unaltered rock in the Piedmont Province of Delaware. Electrical resistivity techniques gave poor to fair results when interpreted without benefit of other data. However, when viewed in light of the seismic results, it was possible to make some correlations. In both techniques some degree of familiarity with the area and some control such as outcrops or test borings are needed as a basis for interpretation.

In future work it is recommended that an energy source greater than that provided by an electric blasting cap be used in situations where external noise is a factor or where overburden is relatively deep. The full capabilities of the instrument used for this study cannot be realized unless this change is made. With prudent interpretation the use of geophysical methods should reduce the number of test borings needed in highway projects.

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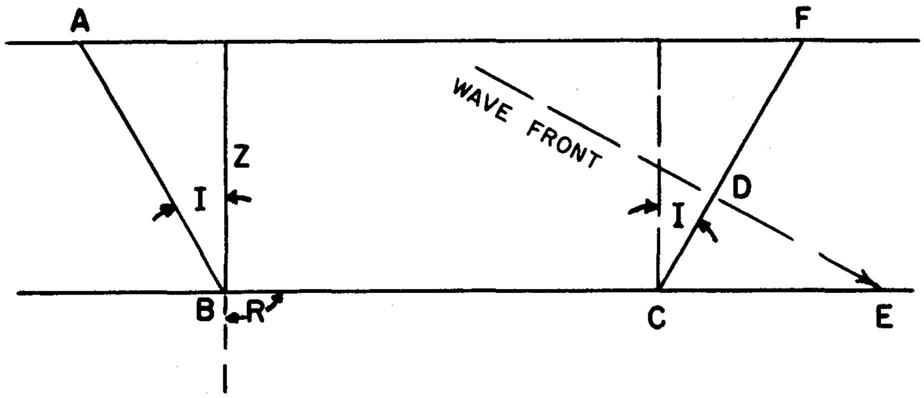
APPENDIX A

DERIVATION OF GENERAL EQUATION FOR FINDING DEPTH TO FIRST INTERFACE



CDF = ray path of refracted wave

According to Snell's Law, a seismic wave will travel along the interface, BC, when the angle of incidence (I) is such that the angle of refraction (R) is 90° to the normal of the interface.

For the refracted wave: $\text{Sin } I = \frac{CD}{CE}$

$CE = V_2 T_2$ Where: V_1 = velocity of first layer (Top)

V_2 = velocity of second layer

T_1 = time in first layer

T_2 = time in second layer

Therefore: $\text{Sin } I = \frac{V_1 T_1}{V_2 T_2}$

When $T_1 = T_2$: $\text{Sin } I = \frac{V_1}{V_2}$

The total refracted wave travel-time to the surface at F

is: $T = T_{ab} + T_{bc} + T_{cf}$

OR

$$T = \frac{Z}{V_1 \text{Cos } I} + \frac{X-2Z \text{ Tan } I}{V_2} + \frac{Z}{V_1 \text{Cos } I}$$

and by trigonometric identities:

$$T = \frac{2Z}{V_1 \text{Cos } I} + \frac{2Z \text{ Sin } I}{V_2 \text{ Cos } I} + \frac{X}{V_2}$$

$$T = \frac{2Z}{V_1 \text{Cos } I} (1-\text{Sin}^2 1) + \frac{X}{V_2} = \frac{X}{V_2} + \frac{2Z \text{Cos } I}{V_1}$$

$$T = \frac{X}{V_2} + 2Z \frac{\sqrt{1-(V_1^2/V_2^2)}}{V_1}$$

$$T = \frac{X}{V_2} + 2Z \frac{\sqrt{V_2^2 - V_1^2}}{V_2 V_1}$$

At the critical distance: T (direct wave, AF) = T (refracted wave, ABCF)

OR

$$\frac{X}{V_1} = \frac{X}{V_2} + 2Z \frac{\sqrt{V_2^2 - V_1^2}}{V_2 V_1}$$

$$Z = \frac{1}{2} \frac{X_c V_1 V_2}{\sqrt{V_2^2 - V_1^2}} \left(\frac{1}{V_1} - \frac{1}{V_2}\right)$$

Where: X_c = critical distance

Z = depth to interface

$$Z = \frac{X_c}{2} \sqrt{\frac{V_2 - V_1}{V_2 + V_1}}$$

APPENDIX B

DESCRIPTION OF EXPOSURES ALONG LINDEN HILL ROAD

(By J. C. Miller)

Stations 10-15:	Wissahickon schist, thinly laminated, moderately weathered, contains lens-like quartz bodies 2-3 feet in length and 3-6 inches thick. Minor pegmatites follow the strike of the schist. Overburden: +5-10 feet thick.
Station 20:	Wissahickon schist, thinly laminated, less weathered than at stations 10-15. Strike N62E, dip N78. Dominant joints are N5W, near vertical.
Station 40:	Wissahickon schist, thinly laminated, slightly weathered, contains quartz pods and lenses 2-3 feet long and 2-4 inches thick. Strike N65E, dip N82. Dominant joints are N54W, S80. Between stations 40 and 50 schist is soft and easily ripped. Hardness increases with depth.
Station 50:	Wissahickon schist, very hard, thickly laminated quartz biotite schist. Strike N70E, dip S75. Dominant joints are N7W, S79; N50W, N82.
Stations 53-57:	Wissahickon schist, less weathered than at preceeding stations except at station 50, considerable fracturing and deformation, possibly a fault zone.
Station 60:	Wissahickon schist, thickly laminated, moderately weathered. Joints are N2E, vertical.
Stations 73-77:	Wissahickon schist, thinly bedded, moderately weathered, small chevron folds and discontinuous pegmatites. Strike N70E, dip S75. Joints are N10W, vertical.

Appendix B (Continued)

Station 83:	Wissahickon schist, thickly laminated, weathered, easily ripped. Several joint sets.
Station 96:	Wissahickon schist, weathered, contains pegmatites.
Stations 102-104:	Wissahickon schist, highly contorted, moderately weathered. Strike N70E, dip near vertical. Cut by pegmatites, several joint sets. Upper part ripped quite readily, lower part hard and resistant to ripping.
Station 122:	Wissahickon schist, contorted and cut by pegmatites, ripping easy.

APPENDIX C

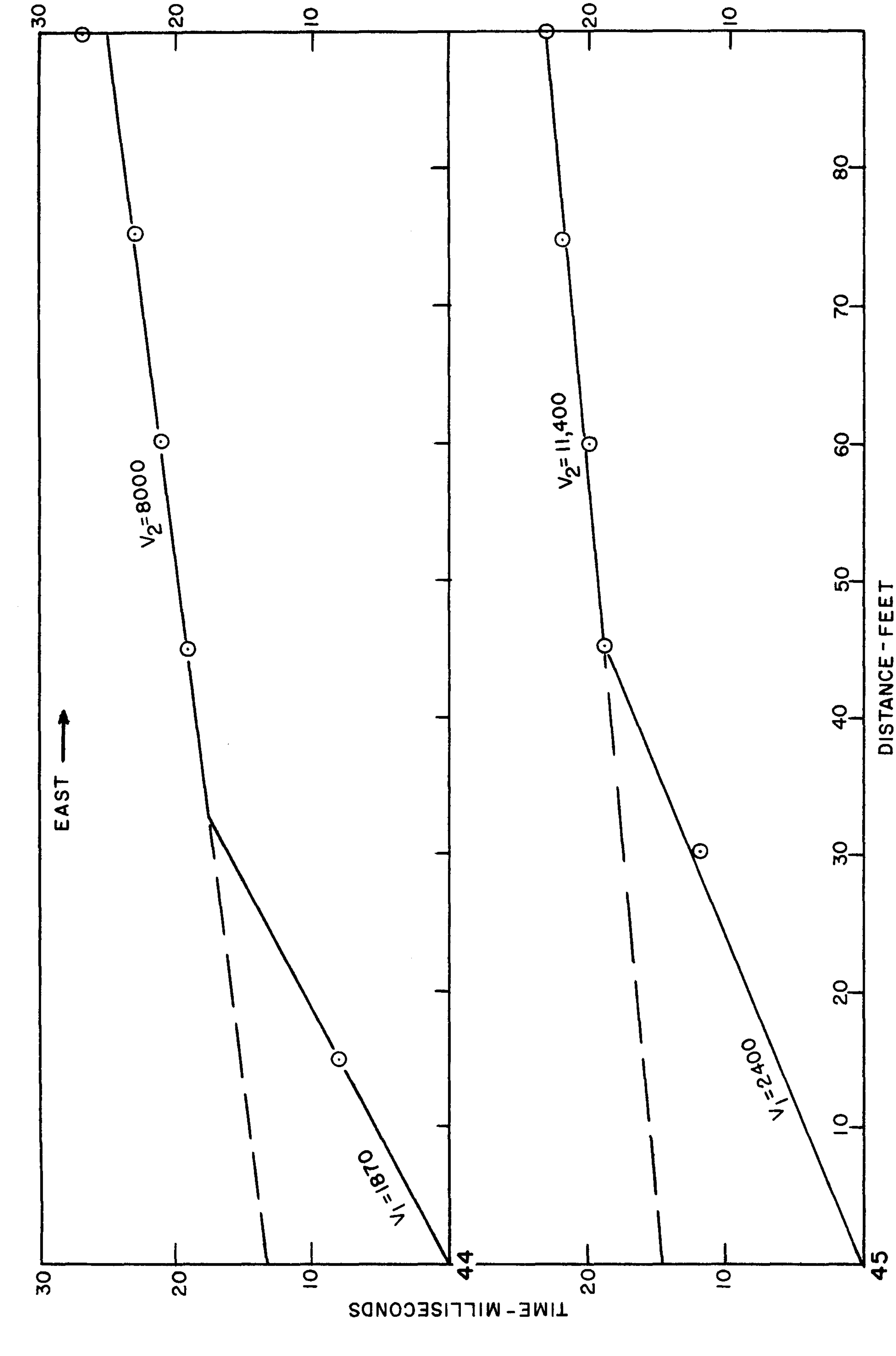
SEISMIC REFRACTION TIME - DISTANCE GRAPHS

V_1 = velocity of first layer in feet per second (top)

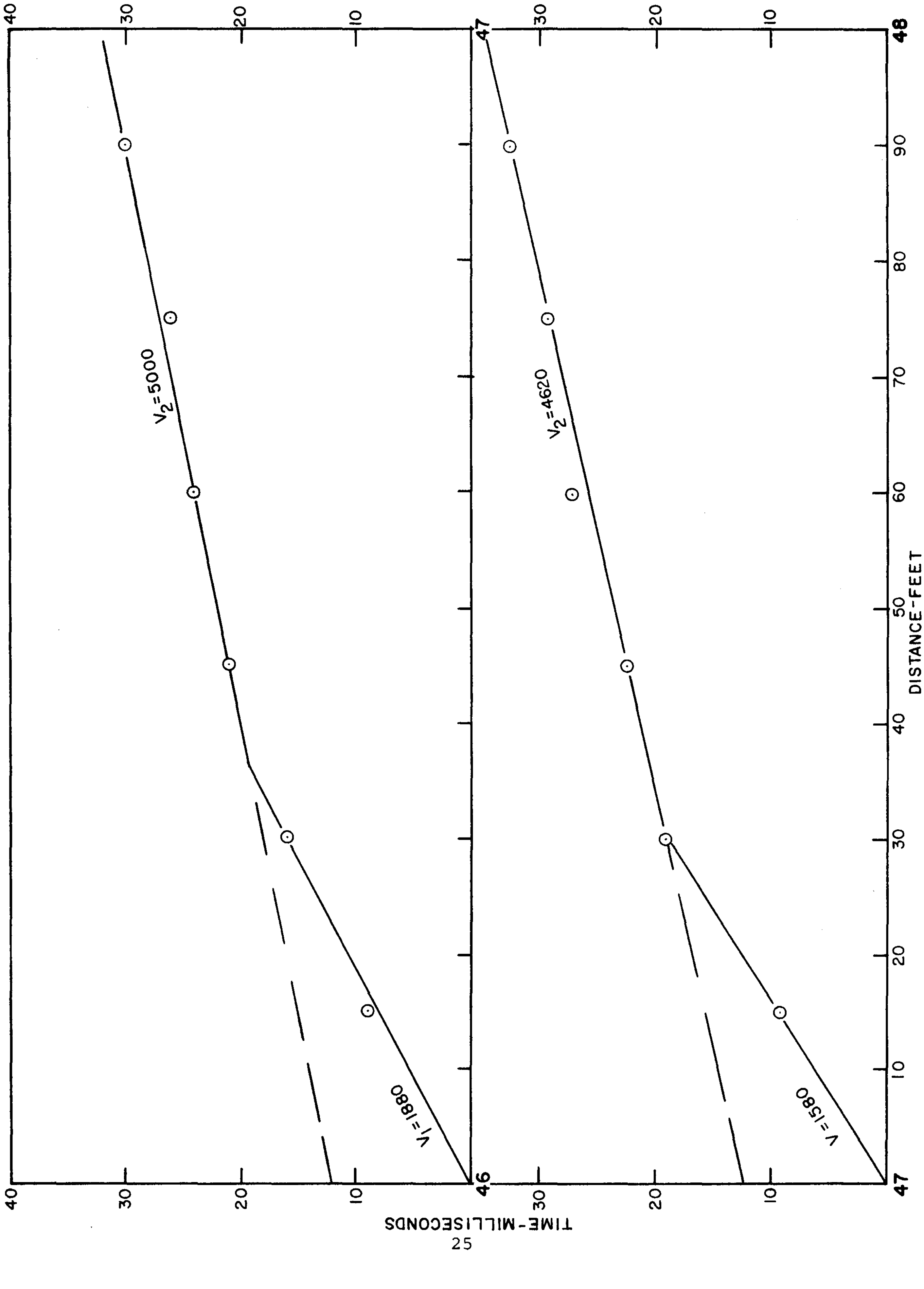
V_2 = velocity of second layer in feet per second

V_3 = velocity of third layer in feet per second

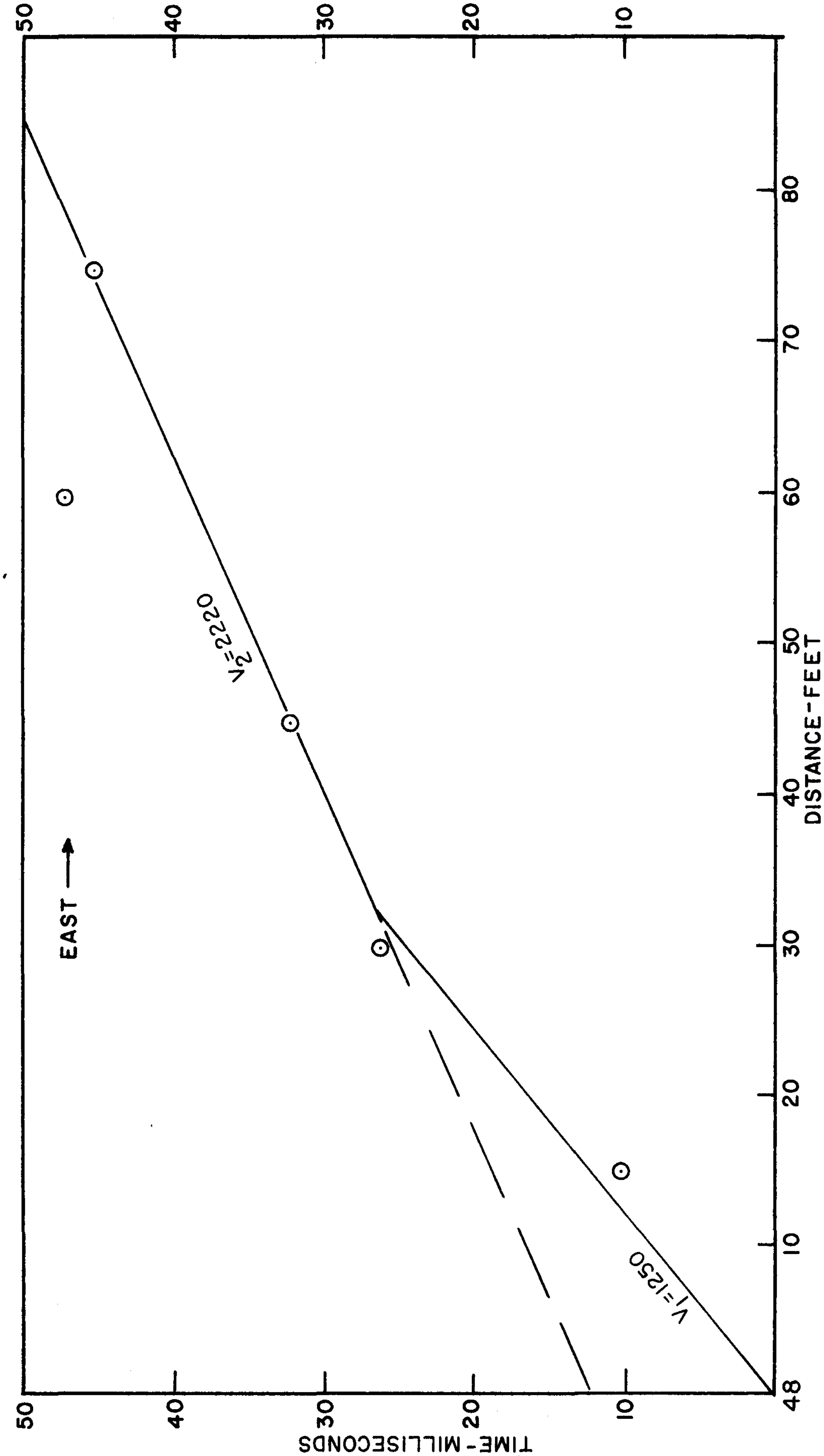
43-48, 55-57, 72-76, 101-108: surveying station numbers

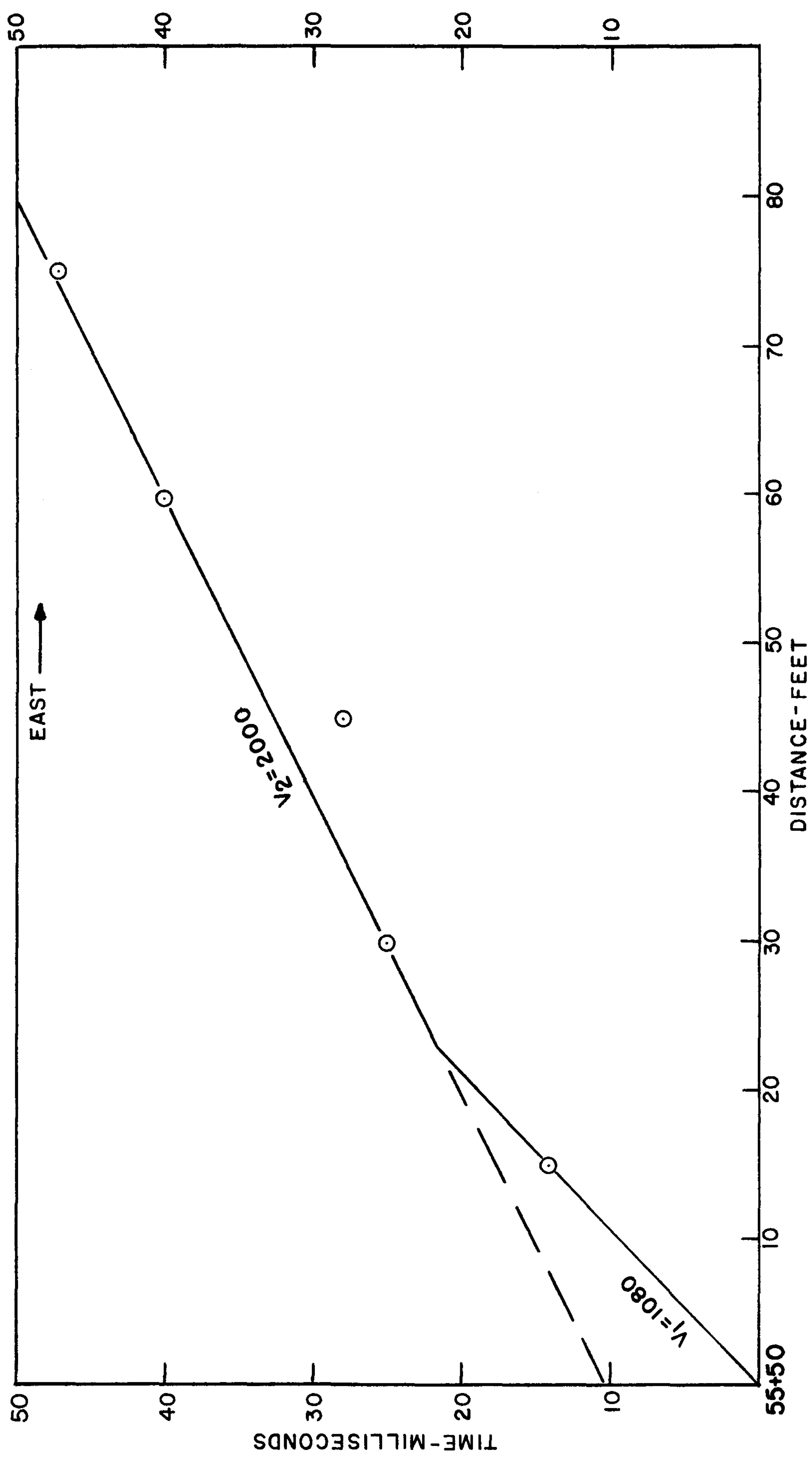


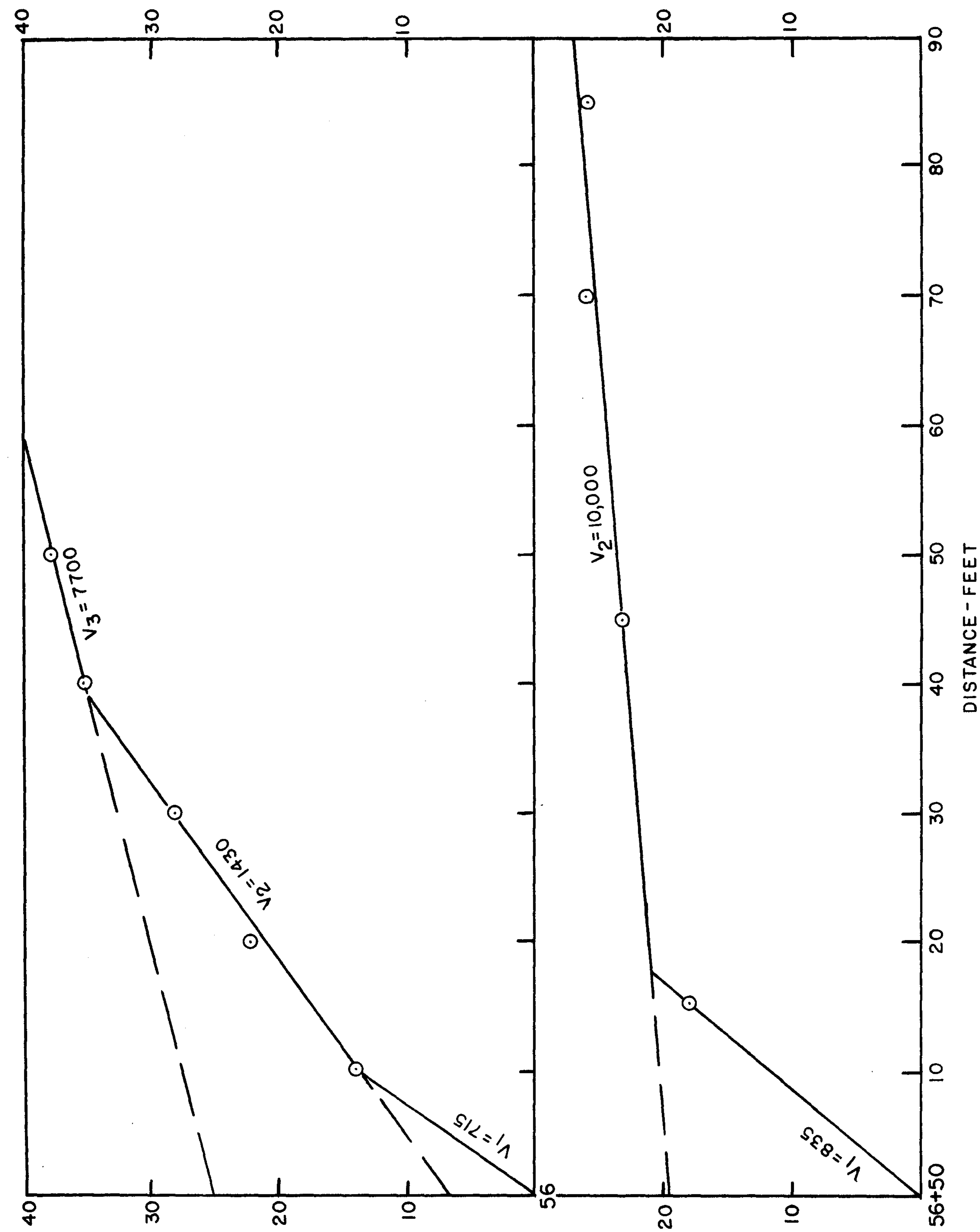
EAST
V_2=8000
V_1=1870
44
V_2=11,400
V_1=2400
45
TIME - MILLISECONDS
DISTANCE - FEET

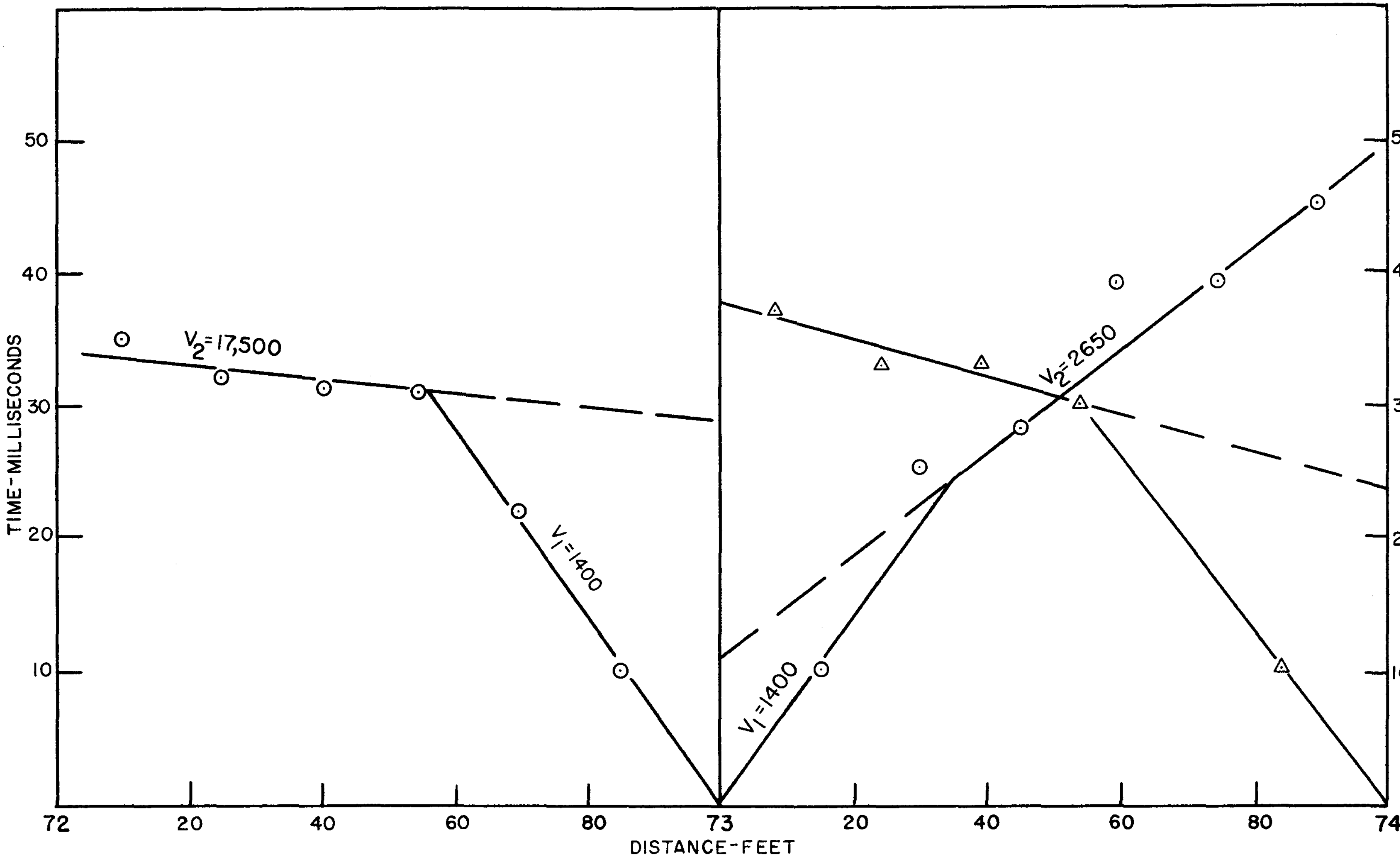


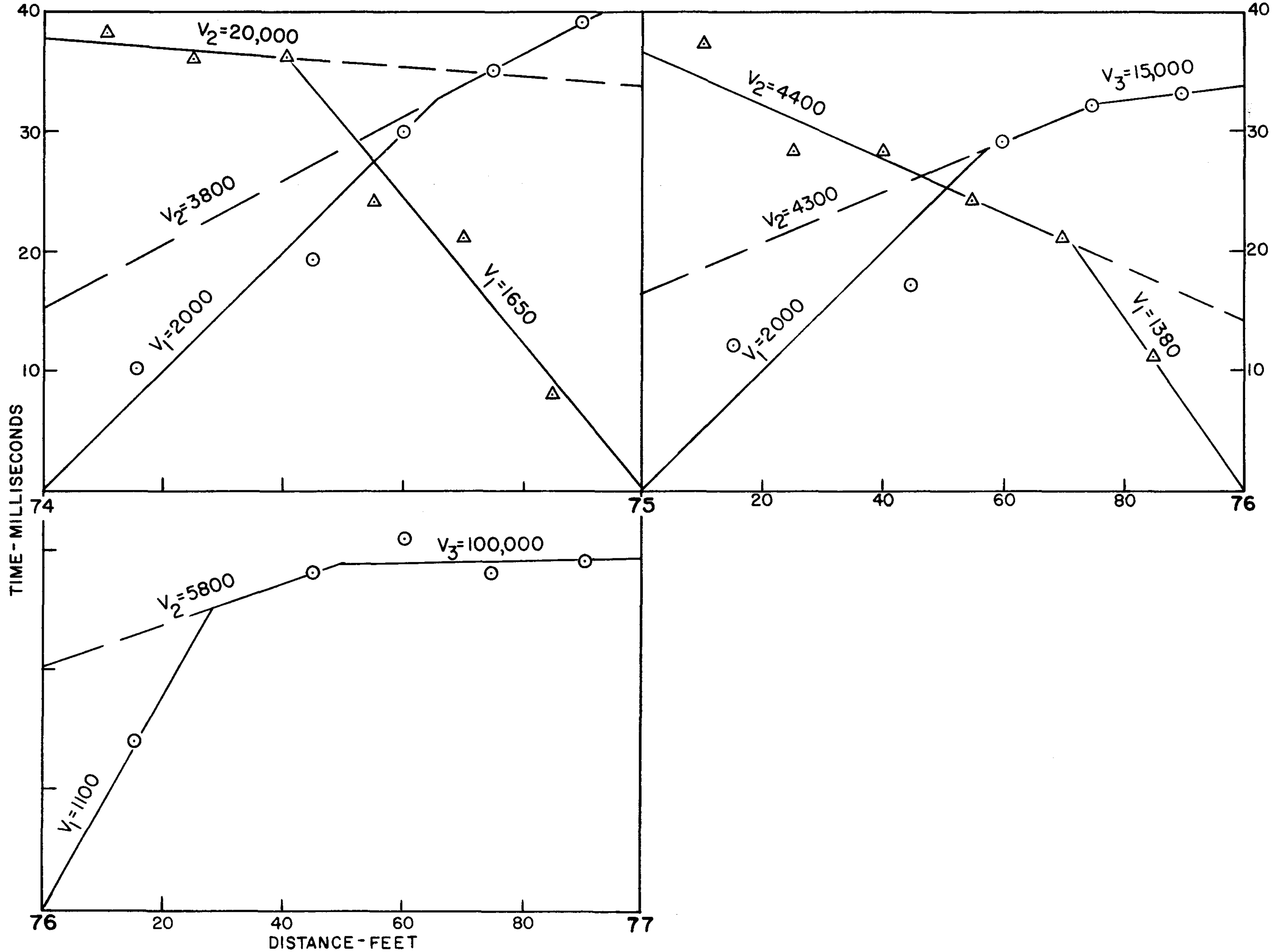
V_2=5000
V_1=1880
V_2=4620
V=1580
DISTANCE-FEET
TIME-MILLISECONDS
46
47
48


EAST
$V_2=2220$
$V_1=1250$
TIME-MILLISECONDS
DISTANCE-FEET
10
20
30
40
50
60
70
80

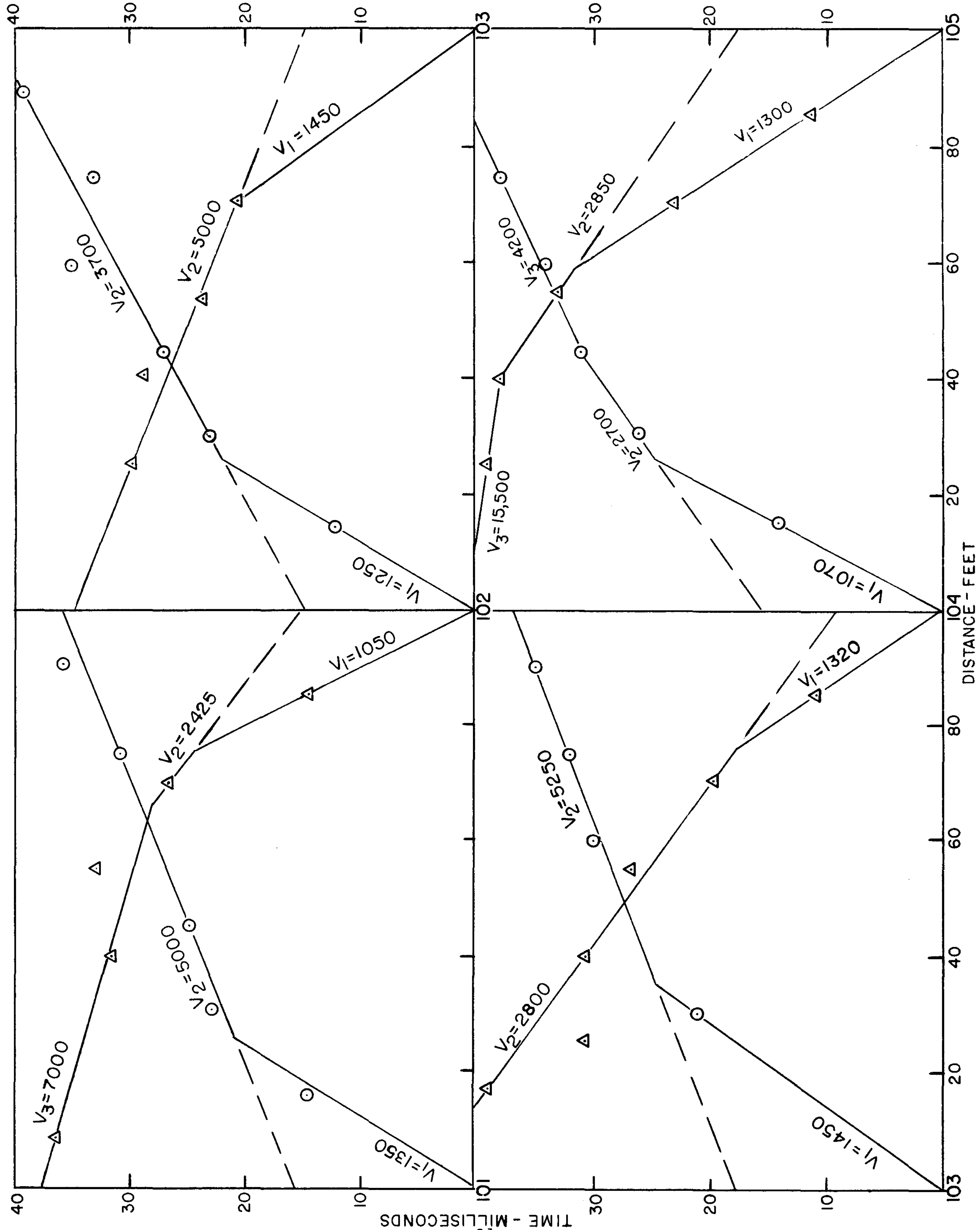

TIME-MILLISECONDS
DISTANCE-FEET
EAST
V_2=2000
V_1=1080
55+50
10
20
30
40
50
60
70
80

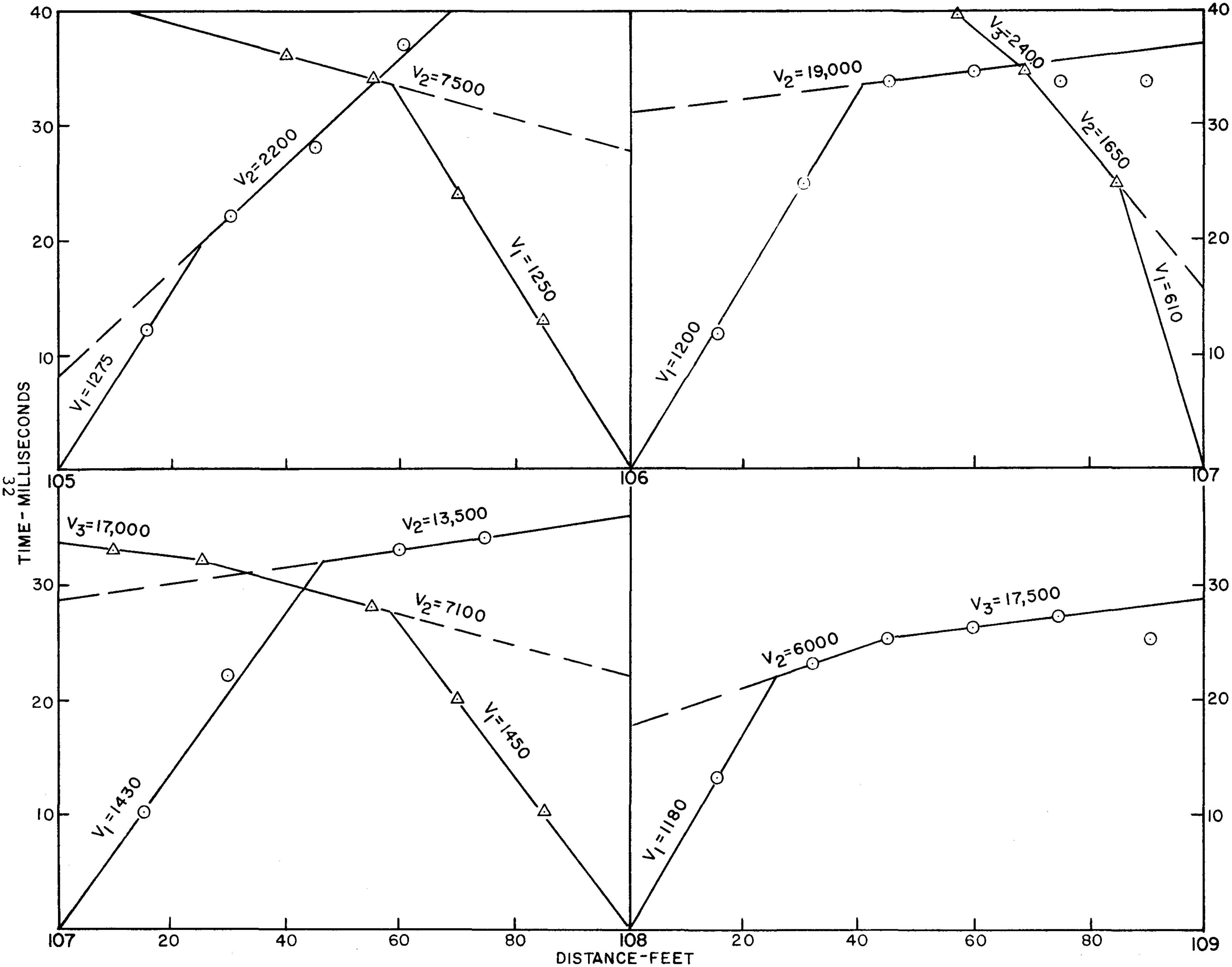

TIME - MILLISECONDS
DISTANCE - FEET
V1 = 715
V2 = 1430
V3 = 7700
V1 = 835
V2 = 10,000
56
56+50
10
20
30
40
50
60
70
80
90


TIME-MILLISECONDS
DISTANCE-FEET
V_2=17,500
V_1=1400
V_1=1400
V_2=2650
72
73
74
20
40
60
80
10
30
50



40
30
20
10
TIME - MILLISECONDS
74
75
76
77
20
40
60
80
DISTANCE - FEET
V_2=20,000
V_2=3800
V_1=2000
V_1=1650
V_2=4400
V_2=4300
V_1=2000
V_3=15,000
V_1=1380
V_3=100,000
V_2=5800
V_1=1100


TIME - MILLISECONDS
DISTANCE - FEET
101
102
103
104
105
V1=1350
V3=7000
V2=5000
V2=2425
V1=1050
V1=1250
V2=3700
V2=5000
V1=1450
V1=1450
V2=2800
V2=5250
V1=1320
V1=1070
V2=2700
V3=15,500
V3=4200
V2=2850
V1=1300



TIME - MILLISECONDS
DISTANCE-FEET
40
30
20
10
105
106
107
108
109
20
40
60
80
V_1=1275
V_2=2200
V_2=7500
V_1=1250
V_2=19,000
V_3=2400
V_2=1650
V_1=610
V_1=1200
V_3=17,000
V_2=13,500
V_2=7100
V_1=1450
V_1=1430
V_3=17,500
V_2=6000
V_1=1180